Burns Cooley Dennis, Inc.
Geotechnical, Pavements and Materials Consultants

# IMPROVED POROUS FRICTION COURSES (PFC) ON ASPHALT AIRFIELD PAVEMENTS

## Volume I: Final Report

**for**

## AAPTP PROJECT 04-06

**Submitted to**

**Airfield Asphalt Pavement Technology Program**

**By**

**Burns Cooley Dennis, Inc.**
**551 Sunnybrook Road**
**Ridgeland, Mississippi 39157**

### ACKNOWLEDGMENT OF SPONSORSHIP

This report has been prepared for Auburn University under the Airport Asphalt Pavement Technology Program (AAPTP). Funding is provided by the Federal aviation Administration (FAA) under Cooperative Agreement Number 04-G-038. Dr. David Brill is the Technical manager of the FAA Airport Technology R&D branch and the Technical manager of the Cooperative Agreement. Mr. Monte Symons served as the Project Director for this project. The AAPTP and the FAA thank the Project Technical Panel that willingly gave of their expertise and time for the development of this report. They were responsible for the oversight and the technical direction. The names of those individuals on the Project Technical Panel follow:

1. Ryan King
2. Gary G. Harvey
3. John Cook

### DISCLAIMER

**July 2007**

# *IMPROVED POROUS FRICTION COURSES (PFC) ON ASPHALT AIRFIELD PAVEMENTS*

***Draft Final Report***

***for***

## *AAPTP Project 04-06*

**Submitted to**

**Airfield Asphalt Pavement Technology Program**

**By**

L. Allen Cooley, Jr., Ph.D.
Senior Materials/Pavements Engineer
Burns Cooley Dennis, Inc.
551 Sunnybrook Road
Ridgeland, Mississippi 39157

R. C. Ahlrich
Principal
Burns Cooley Dennis, Inc.
551 Sunnybrook Road
Ridgeland, Mississippi 39157

Donald E. Watson
Research Engineer
National Center for Asphalt Technology
277 Technology Parkway
Auburn, Alabama 36830

P. S. Kandhal, P.E.
Associate Director Emeritus
National Center for Asphalt Technology
277 Technology Parkway
Auburn, Alabama 36830

June 2007

# Table of Contents

# List of Figures

# List of Tables

# Acknowledgements

The research documented in this Report was performed under Airfield Asphalt Pavement Technology Program Project 04-06 by Burns Cooley Dennis, Inc. L. Allen Cooley, Jr., Senior Pavements/Materials Engineer, of Burns Cooley Dennis, Inc. was the Principle Investigator and was primarily responsible for the technical supervision of this research. Dr. Randy Ahlrich, Principal of Burns Cooley Dennis, Inc., was the Co-Principal Investigator and provided significant assistance and technical oversight. Significant assistance was also provided by Mr. Donald Watson, Research Engineer at the National Center for Asphalt Technology, and Mr. Prithvi Kandhal, Associate Director Emeritus for the National Center for Asphalt Technology.

The authors of this report would like to thank Mr. Monte Symons, Project Director of the Airfield Asphalt Pavement Technology Program, for his input and guidance during the course of this project. The researchers would also like to extend thanks to the Project Panel for comments and guidance provided on quarterly reports. Finally, the authors would like to thank the many Airfield Pavement Engineers that provided valuable information through phone interviews.

# Abstract

Airfield Asphalt Pavement Technology Program Project 04-06, Improved Porous Friction Courses (PFC) on Asphalt Airfield Pavements, was conducted to develop technical guidance and direction to improve the performance of porous friction course mixtures on airfield pavements. The research approach entailed interviewing airfield pavement engineers and conducting a literature review. Information gathered during the research, as well as the experiences of the research team, was synthesized and used to provide guidance in the areas of materials and mix design, production/construction, maintenance and rehabilitation, advantages/disadvantages, and performance. Where applicable, improvements to the current state of practice for airfield porous friction courses were recommended. Also where applicable, recommendations for future research were made.

Porous friction courses have been around since the 1930's. These hot mix asphalt mixture types have proven an effective method for improving the frictional characteristics of pavements, especially in wet weather. Even though porous friction courses have been around for many, many years, performance has been mixed. There have been reports of rapid and catastrophic occurrences of raveling within porous friction course layers. Any raveling that occurs will result in potential foreign object damage (FOD) for aircraft. Also, there have been reports of these layers tearing at locations where high speed turns or locked wheel turns take place.

Because of the safety benefits associated with porous friction courses, the highway industry has conducted a significant amount of research on porous friction courses over the last 10 to 15 years. This research has led to improvements in the methods for specifying materials and design mixtures. These improvements have led to a more durable mixture that has alleviated some of the past problems associated with porous friction courses. In comparison to the highway industry, little work on the use of porous friction courses for airfield pavements has been conducted over the last 10 to 15 years.

Using the experiences of seasoned airfield pavement engineers, published papers, articles, and reports, and the experiences of the research team, guidelines were developed for materials selection, mix design, production/construction, maintenance and rehabilitation. The majority of research available dealt with the specification of materials and the design of porous friction courses. For this reason, recommendations were provided for improving the design of airfield porous friction courses. Experiences of various countries with the maintenance and rehabilitation of porous friction courses were provided. Unfortunately, the practices of each agency evaluated were not always similar. This likely reflects the different environmental conditions experienced by the different agencies. Very little published information was obtained specifically on producing and constructing porous friction courses. The experiences of the airfield pavement engineers and research team along with published best practices for the production and construction of hot mix asphalt were used to develop guidance for the construction of porous friction courses.

# Summary of Findings

Airfield Asphalt Pavement Technology Program Project 04-06, Improved Porous Friction Courses (PFC) on Asphalt Airfield Pavements, was conducted to develop technical guidance and direction to improve the performance of porous friction course mixtures on airfield pavements. The research approach entailed interviewing airfield pavement engineers and reviewing reports, articles and specifications on the use of porous friction courses. No specific laboratory or field investigations were performed. Information gathered during the research, as well as the experiences of the research team, was synthesized and used to provide guidance in the areas of materials and mix design, production/construction, maintenance and rehabilitation, advantages/disadvantages, and performance. Where applicable, improvements to the current state of practice for airfield porous friction courses were recommended. Also where applicable, recommendations for future research were made.

Improvements recommended within this report are in direct response to the documented issues and past failures encountered. The literature and interview with airfield pavement engineers indicated that raveling, moisture damage and delamination have been the primary distresses encountered in PFCs. These distresses can be related to the materials selected, design and construction of PFCs. Porous friction courses are specifically specified to have an open gradation. This open gradation provides the benefits related to improved wet weather friction and reduced potential for hydroplaning. Because of the open grading, there is very little surface area of the aggregates which results in a relatively thick asphalt binder film coating the aggregates. At typical production/construction temperatures, the heavy film of asphalt binder had a propensity to drain form the aggregate structure. Because of the draindown issues, a typical remedy was to reduce production temperatures. This reduction in temperature resulted in an increase viscosity for the asphalt binder which assisted in holding the asphalt binder on the aggregates. However, this reduction in temperature also led to the durability problems listed above. First, because the production temperature was reduced, all of the internal moisture within the aggregates was not removed. Moisture remaining within the aggregates led to increased potential of stripping which resulted in an increased occurrence in raveling. Additionally, the reduced temperatures prevented the new PFC from properly bonding with the tack coat placed on the underlying layer. Both of these issues resulted in FOD.

The recommended mix design method included four primary steps: 1) materials selection; 2) selection of design gradation; 3) selection of optimum asphalt binder content; and 4) evaluation of moisture susceptibility. Within the materials selection step, tests were recommended to better characterize the properties of aggregates used in PFCs. Tests were recommended to evaluate aggregate toughness, durability, angularity, shape and cleanliness. It was also recommended that modified asphalt binders and stabilizing additives be utilized within PFCs in order to improve durability by allowing higher production temperatures, without increasing the potential for draindown. Stabilizing additives recommended were modified asphalt binders and/or fibers. Porous friction course gradation bands were recommended. The recommended bands were selected to maximize the amount of water that could infiltrate the PFC layer while providing sufficient shear strength to resist the actions of braking tires. Within the selection of optimum asphalt binder content step of the mix design procedure, performance related tests were recommended instead of the Centrifuge Kerosene Equivalent method.

Performance related tests included evaluation of the existence of stone-on-stone contact, the Cantabro Abrasion loss test, and draindown potential testing. The Cantabro Abrasion test was recommended to establish a minimum asphalt binder content for durability, while the draindown testing was recommended to establish a maximum asphalt binder content to minimize the potential for draindown during construction.

No specific research was found that evaluated various construction techniques for PFCs. Therefore, the research provided guidelines, or best practices, for the construction of PFCs. Guidance is provided for plant production, transportation, placement, compaction and quality control/quality assurance of PFC mixes for airfield pavements. Much of the guidance was obtained from information on the construction of stone matrix asphalt mixtures. Stone matrix asphalt and PFC mixes are somewhat similar because of the gapped aggregate grading and typical use of modified asphalt binders and stabilizing additives.

Various reports, papers and articles from around the world were reviewed to provide a synthesis of current maintenance practices on PFC pavements. The synthesis provides the experiences of the different agencies with respect to general maintenance and winter maintenance. General maintenance involves maintaining the drainage capacity of PFCs. The ability of PFCs to drain water from the pavement surface greatly minimizes the potential for hydroplaning during rain events. Winter maintenance activities by the various agencies were not always similar and likely reflect the varying environmental conditions common to the different agencies.

# CHAPTER 1
# Introduction and Research Approach

## INTRODUCTION

According to Federal Aviation Administration (FAA) statistics, over 700 million passengers enplaned on commercial flights at primary and non-primary airports within the US during 2005 (1). Because of the vast number of people flying, it is imperative that pavement engineers design safe pavement surfaces for aircraft operations. In order to provide safe pavements, the pavements must be strong, smooth, skid resistant, structurally intact and have adequate surface drainage (2). Pavement strength is related to the ability of the pavement to withstand the loads of aircraft. Structurally intact refers to the existence of distresses on the pavement. For instance, rutting in hot mix asphalt (HMA) layers allows water to become pooled on the pavement surface which can lead to an increased potential for hydroplaning. Additionally, rutting can affect the directional control of aircraft. Also, distresses that result in raveling can cause foreign object damage (FOD).

Pavements that are not smooth can result in aircraft performance and control problems. Because of the high speeds that aircraft travel during take-off and landing, pavement roughness on runways can result in aircraft structural damage and component fatigue; aircraft becoming prematurely airborne; reduction in contact between tires and the pavement surface; aircraft vibrations making on-board instruments difficult to read; and/or discomfort for passengers (2).

Airfield pavements must have adequate surface drainage to promote rapid runoff of water during rain events (2). Without proper surface drainage, water may accumulate on the pavement surface and result in an increased potential for hydroplaning. If pools of water are too deep, aircraft may also encounter problems with directional control.

The final characteristic of a quality airfield pavement is skid resistance. For pavements, skid resistance is generally expressed in terms of friction. Pavement friction is a major safety concern for the performance of both civil and military airfields. For military aircraft carrying ordinance, pavement friction is extremely important (3). Frictional properties are most critical during wet conditions. Friction characteristics on dry pavements tend to vary little (4) and are normally adequate for maneuvers necessary during most airfield circumstances.

## Tire/Pavement Friction

Friction defined is the relationship between the vertical and horizontal forces developed as a tire slides along a pavement surface. ASTM E-867, *Standard Terminology Relating to Traveled Surface Characteristics*, defines friction as the ability of a traveled surface to prevent the loss of traction upon braking. In essence, frictional resistance is the force that is created when a tire that is prevented from rotating slides along the top of a pavement surface (5). The magnitude of frictional resistance developed by a braking vehicle or aircraft depends upon pavement surface characteristics, vehicle/aircraft/tire characteristics and contaminants. Contaminants are defined as dust, oil, fuel, debris, water or other materials that may be on a pavement surface. A summary of important factors that can influence frictional resistance is shown in Table 1.

**Table 1: Factors Influencing Pavement Surface Friction (6, 7)**

| Pavement | Contaminant (fluid) | Tire |
|---|---|---|
| Macrotexture | Chemical Structure | Tread Pattern |
| Microtexture | Viscosity | Rubber Composition |
| Smoothness | Density | Inflation Pressure |
| Chemistry of Materials | Temperature | Rubber Hardness |
| Temperature | Thermal Conductivity | Load (Pressure) |
| Thermal Conductivity | Specific Heat | Sliding Velocity |
| Specific Heat | Film Thickness | Temperature |
| Type Contaminants |  | Thermal Conductivity |
|  |  | Specific Heat |

There are a number of aircraft characteristics that can influence the development of skid resistance. Characteristics such as landing speed, braking system, tire condition, tire inflation pressure, size of aircraft, landing gear configuration, braking assists (spoilers, reverse thrust, etc.) etc. can all influence the frictional resistance developed between an aircraft tire and a pavement surface. However, aircraft operating characteristics are not within the control of the pavement engineer. Therefore, the pavement engineer must ensure sufficient frictional resistance through the proper selection of pavement type, pavement materials and/or surface modifications.

Skid resistance between an aircraft's tire and a pavement surface can be described as the sum of two components: adhesion and hysteresis (8). Adhesion is the product of shear stresses developed between the tire and pavement surface within the tire/pavement contact area. Factors that can influence the magnitude of the adhesion component for resistance to skidding include tire tread pattern, tire inflation pressure, weight of aircraft, method of braking, pavement surface characteristics, etc. Hysteresis is caused by damping losses as the tire forms over and around the texture of the pavement surface. Hysteresis also changes as aircraft characteristics and pavement surface characteristics change.

The pavement surface characteristics related to friction are generally characterized in terms of pavement surface texture. Surface texture is subdivided into three primary categories: microtexture, macrotexture and megatexture. These categories of texture are defined based upon the deviations of a pavement surface from a true planar surface with characteristic dimensions of a wavelength and amplitude (5). Microtexture consists of surface deviations having wavelengths of 1μm to 0.5 mm. Macrotexture consists of surface deviations having wavelengths of 0.5 mm to 50 mm, while megatexture consists of surface deviations having wavelengths of 50 mm to 0.5 m. The relative sizes of these texture categories are illustrated in Figure 1. Of the three categories of pavement surface texture, microtexture and macrotexture are the most important and the most researched with respect to frictional properties. Good megatexture is important for ensuring good pavement/tire contact by limiting wheel deviation and areas that can accumulate water (9). Following are discussions about microtexture and macrotexture.

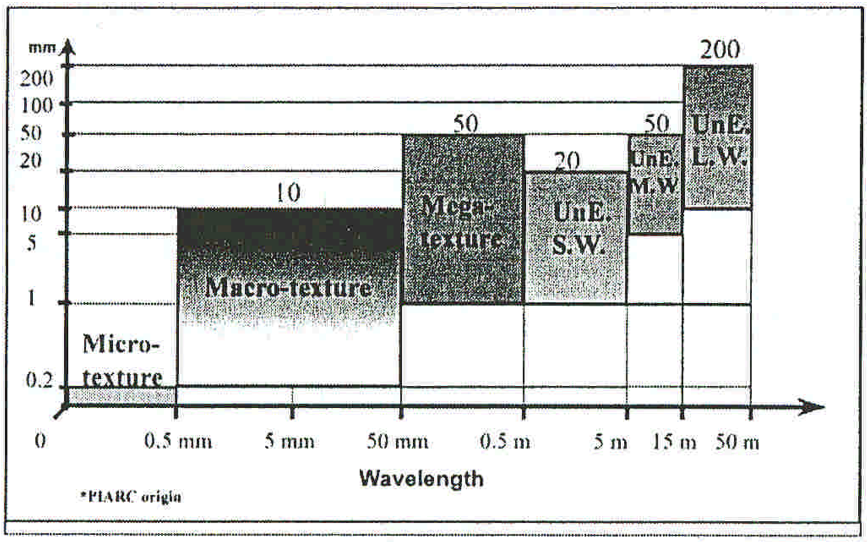

**Figure 1: Wavelengths for Pavement Surface Texture Categories (9)**

*Microtexture*

The adhesion component of skidding resistance is most influenced by microtexture. Therefore, microtexture is the predominant factor affecting frictional resistance of dry pavements. However, microtexture also has benefits during wet conditions. The small deviations in the pavement surface (microtexture) act to penetrate small films of water creating more contact between the tire and the pavement surface. Microtexture is characterized as polished to harsh as illustrated in Figure 2 (5). Generally, adequate microtexture is developed by selection of the proper aggregate mineralogical type that has sufficient angularity, polish resistance and surface texture.

Figure 3 illustrates the importance of aggregate type selection on microtexture. This figure shows wet skid numbers for various HMA mixes from the 2000 National Center Asphalt Technology (NCAT) Test Track (10). These mixes had gradations ranging from fine-graded Superpave designed mixes to stone matrix asphalts (SMAs). Of these mixes, the SMAs have a significant amount of macrotexture; however, when a high polish potential limestone was utilized, the aggregate polished (lost microtexture) and resulted in a pavement with low skid resistance even though the wearing surface had high macrotexture.

Because of the small wavelengths associated with microtexture, contaminants can affect the ability of the microtexture to enhance frictional properties. Dust, debris, oil, etc. that collects on a pavement surface can reduce the beneficial effects of microtexture.

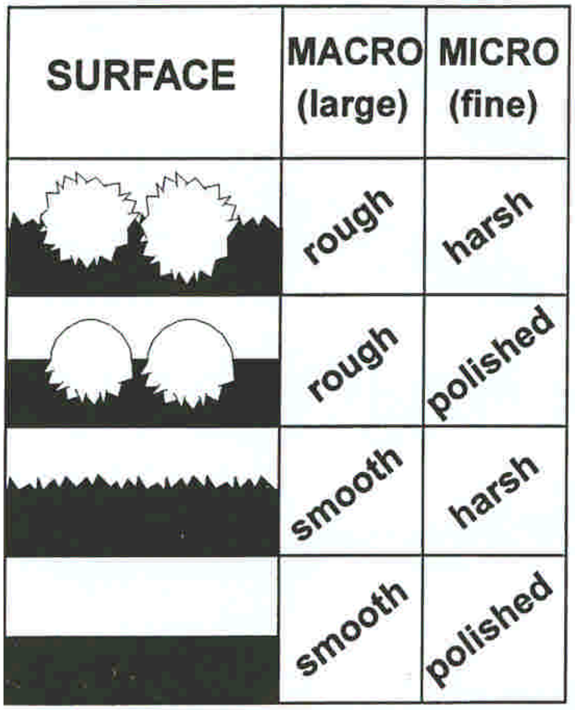

Figure 2: General Scales of Microtexture and Macrotexture (2)

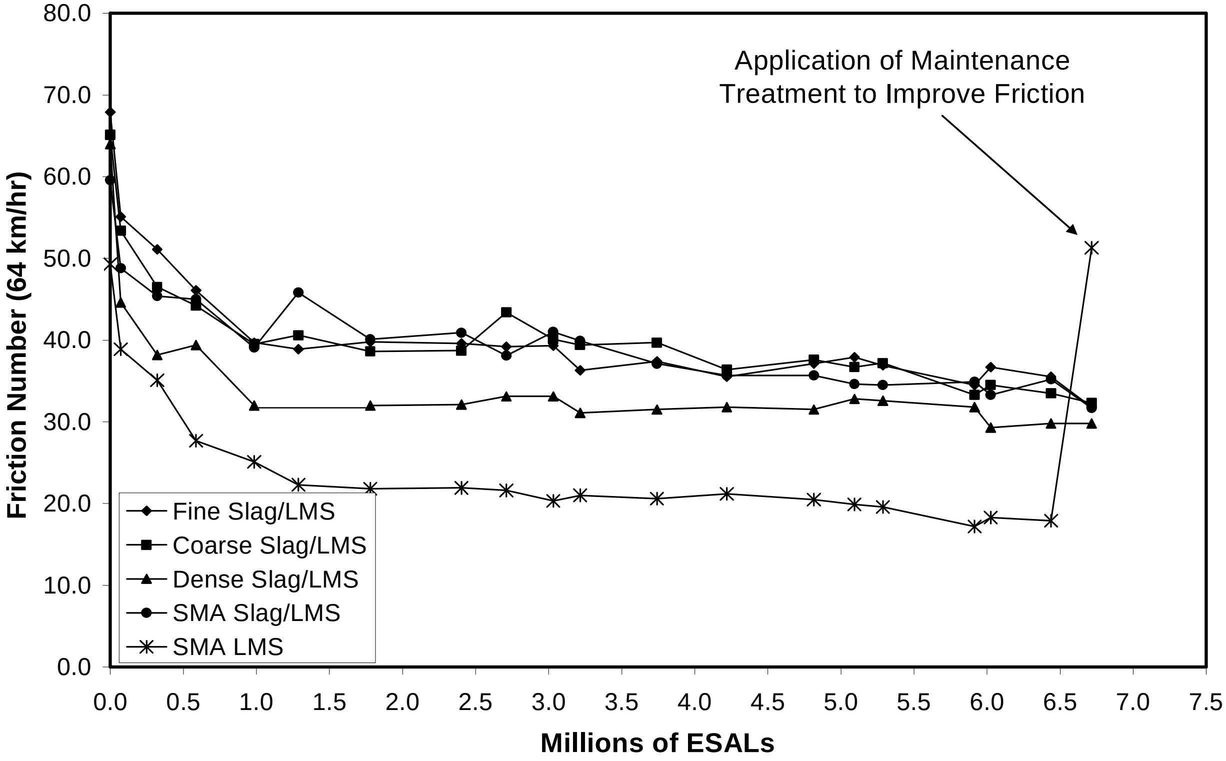

Figure 3: Skid Numbers for Various Mixes From the 2000 NCAT Test Track (10)

### *Macrotexture*

The hysteresis component of skidding resistance is most influenced by the macrotexture on the pavement surface (5). The magnitude of macrotexture is influenced by the shape, size, angularity, density, distribution and arrangement of aggregates within the pavement surface and/or the manipulation of a pavement surface (tining/grooving). An added benefit of increased macrotexture, with respect to skidding resistance, is that the macrotexture provides channels for water to drain off the pavement surface. This draining from the pavement surface helps prevent large water films from building up between a tire and the pavement surface during a rain event, which helps prevent hydroplaning. Hydroplaning is the separation between the tire and the pavement surface due to the buildup of a water film thickness on the pavement surface.

Macrotexture is generally characterized as smooth to rough, as illustrated in Figure 2. Different hot mix asphalt (HMA) types result in varying degrees of macrotexture. Figure 4 illustrates the influence of HMA gradation on macrotexture (10). This figure includes the percent passing the 2.36mm (No. 8) sieve versus mean profile depth, which is a measure of macrotexture. Increasing values of mean profile depth indicate increasing macrotexture. As shown in the figure, as the percent passing the 2.36mm sieve decreases (or the gradation becomes coarser) the mean profile depth increases. Porous friction courses show the highest levels of mean profile depth within this figure.

