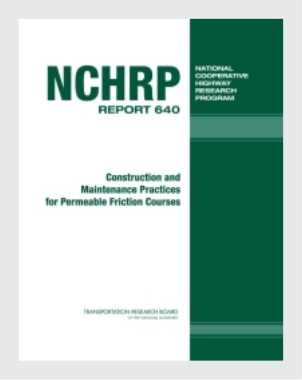


Construction and Maintenance Practices for Permeable Friction Courses

DETAILS

120 pages | | PAPERBACK
ISBN 978-0-309-11796-8 | DOI 10.17226/14310

AUTHORS

Rajib B Mallick; Walaa S Mogawer; Lily D Poulikakos; Manfred N Partl; L Allen Cooley; Jimmy W Brumfield; Gary Hicks; Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 640

Construction and Maintenance Practices for Permeable Friction Courses

L. Allen Cooley, Jr.
Jimmy W. Brumfield
BURNS COOLEY DENNIS, INC.
Ridgeland, MS

Rajib B. Mallick
WORCESTER POLYTECHNIC INSTITUTE
Worcester, MA

Walaa S. Mogawer
UNIVERSITY OF MASSACHUSETTS
North Dartmouth, MA

Manfred Partl
Lily Poulikakos
EMPA
Dübendorf, Switzerland

Gary Hicks
CALIFORNIA STATE UNIVERSITY, CHICO
Chico, CA

Subject Areas
Pavement Design, Management, and Performance • Materials and Construction • Maintenance

---

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2009
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 640

Project 09-41
ISSN 0077-5614
ISBN 978-0-309-11796-8
Library of Congress Control Number 2009934826

COPYRIGHT PERMISSION

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

The Transportation Research Board of the National Academies, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

Copyright National Academy of Sciences. All rights reserved.

COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR NCHRP REPORT 640

Christopher W. Jenks, *Director, Cooperative Research Programs*
Crawford F. Jencks, *Deputy Director, Cooperative Research Programs*
Edward T. Harrigan, *Senior Program Officer*
Eileen P. Delaney, *Director of Publications*
Margaret B. Hagood, *Editor*

NCHRP PROJECT 09-41 PANEL
Field of Materials and Construction—Area of Bituminous Materials

Dale Rand, *Texas DOT, Austin, TX*
Brad W. Allen, *New York State DOT, Albany, NY*
James Mahoney, *University of Connecticut, Storrs, CT*
Kevin K. McGhee, *Virginia DOT, Charlottesville, VA*
Joseph F. Peterson, *California DOT, Marysville, CA*
Ronald A. Sines, *Oldcastle Materials, Leominster, MA*
Michael Arasteh, *FHWA Liaison*
Nelson Gibson, *FHWA Liaison*
Thomas Harman, *FHWA Liaison*
Frederick Hejl, *TRB Liaison*

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 9-41 by Burns Cooley Dennis, Inc. of Ridgeland, Mississippi. Dr. Allen Cooley, Senior Materials/Pavements Engineer of Burns Cooley Dennis, Inc. was the Principal Investigator. Co-Principal Investigators were Dr. Rajib Mallick of Worcester Polytechnic Institute and Dr. Walaa Mogawer of the University of Massachusetts. Other contributing authors were Mr. Jimmy Brumfield of Burns Cooley Dennis, Inc., Manfred Partl and Lily Poulikakos of EMPA, and Gary Hicks of MACTEC.

FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report recommends design, construction, and maintenance guidelines for permeable friction courses (PFC). It presents recommended practices for (1) design and construction of PFC and (2) PFC maintenance and rehabilitation. The report will be of immediate interest to public and private sector engineers with responsibility for the specification, construction, and maintenance of PFC.

Permeable friction courses (PFC), which include new generation open-graded friction courses (OGFC), asphalt-rubber friction courses, and porous European mixes, have wide use throughout the southern and western United States. PFC reduces hydroplaning, splash and spray, and pavement noise, and improves ride quality and the visibility of pavement markings in wet weather. Properly designed and constructed PFCs are durable and exhibit service lives of 10 to 14 years. Perhaps the only hindrance to their wider use in cold climates is a concern that, like the OGFC introduced in the 1970s, PFC might be susceptible to freeze-thaw damage and black ice formation and require more intensive winter maintenance practices.

The objective of this research was to develop practical guidelines for PFC design, construction, and maintenance that maximize the advantages and minimize the disadvantages associated with PFC use. A comprehensive, critical review of the worldwide literature on PFC design, performance, construction, and maintenance was conducted, with attention to PFC use in cold climates, and worldwide agency practice, and specifications for PFC from the United States and the rest of the world were surveyed. Based on an analysis of the results of this review and survey, two key products were prepared: (1) a recommended practice for materials selection, design, and construction of PFC and (2) a recommended practice for PFC maintenance and rehabilitation.

The research was performed by Burns Dennis Cooley, Inc. of Ridgeland, Mississippi. The report fully documents the review and analysis of the highway engineering literature and agency specifications leading to the recommended practices. The recommendations are under consideration for possible adoption by the AASHTO Highway Subcommittee on Construction and Subcommittee on Maintenance.

CONTENTS

SUMMARY

Construction and Maintenance Practices for Permeable Friction Courses

The objective of this project was to recommend design, construction, maintenance, and rehabilitation guidelines that will maximize the advantages and minimize the disadvantages associated with the use of permeable friction courses (PFCs). The research approach entailed two primary tasks: an annotated literature review and a survey of state departments of transportation. As no laboratory or field work was conducted as part of this project, a significant amount of time and effort was spent on the literature review and survey of agencies. Information gathered from these two activities was categorized according to the following subjects: general use of PFCs, benefits of the use of PFCs, materials and mix design, inclusion of PFCs in structural design, construction of PFCs, maintenance of PFCs, rehabilitation of PFCs, performance of PFCs, and limitations on the use of PFCs.

For each of the subjects listed above, the information gathered from the literature review and survey of agencies was used to develop a state-of-practice on the use of PFCs. This state of practice is considered to be representative of practices used around the world, as a significant amount of literature was obtained and reviewed from other countries. The information gathered also was used to develop guidelines on the use of PFCs in order to accomplish the project objectives.

PFCs have been used since the 1970s. The initial use of PFCs was in Europe. Europeans took the U.S. version of open-graded friction courses developed in the 1930s through the 1970s and, through research, improved the performance of these mixes. Improvements primarily included the use of modified asphalt binders and fibers. The modified binders and fibers alleviated some of the problems that were encountered with open-graded friction courses in the United States.

Benefits realized from the use of PFCs are primarily associated with improved safety. PFCs have been shown to improve wet weather frictional properties, reduce the potential for hydroplaning, reduce the amount of splash and spray, and improve visibility. Other benefits identified in the literature included resistance to permanent deformation, smoother pavements (and, hence, improved fuel economy), reduced tire/pavement noise levels, and other environmental benefits.

Materials and mix design properties specified for PFCs were obtained from around the world. Materials used to comprise PFCs are coarse aggregates, fine aggregates, asphalt binders, and stabilizing additives. Stabilizing additives are used in PFCs to minimize the potential for draindown because draindown was identified as a major problem with open-graded friction courses during the 1970s and 1980s. Numerous methods of designing PFC mixes were identified; based on the information, the design of PFC mixes includes four primary steps: selection of appropriate materials, selection of a design aggregate gradation, selection of optimum asphalt binder content, and performance testing.

For the most part, PFCs are not given structural value within pavement structures. The literature did provide evidence, however, that PFCs do lead to cooler temperatures in underlying pavement layers. Cooler temperatures within the underlying layers provide a net increase in stiffness within these layers. This alone indicates that PFCs do add some structural value. The literature also suggested that there are two properties needed in order to establish a minimum lift thickness for PFCs: rain intensity and the permeability characteristics of the PFC layer. This information was used to develop a simple method for determining the minimum lift thickness for a PFC layer.

Construction of PFC layers is similar to most hot-mix asphalt (HMA) mixes with some slight differences. The primary difference in production of PFC is incorporation of stabilizing additives, namely fibers, because special equipment is needed for introduction of fibers. An important step in the construction process is transportation. Precautions should be taken to minimize the amount of cooling that occurs during transportation. Compaction of PFCs also is slightly different than for typical HMA; compaction is not conducted to meet some specified density, but rather, compaction is conducted to seat the aggregates. Only steel wheel rollers are used on PFCs, as vibratory rollers tend to fracture aggregates during compaction and pneumatic tire rollers tend to pick up the PFC.

The survey of agencies suggested that none of the agencies in the United States currently conduct operations to clean clogged PFC layers. Other general activities include preventative surface maintenance and corrective surface maintenance. Winter maintenance on PFCs is a perceived problem worldwide. Definitive methods for addressing PFC winter maintenance were not identified during this project. The literature suggested that experience was the only method for developing a winter maintenance program. However, the literature was explicit that PFC layers require a different winter maintenance program than typical dense-graded layers. PFCs reach freezing temperatures before dense-graded layers and stay at a freezing temperature longer. Therefore, more winter maintenance materials are required.

Rehabilitation of PFC layers is reasonably uniform around the world. In most instances, rehabilitation involves milling the existing PFC layer and replacing it with another PFC layer or another type of HMA. The literature did suggest that PFCs should not be overlaid unless they are sufficiently sealed.

The performance of PFC layers was divided into two separate categories: service life and performance life. Service life was defined as the length of time a PFC maintains its frictional properties and smoothness. Performance life was defined as the length of time the PFC maintains its beneficial properties. No specific literature was found that tracked the service or performance life of PFC layers. However, the literature and survey of agencies did suggest that most agencies expect 8 to 10 years of service life.

Limitations identified within the literature were essentially either related to winter events or clogging of PFC layers. Areas prone to heavy snowfalls are not recommended for placement of PFC layers. Areas that contain a lot of dirt or debris (e.g., near farms) also are not recommended for PFC placement. Other situations where PFCs are not recommended include projects that require long haul times, inlays, projects that require a lot of hand work, and critical pavement locations, including intersections or locations with heavy turning movements.

CHAPTER 1

Introduction and Research Approach

Permeable friction courses (PFC), which include new generation open-graded friction courses (OGFCs), asphalt-rubber friction courses, and porous European mixes (PEM), have gained wide acceptance throughout the southern and western portions of the United States. PFCs are rapidly gaining popularity due to their safety and environmental benefits. Wearing layers comprised of PFC mixes have proven a safe driving surface. These mixes reduce hydroplaning and splash and spray while also improving wet weather friction and visibility of pavement markings, especially in wet weather. PFC layers also have been shown to be beneficial to the environment due to the ability to reduce[m1][m2] tire/pavement noise and improving the quality of water runoff during rain events. PFCs also have been identified as a candidate technology for cool pavements.

There are numerous differences between PFC and the first generation OGFCs widely used in the United States during the 1970s and 1980s. PFCs typically contain at least 20 percent more asphalt binder (by volume) than conventional OGFC mixes. They are generally designed to have 18 percent air voids or more, whereas conventional OGFC mixture typically contained between 10 and 15 percent air voids. The void structure of PFC allows the mix to be more permeable than conventional OGFC and less likely to trap water that could freeze. Unlike conventional OGFC, PFCs may contain fibers, polymer-modified asphalt binders, or asphalt-rubber, alone or in combination. Permeable friction courses are typically placed in thicker layers than conventional OGFC (1.0 to 2.0 inches as opposed to 1.0 inch or less). The thicker, more open void structure allows PFC to drain larger volumes of water off the roadway surface faster than conventional OGFC and keeps the void structure clean longer through the flushing action of high-speed traffic, and therefore, reducing the potential for loss of permeability over time.

These differences have contributed to a longer reported performance life for PFC compared to conventional OGFC. Research on PFC indicates that the mixes typically last between 8 to 12 years, significantly longer than the first generation OGFC mixtures which typically lasted 5 to 7 years. No widespread performance problems with PFC such as raveling have been reported, but concerns remain whether PFC mixes will experience the same performance problems that plagued the first generation OGFC mixes used in freeze-thaw environments. In freeze-thaw environments, the associated inconveniences and increased cost of winter maintenance and the possible related formation of glaze ("black ice") seem to outweigh the benefits of PFC. While black ice can form on any pavement under the right environmental conditions, there is information that it is likely to form on PFC earlier and last longer than on other HMA surfaces. These concerns are a likely reason that PFC mixes are used predominately in the warmer climates found in the southern and western regions of the United States and are not used widely in areas that experience frequent freeze-thaw cycles. Pavement maintenance issues and snow and ice removal also are cited as obstacles to further increased use of PFCs in colder climates.

Objective

The objective of this project was to recommend design, construction, maintenance, and rehabilitation guidelines that will maximize the advantages and minimize the disadvantages associated with the use of PFCs. In the context of this project, PFC was generally, but not exclusively, defined as a highly permeable mix containing polymer-modified asphalt binders or asphalt rubber and fibers, alone or in combination.

Research Approach

In order to accomplish the research objective, a total of five project tasks were required.

Task 1 – Conduct a Comprehensive Review of Worldwide Literature on PFC

For this task, a critical, in-depth, annotated literature review was conducted. Results from this review were of utmost importance to the successful completion of this project and a significant amount of effort was placed on this task. The literature review was conducted to specifically identify methods of designing (including material requirements), constructing, maintaining, and rehabilitating PFCs. Also, emphasis was placed on the safety benefits and performance aspects of constructed PFC pavements along with the use of PFC in freeze-thaw environments. As the literature review was not limited to the United States, it included international literature.

The deliverable of this study was a comprehensive guidelines document that fully encompassed the life of a PFC, from mix design through rehabilitation. Additionally, the guideline document was to address project specific advantages and disadvantages for placing PFC mixes. Therefore, since the project statement did not call for laboratory or field work, the literature review was of paramount importance.

In addition to the literature review, the researchers also reviewed standards and practices on the design, construction, maintenance and rehabilitation of PFCs; performance criteria were particularly important. These documents were collected from around the world and summarized as part of the Task 1 State of Art.

Task 2 – Survey Highway Agencies in the United States and Worldwide on PFC

Subtask 1 – Conduct a Survey of Highway Agencies in the US and Worldwide

A vast wealth of knowledge and experience on PFC exists in the United States and different parts of the world. As the objective of this task was to extract this information through a survey of specifying agencies, it was important that certain good practices be followed in developing and conducting the survey. The following outlines the proposed approach.

The first step was to identify the objectives of the investigation. For NCHRP Project 9-41, the objective of this survey was to obtain as much information as possible regarding methods of design, construction, maintenance, safety, rehabilitation, performance of PFC, and volume of use.

The mode of data collection was a web-based submission form. The web-based survey was proposed because of the following advantages: 1) there was no need for maintaining hard copies; 2) the survey could be accessed from any computer with an Internet connection; 3) the process of combining all responses for each question (and all other post processing) could be automated, and significant amounts of time could be saved; and 4) respondents from around the world would be able to access the survey.

Subtask 2 – Interview Experts

The research team also contacted numerous experts in the design, construction, maintenance, rehabilitation, and performance of PFCs. Experts from the U.S. and around the world were interviewed. The interviews were conducted through phone calls and electronically in order to directly discuss specific topics.

Subtask 3 – Summarize Information Regarding Design and Construction Obtained from Survey and Interviews

The objective of this subtask was to present the survey and interview information in a meaningful and practical manner. The end product of this subtask was a document with two parts: 1) responses to each specific question, from different respondents; and 2) responses summarized under design, construction, maintenance, rehabilitation, and performance.

Subtask 4 – Identify Functional and Performance Criteria

The objective of this subtask was to use the information from Subtask 3 to identify functional and performance criteria for PFC. The information was critically analyzed to provide answers to specific questions regarding good and poor performance. It was very important that any good performance, as well as bad performance, be related to a set of conditions (traffic and climate), materials, and activities (construction and maintenance).

Task 3 – State of Practice for Permeable Friction Courses

Task 3 involved providing a detailed summary of the research efforts conducted during Tasks 1 and 2 in the form of a state-of-art on the use of PFCs. Specific chapters within the state-of-art deal with mix design (including material properties), structural design, construction, maintenance, rehabilitation, performance, and advantages/disadvantages. The chapters include information obtained from the literature review, evaluations of standards and practices, the survey of transportation agencies and interviews of experts. Where needed, our team developed draft standards and/or practices.

Task 4 – Develop Guidelines on the Design, Construction, and Maintenance of PFC

Based upon the results of Tasks 1 through 3, guidelines were developed on the design (including material requirements), construction, maintenance, and rehabilitation. Two practices were developed, in AASHTO format, for these topics. The first practice provides guidance on mix design and construction while the second practice deals with maintenance and rehabilitation.

Task 5 – Prepare Final Report

The final report was compiled according to guidelines established by NCHRP and to present a clear and concise summary of the findings and conclusions generated during Project 9-41.

Report Organization

The draft final report for NCHRP Project 9-41 is divided into three volumes. Volume I of this report includes the current state-of-art for PFCs. This volume provides a synthesis of the annotated literature review, survey results, and areas needing further research. Volume II of this report includes the guidelines for the use of PFC in the form of AASHTO practices. Appendices within Volume II are draft AASHTO standards for use of PFCs. The final volume of the draft final report presents the annotated literature review.

Volumes I and II are published as NCHRP Report 640, and Volume III is published as NCHRP WOD 138.

CHAPTER 2

Results of Agency Survey

To assist the researchers in the successful completion of this project, a survey of transportation agencies was conducted during Task 2 of this research. A summary of the survey results are presented here at the beginning of this report; results from the survey are included within the state-of-art presented in subsequent chapters of this report. The term OGFC is generically used within this chapter because OGFC encompasses all of the mix types covered by this survey. Where appropriate, PFC is used to describe aspects specifically related to these OGFC types.

The objective of the survey was to obtain as much information as possible about methods of design (both mix design and structural design), construction, maintenance, safety, rehabilitation, performance of PFC, and volume of use of PFC. As with any survey, it is seldom possible to get all agencies to respond. Though no response was received from 14 states, many of these states were contacted as the researchers had knowledge of their involvement with PFCs or OGFCs. Where experiences are contained in this report from agencies not completing the survey, that information was obtained from discussion with the agencies through telephone conversations or means other than the survey.

The survey was set up as a web-based survey which allowed respondents the opportunity to fill in all the parts at once or different parts at different times instead of having to complete the entire survey before submission. The five parts in the survey consisted of Part 1: General Use and Structural Design; Part 2: Mix Design; Part 3: Construction; Part 4: Maintenance and Rehabilitation; and, Part 5: Performance. Appendix A presents the survey.

Because there are differences in the types of PFCs used around the world, a brief introduction that described the differences between PFCs and other OGFCs was provided to respondents. The introduction was intended to help respondents answer specific questions related to OGFCs, in general, or PFCs, specifically. The introduction given respondents follows:

> Open-graded friction courses (OGFCs) are specialty hot mix asphalt (HMA) mixtures that contain an open aggregate grading having a large percentage of coarse aggregates and low percentages of mineral matter. OGFCs are designed as a wearing surface to improve frictional resistance, reduce splash and spray, improve nighttime visibility, reduce hydroplaning and/or reduce tire/pavement tire noise. Within the overall category of OGFC, there are two predominant OGFCs used within the U.S.: Permeable Friction Course (PFC) and Asphalt Concrete Friction Course (ACFC).
>
> Permeable Friction Courses are OGFC mixes that are specifically designed to have high in-place air void contents, typically in the range of 18 to 22 percent, for removing water from the pavement surface during a rain event.
>
> The term Asphalt Concrete Friction Course can be used for OGFC mixes that are not specifically designed for removing water from the pavement surface but rather are utilized to simply improve frictional resistance or to reduce tire/pavement noise. Though ACFCs have relatively high air void contents, generally near 15 percent, they are not designed to remove large volumes of water from the pavement surface like PFCs.

The following paragraphs summarize the results of the survey. Each of the five parts is discussed individually.

General Use and Structural Design

General Use

The first question posed to the agencies concerned their use of OGFCs. The researchers not only wanted to know which agencies used OGFCs, but also if the use of OGFCs was limited geographically. Sixty four percent (64 percent) of the U.S. states responded to the survey along with four Canadian provinces, Austria, and Japan. Only 14 states plus British Columbia, Austria and Japan responded that they currently use OGFCs while five states plus Alberta and Yukon stated they did not use OGFCs. Interestingly, of the 32 states responding, 13 states did not respond with a yes or no, but rather related that they either once used OGFCs and stopped (eight states plus Ontario), had a test/trial section planned (three states), used infrequently (one state), or was considering use under special development (one state).

Of the 14 states indicating they use OGFCs and British Columbia and Austria, nine states along with British Columbia and Austria described their OGFC mix as a PFC while only three states described their OGFC as an Asphalt Concrete Friction Course (ACFC). Two states, Arizona and Iowa, did not feel that their OGFC description fit into either of these two categories, though no explanation was given. In the case of Arizona, it is suspected that because of their primary use of rubber modified asphalt and small maximum aggregate size gradation they did not feel that (ACFC) adequately fit their description. Interestingly, with the exception of California and Oregon, the use of PFC in the United States was limited to the southeastern states (Alabama, Georgia, Louisiana, North Carolina, South Carolina, Tennessee, and Texas). It is presently the understanding of the researchers that New Jersey has significant research underway using PFC.

Whether the OGFC is described as PFC or ACFC, the volume of use per year could be described as low compared to the overall usage of HMA. Of those states that described their OGFCs as PFCs, only Georgia and Texas were among the six states reporting usage greater than 100,000 tons. With five states along with British Columbia and Austria reporting usage less than 20,000 tons, one could assume that their PFC use at present is limited to smaller projects. This was reported for British Columbia.

Of interest to the researchers were the types of roadway on which agencies use OGFCs. The respondents were given five roadway types in which to choose: urban freeway, urban arterial, urban collector, rural interstate, and rural primary highway. Again responses were from the 14 states which stated they use OGFCs along with two Canadian provinces (one of which, Ontario, has discontinued use) and Austria. Urban freeway and rural interstate was listed by 75 percent of the respondents while 50 percent of the states and Austria listed rural primary highways. New Mexico, Nevada, and Texas were the only three states that listed OGFCs are used on all five roadway types. Of these states, only Texas classifies their OGFC as a PFC.

The respondents were asked to define the factors involved in their selection of OGFC for a roadway. They were given five factors to choose from along with the opportunity to select "other" if the five categories did not meet their selection criteria. These five included policy, traffic volume, rainfall, design speed, and geometry. Over 78 percent of the agencies that responded selected "policy" as the primary factor for selecting a roadway to receive OGFC with 50 percent selecting "traffic volume." Though each factor was selected, it was noticed that as many as four of the five factors were selected by some states. On the other hand, since the majority selected "policy," one would surmise that each state's policy probably would include the other factors and the respondent did not feel the need to list them separately. The "other" category was selected by five agencies with five different factors listed, including safety, winter maintenance, monitor performance, wet weather accident history, and noise reduction. With the exception of Texas, each state that selected the "other" factor also made a selection of one or more of the researchers' presented factors. Texas apparently only uses PFC pavements based on wet weather history. This response would parallel the response given for using OGFCs on all types of roadways. Austria indicated all five factors were included in the selection of OGFC.

Tied to the factors involved in selection of OGFC for a roadway, the researchers were interested in knowing what limitations the agencies placed on where OGFCs are used. Though some agencies made mention of the number of lanes, traffic volume, etc., the researchers felt that these types of limitations were already established based on the roadway type previously selected. Many agencies made mention of the roadway design speed as a limitation, but there again this, for the most part, would have been previously set by the type of roadway. Design speeds mentioned ranged from greater than 40 mph to greater than 55 mph. Of particular interest were statements from California, North Carolina, and Oregon. California stated that OGFCs were not used on unsound pavements, in snow/icy areas, or at intersections. North Carolina had a concern with temperature in that a brine solution is required in advance of freeze conditions. In Oregon, OGFCs are not used in curbed or urban routes, and their use is avoided in snow plow zones and areas with active slides. In Austria, OGFC is not utilized on roadways with steep slopes, areas with many curves or areas with many intersections.

At least one agency commented on how costs have significantly increased with the use of polymers and fibers even though their use eliminated the raveling issues experienced with earlier OGFCs. The issue of safety seemed to be in the forefront of agencies' general use of OGFCs. Comments on considerations being given to OGFCs use in areas with low skid numbers, history of frequent wet weather accidents and hydroplaning stand out. However, on the negative side of their use, were comments relative to the need for special maintenance practices to maintain pavement porosity and noise characteristics.

Structural Design

Respondents to the survey were asked whether any structural value was assigned to the OGFC layer. From the 50 states, four Canadian provinces, Austria, and Japan, responses were given by 26 agencies. Only 27 percent of the agencies responding said that they assigned a structural value to the OGFC pavement layer. Of those assigning a structural value, over 70 percent stated that the structural value was estimated from layer coefficients. Texas uses a resilient modulus of 300 Ksi (2,000 MPa); however, the use of OGFC is limited to pavements that are already structurally sound. When asked whether a single lift thickness for all OGFC layers was specified, 17 out of 22 responding agencies responded in the affirmative. One state, California, indicated that the thickness had to be at least 30 mm thick and 1.5 times the maximum aggregate size, so in effect they also established a minimum lift thickness. Many responded that the lift thickness of their OGFC layer was less than 1 in. (25 mm) which may explain the tendency for the large number of agencies not assigning a structural value to the OGFC layer.

Mix Design

Aggregates

The agencies were requested to furnish their current gradation requirements for up to three different OGFC mix designs. Tables 1 through 20 present the gradation requirements from those states that presented data in the survey. Only Oregon had a PFC mix design whose maximum aggregate size exceeded

Table 1. Design gradation band for Alabama.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
AL						
19	100	100				
12.5	100	85				
9.5	65	55				
4.75	25	10				
2.36	10	5				
1.18						
0.6						
0.3						
0.15						
0.075	4	2				

Table 2. Design gradation bands for California.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
CA						
19						
12.5						
9.5	89	78				
4.75	37	28	36	29		
2.36	18	7	18	7		
1.18						
0.6						
0.3						
0.15						
0.075						

Table 3. Design gradation band for Connecticut.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
CT						
19						
12.5	100	95				
9.5						
4.75	35	20				
2.36	19	5				
1.18						
0.6						
0.3						
0.15						
0.075	5	1				

Table 4. Design gradation band for Delaware.

Sieve Size, mm	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
DE						
12.5	100	100				
9.5	98	88				
4.75	42	25				
2.36	15	5				
1.18						
0.6						
0.3						
0.15						
0.075	5	2				

Table 5. Design gradation band for Florida.

Sieve Size, mm	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
FL						
19	100	100				
12.5	100	85				
9.5	75	55				
4.75	25	15				
2.36	10	5				
1.18						
0.6						
0.3						
0.15						
0.075	4	2				

Table 6. Design gradation bands for Georgia.

Sieve Size, mm	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
GA						
19	100	100	100	100	100	100
12.5	100	100	100	85	100	80
9.5	100	85	75	55	60	35
4.75	40	20	25	15	25	10
2.36	10	5	10	5	10	5
1.18						
0.6						
0.3						
0.15						
0.075	4	2	4	2	4	1

12.5 mm. Only California had a mix design whose nominal maximum aggregate size was 4.75 mm. The majority of the gradation requirements were for mixes whose maximum aggregate size was 12.5 mm or less.

Respondents were requested to rank seven aggregate characteristics in order of importance: abrasion resistance, durability, polish resistance, angularity, shape, cleanliness, and absorption. Graphical plots of the ranking of each characteristic are presented in Figures 1 through 7. Assigning the point values in order of importance (i.e., a value of 1.0 depicting the most important) that had been given to the respondent and the rankings assigned by the respondents, polish resistance was considered the most important characteristic of aggregates used in OGFC mixtures with absorption being considered the least important. A close second to polish resistance in importance was durability, followed in descending order of importance by angularity, abrasion resistance, shape, and then cleanliness. Two states assigned point values

Table 7. Design gradation band for Indiana.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
IN						
12.5	100					
9.5	83					
4.75	28					
2.36	13					
1.18						
0.6						
0.3						
0.15						
0.075	4	2				

Table 8. Design gradation band for Kentucky.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
KY						
19						
12.5	100	100				
9.5	100	90				
4.75	50	25				
2.36	15	5				
1.18						
0.6						
0.3						
0.15						
0.075	5	2				

Table 9. Design gradation bands for Louisiana.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
LA						
19			100	100		
12.5	100	100	100	85		
9.5	100	90	75	55		
4.75	50	25	25	10		
2.36	15	5	10	5		
1.18						
0.6						
0.3						
0.15						
0.075	5	2	4	2		

to each characteristic based on what appeared to be what they considered level of importance. When these states were eliminated from the summary the ranking did not change. Not including the eliminated states, each characteristic with the exception of the lowest ranking characteristics (cleanliness and absorption) received at least one vote from a respondent who felt it was the most important characteristic.

Asphalt Binder

Agencies were asked the grade of asphalt binder specified in their OGFCs. Of the 21 states and Austria responding, over 70 percent stated that they specified a PG 76-22 binder. Austria did not provide a performance grade, but did indicate a requirement for polymer modification. Where other grades

Table 10. Design gradation band for Missouri.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
MO						
19	100	100				
12.5	100	85				
9.5	75	55				
4.75	25	10				
2.36	10	5				
1.18						
0.6						
0.3						
0.15						
0.075	4	2				

Table 11. Design gradation band for Mississippi.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
MS						
12.5	100	100				
9.5	100	80				
4.75	30	15				
2.36	20	10				
1.18						
0.6						
0.3						
0.15						
0.075	5	2				

Table 12. Design gradation bands for North Carolina.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
NC						
19					100	
12.5	100		100		100	85
9.5	100	75	100	75	75	55
4.75	45	25	45	25	25	15
2.36	15	5	15	5	10	5
1.18						
0.6						
0.3						
0.15						
0.075	3	1	3	1	4	2

different from PG 76-22 were specified, the grade reflected what was typically used in the state with other HMA mixes. For instance, California and Washington specify an AR 4000 or AR 8000. Northern tier states specified a softer grade binder than that used in the south or southwestern states where the climate is much warmer. Almost without exception, states specifying PG 76-22 called for the binder to be polymer modified primarily with some type of elastic polymer (SBS) or rubber. Austria also utilizes an SBS polymer. Agencies were asked if other tests on the binder were conducted beyond those necessary in grading the binder sample. Though different type tests were specified (e.g., infrared trace, Phase angle, ductility, elastic recovery, etc.), the primary reason for running the test was to ensure they were getting an elastomer type polymer.

Table 13. Design gradation band for Nebraska.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
NE						
19	100	100				
12.5	100	95				
9.5	80	40				
4.75	35	15				
2.36	12	5				
1.18						
0.6						
0.3						
0.15						
0.075	3	0				

Table 14. Design gradation bands for Nevada.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
NV						
19						
12.5	100	100				
9.5	100	90	100	95		
4.75	55	35	65	40		
2.36						
1.18	18	5	22	12		
0.6						
0.3						
0.15						
0.075	4	---	5	---		

Table 15. Design gradation band for New York.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
NY						
12.5	100	95				
9.5	56	40				
4.75	30	20				
2.36	14	6				
1.18	12	4				
0.6	9	3				
0.3						
0.15						
0.075	5	2				

Stabilizing Additives

When asked whether stabilizing additives were specified to reduce the potential for draindown, over 90 percent responded in the affirmative. Fibers were listed as the predominant type stabilizing additive required by roughly 85 percent. The percentage of fibers required ranged from 0.2 percent to 0.5 percent, with the average being typically 0.3 percent. Approximately two-thirds of the agencies require a SBR, SBS or SB type polymer modifier while the other third did not specify a specific polymer type. Only one agency required crumb rubber in the asphalt binder while three others allowed its addition as an option.

From the responses given, the overwhelming conclusion drawn is that some type of polymer-modified asphalt binder is specified with OGFC mixtures. Mineral or cellulose fibers

Table 16. Design gradation band for Ohio.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
OH						
12.5	100	100				
9.5	96	85				
4.75	45	28				
2.36	17	9				
1.18						
0.6						
0.3						
0.15						
0.075	5	2				

Table 17. Design gradation bands for Oregon.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
OR						
25	100	99				
19	96	85	100	99		
12.5	71	55	98	90		
9.5						
4.75	24	10	32	18		
2.36	16	6	15	3		
1.18						
0.6						
0.3						
0.15						
0.075	6	1	5	1		

Table 18. Design gradation band for South Carolina.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
SC						
19	100					
12.5	100	85				
9.5	75	55				
4.75	25	15				
2.36	10	5				
1.18						
0.6						
0.3						
0.15						
0.075	4	2				

also are required to reduce the potential for draindown by most agencies.

Mix Design

Over 70 percent of the agencies responding stated that they used laboratory compaction during the design of OGFC mixes. There apparently is not a consistency within the agencies on the type of compaction method used with OGFC mix designs. Even with those agencies that have indicated significant use of OGFC mixtures, the method of compaction seems to be split between the Marshall method and the Superpave gyratory compactor. Where the gyratory method is used, the design number of gyrations typically was 50 though one agency

Table 19. Design gradation band for Tennessee.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
TN						
19	100	100				
12.5	100	85				
9.5	60	35				
4.75	25	10				
2.36	10	5				
1.18						
0.6						
0.3						
0.15						
0.075	4	2				

Table 20. Design gradation bands for Texas.

	Percent Passing					
	Gradation 1		Gradation 2		Gradation 3	
Sieve Size, mm	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit
TX						
19	100	100	100	100		
12.5	80	100	95	100		
9.5	60	35	80	50		
4.75	20	1	8	0		
2.36	10	1	4	0		
1.18						
0.6						
0.3						
0.15						
0.075	4	1	4	0		

utilizes 20 gyrations. The number of blows most often specified when the Marshall hammer was used as the compaction method was 50.

During the mix design procedure, all respondents, except for four, indicated that draindown testing was included as part of mix design. Three of the four agencies that indicated they did not include draindown testing had previously stated in their survey that they had stopped using OGFC pavements. Approximately 65 percent of the agencies using a draindown test stated they used the draindown basket method. The remainder used a glass plate or other method. Where the basket was specified, the requirement called for either 0.2 percent or 0.3 percent maximum draindown allowed.

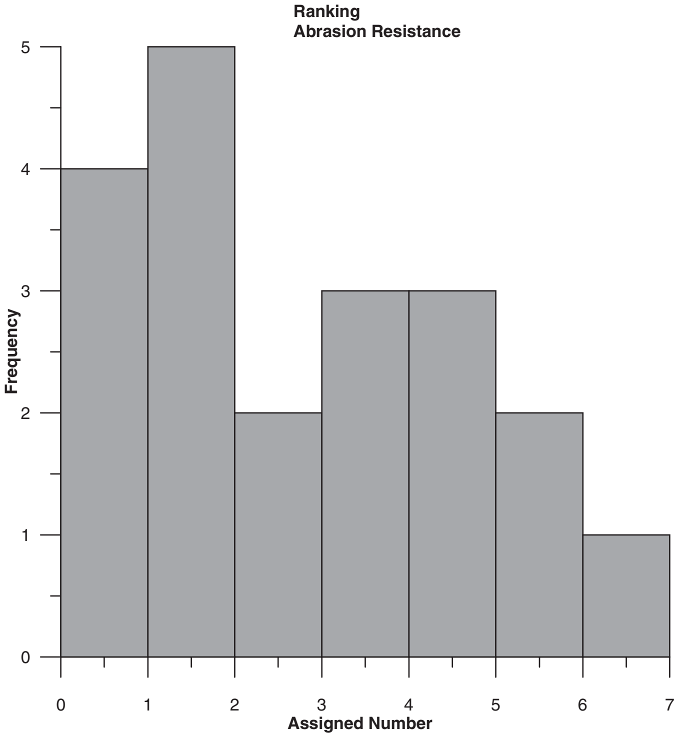
Only three agencies responding indicated that they included permeability testing within the mix design procedure. Apparently with the high design voids required for PFCs, most agencies do not consider it necessary to perform any type permeability test; however, approximately one half of the agencies stated that they specified other laboratory tests during mix design. The majority of these tests consisted of the Cantabro Abrasion Loss test or some other type aggregate abrasion test. Some sort of moisture susceptibility testing was the next most often mentioned requirement with a boil test mentioned by at least three agencies. Only five agencies required a freeze-thaw cycle with their tensile strength ratio test for moisture susceptibility with only one cycle required. Two agencies, neither of which had a moisture susceptibility test, either called for an anti-strip additive or required lime to be added to OGFC mixtures. Austria indicated they utilized loaded wheel testing.

Construction

Production

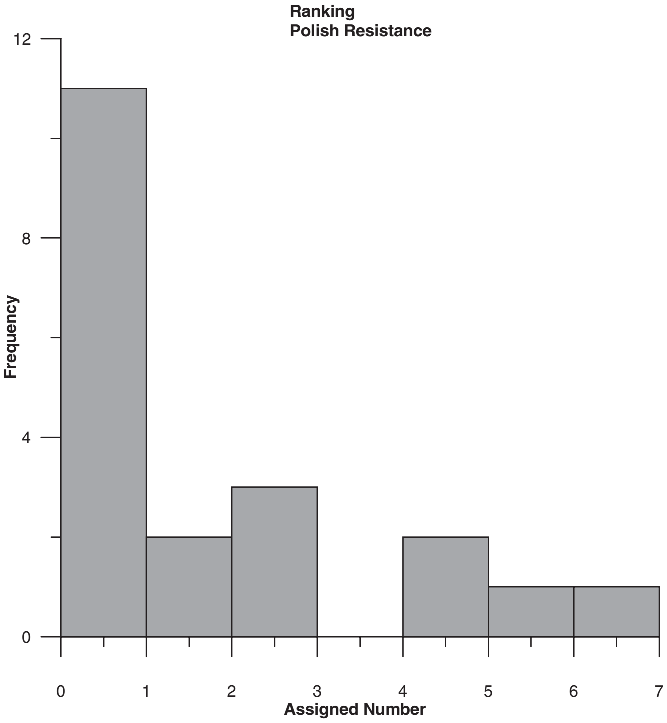
Nearly two-thirds of the agencies reporting indicated that they specified OGFC by Standard Specifications, indicating that OGFC was part of their standard paving operations. The other third used Special Provisions.

The majority of the agencies indicated that any typical plant used for HMA production also was used to produce OGFC. The plants typically being used were drum, batch or both. A batch plant was indicated as being the type of plant exclusively



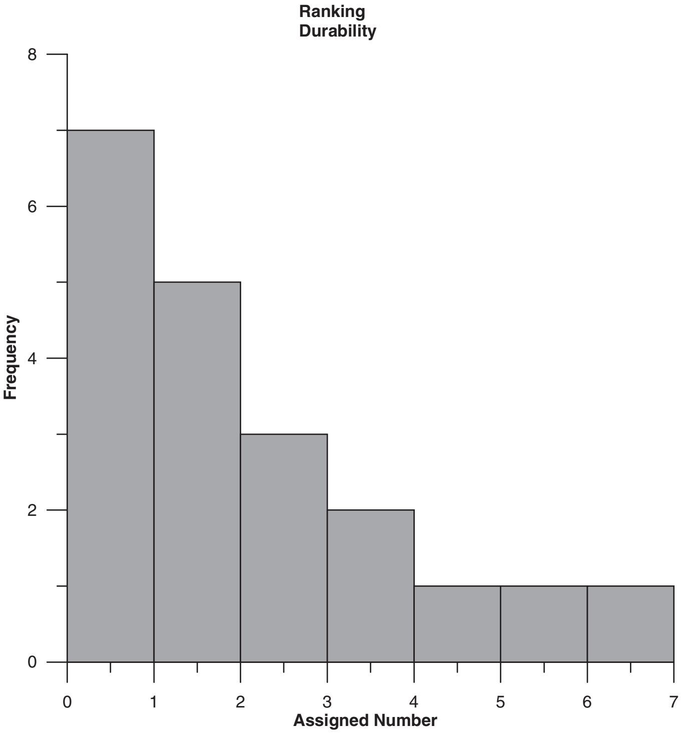
Note: A lower number means a higher ranking

Figure 1. Respondent ranking for aggregate properties – abrasion resistance.



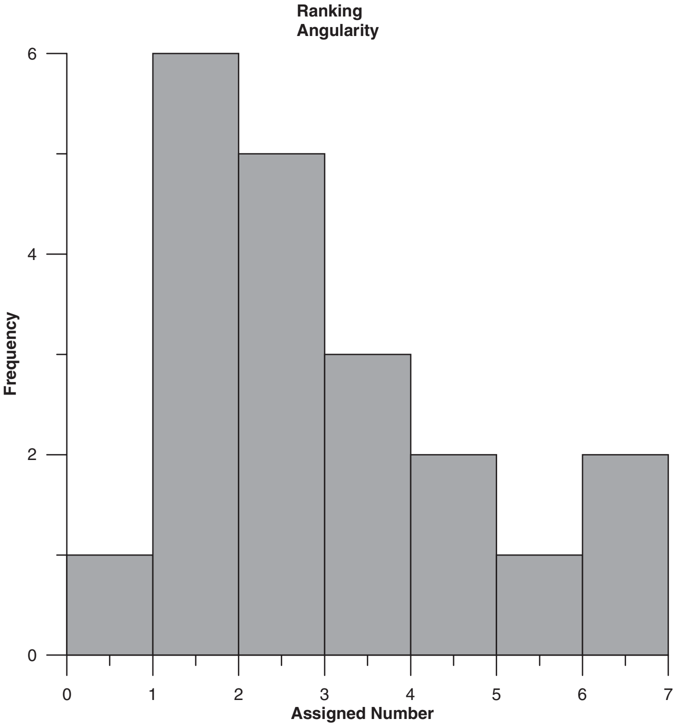
Note: A lower number means a higher ranking

Figure 3. Respondent ranking for aggregate properties – polish resistance.



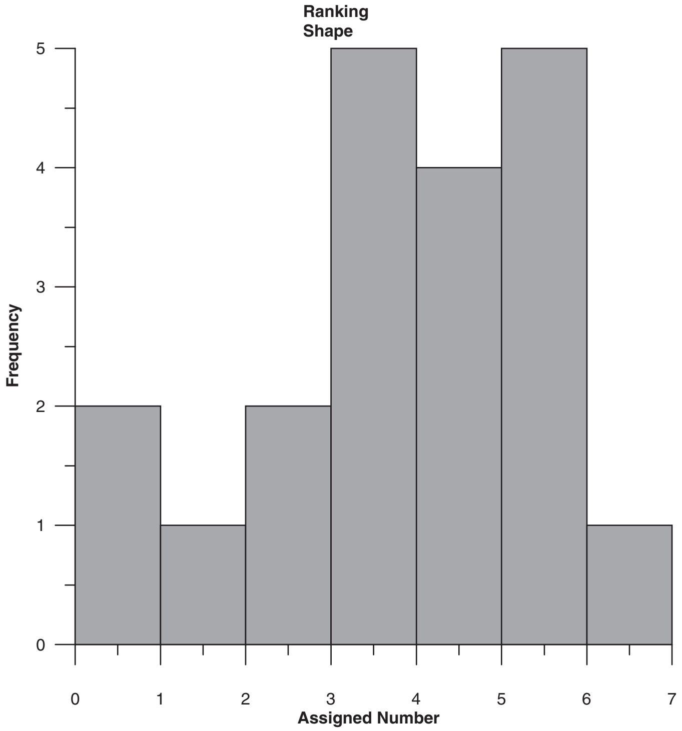
Note: A lower number means a higher ranking

Figure 2. Respondent ranking for aggregate properties – durability.



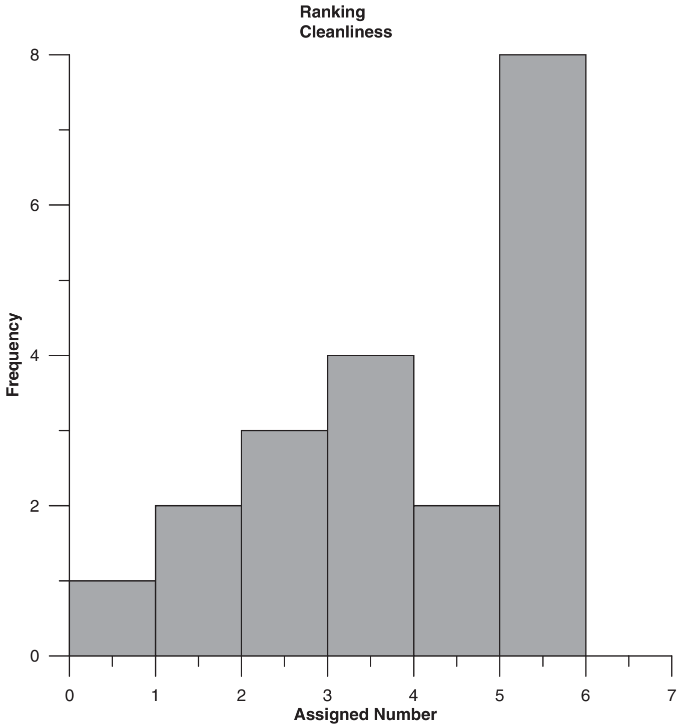
Note: A lower number means a higher ranking

Figure 4. Respondent ranking for aggregate properties – angularity.



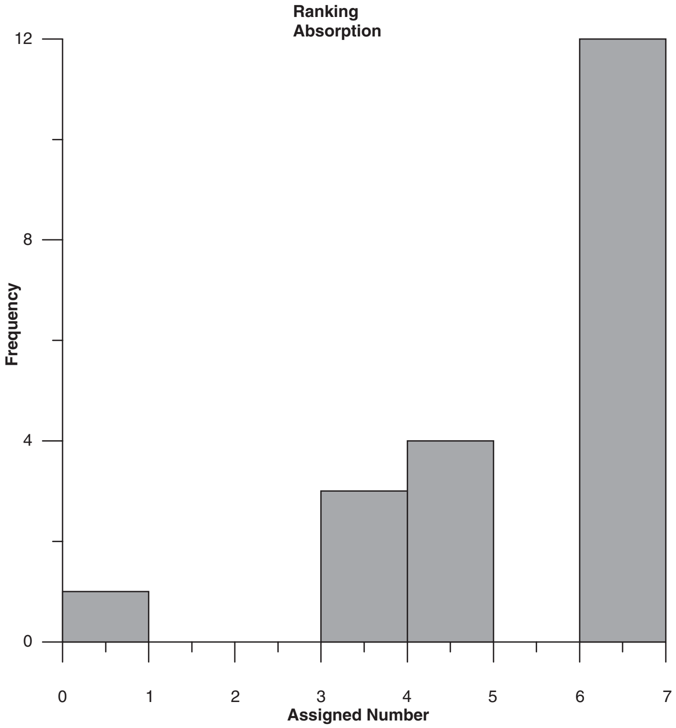
Note: A lower number means a higher ranking

Figure 5. Respondent ranking for aggregate properties – particle shape.



Note: A lower number means a higher ranking

Figure 6. Respondent ranking for aggregate properties – cleanliness.



Note: A lower number means a higher ranking

Figure 7. Respondent ranking for aggregate properties – absorption.

used in only one state, Connecticut. A drum plant was exclusively indicated as the type used in Louisiana, Nebraska, and South Carolina.

Mixing time in the plant for OGFC mixtures was the same for dense-graded mixtures by all agencies except for California, North Carolina, and Ohio. Only three agencies reported having a maximum and/or minimum temperature requirement for mixing in the plant. Responses to what the maximum and/or minimum mixing temperature specified varied among the agencies, but most stated that it was dependent upon the type/grade asphalt binder that was used.

The agencies were equally split on having a maximum silo storage time for OGFC mixtures. Those that had a time limit allowed OGFC to be kept in a silo from 1 hour to 12 hours. Agencies indicating earlier in the survey that they specified a PFC instead of other OGFC types required a shorter time held in the silo. Typically for these agencies the time held was no more than 2 hours.

Transportation

Only two agencies reported that they limited haul distances. Ohio set its limit at a mileage distance (50 miles) with a minimum mixture temperature requirement (not provided). South Carolina limited the haul distance by time (no more than 1 hour). Though the large majority of the agencies (80 percent) did not require insulated trucks, nearly two-thirds did specify that the trucks had to be tarped. Only two agencies require that the haul trucks must be heated. One of these agencies had stated previously in the survey that they used OGFC infrequently while the other had discontinued use. Regardless of the restrictions or limitations placed on the haul distance and truck, all but two of the reporting agencies responded that they had a minimum mix temperature when the truck reached the paving site. This minimum temperature varied from agency to agency. Some reported a fixed minimum temperature with none below 225°F. The temperature went up from there to as high as 300°F. Other agencies set the minimum temperature at 20 to 30°F below the job mix formula or the target compaction temperature.

Release agents are allowed by all agencies reporting except for one, Nebraska. Most indicated that the types allowed had to be non-petroleum (no fuel oil or diesel). Also, most agencies indicated that they had an approved/qualified products list of acceptable agents.

Laydown/Compaction

Less than 30 percent of the reporting agencies require a material transfer vehicle (MTV) in the paving train for placing OGFC. Only one agency, Connecticut, stated they did not require a tack coat to be placed prior to placing the OGFC. The type and application rate of tack coat varied among the agencies. The types of tack coat used included different types of emulsions that included RS-1, RS-2, CRS-2, CRS-2P, SS-1, SS-1h, CSS-1, and CSS-1h. Though the majority of the agencies using tack called for some type of emulsion, some used performance-graded binder such as PG64-22. Other agencies did not report the specific type of tack used. The application rate ranged from a low of 0.04 gallons per square yard to an amount as high as 0.2 gallons per square yard. The use of a calibrated distributor truck to apply the tack was equally split with half of the agencies stating that they did not require one while the other half reported that they did require one. When asked whether other techniques to ensure an impermeable underlying layer other than a tack coat were used, only two agencies reported that they did. One state, Connecticut, stated that it only placed the OGFC on a dense-graded HMA. Texas stated that it sometimes required an underseal if the existing pavement was susceptible to water intrusion; however, it usually did not require the underseal if they were paving on a new layer of hot mix.

There was only one agency that did not have a minimum specified air and/or surface temperature for placing OGFC. Once again, the minimum temperature varied from agency to agency. The lowest minimum temperature reported was 50°F and went up from there to as high as 70°F. In nearly every instance, the temperature reported was ambient air temperature with agencies reporting that this temperature had to be rising. Some agencies specifically stated that the temperature was a surface pavement temperature. At least three agencies indicated that the minimum temperature was dependent on the type binder used in the OGFC with the higher performance grades (i.e., PG76-22 versus PG64-28) requiring a higher minimum temperature.