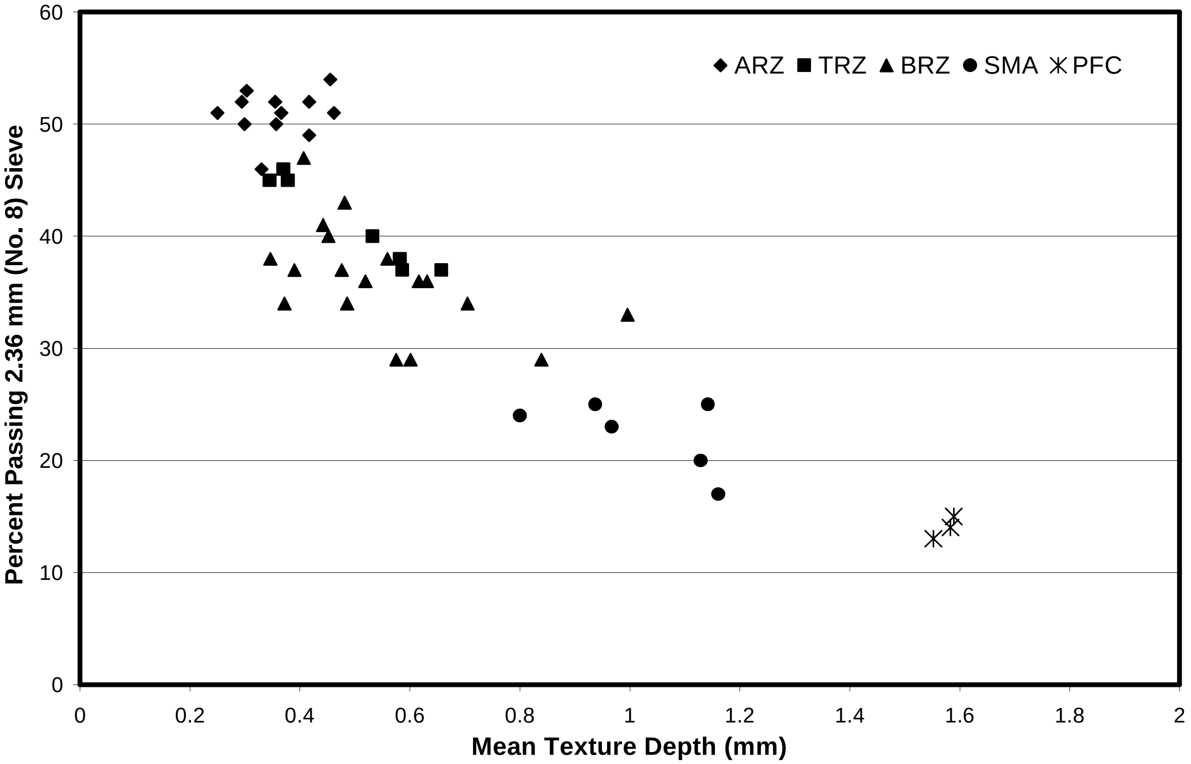

**Figure 4: Effect of Gradation Shape on Macrotexture (10)**

## Airfield Pavement Friction

Because of the high speeds associated with take-offs and landings, the frictional characteristics of runways are of paramount importance. The Federal Aviation Administration (FAA) has published guidelines and procedures for the design and construction of skid resistant pavements. Advisory Circular (AC) 150/5320-12C, *Measurement, Construction and Maintenance of Skid-Resistant Airport Pavement Surfaces*, provides recommendations for runway friction. This AC is also referenced in Unified Facilities Criteria (UFC) 3-260-02, *Pavement Design for Airfields*.

Within AC 150/5320-12C, there is discussion on how the FAA's recommendations for runway pavement surfaces were developed. Based upon various research studies conducted at Langley Research Center, the FAA Technical Center, and the Naval Air Engineering Center, pavement grooving was identified as a method of providing safe pavement surfaces for aircraft operations during wet weather. Subsequent research conducted in the United Kingdom and US showed that porous friction courses also achieve skid resistant pavement surfaces. For both civilian and military airfields, grooving dense-graded HMA wearing layers or placing a porous friction course are the predominant methods for providing safe wearing surfaces on runways. However, the FAA recommends within AC 150/5320-12C that porous friction courses not be constructed on airport runways that have more than 91 turboject arrivals per day per runway end.

## Porous Friction Courses

The term porous friction course (PFC), or open-graded friction course (OGFC), in the US is used to describe an HMA having an open aggregate grading that is used as a wearing course on airfield and highway pavements. The airfield pavement community utilizes the term PFC while the highway industry generally uses the OGFC term. Within the US, OGFCs evolved during the 1930's through experimentation with plant mix seal coats. In the 1970's, the Federal Highway Administration (FHWA) initiated a program to improve the frictional resistance of the nation's roadways (11). The plant mix seal coats were one of the tools an agency could use to improve frictional resistance and, thus, gained popularity. In 1974, the FHWA published a mix design procedure for OGFC. 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 moisture. Open-graded friction course mixtures designed in accordance to the FHWA procedure were successful at performing their intended function:  removing water from the pavement surface and improving wet weather frictional resistance.

Also during the 1970’s, the Waterway’s Experiment Station evaluated PFCs for airfield pavements.  This evaluation occurred because of hydroplaning problems (12) on airfield runways.

Since the 1970’s, some significant improvements have been developed for PFCs, namely the use of modified asphalt binders to improve durability and the incorporation of fibers to prevent draindown.  Additionally, various types of PFCs are commonly used in the U.S.  Some agencies specify PFCs having gradations similar to those recommended by the FHWA in the 1970’s and 1980’s.  Some agencies have adopted coarser gradations (generally called permeable friction courses, new-generation OGFC, or Porous European Mix) that provide higher air void contents and, thus, more capacity to drain water from the pavement surface.  Other agencies construct an asphalt rubber friction course which utilizes a very open gradation; yet, a high percentage of asphalt rubber binder is also used.  These asphalt rubber friction courses do not provide the permeability of other PFCs but provide high macrotexture for skid resistance as well as reduction in noise levels at the tire/pavement interface.

## PROBLEM STATEMENT

Porous friction courses, or OGFCs, have been used within the US since the 1930’s. When placed as a wearing surface, these mixes have proven an effective method for improving the frictional characteristics of pavements, especially in wet weather.  Porous friction courses improve wet weather skid resistance because of the open aggregate grading.  This open gradation results in a significant amount of macrotexture at the pavement surface. Additionally, the open gradation with minimal fines results in water being able to infiltrate into the PFC layer and flow laterally through the PFC layer to the pavement edge. Without the water on the pavement surface, hydroplaning potential is greatly reduced.

Even though PFCs have been around many, many years, the performance of these mix types has been mixed. There have been reports of rapid and catastrophic occurrences of raveling within PFC layers. Any raveling that occurs will result in potential FOD. Also, there have been reports of PFC wearing surfaces tearing at locations where high speed turns or locked wheel turns take place.

Because of the safety benefits associated with PFCs, the highway industry has conducted a significant amount of research on OGFCs over the last 10 to 15 years. Improvements have specifically been made with regards to the methods for specifying materials and designing mixtures. Methods and equipment for constructing PFCs have also improved. Whether the intended use is for airfields or highways, maintenance of PFCs has always been a concern. This concern is primarily due to the potential rapid failure from raveling. Another issue related to maintenance is winter maintenance. Because of the open nature of PFCs, these layers have different thermal properties compared to dense-graded HMA mixes.

In comparison to the highway industry, little work on the use of PFCs for airfield pavements has been conducted in the last 10 to 15 years. Therefore, there is a need to evaluate the current state of practice on the use of PFCs. Information obtained should be used to provide guidance for the use of PFCs on airfields and to identify potential improvements for using PFC wearing layers.

## OBJECTIVES

As stated in the project statement, the objective of this study was to develop technical guidance and direction to improve the performance of PFC mixtures on airfield pavements. This guidance was to consider but not be limited to the following:

1) Performance history of PFC on airfield pavements;
2) PFC mix design requirements and qualities and characteristics of component materials;
3) Construction requirements and limitations;
4) Effect of temperatures and other climatic conditions, especially durability under freeze-thaw conditions, on construction and performance of PFC;
5) Existing surface preparation requirements;
6) Skid resistance characteristics of PFC;
7) Service life and maintenance of PFC;
8) Airfield pavement maintenance, including removal of aircraft tire rubber from the pavement surface;
9) Performance of PFC considering airfield classifications and type of aircraft using the facility; and
10) Compare and contrast design and performance of PFC use on highways and airfields.

## RESEARCH APPROACH

In order to accomplish the project objectives, a total of six tasks were conducted. The following sections describe the activities conducted during each task.

### Task 1 – Review Performance History of PFC/OGFC at Airports

Porous friction course has been placed on numerous civil and military airfields. During Task 1, the researchers contacted and discussed the performance of PFC layers with airfield pavement engineers. The various civil and military airfield personnel were interviewed to determine:

1. Specific concerns about the use of PFC on airfield pavements.
2. Specific areas that have been problematic for PFC.
3. Typical maintenance activities (general and winter) for PFC and their effectiveness.
4. Typical life expectancy for PFC layers.
5. Type aircraft using the facility; airfield classification; and number of operations.

In essence, there are six primary issues that must be addressed: materials and design, production/construction, maintenance, rehabilitation, advantages/disadvantages, and performance. These six items are all related to how a PFC layer performs.

### Task 2 – Identify Recent Improvements in PFC/OGFC

Within recent years, there has been a significant amount of research conducted on PFC mixes. Most of this research has been applied to highway usage; however, this research was very relevant to this project. Therefore, a literature review was conducted to determine the current state of practice with regards to PFC. Of particular interest within this task were improvements that could potentially increase life expectancy, minimize maintenance, maximize the benefits and minimize the disadvantages of PFC.

### Task 3 – Evaluate Recent Improvements

Based upon the results of Tasks 1 and 2, the research team evaluated each of the potential improvements identified to provide an assessment of these improvements for future use on airfield pavements. Potential improvements in all six areas identified in Task 2 were evaluated.

### Task 4 – Develop Revised Draft Specifications and FAA Engineering Brief

Results from Tasks 1 through 3 were used to develop guidance on the design, production, construction, maintenance and rehabilitation of PFCs. Additionally, a draft FAA Engineering Brief was developed on recommendations for future use of PFC for airfield pavements.

### Task 5 – Recommend Additional Work

Tasks 1, 2 and 3 identified current limitations, possible improvements to remedy the limitations and an evaluation of the improvements. For limitations in which solutions could not be identified, additional work was recommended. The recommended additional work encompassed materials and design, production/construction, maintenance, rehabilitation and performance.

### Task 6 – Deliver Final Report

The final task was to submit a draft final report. The draft final report was compiled according to the guidelines established by the AAPTP and presents a clear and concise summary of the findings and conclusions generated from Tasks 1 through 5.

## REPORT ORGANIZATION

The first chapter of this report provides a brief overview of PFCs, the project objectives and research approach.  Chapter 2 discusses the advantages and disadvantages on the use of PFCs for airfield pavements.  The advantages and disadvantages are provided at the beginning of this report because the subsequent chapters provide discussion on methods of maximizing the advantages while minimizing the disadvantages.  The third chapter provides discussion and guidance on the design of PFC mixtures along with material requirements.  Chapter 4 discusses the production and construction of PFCs and Chapter 5 discusses the maintenance and rehabilitation of PFC layers.  Within Chapters 2 through 5, the current state of practice for each topic is provided as well as recent improvements.  Where applicable, recommendations were made for needed future research.  Chapter 6 presents conclusions and recommendations derived from the results of this research project, while the final chapter presents the references utilized during conduct of this research.  A draft FAA Engineering Brief that provides recommendations for future use of PFC for airfield pavements was also developed.

# CHAPTER 2
# Advantages and Disadvantages of PFCs on Airfield Pavements

## INTRODUCTION

This chapter discusses the advantages and disadvantages of using PFC on airfield pavements. Ideally, the results of this project will maximize the advantages of using PFC on airfield pavements while minimizing any disadvantages. The literature indicates a number of advantages that can be realized with the use of PFCs as a wearing layer. For the most part, the benefits are based upon the ability of the PFC layer to drain water from the pavement surface. Lefebvre (13) states that the benefits of PFCs can be categorized based upon three general areas: safety, smoothness and environmental. The primary advantages related to safety are the reduction in hydroplaning potential and improvement in wet weather friction. Porous friction courses generally are smoother than dense-graded HMA layers which helps prevent directional control problems for aircraft and improves fuel economy for vehicles. The environmental benefits cited by Lefebvre (13) are not specifically related to airfield pavements and include reduction in tire/pavement noise levels and improved fuel economy.

The primary disadvantages discussed in the literature were the increased cost and the differences in winter maintenance practices compared to dense-graded HMA. Another perceived disadvantage is that PFCs have been susceptible to rapid deterioration due to raveling.

## ADVANTAGES OF USING PFCS ON AIRFIELD PAVEMENTS

Benefits of PFC related to safety include reduced potential for hydroplaning, improved skid resistance (especially during wet weather), and reduced light reflection. Reduction in light reflection is more applicable to highways because of the angle at which drivers view a pavement surface. Hydroplaning occurs when a layer of water builds up between a tire and the pavement surface (13). This layer of water breaks the contact between the tire and road (13, 14). When this occurs, the aircraft will not respond to braking or turning. 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 (12). The second aspect 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 (5). Therefore, in wet weather conditions, the skid resistance of PFC wearing layers is generally very good.

Many, many references mention that the use of PFCs as a wearing layer 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 (15) cited a number of references in his synthesis on OGFCs describing research conducted in the U.S., Canada and Europe that showed the improved wet pavement frictional properties of PFCs. Much of the research dealt with comparing the speed gradient (or friction gradient) encountered on PFC layers. A frictional speed gradient can be defined as the rate of decrease in the friction number per unit increase in speed. With low speed gradients, the pavement surface maintains its frictional properties even at high speeds, which is vital on airfield runways. Therefore, low frictional speed gradients are desirable. Table 2 presents data from a Pennsylvania Department of Transportation project that showed a decreased frictional speed gradient for PFC layers. Similar work in Oregon and Louisiana presented by Kandhal (15) also showed decreased friction gradients for PFCs compared to dense-graded layers.

**Table 2: Friction Data from Pennsylvania (excerpt from 15)**

| Mix Type | Friction Number | | Friction Gradient |
|---|---|---|---|
| | 30 mph | 40 mph | |
| 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 |

Isenring et al (16) also conducted friction testing on 17 different PFC test sections at different speeds including 40, 60, 80, and 100 kph (25, 37, 50 and 62 mph). Friction measurements were made using the PIARC skid tester 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 (15), the frictional speed gradients for PFC surfaces were lower than for typical dense-graded layers.

Bennert et al (17) presented the results of wet skid tests on various wearing surfaces, including PFCs. 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 64 kph (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, modified OGFC, Novachip, stone matrix asphalt, microsurface, Superpave designed dense-graded HMA and Portland cement concrete. Table 3 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 MOGFC. The PFC layers (AR OGFC and MOGFC) tested did provide higher wet-skid numbers than Novachip and the SMA surfaces.

**Table 3: Wet-Skid Numbers for Various Pavement Surfact Types (excerpt from 17)**

| 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

Recent work in the US by McDaniel and Thornton (18) has also shown that PFCs provide relatively more macrotexture and higher International Friction Index (IFI) values than other HMA wearing layers.  Tables 4 and 5 present macrotexture and friction measurement data for three test sections in Indiana, respectively.  Pavement surfaces included within the research were PFC, stone matrix asphalt, and dense-graded HMA.

**Table 4: Results of Surface Texture Measurement from McDaniel and Thornton (18)**

| Mix | Mean Profile Depth, mm (Standard Deviation) |
|---|---|
| PFC | 1.37 (0.13) |
| SMA | 1.17 (0.14) |
| HMA | 0.30 (0.05) |

**Table 5: Results of Friction Measurement from McDaniel and Thornton (18)**

| 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 |

McDaniel and Thornton (18) indicated that the PFC and SMA wearing layers showed significantly more macrotexture (reported as mean profile depth) than did the dense-graded HMA (Table 4). The PFC layer did provide the highest average mean profile depth measurement. Variability in measured mean profile depths was also 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 (18) reported results of dynamic friction measurements made with the Dynamic Friction Tester (Table 5). 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 friction followed by the SMA and dense-graded surface.

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 (17) did compare the results of ride quality measurements for a number of highway pavement surfaces in New Jersey including: asphalt rubber OGFCs, modified OGFCs, Novachip, stone matrix asphalt, microsurfacing and three types of rigid pavement surfaces (transverse tined, diamond grind and no finish). Table 6 presents results of testing related to ride quality by Bennert et al. 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 (17) 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 were also 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.

**Table 6: Results of Ride Quality Measurements for Various Pavement Surfaces (17)**

| 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

Bennert et al (17) 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 (MOGFC, AR-OGFC, Novachip and microsurfacing), the PFC mixes did have the highest average RQI values. Similar results were obtained using the IRI measurements.

## DISADVANTAGES OF USING PFCS ON AIRFIELD PAVEMENTS

Probably the biggest deterrent cited for using PFC layers is freezing weather. Porous friction courses have a lower coefficient of thermal conductivity than dense-graded HMA. This means that the temperature of the pavement surface drops below freezing sooner than dense-graded HMA, and stays below freezing longer (19).

The primary concern then 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 point of contact between tire and pavement"(20).

Moore et al mention three conditions under which open-graded mix in Oregon is not recommended for use (20, 21). 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 airfield pavements, only the snowplow issue is of importance. As a result of snowplow damage, Oregon's Class F mix is no longer recommended in areas where plowing is frequent (20, 21, 22). The snowplows can cause raveling and gouging resulting in a higher rate of surface deterioration.

Two papers gave a list of disadvantages for using PFCs. Lefebvre in his paper (13) listed several disadvantages. First, Lefebvre stated that PFCs generally cost more than dense-graded layers as a result of requiring high quality, polish resistant aggregates and modified asphalt binders. Also, pavement markings have to be adapted for PFCs. Because of the openness of PFCs, some pavement marking materials will infiltrate into the layer during placement. Special impervious layers specifically placed below PFCs can also increase construction costs. Another disadvantage of using PFCs is the relatively shorter economic life. Most references state that PFCs last 8 to 12 years on highways, while dense-graded layers will last 10 to15 years. The 8 to 12 year expected lift on highways matches the experiences of most airfield pavement engineers interviewed. Finally, Lefebvre stated that maintenance is generally more expensive, especially winter maintenance. In another paper, Bolzan et al (23) mention that 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.

Kandhal (15) provides a number of situations where PFC should not be used. Porous friction courses should likely 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 for OGFC to 56km (35 miles) (21). Porous friction courses should not be used in inlays. Porous friction courses should be free draining at the pavement edge; therefore, they should not be used as an inlay. Handwork is difficult with PFC mixes. Therefore, projects that include a lot of handwork should probably not include PFC. Kandhal (15) noted that PFC should not be used in snow zones where extensive snow plowing is required. Porous friction courses may ravel and shove in some critical pavement locations with heavy turning movements, and other adverse geometric locations. The final limitation noted by Kandhal (15) has to do with underlying layers. Porous friction courses should not be placed on a permeable pavement layer as water can infiltrate through the PFC into a permeable underlying layer causing moisture damage within the underlying layer.

After construction, PFCs generally have a lower friction value when braking with locked wheels. When the wheels lock, they begin to melt the thin layer of binder coating the aggregates on the pavement surface, which creates a slippery surface. This is only true when the wheels are locked. This layer of binder is worn off after approximately 3 to 6 months and friction values increase (19).

During the life of PFC layers, dirt, debris, winter maintenance products and other materials can enter the void structure. These contaminants will lead to clogging of the layer and results in the layer not being able to remove water from the pavement surface. It should be stated; however, that clogged PFCs still maintain their frictional properties because of the high amounts of macrotexture. Another potential problem with debris within the voids of the PFC layers is that the debris can retain moisture after the rain event leading to an increased potential for moisture damage.

## SUMMARY

The advantages and disadvantages of using PFCs are both primarily related to the openness of these mixes. The open nature of PFCs allows water to infiltrate into the layer. Since the water infiltrates into the layer, water films will not develop. Water films on the pavement surface increase the potential for hydroplaning. Hydroplaning can make aircraft lose directional control and the ability to brake.

Because of the open gradation inherent in PFCs, these mix types have a significant amount of surface texture in the wave length and amplitude range of macrotexture. High levels of macrotexture combined with the selection of polish resistant aggregates (to provide microtexture) result in improved frictional properties compared to typical dense-graded HMA layers, especially in wet weather.

A benefit that is not specifically related to the ability of PFCs to remove water from the pavement surface is the improved smoothness compared to typical HMA mixes. The improved smoothness is likely related to the constructability of PFC mixes. As will be discussed in Chapter 4, the goal of PFC compaction is simply to seat the aggregates, not densify the mix to an impermeable compaction level. Therefore, only static-steel wheel rollers are used for PFCs with each roller making relatively few passes. These construction related factors are likely the reason for improved smoothness with PFCs. At the typical high speeds encountered on airfield runways, the improved smoothness will reduce the potential for aircraft structural damage and component fatigue; reduce the potential for aircraft prematurely becoming airborne; improve the contact between tires and the pavement surface; minimize aircraft vibrations; and provide a more comfortable ride for passengers.

The primary disadvantages of using PFC are winter maintenance, rapid raveling of the layer, and moisture damage in underlying layers. Because of the open nature of PFCs, these layers have different thermal properties than typical dense-graded HMA layers. Porous friction course layers will generally reach a freezing temperature prior to dense-graded mixes and stay at a freezing temperature longer. For this reason, PFC layers generally require a different winter maintenance regime than other pavement surface types.

The primary distress that has been associated with the use of PFCs is raveling. Within the highway industry the occurrence and severity of raveling caused a moratorium by some agencies on the use of PFCs within the 1980’s. During the interviews with various airfield pavement engineers, raveling was discussed as a problem with some PFC layers. Rapid deterioration of PFC layers due to raveling was identified as a disadvantage. Raveling of any kind increases the potential for FOD.

Another potential problem identified in several of the airfield pavement engineer interviews was stripping in underlying layers. Stripping in underlying layers has also been noted in highway uses. It is unlikely that changes can be made to the design and construction of PFC mixes to minimize the potential for stripping in underlying layers; however, modifications can likely be made to the design and construction of underlying layers to minimize the potential for stripping.

# CHAPTER 3
# Design of PFC Mixes for Airfield Pavements

## INTRODUCTION

One of the highlighted areas of developing technical guidance and direction to improve the performance of PFCs was mix design requirements.  This section provides discussion on current mix design methods for PFCs used on airfields, current mix design methods for OGFCs for highways and recommendations for improvements to the current airfield mix design methods. Current limitations in the design of PFC mixes are provided and, where needed, additional work recommended in the final section of this chapter.  A tentative mix design method for PFCs that is based upon the recommended improvements is presented in Appendix A.

## CURRENT AIRFIELD MIX DESIGN METHODS FOR PFC

The primary PFC mix design specifications utilized for airfield applications include Item P-402 documented in FAA AC 150/5370-10B and the Department of Defense (DoD), Unified Facilities Guide Specification (UFGS)-32 12 20 (formerly UFGS-02747).  As with the design of other HMA types, the design of PFC mixes outlined within these two specifications entails several steps.  The first step in the mix design process is to select acceptable materials.  Next, the materials must be blended to develop a design aggregate gradation.  Optimum asphalt binder content for the selected materials using the design gradation must next be determined.  The final step in the design is to evaluate the performance of the designed mix.  Both specifications evaluate performance with laboratory moisture susceptibility testing.  The following sections describe the current mix design procedures for PFCs used on airfields.

## Materials Selection

Both mix design methods provide requirements for coarse aggregates, fine aggregates, mineral fillers, asphalt binders and additives. Both methods define coarse aggregates as the fraction of aggregate materials retained on the 4.75mm (No. 4) sieve. Fine aggregates are the fraction passing through the 4.75mm (No. 4) sieve and retained on the 0.075mm (No. 200) sieve. Mineral fillers are the aggregate fraction that passes through the 0.075mm (No. 200) sieve.

Both methods provide requirements on the shape, angularity, toughness and soundness of coarse aggregates. Particle shape is controlled within both specifications using ASTM D4791, *Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate*. However, the two specifications do not have the same requirements. Item P-402 requires that the coarse aggregate fraction contain no more than 8 percent, by mass, of flat or elongated particles, while UFGS-32 12 20 states that the "… quantity of flat and elongated particles in any sieve size shall not exceed 8 percent, by mass." The differences in the requirements include the measure of particle shape as well as the material that is tested.

ASTM D4791 compares the dimensions of aggregate particles in order to define a measure of shape. To conduct this test, aggregate particles are measured with a proportional caliper using a specified ratio. To evaluate flat particles, the proportional caliper is used to compare a particle's thickness to width. Width is defined as the maximum dimension perpendicular to the particle's length; where, length is defined as the maximum dimension of the particle. Thickness is defined as the maximum dimension perpendicular to both the length and width. Elongated particles are defined as those having a ratio of length to width greater than the specified ratio. For evaluating flat and elongated particles, the length of each particle is compared to its thickness. Determination of the percent flat and elongated particles, as required in UFGS-32 12 20, entails determining the percentage of aggregate particles that fail the flat and elongated definition based on the total mass of the aggregate sample. Determination of the percentage of flat or elongated particles, as required in Item P-402, entails determining the combined percentage of aggregate particles that fail either the flat particle or the elongated particle definition based on the total mass of the aggregate sample. Item P-402 references ASTM D693, *Standard Specification for Crushed Aggregate for Macadam Pavements*, which states that the specified ratio for which aggregates are to be evaluated during ASTM D4791 is 5:1. UFGS-32 12 20 does not state the specified ratio for which aggregates are to be compared.

As stated above, another difference between the two mix design methods is the material to be tested. ASTM D4791 calls for the testing of the combined particles larger than the 9.5mm (3/8 in.) sieve. However, UFGS-32 12 20 states "… any sieve size shall not exceed 8 percent…" when referencing coarse aggregates. Though this may be a misinterpretation, the wording of UFGS-32 12 20 indicates that material retained on each sieve should be tested.

Neither Item P-402 or UFGS-32 12 20 reference a particular test method for evaluating the angularity of coarse aggregates; however both have a requirement that the coarse aggregate must contain at least 75 percent , by mass, of crushed particles having two or more fractured faces. Item P-402 further requires that 100 percent of the coarse aggregates have at least one fractured face. Though neither method references a particular test method, both state that for a face to be considered fractured, it must be equal to at least 75 percent of the smallest mid-sectional area of the particle. Similar to the particle shape testing, the wording within UFGS-32 12 20 indicates that the fractured face count should be determined for each size fraction larger than the 4.75mm (No. 4) sieve stating "… gravel retained on the 4.75mm (No. 4 sieve) and each coarser sieve…" Similar wording can be found in the Corps of Engineers test method CRD-C 171, *Standard Test Method of Determining Percentage of Crushed Particles in Aggregate*.

UFGS-32 12 20 also has a requirement for angularity to be applied to fine aggregates. The fractured face count of aggregates passing the 4.75mm (No. 4) sieve and retained on the 0.60mm (No. 30) sieve are to be tested. Within this size fraction, 90 percent of the aggregate particles must have two or more fractured faces. Additionally, UFGS-32 12 20 limits the amount of natural sand to a maximum of 5 percent, by total mass of the aggregates. Item P-402 simply states that the amount of natural sand to be added, if necessary, will be "… to produce mixtures conforming to the requirements…" of Item P-402.

Both specifications utilize ASTM C131, *Resistance to Abrasion of Small Size Coarse Aggregates by Use of the Los Angeles Machine*, to define aggregate toughness. Item P-402 limits the percent loss to a maximum of 30 percent, while UFGS-32 12 20 recommends an upper limit of 25 percent for PFCs used on airfields.

ASTM C88, *Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate*, is required in both methods for defining the soundness of coarse aggregates. A maximum of 12 percent loss is required in both; however, Item P-402 states that sodium sulfate be used, while UGFS-32 12 20 does not recommend whether sodium sulfate or magnesium sulfate be used during testing.

Item P-402 provides requirements for the cleanliness of fine aggregates. The plasticity index cannot be more than 6 and the liquid limit can not be more than 25 when tested in accordance with ASTM D4318, *Liquid Limit, Plastic Limit and Plasticity Index of Soils*.

No specific requirements are listed in Item P-402 or UFGS-32 12 20 for fillers. However, Item P-402 does state that fillers not naturally present within the aggregate shall meet the requirements of ASTM D242, *Mineral Fillers for Bituminous Paving Mixtures*.

Asphalt binders used in PFC must be viscosity-graded according to Item P-402, while both viscosity- and penetration-graded binders are allowable according to UFGS-32 12 20. UFGS-32 12 20 states that "use of modified bituminous materials such as polymers, latex rubbers, and reclaimed tire rubber should be considered for improving PFC pavement performance." Item P-402 requires the addition of synthetic rubber in the asphalt binder in an amount not less than 2 percent. Table 7 presents requirements for asphalt binders listed within Item P-402. An identical table is provided within UFGS-32 12 20 but is only provided as an example.

**Table 7: Asphalt Binder Requirements within Item P-402**

| Property | ASTM | Min. | Max. |
|---|---|---|---|
| Viscosity @ 140˚F, Poises | D2171 | 1600 | 2400 |
| Viscosity @ 275˚F, cSt. | D2170 | 325 | |
| Flash Point, ˚F | D92 | 450 | |
| Ductility @ 77˚F (5 cm/min) cm | D113 | 100 | |
| Ductility @ 39.2˚F (5 cm/min) cm. | D113 | 50 | |
| Toughness, inch-pounds | D5801 | 110 | |
| Tenacity, inch-pounds | D5801 | 75 | |
| Thin Film Oven Test: | | | |
| Tests on Residue | | | |
| Viscosity @ 140˚F, Poises | D2170 | | 8000 |
| Ductility @ 77˚F (5 cm/min)cm | D113 | 100 | |
| Ductility @ 39.2˚F (5 cm/min)cm | D113 | 25 | |

The final material to be selected is additives. Additives include materials such as antistripping agents, antifoaming agents and silicone. UFGS-32 12 20 states that these additives can only be incorporated with approval. Item P-402 only mentions antistripping agents as an additive and states that the additive "…be heat stable, shall not change the asphalt cement viscosity beyond specifications, shall contain no harmful ingredients, shall be added in recommended proportion by approved method and shall be a material approved by the Department of Transportation in which the project is located."

In summary, both Item P-402 and UFGS-32 12 20 provide requirements on the shape, angularity, toughness and soundness of aggregates. Item P-402 also provides requirements for the cleanliness of fine aggregates. Both also require viscosity-graded asphalt binders; however, UFGS-32 12 20 also allows penetration-graded asphalt binders. In general, the material requirements within the two mix design methods are similar. There are, however, some minor differences in the material requirements.

## Selection of Design Aggregate Gradation

Both Item P-402 and UFGS-32 12 20 contain two gradation bands for PFCs. Each has a gradation band for a ¾ in. (19mm) maximum aggregate size gradation and a ½ in. (12.5mm) maximum aggregate size gradation band. Tables 8 and 9 present the gradation requirements contained within Item P-402 and UFGS-32 12 20, respectively. Figures 5 and 6 illustrate the gradations by maximum aggregate size.

**Table 8: Gradation Requirements for Porous Friction Courses - Item P-402**

| Sieve, mm | ¾ in. (19.0 mm) maximum | ½ in. (12.5 mm) maximum |
|---|---|---|
| 19.0 (¾ in.) | 100 | |
| 12.5 (½ in.) | 70-90 | 100 |
| 9.5 (3/8 in.) | 40-65 | 85-95 |
| 4.75 (No. 4) | 15-25 | 30-45 |
| 2.36 (No. 8) | 8-15 | 20-30 |
| 1.18 (No. 30) | 5-9 | 9-17 |
| 0.075 (No. 200) | 1-5 | 2-7 |

**Table 9: Gradation Requirements for Porous Friction Courses - UFGS-32 12 20**

| | Percent Passing by Weight of Total Aggregates | |
|---|---|---|
| Sieve Designation (mm) | Gradation "A" ¾ in. Maximum (Compacted Nominal Thickness, 1 in.) | Gradation "B" ½ in. Maximum (Compacted Nominal Thickness, ¾ in.) |
| 19.0 (¾ in.) | 100 | 100 |
| 12.5 (½ in.) | 70-100 | 100 |
| 9.5 (3/8 in.) | 45-75 | 80-100 |
| 4.75 (No. 4) | 25-40 | 25-40 |
| 2.36 (No. 8) | 10-20 | 10-20 |
| 1.18 (No. 30) | 3-10 | 3-10 |
| 0.075 (No. 200) | 0-5 | 0-5 |

Tables 8 and 9 and Figures 5 and 6 show that there are minor differences in the gradation requirements between the two methods. For ¾ in. maximum aggregate size gradations, the Item P-402 gradation requirements tend to be coarser within the larger aggregate fraction and the two are somewhat similar in the finer fraction. For ½ in. maximum aggregate size gradations, the UFGS-32 12 20 gradation requirement tends to be coarser throughout the entire range of aggregate sizes.

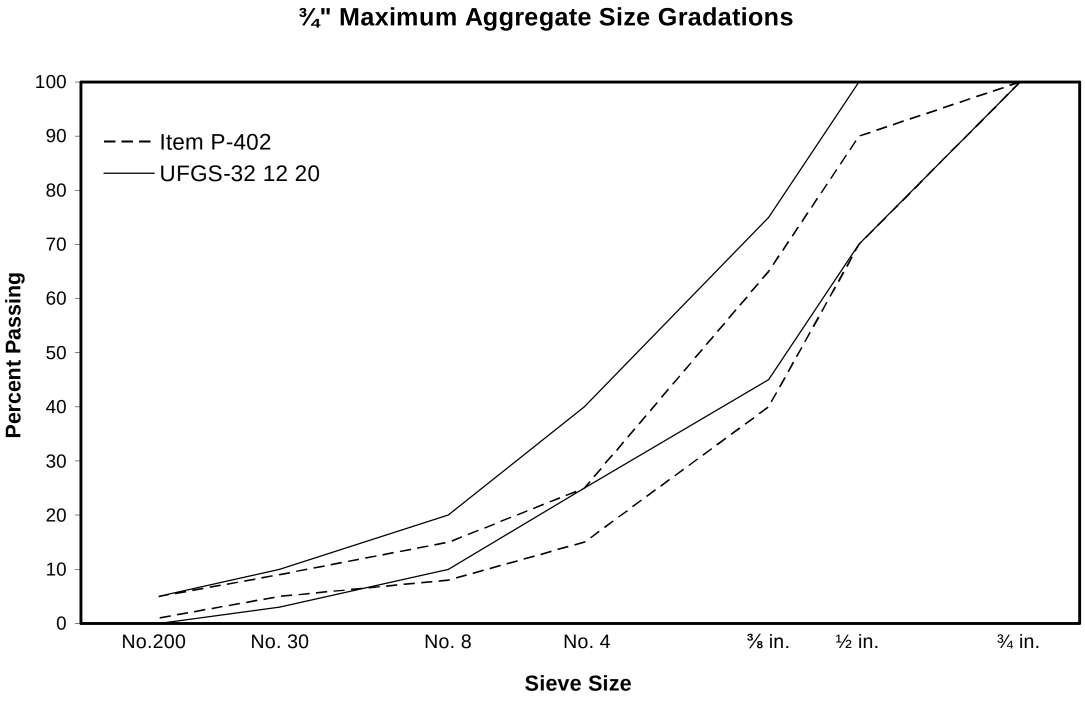

Figure 5: 3/4 in. Maximum Aggregate Size Gradations

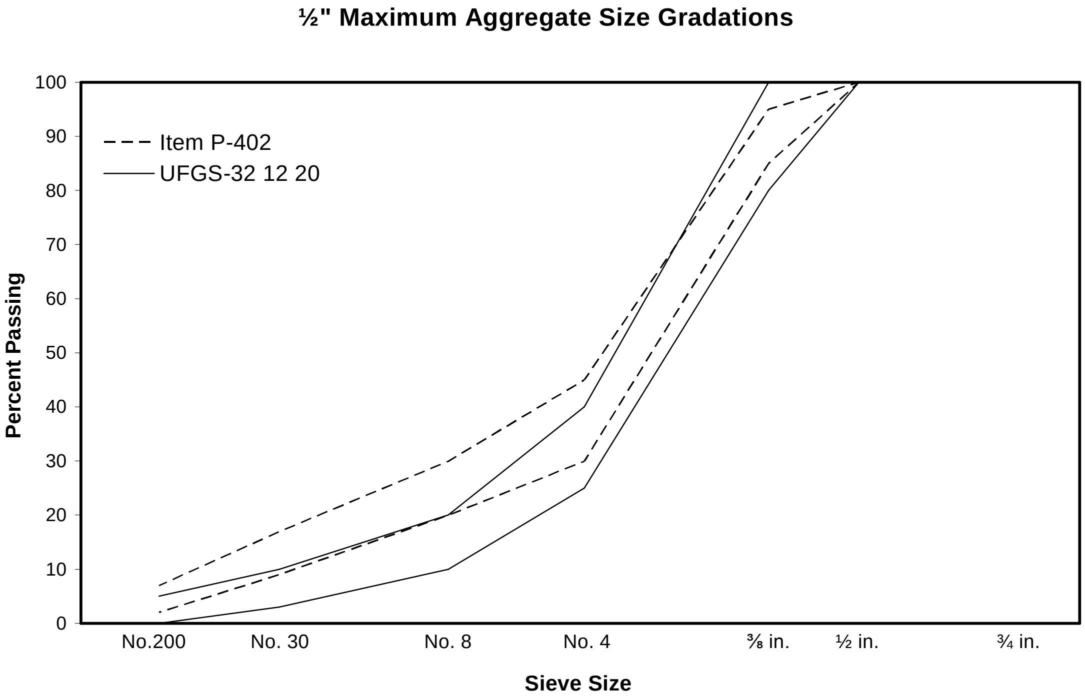

Figure 6: 1/2 in. Maximum Aggregate Size Gradations

## Selection of Optimum Asphalt Binder Content

To determine the estimated optimum asphalt binder content, both methods utilize the Centrifuge Kerosene Equivalent (CKE) method. Item P-402 references the Asphalt Institute's MS-2, Mix Design Method for Asphalt Concrete and Other Hot Mix Types (24), and UFGS-32 12 20 references the California Department of Transportations (CDT) Test 303, *Method of Test for Centrifuge Kerosene Equivalent and Approximate Bitumen Ratio*, for conducting the CKE method. The CKE test method provides a measure of aggregate surface area and the absorption characteristics of the aggregates. For PFCs, the test is conducted on the coarse aggregate fraction only. The test for PFCs entails placing the coarse aggregate fraction of the design blend within a metal funnel. The metal funnel and aggregates are then submerged within a beaker containing SAE No. 10 lubricating oil for 5 minutes at room temperature. Following the 5 minute soak, the funnel is removed from the beaker and allowed to drain for 2 minutes. Next, the funnel and sample are drained an additional 15 minutes at a temperature of 60˚C (140˚F). The difference in aggregate mass before and after is used to determine the percent oil retained. The percent oil retained is then used to determine the Surface Constant ($K_c$) of the aggregates using a graphical relationship between percent oil retained and $K_c$. Equation 1 presents the relationship between estimated optimum asphalt binder content and $K_c$. The value determined from Equation 1 is based upon the dry mass of aggregates and, therefore, must be converted to the percent by total mass of mixture.

$$Estimated\ Optimum\ Binder\ Content = 2K_c + 4.0 \qquad \textbf{Equation 1}$$

### Evaluation of Moisture Susceptibility

Item P-402 does not require testing of the designed mixture for moisture susceptibility; however, UFGS-32 12 20 requires at least 95 percent retained coating. No test method is provided within UFGS-32 120 20 for the percent retained coating. Based upon work by Anderton (21), ASTM D1664, *Test Method for Coating and Stripping of Bitumen-Aggregate Mixtures*, is used to determine the percent retained coating. The test method begins by coating the aggregates with asphalt binder. After coating, the mixture is allowed to cool to room temperature. Next, the mixture is covered with distilled water at room temperature and allowed to sit for 16 to 18 hours. After this time period, the water covered sample is illuminated by a shaded lamp and a visual observation is made of the aggregate surface area that remains coated with asphalt binder. The test results are then reported as the percent aggregates with retained coating. Anderton (25) indicates that this test identifies those mixes with extremely serious stripping potential. Unfortunately, this test method was withdrawn by ASTM without replacement in 1992.

## DESIGN OF OGFCS USED FOR HIGHWAYS

Within the highway industry, open-graded friction course (OGFC) is a generic term to describe a specialty type HMA. The term was coined because of the large fraction of coarse aggregate and low percentages of mineral filler which created an open aggregate structure. In actuality, there are a number of OGFC types that are used for highways. The primary difference between the different OGFC types is the intended function of the mixture as a pavement layer. Some OGFC mixtures are designed specifically to remove large amounts of water from the pavement surface during rain events. This is accomplished by specifying very coarse aggregate gradations and air void contents above 18 percent during mix design. Another type of OGFC is specifically designed to reduce tire-pavement noise on urban highways. These OGFC types generally have small maximum aggregate size gradations (though still open) and incorporate high percentages of crumb-rubber modified asphalt binders. Air void contents within these OGFC types are generally in the 12 to 15 percent range. Another type OGFC is one that was recommended by the Federal Highway Administration (FHWA) approximately 20 years ago. This type of OGFC also contains an open aggregate grading but air void contents are generally around 15 percent. These types of OGFC were recommended specifically to improve frictional properties. It should be stated, however, that all three OGFC types discussed above provide high levels of macrotexture and, therefore, provide improved frictional properties compared to dense-graded HMA layers.

The specific type of OGFC used by a highway agency is generally a direct response to the performance issues that the agency faces. For instance, the Georgia Department of Transportation utilizes an OGFC that is specifically designed to remove large volumes of water from the pavement surface. This is in response to the large amount of rainfall that can be encountered within the southeast US. These OGFC types also allow water to drain through the layer over multiple lanes of traffic. Conversely, the Arizona Department of Transportation utilizes the small maximum aggregate size gradation OGFC with crumb-rubber modified asphalt binder near Phoenix. This is in direct response to high traffic noise levels as this OGFC type has been shown to reduce tire/pavement noise.

The following sections describe the design of OGFC mixes for highway pavements. Unfortunately, a number of the mix design methods used for highway pavements are recipe methods. Therefore, the discussions are more general than the discussion on the two airfield PFC mix design methods.

## Material Properties

Aggregates used in OGFC mixtures should be tough enough to resist degradation due to environmental effects and loading conditions and should provide frictional characteristics sufficient to resist polishing of the aggregate surface. The 1990 FHWA Technical Advisory (26) recommended that the coarse aggregate fraction be 100 percent crushed material. However, it is recommended that the coarse aggregate fraction, defined as the percent retained on the 2.36 mm (No. 8) sieve, have at least 75 percent of the particles, by mass, with at least two fractured faces and 90 percent with one or more fractured faces. While several agencies in the United States require 100 percent quarried material, virtually all European agencies require quarried aggregates be used in OGFCs. South Africa does make provisions for gravel on low volume routes by requiring only 90 percent with two or more fractured faces (27).

The Los Angeles Abrasion test is typically used to determine aggregate toughness. However, there is a wide range in permissible values. British specifications limit the Los Angeles Abrasion loss to a maximum of 12 percent. Other countries in Europe and South Africa have similar requirements with a maximum abrasion loss of 25 percent (27). In contrast, the 1990 FHWA Technical Advisory recommended a maximum abrasion loss of 40 percent (26). It is most likely that agencies have set specification limits dependent on the best quality of locally available aggregates.

One of the most significant changes in production of OGFC mixtures has been the trend toward use of polymer-modified asphalt in order to reduce binder draindown and improve resistance to raveling. National Cooperative Highway Research Program (NCHRP) Synthesis 180 (28) published in 1992 barely mentioned the use of modified asphalt within OGFCs. However, after the European Asphalt Study Tour in 1990, it was learned that the use of fiber and polymer-modified binders were significantly improving the performance of SMA and OGFC mixtures in Europe. NCHRP Synthesis 284 (27) completed in 2000 showed that in the period from 1992 to 2000 there was more widespread usage of both fiber stabilizers and polymer-modified asphalt in OGFCs.

### Selection of Design Aggregate Gradation

There are typically four aggregate gradations that have been used for OGFC mixtures for highway construction (Table 10). The 12.5 mm (1/2 inch) maximum aggregate size gradation shown in Table 10 was recommended in a FHWA 1974 report (29) and in a subsequent 1990 Technical Advisory (22). This open-graded mixture provided benefits such as reduced hydroplaning, increased surface friction, and reduced noise pollution. As traffic volumes grew and roadways became wider, there was a movement toward coarser OGFC mixtures to increase water drainage capacity across multiple lanes of traffic. This led to adoption of the porous European mixtures such as the 19 mm (3/4 inch) maximum aggregate size OGFC shown in Table 10. These mixtures are typically used on roadways with high traffic volumes and high speeds such as interstate-type routes. Both Georgia and Alabama, for example, use a coarse OGFC mixture as the final wearing surface layer on all their flexible pavement interstate projects. Oregon is the only state agency to use the 25 mm (1 inch) maximum aggregate size OGFC mixture on a regular basis. The final gradation shown within Table 10 is for a 9.5mm (3/8 in.) maximum aggregate size. This type of mixture is routinely used in the southwestern portion of the US and generally utilizes asphalt binder modified with crumb rubber. This OGFC type is specifically used to improve frictional properties and reduce tire/pavement noise.

**Table 10: Typical OGFC Gradations for Highway Construction Based on Maximum Aggregate Size (Percent by Mass)**

| Grading Requirements | % Passing | | | |
|---|---|---|---|---|
| Sieve Size, mm | 9.5 mm (3/8") OGFC | 12.5 mm (1/2") OGFC | 19 mm (3/4") OGFC | 25 mm (1") OGFC |
| 25 (1") | | | | 100 |
| 19 (3/4") | | | 100 | 85-100 |
| 12.5 (1/2") | | 100 | 80-100 | 55-70 |
| 9.5 (3/8") | 100 | 95-100 | 35-60 | 10-24 |
| 4.75 (No. 4) | 35-55 | 30-50 | 10-25 | --- |
| 2.36 (No. 8) | 9-14 | 5-15 | 5-10 | --- |
| 0.075 (No. 200) | 0-2.5 | 2-5 | 1-4 | 1-6 |

### Selection of Optimum Asphalt Binder Content

Selection of optimum asphalt binder content varies greatly based on the agency specifying the OGFC. Some agencies simply utilize a recipe method for selecting optimum asphalt binder content. These recipes are based upon local materials and experience and, therefore, are not presented. Local experiences are not suitable for developing a specification that may be used throughout the country and/or world. Other agencies do have formalized mix design methods that are summarized herein.

As discussed previously during the selection of optimum asphalt binder content for airfield applications, some OGFC mix design procedures utilize the CKE method of estimating optimum asphalt binder content. When the CKE method is used, the majority of agencies will also include an additional step to evaluate the draindown potential of the designed mix. Draindown is a term related to a construction problem and is used to describe when asphalt binder drains from the coarse aggregate structure during storage and/or transportation. When draindown occurs, fat spots occur on the pavement surface. These fat spots are areas where the asphalt binder content is high and can result in a pavement surface with poor frictional characteristics. Conversely, there will also be areas with low asphalt binder contents that will be prone to raveling. The most common draindown potential test used with the CKE method of selecting optimum asphalt binder content is the "pie-plate" method. This method entails placing loose OGFC mixture into a pie plate. The mix and pie plate are then placed into an oven at a specified temperature. After a specified time period, the loose mixture and pie plate are removed from the oven. Draindown potential is evaluated by the amount of asphalt binder that drains from the aggregate structure and adheres to the pie plate. The estimated optimum asphalt binder content is then modified based upon results of the draindown testing. If draindown potential is high, the optimum asphalt binder content is lowered, or the mixture is redesigned.

The most performance based mix design method currently used for highway OGFCs was developed by NCAT in 2000 (30). This mix design procedure is for an OGFC that has been called "new-generation" open-graded friction course which is an OGFC specifically designed to remove large volumes of water from the pavement surface. Selection of optimum asphalt binder content is based upon the results of laboratory performance tests.