When asked how they specified compaction, all except one reported that they used a method specification. This one state apparently read the question as “Do you . . . ?” rather than “How do you . . . ?” as they answered with a “no” indicating that they did not specify compaction. This response was verified by their answer to the next question on whether a certain type of roller was specified for compaction. Since they responded that they did not specify a certain type of roller, this was followed by their stating the contractor was required to make two passes with a steel wheel roller only. Therefore, 100 percent of the agencies reported using a method specification while requiring a certain type roller for compaction with no specific density requirement. Without exception, the roller specified was a steel wheel roller though at least one agency used the term of non-pneumatic. Some agencies went as far as to set a minimum weight for the roller. Others set the number of passes. One agency required a minimum of two double-drum steel wheel rollers for compaction. Without exception, when specifically addressed by an agency, the steel wheel roller had to be operated in the static mode. No agency indicated that vibrating was allowed or required with some going as far as stating that if the contractor used a vibratory roller it had to be operated in the static mode.

The practice of tacking of the vertical face of longitudinal joints was not generally used. Only one agency indicated that they allowed tacking of the vertical face of longitudinal joints.

Quality Control/Quality Assurance

Gradation and binder content were the two primary tests required for quality control/quality assurance (QC/QA) of OGFC mixtures. Both of these tests were included in all the state’s QC/QA programs except for two agencies and each agency included one or the other test. There were as many as 12 other tests mentioned by some of the agencies as part of their QC/QA testing. Some of these included modified Lottman test (for stripping), permeability, temperature, draindown, boil test (for stripping), smoothness, moisture content (mix), percent air voids, gyratory density and Rice specific gravity. Of these, only draindown, air voids, and Rice gravity were included by more than one agency.

General Construction Issues

Agencies were asked what materials were used for markings placed on OGFC pavements. Apparently the agencies did not consider the need to specify anything different for markings on OGFC pavements than what they were currently using on dense-graded HMA. Many of the respondents specifically stated that typical pavement markings were used. The most frequently listed markings included waterborne paint and thermoplastic. Some of the northern tier agencies mentioned epoxy. One agency, North Carolina, has a concern about the effects that thermoplastic may have on the ability of OGFC to properly drain. Though Massachusetts did not respond to the survey, research by the team found that the chief engineer of Massachusetts signed an engineering directive dated June 16, 2005 that prohibited the use of thermoplastic markings and required the use of epoxy markings on all OGFC pavements. Further, the directive required the use of slotted in pavement reflectorized pavement markers in place of snowplowable raised reflectorized pavement markers.

Agencies were next asked if rumble strips were constructed at the OGFC pavement edge. Again the results were nearly equally split with slightly more states constructing rumble strips at the pavement edge.

Finally, agencies were asked if they had experienced any distresses related to pavement markings and rumble strips. Only three agencies responded affirmatively. One agency response dealt with pavement markings. Another centered on rumble strips while the third mentioned both. Connecticut indicated that thermoplastic line stripes caused raveling in the OGFC. Nebraska stated that pavement markings may restrict drainage and that grinding in rumble strips pulls out too much aggregate. Texas, on the other hand, stated that rolled in rumble strips did not work as well as grinding in rumble strips. With nearly a 50 percent split on the use of rumble strips, the researchers felt that further investigation was warranted on rumble strip usage. The following is background information on rumble strips along with comments from telephone conversations with individuals from South Carolina and New York on the subject.

Rumble strips in the United States are mainly installed on highway shoulders as a countermeasure against run-off-the-road accidents. There are four types of shoulder rumble strips: milled, rolled, formed, and raised. They differ primarily in how they are installed, their shape and size, and the amount of noise and vibration produced. Rolled and milled rumble strips are used most often on asphalt highway shoulders. The first rumble strips were installed in 1955 in New Jersey and they were called "singing shoulders." They were wavy bumps installed at the concrete paved shoulder of a bridge. In the 1960s, many states adopted rumble strips of various designs. Rolled rumble strips were developed in the 1970s; the Pennsylvania Turnpike Commission created milled rumble strips in 1990 (*1*). The new interest in rumble strips seems to be at least partly the result of a FHWA notice issued in 1986 (see U.S. Department of Transportation Federal Highway Administration, Notice – Shoulder Texture Treatments for Safety, N 7560.9 April 28, 1986). Highway agencies often use all types of shoulder rumble strips, depending on the need and the material. In the United States, a method of milling paved roads was developed in the 1990s and it spread rapidly. This method employs a groove pattern that can be installed intermittently or continuously. The groove pattern, depth, width, shape, and spacing also may change with the road agency. The milled rumble strip method seems to be the preferred choice of most states. Further information on rumble strips can be found in NCHRP Synthesis Report No. 191 published by the Transportation Research Board (*2*).

The purpose here is not to debate the use or nonuse of rumble strips or when used what specific design criterion should be employed by the highway agency; however, there may be some concern as to whether rumble strips can be used with PFCs. Contacts were made to a number of agencies about their practice on installing rumble strips. For those states that daylight the PFC just outside the pavement edge strip, the installation of rumble strips in PFC was not an issue. Other states, such as South Carolina, have recently begun to daylight their PFC pavements at eight feet (8') off the edge line. Conversation with Tim Linberg in South Carolina's Construction Office on January 5, 2006 revealed that their policy was to use milled rumble strips at two feet from the edge stripe. Many early concerns and problems with rumble strips when states first began using them involved curves. States, such as Oregon, experienced problems with the rumble strips, but these issues or problems seemed to center more on the installation procedure and where the rumble strips were located and not that the rumble strips should have been placed or were erroneously placed in the OGFC. One of the early issues involved in using rumble strips with OGFC included premature deterioration of the asphalt in the rumble strip area under winter maintenance activities. This early concern centered primarily on snow plows with chains operating in the rumble strips. It was determined that this problem could be overcome by placement of the rumble strip and by going to milled rumble strips instead of rolled. It was felt that the lack of compaction of the asphalt of the rolled rumble strips attributed to the asphalt failure around the rumble strip. A discussion of the issues that Oregon experienced was reviewed (*2*). Further discussion on rumble strip usage with OGFC pavements was conducted on January 5, 2006 by telephone with Mr. Emmett McDevitt. Mr. McDevitt is a Transportation Safety Engineer for the FHWA New York Division Office. Mr. McDevitt did not know of any issues that would prevent the use of rumble strips with PFCs. Further, he knew of no failures that could be attributed to their use.

It should be pointed out that there has been only a modest amount of PFCs of the type addressed in this research (designed to have air voids of at least 18 percent) constructed in the United States. The majority of the construction has been in the warmer regions of the country and therefore all issues associated with winter maintenance may not have come to light.

Typically milled shoulder rumble strips are placed at least 18 in. (457 mm) or greater from the edge line with approximately a 0.5 in. (13 mm) groove depth and on 12 in. (305 mm) center to center groove spacing. PFC mixtures are typically constructed in thicker layers than conventional OGFC (1.0 to 2.0 in. as opposed to 1.0 in. or less). For PFC pavements placed at these thicknesses, the opinion is that milled rumble strips can be constructed with no adverse problems different from those encountered or expected where rumble strips are placed on other type pavements. However, in colder climates where agencies use sand and salt, the need to perform maintenance that includes cleaning of the PFC pavements is an issue that will need to be addressed.

Maintenance and Rehabilitation

General Maintenance (Non-Winter Related)

When asked to give their most common general maintenance issues for OGFC, the responses could be placed in one of two categories: unclog/clogging and raveling/delamination, with the latter being listed only slightly more than the first. If OGFC pavements have a tendency to clog, then unclogging them would be a concern. Austria indicated that they utilize special equipment to unclog OGFC pavements. However, when asked if any regularly scheduled maintenance activities were scheduled for OGFC pavements, not one agency stated that they did. Further, when asked if they employed maintenance activities to unclog OGFC pavements, not one agency responded that they did. Only one agency responded affirmative to the question whether any field test was used to identify when general maintenance activities were required. Washington responded that they used a high-speed van, and these vans likely are used to identify surface distresses.

Patching OGFC pavements was performed by just over 50 percent of the responding states. Without exception, those agencies that patch OGFC pavements use a dense-graded HMA. Texas indicated that for small patches they used a proprietary OGFC patching mix, but for larger patches used the dense-graded HMA. Georgia stated that on interstates with significant patching being required, they just replaced with OGFC, implying milling and complete replacement.

Winter Maintenance

Only 22 percent of the agencies completing the survey stated they used any type of weather prediction system for winter maintenance activities. Nevada stated that they used a RWIS system for snow plow and anti-icing activities. Weather conditions that would trigger winter maintenance most frequently were snow, freezing rain or sleet, and frost. Interestingly, nearly one-third of the agencies responding to the survey passed on this question.

Calcium chloride and sodium chloride were the two most often mentioned ice control chemicals used by the states. Brine along with sand or aggregate screenings also was listed. One-third of those responding stated that they employed anti-icing methodologies.

To get a feeling of the spread rates used for controlling ice on roadways, respondents also were asked to give their spread rates for both dense-graded mixtures and OGFC mixtures. For the most part these questions were not answered. Most of the agencies gave no response at all or stated that the rates were unknown. Austria indicated that 20 to 50 percent more chemicals are required for OGFC pavements than dense-graded. Others gave a rate for dense-graded, but did not give any rates for OGFC. Of the two agencies that did give responses to both questions, Kentucky and Oregon, the answers varied extremely. Kentucky gave values for dense-graded pavements, and then stated that the same spread rate was used for OGFC. Oregon on the other hand stated that the rate varied according to conditions. They indicated that a single stream nozzle was used on dense-graded surfaces and a triple stream nozzle was used on OGFC, implying triple the rate. One other agency did respond that the rate would be higher for OGFC.

Rehabilitation

Raveling was the answer given most often for the type of problem that triggered rehabilitation. This answer showed up in different forms from the respondents, but essentially meant the same thing. In lieu of the term raveling, some responded with pot holes, delamination, and loss of ride quality. The loss of permeability/noise characteristics was mentioned by one agency. Without exception, when problems arose that called for rehabilitation, agencies milled and replaced the pavement with a new surface.

Only four agencies stated that they were aware of any known or perceived problem with maintenance/rehabilitation techniques. Georgia questioned the placing of OGFC on milled surfaces and stated they were looking at micro-milling for those instances. On the same line, Texas stated that some engineers were concerned about how to mill and replace PFC once it reaches the end of its design. One northern tier agency stated that PFC pavements were more expensive to maintain.

Oregon stated that capping of OGFC pavements with dense-graded HMA or chip seals might cause damage and reduced performance. They stated that they had some inlay projects exhibit isolated shoving spots due to failure of the old layer underneath the OGFC. They felt that the cold planning broke the seal of the pavement mat and the new OGFC pavement allowed water to infiltrate and damage the underlying layer.

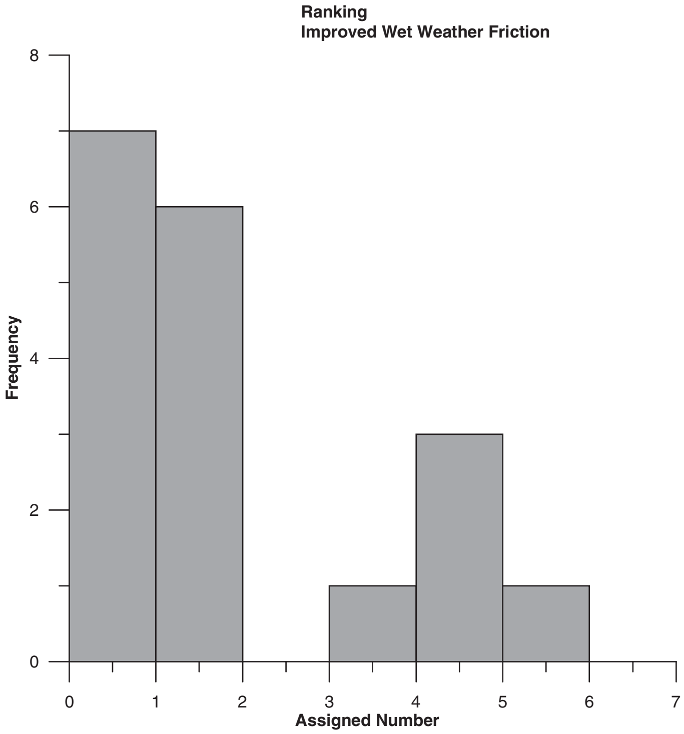
Performance

In the final part of the survey, respondents were asked about the performance aspects of OGFC pavements. The first questions dealt with the estimated average service life of OGFC pavements. Responses could not be grouped based on geographical location. Responses ranged from less than six years to as high as 15 years. Not including those that responded less than six years, each respondent gave a two to three year range. Most of the respondents gave the service life for OGFC pavements as eight to 10 years. This was also the range where the average of all respondents fell.

When asked about the common distresses in OGFC pavements, responses were virtually the same as those given for the first question under Part 4, Section C, on those problems that triggered rehabilitation activities. The most common response was raveling or delamination. Cracking also was mentioned as a distress.

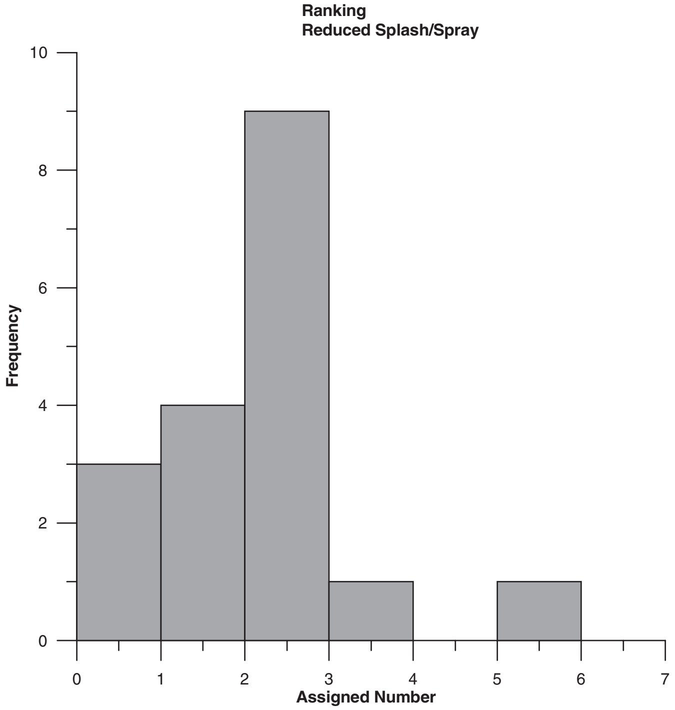
Respondents were asked to rank seven performance characteristics related to OGFCs in terms of their importance. These performance characteristics were improved wet weather friction, reduced splash/spray, smoothness, noise reduction, reduced hydroplaning, improved nighttime visibility, and improved wet weather visibility. Assigning the point values in order of importance that had been given to the respondent and the rankings assigned by the respondents, improved wet weather friction was considered the most important performance characteristic of OGFC pavements with reduced splash/spray and reduced hydroplaning tied for second most important (Figures 8 through 12). Even though noise reduction is one of the leading characteristics of PFC pavements in Europe, noise reduction along with smoothness was considered the least important by the respondents. Improved wet weather visibility fell in the middle of the rankings. Each of the performance characteristics received a number one ranking from at least three or more of the respondents. Only improved wet weather friction and reduced splash/spray did not get a last place vote in the rankings. Obviously, each of the performance characteristics of OGFC pavements is important and beneficial.

Typically, agencies use the same tests/equipment for measuring performance quality characteristics on OGFC pavements as they do on dense-graded pavements. This is particularly true for field tests with friction testing being by nearly all



Note: A lower number means a higher ranking

Figure 8. Respondent rankings of performance characteristics – wet weather friction.



Note: A lower number means a higher ranking

Figure 9. Respondent rankings of performance characteristics – reduced splash/spray.

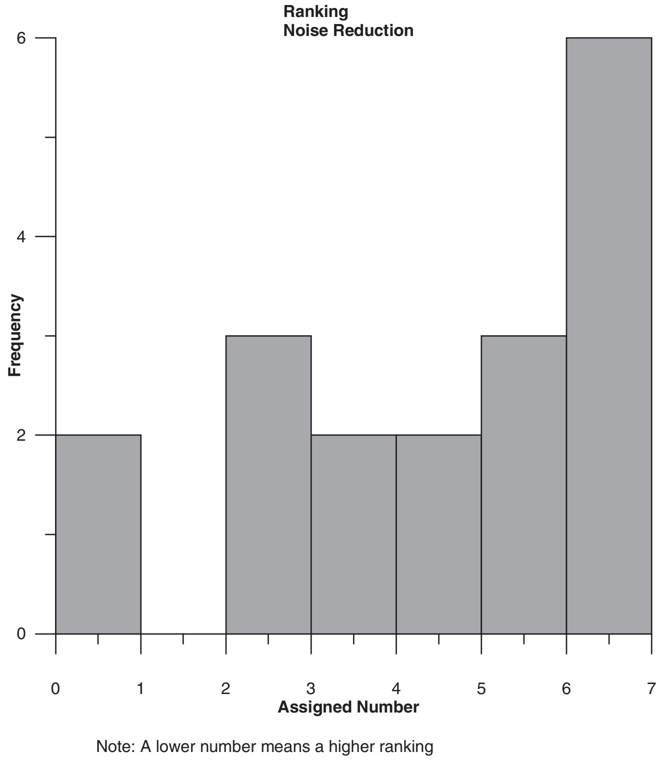


Figure 10. Respondent rankings of performance characteristics – noise reduction.

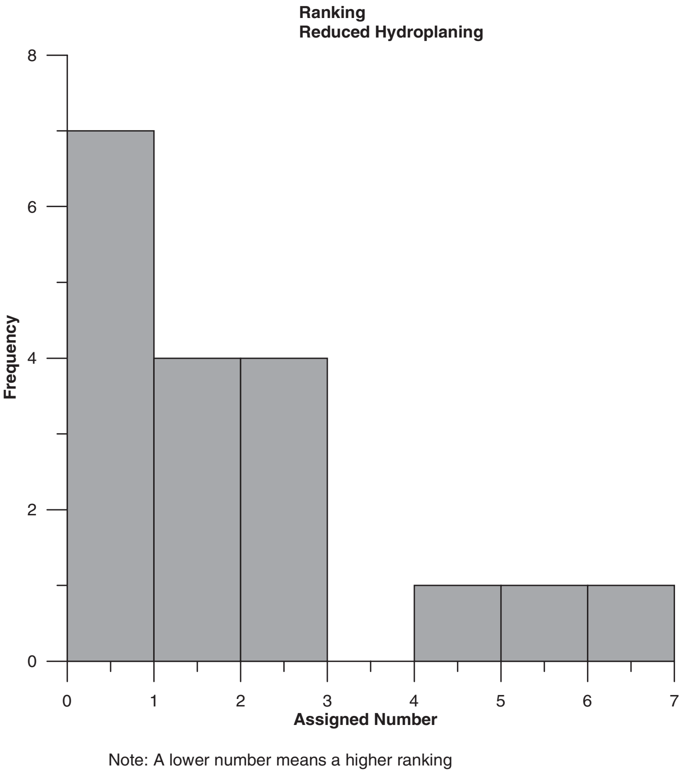


Figure 11. Respondent rankings of performance characteristics – reduced hydroplaning.

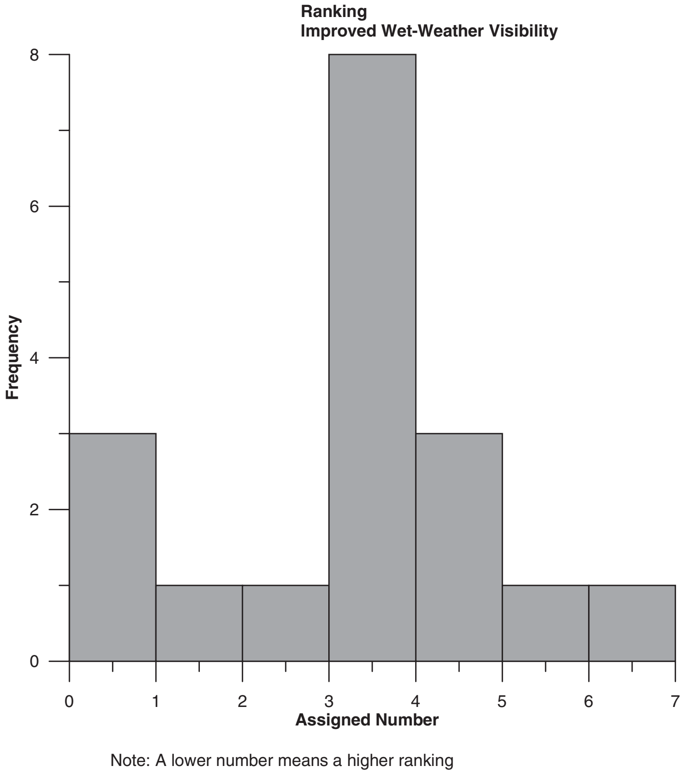


Figure 12. Respondent rankings of performance characteristics – improved wet-weather visibility.

respondents. Only one agency stated that they ran a field water permeability test to determine if the pavement was clogged by fines. Two agencies indicated that they perform noise testing of some type.

Only two agencies stated that they had conducted life cycle cost analysis for OGFC pavements. Oregon stated that though life cycle costs were used to determine pavement type selection and rehabilitation options, wearing course selection was based on other factors besides just economic considerations.

Survey Summary

In general, results from the survey can be considered a success. A significant amount of information was obtained within the five parts of the survey. This section summarizes results from the survey.

The majority of agencies within the United States have used OGFCs. Some agencies have ceased using these mix types because of performance problems in the past. Currently, most of the states within the United States do not utilize OGFCs. Those states that do utilize OGFCs are generally located in warmer weather climates; however, some agencies within the colder climates are successfully using OGFCs. Most of the agencies reporting the use of OGFC state that their mix type would classify as a PFC using the definitions provided in the survey instructions. OGFCs are typically used on high-speed highways with the majority of usage being on interstate type pavements. The decision for using OGFC mixes as a wearing surface is generally a policy decision. Selection of OGFC mixes is likely due to the safety benefits realized when using these mix types. This was confirmed within the performance characteristics section of the survey when the respondents indicated that improved wet weather friction was considered the most important performance trail of OGFCs.

Most agencies do not assign structural values to layers of OGFC. For the most part, agencies utilize a single lift thickness for constructed OGFC layers. Most commonly the lift thickness is less than 1 in. (25 mm); however, thicker lifts are sometimes specified in the United States and internationally for PFC layers.

Gradations used for OGFCs vary from agency to agency. The maximum aggregate size (mas) of OGFC mixes are generally 12.5 mm. Agencies reporting the use of PFCs generally specify gradations coarser than those reported as ACFCs. With respect to aggregate characteristics, the survey respondents identified polish resistance as most important, followed closely by aggregate durability. Other aggregate properties deemed important were angularity and abrasion resistance. Most agencies specify that ground tire rubber be used in OGFCs. Both elastomeric polymers and ground tire rubber are used in OGFCs. For states that reported the use of PFCs, polymers are generally specified. Another material common to PFCs is fiber stabilizers. Roughly 85 percent of the responding agencies indicated that fibers are required. Mineral and cellulose fibers are the most commonly specified fiber types. Fiber dosage rates ranged from 0.2 to 0.5 percent for the two fiber types.

During the design of OGFC mixtures, 70 percent of respondents stated that a laboratory compactive effort is utilized. This would indicate that the remaining 30 percent use a recipe method of designing OGFCs. The compaction methods mentioned were the Marshall hammer and Superpave gyratory compactor. When using the Marshall hammer, 50 blows per face was the most common compactive effort. For the Superpave gyratory compactor, 50 gyrations was the prevalent design compactive effort. Most of the agencies reporting the use of PFCs utilized the Superpave gyratory compactor. A number of other tests were identified as being used during mix designs and include: draindown, moisture susceptibility, Cantabro Abrasion Loss, and permeability.

Nearly two-thirds of the agencies specify OGFC by Standard Specification, indicating that OGFC is part of their standard paving operations. Both batch and drum plants have been used to successfully produce OGFC mixtures. None of the responding states required an increased mixing time for OGFCs. Roughly half of the responding agencies do limit silo storage times with limits ranging from 1 to 12 hours. However, agencies reporting the use the PFCs generally specify a maximum of 2 hours storage time. Haul distances are generally not specified; rather, most agencies specify a minimum mix temperature when the haul trucks reach the paving site. This minimum temperature is typically based upon the grade (type) of asphalt binder used in the mix. Release agents are allowed for truck beds by all agencies.

The type and rate of tack coats vary by agency. Both emulsions and neat asphalt binder have been used successfully as tack coats. Only one agency did not have a minimum specified air and/or surface temperature for placing OGFC. As would be expected, the specified minimum temperature varied by climatic region. One constant related to the specified minimum temperatures was that the temperature must be above the minimum and rising. Compaction of OGFC layers is conducted using static steel wheel rollers. This was consistent with all responding agencies. Some agencies do specify the number of passes during compaction.

Two QC/QA tests are relatively constant among the responding agencies: asphalt content and gradation. Other QC/QA tests mentioned by the agencies included tensile strength ratio, permeability, temperature, draindown, air void content, and Rice specific gravity.

Another construction issue addressed in the survey was pavement markings. Unfortunately, a definitive method (or material) for use with OGFCs was not found. The methods appeared to be agency specific. Likewise, a definitive method of constructing rumble strips was not identified by the survey.

Primary maintenance activities conducted by the responding agencies were related to winter maintenance. Respondents acknowledged the need for general (non-winter) maintenance related to clogged OGFCs; however, no agencies currently utilize a routine maintenance program for evaluating the permeability of OGFC layers. For general maintenance, most agencies do monitor the existence and manifestation of raveling, cracking, and delamination.

For winter maintenance, the primary piece of information observed from the survey was that more deicing chemicals are needed for OGFC layers than for dense-graded layers. Calcium chloride and sodium chloride were identified as the two most common ice control chemicals used for OGFCs. One-third of the respondents did state that they used anti-icing methodologies prior to winter events.

For small distressed areas, the responding agencies indicated that patching with dense-graded mix was the typical method of rehabilitation. When distressed areas are larger, the typical strategy is to remove the existing OGFC by milling and replace with a new OGFC. One state did question placement of OGFC over a milled surface, likely because of the grooves left in the existing pavement. This agency is investigating the need for micro-milling to provide a smoother surface for placing OGFC.

The final portion of the survey was on performance. Most of the respondents indicate that the service life of OGFCs was 8 to 10 years. The most common distresses encountered with OGFCs are raveling and delamination. Cracking also was mentioned as a distress. Respondents were asked to rank seven performance characteristics related to OGFCs. Of these performance characteristics, wet weather friction was identified as the most important performance characteristic. Reduced splash/spray and reduced hydroplaning tied for the second most important performance characteristic. Interestingly, noise reduction and smoothness were considered the least important. This overwhelmingly indicates that the safety benefits related to OGFCs are the primary reason for selecting OGFC layers.

CHAPTER 3

Overview of Permeable Friction Courses

Within the United States, OGFC has been used to describe HMA with an open aggregate grading that is used as a wearing layer to improve frictional properties. These mixes evolved through experimentation with plant mix seal coats. The initial interest in these mix types came from problems associated with chip seals. Primarily, loose aggregates that either were not adequately seated during construction or dislodged by traffic were breaking windshields. Additionally, there was a time constraint problem with setting the chip seal aggregates during a sudden rainstorm (*3*). During the 1930s Oregon began experimenting with the plant mix seal coats to improve frictional properties. During the 1940s, California also began using the plant mix seal coats as drainage interlayers and as an alternative to chip seals and slurry seals. During the late 1940s, a number of the western states began to use these mixes to improve frictional properties. An additional benefit when using these plant mix seal coats as a wearing layer was that hydroplaning and splash/spray was reduced (*3*).

Even though plant mix seals provided excellent frictional properties and reduced potential for hydroplaning and splash/spray, their use did not become widespread until the 1970s. The primary problems with these mixes were related to durability and draindown. Because the plant mix seals had an almost uniform aggregate gradation with little fine aggregate, there was very little aggregate surface area. The term draindown describes the asphalt draining from the aggregates during storage and transportation. Asphalt binder that has drained from the aggregate structure results in pavement areas that have too little asphalt binder and areas that are very rich in asphalt binder. Areas without a sufficient amount of asphalt binder were prone to raveling, while areas rich in asphalt binder could become slick and did not provide the desired frictional properties.

In the 1970s, the FHWA initiated a program to improve the skid resistance of the nation's roadways (*4*). The plant mix seal coats were one of the tools an agency could use to improve frictional resistance and gained popularity. According to the 1978 NCHRP Synthesis Number 49, these plant mix seals became known as OGFCs (*5*). In 1980, the FHWA published a mix design procedure for these mix types (*6*). The procedure entailed an aggregate gradation requirement, a surface capacity of coarse aggregate, determination of fine aggregate content, determination of optimum mixing temperature, and resistance of the designed mixture to water. OGFC mixtures designed in accordance to the FHWA procedure were successful at performing their intended function: removing water from the pavement surface and improving frictional resistance. However, a number of states noted that the OGFC pavements were susceptible to sudden and catastrophic failures (*7*).

Failures observed during the 1970s and 1980s were caused by mix design, material specification, and construction problems. These problems primarily involved mix temperature during construction. Gradations associated with the OGFCs of the 1970s and 1980s were much coarser than typically used dense-graded mixes (Marshall and Hveem designed mixes). Additionally, few states were using modified asphalt binders. Because of the open nature of the aggregate gradings and neat asphalt binders, there were problems of draindown during transportation to the project site. To combat the draindown problems, most owners would allow contractors to reduce the mixture's temperature during production. The draindown and mixture temperature problems led to catastrophic raveling and delamination, respectively. These problems were of such magnitude that a number of states put a moratorium on the use of OGFC mixtures during the 1980s.

A survey of state highway agencies conducted by Kandhal and Mallick in 1998 (*8*) indicated that 19 states (38 percent) were currently using OGFCs. Over 70 percent of the states using OGFCs reported service lives of 8 years or more. The vast majority of the states reporting good performance indicated the use of coarser gradations than the FHWA mix design procedure (*8*) required and the use of stiffer, polymer-modified binders.

The question must be asked, "If OGFCs did not perform in the 1970s and 1980s, why did states continue to evolve them such that performance improved?" The answer is simple, safety. OGFCs most likely provide the safest wearing surface for the nation's roadways. OGFCs have been shown to have excellent frictional resistance, reduce splash and spray, reduce the potential for hydroplaning, improve night visibility and improve visibility of pavement markings. Additional benefits of using OGFCs include reduced pavement noise, smoother pavements, increased fuel economy, and use of relatively thin layers.

The property of OGFC that leads to these safety benefits is the relatively high permeability of OGFC compared to dense-graded HMAs. Because of the very coarse gradation and lack of fines, OGFCs have very high air void contents in the range of 15 to 22 percent. These high air void contents result in interconnected voids that allow water to infiltrate into the OGFC layer. Without water on the pavement surface, the frictional properties of the pavement improve, splash and spray is reduced, and the potential for hydroplaning is greatly reduced.

OGFCs that are designed to have at least 18 percent air voids are termed PFCs, a special type of OGFC specifically designed to have high air void contents, typically 18 to 22 percent, for removing water from the pavement surface. Other types of OGFCs also are used within the United States. In some states, friction courses having an open-grading are used; however, the purpose of these friction courses is to provide a safe riding surface by improving frictional properties and/or to reduce tire/pavement noise. Air void contents for these type OGFCs are generally 12 to 15 percent.

U.S. Experiences with PFCs

OGFCs have been used in the United States for many years; however, PFCs only recently have been utilized as a pavement surface layer option. The Oregon Department of Transportation (DOT) has been using OGFC since the 1970s (*4*). This mix would not explicitly meet the definition of a PFC, but was placed at a thickness (2 in.) that led to rapid removal of water from the pavement surface. Likely, the first specified PFC in the United States was by the Georgia DOT (*10*). In 1992, the Georgia DOT built some test sections on I-75 that were specifically designed to be coarser and have higher air void contents than GDOT's current version of OGFC (*10*). After these field experiments, GDOT developed specifications for what they termed Porous European Mixes (PEM) (*11*). These PEMs are considered the first generation of PFCs used in the United States. Characteristics of these Georgia PFCs were that modified asphalt binders and stabilizing additives were included. A 1998 survey on the use of OGFC in the United States (*8*) indicated that most DOTs reporting good performance with OGFCs had adopted coarser gradations and modified asphalt binders similar to the Georgia DOT PEM mixes.

After the 1998 survey (*8*) was published, the National Center of Asphalt Technology undertook a research project to develop a mix design procedure for new-generation OGFCs. These mixes are considered PFCs. This research study led to a number of DOTs adopting specifications for PFCs. A number of states in the southern part of the United States now utilize PFCs as the wearing layer on all interstates. Based upon the results of the survey conducted during the course of NCHRP Project 9-41, nine DOTs are currently specifying PFCs. Seven of these DOTs are located in the southeast, ranging from Texas to North Carolina. Though they did not respond to the questionnaire, the researchers also are aware that the New Jersey (*12*), Indiana (*13*), and Louisiana (*14*) DOTs have placed PFCs.

In most instances, PFCs are used on high-traffic, high-speed pavements within the United States. Huber (*7*) states that PFC mixes are more desirable on high speed roadways. High speeds are needed to generate enough hydraulic action under vehicle tires to allow the PFC layer to be self-cleaning and, therefore, maintain permeability longer.

European Experiences with PFCs

In 1990, a significant portion of *Transportation Research Record No. 1265* was devoted to the use of OGFCs in Europe. Within most of the articles of this publication, the OGFCs were called porous asphalt. These porous asphalts would classify as PFCs as most are designed to have more than 20 percent air voids. Isenring et al. (*15*) state that PFCs first were used in Switzerland during 1972 on an airport runway and first placed on highway pavements in the late 1970s and early 1980s. As of 1990, Spain had placed more than 3.6 million yd^2 (3 million m^2) of porous asphalt (*16*) with the first application placed in 1980. Within the Netherlands, the first PFC was placed in 1972 (*17*). During the 1980s, placement of PFC became more widespread because of the noise-reduction characteristics provided by these mix types. The literature also showed a number of other European countries that utilize PFCs, including Italy, France, Belgium, Austria, and the United Kingdom (*4, 18*).

Alderson (*19*) provided a comprehensive report on the use of PFCs in Australia. PFC are utilized in Australia because they provide better wet weather skid resistance, reduced noise, reduced splash and spray, improved visibility of pavement markings and smoother riding surfaces.

Based upon the survey described in Chapter 2, both Canada and Japan also are utilizing PFCs. Iwata et al. (*20*) indicate that PFCs are widely used on the expressways of Japan. Iwata et al. (*20*) described an initiative in which the Japan Highway Public Corporation planned to construct almost 7,200 miles (11,520 km) of expressway with PFC being the wearing surface.

CHAPTER 4

Benefits of Permeable Friction Courses

This chapter only presents items identified by the literature as benefits of using PFC mixtures as wearing layers. Chapter 10 will discuss the performance of PFCs, which will include discussions on how long the benefits can be realized on the roadway. For the most part, the benefits are based upon the ability of the PFC layer to drain water from the pavement surface. Lefebvre (*21*) states that the benefits of PFCs can be categorized based upon three general areas: safety, driving comfort and environmental.

Safety Related Benefits

Benefits related to safety include reduced potential for hydroplaning, improved skid resistance (especially during wet weather), reduced splash and spray, and reduced light reflection. Hydroplaning occurs when a layer of water builds up between a tire and the pavement surface (*21*). This layer of water breaks the contact between the tire and road (*21, 22*). When this occurs, the vehicle will not respond to braking or turning by the driver. There are two aspects of PFCs that help prevent the occurrence of hydroplaning. First, because the water drains from the pavement surface into the PFC layer, the film of water is not available to break the bond between the tire and pavement surface (*21*). The second is the macrotexture provided at the pavement surface by PFC layers. Even when clogged, PFCs provide a significant amount of macrotexture. This macrotexture provides small channels for water to be dissipated as a tire crosses over the pavement (*23*). Therefore, in wet weather driving conditions, the skid resistance of PFC wearing layers is generally very good.

Many references mention that OGFCs used on the pavement surface will improve frictional properties, especially during wet weather. Similar to how PFCs reduce the potential for hydroplaning, the ability to drain water from the pavement surface and the relatively high macrotexture of PFCs also improve wet weather friction. Kandhal (*4*) cited a number of references in his synthesis describing research conducted in the United States, Canada, and Europe that showed the improved wet pavement frictional properties of OGFCs. Much of the research dealt with comparing the speed gradient (or friction gradient) encountered on OGFC layers. A frictional speed gradient can be defined as the rate of decrease in the friction number per mile per hour increase in speed. Therefore, low frictional speed gradients are desirable. Table 21 presents data from a Pennsylvania DOT project that shows a decreased friction gradient for OGFC layers. Similar work in Oregon and Louisiana presented by Kandhal (*4*) also showed decreased friction gradients for OGFCs compared to dense-graded layers.

Isenring et al. (*15*) also conducted friction testing in Switzerland on 17 different PFC test sections at different speeds including 25, 37, 50, and 62 mph. Friction measurements were made using the PIARC skid test and a ribbed tire. Results showed that PFC pavement surfaces had much higher coefficients of friction at higher speeds than typical dense-graded surfaces. Similar to the referenced literature by Kandhal (*4*), the friction speed gradients for PFC surfaces were lower than for typical dense-graded layers.

Bennert et al. (*12*) presented the results of wet skid tests on various wearing surfaces, including PFCs, in New Jersey. The skid measurements were made in accordance with ASTM E274-97, Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire. A test speed of 40 mph was utilized using a ribbed-tire on the skid trailer. A total of 19 different pavement sections were tested. Included within the evaluation were asphalt rubber OGFC, PFC (termed modified OGFC), Novachip, stone matrix asphalt (SMA), microsurfacing, Superpave designed dense-graded HMA, and portland cement concrete. Table 22 presents the results of testing on the 19 test sections. Based upon the results, the asphalt rubber OGFC had the highest frictional resistance of the thin lift wearing layers followed by the microsurfacing and PFC. The PFC layers tested did provide higher wet-skid numbers than Novachip and the Stone Matrix Asphalt (SMA) surfaces.

As further evidence that wet weather friction is improved with the use of PFCs, many references stated that the use of

Table 21. Friction data from Pennsylvania (*4*).

Mix Type	Friction Number 30 mph	Friction Number 40 mph	Friction Gradient
OGFC (gravel)	74	73	0.10
OGFC (dolomite)	71	70	0.10
Dense-graded HMA (gravel)	68	60	0.80
Dense-graded HMA (dolomite)	65	57	0.80

PFCs reduced the number of wet weather accidents. Research in Virginia, France, and Canada showed that OGFC and PFC layers reduced wet weather accidents (*4*). In Virginia, wet weather accidents were reduced from 39 percent of all accidents on State Route 23 to 17 percent of all accidents, a reduction of approximately 50 percent. On the A7 Motorway in France, the number of accidents fell from 52 (1979 to 1985) to none (1985 to 1989) after a PFC replaced a dense-graded surface on the roadway. In Canada, the placement of OGFC on a section of roadway reduced the number of wet weather accidents by 54 percent and the total number of accidents by 20 percent (*4*). Greibe (*24*) discussed a study in Austria that showed no difference in traffic accidents on dry pavements but fewer wet weather accidents on PFC surfaces. Iwata et al. (*20*) reported an 80 percent reduction in wet weather accidents when using PFCs in Japan.

Recent work in the United States by McDaniel and Thornton (*13*) also has shown that PFCs provide relatively more macrotexture and a higher International Friction Index (IFI) than other HMA wearing layers. Tables 23 and 24 present macrotexture and friction measurement data for three test sections in Indiana, respectively. Pavement surfaces included within the research were PFC, SMA, and dense-graded HMA.

McDaniel and Thornton (*13*) indicated that the PFC and SMA wearing layers showed significantly more macrotexture (reported as mean profile depth) than did the dense-graded HMA (Table 23). The PFC layer provided the highest average mean profile depth measurement. The variability in measured mean profile depths also was found to be higher for the PFC and SMA layers compared to the dense-graded surface. The authors indicated that this was expected since the PFC and SMA mixes have gap- or open-graded aggregate structures.

McDaniel and Thornton (*13*) also reported results of dynamic friction measurements made with the Dynamic Friction Tester (Table 24). Based upon the raw friction numbers, the PFC and dense-graded surfaces were comparable, whereas the SMA surface showed the lowest values. The authors also converted the mean profile depth and friction number data into the IFI. In terms of IFI, the PFC showed the highest frictional properties followed by the SMA and dense-graded surface.

Another benefit related to safety from the use of PFC wearing layers is the reduction in splash and spray. During rain events, water will sit on the surface of a dense-graded HMA wearing layer. As vehicles pass over the pavement surface, the water will be splashed (splash) or thrown into the air in the form of a mist (spray) (*7*). The existence of the splashed

Table 22. Wet-skid numbers for various pavement surface types (*12*).

Surface Type	Age	Wet-Skid Number (SN_{40})	Avg. Wet-Skid Number (SN_{40}) per Surface
AR-OGFC	9	47.8	51.9
AR-OGFC	10	55.9	
MOGFC	1	47.9	48.0
MOGFC	4	44.8	
MOGFC	2	51.2	
Novachip	3	45.4	45.6
Novachip	8	45.7	
9.5 mm SMA	7	42.5	42.3
12.5 mm SMA	9	42.0	
MS Type 3	1	49.6	49.4
MS Type 3	1	49.1	
12.5 mm SP	10	51.8	53.1
12.5 mm SP	4	54.3	
PCC (no finish)	44	38.6	39.7
PCC (no finish)	39	39.1	
PCC (no finish)	48	41.4	
PCC (Trans. tined)	14	57.2	56.5
PCC (Trans. tined)	14	55.8	
PCC (Diamond Grind)	14	54.6	54.6

AR-OGFC = asphalt rubber open-graded friction course
MOGFC = modified asphalt binder open-graded friction course
SMA = stone matrix asphalt MS = microsurfacing
SP = Superpave PCC = portland cement concrete

Table 23. Results of surface texture measurement (*13*).

Mix	Mean profile depth, mm (Standard Deviation)
PFC	1.37 (0.13)
SMA	1.17 (0.14)
HMA	0.30 (0.05)

or sprayed water reduces visibility more severely than fog because the airborne particles within the mist are larger than the particles within fog (*7*). PFCs reduce (and almost eliminate) the droplets of water caused by vehicles passing over the roadway because water infiltrates into the interconnected voids of the pavement. Greibe (*24*) indicated that splash and spray can be reduced as much as 95 percent when using PFC surface layers compared to dense-graded HMA.

Flintsch (*25*) conducted a study to assess the performance of several roadway surface layers under rain and snow. The pavement surfaces included five HMA mixes and one portland cement concrete. Three of the HMA surfaces were a dense-graded mix, one was SMA, and the final surface was an open-graded mix. This work was conducted on the Virginia Smart Road and utilized artificial rain and snow. During the experiment dealing with rain, Flintsch (*25*) conducted a qualitative evaluation of splash and spray. Based upon the visual observation of the various road surfaces, Flintsch (*25*) stated that the open-graded mixture enhanced splash and spray performance compared to the other HMA surfaces.

In a similar fashion, McDaniel and Thornton (*13*) qualitatively compared the splash and spray of the three test sections in Indiana. Based on visual evaluations, McDaniel and Thornton indicated that sight conditions for the driver improved significantly (even when passing or passed by semi-trailer trucks) with the use of PFC as compared to SMA.

Drivers traveling down a roadway will observe the pavement at a glancing angle of about 1 degree or less. When surfaces are very smooth (e.g., dense-graded layers), the reflection of light will look similar to a mirror in the distance. This is especially true when water is on the pavement surface. PFC will diffuse the reflection of light due to the high macrotexture, even when observed from a glancing angle (*21*). This reduction in glare allows the driver to see pavement markings better, especially at night and/or wet weather, as well as providing overall better visibility.

Driver Comfort Related Benefits

Lefebvre (*21*) identifies increased driving speeds during wet weather as a benefit related to safety. During rain events, the decreased potential for hydroplaning and splash and spray allows drivers increased confidence that results in increased speeds. This increased confidence leads to less traffic moving at lower speeds. The net effect of the increased speeds is a greater traffic capacity during wet weather compared to dense-graded layers. The increased confidence of drivers also leads to less stress to drivers during rain events which increases driver comfort.

Greibe (*24*) stated that less light is reflected by wet PFC layers than dense-graded surfaces. This is due to the fact that water does not pool on the surface of PFC layers. Since less light can be reflected from oncoming vehicles, pavement markings are more visible.

A number of references indicate that the use of PFC wearing layers improves smoothness; however, very little specific research was encountered that provided relative improvements in smoothness when PFCs are utilized. Bennert et al. (*12*) did compare the results of ride quality measurements for a number of pavement surfaces in New Jersey including: asphalt rubber OGFCs, PFCs (termed modified OGFCs within the paper), Novachip, SMA, microsurfacing and three types of rigid pavement surfaces (transverse tined, diamond grind, and no finish). Table 25 presents results of testing related to ride quality by Bennert et al. (*12*). Two measures of ride quality are provided within this table. The Ride Quality Index (RQI) was measured using an ARAN vehicle. Previous studies in New Jersey cited by Bennert et al. (*12*) developed correlations between the ARAN van and user's perceptions to ride quality. The RQI is based upon a scale between 0 and 5, with an RQI of 5 being the "smoothest" ride according to user's perception. Results from the ARAN van also were used to determine the International Roughness Index (IRI) for each of the pavements. According to the IRI definition and scale, lower values of IRI are desirable.

Bennert et al. (*12*) state that based upon the RQI data it was difficult to determine the "best" pavement surface because of so many variables (most notably age). However, for the thin lift HMA mixes included in the study (PFC, AR-OGFC, Novachip, and microsurfacing), the PFC mixes did have the highest average RQI values. Similar results were obtained using the IRI measurements.

Table 24. Results of friction measurement (*13*).

Mix	Average Dynamic Friction Tester (DFT) Number (Standard Deviation)			International Friction Index
	20 kph	40 kph	60 kph	(F_{60})
PFC	0.51 (0.03)	0.45 (0.03)	0.42 (0.03)	0.36
SMA	0.37 (0.01)	0.31 (0.01)	0.29 (0.01)	0.28
HMA	0.52 (0.01)	0.47 (0.01)	0.44 (0.01)	0.19

Table 25. Results of ride quality measurements for various pavement surfaces (*12*).

Surface Type	Age	RQI value	RQI Rating	IRI (inch/mile)	Avg. IRI per Surface Type
AR-OGFC	9	3.54	Good	121	102
AR-OGFC	10	4.34	V. Good	82	
MOGFC	1	4.14	V. Good	90	90
MOGFC	4	4.05	V. Good	68	
MOGFC	2	4.08	V. Good	113	
Novachip	3	4.47	V. Good	65	94
Novachip	8	3.51	Good	123	
9.5 mm SMA	7	4.10	V. Good	84	139
12.5 mm SMA	9	3.72	Good	194	
MS Type 3	1	3.79	Good	108	110
MS Type 3	1	4.02	V. Good	111	
12.5 mm SP	10	4.15	V. Good	56	65
12.5 mm SP	4	4.31	V. Good	74	
PCC (no finish)	44	3.39	Good	178	174
PCC (no finish)	39	3.13	Good	206	
PCC (no finish)	48	3.42	Good	137	
PCC (Trans. tined)	14	2.66	Fair	274	285
PCC (Trans. tined)	14	2.54	Fair	295	
PCC (Diamond Grind)	14	4.21	V. Good	75	75

AR-OGFC = asphalt rubber open-graded friction course
MOGFC = modified asphalt binder open-graded friction course
SMA = stone matrix asphalt MS = microsurfacing
SP = Superpave PCC = portland cement concrete

Because of the increased smoothness when using PFCs, Bolzan et al. (*26*) indicate that fuel economy increases. Research at the National Center for Asphalt Technology also has indicated a relationship between smoothness and fuel economy (*27*); however, this research was not conducted to specifically evaluate PFC layers. Increased fuel economy also is considered a benefit related to the environment.

Decoene (*18*) has stated that a benefit of the use of PFCs is resistance to permanent deformation. Resistance to permanent deformation also was cited by Isenring et al. (*15*). The lack of rutting, combined with other benefits discussed above, leads to improved driver comfort.

Environmental Benefits

Environmental benefits related to the use of PFCs include reduction in tire/pavement noise, pavement smoothness, and use of waste materials. Two relatively recent areas where PGCs have been shown to be beneficial to the environment are filtration of stormwater runoff and a method of potentially providing a cool pavement surface. Of these environmental benefits, likely the most researched is the reduction of tire/pavement noises that result from using PFC wearing layers. Kandhal (*4*) cited numerous research studies that showed PFC layers reduced tire/pavement noise approximately 3 dB(A) compared to dense-graded HMA. To put a 3 dB(A) reduction in tire/pavement noise into perspective, this reduction also can be achieved by reducing the traffic volume in half.

Brousseaud et al. (*28*) reported on the tire/pavement noise reduction of PFCs compared to typical dense-graded HMA surfaces. In France, PFCs have typical noise levels of approximately 71 to 73 dB(A) when measured by the Statistical Pass-By Method. Comparatively, typical dense-graded HMA surfaces will have a noise level of approximately 76 dB(A) when measured by the same method. This indicates a 3 to 5 dB(A) reduction in tire/pavement noise levels when using PFC wearing layers.

Similar reductions in tire/pavement noise also have been reported in Switzerland by Graf and Simond (*29*). In their study, they evaluated four different pavement locations in which a PFC layer had replaced a dense-graded wearing surface. Table 26 presents the results of testing conducted by Graf and Simond (though the method of measuring tire/pavement noise was not provided, it is assumed to be Statistical Pass-By). The results of this testing indicated that PFCs reduced tire/pavement noise on average of about 6 dB(A).

The recent study conducted by Bennert et al. (*12*) compared the noise levels measured using the close proximity (CPX) method of various pavement surface types. In this method, microphones are placed near the tire/pavement interface to directly measure the tire/pavement noise levels. This method was developed in Europe and is defined by ISO Standard 11819-2. Results of the CPX testing on the various pavement surfaces are presented in Table 27. When comparing the thin lift wearing surfaces, the OGFC mixes yielded the lowest average noise levels. The OGFC mixture containing an asphalt-rubber binder had the lowest average noise levels, while the

Table 26. Reduction in noise levels when comparing PFC and dense-graded HMA in Switzerland (*29*).