Within the NCAT recommended mix design method, the selected design gradation is combined with asphalt binder at three binder contents, in increments of 0.5 percent. A draindown test is conducted for each asphalt binder content on loose mix at a temperature 15°C higher than anticipated production temperature. The draindown test is different than the pie-plate method described above. Loose mix is placed within a wire basket. The wire basket and loose mixture are placed into a forced draft oven for one hour. Underneath the wire basket, a plate or container is placed. At the conclusion of the test, the amount of asphalt binder that drains from the loose mixture through the wire mesh basket onto the plate/container is measured. Draindown is expressed as the percentage of asphalt binder draining from the loose mixture based on the original total mass of the sample. Mixture at the three asphalt binder contents is also compacted using 50 gyrations of a Superpave gyratory compactor to evaluate air void contents. The Cantabro Abrasion test is also conducted on laboratory compacted samples using unaged and aged (7 days @ 60°C) samples in order to evaluate durability. The Cantabro Abrasion test is conducted by placing a single compacted sample of OGFC into a Los Angeles Abrasion drum without the charge of steel spheres. The drum is then rotated 300 revolutions at room temperature. At the conclusion of the 300 revolutions, the sample is removed and the abrasion loss is reported as the percent material lost during the test based upon the original mass of the sample. Optimum asphalt binder content is one that meets all of the following criteria.

1. Air Voids. A minimum of 18 percent is acceptable, although higher values are more desirable. The higher the air voids are the more permeable the OGFC.
2. Abrasion Loss on Unaged Specimens. The abrasion loss from the Cantabro test should not exceed 20 percent.
3. Abrasion Loss on Aged Specimens. The abrasion loss from the Cantabro test should not exceed 30 percent.
4. Draindown. The maximum permissible draindown should not exceed 0.3 percent by total mixture mass.

### Evaluation of Moisture Susceptibility

There are two tests that are prevalent for evaluating the moisture susceptibility of OGFC mixtures. The first is using the tensile strength ratio concept. Within this method, samples of OGFC are compacted in the laboratory. A subset of the samples is subjected to moisture conditioning. Several mix design methods include at least one freeze/thaw cycle within the conditioning process. Mallick et al (30) recommended five freeze/thaw cycles for conditioning specimens. After conditioning one subset of samples, the indirect tensile test is conducted on both the conditioned subset and the unconditioned subset. Tensile strength ratios are then developed by dividing the tensile strength of the conditioned subset by the unconditioned subset.

The other prevalent method for evaluating moisture damage is the boil method. This method entails boiling loose OGFC mixture in water. After the prescribed time, the loose mixture is visually evaluated to determine the percentage of aggregates in which the asphalt binder has separated from the aggregates.

## POTENTIAL IMPROVEMENTS TO MIX DESIGN FOR AIRFIELD PAVEMENTS

In order to make recommendations for improving the design of PFC mixes for airfields, some discussion is needed to describe the desirable properties for PFC pavement layers. According to AC 150/5320-12C, *Measurement, Construction, and Maintenance of Skid-Resistant Airport Pavement Surfaces*, PFC pavements are one method for improving runway pavement skid resistance and mitigating hydroplaning. Therefore, the desirable properties of a PFC for airfield applications are a wearing layer that provides high frictional resistance and minimizes the potential for hydroplaning without increasing the potential for FOD. Porous friction course pavements are not utilized on airport runways with over 91 turbojet arrivals per runway end per day. Since some larger aircraft will operate on the PFC, the mixture should also have sufficient shear strength to resist any permanent deformation or gouging (due to locked-wheel turning or braking traffic). As discussed in Chapter 2, one of the perceived disadvantages of PFCs is the occurrence of raveling; therefore, PFCs, should also be durable with low potential for raveling.

Improved frictional properties can be achieved by focusing on two characteristics of PFC pavements. First, an open-grading is needed within the aggregate gradation so that the PFC will have a significant amount of macrotexture. Macrotexture is directly related to the shape, size, angularity, density, distribution and arrangement of aggregates within the pavement surface (5). Many research studies have shown that the open gradations associated with PFC mixes provide a significant amount of macrotexture. However, the amount of macrotexture can be altered by the proportion of coarse aggregates within the gradation. As the fraction of coarse aggregate increases (or, the gradation become more single-sized), macrotexture increases. As shown in Tables 8, 9, and 10, there are a number of gradations that can be used for PFCs (or OGFCs). Each of these gradation requirements will provide a significant amount of macrotexture compared to dense-graded HMA. The second characteristic is proper selection of aggregates. Aggregates with a significant amount of microtexture and polish resistance that are not susceptible to polishing should be selected.

Hydroplaning occurs when a layer of water builds up between a tire and the pavement surface breaking the contact between the tire and pavement surface (12). When this occurs, friction is lost. Hydroplaning can be combated in one of two ways. The first method is to remove water from the pavement surface such that there is no layer of water that can break the contact between the tire and pavement surface. This can be easily accomplished using PFCs as these mixes are generally designed to have a high percentage of air voids. The high percentage of air voids within a PFC layer increases the potential for these air voids to become interconnected. Interconnected air voids provide pathways for water to infiltrate into the PFC layer. Water that infiltrates into a PFC is not available for creating a water layer to allow a break in contact between tires and the pavement surface. However, the water that infiltrates into the OGFC layer must be transported to the pavement edge and discharged from the layer.

The second method of mitigating hydroplaning is to provide a significant amount of macrotexture within the pavement surface (5). Significant macrotexture provides channels at the pavement surface for water pooled on the surface to be displaced due to the pressure created by aircraft tires passing over the pavement surface. A significant amount of macrotexture may reduce the potential for hydroplaning sufficiently so that a significant amount of permeability is not required (though some permeability would be beneficial).

Another characteristic that is important to PFC layers is that the mixture should have enough shear strength to resist the actions of turning or braking aircraft. As larger aircraft turn or brake, very large shear stresses are developed between the tire and pavement surface. If the shear stresses created are larger than the shear strength, particles will become dislodged creating FOD. Therefore, high shear strengths are needed for PFC mixtures.

The final characteristic that is important for PFC is durability. Many of the interviews conducted with the airfield pavement engineers cited raveling as a problem with PFCs. Therefore, any potential improvements should attempt to make PFCs more durable.

Based upon the above discussion, PFCs used for airfield applications must provide a significant amount of macrotexture, have sufficient shear strength and be durable. Recommendations for improvements to the design of PFC mixtures must maximize these qualities without increasing the potential for FOD.

Similar to the discussion on the design of PFCs, the potential areas for improvements will be divided by the steps in designing PFCs.  The following paragraphs describe potential improvements for the design of porous friction courses.

## Materials Selection

As stated previously, materials needing selection include coarse aggregates, fine aggregates, mineral fillers, asphalt binders and additives.  Porous friction courses can be considered a specialty type HMA because they contain an open aggregate grading having a large percentage of coarse aggregate and a low percentage of fine aggregate and minimal mineral filler.  Therefore, the performance of PFCs is directly related to the characteristics of the aggregates, especially coarse aggregates.  Because of the open aggregate grading, the coarse aggregates tend to be in contact with each other within the layer.  This contact of the aggregates is generally termed stone-on-stone contact when designing SMA and has applicability to PFCs.

There are five primary aggregate characteristics that are important to the performance of any HMA, including PFCs:  angularity, shape, toughness, abrasion resistance, soundness and cleanliness.  Table 11 summarizes the current aggregate tests for PFCs used on airfields.

**Table 11: Summary of Current Aggregate Tests for Porous Friction Courses**

| | **P-402** | | **UFGS-32 12 20** | |
|---|---|---|---|---|
| **Characteristic** | **Coarse Aggregate** | **Fine Aggregate** | **Coarse Aggregate** | **Fine Aggregate*** |
| Angularity | Fractured Faces | --- | Fractured Faces | Fractured Faces |
| Shape | Flat or Elongated | --- | Flat and Elongated | --- |
| Toughness | LA Abrasion | --- | LA Abrasion | LA Abrasion |
| Soundness | Sodium Sulfate Soundness | --- | Magnesium Sulfate Soundness | --- |
| Cleanliness | --- | Plasticity Index & Liquid Limit | --- | --- |

*Must consist of clean, sound, durable, angular particles produced by crushing aggregates meeting coarse aggregate requirements.

Kandhal (15) has stated that the aggregate requirements for open-graded friction courses should be similar to those of SMA. This recommendation is appropriate because the coarse aggregates must be adequately strong (tough) to carry the loads of traffic (operations) since both mix types essentially achieve their stability through stone-on-stone contact. Likewise, the aggregates must be angular with the proper shape to provide a stable layer. Tables 12 and 13 provide current aggregate requirements for SMA mixes. These requirements are listed in AASHTO MP-8, *Standard Specification for Designing Stone Matrix Asphalt (SMA)*.

**Table 12: Coarse Aggregate Quality Requirements for SMA**

| Test | | Method | Spec Minimum | Spec Maximum |
|---|---|---|---|---|
| Los Angeles (LA) Abrasion percent loss | | AASHTO T96 | | 30[a] |
| Flat and Elongated, percent[b] | 3 to 1 | ASTM D4791 | | 20 |
| | 5 to 1 | ASTM D4791 | | 5 |
| Absorption, percent | | AASHTO T85 | | 2.0 |
| Soundness (5 cycles), percent | | AASHTO T104 | | |
| Sodium Sulfate, or | | | | 15 |
| Magnesium Sulfate | | | | 20 |
| Crushed Content, percent | | ASTM D5821 | | |
| One Face | | | 100 | |
| Two Face | | | 90 | |

[a] Aggregates with higher LA Abrasion values have been used successfully to produce SMA mixes. However, when the LA Abrasion exceeds 30, excessive breakdown may occur in the laboratory compaction process or during in-place compaction.

[b] Flat and Elongated criteria apply to the design aggregate blend, not individual stockpiles.

[c] Sodium Sulfate or Magnesium Sulfate may be used. It is not a requirement to perform both methods.

**Table 13: Fine Aggregate Quality Requirements for SMA**

| Test | Method | Spec Minimum | Spec Maximum |
|---|---|---|---|
| Soundness[a] (5 Cycles), Percent[b] | AASHTO T104 | | |
| Sodium Sulfate, or | | | 15 |
| Magnesium Sulfate | | | 20 |
| Liquid Limit, percent | AASHTO T89 | | 25 |
| Plasticity Index, percent | AASHTO T90 | Non-plastic | |

[a] Fine Aggregate Quality Requirements may be performed on the parent coarse aggregate.

[b] Sodium Sulfate or Magnesium Sulfate may be used. It is not a requirement to perform both methods.

Tables 12 and 13 show that the test methods used to measure the characteristics of the aggregates for SMA are generally similar to those currently provided in Item P-402 and UFGS-32 12 20 for PFCs. Angularity is defined as the percent fractured faces, particle shape is defined as the percent flat and elongated, toughness is defined as the percent loss in the Los Angeles Abrasion, soundness is defined as sulfate or magnesium soundness and cleanliness is defined as liquid limit and plasticity index. There are, however, some differences in the specification limits. Most notably, the angularity requirements for SMA are higher than those contained within Item P-402 and UFGS-32 12 20. For SMA, the minimum percentage of coarse aggregate particles with two or more fractured faces is 90 percent compared to the 75 percent minimum required for airfield PFCs. Because the stability of PFCs is derived from inter-particle contact, the higher percentage of particles with two or more fractured faces will provide a more stable layer. This requirement should be irrespective of the size aircraft using the airfield.

The literature states that the fractured face test as defined by ASTM D5821, *Determining the Percentage of Fractured Particles in Coarse Aggregate*, is relatively variable. Prowell (31) indicates that the acceptable range between two properly conducted tests by two well-trained operators would be 14.7 percent according to the test method's precision statement. This variability is likely similar when using the definition of a fractured face with Item P-402 and UFGS-32 12 20. An alternative test for measuring the angularity of coarse aggregates is AASHTO T326, *Method A, Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture and Grading)*. This test method has been recommended over the fractured face count test in two recent large research projects conducted for highway HMA (32, 33). Also, Ahlrich (34) recommended this test for heavy duty airfield HMA. To conduct this test, a standard coarse aggregate grading is allowed to fall freely into a cylinder of known volume. Using the bulk specific gravity of the aggregate, the percentage of voids between the coarse aggregate particles is determined. The percentage of voids provides an indication of the aggregate's angularity, shape and surface texture. As the percent voids increase, the angularity, shape and surface texture improve. This test method would be an improvement over the fractured face count test.

The percent loss from the Los Angeles Abrasion test shown in Table 12 (30 percent) is identical to that within Item P-402. However, UFGS-32 12 20 has a suggested maximum limit of 25 percent. From a performance standpoint, there should not be any difference in performance whether the maximum Los Angeles Abrasion Loss requirement is 25 or 30 percent; therefore, a requirement of 30 percent loss is appropriate for PFCs. One note that the SMA specifications contain that is likely warranted is shown under Table 12. This note states, "Aggregates with higher Los Angeles Abrasion values have been successfully used…" A caveat of this nature is similarly contained within UFGS-32 12 20 which states the "… Los Angeles Abrasion test is used in excluding aggregates known to be unsatisfactory or for evaluating aggregates from new sources...Aggregates in the area that have been previously approved or that have a satisfactory service record…" Experiences of the research team also suggest that some aggregates having a Los Angeles Abrasion loss of more than 30 percent have performed satisfactory in both PFCs and SMA. Therefore, the note contained within Table 12 and UFGS-32 12 20 is warranted.

Another slight difference from the airfield specifications in the coarse aggregate requirements presented in Table 12 is that both the sodium and magnesium sulfate soundness tests are allowed for SMA. Recall that Item P-402 requires sodium sulfate and UFGS-32 12 20 allows both. Of the two sulfates that can be used, the magnesium sulfate is the harsher material when conducting soundness testing. Therefore, higher percentages of loss would be expected when using magnesium sulfate. However, the percentage of loss requirement is the same in UFGS-32 12 20 no matter which sulfate solution is used. It is likely best to provide recommended limits for both sodium and magnesium sulfate soundness results. This is especially true since sodium and/or magnesium sulfate is specified by most highway agencies. Therefore, aggregate suppliers will have test results for one or the other, and sometimes both. As for the maximum percentage of loss, a maximum of 12 percent using sodium sulfate soundness and 15 percent using magnesium sulfate soundness appear appropriate.

Requirements for particle shape within the SMA specifications are for flat and elongated. This is identical to UFGS-32 12 20 but differs from Item P-402 where the flat or elongated particles test is specified. Recently completed research conducted through NCHRP (32, 33) has indicated that particle shape as measured by the flat or elongated definition is a better predictor of pavement performance. Therefore, flat or elongated should be included within the aggregate requirements for PFCs. The next question is which ratio should be used. Item P-402 and UFGS-32 12 20 both recommend 5:1; however, the requirements for SMA require 3:1 and 5:1. Additionally, the previously mentioned NCHRP research projects (32, 33) both recommended a 2:1 ratio. The 2:1 ratio was recommended because it had a significant relationship with performance while other ratios of flat or elongated and none of the ratios for flat and elongated provided adequate relationships with pavement performance. Therefore, a ratio of 2:1 for flat or elongated particles is warranted for PFCs. According to research (33), a maximum limit of 50 percent flat or elongated particles at a 2:1 ratio should be utilized.

A requirement included for SMA that is not contained within either Item P-402 or UFGS-32 12 20 is that of limiting aggregate absorption to 2 percent. This requirement is included for SMA to ensure that a significant amount of asphalt binder is not absorbed into the aggregates. Asphalt absorbed into the pores of the aggregates does not enhance the durability of a mixture. While the intent of this requirement is valid, the absorption characteristics of the aggregates can be taken into account during the design of the PFC mixtures. The mixture can be aged in a forced draft oven during the mix design stage to simulate the aging that occurs to the asphalt binder and the amount of asphalt binder absorption that takes place during production and construction. Inclusion of a note that describes how to address absorptive aggregates may be a better method than limiting absorption.

Similar to Item P-402, the cleanliness of fine aggregates is addressed through the use of liquid limit and plasticity index within the current requirements for SMA. UFGS-32 12 20 does not currently have a requirement for the cleanliness of fine aggregates. Another test that could be used to evaluate the cleanliness of the fine aggregate blend is the Sand Equivalency test as defined in ASTM D2419, *Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate*. Conducting this test on the aggregate blend would identify potentially harmful fines that are included within the aggregate stockpiles (e.g., clay coatings on gravel aggregates).

One characteristic of the fine aggregate fraction not directly required within the Item P-402 is that of angularity. Angularity of the fine aggregates is addressed within UFGS-32 12 20 using fractured faces. However, this test is difficult to conduct on fine aggregates. Both airfield PFC mix design methods require the fine aggregates to be crushed byproducts of coarse aggregates; however, both allow some natural sands. A test to evaluate the angularity characteristics of the fine aggregate fraction of the aggregate blend should be included. Table 13 shows that for SMA, the uncompacted voids in fine aggregates as defined by Method A of AASHTO T304, *Standard Test Method for Uncompacted Void Content of Fine Aggregate (As Influenced by Particle Shape, Surface Texture and Grading)*, is used to ensure angular fine aggregates. This test method should be included for PFCs. It is currently included within Item P-401 and UGFS-32 12 15 for the design of dense-graded HMA.

The next material requiring selection is the asphalt binder. Current requirements within Item P-402 are for a viscosity-graded asphalt binder while UFGS-32 12 20 allows both viscosity- and penetration-graded binders. An improvement in the selection of asphalt binders would be to require asphalt binders graded in accordance with the Superpave Performance Grading (PG) system. The Superpave PG system is provided in AASHTO M320, *Standard Specification for*

*Performance Graded Asphalt Binder*. Both Item P-401 and UFGS-32 12 15 now allow Superpave Performance Graded (PG) asphalt binders.

One of the primary improvements the Superpave PG system provides over the viscosity and penetration grading methods is that asphalt binders are evaluated at high, intermediate and low temperatures. The penetration grading method only utilizes an intermediate temperature (25˚C (77˚F)) for evaluating the properties of the asphalt binder, while the viscosity grading method, primarily evaluates the high temperature properties of the asphalt binder (60˚C and 135˚C (140˚F and 275˚F, respectively)). No low temperature properties of the asphalt binder are evaluated as part of either penetration or viscosity grading. Additionally, the viscosity and penetration test do not always accurately reflect the advantages or disadvantages of modified asphalt binders (35).

Figure 7 illustrates the Superpave PG system. The system includes testing within four different temperature regimes that are related to the life/performance of asphalt pavements: construction, permanent deformation, fatigue and low temperature cracking. Another characteristic of the Superpave PG system is that the asphalt binder is subjected to two aging protocols that are supposed to simulate the aging that occurs during production/construction and the amount of aging that occurs after several years of service. The rolling thin film oven test (RTFO) is used to age samples similar to the amount of aging that occurs during production and construction (35). Both the penetration and viscosity grading methods include the thin film oven test within their requirements which also simulates the amount of aging that occurs during production and construction; however, neither of these grading systems include an evaluation of the long term aging characteristics of the asphalt binder as does the Superpave PG system. The pressure aging vessel (PAV) is conducted within the Superpave PG system to simulate the amount of aging that occurs after several years of in-place service (35).

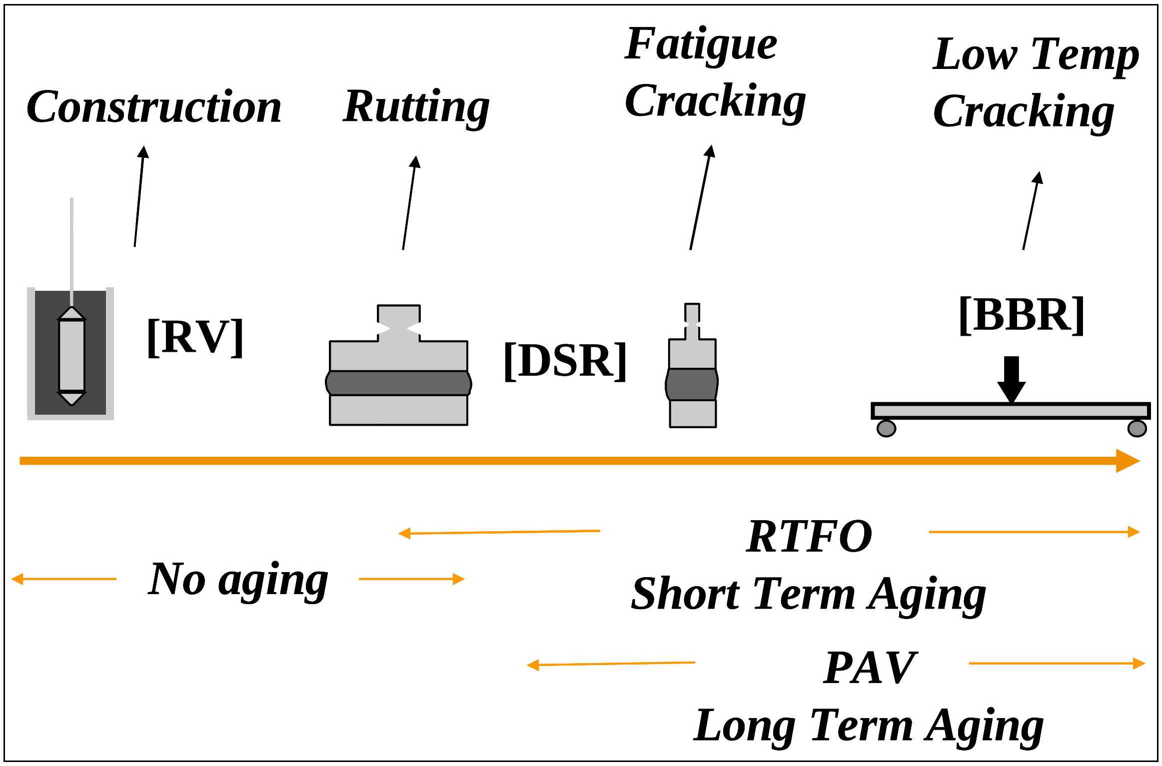

**Figure 7: Superpave Binder Tests**

As shown in Figure 7, a rotational viscometer (RV) is used to characterize asphalt binders at the time of construction. This test is included to ensure that asphalt binders can be pumped at typical production facility temperatures (35). Rotational viscometer testing is conducted on unaged samples of asphalt binder.

Permanent deformation occurs at high temperatures. Additionally, permanent deformation generally occurs within the first few years of service before the asphalt binder stiffens due to aging. Therefore, the contribution of asphalt binder to the stability of a pavement layer is evaluated on unaged and RTFO aged samples using a dynamic shear rheometer (DSR) at high test temperatures (35).

Fatigue cracking generally occurs at low and intermediate pavement temperatures after the pavement has been in-service for some period of time. To evaluate the contribution of the asphalt binder in resisting fatigue-related distresses, the Superpave PG system requires the testing of binders that have been aged in the RTFO and PAV at intermediate temperatures using the DSR (35).

As asphalt binder ages, it stiffens due to oxidation. When the asphalt binder stiffens, the pavement becomes more susceptible to low temperature cracking. Therefore, the potential of low temperature cracking is evaluated using asphalt binders that have been aged in the RTFO and PAV. The bending beam rheometer (BBR) is included to evaluate the low temperature properties of asphalt binders (35).

Results from the tests of the Superpave PG system described above are physical properties of the asphalt binder. Results of the physical property testing provide information on the asphalt binder's contribution to the various performance measures described above. Specified asphalt binders for a given project are characterized by two numbers: high temperature grade and low temperature grade. A typical Superpave PG asphalt binder will have the following form:

PG 64-22

Within the grading system, "PG" indicates that the asphalt binder has been graded in accordance with the Superpave system. The first number, 64, indicates that the asphalt binder meets the physical property requirements above 64˚C. The second number, -22, indicates that the asphalt binder meets the physical property requirements below a temperature of -22˚C.

The above discussion shows that the Superpave PG system is an improvement over the currently specified viscosity- and penetration-grading methods. This is based on the fact that the Superpave PG system utilizes testing at high, intermediate and low temperatures, utilizes test methods that measure a wide range of physical properties, and includes aging techniques that more accurately reflect the amount of oxidative stiffening that occurs during the life of the asphalt binder. The next question that must be asked is "What are the desirable properties of asphalt binders used in porous friction courses?"