Installation date	Location	Reduction in noise emission after the installation of PFC dB(A)
1991	Pertit	4.1 ... 6.2
1993	Morges	5.4 ... 8.6
1999	Lonay	6.2 ... 8.4
1999	Bex	4.5 ... 6.0

PFC (termed MOGFC in the table) had the next lowest average noise levels. Both OGFC types were slightly quieter than the Novachip, SMA, and microsurfacing layers.

McDaniel and Thornton (*13*) showed PFC having lower tire/pavement noise than SMA or dense-graded surfaces. Results of their research are shown in Table 28. McDaniel and Thornton (*13*) included both CPX and Statistical Pass-By testing to evaluate tire/pavement noise. Results of CPX testing indicated that PFC was 4.7 dB(A) quieter than SMA and 3.5 dB(A) quieter than dense-graded HMA surfaces. Similar results also were found when using the Statistical Pass-By method for evaluating tire/pavement noise.

Because of the noise reducing properties of PFC (and other types of OGFC), it has been suggested that these mix types may be an alternative to the construction of sound barriers to mitigate traffic noise (*4*). A reduction in the noise level by 3dB(A) has the net effect of either cutting the traffic volume in half or the noise protection distance to the road can be doubled (*4*). Larsen and Bendtsen (*30*) presented the only paper that specifically compared costs between various noise abatement techniques. Techniques of noise abatement included in the research on noise barriers (walls), building insulation and PFC wearing layers. Larsen and Bendtsen (*30*) evaluated three different scenarios: city streets, arterials, and interstates. Based upon the assumptions and analyses conducted, the authors concluded that PFC layers are an effective method for noise abatement. For each of the three scenarios, PFC was the cheapest noise abatement technique.

A relatively new concept with the use of PFCs to reduce noise consists of using two-layer PFC layers (*31*). A two-layer PFC system is composed of a bottom layer of PFC with a large aggregate size gradation and a top layer of PFC having a smaller aggregate size gradation. The top layer of PFC keeps dirt and debris from clogging the lower layer. The bottom layer utilizes a larger aggregate size gradation in order to produce larger sized air voids. According to Dutch experience (*31*), the two-layer system has good noise reducing characteristics compared to dense-graded layers. France also has utilized a two-layer PFC system (*28*).

Huber (*7*) also indicated that the two-layer systems are used to combat clogging tendencies in slow-speed environments. The smaller aggregate size wearing layer will trap larger debris

Table 27. Tire/pavement noise results for various pavement surfaces (*12*).

Surface Type	Age	Noise Level (dB(A)) at 60 mph	Avg. Noise Level (dB(A)) at 60 mph per Surface
AR-OGFC	9	96.8	96.5
AR-OGFC	10	96.2	
MOGFC	1	97.0	97.7
MOGFC	4	97.6	
MOGFC	2	98.4	
Novachip	3	98.2	98.8
Novachip	8	99.4	
9.5 mm SMA	7	98.0	99.3
12.5 mm SMA	9	100.5	
MS Type 3	1	98.8	98.8
MS Type 3	1	98.8	
12.5 mm SP	10	97.1	97.8
12.5 mm SP	4	98.5	
PCC (no finish)	44	102.9	103.5
PCC (no finish)	39	104.2	
PCC (no finish)	48	103.3	
PCC (Trans. tined)	14	105.6	106.0
PCC (Trans. tined)	14	106.6	
PCC (Diamond Grind)	14	98.7	98.7

AR-OGFC = asphalt rubber open-graded friction course
MOGFC = modified asphalt binder open-graded friction course
SMA = stone matrix asphalt MS = microsurfacing
SP = Superpave PCC = portland cement concrete

Table 28. Results of all sound measurements (*13*).

Method	Speed		Average CPX Sound Pressure Levels (Time averaged level over the length of pavement, LAEQ)		
			PFC	SMA	HMA
CPX	72 kph		89.7 dB(A)	94.2 dB(A)	93.0 dB(A)
	97 kph		92.6 dB(A)	97.6 dB(A)	96.4 dB(A)
	Average		91.2 dB(A)	95.9 dB(A)	94.7 dB(A)
	Difference from PFC		0.0 dB(A)	4.7 dB(A)	3.5 dB(A)
Pass-By	Speed	Vehicle			
	80 kph	Impala	68.1 dB(A)	74.8 dB(A)	72.6 dB(A)
		Volvo	70.1 dB(A)	75.5 dB(A)	75.2 dB(A)
		Silverado	71.6 dB(A)	77.0 dB(A)	74.5 dB(A)
		Average	69.9 dB(A)	75.8 dB(A)	74.1 dB(A)
	Difference from PFC		0.0 dB(A)	5.9 dB(A)	4.2 dB(A)
	110 kph	Impala	71.7 dB(A)	78.5 dB(A)	NA*
		Volvo	74.3 dB(A)	80.5 dB(A)	NA
		Silverado	74.4 dB(A)	79.4 dB(A)	NA
		Average	73.5 dB(A)	79.5 dB(A)	NA
	Difference from PFC		0.0 dB(A)	6.0 dB(A)	---

* Could not be tested due to speed limits.

in order to maintain permeability in the lower layer. Also, the air void space in the lower layer allows a water/jet vacuum machine to restore permeability.

Recent research has indicated that PFCs impact the quality of stormwater runoff. Barrett et al. (*32*) state that the use of PFC wearing surface might be expected to reduce the generation of pollutants, retain a portion of generated pollutants within the void structure, and impede the transport of pollutants to the pavement edge. Barrett et al. (*32*) cited previous research that the constituents within runoff are related to the number of vehicles that pass during a storm event. Splash and spray generated from tires are assumed to wash pollutants from the vehicle's engine compartment and bottoms. Because PFCs reduce the amount of splash and spray, it is assumed that fewer contaminants are washed form vehicles. Barrett et al. (*32*) also suggest that the void structure within a PFC layer may act to filter pollutants, especially suspended soils and other pollutants associated with solid particles.

Barrett et al. (*32*) cited work by Berbee et al. (*33*) in which the researchers compared the concentrations of pollutants in runoff from porous and dense-graded surfaces in the Netherlands. The porous layer was three years old and 55 mm in thickness. Runoff water samples were obtained for a week. Berbee et al. (*33*) found lower concentrations of pollutants in runoff sampled from the pavement having a porous wearing surface than the dense-graded surface. Based upon the test results, the following was observed: 91 percent reduction in total suspended solids (TSS); 84 percent reduction in total Kjeldahl nitrogen (TKN); 88 percent lower chemical oxygen demand; and 67 to 92 percent lower cooper, lead, and zinc.

Another environmental benefit that has recently been observed is the ability of PFC to act as a cool pavement to combat Urban Heat Islands (UHI). Urban heat islands are a temperature phenomenon that occurs in urban areas. The sun's radiation is absorbed by rooftops, pavements, sidewalks, buildings, etc. Because of the close proximity of these types of structures within an urban area, the sun's energy can be reflected or radiated from the structures resulting in increased temperatures. According to the EPA, air temperatures within urban areas can be 50 to 90°F (27 to 50°C) hotter on hot dry days than in nearby more rural areas (*34*).

According to the Heat Island Reduction Initiative being conducted by the EPA, "cool pavements" are a strategy for reducing the UHI. Open-graded mixes, whether PFCs or porous pavement parking lots, are technologies that are considered cool pavements.

Summary

The use of PFC wearing layers provides a number of benefits compared to dense-graded layers. Benefits related to safety include reduced potential for hydroplaning, improved wet weather frictional properties, reduced wet weather accidents, reduced splash and spray, reduced glare, and improved vision in seeing pavement markings. Benefits related to driving comfort include smooth wearing layers (and, thus, improved fuel economy). Environmental benefits include improved smoothness (and, thus, improved fuel economy) and reduced traffic noise.

CHAPTER 5

Materials and Mix Design

The design of PFCs is similar to the design of typical dense-graded HMA mixtures in that the design of PFCs involve four primary steps. First step: select appropriate materials. Materials needing selection include coarse aggregates, fine aggregates, asphalt binder, and stabilizing additives. Second step: blend the selected aggregates to develop a design gradation. Third step: select the optimum asphalt binder content. Fourth step: subject the mixture to performance testing.

This chapter presents the current state of practice on the design of PFCs. Sections within this chapter are divided into the four steps in designing PFCs as described above.

Materials Selection

Materials needing selection include coarse aggregates, fine aggregates, mineral fillers, asphalt binders, and stabilizing additives. The current state of practice for selection of these materials is discussed here.

Aggregate Characteristics

The survey of agencies described in Chapter 2 included a request for the respondents to rank various aggregate characteristics for use in PFCs. Aggregate characteristics included within the survey were abrasion resistance, durability, polish resistance, angularity, shape, cleanliness, and absorption. Results from the survey are illustrated in Figure 13. Respondents were requested to rank the various aggregate characteristics on a scale of 1 to 7, with 1 being the most important property and 7 being the least important. Based upon the results of the survey, there appears to be three levels of importance. Polish resistance and durability were the most important properties as both of these had the lowest average rankings. The next level of importance includes angularity, abrasion resistance, particle shape, and cleanliness. All four of these characteristics have reasonably similar average ratings. The final level of importance was aggregate absorption. The average rating of this characteristic was much higher than the other six characteristics. These results would indicate that test methods and criterion are needed for abrasion resistance, durability, polish resistance, angularity, shape and cleanliness.

Results from the survey agree with the literature reviewed as part of NCHRP 9-41. Desirable aggregate characteristics found in the literature include abrasion/degradation resistance, polish resistance, angularity/surface texture, cleanliness, particle shape, and durability. Unfortunately, the literature was limited to authors only providing specification values for the different aggregate characteristics. No references were found that provided quantitative evaluations of various levels of different aggregate characteristics in order to optimize the desirable properties for aggregates used in PFCs.

As highlighted in the survey results, durability and polish resistance were the two most important aggregate characteristics based upon the survey. In Europe, polish resistance also is considered one of the most important aggregate characteristics (*21*). The polish stone value is the most common requirement specified for ensuring polish resistance (*16, 21*).

The predominant test used to evaluate the durability of aggregates is sulfate soundness. Georgia has a maximum loss of 15 percent when determined using magnesium sulfate (*11*). Oregon utilizes a maximum loss of 12 percent when using magnesium sulfate (*7*).

The Los Angeles abrasion test is the most common test to evaluate aggregate abrasion/degradation resistance. It is specified both in the United States and internationally. Maximum loss values encountered in the literature ranged from a low requirement of 12 percent (*35*) to a high of 50 percent loss (*11*). Within the United States, current recommendations are generally a maximum Los Angeles abrasion loss of 30 percent (*4*).

Coarse aggregate angularity is most often specified as a minimum number of fractured faces. Most commonly, specifications are for the percentage of aggregates with two or more

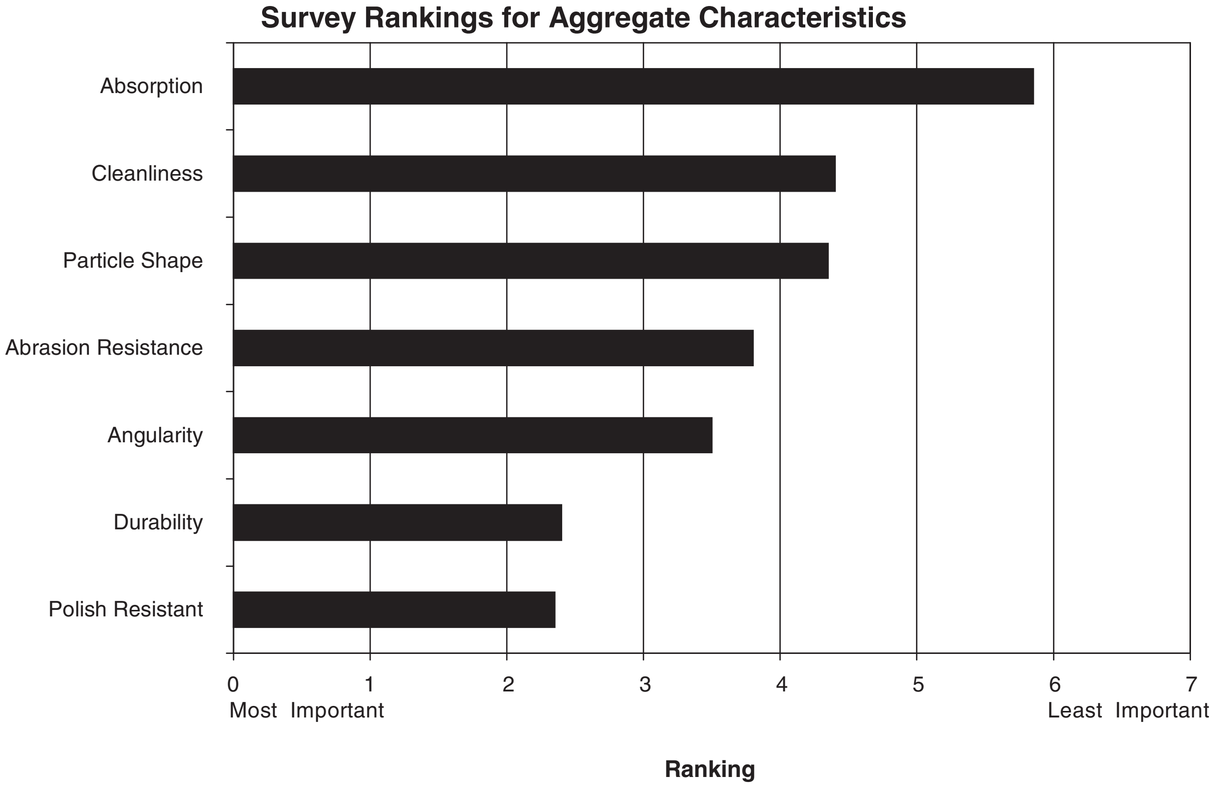


Figure 13. Ranking of aggregate characteristics from agency survey.

fractured faces. Specification values range from a low of 90 percent of the coarse aggregates with two or more fractured faces (*36*) to a high of 100 percent (*7, 21*).

Only one reference was encountered that listed any specification values for fine aggregates. Generally, most references simply stated that the fine aggregate fraction should be crushed indicating an angular material. Kandhal (*4*) recommended using the uncompacted void content of fine aggregate with a specification minimum of 45 percent.

Two tests are generally utilized to specify the desired shape of coarse aggregates, the flakiness index and the flat and elongated test. The flakiness index is generally specified in Europe with a maximum requirement of 25 percent (*7, 37*). Arizona also has utilized this specification for the flakiness index (*7*). Within the United States, the flat and elongated test is the most common test to define coarse aggregate particle shape. Requirements for flat and elongated tests are generally based upon a ratio of 5:1 (*11*) though some guidance specifies ratios of 5:1 and 3:1 (*4*). When a 5:1 ratio is specified, a maximum percentage of flat and elongated particles requirement of 10 percent is common (*11, 36*), though some specify a maximum of 5 percent (*4*). When a 3:1 ratio is specified, a maximum requirement of 20 percent is used (*4, 36*).

Aggregate cleanliness is most often specified based upon the sand equivalent test. Specification values for the sand equivalent test range from a low of 45 (*5, 34*) to a high of 55 (*7*).

Asphalt Binders

A wide range of asphalt binders have been used in PFC mixes. Both unmodified and modified asphalt binders have been used with success. In the NCHRP synthesis by Huber (*7*), he reported many different types of asphalt binders. These binders were graded in accordance with the Superpave performance grading (PG) system, viscosity grading procedure, and penetration grading system. Within Europe, the asphalt binders were predominantly graded using the penetration grading system. Huber (*7*) reported on material requirements from Great Britain, Spain, Italy, and South Africa. At the time, Great Britain utilized a 100 pen asphalt binder with and without polymer modification. Spain utilized either a 60/70 or an 80/100 pen asphalt binder with polymer modification. Italy also used an 80/100 pen asphalt binder with polymer modification. Each of these three countries specify either a styrene butadiene styrene (SBS) or ethylene vinyl acetate (EVA) when using polymer modification. Huber (*7*) indicates that South Africa allows both polymer modification and modification with rubber.

Within the United States, Huber (*7*) reported a wide range of asphalt binders being used. Both PG and viscosity-graded binders were reported. Some U.S. agencies utilized unmodified asphalt binders. For instance, Arizona was specifying a PG 64-16 and Georgia was specifying a PG 67-22 for some OGFC mixes.

When utilizing PFCs, most agencies specified modified asphalt binders. For instance, Oregon specified a viscosity graded AC-30 with 12 percent rubber added to the asphalt binder. Georgia also specified polymer modified binders (*7*).

Alvarez et al. (*35*) also provided a synthesis on mix design criteria for PFCs. This work was published in 2006, six years after Huber's synthesis (*7*). Alvarez et al. (*35*) also report that asphalt binders used in PFCs are generally modified. Within Europe, polymers also are generally used to modify the asphalt binders. Similar to Huber (*7*), the polymer types most often cited were SBS and EVA. Great Britain does allow the use of styrene butadiene rubber (SBR) for polymer modification. The only European country not reporting the use of modified asphalt binders was Switzerland. Australia also allows the use of unmodified binders for lower traffic roadways (*19, 35*). For higher traffic roadways, SBS, SBR, EVA and rubber modified binders are allowed in Australia. Within the United States, Alvarez et al. (*35*) reported on mix design methods that allowed both polymer modified (type not given) and rubber modified asphalt binders.

Proper selection of the asphalt binder to be used within PFCs should be based upon a number of factors. Ruiz et al. (*16*) state that selection of the asphalt binder should be based upon the weather at the project site and the anticipated traffic volume the roadway will carry. Kandhal (*4*) also provides similar factors for selection of asphalt binders for PFCs.

Generally, the literature indicates that binders with a high stiffness are needed for PFCs, hence most agencies require modified asphalt binders. High stiffness binders are needed to help prevent draindown which promotes thick films of asphalt binder coating the aggregates. Molenaar and Molenaar (*38*) indicated that stiff, polymer-modified binders also help prevent short-term raveling. Short-term raveling was defined as raveling caused by intense shearing forces at the tire/pavement interface that occurs within newly placed porous asphalt. Ruiz et al. (*16*) state that asphalt binders that are too soft may tend to bleed during hot weather and lead to rutting problems. Even though stiff binders are desirable, Ruiz et al. (*16*) also suggest that binders that are too stiff can be detrimental. Asphalt binders that are too stiff may reach a critical hardness earlier which could lead to long-term raveling problems.

Stabilizing Additives

According to the survey and literature, one of the primary concerns with open-graded mixes is draindown during construction. Open-graded mixes have an open aggregate grading with a relatively low percentage of material passing the No. 200 (0.075 mm) sieve. Because of the open grading, the surface area of the aggregate blend is much lower than typical dense-graded mixes, and the low aggregate surface area results in relatively thick asphalt binder films coating the aggregates. According to Watson et al. (*39, 40*), typical asphalt binder film thicknesses for PFCs are approximately 30 microns compared to approximately 8 microns for dense-graded HMA.

At typical production/construction temperatures, the thick film of asphalt binder common to PFCs has a propensity to drain from the aggregate structure, termed draindown (*7*). In order to reduce the potential for draindown, stabilizing additives are generally incorporated into PFCs. Two types of stabilizing additives can generally be utilized within PFCs: fibers and asphalt binder modifiers. Many different types of fibers have been used within PFCs including mineral, cellulose, asbestos, polypropylene, polyacrylonitrile, glass, and acrylic fibers. According to the results of the agency survey, 85 percent of the responding agencies specify the use of fibers within open-graded mixes. This value is significantly higher than the 19 percent of agencies reporting the use of fibers within OGFC mixes in the 1998 survey by Kandhal and Mallick (*8*).

The increase in the percentage of agencies specifying the use of fibers within open-graded mixes is likely an indication of the effectiveness of fibers in reducing draindown potential. Figure 14 illustrates the effect of fiber addition on draindown potential. Data used to create Figure 14 is from research conducted by the National Center for Asphalt Technology on PFCs and was published by Watson et al. (*40*) in a slightly different form. Figure 14 clearly illustrates that the addition of fiber significantly reduces draindown potential. Similarly, other research projects have shown that the use of fibers significantly reduces the potential for draindown (*36*). According to Pasetto (*41*), additional benefits can be realized from the addition of fibers within PFC mixes. Pasetto (*41*) showed that the addition of fibers increased the strength of PFC mixes as measured by Marshall stability and indirect tensile testing. Additionally, the use of fibers improved the durability of PFC mixes as measured by the Cantabro Abrasion test.

As stated previously, a wide range of fiber types have been used in open-graded mixes. Within the United States, the most common fiber types used are cellulose and mineral fibers. These two fiber types also are common in Europe (*21*) and Australia (*19*). Addition of fibers is generally at a dosage rate between 0.1 and 0.5 percent, by total mix mass. An important point made by Decoene (*18*) is that the selected fibers must be resistant to temperatures above typical production temperatures. This is especially true when using organic fibers.

The other type of stabilizing additive commonly used in open-graded mixes is asphalt binder modifiers. These modifiers are generally polymers or rubber particles. With respect to draindown, these modifiers serve to increase the viscosity (stiffness) of the asphalt binder, helping to maintain the asphalt binder within the aggregate structure. The benefits of modified asphalt binders are not limited to helping prevent draindown. A series of reports and papers from the National Center

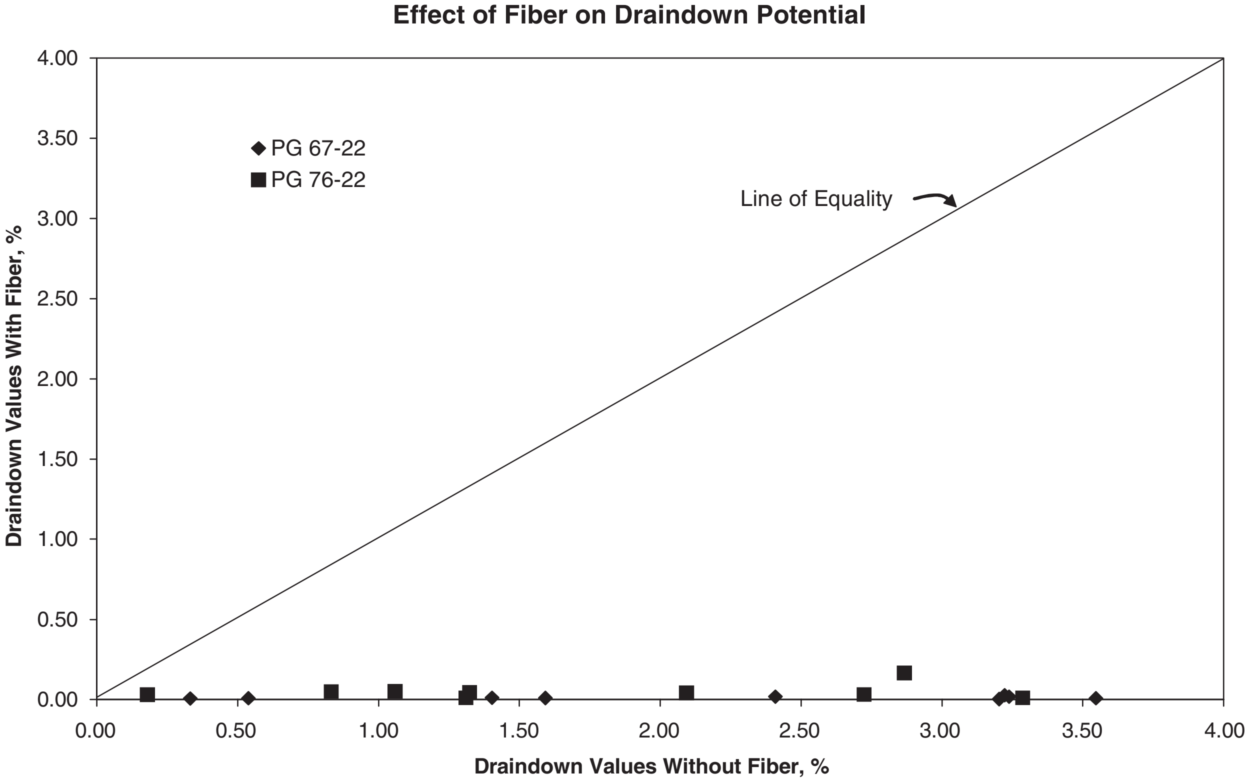


*Figure 14. Effect of fibers on the draindown potential of PFCs (*40*).*

for Asphalt Technology (*40, 42, 43*) have shown that the use of modified asphalt binders that provide higher stiffness at typical in-service temperatures help provide increased durability in the laboratory. These results match field experiences described by Huber (*7*) and the results of the 1998 survey of U.S. agencies by Kandhal and Mallick (*8*). Huber (*7*) indicated that in the past, thick films of unmodified asphalt binder tended to drain downward during hot summer weather due to gravitational forces. The remaining thin films of asphalt binder coating the aggregates would age more rapidly becoming brittle, which resulted in raveling. Use of modified asphalt binders helps to retain the thick asphalt binder film, thus improving durability. In addition, research has shown that the use of modified asphalt binders improves the short-term performance of PFCs. The increased stiffness of the asphalt binder reduces the potential for traffic dislodging aggregate particles shortly after construction. This early age dislodging of aggregate particles has been termed short-term raveling (*38*).

Fillers/Adhesion Agents

A number of agencies from around the world specify the use of fillers or other adhesion agents to improve the bond between aggregates and the asphalt binder. Van Der Zwan et al. (*17*) state that limestone filler is added during the production process to improve bonding in the Netherlands. The limestone filler must have a hydrated lime content of at least 25 percent. Australia also requires the addition of a filler to PFC mixes (*19*). Hydrated lime is the preferred type of filler in Australia; however, portland cement and ground limestone also are allowed. Similarly, Watson et al. (*11*) stated that hydrated lime is required in PFC mixes in Georgia as an anti-stripping agent.

In their 1998 survey of U.S. agencies, Kandhal and Mallick (*8*) evaluated the reported performance of open-graded mixes with various mix design practices. One of the mix design items included within the evaluation was whether the agency specified fillers/adhesion agents. To better evaluate the information, Kandhal and Mallick (*8*) divided the various agencies by the Strategic Highway Research Program climatic zones in which each resided. These climatic zones included wet-freeze, wet-no freeze, dry-freeze, and dry-no freeze. Collectively, of the 19 agencies reporting good performance, 53 percent added some type of filler/adhesion agent whether the material was hydrated lime or liquid antistrip materials. Conversely, only 21 percent of the agencies reporting bad performance with open-graded mixes specified the use of fillers/adhesion agents. Interestingly, all of the agencies reporting good performance within the dry-freeze climatic zone specified hydrated lime, while 75 percent of the agencies reporting bad performance in this climatic zone did not specify fillers/adhesion agents.

Selection of Design Gradation

The next step within the design of PFC mixes is to utilize the selected aggregates to develop a design gradation (or design aggregate structure). Within a typical mix design, this step may include developing several trial gradations and using mix design criteria to select the most appropriate of the trial gradations. Within this section, only typical PFC gradations will be discussed because the following section will provide the different mix design criteria.

The literature review and survey of agencies resulted in a wide range of gradations encountered for PFC mixes. As stated in Chapter 2, nine of the responding agencies categorized their open-graded mixes as PFCs. From these nine agencies, three different maximum aggregate size gradations are specified: 1 in., ¾ in., and ½ in. (25 mm, 19 mm, and 12.5 mm). Here, the term maximum aggregate size indicates the finest sieve which has 100 percent of the aggregates passing. The majority of the gradation requirements encountered throughout the world could potentially be characterized by multiple nominal maximum aggregate sizes (as defined in Superpave) depending upon the actual blended gradation. Therefore, within this document gradations only will be discussed by the maximum aggregate size.

Oregon was the only U.S. agency that had gradation criteria for a 1 in. (25 mm) maximum aggregate size gradation. This gradation is illustrated in Figure 15. This figure shows that the PFC gradation is gapped on the No. 4 sieve. The allowable filler content for this gradation band is 1 to 6 percent.

A number of agencies provide gradation requirements for a ¾ in. (19 mm) maximum aggregate size. Figure 16 illustrates the various PFC gradation bands specified in the United States. Gradations shown within this figure typically are gapped on the No. 4 sieve; however, some allow for gapping the gradation on the No. 8 sieve. Allowable filler contents range from a low of 1 percent to a high of 5 percent. Interestingly, several agencies have identical (or almost identical) gradation requirements for ¾ in. maximum aggregate size PFCs. Alabama, Georgia, Louisiana, and South Carolina all specify essentially the same gradation requirements. These specifications can be traced to the original Porous European Mix utilized by Georgia (*11*) and the research conducted by the National Center for Asphalt Technology (*40*).

Louisiana was the sole agency that provided gradation requirements for a ½ in. (12.5 mm) maximum aggregate size PFC, illustrated in Figure 17. For this gradation band, the aggregates are gapped on the No. 8 sieve. Filler criteria include a minimum of 2 percent and a maximum of 4 percent.

From an international standpoint, there are a number of agencies that specify open-graded mixes that would meet the requirements of a PFC. The primary mix design item that was utilized to determine whether the various open-graded mixes would qualify as PFC was air void content at design. In the literature review, open-graded mixes that were specified to

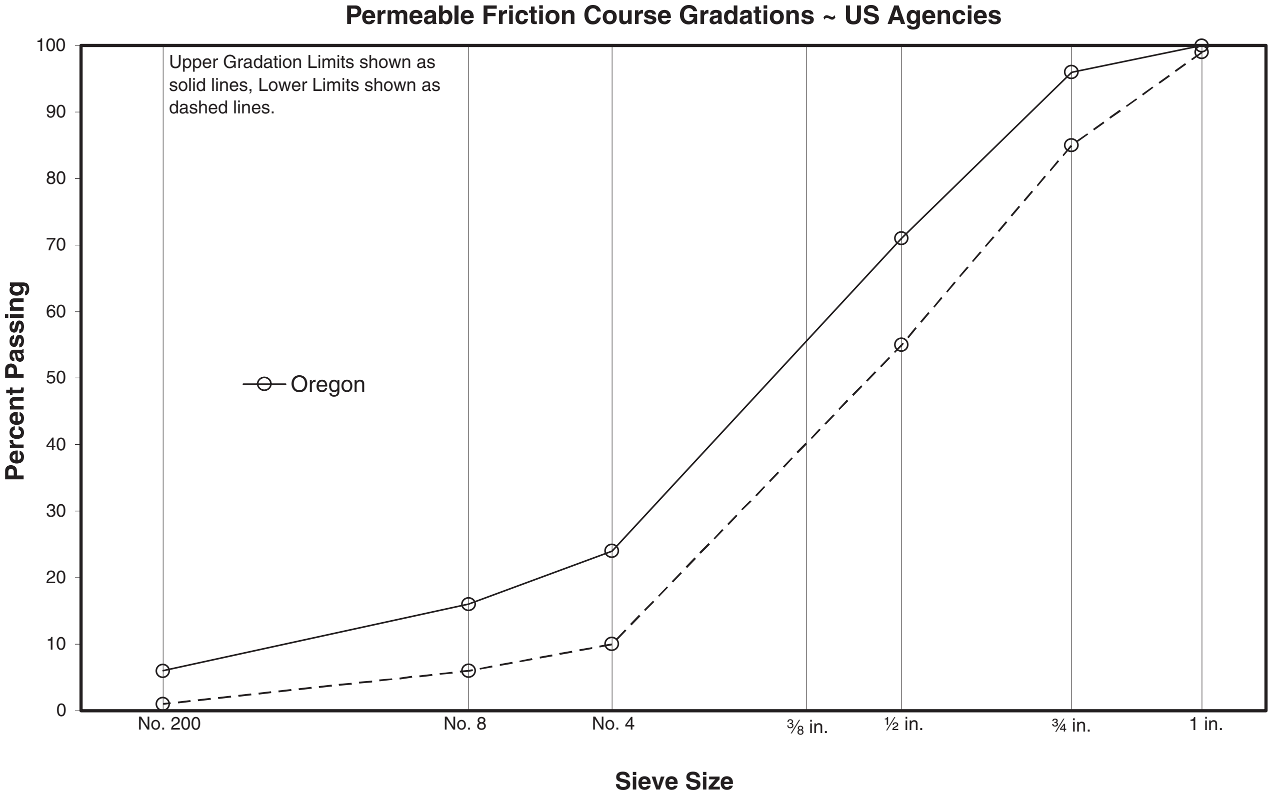


Figure 15. 1 in. PFC gradation requirements from U.S. agencies.

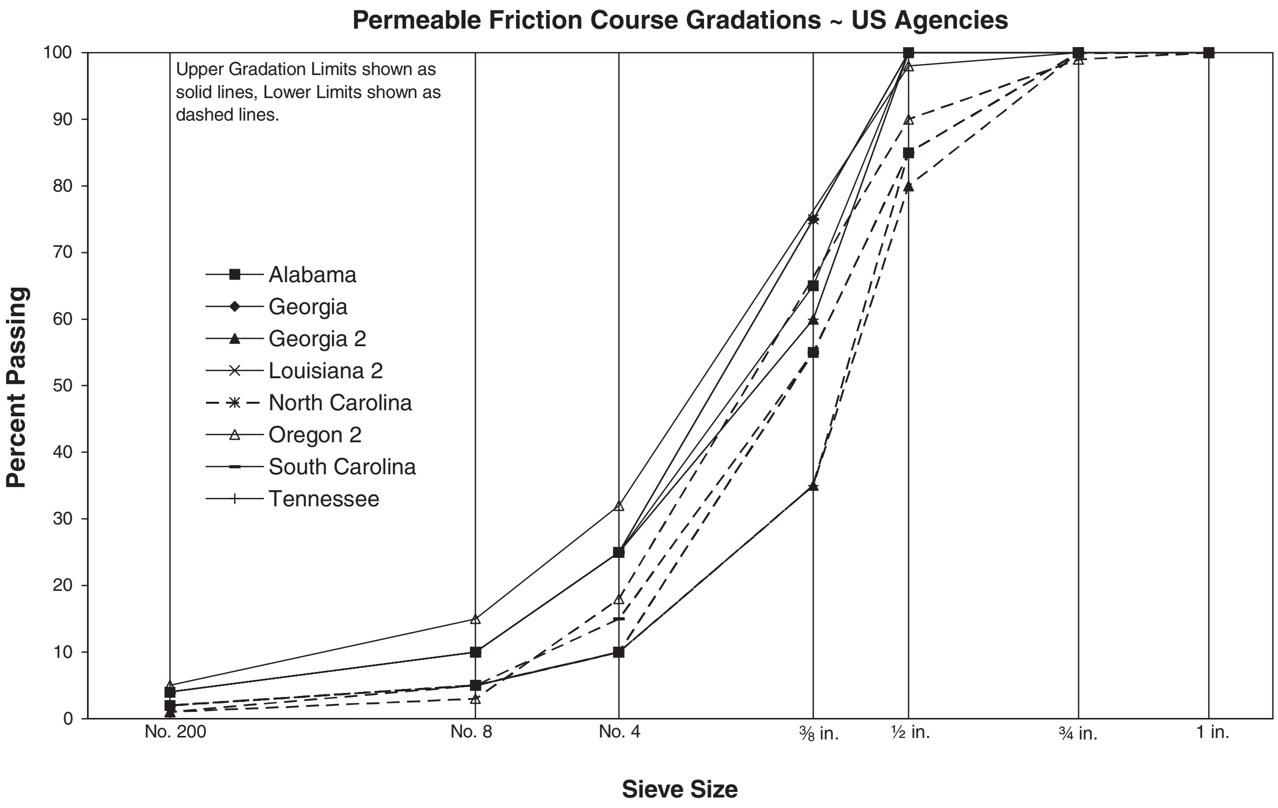


Figure 16. ¾ in. PFC gradation requirements from U.S. agencies.

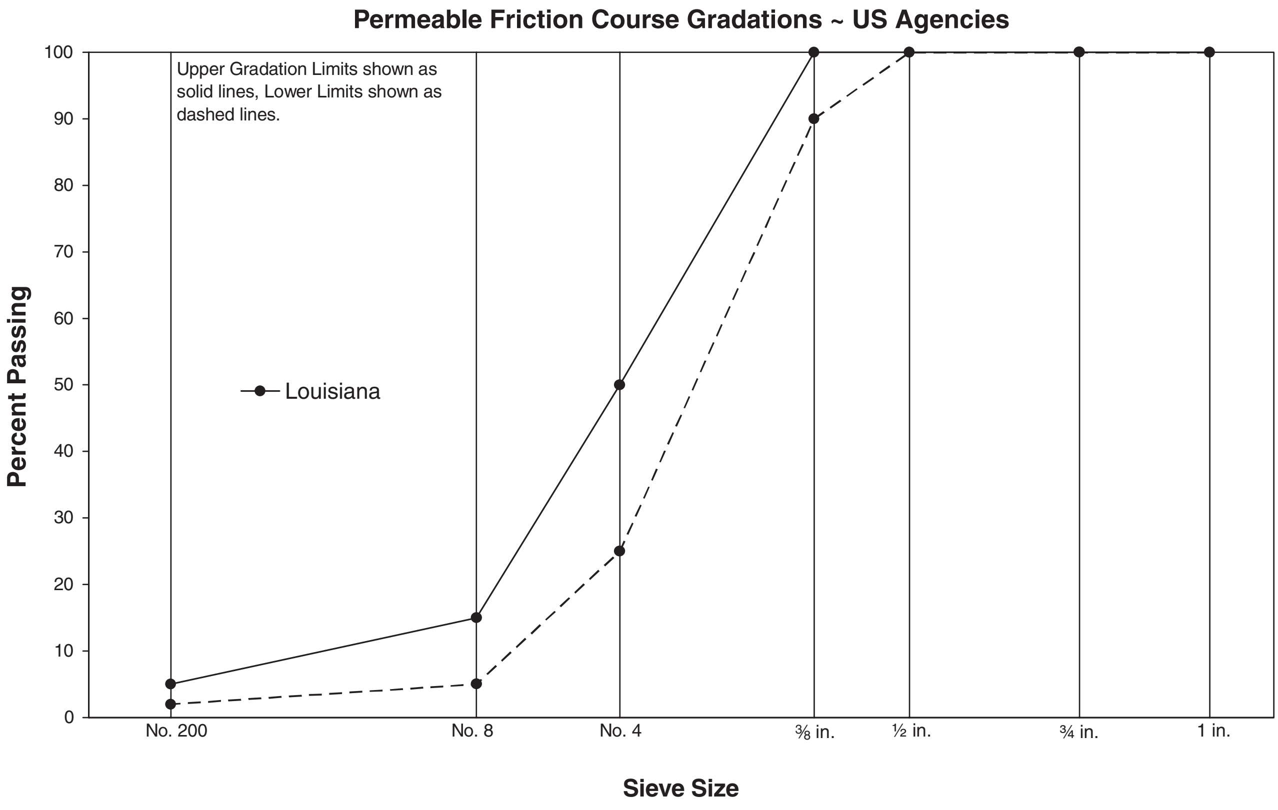


Figure 17. ½ in. PFC gradation requirements from U.S. agencies.

have a minimum of 18 percent air voids were considered PFCs. Similar to the survey of agencies described earlier, three different maximum aggregate size gradations were found in the literature: 1 in., ¾ in., and ½ in. (25 mm, 19 mm, and 12.5 mm).

A single 1 in. (25 mm) maximum aggregate size gradation was encountered in the literature which was from Great Britain. This gradation is illustrated in Figure 18. According to the gradation band, the gradation is gapped near the No. 4 sieve and the allowable filler content is between 3.5 and 5.5 percent.

Similar to what was found with the survey of agencies, most of the gradation requirements specified by international agencies are for a ¾ in. (19 mm) maximum aggregate size gradation. Figure 19 shows the various gradation bands for ¾ in. maximum aggregate size PFC mixes. Again, customary U.S. sieves are shown on the figure. Also shown on this figure is the gradation band recommended by the National Center for Asphalt Technology (*40*). This gradation band is shown to provide a comparison between the typical PFC gradation used in the Unite States (as described earlier) and those used in other countries. As shown on this figure, there is a wide range of allowable gradations for PFCs. For instance, on the ⅜ in. (9.5 mm) sieve, gradation requirements range from a high of approximately 75 percent passing (Spain) to a low of approximately 10 percent passing (Italy). However, recall that all of these gradations are included within mix design methods that specify a minimum of 18 percent air voids or more. The majority of gradation bands would force the aggregate blend to be gapped somewhere between the ⅜ in. (9.5 mm) sieve and the No. 4 (4.75 mm) sieve. Filler contents encountered in the various gradation bands also vary significantly. Italy provides a lower limit of 0 percent passing the No. 200 (0.075 mm) sieve while South Africa allows as much as 8 percent passing the No. 200 sieve.

Figure 20 illustrates the single ½ in. (12.5 mm) maximum aggregate size gradation encountered in the literature review. This gradation band is specified in Great Britain. According to the figure, this ½ in. maximum aggregate size gradation would be gapped on either the No. 4 (4.75 mm) or No. 8 (2.36 mm) sieve. The percentage of filler allowed within this gradation band is between 3 and 6 percent.

Several authors indicated that the maximum aggregate size selected for PFC will have an affect on permeability. Ruiz et al. (*16*) indicated that larger maximum aggregate size gradations result in more permeability.

Selection of Optimum Binder Content

The philosophy of selecting the optimum binder content for PFC mixes is relatively uniform around the world. However, no specific process or procedure that identified an absolute optimum asphalt binder content was identified. Rather, mix

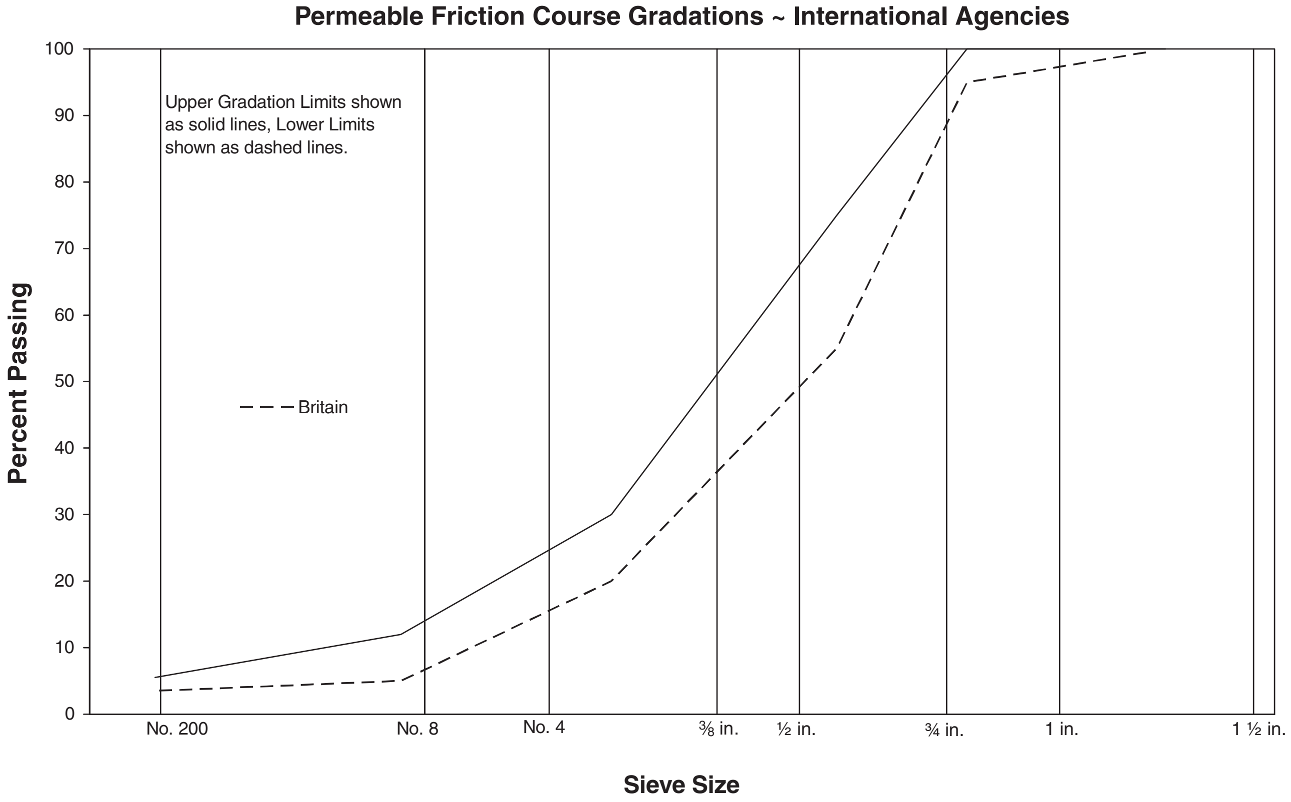


Figure 18. 1 in. PFC gradation requirements from international agencies.

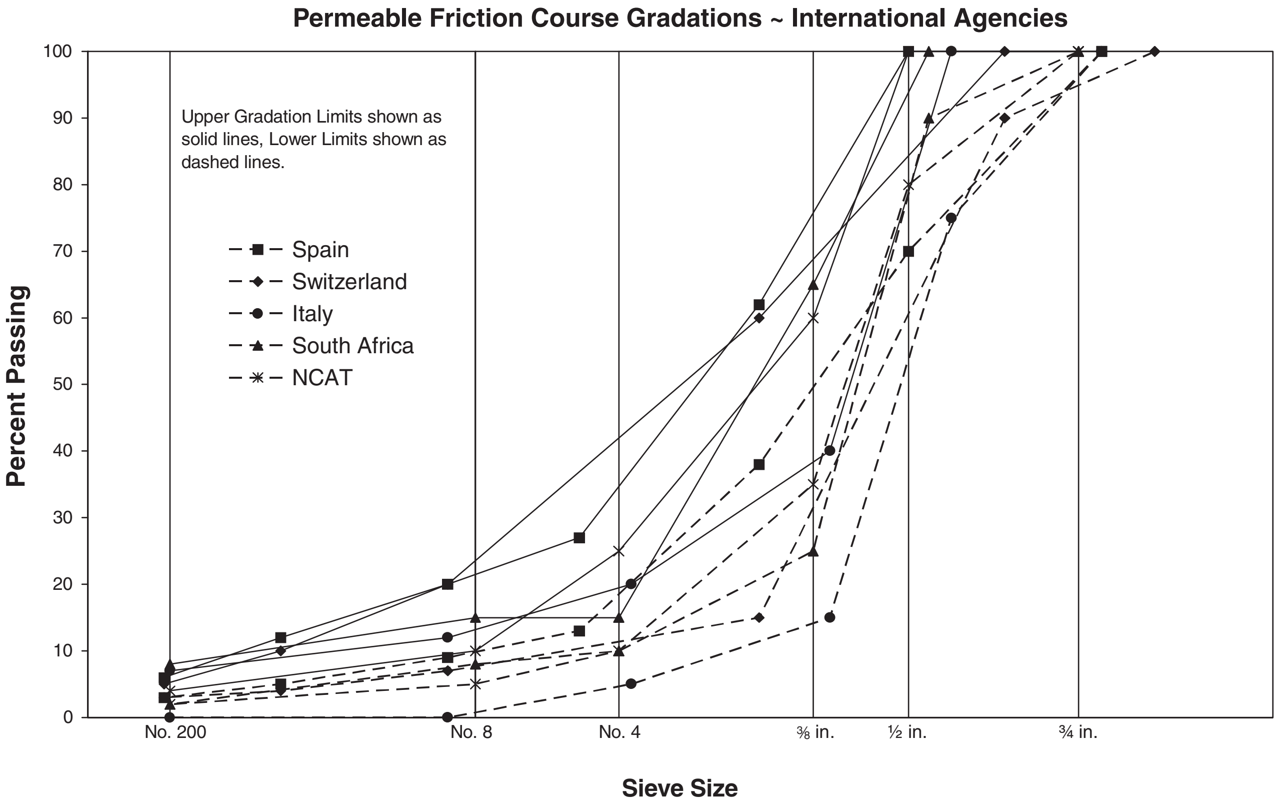


Figure 19. ¾ in. PFC gradation requirements from international agencies.

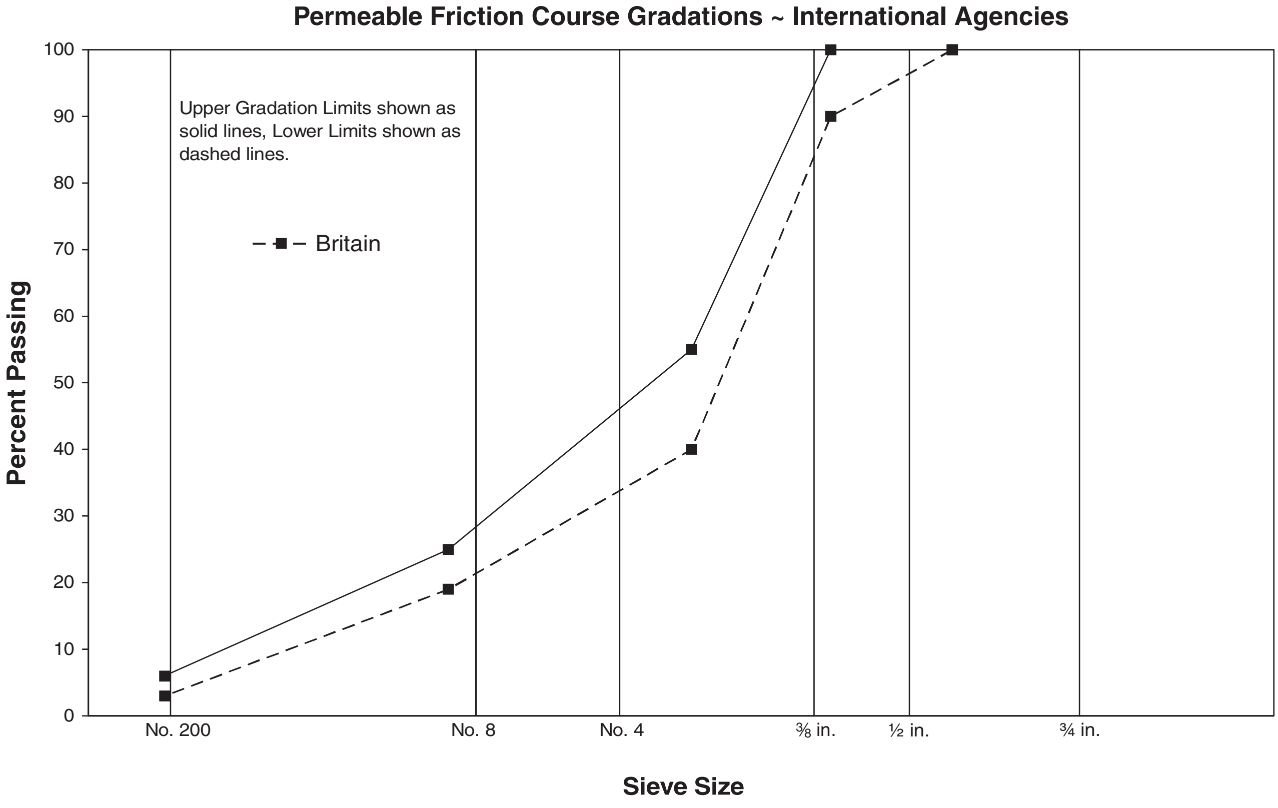


Figure 20. ½ in. PFC gradation requirements from international agencies.

design methods generally identify a range of allowable asphalt binder contents from which the absolute optimum can be selected. Two properties generally are utilized to define the range of allowable binder contents: durability and draindown potential. It should be stated, however, that the mix design methods also require a minimum air void content.