When open-graded friction courses were first developed in the 1930's, neat (unmodified) asphalt binders were utilized. In 1992, Anderton (25) stated that the use of PFCs had not been widespread within the US because of concerns over the lack of durability of these mix types. Problems that were encountered in the past with PFCs include raveling, stripping and delamination (15, 36). Additionally, in most instances, these problems tended to accelerate quickly requiring immediate maintenance or complete removal (27).

Many of the past problems with PFCs can be traced to the selection of the asphalt binder. As discussed previously, PFCs have an open aggregate grading with a relatively low percentage of material passing the 0.075mm (No. 200) sieve. Because of the open grading, there is very little surface area of the aggregate which results in a relatively thick asphalt binder film coating the aggregates. At typical production/construction temperatures, the heavy film of asphalt binder had a propensity to drain from the aggregate skeleton (27). Because of the draindown issues, a typical remedy was to reduce mixing and compaction temperatures (15). This reduction in temperature increased the viscosity of the asphalt binder which assisted in preventing the binder from draining from the aggregates. However, the reduction in temperature also led to the durability problems listed above. First, because the production temperature of the PFC was reduced, all of the internal moisture within the aggregates was not removed during production. Moisture remaining within the aggregates after production led to stripping of the asphalt binder film from the aggregates which resulted in the increased occurrence of raveling (26). Additionally, the reduced temperatures prevented the new PFC from properly bonding with the tack coat placed on the underlying layer. This lack of an adequate bond led to delamination problems (15).

Though the problems described above are not directly related to the fundamental properties of the asphalt binder, they were related to the viscous component of the asphalt binder. In a 1998 survey of state highway agencies, Kandhal and Mallick (36) stated that many of the highway agencies which had experienced good performance with PFCs were utilizing modified asphalt binders and relatively high asphalt binder contents (by using fibers and/or relatively open gradations). Based upon the discussions provided on the past problems with PFCs, the use of modified asphalt binders makes sense. First, the increased viscosity of the asphalt binder helps to hold the asphalt binder on the coarse aggregate structure reducing the potential for draindown. When combined with the proper use of fibers, modified asphalt binders have basically eliminated draindown potential. Without the potential for draindown, production temperatures do not have to be lowered.

The benefits of modified asphalt binders are not limited to helping prevent draindown. A series of reports and papers from NCAT (30,37,38) have shown that the use of modified asphalt binders that provide high stiffness at typical in-service pavement temperature helps provide increased durability. Anderton (25) has also showed that the addition of reclaimed rubber particles to the asphalt binder (i.e., increased viscosity) improved the performance of PFCs.

As alluded to above, one additive routinely added to PFCs used for highways is fibers. Fibers are added to these open-graded mixes to reduce draindown potential. Figure 8 illustrates the effect of fiber addition on draindown potential. Data used to create Figure 8 is from a research project being conducted by the NCAT and was previously published by Watson et al (38) in a slightly different form. Figure 8 clearly shows that the addition of fiber significantly reduces draindown potential. Also, the addition of modified binders and fibers allows for an increase in asphalt binder content which improves durability. Figure 9 illustrates the results of laboratory durability testing at two different asphalt binder contents. Data used to create Figure 9 also comes from Watson et al (38) and is presented here in a slightly different form. The laboratory durability testing depicted in Figure 9 is the Cantabro Abrasion Test.

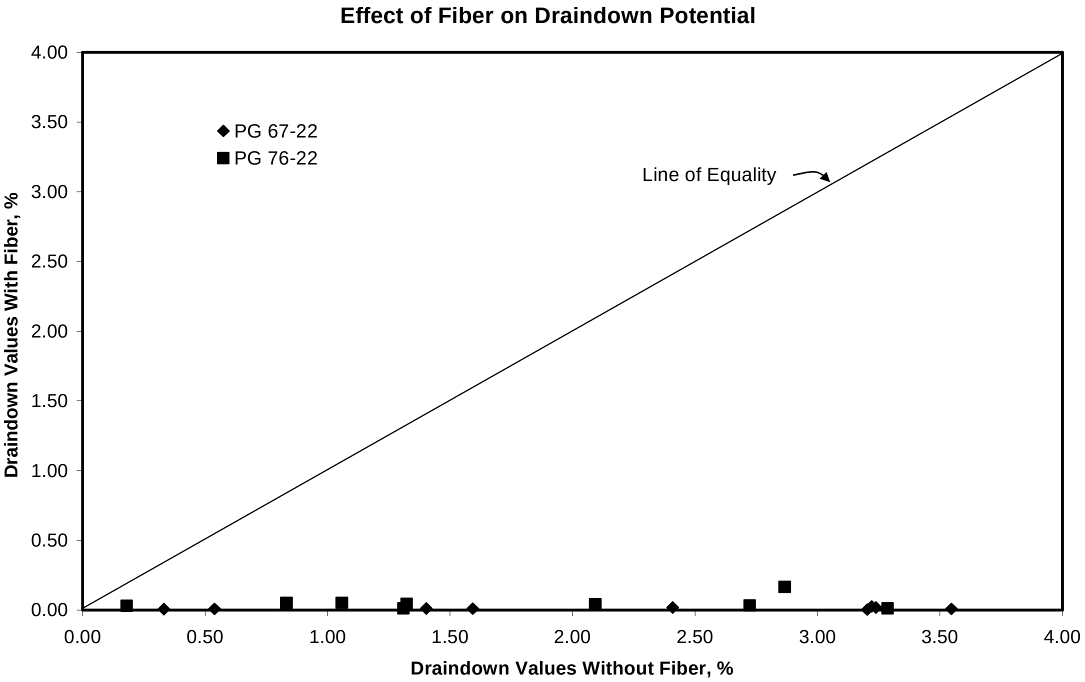

**Figure 8: Effect of Fiber on Draindown Potential (38)**

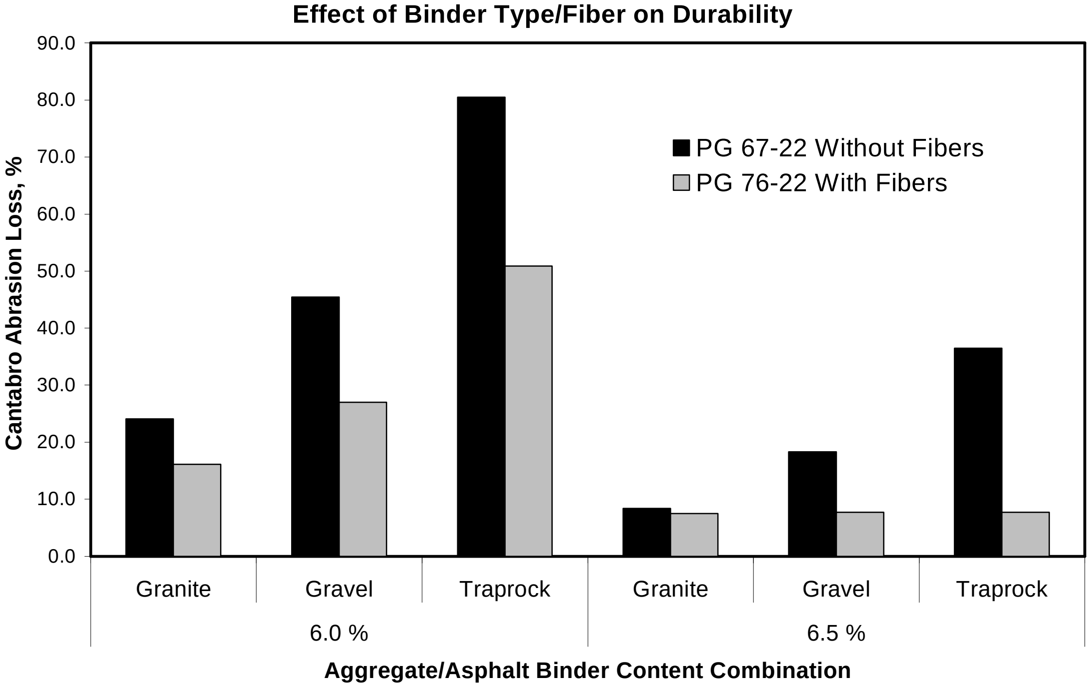

**Figure 9: Effect of Asphalt Binder Type on Cantabro Abrasion Loss (38)**

Figure 9 clearly illustrates two important points. First, as the asphalt binder content increases, the abrasion loss decreases signifying an increase in durability. Secondly, the addition of modified binders and fibers also decreased abrasion loss. Therefore, inclusion of fibers as an additive would be beneficial for PFCs. Fibers would allow for increased asphalt binder contents which, when combined with the use of modified binders, would improve durability.

Other additives added to PFCs generally relate to anti-stripping agents. Both liquid and solid (lime) anti-stripping agents have been used with success. Local experience will likely dictate which form of anti-stripping agent is used.

## Selection of Design Gradation

As stated previously, the purpose of PFCs is to improve the frictional characteristics of a pavement surface. Desirable properties of PFC surfaces include high levels of macrotexture, high air void contents (for permeability) and shear strength. Macrotexture is provided by the gradation of the mixture; therefore, to provide a significant amount of macrotexture it would be desirable to provide a very coarse gradation. An added benefit of very coarse PFC gradations is that these gradations also result in a large number of interconnected air voids that allows water to drain from the pavement surface. Conversely, mixtures having a very coarse gradation will likely have minimal shear strength. Some amount of fine aggregate and filler is needed to provide shear strength. Therefore, the ideal gradations for PFC used on airfields have to balance the need for macrotexture/permeability and shear strength.

Research has shown that there are two predominant methods for increasing the macrotexture of asphalt pavement surfaces. The first method is to move the gradation away from the maximum density line (39). As gradations become coarser, more surface texture is created. The other method of increasing the macrotexture of asphalt pavement surfaces is to increase the maximum aggregate size of the surface mixture. Based upon these two properties, desirable PFC gradations to improve macrotexture would be coarse with relatively large maximum aggregate sizes. An additional benefit of large maximum aggregate size gradations that are very coarse is that these gradation types promote the drainage of water through the layer as would be desired in PFCs.

One of the past problems associated with PFCs is that of raveling. This was especially true when turning or braking traffic passes over PFCs. Because of the very coarse gradation and low filler content, PFC mixes have relatively low shear strength compared to dense-graded HMA. The ability of PFCs to withstand the turning and braking effects of aircraft is more related to the properties of the asphalt binder because of the lack of internal shear strength. One method of improving the shear strength of PFC mixes would be to ensure some amount of filler within the gradation requirements.  The addition of some filler will provide some mortar (combination of filler and asphalt binder) to increase shear strength.  The addition of filler must be balanced, however, with the desired ability of PFCs to drain water.

Based upon the above discussion, two gradation bands for PFCs were developed.  The two gradation bands have the same maximum aggregate sizes as currently included within Item P-402 and UFGS-32 12 20.  The recommended gradation bands, illustrated in Figures 10 and 11 and provided in Table 14, are a compromise between the Item P-402 and UGFS-32 12 20 gradation requirements while considering the desirable properties of PFCs described previously. For the ¾ in. (19.0 mm) maximum aggregate size gradation band, the recommended limits roughly follow the P-402 requirements on the coarse side and pass between the Item P-402 and UFGS-32 12 20 requirements on the fine side.  One difference between the recommended ¾ in. (19.0 mm) maximum aggregate size requirements and the two current airfield requirements is that the minimum filler content was increased to 2 percent.  This was done to include slightly more filler in an effort to improve shear strength.

For the ½ in. (12.5 mm) maximum aggregate size gradation (Figure 11), the recommended limits closely follow the UFGS-32 12 20 requirements on the coarse side and again between the two airfield specifications on the fine side.  Filler content was again set between 2 and 5 percent.  This upper limit of 5 percent is slightly less than the Item P-402 requirements.  Too much filler can reduce the permeability of the PFC layer in the field.

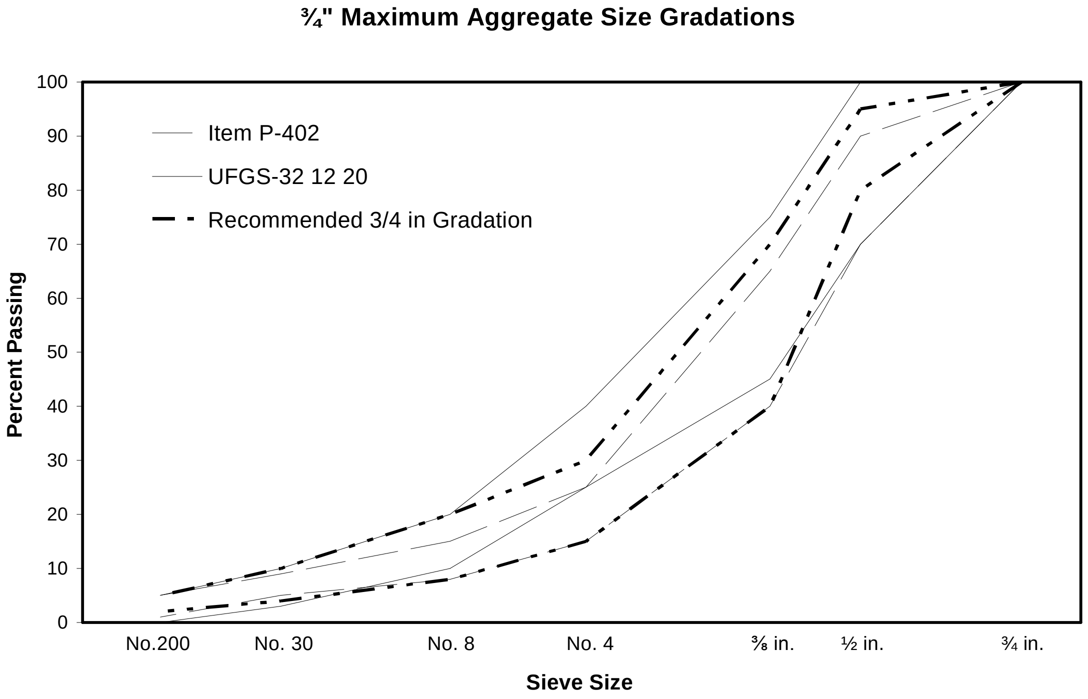

Figure 10: Recommended Gradation Band for 3/4 in Maximum Aggregate Size PFC

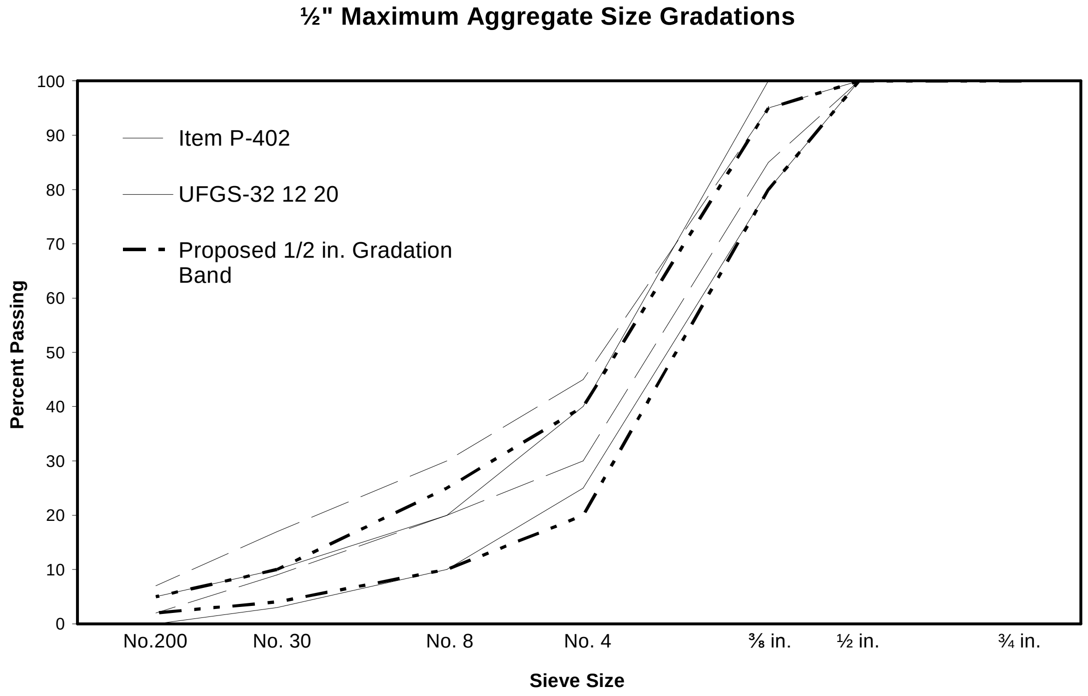

Figure 11: Recommended Gradation Band for 1/2 in Maximum Aggregate Size PFC

**Table 14: Recommended PFC Gradation Bands**

| Sieve, mm | Proposed ¾ in. Max. Aggregate Size Gradation | | Proposed ½ in. Max. Aggregate Size Gradation | |
|---|---|---|---|---|
| | Min. | Max. | Min. | Max. |
| 19.0 (¾ in.) | 100 | 100 | | |
| 12.5 (½ in.) | 80 | 95 | 100 | 100 |
| 9.5 (⅜ in.) | 40 | 70 | 80 | 95 |
| 4.75 (No. 4) | 15 | 30 | 20 | 40 |
| 2.36 (No. 8) | 8 | 20 | 10 | 25 |
| 1.18 (No. 30) | 4 | 10 | 4 | 10 |
| 0.075 (No. 200) | 2 | 5 | 2 | 5 |

## Selection of Optimum Binder Content

Use of the CKE method for selecting optimum asphalt binder content is highly empirical and not a performance related method of selecting optimum asphalt binder content. The purpose of the CKE method is solely to estimate the amount of surface area and absorption for the coarse aggregates. Selection of optimum asphalt binder content should be based upon performance related tests.

There are currently a number of performance related laboratory tests that could be used in selection of the optimum asphalt binder content for PFCs. Performance related tests should be used to select both a maximum and minimum allowable asphalt binder content. Identifying a maximum optimum asphalt binder content will help prevent draindown potential. Identifying a minimum optimum asphalt binder content will help ensure durability, thus, minimizing FOD potential. Also, since part of the function of a PFC is to remove water from the pavement surface, there should be some level of permeability within the layer. Permeability is controlled by air void contents; therefore, evaluation of air voids during mix design should also be considered.

Since setting a maximum asphalt binder content would be to minimize the potential for draindown, a laboratory draindown test should be utilized to help select optimum asphalt binder content. There are a number of draindown tests available, including the draindown basket test (developed by NCAT), the Schellenberger drainage test, and pie-plate method. The draindown basket and pie-plate methods were described previously. The Schellenberger method entails placing loose PFC mix into a glass beaker. The beaker is then placed into an oven at an elevated temperature for a specified time. The amount of binder that drains from the loose mixture and is stuck to the sides and bottom of the beaker is then used to calculate the amount of draindown. Of these three methods, only the draindown basket method currently has a national standard. The test method is provided in AASHTO T305, *Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures,* and ASTM D6390, *Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures*.

In order to use the draindown test within a mix design method to identify a maximum asphalt binder content, samples of PFC should be prepared over a range of asphalt binder contents. At each asphalt binder content the draindown properties should be measured. The asphalt binder content in which the draindown test result exceeds 0.3 percent would be considered a maximum optimum asphalt binder content. Testing should be conducted 15°C above the anticipated production temperature. This temperature was recommended for SMA (40). Testing at this temperature should provide some factor of safety against draindown.

The literature shows that the predominant test used to evaluate a minimum asphalt binder content (for durability) is the Cantabro Abrasion Loss test. This test method is used in the design of OGFC mixtures in the US and Europe. Originally developed in Spain, this test is used to evaluate durability (41). As shown in Figure 9, results of the Cantabro are influenced by the asphalt binder content and the stiffness of the asphalt binder. Porous friction course mixtures that do not have sufficient asphalt binder coating the aggregates will not perform within the Cantabro Abrasion Loss test.

Samples used for the Cantabro Abrasion Loss are laboratory compacted samples. Therefore, the next question is what standard compactive effort should be used for preparing PFC samples. This question is also important for evaluating air void contents for PFCs. Within Europe and the US, the predominant compactive effort has been 50 blows per face of the Marshall hammer. Some agencies have, however, utilized 25 blows (42). One potential problem with specifying the Marshall hammer is that fewer and fewer contractors and laboratories have equipment and experience for conducting the Marshall compaction method. Since the early 1990's, the Superpave gyratory compactor has become the prevalent laboratory compaction method for HMA in the US. AAPTP Project 04-03, Implementation of Superpave Mix Design for Airfield Pavements, is currently being conducted because the vast majority of HMA produced in the US is being designed using the Superpave methods and associated equipment.

Currently, the design of new-generation open-graded friction courses is conducted with 50 gyrations (30) of the Superpave gyration compactor. Samples prepared for Cantabro Abrasion Loss testing within the design method are also compacted to 50 gyrations. Additionally, samples prepared to evaluate air void contents are also compacted to 50 gyrations. This compactive effort is likely applicable to PFCs but may need further evaluation. Based upon research conducted by Watson et al (37), Cantabro Abrasion testing would be conducted on unaged samples prepared with the Superpave gyratory compactor. A minimum asphalt binder content would be defined as the asphalt binder content that resulted in 15 percent loss.

As stated above, PFCs should have the ability to remove water from the pavement surface. Therefore, PFCs should have a minimum air void content. Historically, OGFCs were designed to have a minimum specified air void content of 15 percent (26). The new-generation OGFCs are designed to have a minimum air void content of 18 percent (30). Since PFCs for airfield pavements are not specifically designed to remove large volumes of water from the pavement surface, 15 percent may be more applicable. Additionally, the recommended gradation bands for PFCs are slightly finer than the new-generation OGFCs and, therefore, 18 percent air voids may not be achievable on a consistent basis.

Optimum asphalt binder content can be selected based upon the draindown and Cantabro Abrasion loss testing and the minimum air void content of 15 percent. Optimum asphalt binder content should be at least 0.4 percent below the maximum asphalt content determined form the draindown testing to account for production variability; yield a minimum of 15 percent air voids and meet the requirements for Cantabro Abrasion loss.

Another area that would improve the design of PFC is the evaluation of stone-on-stone contact. This is currently required for new-generation OGFC (30). Evaluation of stone-on-stone contact is conducted to ensure resistance to permanent deformation. The method for evaluating stone-on-stone contact would entail first measuring the voids in coarse aggregate of the coarse aggregate fraction in the dry-rodded condition using AASHTO T19, *Unit Weight and Voids in Aggregates*. This testing is conducted on the coarse aggregate fraction of the aggregate blend. Unlike the current airfield specifications, the coarse aggregate would not be defined by the fraction retained on the 4.75mm (No.4) sieve; rather, coarse aggregate would be those retained on a breakpoint sieve (37). The break point sieve is the finest (smallest) sieve to retain 10 percent or more of the aggregate gradation. The next step in evaluating stone-on-stone contact is to calculate the voids in coarse aggregate of samples compacted to 50 gyrations in the Superpave gyratory compactor. If the voids between the coarse aggregate in the compacted PFC are less than the dry-rodded coarse aggregate, then stone-on-stone contact is achieved (40). This evaluation at the selected optimum asphalt binder content will help ensure a stable layer of PFC.

### Evaluation of Moisture Susceptibility

Of the methods to evaluate the moisture susceptibility of the designed PFC discussed previously, the tensile strength ratio, as defined in AASHTO T283, *Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage*, is the only method with a current nationally standardized test method. Watson et al (38) have indicated that a single freeze/thaw cycle should be included. A minimum tensile strength ratio of 80 percent has been recommended (15).

## RECOMMENDED FUTURE WORK

Use of performance related tests for designing PFC is a major improvement over the CKE method. Appendix A presents a draft mix design procedure for PFCs that is based upon the discussions provided within this chapter. Included within the draft mix design procedure is the Cantabro Abrasion loss test. This test does not currently have a nationally standardized test method. Therefore, a draft test method is provided in Appendix B.