Figure 21 illustrates the general concept for selecting the allowable range of asphalt binder contents from which optimum is selected. Within this figure, durability is defined as the amount of loss from the Cantabro Abrasion test. This test evaluates the resistance of compacted open-graded specimens to abrasion. The test method entails compacting mix to the laboratory standard compactive effort, allowing the specimen to cool to room temperature, weighing the specimen to the nearest 0.1 g, and then placing the specimen into a Los Angeles Abrasion machine without the charge of steel spheres. The Los Angeles Abrasion machine then is operated for 300 revolutions at a rate of 30 to 33 rpm. After the 300 revolutions, the specimen is removed and again weighed to the nearest 0.1 g and the percent mass loss determined based upon the original specimen mass. This test method was developed in Spain during the 1980s (*21*). Within the literature, this is the most common test utilized to evaluate the durability of PFCs.

As shown in Figure 21, the Cantabro Abrasion test is used to identify a minimum asphalt binder content. As asphalt binder content increases, durability is improved. A maximum asphalt binder content is identified by conducting some type of draindown potential test; more asphalt binder improves durability, but too much asphalt binder leads to draindown.

The Cantabro Abrasion test is the most common test utilized worldwide to evaluate the durability of PFC mixes. Each country specifying the Cantabro Abrasion test utilizes the same test method with regards to the number of revolutions and rate of revolution within the Los Angeles Abrasion machine. The only variable identified within the Cantabro Abrasion test is the temperature at which the test is conducted. Spain and Belgium utilize a test temperature of 64°F (18°C) (*21, 35*) and a test temperature of 68°F (20°C) is used in France (*44*). The remaining countries specify a test temperature of 77°F (25°C).

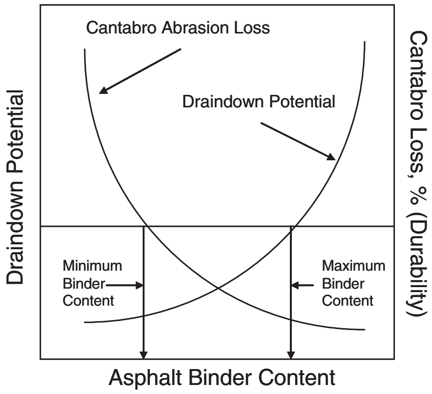


Figure 21. Philosophy of designing PFC mixes.

Criteria for the Cantabro Abrasion test are specified based upon the type of conditioning to which the samples are subjected. There are three different conditions in which samples are tested: unaged, aged, and moisture conditioned. Specification values for the Cantabro Abrasion test conducted on unaged samples are predominantly a maximum percent loss of 25 percent. However, the Texas DOT specifies a maximum of 20 percent loss as does Belgium (*35*). All other agencies specify a maximum of 25 percent loss on unaged specimens. To reach the aged condition, samples are placed within a forced draft oven at a given temperature for a specified amount of time. Mallick et al. (*36*) recommended aging samples at 140°F (60°C) for 7 days prior to testing. After aging, the sample was allowed to cool to the Cantabro Abrasion test temperature of 77°F (25°C). Criteria for samples aged in this manner are a maximum of 30 percent loss. The final conditioned state is moisture conditioning. This is practiced in South Africa (*7*), Italy (*7*), Great Britain (*26*), and Australia (*19*). To moisture condition samples, specimens are submerged in water for a specified amount of time. The only conditions provided in the literature were from Great Britain where specimens are submerged for 24 hours in a 140°F (60°C) water bath (*26*). It should be stated that all of the references above utilized test samples that were compacted with a Marshall hammer. Watson et al. (*40*) developed recommendations for Cantabro Abrasion loss values for samples compacted in a Superpave gyratory compactor. In an unaged condition, abrasion loss should be less than 15 percent.

There are a number of methods for evaluating the draindown potential of PFC mixes. Decoene (*18*) described two methods utilized in Belgium: a basket drainage test and the Schellenberger drainage test. During the basket drainage test, PFC mixes are first compacted in Duriez molds under a pressure of 435 psi (30 bars). The molds containing the compacted PFC then are placed into an oven maintained at 356°F (180°C). Samples are held at this temperature for 7.5 hours. At the conclusion of this test, the percent asphalt binder lost from the samples is calculated as a percent of the initial binder content (*18*).

The Schellenberger drainage test begins by placing 1,000 to 1,100 grams of loose PFC into a glass beaker. The beaker then is placed into an oven maintained at 338°F (170°C) for 1 hour. After the allotted time, the loose PFC is removed from the beaker and the amount of asphalt binder remaining in the beaker is determined. Draindown potential is described as the binder remaining in the beaker and is expressed as a percentage of the initial asphalt binder content (*18*).

Santha (*10*) of the Georgia DOT described the Pyrex bowl method for evaluating draindown potential. For this method, mix is prepared and placed into a clear Pyrex bowl. The bowl then is placed in an oven set at 250°F (121°C) for 1 hour. A visual examination of the bowl is conducted after the 1 hour to qualify the amount of asphalt binder left in the Pyrex bowl. Santha (*10*) also states that the Schellenberg drainage has been utilized by Georgia DOT.

In a subsequent paper to Santha's (*10*), Watson et al. (*11*) indicated that the Georgia DOT had adopted the draindown test developed at the National Center for Asphalt Technology. Mallick et al. (*36*) describe this method as placement of loose mix into a wire basket. The mix and basket are placed into an oven set at the specified temperature. Mallick et al. (*36*) used test temperatures of 320 and 338°F (160 and 170°C, respectively) though later recommendations from the same authors were to conduct testing 27°F (15°C) higher than anticipated production temperatures (*4, 39*). Within the oven and underneath the wire basket, a suitable container of known mass is placed. The mix then was held at the elevated temperature for 1 hour. At the end of 1 hour, the basket is removed from the oven and the mass of the container is determined. Draindown then is calculated based on the mass of binder rather than drains from the mix through the basket into the container, and expressed as a percentage of the total mix mass.

In a later research project, Watson et al. (*40*) conducted draindown tests of various PFC mixes using the draindown basket, but with different size wire mesh to fabricate the baskets. The two mesh sizes represented a No. 4 (4.75 mm) screen mesh and a No. 8 (2.36 mm) screen mesh. The standard mesh size was the No. 4 screen. The smaller mesh size was investigated because Watson et al. (*40*) believed that some intermediate-sized aggregates could pass through the No. 4 sized screen. Another modification to the standard procedure described was that asphalt binder remaining on the basket after the 1 hour was considered as part of draindown. Results of comparisons between the standard draindown test and the modified versions showed very strong correlations. However, Watson et al. (*40*) stated that tests conducted with the No. 8 (2.36 mm) mesh-sized basket resulted in more repeatable test results. They did not recommend changes to how draindown was determined.

During the survey described in Chapter 2, the majority of respondents indicated that draindown testing is included within their mix design methods. Approximately 65 percent of the agencies stated that they utilized the draindown basket method. The remaining agencies utilize the Pyrex bowl method or other technique (not specified).

As defined in this report, PFCs are designed to have air void contents greater than 18 percent. As such, a standard laboratory design compactive effort is needed during mix design. The literature presented two laboratory compaction methods prevalent in designing PFC: the Marshall hammer and Superpave gyratory compactor. Historically, the Marshall hammer has been used to design PFC mixes. The Marshall hammer has been utilized in Belgium (*18*), Georgia (*10*), United Kingdom (*7*), Spain (*7*), Italy (*7*), South Africa (*7*), and Switzerland (*35*). Not all references reported the compactive effort when using the Marshall hammer; however, all that did report the design compactive effort reported 50 blows per face, except one. Santha (*10*) indicated that 25 blows per face were utilized by the Georgia DOT during design (in 1997).

Most of the U.S. agencies that place PFCs are currently utilizing a Superpave gyratory compactor. The most common design compactive effort with the Superpave gyratory compactor is 50 gyrations; however, McDaniel and Thornton (*13*), utilized 20 gyrations in Indiana. The 50 gyrations was selected during research that compared densities achieved by 50 blows per face of the Marshall hammer and various design gyration levels (*40*). Subsequent work by Watson et al. (*40*) conducted a more comprehensive evaluation to determine the appropriate design compactive effort. Within this research, the effect of aggregate breakdown was also evaluated. Watson et al. (*40*) concluded that the design compactive effort of 50 gyrations was appropriate.

Though having different operational characteristics than the Superpave gyratory compactor, Alderson (*19*) reported that Australia also uses a gyratory compactor to design PFCs. In Australia, 80 gyrations of the Australia gyratory compactor are used to design PFCs.

Mallick et al. (*36*) utilized a laboratory permeability test during mix design. The permeability device was described as a falling-head permeameter that was based on an apparatus developed by the Florida DOT. Mallick et al. (*36*) stated that the laboratory test was optional during the mix design, but indicated that a minimum value of 330 ft/day (100 m/day) should be utilized. Faghriand and Sadd (*45*) also utilized permeability testing to evaluate PFC mixes.

A final test recommended during the design of PFC mixes is the dry-rodded test to evaluate the existence of stone-on-stone contact. The concept is similar to that used in the design of SMA and is called voids in coarse aggregate (VCA). Kandhal (*4*) and Watson et al. (*42*) have recommended the VCA concept in designing PFCs. The method entails first measuring the VCA of the coarse aggregate only using AASHTO T19, Unit Weight and Voids in Aggregates. There is a difference between the two references on the definition of coarse aggregate. Kandhal (*4*) defines the coarse aggregates as those aggregates coarser than the No. 4 (4.75 mm) sieve while Watson et al. (*42*) utilize the break point sieve as differing between fine and coarse aggregate. Watson et al. (*42*) defined the break point sieve as the finest sieve to retain 10 percent or more of the aggregate blend. The next step in evaluating stone-on-stone contact is to calculate the VCA of compacted samples. If the VCA of the compacted PFC is less than the VCA of the dry-rodded aggregates, then stone-on-stone contact is achieved

(*4, 42*). Watson et al. (*42*) further verified the existence of stone-on-stone contact using X-ray Computed Tomography.

Performance Testing

The predominant type of performance testing conducted during PFC designs is moisture sensitivity testing. As mentioned under the Cantabro Abrasion Loss discussion above, moisture conditioning of PFC samples prior to testing has been utilized (*7, 19, 24*). To moisture condition samples prior to Cantabro testing, samples are submerged in a heated water bath for a specified amount of time.

The most predominant method found in the literature for conducting moisture susceptibility testing on PFCs is to use indirect tensile strength testing and tensile strength ratios (TSR). This also was found to be true in the survey described in Chapter 2. The conditioning of samples prior to determining TSRs varies within practice. Some have recommended the use of five freeze-thaw cycles prior to testing (*4, 46*), while some agencies responding to the survey indicated that one freeze-thaw cycle was included during TSR testing. In 2004, Watson et al. (*39*) compared TSR results after 1, 3 and 5 freeze-thaw tests. Results from comparisons showed no significant difference in TSRs after 1, 3, and 5 freeze-thaw cycles.

Within the survey of states, the next most common moisture susceptibility test was the boil test. Santha (*10*) also utilized this test method. This test method essentially entails placing loose mix into boiling water for a specified time. After boiling, a qualitative evaluation of the amount of binder that has stripped from the aggregates is made.

The final test identified for evaluating moisture susceptibility was a loaded-wheel tester. Cooley et al. (*43*) loaded samples submerged under water to evaluate moisture susceptibility. The loaded-wheel tester used was an Asphalt Pavement Analyzer.

A number of other tests were identified in the literature to evaluate designed PFC mixes. In the Netherlands, a dynamic bending test was used to evaluate the stiffness of PFC mixes (*17*). No specifics were provided on the test, but it is assumed to be similar to the four-point bending beam fatigue test. Additionally, the Netherlands have used a wheel-tracking device to evaluate the rutting performance of PFC mixes (*17*). Similarly, Mallick et al. (*36*) used the Asphalt Pavement Analyzer to evaluate the stability of PFC mixes. Spillemaeker and Bauer (*46*) discussed a rotary shearing press to evaluate rutting potential. No specifics were provided for this test other than providing the French Standard (NF P 98-252). Another method of evaluating the potential for rutting potential was described by Fortes and Merighi (*44*). These authors described results from a static, unconfined creep test. Again, specific test conditions were not given.

The final two performance tests identified in the literature were reported by Molenaar and Molenaar (*38*). Both of these tests were designed to evaluate the potential for short-term raveling. The first test was called the Wheel Fretting Test (WFT). For the WFT, a treaded tire inflated to 87 psi (600 kPa) and loaded to 675 lb (3kN) was run in a circular path on top of PFC test specimens. The loaded tire had an inclination angle of 2 to 5 degrees. A total of 3 million revolutions were applied to the test samples at a test temperature of approximately 68°F (20°C). The fretting performance was characterized as a mass loss after the wheel passes.

The second short-term raveling test described by Molenaar and Molenaar (*38*) was called the California Abrasion Test, which utilizes a mechanical shaker that is operated at 20 cycles per second with a specified vibration amplitude. A sample of PFC was placed into a container along with water and steel spheres and subjected to the vibration action for 15 minutes at a test temperature of 39°F (4°C). Again, test results are reported as a percent mass loss after the 15 minutes of abrasive action.

CHAPTER 6

Inclusion in Structural Design

Very little has been written on the aspect of structural design of PFC mixtures. Fewer than 20 percent of the papers reviewed contained any discussion on the structural design aspects of PFC mixtures. Most of the papers that did discuss structural design dealt with OGFC mixtures and much of that was from outside the United States. In most instances, agencies simply have a standard lift thickness that is placed and the layer is not considered in the structural capacity of the pavement.

Oregon probably has had more experience with OGFC mixtures than any other state in the United States. Moore et al. indicate that the *1993 AASHTO Guide for Design of Pavement Structures* and other deflection-based procedures are used for structural designs with open-graded asphalt mixes in Oregon (*47, 48*). Deflection testing conducted on the Class F mix indicated that the deflection reduction was comparable to a dense-graded mix of a similar thickness, thus Oregon has not altered it structural design procedure (*48*). A minimum thickness of 2 in. (50 mm) has been specified for Oregon's OGFC class F mix [increased from 1.5 in. (37.5 mm) used in the past, to reduce laydown and compaction problems] (*47, 48*). A maximum thickness of 4 in. (100 mm) (in two lifts) has been used.

In Spain a lift thickness of 1.6 in. (40 mm) has been established for PFCs (*16*). The possibility of using thicker lifts has not been considered. However, this thickness is not based on any structural value, but rather on the water absorption capacity (ability to store and transport water). Ruiz et al. (*16*) indicate that the water absorption capacity with 1.6 in. (40 mm) is thought sufficient; therefore, the thickness specified in Spain is based upon the volume of potential rainfall. The 1.6 in. thickness also is used in Austria (*49*). In Italy, though nothing specifically was discussed on structural design, Ranieri stated that a method of selecting the appropriate layer thickness should be based upon rain intensity (*50*).

Ruiz et al. (*16*) also indicate that the same structural value is assigned to porous asphalt mixtures as other open or semi-open conventional asphalt mixtures such as road bases. When porous asphalt mixtures are used above pavement structures containing cement-treated road bases, an additional ¾ in. (20 mm) of HMA is provided to assist in preventing reflective cracking. Reflective cracking that appears in a PFC will provide an avenue for water to penetrate into the pavement structure, thereby, increasing the potential for pavement deterioration (*16*).

In the Netherlands PFC layers are placed at a thickness of 2 in. (50 mm); this thickness was selected because of the typical rainfall rates experienced (*17, 51*). According to Van Der Zwan et al. (*17*) the pavement design methodology in the Netherlands entails designing to prevent classical bottom-up fatigue cracking. When designing pavement thicknesses, dense-graded mixes are assigned a dynamic modulus value of 1.8 million psi (7,500 MN/m^2) and the mixture also must meet specific fatigue properties. Van Der Zwan et al. (*17*) provided a discussion on the structural contribution of a PFC layer within pavements by comparing dense-graded and PFC. One area that dense-graded and PFC were compared was in terms of dynamic modulus. Van Der Zwan et al. (*17*) indicated that the dynamic modulus of PFC is generally 783,000 psi (5,400 MN/m^2), or about 70 to 80 percent of dense-graded mixes. This value of dynamic modulus was input into their pavement design models and the results indicated that 10 to 20 percent more thickness was required to maintain a specific fatigue strain at the bottom of the pavement layer when using PFC as compared to dense-graded mixes.

Van Der Zwan et al. (*17*) also evaluated the effect of aging and stripping on pavement design. Due to the open nature of PFC, the asphalt binder coating aggregates is susceptible to accelerated oxidative aging. Oxidative aging of the asphalt binder results in an increase in stiffness within the PFC layer which would reduce pavement thickness. Alternatively, the authors state that water within the PFC layer can lead to a loss of adhesion between the PFC layer and the underlying layer. This loss of adhesion impairs the load transfer characteristics of the structure. Van Der Zwan et al. (*17*) state that there is no evidence that the loss of adhesion between layers (delamination) has taken place in the field; they conservatively assumed a loss of adhesion to evaluate the net effect on pavement structure using the BISAR program. When delamination occurs, the effective bearing capacity of the debonded layer is reduced to between two and 10 percent of the original value. By applying Miner's modified linear damage law, the authors stated that the combined effect of aging and stripping (delamination) would result in about 35 to 40 percent effective contribution of PFC when compared to dense-graded layers.

Because PFC has different thermal properties than dense-graded mixes, Van Der Zwan et al. (*17*) also evaluated the effect of temperature on the pavement structure when comparing dense-graded and PFC wearing layers. Van Der Zwan et al. (*17*) provided a hypothesis that the suction and pumping action of tires passing over PFC surfaces, coupled with wind action, promotes continuous air circulation within a PFC layer. As a result, the temperature of the PFC layer will tend to be lower than for comparable dense-graded layers. In order to investigate this hypothesis, the authors conducted experiments on newly placed and 8-year-old PFC layers to compare the temperatures of pavements with porous asphalt and dense-graded wearing layers at the surface and at depth. Results from these experiments, which included one year of data, indicated that the weighted average temperature over a year was found to be 1.8°F (1°C) lower in pavements containing PFC wearing layers. Due to the viscoelastic properties of asphalt, the lower effective temperature in pavements including a PFC wearing layer, means that the stiffness (modulus) of underlying layers is higher. The net result shows that less thickness is required to resist fatigue cracking. The combined effect of these factors suggests that PFC can be expected to contribute about 50 percent of the equivalent structural capacity compared to a dense-graded layer. However, if adhesion between the PFC layer and the underlying layer is not lost (as was conservatively assumed), then the effective contribution of porous asphalt can be 100 to 110 percent of conventional systems (*17*).

Watson et al. (*52*) also concluded that layers underlying open-graded wearing layers are cooler than mixes underlying typical dense-graded wearing layers. These conclusions are based upon temperature measurements made at the pavement surface and at depth on the 2000 National Center for Asphalt Technology Test Track. Layers underlying open-grade surfaces averaged about 3.8°F (2°C) cooler than pavement layers underlying conventional dense-graded layers. Similar to the conclusions of Van Der Zwan et al. (*17*), this would result in an increase in stiffness for underlying layers which would, therefore, improve the structural capacity of underlying layers.

In Switzerland, the typical layer thickness for PFCs ranges from 1.1 to 2 in. (28 to 50 mm) (*15*). According to Isenring et al. (*15*) PFC mixes in Switzerland having a maximum aggregate size of ½ in. (10 mm) are typically placed 1.1 to 1.7 in. (28 to 42 mm) thick while porous asphalt mixes having a maximum aggregate size of 0.625 in. (16 mm) are typically placed from 1.75 to 2 in. (43 to 50 mm) thick.

The British Columbia Ministry of Transportation and Highways currently considers a structural strength value of 1.25 (in terms of Crushed Granular Equivalency) for OGFC. This can be compared to 2.0 for conventional asphalt pavement (*53*) or about 60 percent of the structural value of dense-graded mixes.

According to Van Heystraeten and Moraux (*22*), in Belgium two thicknesses are used with PFCs: 1 and 1.6 in. (25 and 40 mm). To maintain the drainage characteristics and noise-reducing attributes for a longer period of time, they indicate that the 1.6 in. layer thickness is best. They also stated that based upon modulus testing, PFCs constructed with an 80/100 penetration graded asphalt binder will contribute 73 to 79 percent of the structural capacity of typical dense-graded mixes (*22*).

In their paper, Bolzan et al. (*26*) discussed some structural considerations of PFCs layers. On the basis of the facts that PFC is a mixture in which fractions of the aggregate grading are absent, they contend that these mixtures have lower strength than dense-graded mixtures. They mention that some researchers accept that these mixtures have up to 70 percent of the strength of a conventional mixture; others indicate the ratio is only 50 percent while the Spanish believe that they are structurally equivalent with conventional dense-graded asphalt mixtures. They also are considered to be less shear stress resistant. Bolzan et al. (*26*) indicate that Argentina adopted a 50 percent structural capacity for PFC mixtures in the initial projects. The resilient modulus (ASTM D 4123) at 77°F (25°C) and 10 Hz of PFC mixtures, prepared in the laboratory of Argentina, was found to be about 319,000 psi (2200 MPa), approximately 60 percent of the conventional mixtures. However, Bolzan et al. point out that at both higher and lower temperatures, polymer-modified PFC mixes perform better than unmodified conventional mixes and that further research needed to be conducted to reach any definitive conclusions (*26*).

Within the United States, there has recently been a move toward mechanistic-empirical pavement design methods. Within this new pavement design system, HMA mixtures are characterized using the dynamic modulus (E*) test. A single reference was identified that looked at measuring E* for open-graded mixes. Kaloush et al. (*54*) conducted a study to evaluate the E* of asphalt-rubber mixes in Arizona. Of the two different asphalt-rubber mixes evaluated, one was labeled as a Asphalt Rubber Asphalt Concrete-Gap Grade (ARAC) mix and one an Asphalt Rubber Asphalt Concrete Friction Course-Open-Graded (AR-ACFC) mix. Kaloush et al. (*54*) stated that the AR-ACFC had in-place air voids of 18 percent; therefore, it is considered a PFC. Within the research, the authors evaluated various confining pressures including 0, 10, 20 and 30 psi

(0, 69, 138, and 207 kPa, respectively). Kaloush et al. (*54*) concluded that the confining pressure used during testing was important. Using E* values from typical Arizona DOT dense-graded mixes and the asphalt-rubber mixes at 20 psi (138 pKa) confinement, the authors showed that the asphalt-rubber mixes had lower modulus values at low temperatures and higher modulus values at high temperatures. Therefore, asphalt-rubber mixes were ranked above the conventional mixes in terms of both low and high temperature performance. Citing these results, Kaloush et al. (*54*) indicated that confined test results of E* are more appropriate for evaluating gap- and open-graded mixes.

From the web-based survey conducted by the research team, it was learned that only seven states assigned a structural value to OGFC pavements. Most of the states that did assign a structural value used a layer coefficient for estimating structural value. Only Texas used a resilient modulus, but limits the use of PFC mixtures to pavements that are already structurally sound. California does not consider the structural benefits of PFC when determining layer thicknesses for the structural sections even though a structural value is assigned.

Rational Method of Selecting PFC Lift Thickness

Within most of the United States, the thickness of PFC layers placed on the roadway has been based upon experience. No formalized method of determining an appropriate lift thickness was found in the literature. Therefore, a method for selecting an appropriate lift thickness for PFCs was developed. As stated previously, NCHRP Project 9-41 did not include any laboratory or field experiments, and therefore this method has not been validated.

Historically, a single lift thickness of PFC has been specified by a given state agency. For instance, Oregon has long utilized 2 in. (50 mm) as a standard lift thickness. Likewise, Georgia specified ¾ in. (19 mm) for a number of years when utilizing OGFCs and then changed to a standard lift thickness of 1¼ in. (32 mm) for PFCs. Selection of a standard lift thickness of PFC by a state agency that is based upon experience is valid. However, for agencies that have not utilized PFC or only have limited experience with PFCs, a systematic and practical method of determining an appropriate lift thickness is needed. This section provides a practice for selecting appropriate lift thickness for PFC layers.

In order to develop a method for selecting an appropriate lift thickness of PFC, the first question that must be asked is, "What attributes of a PFC layer are desirable?" The literature review and survey provided numerous benefits of PFC. Predominately, these benefits were related to the ability of PFC to drain water during a rain event. Therefore, permeability should be a parameter that is considered during selection of an appropriate lift thickness. Ruiz et al. (*16*) state this property was the criteria utilized in Spain for selecting a lift thickness. Tan et al. (*55*) and Ranieri (*50*) also deemed permeability as an important property for determining an appropriate lift thickness. Obviously, some measure of precipitation for the project location also is needed. Other parameters that would be needed to define the ability of a PFC layer to drain water also would include geometric properties of the pavement section such as lane width and cross-slope.

All of these parameters discussed are known or can be readily obtained at the time of pavement design, except for permeability. Based upon the literature, most, if not all, measures of true PFC permeability have been from laboratory testing. Field tests described in the literature only provide an index of permeability. Unfortunately, the laboratory tests only estimate a vertical coefficient of permeability with no horizontal component. Therefore, an assumption has to be made that the results of laboratory permeability tests are representative of the in-place permeability of PFC and that the coefficient of permeability is uniform in three dimensions.

Methodology

Ranieri (*50*) has indicated that the flow of water through a PFC layer is similar to the flow of water through an unconfined aquifer. This analogy seems appropriate for PFCs. Unconfined aquifers generally have an impermeable layer beneath the aquifer and a free surface of water at the top (Figure 22). The underlying impermeable layer within the pavement system would be represented by a dense-graded HMA along with an appropriately applied tack coat. As long as the PFC is a wearing surface, water residing within the PFC layer would

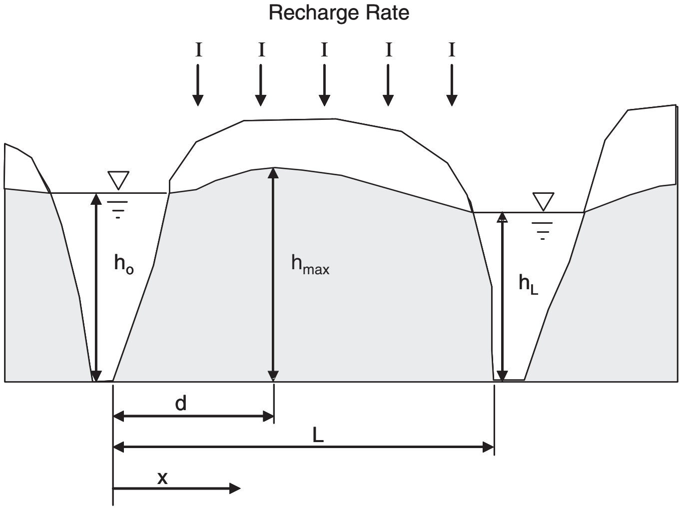


Figure 22. Flow through and unconfined aquifer with constant recharge.

be considered a free surface since the water would be open to atmospheric pressure.

An applicable model utilized in groundwater hydrology for unconfined aquifers is the Dupuit equation. Dupuit developed his model based upon the following assumptions (*56*):

- The free surface is only slightly inclined.
- Streamlines may be considered horizontal and equipotential lines vertical.
- Slopes of the free surface and hydraulic gradient are equal.

Dupuit utilized Darcy's law for one-dimensional flow per unit width and an unconfined aquifer to derive Equation 1. This equation is used to calculate the flow of water through the unconfined aquifer based upon varying heads of water on either side of the aquifer (Figure 22) (*56*).

$$q=\frac{K}{2L}\left(h_o^2-h_L^2\right) \qquad \text{Equation 1}$$

where

q = flow of water through the unconfined aquifer;
K = coefficient of permeability;
L = length of flow path;
h_o = upper hydraulic head of water; and
h_L = lower hydraulic head of water.

Dupuit's equation shown in Equation 1 does not take into account recharge of an aquifer. For the case of a PFC layer, a rain event would represent recharge. When an unconfined aquifer is recharged, the free surface of water takes the form of a parabola as shown in Figure 22 (*56*). This figure also shows the rate of recharge (I), locations of specific hydraulic heads (h_o, h_L and $H_{\max}$), and the distance to the water divide (peak of parabola) (shown as distance d in Figure 22). Dupuit utilized the information shown in Figure 22 and Equation 1 to derive an equation for the shape of the parabola (Equation 2).

$$q=\frac{K}{2L}\left(h_o^2-h_L^2\right)+I\left(x-\frac{L}{2}\right) \qquad \text{Equation 2}$$

where x is distance as shown in Figure 22.

At the peak of the parabola (distance d), a boundary condition exists such that no flow occurs (*56*). Therefore, Equation 2 will take the form of Equation 3 at x = d and q = 0 (*56*).

$$0=\frac{K}{2L}\left(h_o^2-h_L^2\right)+I\left(d-\frac{L}{2}\right) \qquad \text{Equation 3}$$

Figure 23 illustrates the applicability of this approach to a PFC layer having a unit width. The PFC is assumed to be overlying an impermeable layer, which would be a combination of a dense-graded HMA and tack coat. There are two hydraulic heads acting on the flow of water through the layer. The upper hydraulic head (h_o) would be equal to the length (L) times cross slope (α) plus thickness (t) of the PFC layer. The lower hydraulic head (h_2) would essentially be zero. A rain event would represent the recharge rate. Within Equation 3, there is one unknown that must as assumed, the distance to the peak of the parabola (d). Being a parabola, a reasonable assumption would be that the distance to the peak of the parabola is equal to one-third of the length (L/3). Using this simple assumption, Equation 3 can be solved to determine the needed thickness of PFC to prevent a sheet of water from developing at the location of $h_{\max}$. Thickness is contained within the h_o term of Equation 3.

Likely the most important property required to determine the required thickness of a PFC layer is a measure of rain intensity. As rain intensity increases, more thickness would be needed to store and move the water to the pavement edge. An easily accessible database for obtaining a measure of rain intensity is contained on the National Oceanic and Atmospheric Administration (NOAA) web page at http://cdo.ncdc.noaa.gov/cgi-bin/HPD/HPDStats.pl from a link entitled, "Hourly Binned Precipitation in Microsoft Excel Format," as shown in Figure 24. Any designer can download this Microsoft Excel

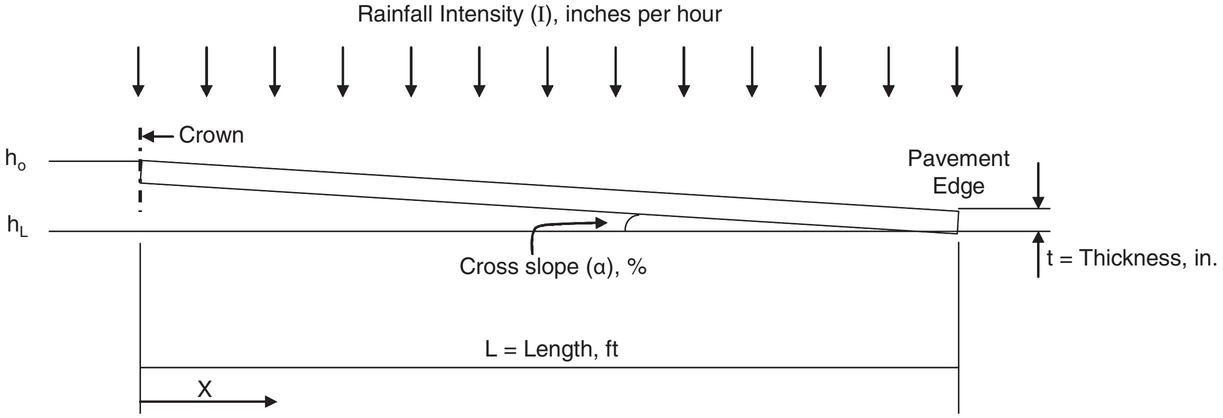
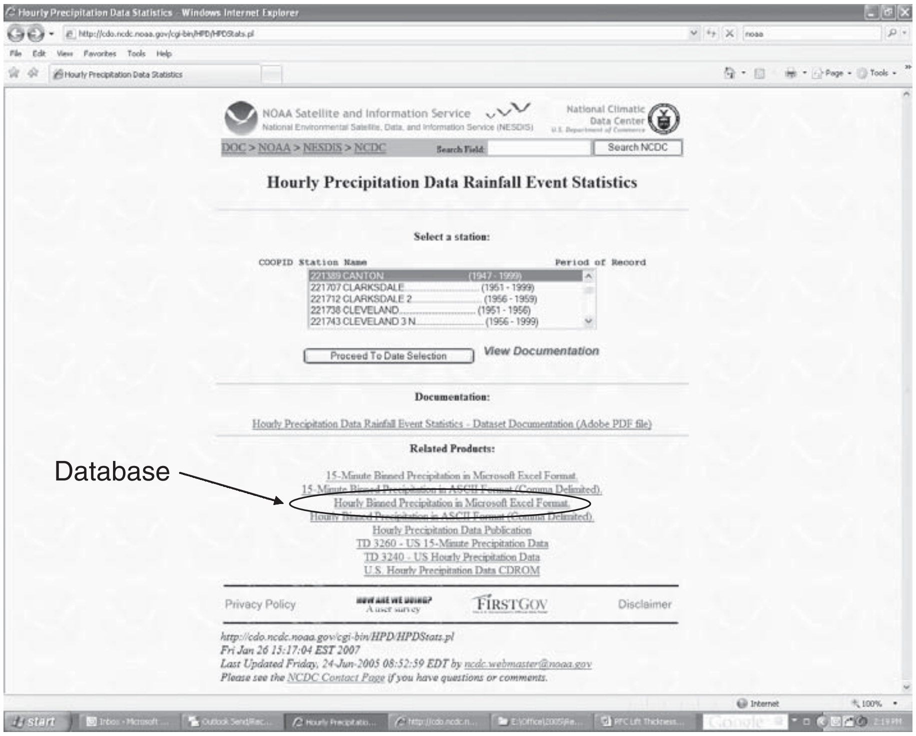


Figure 23. PFC layer simulating an unconfined aquifer with constant recharge.



Hourly Precipitation Data Rainfall Event Statistics

Select a station:

```
COOPID Station Name                 Period of Record
221389 CANTON            (1947 - 1999)
221707 CLARKSDALE........(1951 - 1999)
221712 CLARKSDALE 2......(1956 - 1959)
221738 CLEVELAND.........(1951 - 1956)
221743 CLEVELAND 3 N.....(1956 - 1999)
```

Documentation:

Hourly Precipitation Data Rainfall Event Statistics - Dataset Documentation (Adobe PDF file)

Related Products:

15-Minute Binned Precipitation in Microsoft Excel Format.
15-Minute Binned Precipitation in ASCII Format (Comma Delimited).
Hourly Binned Precipitation in Microsoft Excel Format.
Hourly Binned Precipitation in ASCII Format (Comma Delimited).
Hourly Precipitation Data Publication
TD 3260 - US 15-Minute Precipitation Data
TD 3240 - US Hourly Precipitation Data
U.S. Hourly Precipitation Data CDROM

http://cdo.ncdc.noaa.gov/cgi-bin/HPD/HPDStats.pl
Fri Jan 26 15:17:04 EST 2007
Last Updated Friday, 24-Jun-2005 08:52:59 EDT by ncdc.webmaster@noaa.gov
Please see the NCDC Contact Page if you have questions or comments.

Figure 24. NOAA web page with hourly precipitation database.

database onto a computer. This database (hereafter called the Hourly Precipitation Database), a portion of which is shown in Figure 25, contains hourly precipitation statistics for over 6,000 weather stations. Each weather station is coded within the database by its "COOP ID." The COOP ID can easily be found from the above referenced web page shown in Figure 24. Simply select the state for which the project is to be located and a list of available weather stations will come up. From this list, the designer can select the closest weather station to the project site and obtain the COOP ID station name. Then, within the Microsoft Excel database simply conduct a find query from the "Edit" menu on the COOP ID station number. Alternatively, the COOP ID values are in ascending order within the Hourly Precipitation Database. Therefore, a designer should have no problem finding the specific weather station data within the Hourly Precipitation Database.

Figure 25 illustrates a portion of the data from the Hourly Precipitation Database. The first column is the COOP ID number, and the second and third columns provide the beginning and ending years when data is available for the selected weather station. The fourth column provides the number of days a rain event(s) occurred during the time that data is available. The next two columns provide the number of days and percent of total days the suspect data was obtained. Following the flagged observation data are alternating columns of the number of rain events and percentage of those rain events for various increments of rain intensity in inch per hour units. A breakdown of the data is provided in 0.1 in. increments up to 1.1 in. per hour, then from 1.1 to 1.5 in. per hour and greater than or equal to 1.6 in. per hour.

As an example, the hourly precipitation rainfall statistics were obtained for Canton, Mississippi. Using the web page shown in Figure 24, the State of Mississippi was selected. Of the available weather stations in Mississippi, the Canton station was identified and had a COOP ID of 221389. Next, this COOP ID number was found in the Hourly Precipitation Database. Hourly rainfall data obtained from the database are provided in Table 29. This table shows the increments of rain intensity, the percentage of rain events within each increment, and the cumulative percentage of rain events from the different increments.

Using the larger number of each increment shown in Table 29 and the cumulative percentage within each increment, a chart can be developed that describes the percentage of all rain events below a given intensity (Figure 26). A designer can use the information in Figure 26 to select rainfall intensity for use in selecting the PFC lift thickness that is representative of the project location. In Figure 26, rainfall intensity at 90 percent of all rain events (I_{90}) was approximately 0.4 in. per hour.

As stated previously, other information for determining a minimum PFC lift thickness includes the design cross slope (α) of the roadway as well as the length of drainage path (L). The length of the drainage path would be the length of PFC from the highest point to the lowest, in a transverse direction.

COOP ID	Begin Year	End Year	# of Days	# of Days w/flags	% Flagged	>=.01 <.1 Events	>=.01 <.1 % Of Total	>=.1 <.2 Events	>=.1 <.2 % Of Total	>=.2 <.3 Events	>=.2 <.3 % Of Total	>=.3 <.4 Events	>=.3 <.4 % Of Total	>=.4 <.5 Events	>=.4 <.5 % Of Total	>=.5 <.6 Events	>=.5 <.6 % Of Total	>=.6 <.7 Events
010008	1948	2002	5206	695	13.35	8078	48.98	4762	28.87	1579	9.57	746	4.52	423	2.56	273	1.66	159
010063	1948	2002	5404	530	9.81	9766	48.56	6271	31.18	1942	9.66	894	4.45	429	2.13	262	1.3	154
010140	1963	2002	3903	143	3.66	1677	15.19	5700	51.63	1615	14.63	800	7.25	410	3.71	249	2.26	187
010252	1980	2002	2145	249	11.61		0	2955	59.49	865	17.41	423	8.52	209	4.21	137	2.76	96
010272	1948	2002	877	738	84.15	1125	73.87	199	13.07	81	5.32	58	3.81	22	1.44	16	1.05	5
010369	1948	2002	5464	502	9.19	8317	43.35	6611	34.46	1939	10.11	928	4.84	520	2.71	293	1.53	161
010390	1982	2002	1804	264	14.63		0	2823	63.85	791	17.89	358	8.1	196	4.43	88	1.99	43
010402	1948	2002	3407	292	8.57	4622	42.73	3453	31.92	1112	10.28	547	5.06	292	2.7	187	1.73	144
010407	1965	1982	1626	125	7.69	1987	37.41	1859	35	568	10.69	313	5.89	174	3.28	106	2	75
010425	2000	2002	133	42	31.58		0	135	61.93	45	20.64	16	7.34	10	4.59	4	1.83	2
010427	1948	1962	1320	41	3.11	3024	57.21	1150	21.76	489	9.25	254	4.81	129	2.44	82	1.55	47
010430	1979	1996	1758	63	3.58	1667	29.93	2402	43.13	703	12.62	329	5.91	159	2.86	103	1.85	69
010631	1948	1955	836	22	2.63	1968	61.1	646	20.06	278	8.63	142	4.41	73	2.27	40	1.24	29
010748	1948	2002	4855	654	13.47	7591	46.48	5359	32.81	1514	9.27	752	4.6	390	2.39	231	1.41	157
010790	1948	1967	1922	221	11.5	6193	73.04	1206	14.22	519	6.12	207	2.44	111	1.31	67	0.79	48
010829	1978	1990	1393	2	0.14	4316	71.08	897	14.77	375	6.18	190	3.13	99	1.63	69	1.14	29
010831	1948	2002	5413	99	1.83	12692	60.36	4760	22.64	1605	7.63	779	3.7	414	1.97	243	1.16	169
010836	1949	1949	8	0	0	19	61.29	6	19.35	3	9.68		0	1	3.23		0	
010957	1948	2002	5053	481	9.52	10075	52.4	5705	29.67	1738	9.04	737	3.83	352	1.83	207	1.08	118
011099	1982	2002	1983	210	10.59		0	3494	64.97	973	18.09	420	7.81	200	3.72	109	2.03	70
011315	1948	1967	1773	447	25.21	4276	70.54	860	14.19	388	6.4	173	2.85	116	1.91	72	1.19	42
011819	1951	1980	3343	106	3.17	10464	69.03	2459	16.22	1056	6.97	456	3.01	277	1.83	162	1.07	79
012124	1948	2002	5495	279	5.08	7243	38.62	7127	38	2028	10.81	987	5.26	505	2.69	300	1.6	164
012172	1975	2002	2535	115	4.54		0	3865	57.23	1167	17.28	558	8.26	321	4.75	222	3.29	148

Figure 25. Example of information available in hourly precipitation database.

For two-lane highways with a crown at the centerline, this value would generally be 12 ft (3.6 m). For four-lane divided highways with no crown at the center of the two lanes, this value would be 24 ft (7.3 m).

Figure 26 illustrates the cumulative percentage of rain events versus rain intensity for Canton, Mississippi. Within the example problem, the rainfall intensity at 90 percent of all rain events was identified. The pavement designer must select the cumulative percentage of rain events from which rain intensity is selected. Based upon the relationship between percentage of rain events and rain intensity, a cumulative percentage of 90 percent (I_{90}) seems appropriate for selecting rain intensity. However, a pavement designer can utilize any percentage of rain events desired.

The final piece of information required is an estimate for permeability. This estimate can come from the design of the PFC mixture or assumed as 328 ft/day (100 m/day). Mallick et al. (*36*) have recommended a minimum permeability of 328 ft/day

Table 29. Rainfall intensity data for Canton, Mississippi.

Increment of Rainfall Intensity (in./hr)	Percent Events Within Increment	Cumulative Percentage
>=.01 <.1 % Of Total	31.3	31.3
>=.1 <.2 % Of Total	41.78	73.1
>=.2 <.3 % Of Total	12.39	85.5
>=.3 <.4 % Of Total	5.63	91.1
>=.4 <.5 % Of Total	2.9	94
>=.5 <.6 % Of Total	1.83	95.8
>=.6 <.7 % Of Total	1.25	97.1
>=.7 <.8 % Of Total	0.82	97.9
>=.8 <.9 % Of Total	0.54	98.4
>=.9 <1.0 % Of Total	0.38	98.8
>=1.0 <1.1 % Of Total	0.28	99.1
>=1.1-1.5 % Of Total	0.63	99.7
>=1.6 % Of Total	0.27	100

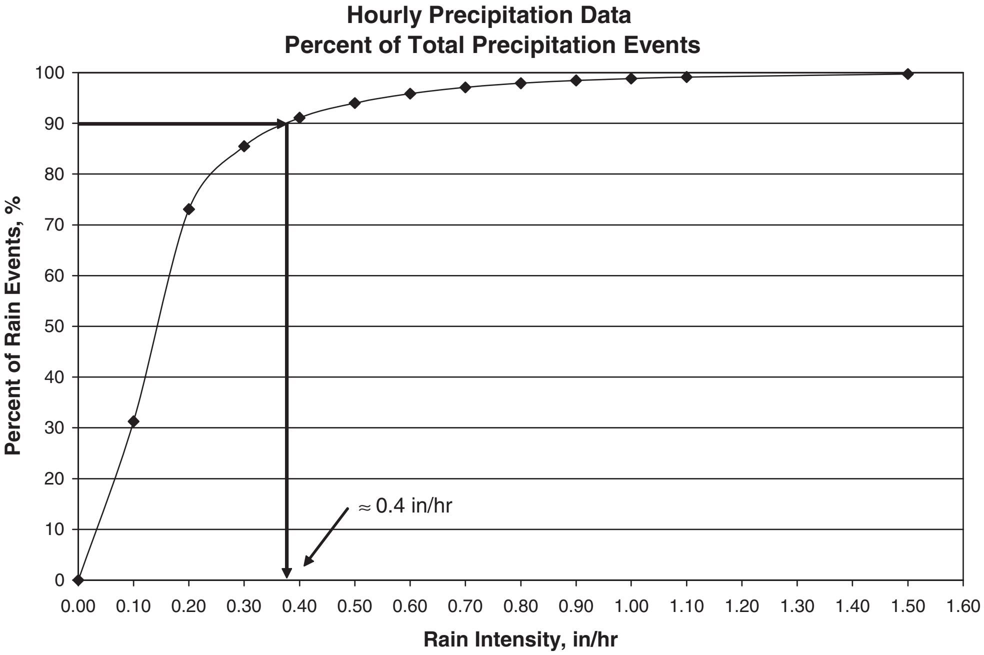


Figure 26. Cumulative percentage of rain events versus rain intensity.

(100 m/day); therefore, this assumption will be conservative. Also, agencies that have conducted research on PFC may have other estimates of permeability for their materials that can be used.

This data described here and Equation 3 was utilized to develop a series of design curves that a designer could use to select the desired PFC lift thickness (Figure 27). The design curves shown in Figure 27 are based upon different design cross slopes. Obviously, the slope of a pavement is ever changing due to horizontal and vertical curves. The cross slope referenced in Figure 27 represents the cross slope in a flat region of roadway (not within a horizontal or vertical curve).

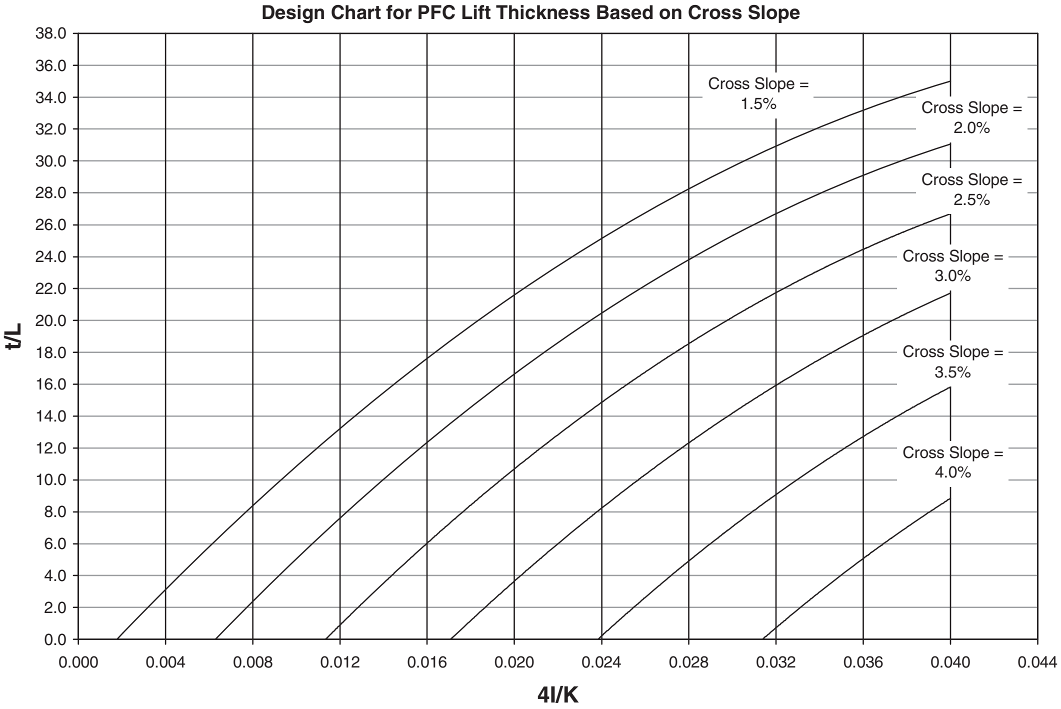


Figure 27. Design curves for selecting PFC layer thickness.

Table 30. Required properties for design curves.

Required Properties	Units
Permeability, K	m/day
Rainfall Intensity, I	in./hr
Length, L	m

To use the design curves shown in Figure 27, the required data previously described must first be obtained. Table 30 presents the required data, along with the applicable units of each property, for using the design curves.

Results from the use of the design curves are a PFC layer thickness in the units of millimeters. In order to show the usefulness of the design curves, three examples are provided for Miami, Florida; Atlanta, Georgia; and Las Vegas, Nevada. For each example, permeability (K) is assumed as 100 m/day (328 ft/day), cross slope (α) of 2.0 percent, and a drainage path (L) of 12 ft (3.6 m).

As stated previously, the first step of the process is to determine the rain intensity values for each location. To obtain this data, the NOAA web page and Hourly Precipitation Database were utilized. Figure 28 presents the rain intensity versus percentage of rain events for all three locations. Based on this figure the rain intensity at a level of 90 percent of all rain events (I_{90}) would be as follows:

Location	I_{90} (in./hr)
Miami, Florida	0.37
Atlanta, Georgia	0.22
Las Vegas, Nevada	0.10

Using the rain intensity data and the assumptions, the designer can go to the design curve chart for a cross slope of 2 percent to determine the required PFC lift thickness. Table 31 and Figure 29 illustrate the progression for determining the required PFC lift thickness. Table 31 also shows the determined lift thicknesses (t).

This example points out that there has to be a practical minimum lift thickness for PFC. In the example, the required thickness of PFC in Las Vegas could not be determined because of the relatively insignificant rainfall intensity (I_{90}) observed there. From a practical standpoint, a minimum layer thickness should be based upon the maximum aggregate size of the PFC gradation. Lift thicknesses should likely be at least 1.5 to 2 times the maximum aggregate size of the gradation. There is limited evidence that thicker PFC layers that have a relatively high level of permeability can maintain permeability for a longer period of time, that is, less clogging.

Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the developed method of determining a PFC lift thickness. In conducting the sensitivity analysis, reasonable input values were assumed in order to evaluate their effect on the resulting layer thickness. As described previously, there are a total of four inputs required for the developed methodology which include: a measure of permeability, rain intensity, design cross-slope, and the length of the flow path (width of pavement from high point to low point).

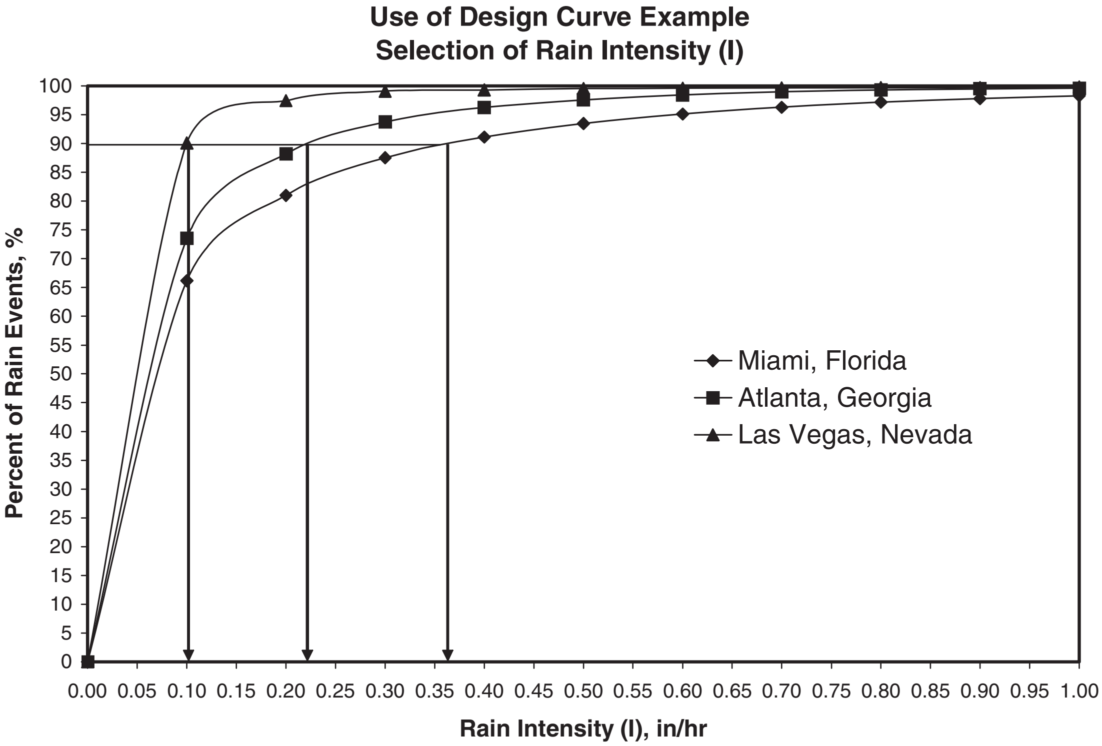


Figure 28. Rain intensity versus cumulative percent rain events for example problem.

Table 31. PFC lift thickness example based upon 2 percent cross slope.

Location	K, m/day	I, in./hr (Figure 31)	4I/K	t/L (Figure 32)	L,m	t,mm
Miami	100	0.37	0.015	11.1	3.6	40.0
Atlanta	100	0.22	0.009	4.0	3.6	14.4
Las Vegas	100	0.10	0.004	---	3.6	---

Figure 30 illustrates the effect of permeability on the resulting lift thickness. For this figure, the rainfall intensity was set at 0.4 inches per hour, cross-slope was set at 2 percent, and the flow path was set at 12 ft (3.6 m). Based upon the figure, as permeability increases the needed thickness decreases, which seems logical. As permeability of the layer increases, the ability of the layer to drain water to the pavement edge increases. Therefore, less volume of water is stored within the PFC at any given moment (assuming a constant rain intensity) leading to less needed thickness. The range of permeability values presented in Figure 30 is 100 to 250 m/day. Within this range of permeability values, Figure 30 shows a significant effect of permeability on the needed PFC layer thickness. This indicates that selection of an appropriate permeability value is very important in using the proposed methodology.

Figure 31 illustrates the influence of rain intensity of the resulting layer thickness. For this figure, the flow path length was 12 ft (3.6 m), cross slope was 2 percent and permeability was 328 ft/day (100 m/day). As rain intensity increases, the needed thickness of PFC also increases. Rainfall intensities included within Figure 31 ranged from 0.25 to 0.5 in./hr. Except within the drier portions of the country, this range appears typical.

The effect of cross slope on the needed PFC layer thickness is shown in Figure 32. As cross slope increases, the needed PFC layer thickness decreases. As cross slope is increased for a given lane width, the hydraulic head also increases which helps to drive the water within the PFC to the pavement edge and, thus, discharge. Within Figure 32, rainfall intensity, I_{90}, was set at 0.5 in. per hour, permeability was set at 328 ft/day (100 m/day) and the length of flow path was 12 ft (3.6 m). Figure 32 (as well as Figure 27) provides an interesting opportunity for pavement designers. In areas susceptible to very intense rain events or multiple lanes (longer flow path), simply increasing the design cross slope by 0.5 percent can significantly reduce the needed thickness of PFC.

The final input into the PFC layer thickness methodology is the flow path length. Flow path length will change as the

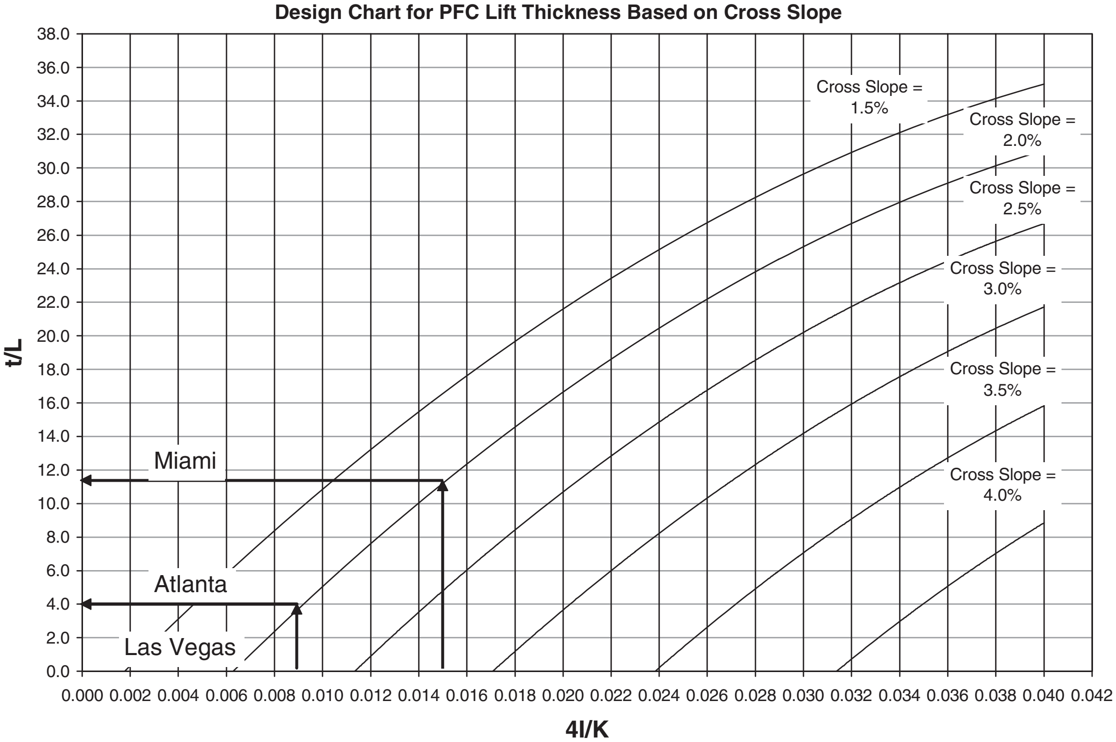


Figure 29. Example problem determining PFC layer thickness.

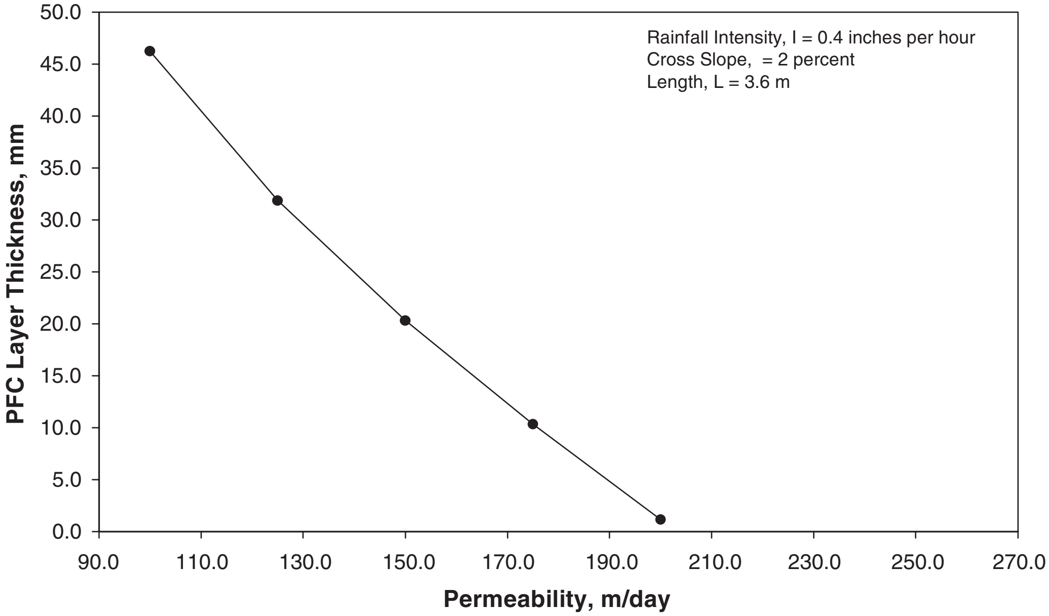


Figure 30. Effect of PFC permeability on design lift thickness.

number of lanes to be paved with PFC changes. Also, extending the PFC the full width of the shoulder will increase the flow path length. Figure 33 illustrates the effect of flow path length on the design lift thickness. For this figure, rainfall intensity (I_{90}) was set at 0.3 in. per hour, the cross slope was set at 2 percent and permeability was set at 328 ft/day (100 m/day). As the flow path length increases, the required thickness of PFC also increases because the longer flow path means that the water is held in the PFC longer. Therefore, more thickness is required to store the water while it drains to the pavement edge. For the data shown in Figure 33, an increase in flow path length from 12 ft (3.6 m) to 24 ft (7.6 m) almost doubled the required thickness of PFC.

These discussions indicate that each of the four input parameters have a significant effect on the resulting thickness of a PFC layer when using the methodology described in this chapter. Therefore, the input values must be carefully selected. Of the four factors, the rainfall intensity (I_{90}) likely has the

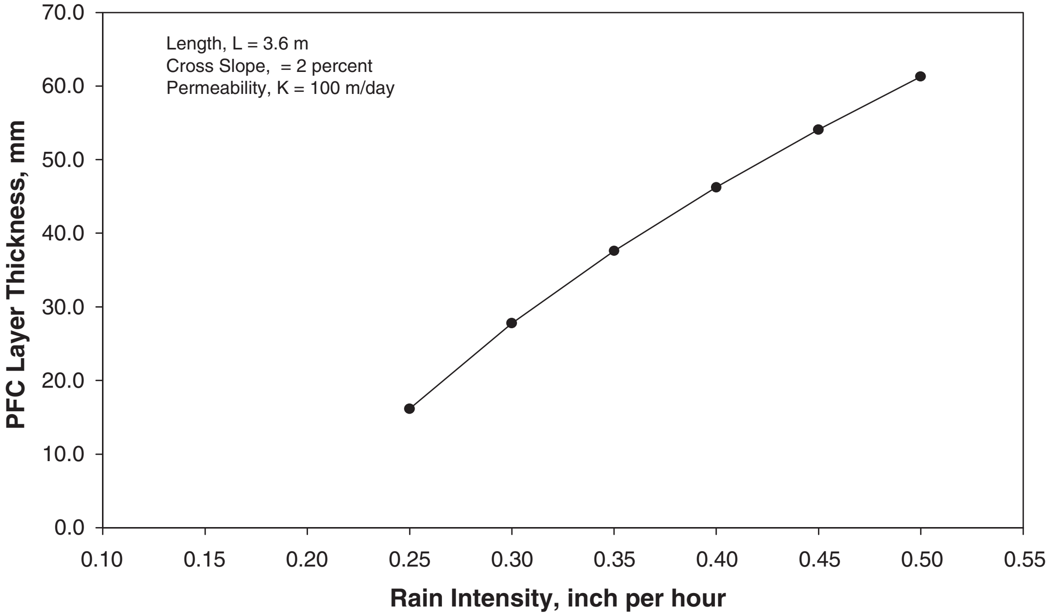


Figure 31. Effect of rain intensity on design lift thickness.

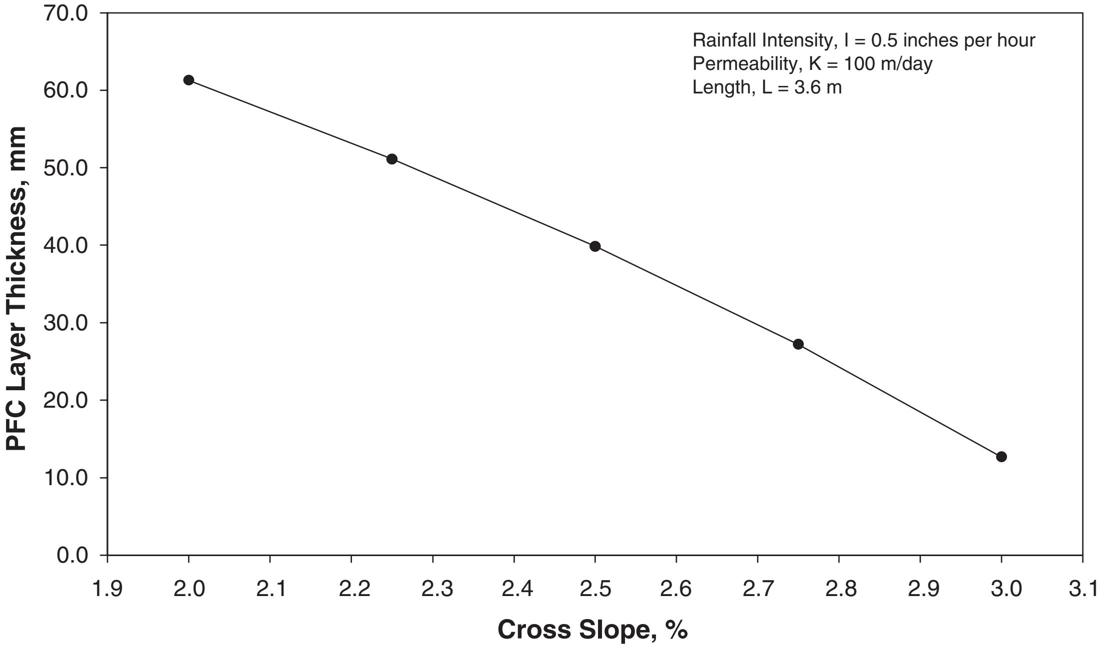


Figure 32. Effect of cross slope on design lift thickness.

most influence on thickness; however, as described, the I_{90} values are generally in a very narrow range.

Discussion of Proposed Methodology

A number of approaches were investigated to develop a methodology for determining a minimum layer thickness of PFC. Of the different approaches, the use of principles associated with an unconfined aquifer was the most logical and practical. The term practical, as used here, means that the resulting minimum lift thicknesses were realistic with current practices. Intuitively, the use of concepts associated with unconfined aquifers is very similar to the flow of water through a PFC layer. Unconfined aquifers have an impermeable layer underneath and a free water surface at the top.

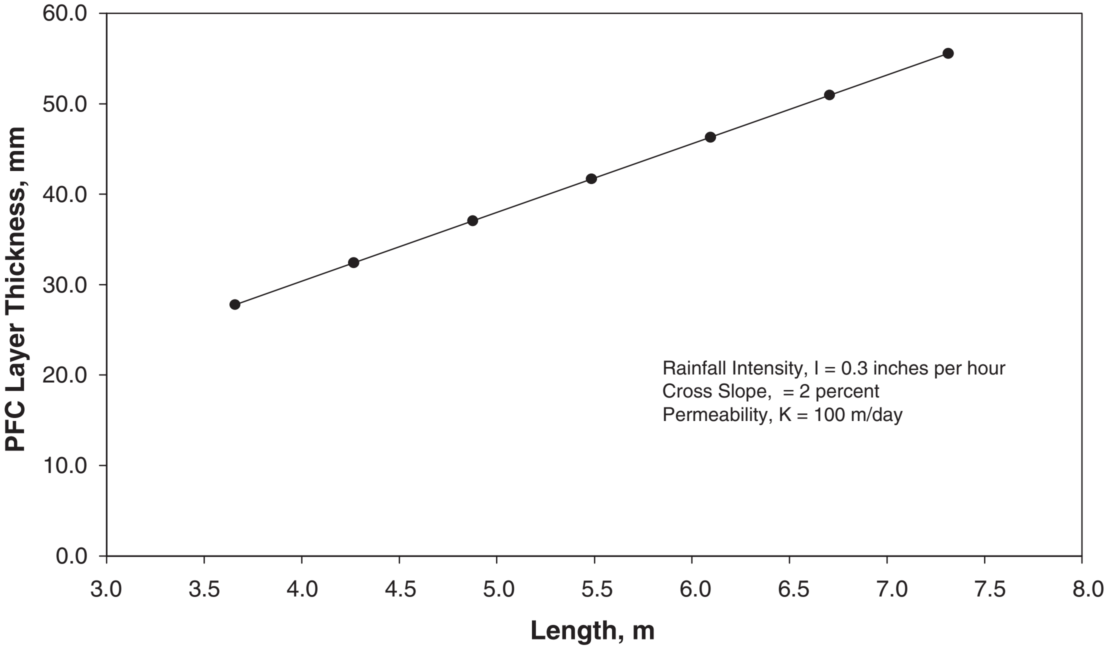


Figure 33. Effect of flow path length on design lift thickness.

The example problem presented earlier indicates that the results from the described approach are realistic. Miami, Florida receives a significant amount of rainfall compared to much of the United States and based upon the design curves and assumptions made, an appropriate thickness is 40 mm. This thickness seems appropriate and is in line with thicknesses used around the United States and in Europe. Therefore, the minimum lift thickness approach passes the test of reasonableness for the Miami example.

The results of the example problem for Atlanta, Georgia were a PFC thickness of 14.4 mm. This value is actually less than the typical PFC thickness used in Georgia of 32 mm. However, using a thickness layer larger than that determined using the design curves should not be discouraged. As stated previously, there is evidence that thicker layers of PFC maintain permeability longer. The action of traffic and the larger volume of voids (not percentage but overall volume) help clean the void structure through hydraulic action of tires passing over the layer.

The one potential problem with the proposed design curves has to do with permeability. No matter how well general maintenance is performed, there always will be some degree of clogging within a PFC layer. If the permeability of the PFC layer becomes lower than the assumed permeability value, theoretically, a sheet of water could exist at the pavement surface. This is not perceived as a problem, however, because the very high macrotexture of a PFC pavement should more than offset any film of water that exists on the pavement surface. The relatively high macrotexture of PFC wearing layers provides channels for water to be displaced when a tire passes over the pavement surface. Additionally, the design curves do not take into account any hydraulic action caused by traffic which results in water being "pushed through" the void structure of the PFC layer, which makes the design curves conservative.

CHAPTER 7

Construction of Permeable Friction Courses

Similar to any HMA mixture, construction of PFC pavement layers includes four primary phases: production, transportation, placement and compaction. Another important aspect of construction is QC/QA. Many of the best practices for constructing PFC pavement layers can be taken from the construction of SMA. Both mix types utilized a large fraction of coarse aggregates and generally require the use of stabilizing additives. Therefore, in addition to the literature, reports, and survey dealing with PFCs (and OGFCs), guidelines developed during NCHRP Project 9-8 (*57*) also were consulted to develop guidelines on the construction of PFCs. Another valuable reference utilized during the development of Construction Guidelines was the *Hot-Mix Asphalt Paving Handbook* (2000) (*58*). This chapter presents best practices guidelines for the construction of PFC pavement layers as no references were identified that evaluated construction practices. Only experiences were found in the literature.

Plant Production

Production of PFC at a typical HMA plant encompasses those same procedures that would ordinarily be performed at the plant to manufacture any HMA mixture. Any HMA production facility capable of producing high-quality HMA can produce high-quality PFC (*7*). This section provides guidance found in the literature review and survey for procedures involving aggregate handling, stabilizing additives, liquid asphalt, mixing times, and plant calibration along with other issues that require special attention when compared to conventional HMA production.

Aggregates

As with the construction of any HMA pavement layer, quality begins with proper aggregate stockpile management. Stockpiles should be built on sloped, clean, stable surfaces with the different stockpiles kept separated (*58*). Every effort should be made to maintain a relatively low moisture content within the aggregate stockpiles. Low moisture contents and low moisture content variability will allow for easier control of mixing temperature (*7*).

A PFC mixture must contain a high percentage of coarse aggregate in order to provide the desired high air void contents and, thus, benefits related to permeability. The high percentage of coarse aggregate within PFC mixtures provides the stone-on-stone contact necessary to provide a stable pavement layer for these high air void content mixes. While it is typical to blend two or three different aggregate stockpiles in the mixture (coarse aggregate, immediate aggregate, and fine aggregate), the coarse aggregate (defined as the material retained on the break point sieve) is usually a high percent of the gradation blend (to 85 percent of the blend). Since the coarse aggregate gradation can have a tremendous effect on the quality of the mixture produced, it is necessary that the aggregates be carefully handled and stockpiled. Consideration should be given to feeding the coarse aggregate stockpile through more than one cold feed bin to provide better control over the production process. Using more than one cold feed bin for the coarse aggregate will minimize variability in the coarse aggregate gradation (*57*).

Liquid Asphalt

The handling and storage of liquid asphalt binder for PFC production is similar to that for any HMA mixture. If not already equipped, the plant facility should have a different, or second, storage tank designated strictly for modified binders. When modified asphalt binders are used, the storage temperature may increase slightly from those of neat asphalt binders. Mechanical agitators may be required within storage tanks when modified binders are used (*7*). Contractors should follow the manufacturers' recommendations for circulation and storage of modified asphalt binders. Metering and introduction of asphalt binder into the mixture may be done by any of the standard methods using a temperature compensating system. It is very important, however, that the asphalt binder be metered accurately (*4*).

Stabilizing Additives

With the high asphalt binder contents and large fraction of coarse aggregate inherent to PFC mixtures, a stabilizing additive of some type must be used to hold the asphalt binder within the coarse aggregate structure during storage, transportation, and placement. Draindown will generally occur at typical production temperatures if a stabilizing additive is not used. When draindown occurs during haul and placement, it results in flushed spots in the finished pavement, termed fat spots (*4*). Eliminating draindown is helped through modifying the asphalt binder and/or the use of fibers. Most PFC mixtures will require the use of both a fiber and a modified asphalt binder to minimize draindown potential and improve durability. Draindown testing conducted during mix design should provide an indication of draindown potential and the needed stabilizing additive(s).

Fibers

Both cellulose and mineral fibers have been used in PFC mixture production. Dosage rates vary, but typically the rates are 0.3 percent for cellulose and 0.4 percent for mineral fiber, by total mixture mass (*4*). The survey of agencies yielded specified rates between 0.1 and 0.5 percent. Fibers can generally be purchased in two forms, loose and pelletized (*4*). Decoene (*18*) indicated that pelletized fibers were specifically developed for the conditions with drum-mix plants. Fibers in a dry, loose state come packaged in plastic bags or in bulk. Fibers also can be pelletized with the addition of some amount of a binding agent. Asphalt binder and waxy substances have been used as binding agents within pelletized fibers. Both fiber types (loose or pelletized) have been added into batch and drum-mix plants with success.

For batch plant production, loose fibers are sometimes delivered to the plant site in bags. The bags are usually made from a material that melts easily at typical mixing temperatures (*18*). The bags can be added directly to the pugmill during each dry mix cycle. When the bags melt, only the fiber remains. Addition of the bags of fibers can be done by workers on the pugmill platform. At the appropriate time in every dry mix cycle, the workers add the correct number of bags to the pugmill. The bags of fiber can be elevated to the pugmill platform by the use of a conveyor belt. While this method of manual introduction works satisfactorily, it is labor intensive.

Another method for addition of fibers into a batch plant is by blowing them into the plant using a machine typically designed and supplied by the fiber manufacturer (Figure 34).

Figure 34. Fiber introduction system.

The dry, loose fiber is placed in the hopper of the machine where it is fluffed by large paddles. The fluffed fiber next enters an auger system which conditions the material to a known density. The fiber is then metered by the machine and blown into the pugmill or weigh hopper at the appropriate time. These machines can meter in the proper amount of fiber by mass or blow in a known volume (*4*).

This fiber blowing method also can be used in a drum mix plant. The same machine is used and the fibers are simply blown into the drum. When using this method in a drum mix plant the fiber introduction line should be placed in the drum within 1 ft (0.3 m) upstream of the asphalt binder line (Figure 35) (*4*). At least one agency has reported that introduction of the fibers at the lime injection point (assuming lime is incorporated into the mix) also worked well (*10*). They indicated that this allowed the fibers to mix with the aggregates prior to the introduction of asphalt binder. No matter the method of introduc-

Figure 35. Typical location for introduction of fibers into drum-mix plant.

tion, it is imperative that fibers be captured by the asphalt binder before being exposed to the high-velocity gases in the drum. If the fiber gets into the gas stream, it will enter the dust control system of the plant (*4*).

Whenever loose fibers are blown into the production process, whether a drum mix or batch plant is used, the fiber blowing equipment should be tied into the plant control system (*57*). The fiber delivery system should be calibrated and continually monitored during production. A common practice is to include a clear section on the hose between the fiber blowing equipment and the introduction point within the production process (Figure 36). This clear section can provide a quick, qualitative evaluation of whether the fiber is being blown properly into the drum. Variations in the amount of fibers within the PFC mix can have a detrimental impact on the finished pavement.

The pelletized form of fibers can be used in both drum-mix and batch plants. Pellets are shipped to the plant in bulk form and when needed are placed into a hopper (Figure 37). From the hopper they can be metered and conveyed to the drum or pugmill via a calibrated conveyor belt. Addition of the pellets generally occurs at the RAP collar of a drum mix plant or they are added directly into the pugmill of a batch plant. Whether in the drum or the pugmill, the pellets are mixed with the heated aggregate and the heat from the aggregates causes the binding agent in the pellets to become fluid. This allows the fiber to mix with the aggregate (*4*). Note that some forms of pelletized fibers do contain a given amount of asphalt binder. In most instances, this amount of asphalt binder is very small and is not included within the total asphalt binder content. Check with the fiber manufacturer to determine the asphalt contents of the pellets.

It is imperative that the fiber addition, whether it be loose or pelletized, be calibrated to ensure that the mixture continually receives the correct amount of fiber. If the fiber content is not accurately controlled at the proper level, fat spots can result on the surface of the finished pavement. Also, portions of the mixture will be dry and unworkable (7). For assistance with the fiber storage, handling, and introduction into the mixture, the fiber manufacturer should be consulted.

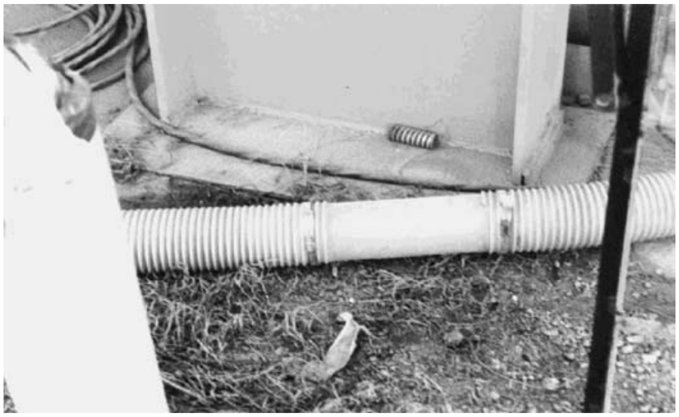


Figure 36. Clear section of fiber introduction line.

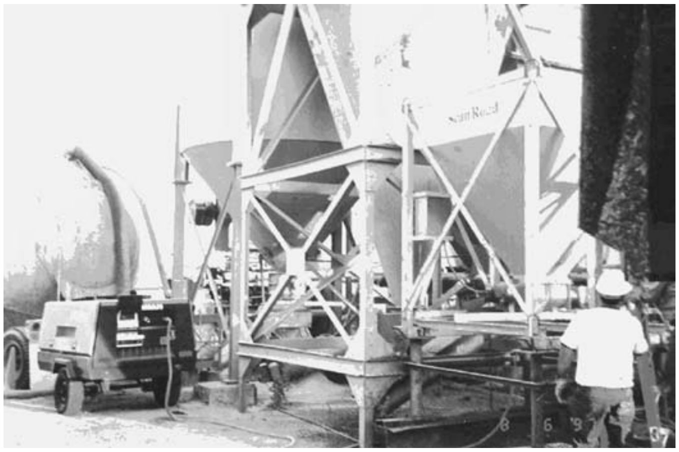


Figure 37. Typical fiber hopper for pelletized fibers.

Asphalt Cement Modifiers

Another method of providing stabilization to PFC is with the use of asphalt binder modifiers. The asphalt binder in PFC can be modified at the refinery or in some cases the modifier is added at the hot mix plant. For the first method, the hot-mix producer takes delivery of the modified asphalt binder and meters it into the PFC mixture in a traditional manner. Special storage techniques and/or temperatures may be required, as discussed previously. With the second method, the contractor must ensure that the proper amount of modifier is added and thoroughly mixed with the asphalt binder (*57*).

When an asphalt binder modifier is added at the hot-mix plant, two different methods are utilized. The modifier is blended into the asphalt binder either before it is injected into the production process or it is added directly to the dry aggregates during production (*57*). Addition of the modifier to the asphalt binder is accomplished by in-line blending or by blending the two in an auxiliary storage tank. If the modifier is added to the aggregates rather than the asphalt binder, it can be added directly into the pugmill or, in a drum-mix plant, it can be delivered to the drum via the RAP delivery system. Use of the RAP belt weigh bridge is not recommended because of poor accuracy and special metering devices may be necessary if the RAP feeder cannot be calibrated (*57*). When a modifier is added directly into the plant and not premixed with the asphalt cement, it is impossible to measure the properties of the modified asphalt binder. The properties of the modified asphalt binder can be estimated in the laboratory by mixing the desired proportion of asphalt cement and modifier and testing (*21*).

Regardless of the form of stabilization, advice and assistance should be sought from the stabilizer supplier. It is imperative that the system used to add the modifier be calibrated to ensure the mixture receives the proper dosage.

Mixture Production

Production of PFC is similar to the production of standard HMA from the standpoint that care should be taken to ensure a quality mixture is produced. Production of PFC is discussed in this section with special emphasis on production areas where PFC quality may be significantly affected.

Plant Calibration

It is important that all the feed systems of the plant be carefully calibrated prior to production of PFC. Operation of the aggregate cold feeds can have a significant influence on the finished mixture, even in a batch plant where hot bins exist. Calibration of the aggregate cold feed bins should be performed with care.

The stabilizing additive delivery system should be calibrated and continually monitored during production. Variations in the amount of additive can have a detrimental impact on the finished pavement. Stabilizing additive manufacturers will usually assist the hot-mix producer in setting up, calibrating, and monitoring the stabilizing additive system.

Plant Production

Similar to the production of typical HMA mixtures, mixing temperatures during the production of PFC mixes should be based upon the properties of the asphalt binder (*57*). Mixing temperatures should not be arbitrarily raised or lowered. Elevated mixing temperatures increase the potential for damage to the asphalt binder due to rapid oxidation. This damage can lead to premature distress within PFC layers. Additionally, artificially increasing the mixing temperature can increase the potential for draindown problems during storage, transportation, and placement of PFC. Arbitrarily lowering the mixing temperature can result in not removing the needed moisture from the aggregates within the drying process. Moisture remaining within the aggregates can increase potential of moisture-induced damage within PFC layers. Additionally, arbitrarily lowering the mixing temperature will likely result in PFC mixture delivered to the construction project that is cooler than the desired compaction temperature. If this occurs, the PFC may not bond with the underlying layer (through the tack coat) and result in increased potential for raveling and delamination. Experience seems to indicate that normal HMA production temperatures or slightly higher are adequate. In addition to the properties of the asphalt binder, the mixing temperature should be chosen to ensure a uniform mixture that allows enough time for transporting, placing, and compaction of the mixture.

When using a batch plant to produce PFC, the screening capacity of the screen deck will need to be considered. Since PFC gradations are generally a single-sized aggregate, override of the screen deck and hot bins may occur (*4*). If this occurs, the rate of production should be decreased.

Choubane et al. (*59*) designed some flushing problems that occurred in Florida during construction of open-graded mixes. Based upon an investigation into the problems, the flushing problems were traced back to start up problems each day. Therefore, they concluded that both proper start-up and clean-out procedures were needed with open-graded mixes.

Mixing Time

When adding fibers to the PFC mixture, experience has shown that the mixing time should be increased slightly over that of conventional HMA (*4*). This additional time allows for the fibers to be sufficiently distributed within the mixture. In a batch plant, this requires that both the dry and wet cycles be increased from 5 to 15 seconds each. In a parallel flow drum plant, the asphalt binder injection line may be relocated, usually extended when pelletized fibers are used (*57*). This allows for more complete mixing of the pellets before the asphalt binder is added. In both cases, the proper mixing times can be estimated by visual inspection of the mixture. If clumps of fibers or pellets still exist intact in the mixture at the discharge chute, or if aggregate particles are not sufficiently coated, mixing times should be increased or other changes made. For other plants such as double-barrel drum mixers and plants with coater boxes, the effective mixing time can be adjusted in a number of ways including reduction rate, slope reduction of the drum, etc.

Mixture Storage

The PFC mixture should not be stored at elevated temperatures for extended periods of time as this could facilitate draindown (*4*). In general, experience has shown that PFC can be stored for 2 hours or less without detriment. In no instance should the PFC mixture be stored in the silo overnight.

During the survey, agencies were equally split on having a maximum silo storage time. Those that did limit storage time had limits from 1 to 12 hours. For those agencies indicating that they specified PFC mixes, the maximum storage time was typically 2 hours.

Transportation

The PFC mixture is transported to the project site using the same equipment used for dense-graded HMA (*7*). Generally, no additional precautions are required; however, there are some best practices that should be followed.

The goal of this phase of construction is to deliver the PFC mix to the project site at the appropriate temperature. There are three methods used to ensure that the PFC will arrive at the appropriate temperature for placement and compaction. The first two limit the amount of time the PFC is in the transport vehicle: limiting haul distance or limiting haul time. These two methods assume that the mix leaves the plant at a temperature near mixing temperature. The third method is to specify a minimum mix temperature upon arrival at the project site. From the survey of agencies, most have requirements for minimum mix temperature at the project site; however, one agency limited haul distance to 50 miles (80 km) and one limited haul time to no more than 1 hour. Minimum delivery temperatures ranged greatly in both the survey and literature review. A specified minimum delivery temperature should be based upon climate and typical asphalt binders used in PFC by the agency.

Hauling

One of the keys to successful PFC projects is having adequate transportation to supply mix to the paver so that the paver does not have to stop and wait on materials (*4*). Since the contractor often does not own the trucks, communication with the trucking operator is essential to avoid delays.

Because of the bonding tendency of the modified asphalt binder generally used in PFCs, the truck beds should be cleaned frequently and a heavy and thorough coat of an asphalt release agent applied. Also, truck beds should be raised after spraying to drain any puddles of the release agent. Excess release agent, if not removed, will cool the PFC and cause cold lumps in the mix (*4*). Most agencies have approved lists of release agents. Use of fuel oils in any form should be strictly prohibited.

Haul trucks should be covered with a tarp to prevent excessive crusting of the mix during transportation (*7*). Based upon the survey, most agencies require trucks to be tarped. Cold lumps do not break down readily and can cause pulls in the mat. Since long haul distances will compound this problem, the haul distance should be kept under approximately 50 miles (80 km). To combat this problem, some agencies require insulated truck beds (*7*).

As an alternative to insulated tuck beds, a “heated dump body” may be used. A heated dump body refers to a transport vehicle capable of diverting engine exhaust (Figure 38) and transmitting the heat evenly throughout the dump body to help keep the PFC from excessively cooling.

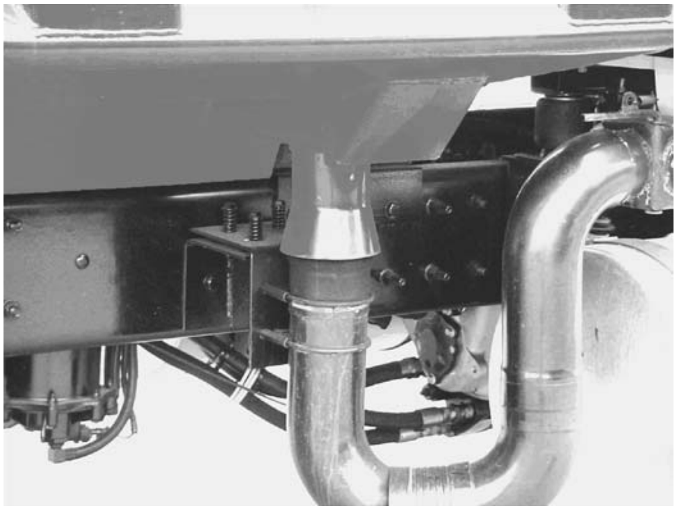


Figure 38. Exhaust system for heated dump body.

Haul Time

Haul distance is important. however, the haul time should govern over haul length. For PFC mixtures, haul time should be limited to less than 2 hours haul time, but preferably less than one hour. Haul times for PFC should be as short as possible. It is important that the temperature of the PFC mixture not be raised arbitrarily high in order to facilitate a longer haul time (*57*). The increased temperature in coordination with the vibration provided during haul can amplify the probability of draindown occurring. The mixture should arrive at the paving site so that it is placed at the appropriate compaction temperature.

Placement

Placement of PFC is similar to placement of typical dense-graded HMA. Typical asphalt pavers are utilized.

Weather Limitations

In order to achieve proper placement and compaction, PFC should not be placed in cold or inclement weather. A minimum pavement temperature of at least 50°F (10 °C) for placement of PFC mixture is recommended (*19*). Ambient air temperature should also be at least 50°F (10°C) and rising though some agencies specify higher temperatures (*19*). However, the ability to place PFC will also depend on wind conditions, humidity, the lift thickness being placed, and the temperature of the existing pavement. Local experience with paving mixtures that include very stiff asphalt binders (polymer-modified) should be considered when specifying weather limitations.

Pavement Surface Preparation

Prior to placing PFC, preparation of the surface to be covered will depend on the type of surface onto which the PFC will be placed. The preparation method used is generally the same as for conventional HMA mixtures. PFCs should enable rain water to penetrate the surfacing and be laterally drained off to the side of the road by flowing on an impermeable interface between the PFC and underlying layer. Therefore, the PFC should only be placed on an impermeable HMA layer or on a portland cement concrete pavement (*21*). Placement on an impermeable layer will help ensure that during rainfall, the water will pass through the PFC and not be trapped in the underlying pavement layer, thus helping to minimize the potential for moisture damage (stripping). PFC should not be placed on rutted asphalt pavement. The rutted surface should be milled first or reshaped to that depth, which allows the water to flow to the side of the road before placement of the PFC mixture.

The PFC mat should be daylighted on the shoulder so that rain water percolating through the PFC can drain out freely at its edge (*21*). A strip at least 4 in. (0.1 m) wide should be left between the PFC and any grass area. If the PFC is not laid over the entire width of an existing pavement, including the paved shoulder, then it should extend at least 12 to 20 in. (0.3 to 0.5 m) onto the paved shoulder with a tapered profile for safety associated with pavement edge drop-off. Wagner and Kim (*60*) described a device to construct tapered pavement edges.

Two methodologies of constructing shoulders have been used in Spain (*16*). First, PFC has been extended over the entire shoulder and the second method has been to extend the PFC 1.6 ft (50 cm) onto the shoulder. Lefebvre (*21*) illustrated three methods for construction of shoulders with PFC (Figure 39).

To have an impervious underlying layer, or to make it impervious, is one of the imperatives of PFC. When overlaying an existing asphalt road with PFC, the underlying asphalt should be as impervious as possible. When an old pavement surface is to be covered by a PFC then proper repair should first be performed (*16*). Areas containing large permanent deformations should be milled or filled using a leveling course. If the condition of the in-place mix is sufficiently bad, it may have to be removed to some predetermined depth. Any distressed areas should be properly repaired.

A freshly compacted dense-graded HMA course may have as much as 8 percent air voids in the mat and thus may be permeable to water. Alderson (*19*) states that pavements can be considered impervious if they have less than 5 percent air voids. If this condition is not available, the existing pavement should be sealed using a heavy tack coat, fog coat or other type seal (*19*). It is essential to provide a uniform tack coat at an adequate application rate to fill and seal the surface voids of the underlying layer.

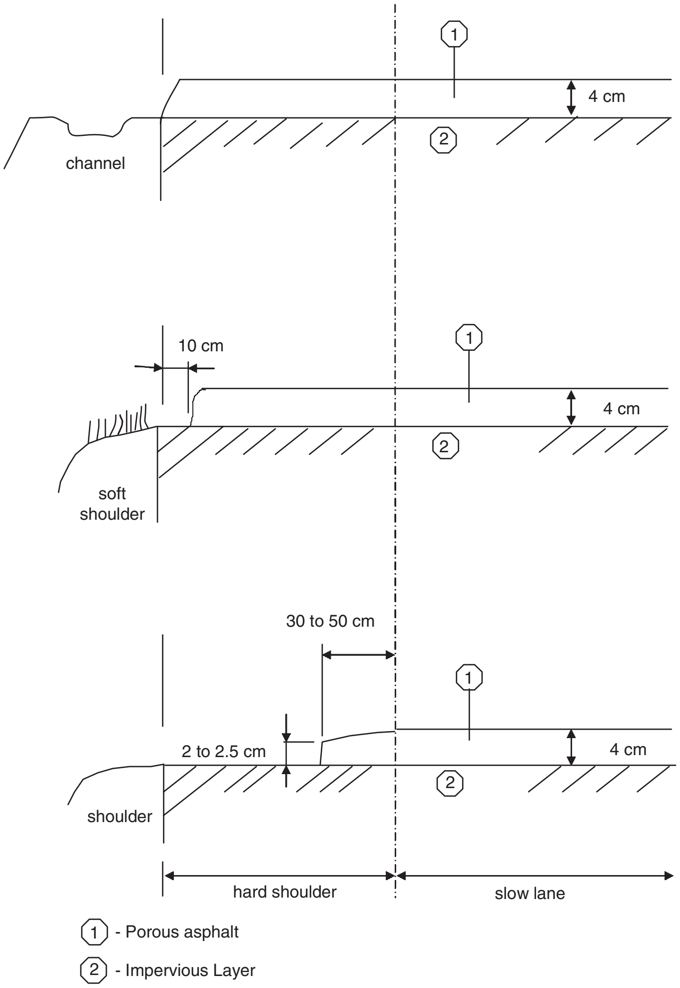


Figure 39. Examples of daylighting porous asphalt mixtures (21).

For old distressed surfaces, the method used to make the surface impermeable will depend on the severity of the pavement distress. Lightly and randomly cracked surfaces should have wide cracks cleaned and sealed by bridging. If the entire surface is randomly cracked, a full-width treatment is necessary to make it impervious. Types of materials and their application rates need not vary from that of conventional HMA construction. When sealing the underlying pavement with a tack coat it is recommended that a 50 percent diluted slow-setting emulsion tack coat at a rate of 0.05 to 0.10 gallons per square yard be applied (4). Ruiz et al. (*16*) recommended 0.11 to 0.13 gallons per square yard. In British Columbia, a rate of 0.17 gallons per square yard is utilized (*53*). The application rate should be high enough to completely fill the surface voids. A slow-setting emulsion tack coat is likely to penetrate the surface voids more effectively than an asphalt cement tack coat (*4*). However, others have recommended quick-setting emulsions (*16*). Most dense-graded HMA surfaces become reasonably impervious after two to three years of traffic. Such surfaces will not need any sealing prior to placing PFC. However, if the existing surface is highly polished, a slurry seal may be required (*16*). Severely cracked surfaces may require a impervious membrane be used. The survey indicated that a wide range of tack coat materials have been used with PFCs including emulsions and neat asphalt binder.

Sealing or use of a tack coat should never be used when a PFC is placed on another PFC surface.

Paver Operation

PFC mixtures are placed using conventional asphalt pavers. However, a hot screed is very important to prevent pulling of the mat. A propane torch or some other means to heat the paver screed before each startup is important.

Charging the Paver

The PFC mixture is normally delivered to the paver in the traditional manner of backing in trucks. A material transfer vehicle (MTV) also can be used for PFC. Some agencies currently specify MTVs. The use of a remixing material transfer device for transferring the PFC from the trucks to the paver is optional, but highly recommended. It remixes most cold lumps produced during transportation, and also allows continuous operation of the paver for smoother surfaces. If the mixture is dumped directly into the hopper of the paver, the trucks should not back into the paver. With PFCs, the resulting depression is more difficult to roll smooth than for dense-graded HMA.

Placing PFC mixture in a windrow for pick-up is allowed; however, the length of the windrow should be closely controlled. Mixture placed within a windrow will lose heat more quickly than mixture placed with a MTV or directly into the hopper. Weather conditions also should be considered before using the windrow technique. During favorable weather conditions, windrow length should not be more than 150 ft (50 m) (*7*).

Paver Calibration

Prior to placement of the PFC, the paver should be correctly calibrated. This is no different than when placing conventional HMA and involves the flow gates, the slat conveyors, and the augers. The flow gates should be set to allow the slat conveyors to deliver the proper amount of mixture to the augers. When extendable screeds are utilized, auger extensions should be used (*7*). Without the use of auger extensions, the coarse aggregates tend to be pushed to the edge of the mat, leaving the asphalt binder behind.

Paver Speed

When placing PFC, the paving speed is for the most part dictated by the ability of the rolling operation to compact the mixture. It is critical that the plant production, mixture delivery, and ability to compact be coordinated so that the paver does not have to continually stop and start (*58*). Paver stops and starts should be held to an absolute minimum because they will likely have a significant negative impact on ride quality (smoothness).

In addition to continuous paver movement, the PFC mixture delivery and paver speed should be calibrated so that the augers can be kept turning 85-90 percent of the time (*57*). This helps ensure the slowest possible speed for the augers. Running the augers very fast for short periods of time should be avoided. The high auger speed may have a tendency to shear the mortar from the coarse aggregate thus causing fat spots in the pavement. The paver wings should not be lifted except when the material is to be discarded.

Lift Thickness

The majority of PFC pavements placed in the United States have been placed between 1.25 to 2 in. (32 and 50 mm) in thickness. It is imperative that the construction inspector not try to balance yield by adjusting the thickness of the PFC lift. This can cause unsatisfactory pavements to be built. A tolerance of ± 0.25 in. (6 mm) in the lift thickness should be allowed (*57*). Though no guidance was found, minimum lift thicknesses should be about two times the maximum aggregate size of the gradation.

Placement and Finishing

Immediately behind the paver, PFC mixtures are known to be harsh and very sticky. For this reason a minimum of raking and hand work should be performed (*21*). When needed, hand placement of the material can be accomplished with care.

Longitudinal joints in the PFC pavement are constructed by placing the mix approximately ⅛ in. (3 mm) above the previously placed and compacted lane. Therefore, it is important for the edge of the screed or extension to follow the joint exactly to prevent excessive overlap. Longitudinal joints should not be tacked unless they are at the crown of the pavement (*4*). Tacked longitudinal joints will prevent the flow of water across the joint. Transverse joints placed against a previously laid PFC are constructed by starting with the screed one foot behind the joint and laying the screed flat on the previously laid PFC mat (*57*). Then hot PFC mix is augered in front of the screed and then drug off the new joint when travel begins. The joint should then be cross rolled with a steel wheel breakdown roller.

Compaction

Initially, compaction should be as intense as in the case of traditional bituminous mixes, in order to keep subsequent post-compaction as reduced as possible. To achieve correct compaction on PFC, the roller must follow close behind the paver, passing over immediately after the laying, in order for the temperature to be sufficient (*57*).

Conventional steel wheel rollers are used to compact the PFC. No pneumatic tire rolling is required. It is critical to keep the breakdown roller within 50 ft (15 m) of the paver to compact while it is still hot and workable. The breakdown roller usually completes one to two complete coverages of the mat in static mode to compact a thin lift (¾ in. or 20 mm) PFC.

Rolling

No minimum density is recommended for PFC. Rather than having a density requirement, some agencies control compaction by permeability tests performed on the completed PFC mat (*13*), though this practice is not common. Densification of PFC mixture should be accomplished as quickly as possible after placement. By its very nature PFC becomes difficult to compact once it begins to cool. For this reason it is imperative that the rollers be kept immediately behind the paver (*57*).

Rolldown of PFC mixtures is slightly less than one-half that for conventional mixtures. While conventional HMA mixtures rolldown approximately 20-25 percent of the lift thickness, PFC will normally rolldown 10 to 15 percent of the lift thickness (*7*).

Breakdown rolling should begin immediately behind the paver and the roller should stay close behind the paver at all times. If the rolling operation gets behind, placement of PFC should slow until the rollers catch up with the paver (*57*).