With the recommendation of any new or modified mix design method, the draft mix design procedure should be verified both in the laboratory and the field. The draft PFC mix design procedure was developed based upon a literature review and the desired properties of PFCs on airfield pavements. Specific areas that need to be evaluated in the laboratory include:

- Aggregate quality requirements

- Asphalt binder requirements
- Additive requirements
- Gradation bands
- Laboratory compactive effort
- Stone-on-stone requirements
- Cantabro Abrasion Loss test requirements
- Tensile Strength ratio test method and requirements

The additional work to evaluate the above areas would entail obtaining several sources of aggregate, specifically different mineralogies, designing PFCs according to the draft mix design method and evaluating the designed mixes. Evaluations of the designed mixes should be conducted for both stability and durability. At the conclusion of the laboratory work, any modifications to the draft mix design method should be made.

After any modifications to the mix design method have been made, if needed, the mix design method should be field validated. Field validation would entail making sure that the designed mix can be properly produced and constructed. A project, or projects, in which PFC is planned, should be identified. The PFC mix should be designed in accordance with the draft mix design procedure. During construction, plant-produced mix should be tested to ensure that the mix design criteria can be met during production. Field work should also be conducted on the constructed PFC layer to ensure that mixes designed in accordance with the tentative mix design method can be properly constructed.

Following construction of the project, or projects, the tentative mix design procedure should be modified as needed. At the conclusion of the additional work, a laboratory and field validated mix design procedure for PFC will be available.

# CHAPTER 4
# Production and Construction of PFC Mixes for Airfield Pavements

## INTRODUCTION

The renewed interest in OGFC mixtures within the highway industry over the last 10 to 15 years has been due to resolution of previous problems from the late 1970s and early 1980s that were related to premature raveling and fat spots (excessive asphalt) caused by draindown. These problems were directly related to adjustments made during production and placement of the mixture. Mix production temperature was decreased to 110 to 120°C (230 to 250°F) in order to increase the binder viscosity and reduce the potential for draindown. This practice led to mixtures being produced without adequate drying time to remove internal moisture within the aggregate particles. As a result, the binder lacked the bond needed with the aggregate particles and raveling soon developed.

Little formal research has been conducted to evaluate the production and construction of PFC layers. The majority of information contained in the literature is based upon years of experience. Therefore, this chapter contains guidance for producing and constructing PFC layers in the form of a best practices document.

Similar to any HMA mixture, construction of PFC pavement layers includes four primary phases: production, transportation, placement and compaction. Another very important aspect of construction is quality control/quality assurance (QC/QA). Many of the best practices for constructing PFC pavement layers can be taken from the construction of SMA (15). Both mix types utilize a large fraction of coarse aggregates and generally require the use of stabilizing additives. Therefore, in addition to the literature, reports and interviews dealing with PFCs, guidelines developed for constructing SMA (40) were also consulted to develop guidelines on the construction of PFCs. Another valuable reference utilized during the development of guidelines was the "Hot-Mix Asphalt Paving Handbook (2000)" (43).

## 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 that is capable of producing high quality HMA can produce high quality PFC (27). This section provides guidance 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 (43). 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 (27).

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 also 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 percentage of the gradation blend (on the order of 75 to 85 percent of the blend). Since the coarse aggregate gradation can have a tremendous effect on the quality of the PFC 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 (43).

## Liquid Asphalt

Porous friction course mixtures produced meeting the proposed draft mix design method may require that some type of modifier be used in order to enhance binder properties. The modifiers typically are combinations of styrene, butadiene, latex rubber, or crumb rubber. These products may require special blending through a shear mill or extra agitation and time for dispersion. The blending needed is usually done at an asphalt refinery or terminal. Since the modifier particles may have a different specific gravity than the binder they are used in, there is some concern that the modifier particles may separate out over a period of time. This concern has led some agencies to require additional tests, such as a separation test, be added to the normal binder testing regimen. Contractors are also required to provide asphalt storage containers that will provide continuous agitation of the binder in order to avoid any separation of binder and modifier. Vertical storage tanks (Figure 12) are often used in place of conventional horizontal tanks because the efficiency of agitation and product circulation may be improved.

**Figure 12: Vertical Asphalt Binder Storage Tanks (Courtesy Heatec, Inc.)**

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.

## Stabilizing Additives

With the high asphalt binder contents and large fraction of coarse aggregate inherent to PFC mixtures, a stabilizing additive of some type is generally used to hold the asphalt binder within the coarse aggregate structure during storage, transportation and placement. Draindown can 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. Eliminating draindown is helped through modifying the asphalt binder and/or the use of fibers. Some PFC mixtures will require the use of both a fiber and a modified asphalt binder to minimize draindown potential and improve durability. Additionally, use of fibers and modified asphalt binders will allow for higher production temperatures without draindown occurring.

### *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 (15). Fibers can generally be purchased in two forms, loose and pelletized. Fibers in a dry, loose state come packaged in plastic bags or in bulk. Fibers can also be pelletized with the addition of some amount of a binding agent. Asphalt binder and waxy substances have both 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 which melts easily at typical mixing temperatures (40). Therefore, 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. The dry, loose fiber is placed in the hopper of the machine where it is fluffed by large paddles (Figure 13). 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 (15).

**Figure 13: Fiber Pugmill-Type Dispersion System**

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 introduction line should be placed in the drum within 0.3 to 0.5m (12 to 18 inches) upstream of the asphalt binder line (15). Figure 14 illustrates a typical fiber injection point within a drum-mix plant. 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 (42). They indicated that this allowed the fibers to mix with the aggregates prior to the introduction of asphalt binder. No matter the method of introduction, 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, they will enter the dust control system of the plant (15).

**Figure 14: Fiber Injection Point in a Drier-Drum Plant**

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. 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. This clear section can provide a quick, qualitative evaluation of whether the fiber is being blown 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. The pellets are shipped to the plant in bulk form and when needed are placed into 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. Whether in the drum or the pugmill, the pellets are mixed with the heated aggregate and the heat from the aggregates cause the binding agent in the pellets to become fluid. This allows the fiber to mix with the aggregate (15). 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. The contractor should check with the fiber manufacturer to determine the asphalt contents of the pellets.

It is again 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 dosage rate, fat spots will likely 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.

### *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 (40).

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 (40). 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 sensitivity due to the relatively small weights and special metering devices may be necessary if the RAP feeder cannot be calibrated (40). 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.

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, therefore, be performed with care.

The stabilizing additive delivery system should be calibrated and continually monitored during production. 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. 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, both being causes for FOD. 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 (15). If this occurs, the rate of production should be decreased.

### *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 (15). 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. 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. 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 a silo overnight.

## TRANSPORTATION

The PFC mixture is transported to the project site using the same equipment used for dense-graded HMA (27). Generally, no additional precautions are required; however, there are some best practices that should be followed.

### 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 (43). Since the contractor often does not own the trucks, communication with the trucking operation is essential to avoid delays in production and placement.

Because of the bonding tendency of the modified asphalt binder generally used in PFCs, 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. Most agencies have approved lists of release agents (15). Use of fuel oils in any form should be strictly prohibited.

Haul trucks should be covered with a tarpaulin to prevent excessive crusting of the mix during transportation (27). Cold lumps do not break down readily and may cause pulls in the mat. It is also recommended that trucks have insulated front and sides to help prevent heat loss. This insulation may be builder’s insulating board so long as it has a minimum “R” value of 4.0

and can withstand over 177°C (350°F) temperatures (44). The insulation must be protected from exposure to the environment so that it does not deteriorate or become contaminated.

As an alternative to insulated truck beds, a "Heated Dump Body" may be used. A "Heated Dump Body" refers to a transport vehicle that is capable of diverting engine exhaust (Figure 15) and transmitting the heat evenly throughout the dump body to help keep the PFC at the desired temperature (45).

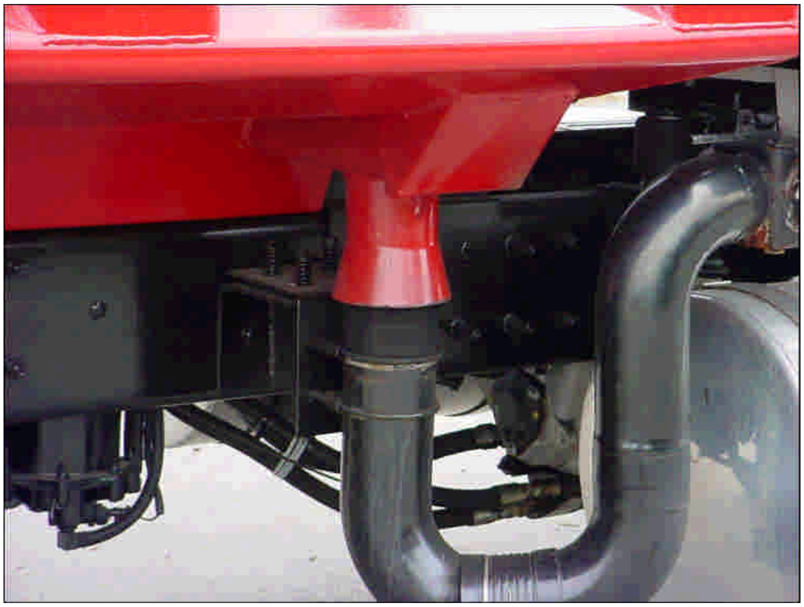

**Figure 15: Exhaust System of Heated Dump Body**

## Haul Time

Haul time should govern over haul length; however, some agencies restrict haul distance. For PFC mixtures, haul time should be limited to less than two hours, 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 (40). 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 very similar to placement of typical dense-graded HMA. Typical asphalt pavers are utilized.

### Temperature and Seasonal Limitations

Porous friction course mixtures are typically placed in thin lifts of 15 to 32 mm (5/8 – 1 1/4 inch) thick. These thin layers lead to rapid cooling from the ambient temperature as well as from the cooler existing pavement surface temperature. The open texture of the mix also leads to more rapid cooling than is experienced with dense-graded mixtures. Likewise, the crust of material that develops around the cone of mix and sides of the bed within the haul vehicle can lead to rough texture and premature raveling unless the cold mixture is remixed with the hot mixture remaining in the truck bed or spreader hopper to obtain a homogeneous temperature.

Because of the sensitivity of PFC to cool temperatures, some agencies specify minimum placement temperatures and in some cases require a Materials Transfer Vehicle (MTV) that will remix the material to a uniform temperature before placement. The term “uniform temperature” may be defined in this application as a temperature range such that the difference between the highest and lowest values do not exceed 11°C (20°F) when measured transversely across the mat within three feet of the back of the paver screed (45).

Most agencies have a minimum ambient temperature requirement based on layer thickness to help ensure that the mix can be placed before it becomes too cool to place without objectionable pulls and tears in the mat surface. The minimum temperature range varies among agencies but is typically 7°C to 18°C (45°F to 65°F) (46,47). In addition to ambient temperature, the surface temperature may be specified as well. For example, Texas requires the existing surface temperature to be at least 21°C (70°F) unless special approval is granted (47). FAA Guidelines restrict PFC placement to when the atmospheric temperature is 10°C (50°F) and rising (at calm wind conditions) and when the weather is not foggy or rainy (48).

### 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. Porous friction courses should enable rain water to penetrate the surfacing and be laterally drained off to the side of the pavement by flowing on the interface between the PFC and underlying layer. Therefore, the PFC should only be placed on an impermeable pavement layer. Placement on an impermeable layer will help ensure that during rainfall, the water will pass laterally through the PFC and not be trapped in the underlying pavement layer, thus helping to eliminate the potential for moisture damage (stripping) in the underlying layer. In order to laterally drain water that infiltrates into the PFC layer, the underlying layer must also have an appropriate cross slope. Cross slopes should be as high as possible without affecting the operational characteristics of aircraft. Steeper cross slopes help push water tot he pavement edge. Additionally, the increased hydraulic gradient caused by steeper cross slopes helps force debris to the pavement edge. Steeper cross slopes combined with higher air void contents provide a self cleaning mechanism within PFC layers.

Porous friction course should not be placed on rutted asphalt pavement. The rutted surface should first be milled or reshaped to that depth which allows the water to flow laterally to the side of the pavement before placement of the PFC mixture. The PFC mat should be day lighted at the pavement edge so that rain water percolating through the PFC can drain out freely at its edge (27). A strip at least 0.1 m (4 inches) wide should be left between the PFC and any grass area.

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. The application rate should be high enough to completely fill the surface voids. A slow-setting emulsion tack coat is likely to penetrate the surface voids more effectively than an asphalt cement tack coat. Most dense-graded HMA surfaces become reasonably impervious after two to three years of traffic. Such surfaces will not need any sealing prior to placing PFC. Severely cracked surfaces may require a impervious membrane to be used.

A freshly compacted dense-graded HMA course may have as much as 8 percent air voids in the mat and may be permeable to water. Therefore, it is essential to provide a uniform tack coat at an adequate application rate to fill and seal the surface voids of the underlying layer.

## 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*

When placing PFC mixtures it is essential that the operation keep moving in order to avoid excessive roughness or blemishes from cold mix. While a MTV is not mandatory, it is recommended so that continuity of operations can be maintained. The MTV must also have remixing capability so that cold lumps of mixture are eliminated. Another advantage of the MTV is that the equipment can operate in the paving lane adjacent to the paver so that haul truck tires do not pick up or track the tack application. The MTV may have additional onboard storage capacity or may rely on a hopper insert that is mounted over the conveyor system within the paver hopper, or both may be used together. Contractors who try to place the smoothest pavement possible often use MTV equipment to avoid paver delays and mat defects caused by cold mix. If the MTV were to run out of material, the conveyors will need to be turned off. During normal operation, fines with high asphalt content tend to build up on the conveyor systems of the MTV. There have been “fat” spots in some PFC projects that were determined to be caused by the buildup of fines on the conveyors slinging off when the conveyor did not have material to transfer.

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 should also be considered before using the windrow technique. During favorable weather conditions, windrow length should not be more than 50m (150 ft) (27).

### *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 (27). 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 (45). Paver stops and starts should be held to an absolute minimum because they will likely have a significant negative impact on 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 to 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. The paver wings should not be lifted except when the material is to be discarded.

### *Paver Control*

A mobile reference ski is typically used in conjunction with electronic grade controls to improve smoothness results. The paver normally averages the roughness between the front and rear tires, a distance of about 3.0 m (10 feet). A mobile ski of 7.5 to 9.0 m (24 to 30 foot) extends the distance over which the roughness is averaged. Item P-402 states that the ski must be 9.0m (30 ft) or longer. Some contractors use a mobile reference that extends over the screed so that the front of the grade reference slides, or rolls, over the existing pavement while the rear of the grade reference slides over the finished mat. This system provides the best grade reference possible for the paver electronics to operate on in order to maximize smoothness.

The sensitivity of the electronic grade control should be checked during paver operation. If the grade control unit is too sensitive it will constantly “hunt,” or move up and down, trying to establish the correct grade reference. If the grade unit is not sensitive enough, it will rise for a prolonged distance and then drop for a similar distance. The slow reaction time will result in long waves in the finished profile. A quick check can be made to determine if the sensitivity of the grade control unit is set correctly by using a couple of U.S. coins. If a U.S. dime is slid between the wand of the grade sensor and the reference ski, the tow arm should not move; however, if a nickel is inserted under the sensor wand the tow arm should move (49).

## Lift Thickness

Porous friction courses are generally not placed as thick as typical dense-graded mixtures for the same maximum aggregate size (MAS). Fine-graded PFC mixtures, for example, have been historically placed at about 16 mm (5/8 inch) thick which is just slightly thicker than the size of the largest aggregate particle. In order to improve water drainage and avoid pulls and tears in the mat from thin sections, some highway agencies have begun placing these mixes 32 to 50 mm (1.25-2.0 inches) thick. It has been common practice in Europe to place these mixes at 38 to 50 mm (1.5 to 2.0 inches) in thickness. Studies of multi-lane highways have shown that when three or more lanes slope in the same direction, 19 mm (3/4 inch) thick layers can become flooded in all but low intensity rainfall which will result in reduced effectiveness (50). A similar experience was reported in a Michigan study of 13 highway and five airport runways. The study determined that use of PFC was especially appropriate for high speed roadways and airport runways due to the ability to drain water rapidly, but that the mixture should not be placed less than 32 mm (1.25 inches) thick (51).

## Joints

Transverse joints at the beginning and end of a project may need a transition area for the layer to taper from minimum thickness to the specified plan thickness. To avoid a rough bump at these transverse joints, it may be necessary to mill a short taper that will provide the proper depth for which to begin the layer. When constructing the transverse joint, spacers are to be added under the screed to provide for the necessary uncompacted depth. The amount of roll-down is only about 15 to 20 percent of the initial thickness.

Longitudinal joints should be constructed by overlapping the previous lane placed by about 12.5 mm (1/2 inch). This small amount of overlap will eliminate the need for raking the joint but will provide enough mixture to eliminate raveling or joint separation as one might encounter with dense-graded mixtures. Care should be taken to see that the vertical face of the longitudinal joint is not tacked because that would result in impeded flow of water across the pavement from adjoining sections or lanes.

### Handwork

Porous friction course mixtures with polymer or rubber-modified asphalt binder will be difficult to manage with handwork. The mixture is both coarse and sticky which makes workability very limited and buildup on hand tools becomes frustrating to deal with. Around transverse joints and curved areas where hand work is necessary, tools should be sprayed with a release agent (other than fuel oil) to prevent the mix from sticking to and building up on the hand tool. A standard garden-type rake usually works better than the lute used with dense-graded mixtures for making minor repairs to correct surface texture or remove cold lumps of material. Even when constructing transverse joints, it is easier to use a small bucket loader to handle the material than to use hand tools.

## COMPACTION

As far as the compaction is concerned, initially it should be as intense as in the case of traditional bituminous mixes, in order to keep subsequent post-compaction as reduced as possible. As a result, in order to achieve correct compaction on PFC, the rollers must follow close behind the paver, passing over immediately after placement, in order for the temperature to be sufficient.

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

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

Two or three rollers are typically used in conventional HMA construction. This number normally serves well for PFC also. Steel wheeled rollers weighing 9 Mg (10 tons) should be used when compacting the PFC mixture (52). Roller speed should not exceed 5 km/hr (3 miles/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.

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.

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.  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.

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 PFC mixtures, compaction equipment is used only to seat the mixture in the tack coat in order to provide a good bond at the interface of layers. Otherwise, the mixture is intended to be highly permeable in order 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 15 to 20 percent air voids immediately after construction.

## Density Requirements

Density of OGFC mixtures is seldom checked since there is no attempt to compact the mix. If density results are desired in order to verify the field 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 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 TP 69-04. 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 (37).

## QUALITY CONTROL/QUALITY ASSURANCE

Porous friction course mixture furnished by the contractor should conform to the job-mix formula requirements, within allowable deviations from the targets.  Testing included within a quality control/quality assurance 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.

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.

# CHAPTER 5
# Maintenance of PFC Airfield Pavements

## INTRODUCTION

The FAA has AC 150/5380-6A dated July 14, 2003, *Guidelines and Procedures for Maintenance of Airport Pavements*, which recommends actions to undertake during preventive and remedial maintenance of rigid and flexible airfield pavements. However, the open nature of PFC compared to conventional dense-graded asphalt pavements, requires specific general and winter maintenance.

A substantial amount of research (15, 53) has been conducted and published in the US and Europe concerning general and winter maintenance of PFC highway pavements. This research is applicable to PFC airfield pavements as well. However, airfield pavements have special requirements because of wider runway pavements which must be effective in removing water over longer distances; keeping the pavement surface completely free from FOD; rubber buildup which will also diminish the ability of the PFC in removing water from the surface; and the need for prompt and effective control of snow and ice in view of airfield safety. Therefore, general and winter maintenance of PFC pavements specific to airfield pavements are discussed here.

## GENERAL MAINTENANCE

General maintenance consists of cleaning clogged PFC; removal of rubber buildup; preventive surface maintenance; corrective surface maintenance; and rehabilitation.

## Cleaning of Clogged PFC

If a relatively dense-graded PFC is used, it may gradually be choked and partially lose its permeability (15). Therefore, 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 (54). The special cleaning vehicle manufactured by FROMOKAR of 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 3,450 kPa (500 psi) 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. Method (b), cleaning with a high pressure cleaner, was found to be most effective based on permeability tests after cleaning.

A similar piece of equipment for Japan was reported on at the meeting of the International Conference on Asphalt Pavements held in Copenhagen, Denmark (55). A high-pressure water blast (860 kPa or 125 psi) followed by a vacuum to remove the solids and water is used. Experienced contractors with specialized equipment do such work. The first cleaning of PFC highway pavement is done three months after construction. Thereafter cleaning is done semi-annually. If a PFC pavement is not cleaned regularly, it could become too clogged to be cleaned efficiently after two years or less. In Denmark, a PFC pavement is considered clogged if its permeability becomes less than 10 cm. This value for permeability represents the head drop after a specified period of time using a field permeameter. The Danish Road Institute is conducting research to clearly establish the benefits of cleaning.

The FAA should evaluate similar equipment in the US for cleaning clogged PFC airfield pavements. Some of the equipment currently used in the US for removing rubber buildup (as discussed later) can potentially be adapted for this task.

## Removal of Rubber Buildup

Rubber buildup is a problem on all types of airfield pavements including PFC. When aircrafts land considerable heat is generated due to friction between tires and pavement, which causes deposition of tire rubber in a thin layer on the airfield pavement. Generally, about 300 meters of runway receives the rubber buildup. With repeated landings of aircrafts more and more rubber fills the macrotexture of the pavement surface and the pavement continues to lose its wet weather skid resistance. As tire rubber builds up it can also affect the ability of PFC to drain water. If sufficient rubber exists on a PFC surface, water may pool on the rubber leading to an increased potential of hydroplaning. The use of continuous friction measuring equipment (CFME) should assist in deciding when maintenance related to rubber buildup is required.

Unified Facilities Guide Specifications UFGS S-32 01 11.52, dated April 2006, pertains to runway rubber removal requirements. These specifications list the rubber removal equipments as follows:

A. Mechanical Rubber Removal Equipment

Mechanical rubber removal equipment includes water blasting, shot blasting, sandblasting, and other non-chemical systems. The specifications state that the equipment to be used on asphalt concrete should be controlled to remove rubber accumulations and minimize disturbance to asphalt mixtures. The specifications also state, “Extremely good control shall be exercised for porous friction courses.” Water blasting uses water only, shot blasting involves propelling abrasive particles at high velocities on the rubber. Sandblasting produces a pressurized stream of sand and air to remove rubber from the pavement surface without filling voids with debris in asphalt pavements. However, intuitively it may be difficult to sandblast PFC mixtures without filling some voids with sand. The FAA should evaluate all three mechanical methods specifically for PFC pavements and specify the method, which is not detrimental to the integrity of PFC. It is quite possible that shot blasting and sandblasting may be too harsh to PFC, but this needs to be investigated in controlled field trials.

B. Chemical rubber removal equipment

Chemicals that are environmentally safe and effective in cleaning rubber deposits have been developed. The chemicals are sprayed on the surface, scrubbed, brushed, and worked into rubber for about four hours or more. The chemicals break down the rubber into a soft, jelly-like material, which is then flushed off by water blasting. It is not known whether chemical method has been tried in the case of rubber buildup on PFC. The FAA should investigate this method for PFC. Included within this investigation should be an evaluation of PFC that utilizes rubber modified asphalt binder. It is unclear whether the chemicals will harm the asphalt-rubber binder.

The Illinois University at Urbana conducted a study (56) on rubber removal from porous friction course runways in 1983. The objectives of that study were to examine the seriousness of the occurrence of rubber buildup on PFC runways and investigate methods to remove the buildup. Several innovative techniques were attempted but could not be evaluated because the PFC surfaces had been replaced or resurfaced. The FAA should initiate similar studies now.

## 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, which is a potential source for FOD. 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 (57). The Federal Highway Administration (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 (22). Research in Oregon has indicated that the PFC pavement retains its porosity and the rough texture after application of a fog seal (57). However, these parameters have not been quantified. A decrease in pavement friction was observed after the fog seal but the pavement friction increased considerably by traffic action during the first month. In view of safety considerations, application of fog seal on PFC airfield pavements, especially on runways, should be researched carefully and thoroughly before it is recommended in the maintenance guidelines.

## Corrective Surface Maintenance

Occasionally, the PFC airfield pavement will require repair of delaminated areas and potholes. Milling and inlay using PFC mix has been recommended by the Oregon Department of Transportation 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 (57). The FHWA advises to consider the drainage continuity of the PFC when undertaking patch repairs (26). 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 degree to provide a diamond shape is recommended because it will facilitate the flow of water along the dense mix patch and will also diminish wheel impact on the patch joint (57). In Britain, patch repairs are recommended with PFC material only both for small and large potholes. If a dense mix is used in urgency it must be replaced with PFC mix later (58).

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 coat will impede the flow of water through the patch. The FAA should develop its own guidelines for patch repairs of PFC based on the preceding discussion related to highway pavements.

The PFC airfield pavement can also 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. Such cracks can be sealed in accordance with procedures and crack sealing materials (such as rubberized asphalt binder) given in FAA AC 150/5380-6A.

Sealing longitudinal cracks in PFC is problematic because the crack sealer would 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 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. Because of the preceding problem in sealing longitudinal cracks, it is recommended to construct hot longitudinal joints both in the underlying course and the PFC using multiple pavers in echelon.

### Rehabilitation

If the PFC has lost its functionality in terms of permeability only and has not lost its integrity, it can be allowed to remain service because it will behave essentially like a dense-graded asphalt course with low permeability (27). However, if PFC must be rehabilitated because it has developed raveling, delamination, or potholes it is recommended to mill it off and replace with new PFC. Direct placement of new dense-graded asphalt course over existing PFC is not recommended because water/moisture accumulation in the existing PFC layer is likely to induce stripping in the overlying dense asphalt course (and possibly delamination) and thus shorten its life.

## WINTER MAINTENANCE

Winter maintenance (snow and ice removal) has often been cited and assumed to be a serious problem with PFC. However; there has been little difficulty in this regard in Europe. Porous friction course has different thermal and icing properties than conventional dense-graded asphalt pavement, and needs its own winter maintenance regimen. Porous friction course, being a mix with high air voids, has a different thermal conductivity (40 to 70 percent less than dense asphalt pavement) and, therefore, acts like an insulating layer. Porous friction course layers may have a temperature of 2° C lower than dense-graded asphalt pavement layers. Frost and ice will accumulate earlier, more quickly, and more frequently on PFC compared to other surfaces. These conditions may also persist for longer periods. Therefore, larger amounts and more frequent applications of deicer agents are required; which increase maintenance costs for PFC.

It is important to give special and repeated training to drivers of snowplows and spreaders. The FHWA recommends developing snow and ice control for PFC using chemical deicers and plowing and avoiding the use of abrasive materials such as sand to improve traction because such materials are likely to choke the PFC (26).

"Preventive salting" of the PFC at the right time is important as practiced in Britain (59). They also resort to prompt plowing of snow using plows fitted with rubber edges on the blade to prevent surface damage to PFC.

Salting is only successful on a dry pavement when temperatures are lower than –10°C. A combination of 70 percent dry salt and 30 percent salt-water solution (20 percent calcium chloride) applied at the rate of 10-20 grams per sq. meter has been determined to be effective in Austria (60). It has been found in Holland that the use of brine is extremely effective and reduces the salt consumption to only 15 percent of normal. Brine cannot be used effectively on dense surfaces because it would run off quickly (60). According to experience in Netherlands (61) about 25 percent more salt is required for PFC. The timing of application is very important.

Up to 50 percent increase in salt use has been reported in Italy for PFC compared to dense asphalt pavements. An interesting observation from Italy is that the amount of salt diminishes as the maximum aggregate size of the PFC decreases (62). By reducing the maximum aggregate size from 20 mm to 16 mm, road conditions improve 15 percent during the winter months and the amount of salt is reduced significantly.

Black ice can also form on the PFC if water is allowed to accumulate. Pre-wetted salts seem to work quite well on black ice according to experience in Denmark and the Netherlands.

Calcium chloride and pre-wetted salt are used there to ensure even distribution of the salt and to prevent formation of black ice.

It is evident from the preceding discussion that a lot of experience has been gained in the US and Europe in snow and ice control on PFC highway pavements, which can also be applied to PFC airfield pavements. It is also evident that the experiences presented above do not all agree. It is recommended that the FAA initiate a field study for evaluating different snow and ice control strategies on PFC airfield pavements under different environmental conditions so that the best practices can be established specifically for PFC pavements.

# CHAPTER 6
# Conclusions and Recommendations

This section provides conclusions and recommendations derived from the work conducted during this project. Specific conclusions presented herein are based upon the interviews of airfield pavement engineers, literature reviews and experiences of the research team. Recommendations are divided into two different categories: potential improvements and additional research needed. Recommendations categorized as potential improvements are those that the research indicates would improve the current state of practice for airfield PFC. Some of the recommendations that are categorized as potential improvements to the current state of practice may require additional work in order to become implementable; therefore, some recommendations are listed under the category of additional research needed.

Based upon the research conducted during this project, a draft Engineering Brief which provides a revised Item P-402 specification was developed. This draft Engineering Brief is provided in Appendix C.

## Conclusions

Porous friction courses are a specialty type hot mix asphalt that are designed to have an open aggregate grading and used as a wearing surface on airfield runways. The following conclusions are provided based upon the research conducted during this project.

- Porous friction courses are an effective method for improving the frictional properties of airfield pavements, especially during wet weather. The improved wet weather frictional characteristics are derived from the open aggregate grading. The open aggregate grading allows water to infiltrate into the PFC layer and also results in a significant amount of macrotexture.

- Porous friction courses used as a wearing surface significantly reduce the potential for hydroplaning on airfield runways. This reduce in hydroplaning potential is also related to the open aggregate grading.
- Porous friction courses produce lower frictional speed gradients than dense-graded HMA wearing layers. Therefore, PFCs maintain their improved frictional properties at higher speeds.
- Porous friction courses provide higher values of macrotexture than typical dense-graded HMA wearing layers.
- Immediately after construction, the frictional properties of PFC wearing layers are lower when braking with locked wheels. This is because of the relatively thick film of asphalt binder that coats the aggregate with a PFC layer. When the wheel locks, the thin film of asphalt binder will melt creating a slippery surface. This is only true when wheels lock during breaking. Frictional properties will improve after the as asphalt is worn off by aircraft operations.
- Porous friction courses result in smoother wearing surfaces compared to typical typed dense-graded HMA surfaces. Smooth wearing layers improve aircraft operational control.
- Porous friction courses have different thermal properties than typical dense-graded HMA. The temperature of PFC wearing layers will drop below freezing sooner than dense-graded layers and stay below freezing for a longer time. Therefore, winter maintenance practices will generally be different for PFC layers compared to dense-graded layers.
- Snow plows can damage PFC wearing layers. Use of rubber tipped snow plow blades can reduce the potential for damage to PFC layers.

- Porous friction courses will generally not last as long as dense-graded HMA layers. Porous friction courses will generally last for 8 to12 years while dense-graded layers will last for 10 to 15 years.
- Rapid deterioration of PFC layers due to raveling have been reported. Also, there are reports of delamination problems with PFCs. Raveling and delamination increase FOD.
- Research conducted on OGFCs for highways shows improved durability when modified asphalt binders are used in the mixture.
- Proper addition of stabilizing additives in PFCs will significantly reduce the potential for draindown. Stabilizing additives include asphalt binder modifiers and/or fibers.
- Use of performance graded asphalt binders is an improvement over the viscosity or penetration graded asphalt binders.
- Use of modified asphalt binders and fibers improves the durability of PFC mixes as measured by the Cantabro Abrasion Loss test.
- Use of stabilizing additives allows higher production temperatures.
- Both cellulose and mineral fibers have been successfully incorporated into PFC mixes.
- Vertical faces of longitudinal joints should not be tacked. Tacking of these vertical faces will impede the flow of water through the PFC layer.
- Compaction of PFC layers should be accomplished using 9 Mg (10 ton) steel wheel rollers. Compaction should be conducted to seat the aggregates and not to a specific density.
- Pneumatic-tired rollers should not be used to compact PFC mixes.
- Porous friction courses can be clogged over time due to dust and debris infiltrating the void structure or rubber build-up.

- The experiences of agencies for winter maintenance are mixed. Some agencies report an increase in the usage of deicing salts while some agencies report less need for deicing salts when combined with the use of brine.

## Recommendations

As stated above, recommendations are divided into three categories: implementable, potential improvements, and additional research needed. Following are recommendations based upon the research conducted in this report.

### Potential Improvements

- The design of PFC mixes used for airfield pavement should include four primary steps. First, suitable materials should be selected to comprise the PFC mix. Next, the selected aggregates should be used to blend trial gradations. Included within this second step is also evaluation of the trial gradations in order to select the design gradation. The third step in the mix design procedure is to select the design optimum asphalt binder content for the selected gradation. The final step would be to evaluate the designed mixture.
- The Los Angeles Abrasion and Impact test should be used to evaluate coarse aggregate toughness. A maximum percent loss of 30 percent should be specified. However, if experience suggests that coarse aggregate yielding higher loss vales will perform satisfactorily they should be allowed. In no circumstance should aggregate having more than 50 percent loss be allowed.
- The flat or elongated test should be used to specify coarse aggregate particle shape utilizing a critical ratio of 2:1. A maximum of 50 percent flat or elongated particles should be specified.

- Both sodium and magnesium sulfate soundness should be allowed to evaluate the soundness of aggregates. Maximum loss values should be 15 and 20 percent, respectively.
- Coarse aggregate angularity should be specified using the uncompacted voids in coarse aggregate test. A minimum percent voids of 45 percent should be specified.
- Fine aggregate angularity should be specified using the uncompacted voids in fine aggregate test. A minimum percent voids of 45 percent should be specified.
- The cleanliness of fine aggregates should be specified using the sand equivalency test. A minimum clay content of 50 percent should be specified.
- Modified asphalt binders should be used within PFC mixtures to improve durability.
- Stone-on-stone contact should be specified when designing PFC mixes for airfield pavement layers. Ensuring stone-on-stone contact will result in a stable layer of PFC.
- A minimum asphalt binder content should be specified to yield a durable PFC. The minimum asphalt binder content should be based upon the combined bulk specific gravity of the aggregates.
- Draindown testing should be utilized during mix design. The draindown basket method should be utilized for this testing. A maximum percent draindown of 0.3 percent, by total mix mass, should be specified. Testing of the mixture should be conducted 15°C higher than the anticipated production temperature.
- Mixing and compacting temperature should be based upon the properties of the asphalt binder.

- The Cantabro Abrasion test should be utilized within the design of PFC mixes. The Cantabro Abrasion test is a performance related test used to evaluate the durability of PFC mixes.
- Silo storage time should be limited to two hours.
- Haul time should be limited to two hours.

## Recommendations for Future Research

- The proposed draft mix design for PFC mixes should be laboratory and field validated.
- Research should be conducted to evaluate methods of cleaning PFC layers. Clogged PFC layers lose the ability to remove water from the pavement surface.
- Research should be conducted on the best method(s) for removing rubber buildup on airfield runways.
- Research should be conducted to evaluate the effect of chemical rubber removal on PFCs that utilize rubber modified asphalt binder.
- Research should be conducted to evaluate winter maintenance activities for PFC layers.
- Research should be conducted to evaluate the best method(s) for rehabilitation of PFC layers.

## REFERENCES

1. "CY 2005 Boarding and All-Cargo Data: primary and Non-Primary Commercial Service Airports."http://www.faa.gov/airports_airtraffic/airports/planning_capacity/passenger_allcargo_stats/passenger/media/cy05_primary_np_comm. Downloaded April 30, 2007.
2. "Pavement Quality Characteristics." http/www.tc.gc.ca/civilaviation/International/Technial/Pavement/quality/menu.htm. Downloaded May 7, 2007.
3. "Skid Resistance Criteria for Airfield Pavements." Interim Technical Guidance (ITG). From Commander, Naval Facilities Engineering Command. March 24, 1999.

4. Moore, A.B. and J. B. Humphreys, "High-Speed Skid Resistance and the Effects of Surface Texture o the Accident Rate." *Skid Resistance of Highway Pavements*, ASTM STP 530, American Society for Testing and Materials. Pp 91-100, 1973

5. Titus-Glover, L. and S.D. Tayabji. "Assessment of LTPP Friction Data." Report FHWA-RD-99-037. Federal Highway Administration, March 1999.

6. Kummer, H.W., "Unified Theory of Rubber and Tire Friction. Engineering Research Bulletin B-94. The Pennsylvania State University, Department of Mechanical Engineering, 1966.

7. Sandberg, U. Influence of Road Surface Texture o Traffic Characteristics Related to Environment, Economy and Safety. VTI notat 53A-1997. Swedish National Record and Transport Research Institute, 1997.

8. Henry, J.J. "Skid Resistance, NCHRP Synthesis of Highway Practice No. 14." National Cooperative Highway Research Program. Highway Research Board. Washington, D.C., 1972.

9. Gothie, Michel. "Skid Resistance Evolution of Different Wearing Course Techniques According to Traffic." Proceedings of North International Conference on Asphalt Pavements. Copenhagen, Denmark, 2002.

10. 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. November 13-14, 2002.

11. Smith, R.W., J.M. Rice and S.R. Spelman. "Design of Open-Graded Asphalt Friction Courses." Report FHWA-RD-74-2. Federal Highway Administration. January 1974.

12. Johnson, E. A. and T. D. White. "Porous Friction Course Solves Airport Hydroplaning Problem." *Civil Engineering*. American Society of Civil Engineers. Volume 46, No. 4. pp 90-92. April 1976.

13. Lefebvre, G. "Porous Asphalt." PIARC Technical Committee of Flexible Roads and Association of Road Congresses. 1993.

14. Van Heystraeten, G. and C. Moraux. "Ten Years' experience of Porous Asphalt in Belgium." Transportation Research Record No. 1265. Transportation Research Board. National Research Council. Washington, D. C. pp 34-40. 1990.

15. Kandhal, P.S. "Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses." National Asphalt Pavement Association. Information Series 115. Lanham, Maryland. 2002.

16. Isenring, T., H. Koster and I. Scazziga. "Experiences with Porous Asphalt in Switzerland." Transportation Research Record No. 1265. Transportation Research Board. National Research Council. Washington, D.C. pp 87-94. 1990.

17. Bennert, T., F. Fee, E. Sheehy, A. Jumikis and R. Suber. "Comparison of Thin-Lift HMA Surface Course Mixes in New Jersey." Transportation Research Record No. 1929. Transportation Research Board. National Research Council. Washington, D.C. pp 59-68. 2005.

18. McDaniel, R. S. and W. Thornton. “Field Evaluation of a Porous Friction Course for Noise Control.” TRB 2005 Annual Meeting CD-ROM. Transportation Research Board. National Research Council. Washington, D. C. 2005.

19. Greibe, A.P. “Porous Asphalt and Safety.” Proceedings of the Ninth International Conference on Asphalt Pavements. Copenhagen, Denmark. August 2002.

20. Rogge, D. and E. A. Hunt. “Development of Maintenance Practices for Oregon F-Mix – Interim Report SPR371.” Oregon Department of Transportation. Salem, OR. August 1999.

21. Moore, L. M. R. G. Hicks, and D. F. Rogge. “Design, Construction and Maintenance Guidelines for Porous Asphalt Pavements.” Transportation Research Record 1778. TRB. National Research Council. Washington, D. C. 2001. pp 91-99.

22. Martinez. F. C. and R. A. Poecker. “Evaluation of Deicer Applications on Open-Graded Pavements. FHWA-OR-RD-06-12. Oregon Department of Transportation. Salem, Oregon. April 2006.

23. Bolzan, P.E., J. C. Nicholls, G. A. Huber, Searching for Superior Performing porous Asphalt Wearing Courses, TRB 2001 Annual Meeting CD-ROM, transportation research board. National Research Council. Washington, D. C. 2001.

24. “Mix Design methods for Asphalt Concrete and Other Hot-Mix Types.” MS-2. Sixth Edition. Asphalt Institute. Lexington, Kentucky. 1995.

25. Anderton, G.L. “Evaluation of Asphalt Rubber Binders in Porous Friction Courses.” Technical Report CPAR-GL-92-1. US Army Corps of Engineer. Waterways Experiment Station. May 1992.

26. Technical Advisory T 5040.31, US Department of Transportation, Federal Highway Administration. Washington, D.C. December 26, 1990.

27. Huber, G. NCHRP Synthesis 284. “Performance Survey on Open-Graded Friction Course Mixes.” Transportation Research Board. National Research Council. Washington, D.C. 2000.

28. Smith, H.A. “Performance Characteristics of Open-Graded Friction Courses.” NCHRP Synthesis 180. Transportation Research Board. National Research Council.. Washington, D.C. 1992.

29. Smith, R.W., J.M. Rice, and S.R. Spelman. “Design of Open-Graded Asphalt Friction Courses.” Interim Report No. FHWA-RD-74-2. Federal Highway Administration. Washington, D.C. 1974.

30. Mallick, R.B., P.S. Kandhal, L.A. Cooley, Jr., and D. E. Watson. “Design, Construction and Performance of New-Generation Open-Graded Friction Course.” Journal of the Association of Asphalt Paving Technologists. Volume 69. pp 391-423. 2000.

31. Prowell, B.D., J. Zhang and E.R. Brown. “Aggregate Properties and Their Relationship to the Performance of Superpave-Designed HMA: A Critical Review.” Final Report. NCHRP Project 9-35. Auburn University. National Center for Asphalt Technology. Auburn, Alabama. October 2004.

32. Kandhal, P.S. and F. Parker, Jr. “Aggregate Tests Related to Asphalt Concrete Performance in Pavements.” National Cooperative Highway Research Program Report 405. Transportation Research Board. National Research Council. Washington, D.C. 1998.

33. White, T.D., J.E. Haddock, and E. Rismantojo. “Aggregate Tests for Hot Mix Asphalt Mixtures Used in Pavements.” National Cooperative Highway Research Program Report 557. Transportation Research Board. National Research Council. Washington, D.C. 2006.

34. Ahlrich, R. C. “Influence of Aggregate Gradation and Particle Shape/Texture on Permanent Deformation of Hot Mix Asphalt Pavements.” Dissertation. Submitted to the Graduate Facility of Auburn University. Auburn, Alabama. 1985.

35. McGennis, R.B., R.M. Anderson, T.W. Kennedy, and M. Solaimanian. “Background of Superpave Asphalt Mixture Design and Analysis.” Report No. FHWA-SA-95-003. Federal Highway Administration. Washington, D. C. November 1994.

36. Kandhal, P.S. and R. B. Mallick. “Open-Graded Friction Course: State of the Practice.” Transportation Research Circular E-C005. Transportation Research Board. National Research Council. Washington, D.C. 1998.

37. Watson, D.E., K. A. Moore, K. Williams, and L. A. Cooley, Jr. “Refinement of New Generation Open-Graded Friction Course Mix Design.” Journal of the Transportation Research Record. No. 1832. Transportation Research Board. National Research Council. pp 78-85. 2003.

38. Watson, D.E., L. A. Cooley, Jr., K. A. Moore and K. Williams. “Laboratory Performance Testing of OGFC Mixtures.” Journal of the Transportation Research Record. No. 1891. Transportation Research Board. National Research Council. pp 40-42. 2004.

39. Sullivan B.W. “Development of a Fundamental Skid Resistance Asphalt Mix Design Procedure.” International Conference on Surface Friction. Christchurch, New Zealand. May 2005.

40. Brown, E.R. and L. A. Cooley, Jr., “Designing Stone Matrix Asphalt Mixtures for Rut-Resistance Pavements.” National Cooperative Highway Research Program Report 425. Transportation Research Board. National Research Council. Washington, D.C. 1999.

41. Ruiz, A., R. Alberola, F. Perez and B. Sanchez. Transportation Research Record No. 1265. Transportation Research Board. National Research Council. Washington, D. C. pp 87-94. 1990.

42. Santha, L. “Comparison of Standard Open-Graded Friction Courses with Modified Open-Graded Friction Courses.” GDOT Research Report No. 9110. Georgia Department of Transportation. Office of Materials and Research. Forest Park, Georgia. April 1997.

43. “Hot-Mix Asphalt Paving Handbook.” AC 150/5370-14A. Appendix 1. Federal Aviation Administration. US Army Corps of Engineers. 2000.

44. Standard Specifications, Section 400, Georgia Department of Transportation, Atlanta, GA, 2001.

45. Special Provisions, Section 400, Georgia Department of Transportation, Atlanta, GA, 2007.

46. Standard Specifications, Section 337, Florida Department of Transportation, Tallahassee, FL, 2004, from website: http://www.dot.state.fl.us/specificationsoffice/2004BK/toc.htm.

47. Standard Specifications, Section 342, Texas Department of Transportation, 2004, from website: http://www.dot.state.tx.us/business/specifications.htm.

48. P-402: Porous Friction Course, FAA Advisory Circular 150/5370-10, U.S. Department of Transportation, Federal Aviation Administration, Landover, MD, 2005.

49. Paver Operations for Quality, NAPA Information Series 125, Lanham, MD., 1996.

50. H. Smith, Synthesis of Highway Practice 180: Performance Characteristics of Open-Graded Friction Courses, TRB/NAS, Washington, DC, 1992.

51. F. Copple and F. Corian, Michigan's Experience with Open-Graded Asphalt Friction Course, Michigan Department of Transportation, 1987.

52. J. Nicholls, Review of UK Porous Asphalt Trials, TRL Report 264, Transport Research Laboratory, London, United Kingdom, 1997.

53. Alvarez, A. E., A. E. Martin, C. K. Estakhri, J. W. Button, C. J. Glover, and S. H. Jung. Synthesis of Current Practice on the Design, Construction, and Maintenance of Porous Friction Courses. Texas Department of Transportation Report No. FHWA/TX-06/0-5262-1, May 2006.

54. Hiersche, E. U. and H. J. Freund. Technology and In-Situ Trial of a Noise Absorbing Pavement Structure. Proc. 7th International Conference on Asphalt Pavements, University of Nottingham, U. K., August 1992.

55. Abe, T. and Y. Kishi. Development of a Low Noise Pavement Function Recovery Machine. Proc. 9th International Conference on Asphalt Pavements, Copenhagen, Denmark, 2002.

56. Carpenter, S. H. and E. J. Barenberg. Rubber Removal from Porous Friction Course. Illinois University at Urbana, Final Report, September 1983.

57. Rogge, D. Development of Maintenance Practices for Oregon F-Mix. Oregon Department of Transportation Report no. FHWA/OR-RD-02-09, 2002

58. The Highway Agency, The Department of Environment for Northern Ireland. Design Manual for Roads and Bridges. Vol. 7: Pavement Design and Maintenance Bituminous Surfacing Materials and Techniques, 1990.

59. Fabb, T. R. J. "The Case for the Use of Porous Asphalt in the U. K." The Asphalt Year Book, The Institute of Asphalt Technology, U.K. 1993.

60. Weyringer, H. W. In the Bleak mid-Winter. World Highways, January/February 1993.

61. Westerop, A. J. M. "Porous Asphalt in the Netherlands." The Asphalt Year Book, The Institute of Asphalt Technology, U.K. 1993.

62. Litzka, J. "Austrian Experiences with Winter Maintenance on Porous Asphalt". Proc. 9th International Conference on Asphalt Pavements, Copenhagen, Denmark, 2002.

# APPENDIX A

# DRAFT MIX DESIGN PROCEDURES FOR AIRFIELD PFC

## RECOMMENDED MIX DESIGN PROCEDURE FOR PFCS

The design of PFC mixtures is similar to the design of SMA in that PFC should have stone-on-stone contact, low potential for draindown and be durable. The design of PFCs contains four primary steps (Figure A-1). The first step in the design of PFC mixes is to select suitable materials. Materials needing selection include coarse aggregates, fine aggregates, asphalt binder and stabilizing additives. Step 2 includes blending three trial gradations using the selected aggregate stockpiles. For each trial gradation, asphalt binder is added, the mixture compacted and the design gradation selected. Next, the selected design gradation is fixed and the asphalt binder content is varied. The resulting mixtures are evaluated in order to select optimum asphalt binder. Finally, the design gradation at optimum asphalt binder content is evaluated for moisture susceptibility.