Steel wheeled rollers weighing 9 Mg (10 tons) should be used when compacting the PFC mixture (*7*). Roller speed should not exceed 3 miles/hr (5 km/hr) and the drive roll should be kept nearest the paver. Two to four passes of the breakdown rollers should be sufficient. If it becomes necessary for the rollers to sit idle they should be taken off the mat if possible. Idle rollers sitting on the mat can cause unnecessary roughness in the finished surface. Static steel wheel finish rollers are used to remove any roller marks from the pavement surface.

It is normal practice to mix a minimum amount of release agent with the water in the roller drum to prevent the asphalt binder from sticking to the drum. Excessive amounts of water should not be used (*57*).

Vibratory rollers should not be used on PFC. The breakdown roller may have to be operated in a vibratory mode at transverse joints and occasionally longitudinal joints to help knock down a high joint. Generally, use of vibratory compaction should be discouraged (*4*). If vibrating is allowed, it must be used with caution. The vibration of the roller may break aggregate and/or force the mortar to the surface of the mat.

Pneumatic-tired rollers are not recommended for use on PFC (*4*). The rubber tires tend to pick up the mortar causing surface deficiencies.

One of the main differences between PFC and dense-graded mixtures is that the goal for compaction is quite different. With dense-graded mixtures, compaction is necessary to make the mixture impermeable so that water does not infiltrate the layer through interconnected air voids. With the PFC mixtures, compaction equipment is used only to seat the mixture in the tack coat to provide a good bond at the interface of layers. Otherwise, the mixture is intended to be highly permeable to transfer water through the layer onto the shoulder or edge of the pavement. Where air voids during construction are generally reduced to between 5 to 7 percent for dense-graded mixtures, PFC should have above 18 percent air voids immediately after construction.

Density Requirements

Density of PFC mixtures is seldom checked since there is no attempt to compact the mix to a minimum density level. If density results are desired in order to verify that field air voids are adequately high enough to promote water drainage, the method of determining in-place air voids is critical. Since water freely drains from the mixture, the conventional method of using the saturated surface-dry condition (AASHTO T166) does not apply. One method is to measure the height and diameter of a core specimen and calculate the bulk specific gravity based on a volumetric relationship. Another alternative is to use the vacuum sealing method described in AASHTO TP69-04. In previous research conducted at the National Center for Asphalt Technology (NCAT), the plastic bags used in the vacuum sealing procedure frequently developed punctures so that a double-bag procedure was used with the test method (*40*).

Quality Control/Quality Assurance

PFC mixture furnished by the contractor should conform to the job-mix formula requirements, within allowable deviations from the targets. Testing included within a QC/QA program should include gradations, asphalt binder content, and draindown. Gradations and asphalt binder content testing is conducted to provide an indication that the mixture is produced according to the job mix formula, while draindown testing is conducted to ensure that the stabilizing additives are being properly added. In Spain, air void contents are controlled (*16*) by dry production.

After completion of construction, smoothness testing should be conducted. Smoothness testing should be conducted to ensure that construction practices occurred that would not adversely affect operational control of aircraft.

In Belgium, a field permeability device is specified at the time of construction to evaluate whether the PFC layer was properly constructed (*18*). In Spain, permeability testing is

Table 32. Specification limits for OGFC (*61*).

Property	Median Standard Deviation	Calculated Specification Limits (standard deviation * 1.645)	Implemented Specification Limits
Asphalt Binder Content, %	0.24	0.39	±0.45
Percent passing the 3/8 in. sieve	2.99	4.92	±6.00
Percent passing the No. 4 sieve	2.10	3.46	±4.50
Percent passing the No. 8 sieve	1.04	1.72	±2.50

conducted to control the amount of compaction under the roller (*16*). Similarly, permeability has been used as quality control in Argentina (*26*) and Japan (*20*).

Another test that has been adopted in quality control practices is the Cantabro Abrasion loss test. This method has been utilized in Argentina during quality control (*26*).

Sholar et al. (*61*) described the development of percent within limits (PWL) for open-graded mixes in Florida. They indicated that development of the PWL system for open-graded mixes was done in a manner similar to development by PWL specifications for dense-graded Superpave design HMA; however, the material properties used for payment, standard deviations and specification limits recommended are unique to open-graded mixes. Four material properties were selected that were believed to be related to performance: asphalt binder content, percent passing ⅜ in. (9.5 mm) sieve, percent passing No. 4 (4.75 mm), and percent passing No. 8 (2.36 mm) sieve. Quality control data from five different construction projects were used to develop variance and standard deviation values for each of these properties. The standard deviations along with calculated specification limits and implemented specification are provided in Table 32. For each material property, pay factors are calculated as:

$$\text{Pay Factor } (\%) = 55 + 0.5 * \text{PWL} \qquad \text{Equation 4}$$

Using the pay factor for each material property, a composite pay factor is calculated by multiplying the respective weights for each material property by the individual pay factors. The weightage of each material property was: 1) asphalt binder content (40 percent); 2) percent passing ⅜ in. sieve (20 percent); 3) percent passing No. 4 sieve (30 percent); and 4) percent passing No. 8 sieve (10 percent). Sublots were selected as 500 tons of produced mix with four sublots comprising a lot. Production resulting in less than three sublots was considered "small production" and treated separately. The pay table for small production is presented in Table 33.

Pavement Markings

A potential problematic area during the life of PFC pavements is pavement markings. The Massachusetts Highway Department has reported performance issues with the use of thermoplastic paint (*61*). The thermoplastic paint can heat up the asphalt binder at the PFC surface and cause localized draindown. They indicate that this can cause delamination and/or raveling under thermoplastic line markings. No resolutions to this problem were provided.

Corrigan et al. (*63*) conducted a study to develop a specification for longer-lasting and better-performing thermoplastic

Table 33. Pay table for small production (*61*).

Property	Pay Factor	1-Test Deviation	2-Test Average Deviation
Asphalt Binder Content, %	1.00	0.00-0.50	0.00-0.35
	0.90	0.51-0.60	0.36-0.42
	0.80	>0.60	>0.42
Percent passing the 3/8 in. sieve	1.00	0.00-6.50	0.00-4.60
	0.90	6.51-7.50	4.61-5.30
	0.80	>7.50	>5.30
Percent passing the No. 4 sieve	1.00	0.00-5.00	0.00-3.54
	0.90	5.01-6.00	3.55-4.24
	0.80	>6.00	>4.24
Percent passing the No. 8 sieve	1.00	0.00-3.00	0.00-2.12
	0.90	3.01-3.50	2.13-2.47
	0.80	>3.50	>2.47

pavement markings. The authors stated durability problems resulting from the use of snowplows as a primary cause for the research. Two parameters were considered: durability and retro-reflectivity of the markings. Both recessed and non-recessed markings were evaluated. Conclusions from the study were that fully recessed thermoplastic traffic markings resulted in the least snowplow change. Permanent inlaid marking tape lacked the needed durability to withstand snowplows. A cost analysis showed that fully recessed thermoplastic traffic markings was cost effective.

During the survey, agencies were asked what materials were used for pavement markings on open-graded mixes. Many respondents stated that typical pavement markings were used. The most frequently listed marking type included waterborne paint and thermoplastic. Some northern tier agencies mentioned epoxy.

CHAPTER 8

Maintenance of Permeable Friction Courses

A substantial amount of research has been conducted and published in the United States and Europe concerning general and winter maintenance of PFC highway pavements. Following are discussion on general and winter maintenance of PFC pavements.

General Maintenance

General maintenance consists of cleaning clogged PFC, preventive surface maintenance, and corrective surface maintenance.

Cleaning Clogged PFC

Over time PFCs may gradually be choked and partially lose permeability (*48*) due to dirt and debris entering the void structure. Frequent cleaning may be necessary. Three methods of cleaning PFC: (a) cleaning with a fire hose, (b) cleaning with a high-pressure cleaner, and (c) cleaning with a specially manufactured cleaning vehicle were tested for effectiveness in Switzerland (*64*). The special cleaning vehicle manufactured in Switzerland can wash and vacuum clean the surface in one pass. Deposited dirt in the PFC is washed out by a high-pressure water stream with a working pressure of about 500 psi (3,450 kPa) from a front washing beam, mounted on the vehicle. The water-dirt mixture on the pavement is then sucked into a container by a heavy-duty vacuum cleaner. During the investigation, cleaning with the high-pressure cleaner was found to be most effective based on permeability tests after cleaning.

A similar piece of self-contained equipment (Figure 40) from Japan was reported on for cleaning PFC layers at the meeting of the International Conference on Asphalt Pavements held in Copenhagen, Denmark (*65*). A high-pressure water blast (125 psi or 860 kPa) followed by a vacuum to remove the solids and water was used. The primary difference between the Japanese equipment and Swiss equipment is that the Japanese system causes cavitation of the water through the use of special nozzles. Field trials with the equipment were successful at restoring permeability to PFC layers.

Isenring et al. (*15*) stated that cleaning clogged PFC layers can be difficult. They suggest that cleaning techniques should begin while the layer is still permeable. By starting while the layer is still permeable, regular maintenance should maintain permeability of the layer for a longer time period.

The summary of agencies indicated only one agency, Austria, conducts maintenance to unclog PFC layers. Austria stated that they use a special equipment to unclog PFC layers, but no specifics were provided. It is assumed to be similar to the equipment from Switzerland or Japan described above.

Preventive Surface Maintenance

It is expected that the asphalt binder in the PFC pavement will get oxidized and become brittle after many years service. This may precipitate surface raveling. Many highway agencies such as those in New Mexico, Wyoming, South Carolina, and Oregon have used fog seals to perform preventive maintenance of PFC pavements. Fog seals provide a thin film of neat asphalt binder at the surface and, therefore, are believed to extend the life of PFC pavements (*66*). The FHWA recommends fog seal application in two passes (at the rate of 0.05 gal per sq. yd. in each pass) using a 50:50 mixture of asphalt emulsion and water without any rejuvenating agent (*9*).

Research in Oregon (*66*) indicated that the application of fog seals reduces the permeability of PFC layers. Also, application of fog seals to PFC layers will reduce the frictional properties of PFC layers. However, friction increases significantly in the first month after application as the fog seal is worn away by traffic. Fog seals did not affect the macrotexture of PFC layers; therefore, the reduced potential for hydroplaning was maintained. Rogge (*66*) concluded that the expected benefits of fog seals to prolong the lift of PFC layers were not substantiated with quantitative studies. Additionally, he recommended that when it was acceptable to abandon the free draining characteris-

Figure 40. Truck mounted PFC cleaning system (*65*).

tics of PFC layers and the pavement structure was sound, chip seals may be applied. Chip seals are, however, more expensive but they more completely seal the surface than fog seals (*66*). However, Oregon responded in the survey that they had concerns with the use of chip seals. These concerns were related to increased potential for moisture damage in underlying layers. None of the agencies indicated that they currently utilize fog seals.

Ruiz et al. (*16*) also stated that the primary problem with PFC in Spain has been raveling. The raveling generally occurs shortly after traffic is applied to the pavement layer. They indicated that this problem generally originates from placing PFC too cold, not enough compaction, or draindown problems. In British Columbia, light raveling is addressed by applying a light application of asphalt sealant. Wimsatt and Scullion (*67*) stated that it was standard practice by Texas DOT to use seal coats over distresses open-graded surfaces.

Corrective Surface Maintenance

Occasionally, the PFC layers will require repair of delaminated areas and potholes. Milling and inlay using PFC mix has been recommended by the Oregon DOT to repair PFC when the quantities of material are enough to justify this activity. If only a small quantity is needed, a dense-graded conventional asphalt mix is suggested for such patch repairs (*66*). The FHWA advises to consider the drainage continuity of the PFC when undertaking patch repairs (*9*). When the patched area is small and the flow of water around the patch can be ensured, use of dense-graded asphalt mix can be considered. Rotation of the patch to 45 degrees to provide a diamond shape is recommended because it will facilitate the flow of water along the dense mix patch and also will diminish wheel impact on the patch joint (*3*). In Britain, patch repairs are recommended with PFC material only both for small and large potholes. Patching with dense-graded mix is limited to sizes 1.64 ft by 1.64 ft (*35*). If a dense mix is used in urgency it must be replaced with PFC mix later (*68*).

When patch repairs are made with PFC material, only a light tack coat (preferably emulsion) should be applied to the vertical faces of the existing pavement. Heavy tack coats will impede the flow of water through the patch.

The PFC pavement also can develop transverse and longitudinal cracks while in service. Narrow cracks are usually not visible on the PFC surface because of its very open texture. When cracks appear on the PFC surface they need to be sealed. There is no problem in sealing the transverse cracks because the crack sealer will not impede the flow of water within the PFC, which takes place in a transverse direction (*69*).

Sealing longitudinal cracks in PFC is problematic because the crack sealer could impede the transverse flow of water within the PFC. One potential solution, although expensive, is to mill off the PFC in a narrow strip right over the longitudinal crack and place an inlay with PFC material. If the longitudinal crack also is present in the underlying course, it must be sealed properly. Only a light tack coat should be applied to the vertical faces of the existing pavement. The other option is to rehabilitate the pavement if the severity of the crack becomes too high (*69*).

Winter Maintenance

The intent of this chapter was to provide the state of practice on maintenance, with this section specifically dealing with winter maintenance. However, after evaluating all of the information from the literature review and survey, it became obvious that each agency appears to have different thoughts on proper winter maintenance of PFC surfaces. This statement is backed up by statements from three different authors from three different countries. Padmos (*51*) stated there is no definitive solution for winter maintenance of PFCs. Greib (*24*) stated that since the behavior of the road salts on different PFC surface is so different, special locally adjusted strategies are needed. Brousseaud et al. (*28*) stated experience is the only true method of developing a winter maintenance program. Therefore, this section presents the experiences with winter maintenance of PFCs found in the literature.

Winter maintenance (snow and ice control) often has been cited and assumed to be a serious problem with PFCs (*4*). Isenring et al. (*15*) listed some advantages and disadvantages of PFCs during winter conditions. Some advantages of PFC during winter conditions include: 1) ice does not generally form on wet PFC surfaces mixes; 2) the high level of macrotexture is beneficial when snow and slush exist; and 3) the tendency for ice formation within wheelpaths covered in snow is reduced due to the macrotexture, permeability, and limited thaw. Disadvantages of PFC in winter conditions listed by Isenring et al. (*15*) include: 1) the need for deicing salts and other products; 2) the use of sand and small aggregates to improve frictional properties is not a viable option because these materials clog the void structure of PFCs; 3) snow and ice tend to stick to PFC layers sooner because the surface is generally cooler by about 1°F (0.5°C) than dense-graded mixes; 4) snow and icing rain can form earlier on PFC because deicing salts do not remain on the pavement surface; 5) preventative salting is not as beneficial because the salt penetrates into the void structure; 6) if the PFC's permeability is reduced, ice can build up within the layer and expand onto the pavement surface; and 7) some icing problems can occur within the initial portion of a subsequent dense-graded surface because transportation of salt by traffic is reduced with the use of PFCs.

Lefebrve (*21*) describes three winter conditions that cause concern for PFC layers. The first is a freezing fog/hoar frost. This condition occurs at certain humidity temperature combinations and results in a very thin layer of ice on the pavement surface due to condensation and near freezing temperatures. Ketcham (*70*) defines the cause of hoar frost as dew or water vapor forming ice crystals in the form of scales, needles, feathers, or fans on surfaces when the temperature of the pavement is at or below freezing. Lefebrve (*21*) stated that both France and the Netherlands have shown PFC layers are generally 3.6 to 5.4°F (1 to 2°C) lower than dense-graded layers. He also stated that research in Austria indicated that PFC behaves differently at temperatures in the range of 23 to 32°F (-5 to 0°C) than dense-graded layers. Below this temperature range, PFCs act similar to dense-graded layers. The second condition listed by Lefebrve (*21*) was frozen wet surfaces. This condition consists of ice building up on the pavement surface due to rain falling on a frozen PFC layer. Finally, snow or sleet falling onto PFC layers is a concern.

There is evidence that PFC layers have different thermal properties than typical dense-graded layers. Huber (*7*) states that the heat conductivity of PFC layers is 40 to 70 percent that of dense-graded layers. As stated above, PFC layers during cold climates are generally cooler than nearby dense-graded layers. Research has indicated that PFC layers will be 3.6 to 5.4°F cooler than dense-graded layers (*7*). This means that the PFC layer can drop below freezing sooner, resulting in the formation of ice/frost when nearby dense-graded surfaces do not freeze. Also, PFC layers will stay frozen longer than dense-graded layers.

Iwata et al. (*20*) conducted an experiment in Japan to compare the temperature of PFCs and dense-graded surfaces during cold weather. During the daytime, the pavement surface of dense-graded layers was higher than nearby PFC by about 3.6°F (2°C). At nighttime, the road surface temperature was higher on PFC layers by about 1°F (0.5°C). During snowfalls, Iwata et al. (*20*) indicated that the temperature of PFCs was about 0.4°F (0.2°C) lower.

Iwata et al. (*20*) also conducted a qualitative evaluation of road surface conditions comparing PFC and dense-grade surfaces during winter events. Tables 34 and 35 present the results of these evaluations. The upper right part of each table represents the number of cases where the visual surface condition of PFC layers was considered to be worse than nearby dense-graded surfaces. The lower left portion of the table represent when the visual surface conditions were considered worse on comparison dense-graded surfaces.

Iwata et al. (*20*) highlighted two conditions from the tables. First was when the dense-graded layer was wet. In this situation, the snow falling onto the dense-graded surface was melting while on the PFC surface it was becoming slush. The second condition noted was when the dense-graded surfaces were covered with ice and the surface of the PFC was either wet, slush, or snow. This suggested that it was difficult for freezing of PFC surfaces.

Another experiment conducted by Iwata et al. (*20*) included monitoring the salinity concentration on the pavement surface using three different spreading methods: solution, solid, and wet salt. Data presented by the authors suggested that the rate of decrease in salinity concentration was generally less on PFC surfaces than for dense-graded.

Layers of PFC contain more interconnected voids than dense-graded mixes; therefore, the salt disappears into the void

Table 34. Road surface conditions during a snowfall (rutted sections) (*20*).

Rutted Sections		Porous Asphalt Pavement					
		dry	wet	slush	snow	ice	total
Dense-Graded Pavement	dry	33					33
	wet	1	297	23			321
	slush		14	96	2		112
	snow		10	2	88		100
	ice		10	3	3	23	39
	total	34	331	124	93	23	605

Table 35. Road surface conditions during a snowfall (non-rutted sections) (*20*).

Non-Rutted Sections		Porous Asphalt Pavement					
		dry	wet	slush	snow	ice	total
Dense-Graded Pavement	dry	34					34
	wet	2	247	29	4		282
	slush		13	114	8	3	138
	snow		1	11	109	2	123
	ice		4	5	1	18	28
	total	36	265	159	122	23	605

structure. This leads to an increased need for salt. Greibe (*24*) reports a 25 to 100 percent increase in salt consumption. The pumping action caused by traffic passing over PFC will continually circulate the salt solution within the void structure of the layer. This may explain the observations of Iwata et al. (*20*) when they observed a lower rate of decrease in salinity for PFC surfaces when compared to dense-graded. As long as the traffic volume remains high, drivers should not notice any difference between PFC and dense-graded surfaces. The influence of traffic volume on winter performance also was noted by Bennert and Cooley (*71*). They showed a clear influence of traffic volume on surface friction in two separate winter storm events. When evaluating surface friction on both the passing lane and travel lane during snow events, skid numbers for the travel (design) lane were maintained at a higher level. Also, Padmos (*51*) stated that in the Netherlands, all lanes are closed except for the design lane during severe winter events.

Similar to Bennert and Cooley (*71*), Iwata et al. (*20*) showed higher skid numbers for PFC than dense-graded surfaces using a locked wheel skid tester. One exception to this observation was when PFC layers were covered with compacted snow. In this instance, skid numbers were similar for both wearing surfaces. This indicated that the PFC maintained equal or higher friction coefficients than dense-graded surfaces during snow events.

Litzka (*49*) provided an overview of the evolution in winter maintenance of PFCs in Austria as well as a summary of a summit held in 1999 on European winter maintenance practices. Because of their open nature, PFC surfaces are about 1.8°F (1°C) cooler when compared to dense-graded surfaces. Therefore, PFCs remain at a colder temperature longer and reach freezing temperatures earlier than dense-graded surfaces. Because of the extended time at freezing temperatures, the consumption of deicing materials is higher. During slushy conditions, Litzka (*49*) indicates that the performance of PFCs is slightly poorer than dense-graded surfaces. Snowplows tend to push the slushy material into the void structure of PFC layers. Freezing temperatures cause the slushy material to swell, such that the slushy materials become a road hazard. To prevent the slushy material from swelling, salting of the roadway must be conducted immediately after the snowplows pass. In Austria, this is in contrast to dense-graded layers. The extra placement of salt results in the increased usage of deicing materials.

An Austrian survey described by Litzka (*49*) indicated that preventative application of anti-icing materials may delay or prevent icing. However, on PFCs, immediate and continuing applications of anti-icing materials are required. When road salt is applied to PFC too late or the anti-icing materials are ineffective, the removal of the resulting ice layer is much more difficult on PFC layers than dense-graded.

Litzka (*49*) summarized that PFC layers will require 25 to 50 percent more deicing agents. Winter maintenance crews must be able to respond quickly and flexibly to different weather and road conditions. Weather forecasting and electronic monitoring systems are very helpful in this quest.

Litzka (*49*) also documented a 1999 International Exchange of Experiences held in Austria that brought together experts from throughout Europe to discuss issues with PFC layers. In Germany, winter maintenance of PFC is generally considered more expensive and slightly more difficult than dense-graded surfaces. The standard quantity of salt applied to PFC surfaces is 0.02 lb per sq yd (10 gr per sq m); however, within problem areas the required quantity of salt may reach 0.07 lb per sq yd (40 gr per sq m). The availability of weather forecasting systems helps facilitate timely response to winter maintenance activities. In Italy, salt is generally applied to wet pavements in quantities of 0.02 to 0.04 lb per sq yd as a preventative maintenance technique. During snowfalls, the dry rodded salt is again applied at the same rate. After snowplows have removed the snow, another 0.02 to 0.06 lb per sq yd of road salt is applied, depending upon the road conditions. Litzka (*49*) noted that Italy stated that a change from a 20 mm maximum aggregate size PFC to a 16 mm maximum aggregate size PFC had led to a significant improvement in road conditions during winter conditions. In the Netherlands, road salt consumption increased by about 25 percent when

Table 36. Forms in which salts are used in Europe and Japan (*21*).

	Austria	Belgium	Denmark	France	Germany	Italy	Japan	Netherlands	Sweden	Switzerland	United Kingdom
Solid NaCl	VC	VC	VC	VC	VC	VC	VC	VC	VC	VC	VC
NaCl brine	RE			RE		RE	VC		RE		
$CaCl_2$ flakes		VC		RE	RE	VC	VC			LC	
$CaCl_2$ brine		RE				VC	VC				
Solid mixture NaCl/$CaCl_2$	LC			LC		RE				VC	
Wet salt method NaCl + $CaCl_2$ solution	VC	RE		LC	VC	RE		VC		LC	RE
Wet salt method NaCl + NaCl solution	LC		VC					LC	VC	RE	RE

VC = very commonly used
LC = less commonly used
RE = rather exceptionally used
Blank = never used

using PFCs. In very severe winter conditions, speed limits or road closures had been employed. In Slovenia, salt consumption is up to 100 percent higher for PFCs. Finally, Litzka (*49*) reported that salt usage in Austria was about 25 percent higher for PFCs. Best results occur when using a wet salt application (salt/brine ratio of 2:1).

Lefebvre (*21*) provided typical chemicals used as deicing materials in Europe and Japan. Table 36 presented the typical materials and Tables 37 through 39 provide typical dosage rates. Van Doorn (*72*) did warn that too much dry deicing salt placed on a PFC surface during dry conditions can lead to slipperiness. Also, when the temperature is below -26°F (-15°C), the rock salt can freeze. In these instances, calcium chloride can be sprayed onto the pavement surface.

Giuliani (*73*) reported on the use of anti-icing techniques on PFCs in Italy. Anti-icing techniques were defined as those operations necessary to avoid the formation and development of bonded snow or ice on the pavement surface. Anti-icing differs from deicing as deicing is the process of weakening or destroying the bond between snow or ice and the pavement. Giuliani (*73*) states that PFC makes anti-icing operations difficult and expensive. The porous structure of PFCs allows the saline substances to drain from the surface. Therefore, approximately 30 percent more anti-icing materials are needed compared to dense-graded layers. With respect to traffic safety, late application of anti-icing techniques can lead to safety issues. When winter precipitation occurs without anti-icing operations, tires cannot achieve sufficient traction because the void structure becomes clogged with fresh snow. The snow is compacted by passing vehicles forming an ice layer within the pavement layer. Because of the potential problems, Giuliani developed a system of heating elements to be placed under a PFC layer that would maintain the temperature of a PFC layer at about freezing.

Bennert et al. (*12*) reported on experiences with winter maintenance on PFC mixes in New Jersey. They mention that the New Jersey DOT uses rock salt for deicing, whereas the New Jersey Garden State Parkway (NJGSP) uses liquid magnesium chloride. The New Jersey DOT has found that PFC layers are more difficult to maintain ice-free than nearby dense-grade

Table 37. Average spreading rates for solid NaCl (g/m^2) (*21*).

Country	Normal Treatment	Preventive Treatment
Germany	10-20	
	20-30	-
Belgium	20-30	7-20
Denmark	>10	5-10
France	20-30	10-15
Italy	15-30	10-15
Japan	<100	>10
Netherlands	5-20	-
United Kingdom	20-40	10-20
Sweden	20	5-10
Switzerland	15-20	10-15

Table 38. Average spreading rates for $CaCl_2$ flakes (g/m^2) (*21*).

Country	Normal Treatment	Preventive Treatment
Belgium	20-30	7-20
France	20-30	-
Italy	10-20	5-10
Japan	10-50	10-50
Switzerland	15-40	15-30

Table 39. Average spreading rates for wet salt (g/m^2) (*21*).

Country	Normal Treatment	Preventive Treatment
Germany	10-30	10-15
Austria	-	10
Belgium	20-30	7-20
Denmark	>10	5-10
France	-	10-15
Netherlands	5-20	5-7
Sweden	15	5
Switzerland	-	5-15

layers. The NJGSP, on the other hand, has had good success with liquid magnesium chloride although PFC requires twice the amount. Also, the NJGSP continually monitors forecasts of temperature and measures pavement surface temperatures. The NJGSP pre-treats PFC surfaces with liquid magnesium chloride to avoid icing. By pre-treating, the NJGSP has found the PFC surfaces manageable and can be lowed the same as dense-graded mixes.

CHAPTER 9

Rehabilitation of Permeable Friction Courses

Van Der Zwan et al. (*17*) state that minor rehabilitation strategies are similar to conventional dense-graded layers; however, they also state that the inherent drainage characteristics of the porous asphalt should be maintained and that the preferred method of rehabilitating porous asphalt layers is to mill the existing layer and replace with a new wearing layer. Lefebvre (*21*) indicates that a distinction needs to be made between minor and major rehabilitation of PFC layers. According to Lefebvre (*21*) minor rehabilitation entails small local repairs necessary because of small damage or distress while the rest of the pavement layer is in good condition. These circumstances were covered in Chapter 8, Corrective Surface Maintenance. Major rehabilitation is conducted when the entire layer is in need of repair. Major rehabilitation techniques include replacement of the entire layer or refurbishment of the entire layer. Replacement of the PFC would include completely removing the layer and replacing with a new layer. Refurbishment of the layer would include in-situ recycling. Though largely unsuccessful, it was noted that the Netherlands have been using hot in-place recycling to rehabilitate PFC (*21*).

Pucher et al. (*68*) state that as of 1997, very little, if any, recycling of porous asphalt had occurred in Europe. However, they indicate that both cold-mix and hot-mix recycling are options for PFC layers. Cold-mix recycling would be a process where the reclaimed PFC would be combined with new asphalt and/or recycling agents to produce cold base mixtures. In contrast, hot-mix recycling would be the process of taking reclaimed PFC and combining with new materials through a hot-mix production facility. According to a European point of view, hot-mix recycling would be the highest level of value. Due to expected large amounts of PFC planned by the Dutch, they are placing an emphasis on recycling PFC, both in-plant and in-place.

The web-based survey conducted as a part of this research project indicated that the average service of life of PFC pavements was between 8 and 10 years. Regardless of the life expectancy, at some point the PFCs will have to be rehabilitated (*24*). Rogge (*66*) states that there are three methods for PFC rehabilitation: mill and inlay, in-place recycling or repaving, and overlays. In the same light, Brousseaud et al. (*28*) mentioned three rehabilitation techniques used in France: replacement with a new PFC, overlaying (with or without seal coat), and recycling in-place or in a plant. According to Rogge (*66*), mill and inlay only occurs when Oregon's F-mix is placed on the shoulders. From the survey, when a PFC has reached the end of its functional life or when problems arose that called for rehabilitation, without exception, states milled and replaced the pavement with a new surface. Most agencies will remove the PFC by milling it off and replacing it with another PFC layer. Kandhal (*4*) states that it is generally recommended to mill off the existing OGFC and replace with a new OGFC or other type HMA. The Georgia DOT did express concern in the survey with placing PFC on milled surfaces. Through no explanation was given, it is assumed that the concern is about the grooves left in the underlying layer. These grooves may hold water. Within the responses to the survey, Georgia DOT indicated that they were investigating micro-milling. Winsatt and Scullion (*67*) reported major distresses on pavements which had overlays over the top of open-graded mixes.

Moore and Hicks (*47*) indicate two types of rehabilitation practices and Hicks for open-graded asphalt mixes: overlays and mill and fill. They mention that overlays are performed using open-graded or dense-graded mixes, and that mill and fill operation consists of milling off the open-graded mix and replacing with another open-graded mix. They mention that adequate care should be taken to ensure the new material placed as part of the mill and fill operation is able to drain completely. The authors mention that there are several considerations that need to be made for rehabilitation of pavements with open-graded asphalt mixes, and that the appropriate method of rehabilitation of such pavements is being researched. They indicate that a small number of such projects have been rehabilitated or have been marked for rehabilitation and that important considerations include inlay repairs prior to overlaying, changing the wearing surface mix type, and drainage issues with a middle layer of open graded asphalt. Moore and Hicks (*47*) mention that the European experience indicates a preference for mill and inlay with recycling and that this approach eliminates the challenges associated with overlays and PFC pavements. Overlaying the in-place layer with a dense-graded or open-graded mix or mill and inlay are further emphasized by Moore and Hicks (*47*). From a state perspective, Massachusetts Highway Department offers the following rehabilitation techniques: the most desired practice is to mill out the OGFC to a depth of 2-½ in. and replace it with 1-¾ in. of dense binder and ¾ in. of OGFC; the second option is to mill the OGFC to the top of the dense binder and replace it with ⅜ in. or less of surface treatment; and, the final option is to micro-mill the OGFC to the top of the dense binder (*36*).

Bishop and Oliver (*53*) cite references and experiences to contend that life expectancies for OGFC pavements in British Columbia are about 12 years, compared to 14 to 15 years for conventional pavements. They mention that while riding surfaces will not be obtained by using methods such as hot in-place recycling on existing OGFC mixes, it is possible to use another OGFC layer as a rehabilitation method, provided the existing OGFC is sealed properly. They also mention that it is important to rehabilitate the entire pavement, including the shoulders to make sure that adequate drainage is maintained (*53*).

CHAPTER 10

Performance of Permeable Friction Courses

Throughout the history of using open-graded mixes as wearing layers, there have been two predominant performance-related problems: raveling and delamination. These two problems led to moratoriums on the use of OGFCs by many state highway agencies during the 1980s (*7, 14*). These problems have been noted not only in the United States, but also in Europe (*17, 21, 51*). This chapter describes the performance of PFCs from around the world. The first section describes the distresses encountered with PFC layers, the second section describes the performance life of PFCs, and the final section discusses performance measures for PFCs.

Typical Distresses with PFC

The Long Term Pavement Performance Program (LTPP) has identified a number of distresses related to HMA layers (*74*). Within this document, distresses are categorized according to the following general distress types: cracking, patching/potholes, surface deformation, surface defects and miscellaneous distresses. Table 40 lists the distresses defined by LTPP within each of these categories.

Of the distresses listed in Table 40, only raveling has been reported as common to PFCs. Huber (*7*) states that OGFCs typically fail by raveling. Molenaar and Molenaar (*38*) have described two forms of raveling: short-term and long-term raveling. Short-term raveling is caused by intense shearing forces at the tire/pavement interface that occurs within newly placed PFCs. Pucher et al. (*68*) state that short-term raveling generally occurs quickly once the flow of traffic begins. Conditions that enhance the potential for short-term raveling include placing the PFC at too low of a temperature, incomplete seating of the aggregates during compaction and draindown (areas lean in asphalt binder). Long-term raveling was described by Molenaar and Molenaar (*38*) as being caused by long-term segregation of the asphalt binder from the aggregates due to gravity. As the asphalt binder drains from the coarse aggregate structure due to gravity, the aggregates near the surface of the layer are underasphalted. The action of traffic can dislodge the aggregates, resulting in raveling. It should be stated that the long-term draindown of the asphalt binder due to gravity was mostly encountered in PFC mixes that did not include modified asphalt binders.

Pucher et al. (*68*) state that up to a life of 5 to 10 years, PFCs deteriorate slowly. After this time, the rate of deterioration increases. Raveling is the distress most commonly observed due to this increase in degradation.

As stated above, delamination is the other distress most commonly associated with PFCs. Delamination of PFC layers could, however, be construed as potholes once the layer has been removed by traffic.

The raveling and delamination problems that have plagued OGFC mixes in the past can likely be traced back to mix design, specifically materials selection, and construction problems. Permeable friction courses have an open gradation with a relatively low percentage of material passing the No. 200 (0.075 mm) sieve. Because of the open grading, there is very little aggregate surface area which results in a relatively thick film of asphalt binder coating the aggregates. At typical HMA production/construction temperatures, the heavy film of asphalt binder had a propensity to drain from the aggregate skeleton (*7*). Because of the draindown issues, a typical remedy was to reduce either the asphalt binder content or the mixing and compaction temperatures during production/construction (*4*). Reduced asphalt binder contents meant that the OGFC mixes were underasphalted which would increase the potential for raveling. The reduction in temperature increased the viscosity of the asphalt binder which assisted in preventing the asphalt binder from draining from the aggregate skeleton. However, this reduction in temperature also led to the increased potential for raveling and delamination.

When production temperatures of the PFC are reduced, all of the internal moisture within the aggregates is not removed. Moisture remaining within the aggregates after plant mixing increases the potential for the asphalt binder stripping from

Table 40. LTPP defined distresses for HMA Pavements (*74*).

Cracking	Patching and Potholes	Surface Deformation	Surface Defects	Miscellaneous
Fatigue Block Edge Longitudinal Reflection Transverse	Patch Deterioration Potholes	Rutting Shoving	Bleeding Polished Agg. Raveling	Lane-to-shoulder drop-off Water Bleeding and Pumping

the aggregates leading to the aggregates being raveled out due to traffic (*7*). Reduced mixing temperatures also resulted in reduced compaction temperatures. Mixture delivered to the roadway that was not at an appropriate compaction temperature had difficulty bonding to the tack coat placed on the existing roadway surface. This resulted in an inadequate bond between the OGFC and underlying layer. The lack of an adequate bond increased the potential for delamination problems (*4*).

Evidence that raveling and delamination problems of the past were related to mix design and production/construction practices was provided by Kandhal and Mallick (*8*). Based upon a 1998 survey, they stated that highway agencies that had experienced good performance with OGFCs were utilizing polymer-modified asphalt binders and relatively high asphalt binder (by using fibers and/or relatively open gradations). The combination of modified asphalt binders and fibers helped hold the asphalt binder on the PFC's aggregate skeleton, minimizing the potential for draindown. Without the potential for draindown (and relatively high asphalt binder contents), there was no need to lower mixing and compaction temperatures which minimized the potential for both raveling and delamination.

Though raveling and delamination are the two most common distresses listed in the literature, other distresses have been mentioned. Rogge (*66*) conducted a survey of maintenance supervisors from the Oregon Department of Transportation (ODOT). One question within the survey concerned typical distresses encountered on PFC pavements. Figure 41 illustrates the typical distresses encountered in Oregon on PFC pavements as reported by 78 respondents to the survey. Within Figure 41, the maintenance engineers were requested to rank the various distresses by their frequency using a ranking system of 1 to 4. The higher the ranking, the more frequent the distress encountered. Based upon the survey, tire stud rutting was considered the most common distress. Raveling was the second highest rated distress (icing problems is considered a win-

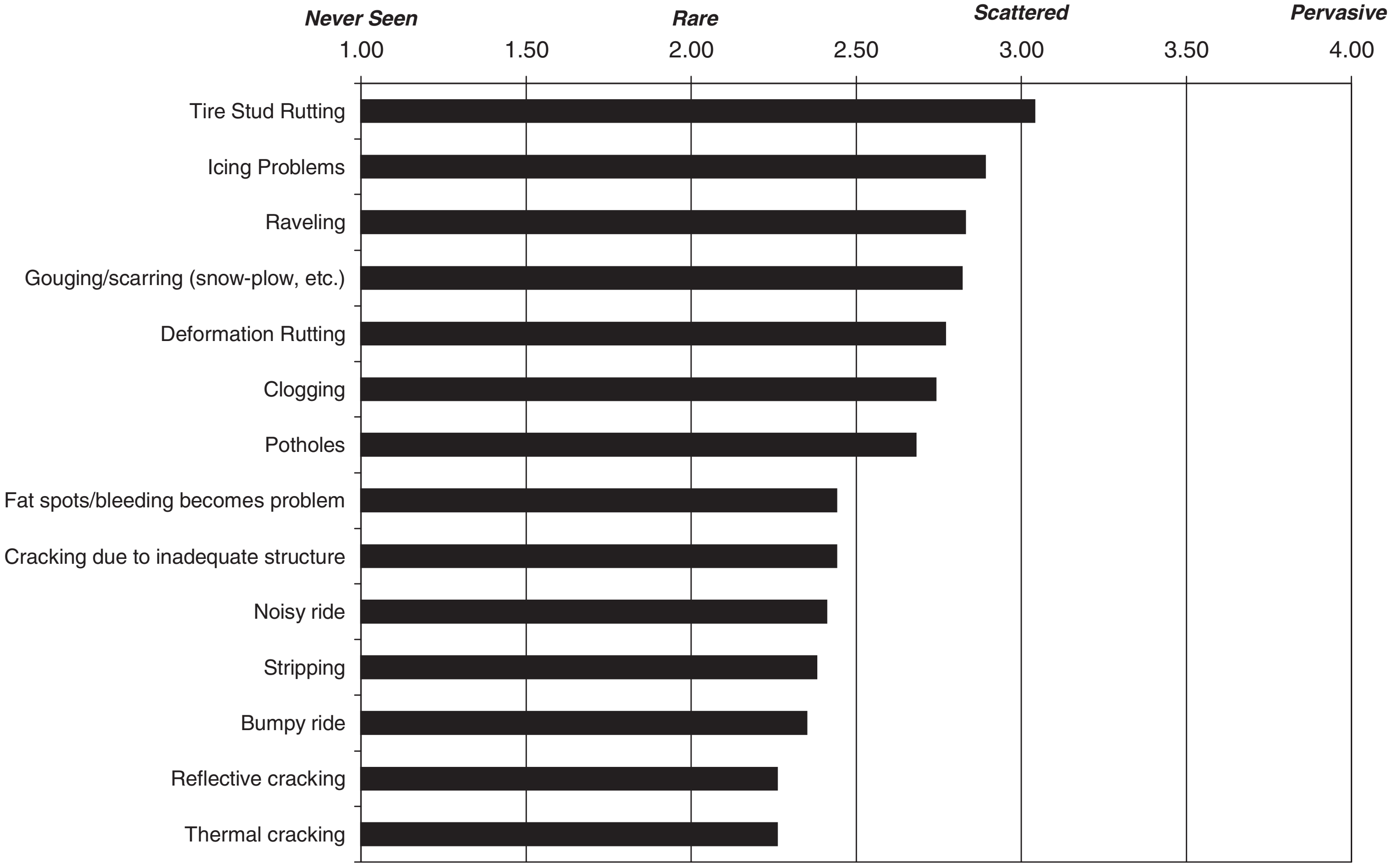


Figure 41. Results of 2001 survey of ODOT maintenance supervisors (66).

ter maintenance issue). Other distresses that rank closer to scattered than rare included gouging/scarring, deformation rutting, and potholes (clogging is considered a general maintenance issue).

Because of the environment in Oregon, the existence of tire-stud rutting is not unexpected. However, tire-stud rutting should not be considered the same as the traditional rutting seen on typical dense-graded HMA pavements (plastic deformation). Tire-stud rutting as described by Rogge (*66*) is likely raveling within the wheel paths. Studded tires can dislodge aggregate particles in the wheel path giving the appearance of classical rutting.

Rogge's report (*66*) was the only reference found in the literature that listed rutting as a distress on PFC pavements. Several papers/reports from Europe list resistance to permanent deformation as a benefit of PFC pavement layers (*5, 2*). Permeable friction courses should generally not be associated with plastic deformation rutting. Similar to SMAs, PFCs have a very coarse gradation that results in stone-on-stone contact (*40*). Because of the stone-on-stone contact, PFCs should not rut due to plastic deformation unless there are mix design or construction problems.

The only other distress found in the literature was not specifically related to OGFC/PFC mixtures; rather, it was the occurrence of stripping in layers underlying the OGFC/PFC surface. Huber (*7*) states that open-graded mixes can change the moisture balance within a pavement structure. PFCs or OGFCs can create a moist microenvironment at the surface of the underlying layer. When this exists, the increased humidity created by the moist microenvironment can retard evaporation of water from the underlying layer. This, in essence, traps water within the underlying layer. When PFCs become clogged, the underlying layer may even become wetter. Therefore, if the HMA mixture underlying the PFC layer contains materials susceptible to moisture, then stripping of the underlying layers may occur.

Performance of PFC

According to Huber (*7*), the performance of PFC (or OGFC) pavements in general can be put into one of two categories: performance life and service life. The category of performance life is used to describe the length of time an OGFC pavement maintains its beneficial characteristics. With respect to PFC pavements, these characteristics would include permeability (reduction in potential for hydroplaning and splash and spray and improvement in pavement marking visibility) and the ability to reduce tire/pavement noise. Service life describes the length of time that a PFC pavement maintains its frictional properties and smoothness. Structural failure of the PFC also would be included in service life.

Service Life

Of the two categories of performance, service life generally will be longer. Service life generally relates to the time that a PFC layer needs to be rehabilitated. The vast majority of reports/papers suggest that PFC pavement layers will have an average service life of about 10 years, though longer periods have been cited. A number of European countries, including the Netherlands (*17*), Switzerland (*21*), and Spain (*16*), indicate that the service life of PFC pavements is approximately 10 years. Similarly, Australia also has indicated 8 to 10 years of service life (*19*). In the United States, a survey of state highway agencies on OGFCs conducted in 1998 by Kandhal and Mallick (*8*) showed that 73 percent of the state agencies obtained an estimated average service life of greater than 8 years (Figure 42). Forty-three percent of the state agencies estimated an average service life of greater than 10 years. The majority of the agencies indicating an average service life greater than 10 years were utilizing OGFC mixes that would classify as PFCs.

No specific literature was found that presented a research approach that followed the frictional properties or smoothness of a PFC layer until the end of the service life. Survey results depicted in Figure 42 likely reflect more of an issue with smoothness than friction. Smoothness would be affected by raveling problems associated with PFC pavements and raveling was cited by the vast majority of papers/reports reviewed as the primary performance problem with OGFC layers. Additionally, delamination, which also has been labeled as a major problem with OGFC layers (*6*), also would negatively affect smoothness.

Figure 41 showed distresses observed in Oregon on OGFC pavement layers as well as the frequency in which those distresses are encountered (*66*). Based on this figure, most of the distresses that had a frequency closer to scattered than rare would affect smoothness. As tire-stud rutting, raveling, gouging/scarring, deformation rutting and potholes increase, smoothness would decrease.

As stated previously, Pucher et al. (*68*) indicated that up to 5 to 10 years, PFCs deteriorate slowly. After this time, the rate of deterioration increases. Raveling is the distress most commonly observed due to this increase in degradation.

Similar to smoothness, no specific literature was found that followed the frictional properties of a PFC pavement layer from construction till the end of the service life. The literature does suggest that the frictional characteristics of PFC layers are relatively low (but acceptable) immediately after construction (*10, 21, 51*). PFCs are intentionally designed to include a relatively high asphalt binder content. After production and placement, aggregates within the PFC layer will be coated with a thick film of asphalt binder. This thick film of asphalt binder prevents a vehicle tire from adhering to the aggregates

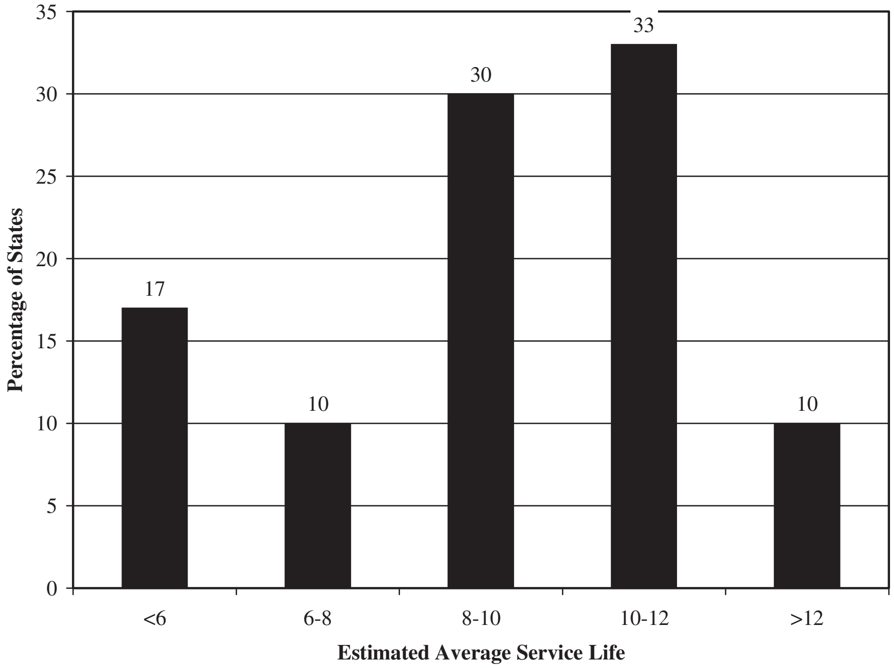


Figure 42. Reported estimated average service lives for OGFC layers (8).

(microtexture) at the surface of the layer (*51*). Greibe (*24*) stated that when the wheels lock during a braking action, the friction created between the tire and pavement surface begins to melt the asphalt binder coating the aggregates which hinders friction. This is only true when wheels are locked. When an anti-lock braking system is used, the baking distance on porous asphalt is similar to that of dense-graded HMA. Some literature indicates that it can take 3 to 6 months for the asphalt binder film to wear from the aggregates at the surface of the layer (*24, 51*). However, a research study in Georgia indicated that the asphalt binder layer wore off within 2 weeks (*10*). Table 41 illustrates the results of skid trailer friction testing conducted on six OGFC test sections over a 3.5 year time period just south of Atlanta, Georgia (*10*). All of the sections listed within Table 41, except the "Standard OGFC" section, are considered PFC sections. Within this table, the first friction tests were conducted the day after construction. These measurements were all relatively low compared to the subsequent test dates. The data clearly shows that once the asphalt binder film has worn from the aggregates, friction will increase.

There are two primary reasons for the good frictional properties of an PFC layer: permeability and macrotexture. Because of the high percentage of air voids associated with PFC layers, water will readily drain from the pavement surface into the interstitial voids of the PFC layer. Water that drains into the PFC layer is not available to be trapped between the vehicle tire and pavement surface in the form of water films, thus improving wet weather friction (*15, 19, 20*). Because of the open grading of PFC mixtures, these mix types result in a relatively high amount of macrotexture (*13, 19, 75*). Table 42 presents macrotexture measurements from a research study conducted in Indiana that compares the texture of a porous friction test section to other types of HMA. Results shown in Table 42, expressed as mean profile depth (MPD), were obtained using

Table 41. Average friction test results for six PFC test sections (*10*).

Test Section Designation	Friction Number (ASTM E274)			
	10/27/92	11/11/92	4/12/93	2/6/96
Std. OGFC (d)	42	53	52	50
Coarse OGFC (D)	41	50	52	51
D + Mineral Fibers (DM)	39	50	53	49
D + Cellulose Fibers (DC)	37	47	53	49
DC + SB Polymer (DCP)	35	46	52	50
D + SB Polymer (DP)	32	47	51	51
D + 16% Crum Rubber (D16R)	37	48	53	51

Table 42. Results of surface texture measurements using circular texture meter (*13*).

Mix Type	Mean Profile Depth, mm (Standard Deviation)
Porous Friction Course	1.37 (0.13)
Stone Matrix Asphalt	1.17 (0.14)
Dense-Graded HMA	0.30 (0.05)

a circular texture meter and show that porous friction courses have significantly more surface texture than dense-graded HMA layers and markedly more surface texture than SMA layers. McDaniel and Thornton (*13*) also used the results of friction testing with the dynamic friction tester to determine the IFI for the three mix types shown in Table 42. The IFI utilizes the results of friction measurements along with MPD data to provide a harmonized frictional characteristic measure independent of the equipment used. Results, shown in Table 43, indicate that the PFC had the highest IFI followed by the SMA and dense-graded HMA, respectively. These results show the significant influence of surface texture on the IFI.

Because of the significant amount of macrotexture produced within PFC pavement surfaces, PFC layers will maintain adequate frictional characteristics even after becoming clogged (*15*). The macrotexture will allow water films to be dissipated under tires during rain events.

Performance Life

Similar to smoothness and friction, no specific references were identified that followed the permeability and noise-reducing characteristics of PFC layers over time. Generally, the performance life will be shorter than the service life. This will especially be true in areas that do not employ a general maintenance program for cleaning flogged PFC layers. Isenring et al. (*15*) listed a number of causes for reduction in permeability within PFC layers. First, dust and debris can fill the void structure causing the layer to become clogged. Secondly, slight densification of the layer under traffic will reduce permeability from initial values. Other factors that can lead to reduced permeability include environment (amount of rain) and type of traffic volume. Isenring et al. (*15*) state that permeability will generally be maintained within wheelpaths. Wheelpaths will maintain permeability longer because of the cleaning pressure suction action caused by tires traveling over the layer. Van Heystraecten and Moraux (*22*) also reported that clogging potential is reduced with intense traffic. Isenring et al. (*15*) state that some PFC layers will maintain permeability for more than 5 years without maintenance while some will become almost impermeable within one year. As stated in Chapter 8, in order to maintain permeability through proper maintenance, maintenance should take place while the layer is still permeable (*15*).

Isenring et al. (*15*) listed a number of favorable conditions for maintaining permeability including: areas with reduced amounts of dirt and debris; good drainage (daylighted edge and sufficient cross slope in underlying layer); high air void contents within the PFC; and the cleaning action of rapid and intense traffic. Additionally, they stated that larger maximum aggregate size gradations maintained permeability longer than smaller maximum aggregate size gradations. Ruiz et al. (*16*) reported less clogging in PFC mixes having more than 20 percent air voids. British Columbia indicated that no clogging or reduction of permeability had been observed (*53*).

Isenring et al. (*15*) conducted a number of noise measurements to compare PFC and dense-grade surfaces. They evaluated sound absorption, tire/pavement noise (using a trailer) and wayside measurements. For sound absorption, their research showed that PFC layers that are in good functional condition (permeability has been maintained) are capable of absorbing sound. Layers of PFC thicker than 2 in. (50 mm) had the potential for absorbing more sound. Isenring et al. (*15*) also showed a relationship between permeability and sound absorption. As permeability increased, sound absorption also increased. However, the surface texture (macrotexture) seemed to be more important than permeability. Several pavements exhibiting low permeability values (clogged) still had the ability to absorb sound.

When measuring the tire/pavement noise, Isenring et al. (*15*) found that PFCs in good functional condition had lower noise levels than typical dense-graded layers. At speeds above 30 to 35 mph (50 to 60 km/hr) the difference between the two wearing layers became larger. Testing with the noise trailer also resulted in a relationship between permeability and noise levels. As permeability increased, noise levels generally decreased. Also, PFCs having a smaller maximum aggregate size generally resulted in lower noise levels than coarser gradations. McDaniel and Thornton (*13*) also used a noise trailer to show a 4 to 5 dB(A) reduction in noise levels when comparing PFC to SMA and dense-graded layers.

Table 43. IFI data (*13*).

Mix	Average Dynamic Friction Tester (DFT) Number (Standard Deviation)			International Friction Index
	20 kph	40 kph	60 kph	(F_{60})
PFC	0.51 (0.03)	0.45 (0.03)	0.42 (0.03)	0.36
SMA	0.37 (0.01)	0.31 (0.01)	0.29 (0.01)	0.28
HMA	0.52 (0.01)	0.47 (0.01)	0.44 (0.01)	0.19

Isenring et al. (*15*) also reported on wayside measurements. The evaluations were conducted where a comparison in noise levels between PFC and dense-graded layers could be made. For single vehicle cars, a level in noise reduction of between 1 and 5 dB(A) was observed when testing PFCs. Noise levels for a traffic stream showed reductions between 0 and 3.5 dB(A). Brousseaud et al. (*28*) used wayside measurements to show a 3 to 5 dB(A) reduction in noise levels when using the Statistical Pass-By Method.

The Danish government has an initiative to reduce the number of dwellings exposed to a noise level of 65 dB(A) by two-thirds (*31*). The two-layer PFC system was identified as potentially the most effective means of achieving this goal. According to Dutch experience (*31*), two-layer PFC systems have good noise-reducing characteristics compared to dense-graded layers. The reason for this is the structure of the system which contains a large number of interconnected voids. Tires rolling on the surface result in air pumping as the tire pushes air into the layer and then the air is sucked out as the tire passes. This pumping action generates a high-frequency noise. On PFCs, the pumping is reduced because the air is pumped into the interconnected voids of the layer.

Similar to the work of Isenring et al. (*15*), the Dutch state that PFC layers also reduce noise levels by absorbing some of the noise emitted by vehicles (*31*). On dense-graded layers, noise emitted towards the pavement is reflected to the surroundings; however, on PFC some of this noise is absorbed by the pavement through the interconnected void structure.

Huber (*7*) cited a number of references that indicated PFCs maintain their sound attenuation for five years or more as long as their design air voids are above 18 percent.

A number of references reported on how the noise-reducing ability of PFCs compared to dense-graded surfaces; however, how the noise levels were measured was not reported. British Columbia reported a reduction in noise levels of 5 dB(A) (*53*). Iwata et al. (*20*) reported a reduction of 3 dB(A). Kandhal (*4*) cited numerous references that also stated PFCs resulted in a 3 dB(A) reduction in noise levels when using PFCs. Graf and Simond (*29*) reported an average reduction of 6 dB(A) after installation of a PFC layer in Switzerland. Some limited work by Graf and Simond showed that PFCs maintained the ability to reduce noise levels for up to 9 years.

Performance Measures

The preceding sections on service life and performance life highlighted the various performance measures encountered in the literature. Three performance measures were mentioned more than others: noise levels, friction, and permeability. These three measures represent the reasons that PFC are a desirable HMA for pavement surfaces. The literature was explicit that PFCs improve wet weather friction and reduce noise levels. Improved wet weather friction can be directly related to the ability of PFCs to remove water from the pavement surface (permeability). Also, Isenring et al. (*15*) reported relationships between noise levels and permeability. Within Chapter 4, a number of benefits were discussed when utilizing PFCs. The vast majority of these benefits are directly related to permeability. Therefore, permeability is likely the most important performance measure for PFCs.

Several pieces of equipment for determining the permeability characteristics of PFC layers were described. Without exception, the various equipment utilized a falling-head concept. Isenring et al. (*15*) provided the most complete description of a permeability device utilized for PFCs called an IVT Permeameter. It was made of a plexiglass cylinder (or single standpipe) having air interior diameter of 7.5 in. (190 mm) and a height of 10 in. (250 mm). The plexiglass cylinder contained five engraved markings that were 0.8 in. (20 mm) apart with the “zero” marking being a height of 10 in. above the pavement surface. Special putty was used to seal the flow of water under the cylinder through the surface texture. An index of permeability is expressed as the amount of time required for water to travel between the “zero” mark and 3.2 in. (80 mm) mark. Isenring et al. (*15*) stated that this test is a single point estimator of permeability and that many locations should be conducted in order to adequately characterize the properties of the pavement.

CHAPTER 11

Limitations on the Use of Permeable Friction Courses

Probably the biggest deterrent for states to use PFC pavements is freezing weather. This probably is the primary reason that, with only a few exceptions, southern tier states are currently the predominant users of PFCs in the United States. It stands to reason that one limitation with the use of PFC pavements would be snow and ice. PFCs have lower thermal conductivity than dense-graded mixes which means that the temperature of the road surface drops below freezing sooner than dense asphalt and will stay below freezing longer than for dense-graded mixtures (*24*).

The primary concern becomes a winter maintenance issue, especially winter icing. Winter maintenance is different for porous pavements because of the

> . . . different temperature behavior for porous asphalt, and because of difficulty in maintaining a sufficient salt level at the level of contact between tire and pavement"(*49*).

Other authors have concluded that ice forms quicker on porous asphalt than a dense mix. Porous asphalt will contain moisture in its voids if the humidity level is high for a long period of time, allowing the porous asphalt to be more susceptible to freezing when the road is wet (*24*). Although not mentioned specifically, Bishop and Oliver caution against the use of OGFC mixes in areas that would not get early or close attention for winter maintenance because of their location or importance (*53*).

In their paper, Ruiz et al. (*16*) indicate that the use of porous asphalt mixtures should be studied carefully prior to being placed in the following four situations: areas of frequent snow, urban or industrial areas, areas with a high potential for reflective cracking, and bridge pavements. In his paper, Alderson identified intersections near quarries or farms as additional limitations where PFC pavements are not recommended (*19*). Quarries and farms would increase the potential for rapid clogging from debris.

Moore and Hicks (*47*) mention three conditions under which open-graded mix in Oregon is not recommended for use. These are: 1) low-volume roads with ADT of less than 1,000; 2) curbed areas or areas requiring handwork; and 3) heavily snow plowed areas where steel plow blades are used. For this level of traffic the technical benefits are not as noticeable due to the low volume of traffic and lack of heavy loads. Oregon's Class F mix is not recommended for use in areas with curbs or where a significant amount of handwork or feathering is required. The mix's aggregate size and aggregate gradation make handwork difficult around utility appurtenances and at driveways. Also, curbs block the drainage of the Class F mix. As a result of snowplow damage Oregon's Class F mix is no longer recommended in areas where plowing is frequent (*47, 48, 66*). The snowplows can cause raveling and gouging resulting in a higher rate of surface deterioration. The determination of frequency of plowing is on an individual project basis, but generally involves the elevation, any existing plow damage, and existing chain-up areas or snow zones (*47, 48*).

Though clogging is a major concern for PFC pavements, it is mentioned here as a limitation, but should be more of a maintenance issue with states rather than a deterrent or limitation for using PFC. Clogging is a concern mainly in the shoulder areas of the roadway because of the collection of debris. Other authors have suggested placing an impermeable surface dressing to mitigate these problems. Rogge and Hunt note that clogging occurs,

> . . . but clogged pavements still allows drainage through the pavement, whereas dense-graded pavements do not (*48*).

As pavement life proceeds, the clogging of the drainage structure from debris and fines leads to the reduction in the permeability of the surface over a period of time (*76, 77*). A clogged permeable layer will have reduced drainage and water storage capacity (*78*). Huber in his NCHRP synthesis paper (*7*) stated that significant clogging will reduce all of the benefits related to permeability. Huber also states that clogged PFC pavements also may accelerate moisture damage within underlying pavement layers. Huber states that the placement of PFC may create a moist microenvironment at the surface of the underlying layer (bottom of the PFC). The increased humidity caused by the moisture may retard the evaporation of moisture from the underlying layer resulting in moisture damage within the existing pavement. In their paper, Van Heystraeten and Moraux (*22*) stated that roads with a high potential for debris, such as near farming operations, should not include PFC because of the high potential for rapid clogging. They also stated that PFCs should not be used on low-volume, low-speed pavements because when traffic volumes or traffic speed is low, the self-cleaning attributes of PFC are negated. Self-cleaning occurs because of the pumping and suction of the tires of numerous fast-moving vehicles. The final location that Van Heystraeten and Moraux (*22*) recommended not using porous asphalt included areas subjected to very high shearing forces at the tire/pavement interface.

Although not labeled as limitations, two papers gave a list of disadvantages when using PFCs. Lefebvre (*21*) listed some disadvantages, stating that PFCs generally cost more than dense-graded layers as a result of requiring high-quality, polish-resistant aggregates and polymer-modified asphalt binders. Also, pavement markings have to be adapted for PFCs. Special impervious layers specifically placed below PFCs also increase construction costs. Another disadvantage of using PFCs is the relatively shorter economic life. Finally, Lefebvre (*21*) stated that maintenance is generally more expensive, especially winter maintenance. In another paper, Bolzan et al. (*26*) in their opening paragraph provide several disadvantages of using PFCs. They mention that these disadvantages include increased costs, relatively low structural strength due to its high void content, possibly shorter service life, complications to winter maintenance procedures, maintenance patching difficulties, susceptibility to high stress sites, and requirement of minimizing the drainage path length to allow water passing through the layer to enter the drainage system (*26*).

Kandhal (*4*) provides a number of situations where PFC should not be used. PFCs should not be used on projects that include long-haul distances. Long-haul distances increase the potential for draindown and/or cooling of the mix. Oregon restricts haul distance to 35 miles (56 km). PFCs should be free draining at the pavement edge and should not be used as an inlay. Handwork is difficult with PFC mixes, so projects that include a lot of handwork should probably not include PFC. Kandhal (*4*) noted that PFC should not be used in snow zones where extensive snow plowing is required. PFCs may ravel and shove in some critical pavement locations such as intersections, locations with heavy turning movements, ramp terminals, curbed sections, and other adverse geometric locations. The final limitation noted by Kandhal (*4*) has to do with underlying layers. PFCs should not be placed on a permeable layer, as water can infiltrate a permeable underlying layer causing moisture damage.

The Massachusetts Highway Department recognizes the following limitations of open-grade mixes:

1. They can be prone to premature raveling and weathering due to oxidation and hardening of the binder.
2. Application of thermoplastic paint markings can heat up the pavement surface and cause localized draindown of the binder material from the aggregate. This can lead to delamination and /or raveling of the mix under the thermoplastic line markings.
3. Snow plows can strike off raised markers and bounce along the surface causing a “chatter” or plow marks in the surface of the layer.
4. Primary causes for failure were raveling and delamination (*62*).

Though these conclusions were drawn by the pavement management section of the Massachusetts Department of Highways in February 2001, it is not clear whether the experiences were related to older OGFC pavements rather than the new generation PFC mixtures. Definitely raveling and delamination was an issue with the older OGFC pavements. The open structure of PFC mixtures exposes the surface to the effects of air and water, thus leading to rapid aging of the binder which in turn can lead to particle loss and adhesive failure (*77*). However, these drawbacks have been vastly improved with the use of polymer-modified binders and fibers.

Rogge and Hunt (*48*) also concluded that the main physical/mechanical distress in PFC is raveling or particle loss. However, they concluded the problem results from cold mix, low compaction, or segregation from the binder at the time of construction.

After construction, PFC contains a lower friction value when braking with locked wheels. When the wheels lock, they begin to melt a thin layer of binder on the pavement surface, which creates a slippery surface. This is only true when the wheels are locked. When the ABS braking system is used, the braking distance on porous asphalt is similar to that of dense-graded hot mix asphalt, maybe even shorter. This layer of binder is worn off after approximately 3-6 months (*24*).

Bolzan et al. (*26*) mentioned the increased costs as a limitation for use of PFC pavements. Until states realize the benefits of PFC pavements over conventional dense-graded pavements, costs will be a deterrent. It is felt that costs should not be considered a limitation. States use costs as a deterrent for using new-generation products as there are never funds available to accomplish the needs before them. As environmental issues (such as noise reduction in pavements) are moved to the forefront, PFCs will be given greater attention for use. When this occurs, the biggest challenge the states will face is the necessary maintenance required when PFC pavements are used.

CHAPTER 12

Future Research Needs

Based upon the literature review and survey of agencies, it is obvious that the use of PFC layers provides a safe riding surface for the traveling public. Benefits related to PFCs include: reduced potential for hydroplaning, reduced splash/spray, improved wet weather frictional properties, improved visibility of pavement markings, reduced glare, smooth riding layers, and resistance to permanent deformation. Because of these benefits, PFCs should be considered as a viable option on any high-speed, high-traffic volume roadway. However, there are some areas that need to be further researched. Following are areas deemed needing further research:

1. As discussed within the section on winter maintenance, there are really no consistent guidelines for winter maintenance of PFC layers. Research is needed to evaluate the effectiveness of various winter maintenance techniques. Included within this research should be comparisons between different winter maintenance chemicals and application rates on existing PFC layers. These evaluations of chemicals and rates should be conducted for various winter conditions. The literature seemed to indicate different problems encountered for different winter conditions. Winter conditions that should be evaluated include hoar frosts, light snowfalls, heavy snowfalls, sleet, freezing rain, slush, etc. Consideration of snowplow operations also could be included. The research should not be limited to northern tier states as hoar frosts also are considered a concern in southern tier states.
2. One of the methods for maintaining the beneficial characteristics of PFCs is to conduct general maintenance, specifically cleaning dirt and debris from the PFC layer. General maintenance of this type many extend the performance life of PFC layers. Within the United States, these general maintenance activities have not been practiced. Research is needed to identify an effective method(s) for cleaning PFC layers that are not cost prohibitive. The selected method(s) must efficiently clean PFC layers while not damaging the PFC. Also included within this research would be documenting how the cleaning activities influence the beneficial characteristics of PFC layers. Test pavements should be identified and several techniques of cleaning evaluated. A measure of permeability should be used as the performance measure to define the effectiveness of each cleaning technique. Noise levels, wet weather, friction and permeability should be conducted during the life of the pavement to determine the effectiveness of this general maintenance activity in maintaining the beneficial attributes.
3. A need for evaluating PFC layers is a standard piece of equipment and test method for estimating permeability. As described in the previous chapter, permeability was identified as the most important performance measure for PFCs. Research is needed to develop/select a piece of equipment and test method to evaluate permeability.
4. As a potential surrogate to a permeameter, equipment that measures the amount and density of splash and spray may be warranted. A device of this nature would likely indicate when PFCs have become clogged and provide a trigger for when general maintenance is needed. A device of this nature should be vehicle mounted with its own source of water. A very important benefit of equipment of this nature would be that testing could be conducted near highway speeds and negate the need for fixed traffic control. To the authors' knowledge there is no such piece of equipment. Therefore, research activities would involve development, evaluation and standardization.
5. Within Volume II of this report, a mix design practice was proposed. This mix design method should be field validated. Research should be conducted to validate the procedure in the laboratory and field. Laboratory validation would entail identifying a range of materials having a range of physical properties and determining whether the method can successfully proportion the materials to meet the mix design specifications. Field validation would entail determining whether the designed PFC mixes can be successfully

produced and placed. Performance of the constructed test sections should be monitored over time.

6. A potential need within the mix design method is another method for measuring moisture sensitivity. Past moisture susceptibility tests, namely tensile strength ratios, have been conducted using Marshall compacted samples. It is unclear how the Superpave gyratory compactor will affect tensile strength measurements on PFC mixes. Other tests also have been specified in Europe. Moisture conditioning of Cantabro Abrasion loss samples may prove successful. Research should be conducted to determine the best method for evaluating moisture resistance of PFCs. Materials of known moisture performance should be used in this research.
7. Three issues related to the inclusion of PFCs in pavement design need to be researched. First, a method for selecting minimum lift thickness was proposed. This method should be validated. Validation should include field work to document how water flows within a PFC layer. Findings from this research can be used to refine the selection procedure to prevent water sheets on the PFC surface. Also included in the research should be determination of a representative value for permeability. This research would entail designing various PFC mixtures and determining the level of permeability. These values can be validated by permeability testing of constructed PFC layers.
8. A practical problem related to minimum lift thickness that needs to be researched is determination of a minimum lift thickness to maximum aggregate size ratio (t/mas). Within this document, a minimum ratio of 2 was approximated; however, no references were found to substantiate this value. A minimum t/mas should be selected based on construction issues. A proper t/mas will allow the PFC to be placed and compacted using typical construction procedures while maintaining an appropriate level of permeability. Another element that should be included within this research is the influence of lift thickness on the ability of the PFC layer to maintain permeability. Some references indicated that thicker layers of PFC had better self-cleaning characteristics.
9. The final research need related to structural design is to determine how to account for PFCs in structural capacity. There are several aspects that need to be investigated. First is the proper method to characterize the properties of PFC for use in the Mechanistic-Empirical pavement Design Guide. Currently, HMA is characterized using the dynamic modulus test. However, research is needed to determine the needed input values for PFCs. One reference showed confined testing was appropriate for PFCs; however, no recommendations were provided for the correct confining pressure. Research should be conducted to determine if the dynamic modulus test is the appropriate test and the proper test conditions if it is the appropriate test. The second issue related to structural design is the reduced temperatures in layers underlying PFCs. Current temperatures with pavement depth models do not account for the increased stiffness of underlying layers and, hence, increased structural capacity. Accounting for the increased capacity of underlying layers may improve the cost-benefit of using PFCs, especially combined with all of the other safety benefits realized when utilizing PFC layers.

CHAPTER 13

Conclusions

The objective of this project was to recommend design, construction, and maintenance guidelines that will maximize the advantages and minimize the disadvantages associated with PFC use. Within this project, PFCs have been defined as specialty type open-graded friction courses that are specifically designed to have high air void contents, above 18 percent, for removing water from the pavement surface. In order to accomplish the project objectives, a literature review and survey of agencies was conducted. No field or laboratory research was conducted. Following are conclusions based on the findings of this research:

- The use of PFC layers has many benefits that can be categorized as related to safety, driver comfort, and environmental. Benefits related to improved safety included reduced potential for hydroplaning, improved wet weather friction, reduced splash/spray, reduced glare, and improved visibility of pavement markings. Benefits related to improved driver comfort include smooth pavements, increased confidence of drivers during rain events through the reduced potential for hydroplaning, reduced splash and spray and reduced glare, and reduced potential for permanent deformation. Benefits related to the environment include smoother pavements, thus improved fuel economy, and reduced pavement noise levels.
- The design of PFC mixes contains four primary steps: 1) selection of appropriate materials; 2) selection of a design gradation; 3) selection of optimum asphalt binder content; and 4) performance testing. The literature indicated that angular aggregates having the proper shape are desirable within PFCs. Stiff, modified binders have provided the best performance. Optimum asphalt binder content should be selected based upon balancing durability and draindown potential. The Cantabro Abrasion loss test is the most common test method for evaluating the durability of PFC mixes. Use of the voids in coarse aggregate concept for ensuring stone-on-stone contact should be included within the design of PFC mixes. Fibers are the most efficient method for minimizing the potential for draindown problems.
- Inclusion of PFC within the structural capacity of pavements varies greatly. Some agencies do not account for any structural capacity for PFC layers while others assign some percentage of structural capacity of dense-graded layer. When characterizing PFC mixes for inclusion of the new Mechanistic-Empirical Pavement Design Guide using the dynamic modulus test, a confinement pressure is needed. Two parameters are important in selecting an appropriate lift thickness for PFCs: rain intensity and PFC permeability.
- Construction of PFC mixes is similar to typical dense-graded HMA with some slight modification. The primary modification is the need for addition of fibers to the production process, if used. Mixing times should be slightly longer than typical mixes to ensure that the stabilizing additives are sufficiently dispersed within the mix. The mix should be protected from cooling during transportation. At a minimum, tarps should be used to minimize the amount of cooling that takes place during transportation. Material transfer vehicles that remix the PFC before being deposited into the paver are desirable. Conventional steel wheel rollers should be used to compact the PFC. Vibratory rollers should be discouraged as these rollers have the potential to fracture aggregates during compaction. Pneumatic tire rollers should not be used on PFC layers. Pneumatic tire rollers tend to pick-up mix during compaction. Typically, two to four passes of a breakdown roller and one to two rolls of a finish roller are sufficient to compact PFC layers. The goal of compaction is not to achieve a certain density; rather, the goal is to seat the aggregates. Roll-down of PFC is about 10 to 20 percent of the lift thickness.
- Cleaning of clogged PFC layers is not a common practice within the Untied States. General maintenance activities usually include small patches in localized areas. When

dense-graded mix is used for small patches, the patch should be rotated 45 degrees so that water can flow around the patch. No evidence was found that fog seals are an effective maintenance technique. Winter maintenance activities vary greatly around the United States and the world. Several references were found that indicated that experience was the best method for developing a winter maintenance program. The literature was explicit in stating that winter maintenance of PFC layers is more difficult than for dense-graded layers. PFCs are generally colder than dense-graded layers, indicating that PFC layers reach freezing sooner than dense-graded layers and stay at freezing temperatures longer. As such, more winter maintenance chemicals are needed for PFCs. When snowplows are employed, rubber-tipped blades have decreased the amount of damage to PFC layers.

- The most common rehabilitation method for PFC layers is to mill and replace. There is evidence that overlays should not be placed over PFC layers without sufficiently sealing the PFC layer. Overlays of unsealed PFC layers have shown the propensity for moisture damage within the pavement structure.
- There are few specific limitations on the use of PFCs. These mixes should not be utilized in areas with large amounts of dirt and debris. This will lead to the PFC layers clogging. PFCs should not be used in areas with high yearly snow fall rates. Winter maintenance can be expensive in these areas and snowplows have been shown to damage PFC layers. PFCs should not be used when long haul distances or haul times are needed. This will allow the PFC to cool during transportation and likely cause construction problems.

References

1. Cher, C., E. O. Darko, and T. N. Richardson. Optimal Continuous Shoulder Rumble Strips and the Effects on Highway Safety and the Economy. *Institute of Transportation Engineers Journal,* Volume 73, No. 5, 2003, pp. 30–41.
2. Harwood, D. W. *NCHRP Synthesis of Highway Practice 191: Use of Rumble Strips to Enhance Safety.* TRB, National Research Council, Washington, D.C., 1993.
3. *Open-Graded Friction Course Usage Guide.* California Department of Transportation Division of Engineering Services. Materials Engineering and Testing Services MS#5. Sacramento, California. February 2006.
4. Kandhal, P. S. "Design, Construction and Maintenance of Open-Graded Asphalt Friction Courses." National Asphalt Pavement Association Information Series 115. May 2002.
5. *NCHRP Synthesis of Highway Practice 49: Open-Graded Friction Courses for Highways.* TRB, National Research Council, Washington, D.C., 1978.
6. *Open-Graded Friction Course FHWA Mix Design Method.* Technical Advisory T 5040.31. Federal Highway Administration, Department of Transportation, Washington, D.C., 1980.
7. Huber, G. *NCHRP Synthesis of Highway Practice 284: Performance Survey on Open-Graded Friction Course Mixes.* TRB, National Research Council, Washington, D.C., 2000.
8. Kandhal, P. S. and R. B. Mallick. *Transportation Research Circular E-C005: Open Graded Asphalt Friction Course: State of Practice.* TRB, National Research Council, Washington, D.C., 1998.
9. *Open-Graded Friction Course FHWA Mix Design Method.* Technical Advisory T 5040.31. Federal Highway Administration, Department of Transportation, Washington, D.C, 1990.
10. Santha, L. *A Comparison of Modified Open-Graded Friction Courses to Standard Open-Graded Friction Course.* FHWA-GA-97-9110. Georgia Department of Transportation, Forest Park, Georgia, April 1997.
11. Watson, Donald, Andrew Johnson and David Jared. Georgia Department of Transportation's Progress in Open-Graded Friction Course Development. In *Transportation Research Record 1616,* TRB, National Research Council, Washington, D.C., 1998, pp. 30–35.
12. Bennert, Thomas, Frank Fee, Eileen Sheehy, Andris Jumikis and Robert Sauber. Comparison of Thin-Lift HMA Surface Course Mixes in New Jersey. TRB 2005 Annual Meeting (CD-ROM), TRB, National Research Council, Washington, D.C., 2005.
13. McDaniel, R. S. and William Thornton. Field Evaluation of a Porous Friction Course for Noise Control. TRB 2005 Annual Meeting (CD-ROM), TRB, National Research Council, Washington, D.C., 2005.
14. Cooper S. B., C. Abadie, and L. N. Mohammad. Evaluation of Open-Graded Friction Course Mixture. Louisiana Transportation Research Center Technical Assistance Report Number 04-1TA. October 2004.
15. Isenring, T., H. Köster, and I. Scazziga. Experiences with Porous Asphalt in Switzerland. In *Transportation Research Record 1265,* TRB, National Research Council, Washington, D.C., 1990, pp. 41–53.
16. Ruiz, A., R. Alberola, F. Pérez, and B. Sánchez. Porous Asphalt Mixtures in Spain. In *Transportation Research Record 1265,* TRB, National Research Council, Washington, D.C., 1990, pp. 87–94.
17. Van Der Zwan, J. T., T. Goeman, H. J. A. J. Gruis, J. H. Swart, and R. H. Oldenburger. Porous Asphalt Wearing Courses in the Netherlands : State of the Art Review. In *Transportation Research Record 1265,* TRB, National Research Council, Washington, D.C. 1990, pp. 95–110.
18. Decoene, Y. Contribution of Cellulose Fibers to the Performance of Porous Asphalts. In *Transportation Research Record 1265,* TRB, National Research Council, Washington, D.C., 1990, pp. 82–86.
19. Alderson, Allan. *The Design of Open Graded Asphalt.* Australian Asphalt Pavement Association, CR C5151, November 1996.
20. Iwata, H., T. Watanabe, and T. Saito. *Study on the Performance of Porous Asphalt Pavement on Winter Road Surface Conditions.* XIth International Winter Road Conference, World Road Association (PIARC), Sapporo, Japan, 2002.
21. Lefebvre, G. *Porous Asphalt.* Permanent International Association of Road Congresses, 1993.
22. Van Heystraeten, G. and C. Moraux. Ten Years' Experience of Porous Asphalt in Belgium. In *Transportation Research Record 1265,* TRB, National Research Council, Washington, D.C., 1990, pp. 34–40.
23. Titus-Glover, L. and S. D. Tayabji. Assessment of LTPP Friction Data. Report FHWA-RD-99-037. Federal Highway Administration. Department of Transportation, Washington, D.C., March 1999.
24. Greibe, A. P. Porous Asphalt and Safety. *Proceedings of the Ninth International Conference on Asphalt Pavements,* Copenhagen, Denmark, August 2002.
25. Flintsch, G. W. Assessment of the Performance of Several Roadway Mixes Under Rain, Snow, and Winter Maintenance Activities. Final Contract Report, VTRC-04-CR18, Virginia Transportation Research Council, Charlottesville, Virginia, 2004.
26. Bolzan, P. E., J. C. Nicholls, and G. A. Huber. Searching for Superior Performing Porous Asphalt Wearing Courses. TRB 2001 Annual Meeting (CD-ROM), TRB, National Research Council, Washington, D.C., 2001.
27. Brown, E. R., A. Cooley, D. Hanson, C. Lynn, B. Powell, B. Prowell, and D. Watson. "NCAT Test Track Design, Construction, and

Performance." National Transportation Symposium, National Center for Asphalt Technology, Auburn, Alabama. November 2002.

28. Brousseaud, Y. and F. Anfosso-Lédée. Silvia Project Report: Review of Existing Low Noise Pavement Solutions in France. SILVIA-LCPC-011-01-WP4-310505. Sustainable Road Surfaces for Traffic Noise Control, European Commission, May 2005.
29. Graf, B. and E. Simond. Erfahrungen mit Dränasphaltbelägen im Kanton Waadt. (The Experience with Porous Asphalt in Canton Vaud). VSS publication Strasse und Verkehr, Route et Trafic, April 2005.
30. Larsen, L. E. and H. Bendtsen. Noise Reduction with Porous Asphalt– Costs and Perceived Effect. Ninth International Conference on Asphalt Pavements, International Society of Asphalt Pavements, Copenhagen, Denmark, 2002.
31. Noise-Reducing Pavements for Urban Roads. Danish Road Directorate (DRD), Nordic Road & Transport Research, Volume No. 3, 1999.
32. Barrett, M. et al. *Pollutant Removal or Vegetated Highway Shoulders.* Report No FHWA/TX-05/0-4605-1. Center for Transportation Research, The University of Texas, Austin, Texas, January 2006.
33. Berbee, R., G. Rijs, R. de Brower, and L. Velzen. Characterization and Treatment of Runoff form Highways in the Netherlands Paved with Impervious and Pervious Asphalt. *Water Environment Research,* Vol. 71, No. 2. 1999, pp. 183–190.
34. Kubo, K., H. Kido, and M Ito. Study on Pavement Technologies to Mitigate the Heat Island Effect and Their Effectiveness. 10th International Conference on Asphalt Pavements, Quebec City, 2006.
35. Alvarez, A. E., A. Epps-Martin, C. K. Estakitiri, J. W. Button, C. J. Glover, and S. H. Jung. "Synthesis of Current Practice on the Design, Construction, and Maintenance of Porous Friction Courses." FHWA/TX-06/0-5262-1. Texas Transportation Institute. College Station, Texas. July 2006.
36. Mallick, R. B., P. S. Kandhal, L. A. Cooley, Jr., and D. E. Watson. *Design, Construction, and Performance of New Generation Open-Graded Friction Courses.* NCAT Report No. 2000-01. National Center for Asphalt Technology, Auburn University, 2000.
37. Poulikakos, L. D., S. Takahashi, and M. N. Partl. *Evaluation of Improved Porous Asphalt by Various Test Methods.* Report No. 113/13 (EMPA No. FE 860076), EMPA, October 2006.
38. Molenaar, J. M. M. and A. A. A. Molenaar. An Investigation into the Contribution of the Bituminous Binder to the Resistance to Raveling of Porous Asphalt. 2nd Eurasphalt & Eurobitume Congress, Barcelona, Spain, 2000, pp. 500–508.
39. Watson, Donald E., L. Allen Cooley, Jr., Kathryn Ann Moore, and Kevin Williams. Laboratory Performance Testing of Open-Graded Friction Course Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board, No 1891,* TR, National Research Council, Washington, D.C., 2004, pp. 40–47.
40. Watson, Donald E., Kathryn Ann Moore, Kevin Williams, and L. Allen Cooley, Jr. 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.
41. Pasetto, M. Porous Asphalt Concretes with Added Microfibres. 2nd Eurasphalt & Eurobitumen Congress, Barcelona, Spain, 2000, pp. 438–447.
42. Watson, Donald E., Eyad Masad, Kathryn Ann Moore, Kevin Williams, L. Allen Cooley, Jr. Verification of Voids in Course Aggregate Testing to Determine Stone-On-Stone Contact of Hot-Mix Asphalt Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1891,* TRB, National Research Council, Washington, D.C., 2004, pp. 182–190.
43. Cooley, L. Allen, Jr., E. Ray Brown, and Donald E. Watson. Evaluation of Open-Graded Friction Course Mixtures Containing Cellulose Fibers. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1723,* TRB, National Research Council, Washington, D.C., 2000, pp. 19–25.
44. Fortes, R. M. and J. V. Merighi. Open-Graded HMAC Considering the Stone-on-Stone Contact. *Proceedings of the International Conference on Design and Construction of Long Lasting Asphalt Pavements,* Auburn, Alabama, June 2004.
45. Faghri, Mohammad and Martin H. Sadd. Performance Improvement of Open Graded Asphalt Mixes. Report on URI_TC Project No. 536144, October 2002.
46. Spillemaeker, P. E., and P. Bauer. Development of 0/6 Porous Asphalt. 2nd Eurasphalt & Eurobitume Congress, Barcelona, Spain, 2000, pp. 553–557.
47. Moore, Lucinda. M. and R. G Hicks. Design, Construction, and Maintenance Guidelines for Porous Asphalt Pavements. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1778.* TRB, National Research Council, Washington, D.C., 2001, pp. 91–99.
48. Rogge, D. and E. A. Hunt. Development of Maintenance Practices for Oregon F-Mix – Interim Report SPR371. Oregon Department of Transportation, Salem, Oegon, August 1999.
49. Litzka, J. Austrian Experiences with Winter Maintenance on Porous Asphalt. *Proceedings of the Ninth International Conference on Asphalt Pavements,* Copenhagen, Denmark, August 2002.
50. Ranieri, Vittorio. Runoff Control in Porous Pavements. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1789,* Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 46–55.
51. Padmos, C. Over Ten Years Experience with Porous Road Surfaces. Ninth International Conference on Asphalt Pavements, International Society of Asphalt Pavements, Copenhagen, Denmark, 2002.
52. Watson, Donald E., Jingna Zhang, R. Buzz Powell. Analysis of Temperature Data for the National Center for Asphalt Technology Test Track. In *Transportation Research Record: Journal of the Transportation Research Board, No. 189.* Transportation Research Board of the National Academies, Washington, D.C. 2004, pp. 68–75.
53. Bishop, Michael C. and Michael F. Oliver. Open Graded Friction Course Pavements in British Columbia. *Proceedings of the 46th Annual Conference of the Canadian Technological Asphalt Association,* Toronto, Canada, 2001.
54. Kaloush, Kamil E., Matthew W. Witczak, Andres C. Sotil and George B. Way. Laboratory Evaluation of Asphalt Rubber Mixtures Using the Dynamic Modulus (E*) Test. TRB 2003 Annual Meeting (CD-ROM), TRB, National Research Council. Washington, D.C., 2003.
55. Tan, S. A., T. F. Fwa, and K. C. Chai. Drainage Considerations for Porous Asphalt Surface Course Design. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1868.* Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 142–149.
56. Bedjent, P. B., and W. C. Huber. *Hydrology and Floodplain Analysis.* Addison-Wesley Publishing Company, Reading, Massachusetts,1988.
57. Brown E. R. and L. A. Cooley, Jr. *NCHRP Report 425: Designing Stone Matrix Asphalt Mixtures for Rut Resistant Pavements.* TRB, National Research Council, Washington, D.C., 1999.

58. *Hot Mix Asphalt Paving: Handbook 2000.* U.S. Army Corps of Engineers, Federal Highway Association,. AC 150/5370-14A, Appendix 1, 2000.
59. Choubane, Bouzid, James A. Musselman, and Gale C. Page. Forensic Investigation of Bleeding in Open-Graded Asphalt-Rubber Surface Mixes. TRB 1999 Annual Meeting (CD-ROM), TRB, National Research Council, Washington, D.C., 1999.
60. Wagner, C. and Y. S. Kim. Construction of a Safe Pavement Edge: Minimizing the Effects of Shoulder Dropoff. TRB 2005 Annual Meeting (CD-ROM). TRB, National Research Council, Washington, D.C., 2005.
61. Sholar, Gregory A., Gale C. Page, James A. Musselman, Patrick B. Upshaw and Howard L. Moseley. Development of the Florida Department of Transportation's Percent Within Limits Hot-Mix Asphalt Specification. TRB 2005 Annual Meeting (CD-ROM), TRB, National Research Council, Washington, D.C. 2005.
62. Performance Characteristics of Open-Graded Friction Courses. Massachusetts Highway Department, Pavement Management Section. Boston, Mass. February 15, 2001.
63. Corrigan, Sean., K. Wayne Lee, and Stephen A. Cardi. Implementation and Evaluation of Traffic Marking Recesses for Application of Thermoplastic Pavement Markings on Modified Open Graded Friction Course. TRB 2001 Annual Meeting (CD-ROM), TRB, National Research Council, Washington, D.C., 2001.
64. Hiershe, E. U. and H. J. Freund. Technology and In-Situ Trail of Noise Absorbing Pavement Structure. Proc. 7th International Conference on Asphalt Pavements, University of Nothinghan, United Kingdom, August 1992.
65. Abe, T. and Y. Kishi. Development of Low-Noise Pavement Function Recovery Machine. *Proceedings of the Ninth International Conference on Asphalt Pavements,* Copenhagen, Denmark, August 2002.
66. Rogge, D. Development of Maintenance Practices for Oregon F-Mix. Oregon Department of Transportation, FHWA-OR-RD-02-09, Corvallis, Oregon, 2002.
67. Wimsatt, Andrew J. and Tom Scullion. Selecting Rehabilitation Strategies for Flexible Pavements in Texas. TRB 2003 Annual Meeting (CD-ROM), TRB, National Research Council, Washington, D.C., 2003.
68. Pucher, E., J. Litzka, J. Haberl, and J. Girard. Silvia Project Report: Report on Recycling of Porous Asphalt in Comparison with Dense Asphalt. SILVIA-036-01-WP3-260204. Sustainable Road Surfaces for Traffic Noise Control, European Commission, February 2004.
69. Cooley, Jr., L. A., R. C. Ahlrich, D. E. Watson, and P. S. Kandhal. Improved Porous Friction Courses (IPFC) on Asphalt Airfield Pavements. Final Report. Airfield Asphalt Pavement Technology Program, Auburn University, Auburn, Alabama, June 2007.
70. Ketcham, S. A., L. D. Minsk, R. B. Blackburn, and E. J. Fleege. Manual of Practice for an Effective Anti-Icing Program. A Guide for Highway Winter Maintenance Personnel. FHWA-RD-95-202. U.S. Department of Transportation, Federal Highway Administration, June 1996.
71. Bennert, T. and L. A. Cooley, Jr. Comparison of Friction Properties of Friction-Course Pavement Systems During Winter Storm Events. *International Journal of Pavements,* Volume 5, Number 1, January 2006, pp. 1–12.
72. Van Doorn, Roland. Winter Maintenance in the Netherlands. Ministry of Transportation, Public Works and Water Management. Compiled from COST344 Snow and Ice Control on European Roads and Bridges Task Group 3, Best Practices, March 2002.
73. Giuliani, F. Winter Maintenance of Porous Asphalt Pavements. XIth International Winter Road Conference, World Road Association (PIARC), Sapporo, Japan, 2002.
74. *Distress Identification Manual for the Long-Term Pavement Performance Project.* Strategic Highway Program. SHRP–P-338. TRB, National Research Council, Washington, D.C., 1993.
75. Flintsch, Gerardo W., Edgar de León, Kevin K. McGhee, and Imad L. Al-Qadi. Pavement Surface Macrotexture Measurement and Application. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1860,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 168–177.
76. Hardiman, C. The Improvement of Water Drainage Function and Abrasion Loss of Conventional Porous Asphalt. *Proceedings of the Eastern Asia Society for Transportation Studies,* Volume 5, 2005, pp. 671–678.
77. Poulikakos, L. D., S. Takahashi, and M. N. Partl. A Comparison of Swiss and Japanese Porous Asphalt through Various Mechanical Tests. *3rd Swiss Transport Research Conference,* Monte Verita/Ascona, March 19–21, 2003.
78. Tan, S. A., T. F. Fwa, and C. T. Han. Clogging Evaluation of Permeable Base. *Journal of Transportation Engineering.* American Society of Civil Engineers, Reston, Virginia, Volume 129, Issue 3, May 2003, pp. 309–315.

APPENDIX A

Questionnaire on PFC, Conventional OGFC, and Similar Materials

Questionnaire on PFC, Conventional OGFC, and Similar Materials

PART 1: General Use and Structural Design

A. General Use

1. Do you currently use OGFC?
   If your answer is No, please continue the survey and provide your input wherever you deem important.
2. Based on the above descriptions of PFC and ACFC, which term best describes your OGFC mix? If other, please explain.
3. What is your approximate volume of use per year?
4. On what type of roadways do you use OGFC?
5. What are the factors involved in selection of OGFC for a roadway?
6. Are there limitations on where OGFC is used (for example: elevation, temperature, speed, geometry, etc.)?
7. Are there any other comments on general use of OGFC?

B. Structural Design

1. Do you assign any structural value to the OGFC layer?
2. If answer to the above question is Yes, how do you estimate structural value? If other, please explain:
3. Do you specify a single lift thickness for all OGFC layers?
4. If the answer to the above question is No, what factors are involved in selecting lift thickness (for example: maximum aggregate size, rainfall intensity, pavement classification, traffic level, etc.)?

PART 2: Mix Design

Mix Design

A. Aggregates

1. Can you provide your current gradation requirements for OGFC?
2. Please rank from 1 to 7 the following aggregate characteristics for use in OGFC in order of their importance, 1 being the most important.

B. Asphalt Binder

1. What grade of asphalt binder do you specify?
2. Are there other tests that you specify for asphalt binders other than those required in grading a sample? What is your reason for specifying other tests (e.g., ensure a certain polymer, ensure polymer is added, etc.)?

C. Stabilizing Additives

1. Do you specify stabilizing additives (for example: fibers, polymers, crumb rubber, etc.) to reduce the potential for draindown?
2. If the answer to the above question is Yes, what type of stabilizing additive do you require?
3. If you specify fibers, what type and percentage do you require?
4. Do you specify certain polymer modifiers in asphalt binders? If so, do you specify a certain type (for example: SBR, SBS, SB, EVA, etc.)?
5. Do you specify crumb rubber in asphalt binders? If so, what type and what manufacturing process do you specify?

D. Mix Design

1. Do you use laboratory compaction during mix design?
2. If yes, what compaction method (e.g., Marshall, Superpave gyratory compactor, etc.) and compactive effort (e.g., 50 blows per face, 50 gyrations, etc.) do you use?
3. Do you include draindown testing within the mix design procedure? If yes, what method do you specify (e.g., draindown basket, Schellenberger, etc.) and what are the requirements?
4. Do you include permeability testing within the mix design procedure? If yes, what method do you specify and what are the requirements?
5. Do you specify other laboratory performance tests during mix design (e.g., Cantabro Abrasion loss, Voids in Coarse Aggregate, permanent deformation testing, moisture susceptibility test, permeability, etc.) and what are the requirements?

6. If you specify the tensile strength ratio test for moisture susceptibility, how many freeze-thaw cycles do you utilize to condition the samples?
7. Please provide any other comments on materials and mix design for OGFC?

PART 3: Construction

A. Production

1. How do you specify OGFC?
2. What type of plants are used to produce OGFC?
3. Do you require a longer mixing time for OGFC mixes than for dense-graded mixes?
4. Do you have a maximum and/or minimum temperature requirement for mixing?
5. If answer to above question is Yes, please specify.
6. Do you have a limit on silo storage time?
7. If answer to above question is Yes, please specify.

B. Transportation

1. Do you limit haul distances?
2. If answer to above question is Yes, please specify.
3. Do you require insulated trucks?
4. Do you specify tarping of trucks?
5. Do you require heated trucks?
6. Do you specify a minimum temperature when the truck reaches the paving site?
7. If answer to above question is Yes, please specify.
8. Do you allow the use of release agents?
9. If answer to above question is Yes, please specify.

C. Laydown/Compaction

1. Do you require a Material Transfer Vehicle?
2. Do you require a tack coat on the underlying layer?
3. If answer to above question is Yes, please specify type and rate, with units.
4. Do you require a calibrated distributor truck to apply the tack coat?
5. Do you require any other techniques to ensure an impermeable underlying layer besides using tack coat (for example: seal coat, paving fabric, SAMI, etc.)?
6. If answer to above question is Yes, please specify.
7. Do you have a minimum specified air and/or surface temperature for placing OGFC?
8. If answer to above question is Yes, please specify.
9. How do you specify compaction of OGFC layer?
10. Do you specify a certain type of roller?
11. If answer to above question is Yes, please specify.
12. Do you allow tacking of the vertical face of longitudinal joints?

D. Quality Control/Quality Assurance

1. What tests do you require for Quality Control/Quality Assurance of OGFC?

E. General Construction Issues

1. What materials do you utilize for OGFC pavement markings?
2. Do you construct rumble strips at the OGFC pavement edge?
3. Have you experienced any distress related to pavement markings and rumble strips? If Yes, please explain.

PART 4: Maintenance and Rehabilitation

A. General Maintenance (Non-Winter Related)

1. What are your most common general maintenance issues for OGFC?
2. Do you have any regularly scheduled maintenance activities specifically for OGFC?
3. If answer to above question is Yes, please specify.
4. Do you employ maintenance activities to unclog OGFC pavements?
5. If answer to above question is Yes, please specify.
6. Do you use any field test to identify when general maintenance activities are required?
7. If answer to above question is Yes, please specify.
8. Do you patch OGFC?
9. If answer to above question is Yes, please specify the type of material you use (e.g., dense-graded HMA, OGFC, etc.).

B. Winter Maintenance

1. Do you use any type of weather prediction system for winter maintenance activities?
2. What weather conditions (for example: air temperature, snow, rain, etc.) trigger winter maintenance?
3. What type(s) of snow and ice control chemicals do you use?
4. Do you employ anti-icing methodologies?
5. What are the typical spread rates for snow and ice control chemicals for your *dense graded* mixes?
6. What are the typical spread rates for snow and ice control chemicals for your *OGFC* mixes?

C. Rehabilitation

1. What typical problems trigger rehabilitation activities?
2. For the problems listed above, what are the typical rehabilitation activities (for example: mill and replace)?

3. Are you aware of any known or perceived problem with any of the above maintenance/rehabilitation techniques of OGFC?
4. If answer to above question is Yes, please specify.

PART 5: Performance

1. What is the estimated average service life of OGFC?
2. What are common distresses in OGFC and which one is the most common?
3. Please rank the following performance characteristics from 1 to 7 in terms of their importance, 1 being the most important.
4. What tests/equipment have you used to measure performance quality characteristics (laboratory or field)?
5. Has your agency conducted life cycle cost analysis for OGFC?

Guidelines on the Use of Permeable Friction Courses

CONTENTS

Introduction

Within the United States, the term open-graded friction (OGFC) has been used to describe hot-mix asphalt (HMA) having an open aggregate grading that is used as a wearing layer to improve friction properties. These mixes evolved through experimentation with plant mix seal coats. The initial interest in these mix types resulted from problems associated with the construction and performance of chip seals. Primarily, loose aggregates that either were not adequately seated during construction or dislodged by traffic were breaking windshields. Additionally, there was a time constraint problem with setting the chip seal aggregates during a sudden rainstorm. During the 1930s Oregon began experimenting with the plant mix seal coats to improve frictional properties. During the 1940s, California also began using the plant mix seal coats as drainage interlayers and as an alternative to chip seals and slurry seals on pavement surfaces. During the late 1940s, a number of the western states began to use these mixes to improve frictional properties. An additional benefit from using these plant mix seal coats as a wearing layer was that hydroplaning and splash/spray was reduced.

Even though plant mix seals provided excellent frictional properties and reduced potential for hydroplaning and splash/spray, their use did not become widespread until the 1970s. The primary problems encountered with these mixes were related to durability and draindown. Because the plant mix seals had an almost uniform aggregate gradation with little fine aggregate, there was very little aggregate surface area. The term draindown is used to describe when the asphalt drains from the aggregates during storage and transportation. Asphalt binder that has drained from the aggregate structure results in pavement areas that have too little asphalt binder and areas that are very rich in asphalt binder. Areas without a sufficient amount of asphalt binder were prone to raveling, while areas rich in asphalt binder could become slick and did not provide the desired frictional properties.

In the 1970s, the Federal Highway Administration (FHWA) initiated a program to improve the frictional resistance of the nation's roadways. The plant mix seal coats were one of the tools an agency could use to improve frictional resistance and, thus, gained popularity. According to the 1978 NCHRP Synthesis Number 49, these plant mix seals became known as OGFCs. In 1980, the FHWA published a mix design procedure for these mix types. The procedure entailed an aggregate gradation requirement, a surface capacity of coarse aggregate, determination of fine aggregate content, determination of optimum mixing temperature, and resistance of the designed mixture to water. OGFC mixtures designed in accordance to the FHWA procedure were successful at performing their intended function: removing water from the pavement surface and improving frictional resistance. However, a number of states noted that the OGFC pavements were susceptible to sudden and catastrophic failures.

The failures observed during the 1970s and 1980s were caused by mix design, material specification, and construction problems. These problems primarily involved mix temperature during construction. Gradations associated with the OGFCs of the 1970s and 1980s were much coarser than typically used dense-graded mixes (Marshall and Hveem designed mixes). Additionally, very few states were using modified asphalt binders. Because of the open nature of the aggregate gradings and neat asphalt binders, there were problems of draindown during transportation to the project site. To combat the draindown problems, most owners would allow contractors to reduce the mixture's temperature during production. The draindown and mixture temperature problems led to catastrophic raveling and delamination, respectively. These problems were of such magnitude that a number of states put a moratorium on the use of OGFC mixtures during the 1980s.