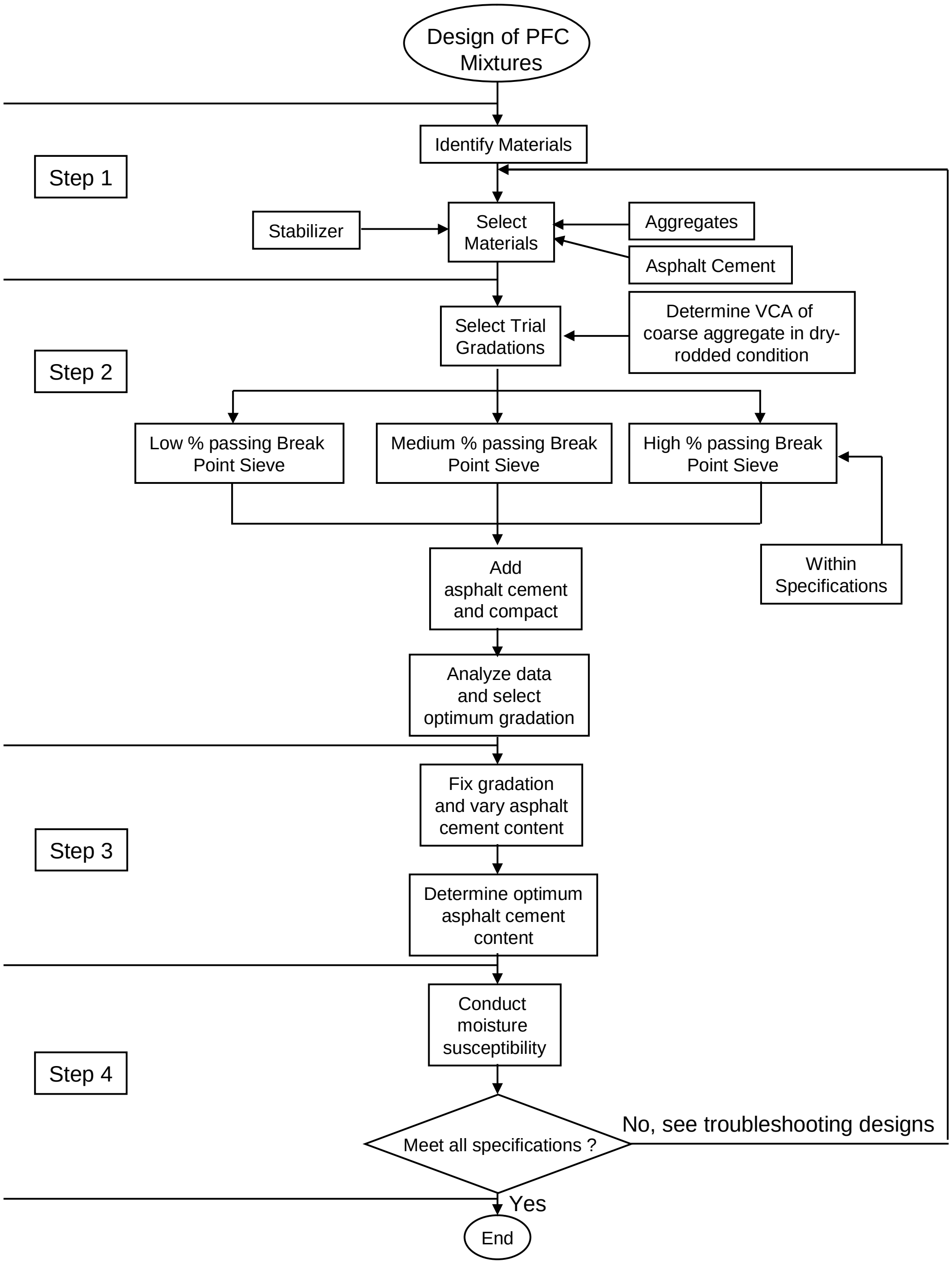

**Figure A-1: Flow Diagram Illustrating OGFC Mix Design Methodology**

## Step 1 - PFC Materials Selection

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

Aggregates used in PFC should be cubical, angular and have surface texture. The stability/strength of PFCs is derived from the stone skeleton and, therefore, the shape and angularity should be such that the aggregates will not slide past each other. Angular, cubical and textured aggregate particles will lock together providing a stable layer of PFC.

Because of the open-grading of aggregates, PFCs contain very low aggregate surface area. Similar to SMA, PFC mixes are required to have a relatively high asphalt binder content. Therefore, the aggregates are coated with a thick film of asphalt binder and the properties of the asphalt binder are important to the performance of PFC. The asphalt binder must be very stiff at high temperatures to resist the abrading action of traffic; however, they should also perform at intermediate and low temperatures. Modified binders are not necessarily required; however, experience indicates better and longer service when modified binders are utilized.

Porous friction courses have a high potential for draindown problems. In order to combat the draindown problems, stabilizing additives are utilized. The most common form of stabilizing additive is fiber. Asphalt binder modifiers that stiffen the asphalt binder can also be a considered stabilizing additive. However, fibers are more effective at reducing draindown potential.

The following sections provide requirements for the various materials used to fabricate PFC.

*Coarse Aggregates*

Similar to SMA, the success of a PFC pavement is largely dependent upon the existence of particle-on-particle contact. Therefore, in addition to particle shape, angularity and texture, the toughness and durability of the coarse aggregates must be such that they will not degrade during production, construction and service life. Table A-1 presents coarse aggregate requirements for PFC mixtures.

**Table A-1: Coarse Aggregate Quality Requirements for PFC**

| Test | Method | Spec. Minimum | Spec. Maximum |
|---|---|---|---|
| Los Angeles Abrasion, % Loss | ASTM C131 | - | 30[A] |
| Flat or Elongated, % | ASTM D4791 | | |
| 2 to 1 | | - | 50 |
| Soundness (5 Cycles), % | ASTM C88 | | |
| Sodium Sulfate | | - | 15 |
| Magnesium Sulfate | | - | 20 |
| Uncompacted Voids | AASHTO T326 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.

*Fine Aggregates*

The fine aggregates' role within a PFC is to assist the coarse aggregate particles in maintaining stability. However, the fine aggregates must also resist the effects of weathering.

Therefore, the primary requirements for fine aggregates within a PFC are to ensure a durable and angular material. Requirements for fine aggregates within PFC are provided in Table A-2.

**Table A-2: Fine Aggregate Quality Requirements for PFC**

| Test | Method | Spec. Minimum | Spec. Maximum |
|---|---|---|---|
| Soundness (5Cycles), % | ASTM C80 | | |
| Sodium Sulfate | | - | 15 |
| Magnesium Sulfate | | - | 20 |
| Uncompacted Voids | ASTM C1252, Method A | 45 | - |
| Sand Equivalency | ASTM D2419 | 50 | - |

*Asphalt Binder*

Asphalt binders should be a Superpave performance grade (PG) meeting the requirements of AASHTO M320-04. Relatively high asphalt binder contents are required for PFC mixtures to ensure durability and, thus, minimize FOD potential. Because of the open-grading of the aggregate, a stiff asphalt binder is needed to ensure a durable mixture. The asphalt binder high temperature grade should be increased by two grades over the standard asphalt binder for the project location. Most asphalt binders utilized in PFC have been modified with either polymers or rubber.

*Stabilizing Additives*

Stabilizing additives are needed within PFC to prevent the draining of asphalt binder from the coarse aggregate skeleton during transportation and placement. Stabilizing additives such as cellulose fiber, mineral fiber, and polymers have been used with success to minimize draindown potential. When using polymer or rubber as a stabilizer, the amount of additive added should be that amount necessary to meet the specified PG grade of the asphalt binder.

Cellulose fibers are typically added to a PFC mixture at a dosage rate of 0.3 percent by total mixture mass. Mineral fibers are typically added at a dosage rate of 0.4 percent of total mixture mass. Experience has shown that fibers are the best draindown inhibitor.

## STEP 2 – TRIAL GRADATIONS

As with any hot mix asphalt (HMA), specified aggregate gradations should be based on aggregate volume and not aggregate mass. However, for most PFC mixtures, the specific gravities of the different aggregate stockpiles are close enough to make the gradations based on mass percentages similar to that based on volumetric percentages. The specified PFC gradation bands presented in Table A-3 are based on percent passing by volume.

**Table A-3: PFC Gradation Specification Bands**

| Sieve Size, mm | % Passing, Maximum Aggregate Size | |
|---|---|---|
| | ½ in. (12.5 mm) PFC | ¾ in. (19mm) PFC |
| ¾ in. | | 100 |
| ½ in. | 100 | 80-95 |
| 3/8 in. | 80-95 | 40-70 |
| No. 4 | 20-40 | 15-30 |
| No. 8 | 10-25 | 8-20 |
| No. 30 | 4-10 | 4-10 |
| No. 200 | 2-5 | 2-5 |

## Selection of Trail Gradations

The initial trial gradations must be selected to be within the master specification ranges presented in Table A-3. It is recommended that at least three trial gradations be initially evaluated. It is suggested that the three trial gradations fall along the coarse and fine limits of the gradation range along with one falling in the middle. These trial gradations are obtained by adjusting the amount of fine and coarse aggregates in each blend.

## 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 of the blend 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 ($VCA_{DRC}$) is determined using ASTM C29. 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:

$$VCA_{DRC} = \frac{G_{ca}\,\gamma_w - \gamma_s}{G_{ca}\,\gamma_w} * 100 \qquad \text{Equation 2}$$

where,

$VCA_{DRC}$ = voids in coarse aggregate in dry-rodded condition

$\gamma_s$ = unit weight of the coarse aggregate fraction in the dry-rodded condition (kg/m$^3$),

$\gamma_w$ = 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 ($VCA_{MIX}$). Similar to SMA, when the $VCA_{MIX}$ is equal to or less than the $VCA_{DRC,}$ stone-on-stone contact exists.

## Selection of Trial Asphalt Content

The minimum desired asphalt binder content for PFC mixtures is presented in Table A-4. Values in this table reflect the minimum asphalt binder contents for PFCs. Table A-4 illustrates that the minimum asphalt binder content for PFCs is based upon the combined bulk specific gravity of the aggregates used in the mix. 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.

## Sample Preparation

As with the design of any HMA, 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 12.5mm
12.5 to 9.5mm
9.5 to 4.75mm
4.75 to 2.36mm
Passing 2.36 mm

**Table A-4: Minimum Asphalt Content Requirements for Aggregates with Varying Bulk Specific Gravities**

| 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 |

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

The mixing and compaction temperatures are determined in accordance with ASTM D6926, 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 polymer 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 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. For aggregate blends having combined water absorption values less than 2 percent, the mixture should be aged for 2 hours. If the water absorption of the aggregate blend is 2 percent or more, the mixture should be aged for 4 hours.

### Number of Samples

A total of eighteen samples are initially required: four samples for each trial gradation. 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 ASTM D2041.

### Sample Compaction

Specimens should be compacted at the established compaction temperature after laboratory short-term aging. Laboratory samples of PFC are compacted using 50 revolutions of the Superpave gyratory compactor (SGC). More than 50 revolutions should not be used; PFC is relatively easy to compact in the laboratory and exceeding this compactive effort can cause excessive aggregate breakdown.

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. Uncompacted samples are used to determine the theoretical maximum density, $G_{mm}$ (ASTM D2041). Using $G_{mb,}$ $G_{mm}$ and $G_{ca,}$ percent air voids (VTM), and $VCA_{MIX}$ are calculated. The VTM and $VCA_{MIX}$ are calculated as shown below.

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

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

where:

$P_{ca}$ = percent of coarse aggregate in the mixture
$G_{sb}$ = 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 A-5 presents the requirements for PFC designs. If the PFC mixture being designed is a PFC, the trial blend with the highest air voids that meets the 15 percent minimum and exhibits stone-on-stone contact is considered the design gradation.

**Table A-5: PFC Mixture Specification for SGC Compacted Designs**

| Property | Requirement |
|---|---|
| Asphalt Binder, % | See Table A-4 |
| Air Voids, % | 15 min. |
| Cantabro Loss % | 15 max. |
| $VCA_{MIX}$% | Less than $VCA_{DRC}$ |
| Tensile Strength Ratio | 0.70 min. |
| Draindown at Production Temperature, % | 0.30 max |

### Step 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 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 A-5.

#### *Cantabro Abrasion Loss Test*

The Cantabro Abrasion test is used as a durability indicator during the design of PFC mixtures. In this test, three PFC specimens compacted with 50 gyrations of the Superpave gyratory compactor are used to evaluate the durability of an PFC mixture at a given asphalt binder content. To begin the test, the mass of each specimen is weighed to the nearest 0.1 gram. A single test specimen is then placed in the Los Angeles Abrasion drum without the charge of steel spheres. The Los Angeles Abrasion machine is operated for 300 revolutions at a speed of 30 to 33 rpm. The test temperature is 25±5˚C. After the 300 revolutions, the test specimen is removed from the drum and its mass determined to the nearest 0.1 gram. The percentage of abrasion loss is calculated as follows:

$$PL = \frac{\left(P_1 - P_2\right)}{P_2} 100 \qquad \text{Equation A-4}$$

where:

PL = percent loss
$P_1$ = mass of specimen prior to test, gram
$P_2$ = mass of specimen after 300 revolutions, gram

The test is repeated for the remaining two specimens. The average results from the three specimens are reported as the Cantabro Abrasion Loss. Resistance to abrasion generally improves with an increase in asphalt binder content and/or the use of a stiffer asphalt binder. Figure A-2 illustrates a sample after the Cantabro Abrasion Loss test.

**Figure A-2: Illustration of Sample after Cantabro Abrasion Test**

*Draindown Sensitivity*

The draindown sensitivity of the selected mixture is determined in accordance with ASTM D6390 except that a 2.36mm wire mesh basket should be used. Draindown testing is conducted at a temperature of 15˚C higher than the anticipated production temperature.

### Step 4 - Moisture Susceptibility

Moisture susceptibility of the selected mixture is determined using the modified Lottman method in accordance with ASTM D4867 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 selected 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.

## Trouble Shooting PFC Mix Designs

If the designer is unable to produce a mixture that meets all requirements, remedial action will be necessary. Some suggestions to improve mixture properties are provided below.

### *Air Voids*

The amount of air voids in the mixture can be controlled by the asphalt binder content. However, lowering the asphalt binder content below the minimum to achieve a proper amount of air voids violates the required minimum asphalt binder content (Table A-4). Instead, the aggregate gradation must be modified to increase the space for additional asphalt binder can be added without decreasing the voids below an acceptable level. Decreasing the percent passing the breakpoint sieve will generally increase the level of air voids at a given asphalt binder content.

### *Voids in the Coarse Aggregate*

If the $VCA_{mix}$ is higher than that in the dry-rodded condition ($VCA_{DRC}$) then the mixture gradation must be modified. This is typically accomplished by decreasing the percent passing the breakpoint sieve.

### *Cantabro Abrasion Loss*

If the Cantabro Abrasion loss is greater than 15 percent, then either more asphalt binder or a stiffer (at high temperatures) asphalt binder is needed.

### *Moisture Susceptibility*

If the mixture fails to meet the moisture susceptibility requirements, lime or liquid anti-strip additives can be used. If these measures prove ineffective, the aggregate source and/or asphalt binder source can be changed to obtain better aggregate/asphalt binder compatibility.

### *Draindown Sensitivity*

Problems with draindown sensitivity can be remedied by increasing the amount of stabilizing additive or by selecting a different stabilizing additive. Fibers have been shown to be very effective in reducing draindown.

# APPENDIX B
# DRAFT TEST METHOD FOR CANTABRO ABRASION LOSS

# D R A F T

Standard Method of Test for

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

## 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 Standard:*

- 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 are 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 110mm to 120mm 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 0.1mm 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 2:** 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

# APPENDIX C

# DRAFT ENGINEERING BRIEF ON THE USE OF POROUS FRICTION COURSES

# DRAFT ENGINEERING BRIEF

## IMPROVED POROUS FRICTION COURSES (PFC) ON ASPHALT AIRFIELD PAVEMENTS

**PURPOSE:** The purpose of this draft Engineering Brief is to provide technical guidance and direction to improve the performance of porous friction courses on airfield pavements.

**DEFINITION:** Porous friction courses (PFCs) are specialty type hot mix asphalt (HMA) that are specifically designed to remove water from the pavement surface and to improve the wet weather friction of runway pavements. Porous friction courses have an open aggregate gradation with minimal fine aggregates and little mineral filler. The combination of the almost single-sized coarse gradation and minimal fine aggregates and mineral filler results in a wearing layer with a high percentage of air voids, typically 15 percent or more. Because of the high percentage of air voids, the void structure within PFCs is comprised of interconnected voids which allows water to infiltrate into the PFC layer. Additionally, the open gradation of PFCs results in a significant amount of macrotexture on the pavement surface. The combination of the interconnected voids and the high level of macrotexture greatly reduces the potential for hydroplaning and improves wet weather skid resistance.

**BACKGROUND:** Within the US, open-graded friction course (OGFC) has been used to describe a hit mix asphalt (HMA) having an open aggregate grading that is used as a wearing layer to improve wet weather frictional properties of pavements. Open-graded friction courses evolved through experimentation with plant mix seal coats. Initial interest in these mixes resulted from problems associated with chip seals. Primarily, loose aggregate from the chip seals that were either not adequately seated during construction or dislodged by traffic were breaking windshields. During the 1930’s, Oregon began experimenting with plant mix seal coats in order to adequately coat the aggregates. A by product of these plant mix seal coats was improved skid resistance.

Even though the plant mix seal coats provided improved skid resistance, their use did not become widespread until the 1970’s. The primary problems encountered with these mixes were related to durability and draindown. Because the plant mix seal coats had an almost uniform aggregate size gradation with little fine aggregates, there was very little aggregate surface area to hold the asphalt binder, leading to draindown problems. The term draindown is used to describe asphalt binder draining from the aggregate structure during storage and transportation. Asphalt binder that has drained from the aggregate structure results in areas that have too little asphalt binder and areas that are very rich in asphalt binder. Areas with too little asphalt binder were prone to ravel, while areas rich in asphalt binder become slick and do not provide the desired skid resistance.

Renewed interest in the plant mix seal coats (or OGFC as they became known) began in the early 1970’s due to a program to improve the frictional properties of highway pavements initiated by the Federal Highway Administration (FHWA). The OGFCs were identified as a method for improving the skid resistance of pavements. Around the same time, some airfields were experiencing problems with hydroplaning. These open-graded mixes were identified as a means of reducing hydroplaning potential. The term porous friction course (PFC) is used for these mixes within the airfield pavement community.

The problems encountered in the past with open-graded mixes were caused by mix design, material specifications and construction problems related to draindown. To combat the draindown problem, most owners would reduce production temperature. Reducing the production temperature increased the viscosity of the asphalt binder and, thus, reduced the potential for draindown problems. However, because of the reduced temperatures, the aggregates were not always completely dried, leaving moisture within the aggregates. This led to moisture problems and, hence, raveling problems. Additionally, the lower mix temperatures sometimes prevented the mix from adequately bonding to the underlying layer through the tack coat. This led to delamination problems.

Since the 1970's and 1980's, some significant improvements have been made for PFCs. Namely, the use of modified asphalt binders to improve durability and the incorporation of stabilizing additives to prevent draindown. Most of these improvements have been mad for the OGFCs used for highways. Therefore, research was conducted through the Airfield Asphalt Pavement Technology Program (AAPTP), Project 04-06, to recommend improvements to PFCs for airfield pavements. Findings from the research are posted at www.aaptp.us. Airports are encouraged to refer to the AAPTP report to obtained detailed information from this research.

**RECOMMENDATIONS:** Based upon the findings of the AAPTP research, several improvements were recommended during materials selection and mix design. The recommended mix design method included four primary steps: 1) materials selection; 2) selection of design gradation; 3) selection of optimum asphalt binder content; and 4) evaluation of moisture susceptibility. Within the materials selection step, tests were recommended to better characterize the properties of aggregates used in PFCs. Tests were recommended to evaluate aggregate toughness, durability, angularity, shape and cleanliness. It was also recommended that modified asphalt binders and stabilizing additives be utilized within PFCs in order to improve durability by allowing higher production temperatures without increasing the potential for draindown. Stabilizing additives recommended were modified asphalt binders and/or fibers. Porous friction course gradation bands were recommended. The recommended bands were selected to maximize the amount of water that could infiltrate the PFC layer while providing sufficient shear strength to resist the actions of braking tires. Within the selection of optimum asphalt binder content step of the mix design procedure, performance related tests were recommended instead of the Centrifuge Kerosene Equivalent method. Performance related tests included evaluation of the existence of stone-on-stone contact, the Cantabro Abrasion loss test, and draindown potential testing. The Cantabro Abrasion test was recommended to establish a minimum asphalt binder content for durability, while the draindown testing was recommended to establish a maximum asphalt binder content to minimize the potential for draindown during construction.

No specific research was found that evaluated various construction techniques for PFCs. Therefore, the research provided guidelines, or best practices, for the construction of PFCs. Guidance is provided for plant production, transportation, placement, compaction and quality control/quality assurance of PFC mixes for airfield pavements. Much of the guidance was obtained from information on the construction of stone matrix asphalt (SMA) mixtures. Stone matrix asphalt and PFC mixes are somewhat similar because of the gapped aggregate grading and typical use of modified asphalt binders and stabilizing additives.

Various reports, papers and articles from around the world were reviewed to provide a synthesis of current maintenance practices on PFC pavements. The synthesis provides the experiences of the different agencies with respect to general maintenance and winter maintenance. General maintenance involves maintaining the drainage capacity of PFCs. The ability of PFCs to drain water from the pavement surface greatly minimizes the potential for hydroplaning during rain events. Winter maintenance activities by the various agencies were not always similar and likely reflect the varying environmental conditions common to the different agencies.

Based upon the results of the research study, a draft revised Item P-402 was developed. This revised document is attached.

## FUTURE ACTIVITIES:

# ITEM P-402 POROUS FRICTION COURSE
## (Central Plant Hot Mix)

## DESCRIPTION

**402-1.1** This item shall consist of a plant mixed, open-graded porous friction course, composed of mineral aggregate, bituminous material and additives, mixed in a central mixing plant, and placed on a prepared surface in accordance with these specifications and shall conform to the dimensions and typical cross section as shown on the plans.

*** * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ***

**The porous friction course (PFC) shall be designed as a free draining wearing surface of uniform thickness. The PFC must be placed on a prepared surface, which drains freely and does not allow ponding. The PFC should not be applied over an existing PFC. Any existing PFC should be removed and the entire surface leveled prior to placement of a new PFC.**

*** * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ***

## MATERIALS

**402-2.1 AGGREGATE**. The aggregate shall consist of crushed stone, crushed gravel, or crushed slag with or without other inert finely divided mineral aggregate. The aggregate shall be composed of clean, sound, tough, durable particles, free from clay balls, organic matter, and other deleterious substances. The portion of the material retained on the No. 4 sieve shall be known as coarse aggregate, the portion passing the No. 4 sieve and retained on the No. 200 sieve as fine aggregate, and the portion passing the No. 200 sieve as mineral filler.

**a. Coarse Aggregate.** Coarse aggregate shall meet the requirements of Table 1. Los Angeles Abrasion wear and soundness testing shall be conducted on each coarse aggregate stockpile. Flat or Elongated and Uncompacted Voids testing shall be conducted on the porous friction course aggregate blend used during design.

**Table 1: Coarse Aggregate Requirements**

| Test | Method | Spec. Minimum | Spec. Maximum |
|---|---|---|---|
| Los Angeles Abrasion, % Loss | ASTM C131 | - | 30[A] |
| Flat or Elongated, % | ASTM D4791 | | |
| 2 to 1 | | - | 50 |
| Soundness (5 Cycles), % | ASTM C88 | | |