A survey of state highway agencies conducted in 1998 indicated that 19 states (38 percent) were currently using OGFCs. Over 70 percent of the states using OGFCs reported service lives of 8 years or more. The vast majority of the states reporting good performance indicated the use of coarser gradations than the FHWA mix design procedure required and the use of stiffer, modified binders.

The question must be asked, "If OGFCs did not perform in the 1970s and 1980s, why did states continue to evolve these mixes such that performance improved?" The answer is simple, safety. OGFCs most likely provide the safest wearing surface for our nation's roadways. OGFCs have been shown to have excellent frictional resistance, reduce splash and spray, reduce the potential for hydroplaning, improve night visibility, and improve visibility of pavement markings. Additional benefits of using OGFCs include reduced tire-pavement noise, smooth pavements, thereby increased fuel economy, and use of relatively thin layers.

The property of OGFC that leads to the safety benefits mentioned above is the relatively high permeability of OGFC compared to dense-graded HMAs. Because of the very coarse gradation and lack of fines, OGFCs have very high air void contents in the range of 15 percent to 22 percent. These high air void contents result in water infiltrating into the OGFC layer. Without water on the pavement surface, the frictional properties of the pavement improve, splash and spray is reduced, and the potential for hydroplaning is greatly reduced.

OGFCs that are designed to have at least 18 percent air voids are called permeable friction courses (PFCs). PFCs are a special type of OGFC that are specifically designed to have high air void contents, typically 18 to 22 percent, for removing water from the pavement surface. Other types of OGFCs also are used within the United States. In some states, friction courses having an open grading are used; however, these friction courses are not designed to be as permeable as PFCs. The purpose of these friction courses is to provide a safe riding surface by improving frictional properties and/or to reduce tire/pavement noise.

In 1992, the Georgia Department of Transportation (GDOT) built some test sections on Interstate 75 south of Atlanta, Georgia that were specifically designed to be coarser and have higher air void content than GDOT's current version of OGFC. After these field experiments, the GDOT developed specification for what they termed as porous European Mixes (PEM). These PEM mixes are considered the first generation of PFCs used in the United States. A 1998 survey on the use of OGFC in the United States indicated that most DOTs reporting good performance with OGFCs had adopted coarser gradation than those specified in the FHWA procedure and were utilizing modified asphalt binders.

After the 1998 survey was published, the National Center for Asphalt Technology (NCAT) undertook a research project to develop a mix design procedure for what they termed new-generation OGFCs. These new-generation OGFCs are considered PFCs because they are designed to have air void contents above 18 percent. Following the NCAT study, a number of DOTs developed specifications for PFCs. The survey conducted as part of NCHRP 9-41 indicated that nine DOTs are currently utilizing PFCs. Seven of these DOTs are located in the southeast, ranging from Texas to North Carolina. Other DOTs currently utilizing PFCs include California, Oregon, and New Jersey.

The use of PFCs in Europe has a longer history than in the United States, dating back to the 1970s. Within Europe, PFCs are called porous asphalt. Many of the European countries utilize PFCs including Switzerland, Spain, the Netherlands, Austria, France, Denmark, and the United Kingdom. In addition to Europe, PFCs also are used in Australia, New Zealand, and Japan.

Objective

The objective of this project was to recommend design, construction, maintenance, and rehabilitation guidelines that will maximize the advantages and minimize the disadvantages associated with the use of PFC. In the context of this project, PFC was generally, but not exclusively, defined as a highly permeable mix containing polymer-modified asphalt binders or asphalt rubber and fibers, alone or in combination.

Report Organization

The draft final report for NCHRP Project 9-41 is divided into three volumes. Volume I of this report includes the current state-of-art for PFCs. This volume provides a synthesis two draft AASHTO Practices. The first practice was developed for the design and construction of PFCs, while the second practice was developed for the maintenance and rehabilitation of PFC layers. Also within this volume is a draft AASHTO test method for determining the abrasion loss of PFC samples using the Cantabro Abrasion Loss test. The final volume of the draft final report presents the annotated literature review.

Standard Practice for Materials, Design and Construction of Permeable Friction Courses

AASHTO Format

D R A F T

Standard Practice for

Materials, Design and Construction of Permeable Friction Courses (PFC)

AASHTO Designation: PP XXX-YY

---

1. SCOPE

1.1 This standard covers the materials requirements, mix design and construction of permeable friction course (PFC) asphalt mixtures.

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

---

2. REFERENCED DOCUMENTS

2.1 *AASHTO Standard:*

- M 156, Requirements for Mixing Plants for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures
- M 231, Weighing Devices Used in the Testing of Materials
- M 320, Performance-Graded Asphalt Binder
- R 30, Mixture Conditioning of Hot-Mix Asphalt (HMA)
- T 19, Bulk Density (‘Unit Weight”) and Voids in Aggregates
- T 96, Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
- T 104, Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate
- T 209, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
- T 283, Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage
- T 305, Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures
- T 312, Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor
- TP XXX, Determining the Abrasion Loss of Permeable Friction Course (PFC) Asphalt Specimens by the Cantabro Procedure

2.2 *ASTM Standards:*

- D 2995, Practice for Estimating Application Rate of Bituminous Distributors

- D 3549, Standard Test Method for Thickness or Height of Compacted Bituminous Mixture Specifications
- D 4791 Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate

---

3. TERMINOLOGY

3.1 *Definitions:*

3.1.1 *permeable friction course (PFC)*—a special type of porous hot mix asphalt mixture with air voids of at least 18% used for reducing hydroplaning and potential for skidding, where the function of the mixture is to provide a free-draining layer that permits surface water to migrate laterally through the mixture to the edge of the pavement.

3.1.2 *asphalt binder*—an asphalt-based cement that is produced from petroleum residue either with or without the addition of non-particulate organic modifiers.

3.1.3 *abrasion loss*—the loss of particles under the effect of abrasion.

3.1.4 *air voids*—the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the total volume of the compacted specimen.

3.1.5 *breakpoint sieve* – the finest sieve to have at least 10 percent of the aggregate fraction retained.

3.1.6 *draindown* – separation of asphalt binder from the coarse aggregate structure, generally during storage or transportation.

3.1.7 *stabilizing additive*—materials used to minimize draindown of asphalt during transport and placement of PFC.

3.1.8 *voids in coarse aggregate* – the volume of voids between the coarse aggregate particles, where this volume includes filler, fine aggregate, air voids, asphalt binder, and stabilizing additives, if used.

3.1.9 *stabilizing additive* – polymer, crumb rubber, and/or fibers, used to minimize the draindown.

---

4. SUMMARY OF PRACTICE

4.1 Aggregates, asphalt binder, stabilizing additives are selected that meet specification values. Selected aggregates are blended to meets specified gradation bands and compacted with a trial asphalt binder content in order to evaluate the trial mixes and select the design gradation. Once the trial gradation is selected, the asphalt binder content is altered and the optimum asphalt binder content selected. The designed mixture is then evaluated for resistance to moisture susceptibility.

4.2 Permeable friction courses are constructed as wearing layers over a clean stable pavement structure. Permeable friction courses are produced in a manner similar to typical dense-graded hot mix asphalt (HMA). In some instances, special equipment is needed to introduce stabilizing additives. Transportation and placement of PFC is similar to other conventional HMA mixtures. Compaction of PFC is conducted to set the aggregates.

5. SIGNIFICANCE AND USE

5.1 The procedure described in this practice is used to select materials, design and construct permeable friction courses that will provide good performance in terms of permeability and durability when subjected to high volumes of traffic.

6. MATERIALS SELECTION AND MIX DESIGN

6.1 The first step in the design process is to select suitable materials. Materials needing selection include coarse aggregates, fine aggregates, asphalt binder and stabilizing additives.

6.1.1 *Coarse Aggregates*—Table 1 presents the coarse aggregate requirements for permeable friction courses.

Table 1: Coarse Aggregate Quality Requirements of PFC

Test	Method	Spec. Minimum	Spec. Maximum
Los Angeles Abrasion, % Loss	AASHTO T96	-	30
Flat or Elongated, %	ASTM D4791		
2 to 1		-	50
Soundness (5 Cycles), %	AASHTO T104		
Sodium Sulfate		-	10
Magnesium Sulfate		-	15
Uncompacted Voids	AASHTO TP-56 Method A	45	-

[A] Aggregates with L.A. Abrasion loss values up to 50 have been successfully used to produce OGFC mixtures. However, when the L.A. Abrasion exceeds approximately 30, excessive breakdown may occur in the laboratory compaction process or during in-place compaction.

6.1.2 *Fine aggregates*—Table 2 presents the fine aggregate requirements for permeable friction courses.

Table 2: Fine Aggregate Quality Requirements for OGFC

Test	Method	Spec. Minimum	Spec. Maximum
Soundness (5Cycles), %	AASHTO T104		
Sodium Sulfate		-	10
Magnesium Sulfate		-	15
Uncompacted Voids	AASHTO T304, Method A	45	-
Sand Equivalency	AASHTO T176	50	-

6.1.3 *Asphalt Binders*—Asphalt binders should be a Superpave performance grade (PG) meeting the requirements of AASHTO M320. Relatively high asphalt binder contents are required for permeable friction courses. Because of the open grading of the aggregate, a stiff asphalt binder is needed to ensure a durable mixture. For high-volume roadways or pavements with slow to standing traffic, the asphalt binder high-temperature grade should be increased by two grades over the standard asphalt binder. Adjustments should be an increase of one high-temperature grade for all other roadways.

6.1.4 *Stabilizing Additives*—Stabilizing additives are needed within permeable friction courses to prevent the draining of asphalt binder from the coarse aggregate skeleton during transportation and placement. Stabilizing additives such as cellulose fiber, mineral fiber, crumb rubber and polymers have been used with success to minimize draindown potential.

6.2 *Design Gradation*—In order to provide the high level of permeability desirable with permeable friction courses, an aggregate gradation having a very open gradation is needed. Table 3 presents the specified gradation ranges.

Table 3: PFC Gradation Specification Bands

Sieve Size	⅜ in. PFC	½ in. PFC	¾ in. PFC
Grading Requirements		% Passing	
1 in. (25 mm)			100
¾ in. (19 mm)		100	85-100
½ in. (12.5 mm)	100	80-100	55-70
⅜ in. (9.5 mm)	85-100	35-60	---
No. 4 (4.75 mm)	20-30	10-25	10-25
No. 8 (2.36 mm)	5-15	5-10	5-10
No. 200 (0.075 mm)	0-4	0-4	0-4

6.2.1 *Selection of Trial Gradations*—The initial trail gradations must be selected to be within the master specification range shown in Table 3. To design a permeable friction course mix, it is recommended that at least three trial gradations be initially evaluated. It is suggested that the trial gradations fall along the coarse and fine limits of the gradation range along with one falling in the middle. These trial gradations are obtained by adjusting the amount of fine and coarse aggregates in each blend.

6.2.2 *Determination of VCA in the Coarse Aggregate Fraction*—For best performance, the PFC mixture must have a coarse aggregate skeleton with stone-on-stone contact. The coarse aggregate fraction is that portion of the total aggregate retained on the breakpoint sieve. The breakpoint sieve is defined as the finest (smallest) sieve to retain 10 percent of the aggregate gradation. The voids in coarse aggregate for the coarse aggregate fraction (VCA_{DRC}) are determined using AASHTO T19. When the dry-rodded density of the coarse aggregate fraction has been determined, the VCA_{DRC} for the fraction can be calculated using the following equation:

$$VCA_{DRC} = \frac{G_{ca}\,\gamma_w - \gamma_s}{G_{ca}\,\gamma_w} * 100 \qquad \text{Equation 1}$$

where,
VCA_{DRC} = voids in coarse aggregate in dry-rodded condition
γ_s = unit weight of the coarse aggregate fraction in the dry-rodded condition (kg/m^3),
γ_w = unit weight of water (998 kg/m^3), and
G_{ca} = bulk specific gravity of the coarse aggregate

The results from this test are compared to the VCA in the compacted PFC mixture (VCA_{mix}). When the VCA_{mix} is equal to or less than the VCA_{DRC}, stone-on-stone contact exists.

6.2.3 *Selection of Trial Asphalt Content*—The minimum desired asphalt binder content for permeable friction course mixtures is presented in Table 4. These minimum asphalt binder contents are provided to ensure sufficient volume of asphalt binder exists in the PFC mix. It is recommended that the mixture be designed at some amount over the minimum to allow for adjustments during plant production without falling below the minimum requirement. As a starting point for trial asphalt binder contents of PFCs, for aggregates with combined bulk specific gravities less than or equal to 2.75, an asphalt binder content between 6 and 6.5 percent should be selected. If the combined bulk specific gravity of the coarse aggregate exceeds 2.75, the trial asphalt binder content can be reduced slightly.

Table 4: Minimum Asphalt Content Requirements for Aggregates with Varying Bulk Specific Gravities - Permeable Friction Courses

Combined Aggregate Bulk Specific Gravity	Minimum Asphalt Content Based on Mass, %
2.40	6.8
2.45	6.7
2.50	6.6
2.55	6.5
2.60	6.3
2.65	6.2
2.70	6.1
2.75	6.0
2.80	5.9
2.85	5.8
2.90	5.7
2.95	5.6
3.00	5.5

6.2.4 *Sample Preparation*—As with the design of any hot mix asphalt, the aggregates to be used in the mixture should be dried to a constant mass and separated by dry-sieving into individual size fractions. The following size fractions are recommended:

19.0 to 12.5 mm
12.5 to 9.5 mm
9.5 to 4.75 mm
4.75 to 2.36 mm
Passing 2.36 mm (if 2.36 mm sieve is breakpoint sieve)
2.36 to 1.18 (if 1.18 mm is breakpoint sieve)

After separating the aggregates into individual size fractions, they should be recombined to the proper percentages based upon the gradation blend being used.

The mixing and compaction temperatures are determined in accordance with AASHTO T245, section 3.3.1. Mixing temperature will be the temperature needed to produce an asphalt binder viscosity of 170±20 cSt. Compaction temperature will be the temperature required to provide an asphalt binder viscosity of 280±30 cSt. However, while these temperatures work for neat asphalt binders, the selected temperatures may need to be changed for modified asphalt binders. The asphalt binder supplier's guidelines for mixing and compaction temperatures should be used.

When preparing PFC in the laboratory, a mechanical mixing apparatus should be utilized. Aggregate batches and asphalt binder are heated to a temperature not exceeding 50°F (28°C) more than the temperature established for mixing temperature. The heated aggregate batch is placed into the mechanical mixing container. Asphalt binder and any stabilizing additive are placed into the container at the required masses. Mix the aggregate, asphalt binder, and stabilizing additives rapidly until thoroughly coated. Mixing times for PFC should be slightly longer than for conventional mixtures to ensure that the stabilizing additives are thoroughly dispersed within the mixture. After mixing, the PFC mixture should be short-term aged in accordance with AASHTO R30.

6.2.5 *Number of Samples per Trial Blend*—A total of eighteen samples are initially required: three samples for determining air voids and three uncompacted samples for determining theoretical maximum density at each binder content. Each sample is mixed with the trial asphalt binder content and three of the four samples for each trial gradation are compacted. The remaining sample of each trial gradation is used to determine the theoretical maximum density according to AASHTO T209.

6.2.6 *Sample Compaction*—Specimens should be compacted at the established compaction temperature after aging. Laboratory samples of PFC are compacted using 50 revolutions of the Superpave gyratory compactor in accordance with AASHTO T312. More than 50 revolutions should not be used; OFGC is relatively easy to compact in the laboratory and exceeding this compactive effort can cause excessive aggregate breakdown.

6.2.7 After the samples have been compacted, extruded and allowed to cool, they are tested to determine their bulk specific gravity, G_{mb} using dimensional analysis. Dimensional analysis entails calculating the volume of the sample by obtaining four height measurements with a calibrated caliper, with each measurement being 90 degrees apart. The area of the specimen is then multiplied by the average height to obtain the sample volume. The G_{mb} is determined through dividing the dry mass of the sample by the sample volume determined in accordance with D 3549. Uncompacted samples are used to determine the theoretical maximum density, G_{mm} (AASHTO T209). Using G_{mb}, G_{mm} and G_{ca}, percent air voids (VTM), and VCA_{mix} are calculated. The VTM and VCA are calculated as shown below.

$$VTM = 100 * \left(\frac{1 - G_{mb}}{G_{mm}} \right) \qquad \text{Equation 2}$$

$$VCA_{mix} = 100 - \left(\frac{G_{mb} * P_{ca}}{G_{ca}} \right) \qquad \text{Equation 3}$$

where:
P_{ca} = percent of coarse aggregate in the mixture
G_{mb} = combined bulk specific gravity of the total aggregate
G_{ca} = bulk specific gravity of the coarse aggregate

Once the VTM and VCA_{mix} are determined, each trial blend mixture is compared to the PFC mixture requirements. Table 5 presents the requirements for OGFC designs. Of the three trial blends, the trial blend with the highest air void content that meets the 18 percent minimum and exhibits stone-on-stone contact is considered the design gradation.

Table 5: PFC Mixture Specification for SGC Compacted Designs

Property	Requirement
Asphalt Binder, %	Table 4
Air Voids, %	18 to 22
Cantabro Loss %	15 min.
VCA_{mix}%	Less than VCA_{DRC}
Tensile Strength Ratio	0.70 min.
Draindown at Production Temperature, %	0.30 max

6.3 *Selection of Optimum Asphalt Binder Content*—Once the design gradation has been selected, it is necessary to evaluate various asphalt binder contents in order to select an optimum binder content. Additional samples are prepared using the design gradation and at least three asphalt binder contents. The number of samples needed for this procedure is eighteen. This provides for three compacted (for G_{mb} and Cantabro Abrasion Loss) and three uncompacted samples (one for determination of theoretical maximum density and two for draindown testing) at each of the three asphalt binder contents. Optimum asphalt binder content is selected as the binder content that meets all of the requirements of Table 5.

6.3.1 *Cantabro Abrasion Loss*—The Cantabro Abrasion test is used as a durability indicator during the design of OGFC mixtures. In this test, three OGFC specimens compacted with 50 gyrations of the Superpave gyratory compactor are used to evaluate the durability of an OGFC mixture at a given asphalt binder content. The test is conducted in accordance with the TP XXX.

6.3.2 *Draindown Sensitivity*—The draindown sensitivity of the selected mixture is determined in accordance with AASHTO T305 except that a 2.36-mm wire mesh basket should be used. Draindown testing is conducted at a temperature of 27°F (15˚C) higher than the anticipated production temperature.

6.3.3 *Permeability (optional)*—An optional test is to conduct laboratory permeability tests. Laboratory permeability values greater than 528 ft/day (100 m/day) are recommended.

6.4 *Evaluation of Moisture Susceptibility*—Moisture susceptibility of the selected mixture is determined using the modified Lottman method in accordance with AASHTO T283 with one freeze-thaw cycle. The AASHTO T283 method should be modified as follows: (a) PFC specimens should be compacted with 50 gyrations of the Superpave gyratory compactor at the optimum asphalt binder content; (b) no specific air void content level is required; (c) apply a vacuum of 26 inches of Hg for 10 minutes to saturate the compacted specimens; however, no saturation level is required; (d) keep the specimens submerged in water during the freeze-thaw cycle.

6.5 Reports

6.5.1 The report should include the following information:

6.5.2 Identification of the project and the project number.
6.5.3 Aggregate source, asphalt source and grade, type and amount of stabilizing additive, and materials quality characteristics.
6.5.4 Results of the grading optimization or selected grading from experience.
6.5.5 Selected optimum grading and optimum asphalt content.
6.5.6 Volumetric properties, abrasion loss on unaged specimens, and draindown for each trial blend and at the optimum asphalt binder content.
6.5.7 Moisture susceptibility recommendations, and
6.5.8 Recommended job-mix formula for the permeable friction course.

---

7. CONSTRUCTION OF PFC LAYERS

7.1 Production of PFC Mixture

7.1.1 Aggregates – To obtain the coarse aggregate-on-coarse aggregate contact inherent in PFCs, the mixture must contain a high percentage of coarse aggregate. Thus the gradation of the coarse aggregates can have a tremendous effect on the quality of the mixture produced. Therefore, it is imperative that the aggregates be carefully handled and stockpiled. Each coarse aggregate stockpile may need to be fed through more than one cold feeder since a high percentage of material is being fed. Using more than one feeder will also minimize variability in the gradation of coarse aggregate stockpiles.

7.1.2 Liquid Asphalt - The handling and storage of liquid asphalt binder for PFC production is similar to that for any HMA mixture. When modified asphalt binders are used, typically the storage temperatures may increase slightly from those of neat asphalt binders. However, contractors should follow the manufacturer's recommendations for circulation and storage of modified asphalts. Metering and introduction of the asphalt binder into the mixture may be done by any of the standard methods using a temperature compensating system. It is very important however that the asphalt binder be metered accurately.

7.1.3 Stabilizing Additives - Due to the high asphalt binder contents in the PFC, a stabilizing additive of some type may be used to hold the binder on the coarse aggregate during hauling and placement. Two types of stabilizing methods have been used. One method is the use of fibers such as cellulose or mineral fibers. The second stabilizing method is to modify the asphalt binder in some manner. This may be done by modifying the asphalt binder at the refinery or by adding an asphalt binder modifier to the PFC mixture during production. Some projects have utilized both a fiber and a modified asphalt binder.

7.1.3.1 *Fibers* - Both cellulose and mineral fibers have been used. Typical dosage rates are 0.3% for cellulose and 0.4% for mineral fiber by total mixture mass. Fibers can generally be purchased in two forms, loose fibers and pellets. Fibers in a dry, loose state come packaged in plastic bags or in bulk. Both fiber types have been added into batch or drum mix plants with good success. For batch plant production, loose fibers are sometimes delivered to the plant site in bags. The bags are usually made from a material which melts easily at mixing temperatures. The bags can therefore be added to the pugmill during each dry mix cycle. When the bags melt only the fiber remains. Addition of the bags of fibers is done by workers on the pugmill platform. At the appropriate time in every dry mix cycle, the workers add the correct number of bags to the pugmill. The bags of fiber can be elevated to the pugmill platform by the use of a conveyor belt. While this method of manual introduction works satisfactorily, it is labor intensive.

Another method for addition of fibers into a batch plant is by blowing them into the plant using a machine typically designed and supplied by the fiber manufacturer. The dry, loose fiber is placed in the hopper of the machine where it is fluffed by large paddles. The fluffed fiber next enters the auger system which conditions the material to a known density. The fiber is then metered by the machine and blown into the pugmill or weigh hopper at the appropriate time. These machines can meter in the proper amount of fiber by mass or blow in a known volume. This fiber blowing method can also be used in a drum mix plant. The same machine is used and the fibers are simply blown into the drum. When using this method in a drum mix plant, the fiber line may be placed in the drum beside the asphalt binder line and merged into a mixing head. This allows the fibers to be captured by the asphalt binder before being exposed to the high-velocity gases in the drum. If the fiber does get into the gas stream in large quantities, it will enter the dust control system of the plant.

The pelletized form of fibers can be used in both drum mix and batch plants. The pellets are shipped to the plant in bulk form and when needed are placed in a hopper. From the hopper they can be metered and conveyed to the drum or pugmill via a calibrated conveyor belt. Addition of the pellets occurs at the RAP collar of the drum mix plant or they are added directly into the pugmill of a batch plant. Here the pellets are mixed with the aggregate where the heat from the aggregates causes the asphalt binder in the pellets to become fluid allowing the fiber to mix with the aggregate.

The pelletized fibers do contain a given amount of asphalt binder that must be accounted for in the overall asphalt content of the mixture. Check with the fiber manufacturer to determine the asphalt contents of the pellets. It is again imperative that the fiber addition, whether it be bulk or pelletized, be calibrated to ensure that the mixture continually receives the correct amount of fiber. If the fiber content is not accurately controlled at the proper level, fat spots will almost certainly result on the surface of the finished pavement. For assistance with the fiber storage, handling, and introduction into the mixture, the fiber manufacturer should be consulted.

7.1.3.2 *Asphalt Cement Modifiers* - Another method of providing stabilization to PFC is with the use of asphalt binder modifiers. The asphalt binder in PFC can be modified at the refinery, or, in some cases, the modifier is added at the hot mix plant. For the first method, the hot mix producer takes delivery of the modified asphalt binder and meters it into the mixture in a traditional manner. Special storage techniques and/or temperatures may be required. With the second method, the contractor must ensure that the proper amount of modifier is added and thoroughly mixed with the asphalt binder.

When an asphalt binder modifier is added at the hot mix plant, two different methods are utilized. The modifier is either blended into the asphalt binder before it is injected into the mixture or it is added directly to the dry aggregates during production. Addition of the modifier to the asphalt binder is accomplished by in-line blending or by blending the two in an auxiliary storage tank. If the modifier is added to the aggregates rather than the asphalt binder, it can be added directly into the pugmill or, in a drum mix plant, it can be delivered to the drum via the RAP delivery system. Use of the RAP belt weigh bridge is not recommended because of poor accuracy and a special metering device may be necessary if the RAP feeder cannot be calibrated.

7.2 Mixture Production - Production of PFC is similar to production of standard HMA from the standpoint that care should be taken to ensure a quality mixture is produced. Production of PFC is discussed in this section with special emphasis on production areas where PFC quality may be significantly affected. Facilities utilized to produce PFC should meet the requirements of M156.

7.2.1 Plant Calibration - It is important that all the feed systems of the plant be carefully calibrated prior to production of PFC. The aggregate cold feeds can make a large difference in the finished mixture even in a batch plant where hot bins exist. Calibration of the aggregate cold feed bins should therefore be performed with care.

The stabilizing additive delivery system should be calibrated and continually monitored during production. Whether fibers, an asphalt binder modifier, or both are being utilized, variations in the amount of additive can have a detrimental impact on the finished pavement. Stabilizing additive manufacturers will usually assist the hot mix producer in setting up, calibrating, and monitoring the stabilizing additive delivery system.

7.2.2 Plant Production Temperature - Production temperatures of PFC mixtures vary somewhat according to aggregate moisture contents, weather conditions, grade of asphalt binder and type of stabilizing additive used. However, experience indicates that normal HMA production temperatures or slightly higher are adequate. Typically, a temperature of 293-310°F (145-155°C) can be used when a polymer is not included. Temperatures higher than this may be needed on some occasions, such as when a polymer modifier is added, but should be used with caution as rapid oxidation begins to occur at higher temperatures. The PFC mixture should never be heated above 350°F (176°C) since this may excessively damage the asphalt binder and may increase plant emissions. As the mixture temperature is increased, the chance of the mortar draining from the coarse aggregate also increases. The temperature should be chosen to ensure a uniform mixture that allows enough time for transporting, placing, and compaction of the mixture.

7.2.3 Mixing Time - When adding fibers to the PFC mixture, experience has shown that the mixing time should be increased slightly over that of conventional HMA. This additional time allows for the fiber to be sufficiently distributed in the mixture. In a batch plant this requires that both the dry and wet mix cycles be increased from 5 to 15 seconds each. In a parallel flow drum mix plant, the asphalt binder injection line may be relocated, usually extended, if necessary to provide improved mixing. When blowing fibers into a drum mix plant, it is imperative that the fiber line be placed in the drum beside the asphalt binder line and merged into a mixing head.The proper mixing times can be estimated by visual inspection of the mixture. If clumps of fibers or pellets still exist intact in the mixture at the discharge chute, or if aggregate particles are not sufficiently coated, mixing times should be increased or other changes made. For other plants such as double barrels and plants with coater boxes, the effective mixing time can be adjusted in a number of ways including reduction in production rate, slope reduction of the drum, etc.

7.2.4 Mixture Storage - The PFC mixture should not be stored at elevated temperatures for longer than 2 hours. This could facilitate draindown.

7.3 Placement and Compaction Procedures

7.3.1 Weather Limitations - In order to achieve proper placement and compaction, PFC should not be placed in cold or inclement weather. It is recommended that a minimum pavement temperature of 50°F (10°C) be achieved prior to placement. However, the ability to place PFC will also depend on wind conditions, humidity, the lift thickness being placed and the temperature of the existing pavement.

7.3.2 Mixture Transportation - Haul times for PFC should be as short as possible. It is important that the temperature of the PFC mixture not be raised arbitrarily high in order to facilitate a longer haul time. Most agencies limit haul distance to 50 miles or haul times to 1 hour. Due to high asphalt binder contents, PFC may adhere to truck beds somewhat more than conventional HMA mixtures. This is particularly true when asphalt binder modifiers are employed in the mixture. It is therefore prudent to use a release agent and clean the truck beds frequently. Most agencies have approved lists of release agents. However, if not carefully utilized, these agents may cause problems. If the agent is allowed to pool in the bottom of the truck it may cause cold spots. The bed of the truck should be coated and the excess agent removed before loading. This can be accomplished by raising the truck bed after the agent has been sprayed into the truck. Any excess agent will then be discharged. Use of fuel oils in any form should be strictly prohibited. All transport vehicles should be tarped with the tarps tightly drawn and tied over the truck bed.

7.4 Pavement Surface Preparation - When placing PFC, preparation of the surface to be covered will depend on the type of surface; this preparation is generally the same as for conventional HMA. PFC is normally applied in any of several situations: over an old HMA pavement, over an old Portland cement concrete pavement or over a new HMA binder course. If an old pavement surface is to be covered by PFC then proper repair should first be performed. Areas containing large permanent deformations should be milled or filled using a leveling course. If the condition of the in-place mix is sufficiently bad it may have to be removed to some predetermined depth. Lightly and randomly cracked surfaces should have wide cracks cleaned and sealed. If the entire surface is randomly cracked a full-width treatment is needed to make the surface impermeable. Any distressed areas should be properly repaired. A tack coat should be applied after repairs and prior to placement of the PFC. For old and new surfaces, a tack coat should be used. Types of materials and their application rates need to vary from that of conventional HMA construction. Freshly compacted dense-graded HMA may be as much as 8 percent air voids and permeable to water. A uniform tack coat should be applied prior to placement of the PFC. Tack coats should be applied using a distributor truck that has been calibrated in accordance with D2995.

7.5 Paver Operation

7.5.1 Charging the Paver - The PFC mixture is normally delivered to the paver in the traditional manner of backing in trucks. A material transfer vehicle (MTV) can also be used for PFC

7.5.2 Paver Calibration - Prior to placement of the PFC, the paver should be correctly calibrated. This is no different than when placing conventional HMA and involves the flow gates, the slat conveyors, and the augers. The flow gates should be set to allow the slat conveyors to deliver the proper amount of mixture to the augers so that the augers turn 85-90 percent of the time.

7.5.3 Paving Speed - When placing PFC, the paving speed is for the most part dictated by the ability of the rolling operation to compact the mixture. It is critical that the plant production, mixture delivery, placement, and compaction be coordinated so that the paver does not have to continually stop and start. Paver stops and starts should be held to an absolute minimum because they will likely have a significant negative impact on the ride. In addition to continuous paver movement, the PFC mixture delivery and paver speed should be calibrated so that the augers can be kept turning 85-90 percent of the time. This helps ensure the slowest possible speed for the augers. Running the augers very fast for short periods of time should be avoided. The high auger speed may have a tendency to shear the mortar from the coarse aggregate thus causing fat spots in the pavement. Generally, the paver wings should not be lifted except when the material is to be discarded.

7.5.4 Lift Thickness - The majority of PFC pavements have been placed ¾ to 1¼ inches thick. It is imperative that the construction inspector not try to balance yield by adjusting the thickness of the PFC lift. This can cause unsatisfactory pavements to be built. A tolerance of ± ¼ inch in the lift thickness is allowable.

7.5.5 Placement and Finishing - Immediately behind the paver, PFC mixtures are known to be harsh and very sticky. For this reason a minimum of raking and hand working should be performed. When needed, hand placement of the material can be accomplished with care.

7.6 Rolling – Compaction of PFC is conducted to seat the aggregates. Rolldown of PFC mixtures is slightly more than one-half that for conventional HMA mixtures. While conventional HMA mixtures roll down approximately 20-25 percent of the lift thickness, PFC will normally roll down 10-15 percent of the lift thickness. Therefore, to match longitudinal joints, the hot side should be 10-15 percent of the lift thickness or higher. Static, steel-wheel rollers should be used to compact PFC mixes. Rubber-tire pneumatic rollers should not be used as they tend to pick up material. Vibratory steel-wheel rollers should only be used for transverse joints.

7.7 Quality Control/Quality Assurance

7.7.1 Aggregates - As with conventional HMA, the producer should periodically monitor the aggregate stockpiles being used for the production of the PFC mixture. Stockpile gradations can change as additional material is added to the stockpile during mixture production. Even if the stockpiles do not receive additional aggregates during mixture production, their gradations may change due to stockpiling and/or load out procedures. Therefore the monitoring program must be frequent enough to warn the producer that a change has taken place before a significant amount of the aggregate has been used in PFC mixtures. In batch plant operations, hot bin analyses should also be performed. This testing serves as a further check of aggregate gradations. In both batch and drum mix plants the cold feed gradations should be monitored. Variations or deviations of aggregate gradation from the specified job-mix-formula are often more critical to the performance of PFC mixtures than they are for HMA. Therefore, close control of gradation must be accomplished for these mixtures.

7.7.2 Asphalt Binder - The asphalt binder used in the PFC should be tested as it is for any conventional HMA project. Some modified asphalt binders may require special testing techniques.

7.7.3 Trial Sections - Prior to full-scale production and placement, a trial section of the mixture should be produced and placed by the contractor. This trial section should be at the actual construction site and should be at least two paver widths wide. The trial section should consist of between 220 and 550 tons (200 and 500 Mg) of mixture. The length of the trial section will depend upon the capacity of the plant and other variables in the mixture production and placement. However, the trial section needs to be of sufficient size to allow the plant components to operate to the point of producing consistent mixture. The trial section is a good opportunity to determine any proportioning problems with the final job-mix-formula (JMF). The trial section should be constructed in advance of the production paving so as to allow for testing and adjustment in the JMF and to allow for a second trial section if major adjustments need to be made.

7.7.4 Mixture Sampling - Most agencies have established their own requirements for where and how mixture sampling must be done. PFC should be sampled according to these recognized procedures. Experience has shown that quartering of PFC can be difficult due to its tendency to stick to the tools thus potentially causing a low asphalt content to be measured. Frequency of sampling and testing is usually established by the owner. As a minimum, at least two test series per day (gradations, asphalt contents, volumetrics and draindown) should be performed. More frequent testing is advisable in order to maintain good quality control. Many agencies divide the mixture into lots and sublots and require two or three test series per lot. In addition, the time at which samples are taken should be obtained randomly so as not to bias the results.

7.7.5 Mixture Tests -Certain test data on the mixture must be collected to allow the producer of PFC to control the mixture as well as to allow the owner the ability to accept or reject the mixture. These tests are generally similar to those performed on conventional HMA.

7.7.5.1 *Laboratory Compacted Specimens* - Laboratory compacted specimens should be examined for compliance with volumetric properties established for the mixture. These tests consist of compacting specimens using 50 gyrations of the Superpave Gyratory Compactor (SGC). The bulk specific gravity of the specimens can be determined by dimensional measurements, while the maximum theoretical specific gravity is determined by AASHTO T209. Air voids may then be determined. The resulting air voids should be within the specified range shown in Table 5.

7.7.5.2 *Asphalt Content and Gradation* - The stabilizing additives used in PFC can sometimes hinder the extraction process and some experimentation may be necessary to determine the optimum method of extracting the mixture. Most agencies allow one or more of any of the methods discussed in AASHTO T164. Note that while Method B is very reliable, it is generally not suited for field work due to the length of time needed for the test. The asphalt content by ignition method (T308) has also been shown to work well for determining the asphalt binder content of PFC. After removing the asphalt binder the aggregate should be graded according to AASHTO T27. The resulting gradation and asphalt content should meet the JMF established for the mixture within the tolerance limits specified. Typical tolerance limits for gradations are shown in Table 6.

Table 6: Gradation Tolerances for Extracted PFC Samples.

Sieve Size	Percent Passing Tolerance
19.0-mm (¾ Inch)	± 4.0
12.5-mm (½ Inch)	± 4.0
9.5-mm (⅜ Inch)	± 4.0
4.75-mm (No. 4)	± 3.0
2.36-mm (No. 8)	± 3.0
0.60-mm (No. 30)	± 3.0
0.30-mm (No. 50)	± 3.0
0.075-mm (No.200)	± 2.0
Asphalt Content (%)	± 0.3

7.7.5.3 *Draindown Test* - Since the PFC mixture must have some stabilizing additive to prevent draindown of the mortar from the coarse aggregate, mixture samples should also routinely be checked for compliance with draindown requirements in accordance with T305.

Standard Method of Test for Determining the Abrasion Loss of Permeable Friction Course (PFC) Asphalt Specimens by the Cantabro Procedure

AASHTO Format

DRAFT

Standard Method of Test for

Determining the Abrasion Loss of Permeable Friction Course (PFC) Asphalt Specimens by the Cantabro Procedure

AASHTO Designation: T XXX-YY

1. SCOPE

1.1 This standard covers a test method for determining the percent abrasion loss of permeable friction course (PFC) asphalt specimens using the Los Angeles abrasion machine.

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

2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards:*

- M 231, Weighing Devices Used in the Testing of Materials
- R 30, Mixture Conditioning of Hot-Mix Asphalt (HMA)
- T 96, Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
- T 209, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
- T 312, Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor

2.2 *ASTM Standards:*

- E 1, Specification for ASTM Thermometers
- D 3549, Standard Test Method for Thickness or Height of Compacted Bituminous Mixture Specifications
- D 7064, Standard Practice for Open-Graded Friction Course (OGFC) Mix Design

2.3 *European Standards:*

- EN 12697 - 17, Bituminous mixtures. Test methods for hot-mix asphalt. Particle loss of porous asphalt specimen

3. TERMINOLOGY

3.1 *Definitions:*

3.1.1 *permeable friction course (PFC)*—a special type of porous hot-mix asphalt mixture with air voids of at least 18% used for reducing hydroplaning and potential for skidding, where the function of the mixture is to provide a free-draining layer that permits surface water to migrate laterally through the mixture to the edge of the pavement.

3.1.2 *asphalt binder*—an asphalt-based cement that is produced from petroleum residue either with or without the addition of non-particulate organic modifiers.

3.1.3 *abrasion loss*—the loss of particles under the effect of abrasion.

3.1.4 *air voids*—the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the total volume of the compacted specimen.

3.1.5 *stabilizing additive*—materials used to minimize draindown of asphalt during transport and placement of PFC.

4. SUMMARY OF TEST METHOD

4.1 A single specimen of compacted PFC is placed within the drum of a Los Angeles abrasion machine without the charge of steel spheres. The specimen is subjected to a total of 300 revolutions within the Los Angeles abrasion drum. At the conclusion of the test, the percent material loss is determined based upon the original mass of the specimen.

5. SIGNIFICANCE AND USE

5.1 The procedure described in this test standard is used to indirectly assess the cohesion, bonding, and effects of traffic abrasion and, when used with other tests, to determine the optimum asphalt binder content during PFC mixture design that will provide good performance in terms of permeability and durability when subjected to high volumes of traffic. The procedure can be used for either laboratory or field specimens.

6. APPARATUS

6.1 *Los Angeles Abrasion Machine*—as specified in AASHTO T 96.

6.2 *Thermometers*—armored, glass, or dial-type with metal stems as set out in ASTM E 1. To measure the temperatures of the aggregates, binder, and PFC mixture, metal thermometers with a scale up to 200 ºC (392 ºF) and an accuracy of ±3 ºC (±5 ºF) or better shall be used. To measure the test temperature, a thermometer with a scale from 0 ºC to 40 ºC (32 ºF to 104 ºF) and an accuracy of ±0.5 ºC (±1 ºF) shall be used.

6.3 *Balances*—meeting the requirements as set out in AASHTO M 231 having suitable capacity and accuracy of 0.1% of the mass to be weighed.

6.4 *Oven*—meeting the requirements of M 231 with closed ventilation system, or chamber thermostatically controlled to maintain test temperature at ±1 ºC (±2 ºF) in the vicinity of the samples. The oven shall be capable of maintaining the temperature required in accordance with AASHTO R 30.

6.5 *Chamber*—or enclosed room large enough to hold the Los Angeles machine with temperature controls adjustable to a maximum margin of error of ±2 ºC (±4 ºF). This temperature being measured in the air close to the Los Angeles machine.

6.6 *General materials*—trays, pots, spatulas, heat-resistant gloves, grease pencils, curved scoops, filter paper rings, etc.

7. HAZARDS

7.1 Use standard safety precautions and protective clothing when handling hot materials and preparing test specimens.

8. SAMPLES AND TEST SPECIMENS

8.1 Specimens may be either laboratory-molded PFC mixtures.

8.2 A total of three (3) specimens are required per mixture being tested.

8.3 Preparation of Laboratory-Molded Specimens

8.3.1 Prepare replicate mixtures (Note1) at the appropriate aggregate gradation and asphalt binder content.

NOTE 1: Three replicate specimens are required, but five specimens may be prepared if so desired. Generally, 4500 to 4700 g of aggregate is sufficient for each compacted specimen with a height of 110 mm to 120 mm for aggregates with combined bulk specific gravities of 2.55 to 2.70, respectively.

8.3.2 Condition the specimens according to R30 and compact the specimens to 50 gyrations in accordance with T312. Record the specimen height to the nearest 0.1 mm after each revolution.

8.3.3 *Density and Voids*—Once the specimens have been compacted, cooled to ambient temperature, and removed from the molds, determine their relative density and voids content using bulk specific gravity (see NOTE-2) and AASHTO T 209.

NOTE 2: The bulk density of a cylindrical-shaped specimen of PFC shall be calculated from the compacted specimen's dry mass (in grams) and volume (in cubic centimeters). In order to obtain the specimen volume, determine the height of the specimen in accordance with ASTM E3549 using calibrated calipers and the diameter of the specimen as the average of four equally spaced measurements using the same calipers. Calculate the area of the sample using the average diameter determined as described above. Calculate the volume of the specimen by multiplying the sample area and the average height. Calculate the bulk density by dividing the dry mass of the specimen by the calculated volume of the specimen. Convert the bulk density to bulk specific gravity by dividing by 0.99707 g/cm^3, the density of water at 25ºC (77ºF).

---

9. PROCEDURE

9.1 The test temperature is 25ºC (77ºF) and should be maintained during the test with a maximum margin of error of ±2 ºC (±4 ºF).

9.2 The mass of the compacted specimen shall be determined to within ± 0.1 g and the value recorded as $W1$. Before testing, specimens must be kept at the test temperature for at least 4 hours.

9.3 After the specimens have been kept at the test temperature for the required period of time, one specimen is placed inside the Los Angles abrasion machine drum and, without the charge of steel spheres, the drum is turned at 300 revolutions at a velocity of 188 to 207 radians per second (30 to 33 revolutions per second) per T96.

9.4 When the test is completed, the specimen is removed from the drum, slightly cleaned with a cloth eliminating particles that are clearly loose, and weighed again to within ± 0.1 g and this value recorded as $W2$.

9.5 The test is repeated in the same way for each of the specimens prepared.

---

10. INTERPRETATION OF RESULTS

10.1 For each sample, the particle loss (percent) is determined using the following equation:

$$PL = [(W1 - W2) / W1] \times 100$$

where:

PL = Cantabro abrasion percent loss,
$W1$ = initial weight of the specimen, and
$W2$ = final weight of the specimen

10.2 Calculate the mean particle loss of all specimens tested. Round the result to the nearest 1%.

10.3 The values obtained from the test and, if required, the density and voids of specimens, are reported together with the test temperature.

NOTE 3: The Cantabro abrasion test method was originally developed in Spain in 1986 and entitled *Cantabrian Test of Abrasion Loss*. The original Spanish test was based on a 50 blow Marshall compaction effort. If the user is unfamiliar with the Cantabro test, the results should be evaluated with considerable engineering judgment until some experience related to actual performance has been developed. ASTM D 7064 and European Standard EN 12697-17 were used to assist in the development of this test procedure.

11. REPORT

11.1 Report the following information, if applicable:

11.1.1 Project name;

11.1.2 Date(s) of preparation and testing;

11.1.3 Specimen identification;

11.1.4 Percent binder in each specimen, nearest 0.1 percent;

11.1.5 Mass of each specimen, $W1$, nearest 0.1 g;

11.1.6 Mass of each specimen, $W2$, nearest 0.1 g;

11.1.7 Test temperature;

11.1.8 Maximum specific gravity (G_{mm}) of each specimen by T 209, nearest 0.001;

11.1.9 Bulk specific gravity (G_{mb}) of each specimen, nearest 0.001;

11.1.10 The particle loss for each specimen tested and the mean value for all specimens, nearest 1%.

11.1.11 Density and voids of each specimen, if required.

12. PRECISION AND BIAS

12.1 The research required to determine the precision of this standard has not been performed. There is no information that can be presented on the bias of the procedure because no material having an accepted reference value is available.

13. KEYWORDS

13.1 permeable friction courses, gyratory, Cantabro Abrasion

Standard Practice for Maintenance and Rehabilitation of Permeable Friction Courses (PFC)

AASHTO Format

D R A F T

Standard Practice for

Maintenance and Rehabilitation of Permeable Friction Courses (PFC)

AASHTO Designation: PP XXX-YY

1. SCOPE

1.1 This standard covers activities related to the maintenance and rehabilitation of permeable friction course (PFC) asphalt mixtures.

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

2. REFERENCED DOCUMENTS

2.1 AASHTO Standard

3. TERMINOLOGY

3.1 Definitions

3.1.1 *Permeable Friction Courses (PFC)* – special type of porous hot-mix asphalt mixture with air voids of at least 18 percent used for reducing hydroplaning and potential for skidding, where the function of the mixture is to provide a free-draining layer that permits surface water to migrate laterally through the mixture to the edge of the pavement.

4. SUMMARY OF PRACTICE

4.1 Maintenance of PFC mixtures is different than conventional dense-graded hot-mix asphalt. Maintenance can be generally grouped into one of two categories: general maintenance and winter maintenance. General maintenance involves activities such as cleaning of clogged PFC, preventative surface treatments, and corrective surface treatments. Winter maintenance involves those activities required to maintain a safe driving surface during winter events.

4.2 Rehabilitation of PFC layers involves those activities required to correct major surface distresses.

---

5. SIGNIFICANCE AND USE

5.1 The information in this practice is used to make decisions on methods for maintaining or rehabilitating PFC pavements.

---

6. MAINTENANCE

6.1 Maintenance activities can be broadly grouped into one of three categories: cleaning clogged PFC, preventative surface maintenance and corrective surface maintenance.

6.1.1 Over time, PFCs may gradually become choked and lose the ability to drain water due to dirt and debris entering the void structure. Therefore, cleaning may be necessary. Three methods have been utilized for cleaning PFC layers: a) cleaning with a fire hose, b) cleaning with a high water pressure cleaner, and c) cleaning with a specially manufactured cleaning vehicle. Research has indicated that cleaning PFC layers can be difficult if the cleaning activities are initiated after the layer has become clogged. Best results have been encountered when cleaning activities are initiated prior to the layer becoming clogged.

6.1.2 Fog seals have been used as a preventative surface maintenance treatment. Fog seals do reduce the permeability of PFC layers. Additionally, fog seals will reduce the frictional properties of the surface until the fog seal is worn away by traffic. Experience suggests this will take approximately one month. Fog seals do not affect the macrotexture of PFC layers; therefore, the reduced potential for hydroplaning is maintained.

6.1.3 Corrective surface maintenance activities are those conducted to repair minor surface distresses in PFC layers. Corrective surface maintenance can also be considered minor rehabilitation.

6.1.3.1 Occasionally, PFC layers will require the repair of delaminated areas and potholes. When distressed areas are large enough to justify, milling and overlaying with PFC has been recommended. If the distressed area is relatively small, a dense-graded hot-mix asphalt can be utilized for such patch repairs. It is desirable to maintain the drainage characteristics of the PFC layer when undertaking patch repairs. When the patch area is small and the flow of water around the patch is ensured, dense-graded hot-mix asphalt can be used. Rotation of the patch to a 45-degree angle to provide a diamond shape is recommended because it will facilitate the flow of water along the patch material and will also diminish wheel impact on the patch joint. When patching with PFC material, only a light tack coat should be applied to vertical faces.

6.1.3.2 PFC layers can develop transverse and longitudinal cracks while in service. Narrow cracks are generally not visible because of the open texture of the PFC surface. When cracks appear, they should be sealed. There is no problem in sealing the transverse cracks because the crack sealer will not impede the flow of water within the PFC. Sealing longitudinal cracks in PFC is problematic because the crack sealer could impede the transverse flow of water within the layer. One potential solution is to mill off the PFC in a narrow strip over the longitudinal crack and place an inlay with PFC material. If the longitudinal crack is also present in the underlying course, it must be sealed properly. Only a light tack coat should be applied to the vertical faces of the existing pavement. The other option is to rehabilitate the layer if the severity of the crack becomes too high.

6.2 Winter Maintenance

6.2.1 The literature and experience suggest several constants that are related to the winter maintenance of PFCs, including: a) PFC layers behave differently than dense-graded layers during winter events; b) PFC layers have a pavement temperature cooler than typical dense-graded layers at ambient temperatures just above and below freezing; c) PFC layers reach freezing temperature prior to dense-graded layers and stay at freezing temperatures longer than dense-graded layers; and d) PFC layers required more winter maintenance chemicals than typical dense-graded layers during winter events. Beyond these constants, the literature and experience suggest that each agency appears to have different winter maintenance strategies. Experience suggests that each agency should utilize special, locally adjusted strategies for winter maintenance.

7. REHABILITATION OF PERMEABLE FRICTION COURSE

7.1 Rehabilitation of PFC layers can be categorized as minor or major rehabilitation activities. Minor rehabilitation involves correcting small, localized areas. Minor rehabilitation activities are identical to the corrective surface maintenance activities described in Section 6.1.3.1. Major rehabilitation is conducted when the entire layer is in need of replacement or refurbishment.

7.1.1 The most common method of rehabilitating PFC layers is to mill the entire old PFC layer and replace with another PFC layer or other type hot-mix asphalt layer. Some agencies have milled a PFC layer and placed a PFC inlay; however, this would only occur if the shoulders are also a PFC. One agency has expressed concerns about placing PFC on milled surfaces. The concern is that the grooves left by the milling operation may hold water due to the permeable nature of a PFC. This agency is investigating micro-milling as an alternative to milling.

7.1.2 PFC layers should not be overlaid with dense-grade hot-mix asphalt.

7.1.3 There is some evidence in Europe that hot in-place recycling can be utilized to rehabilitate a PFC layer.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation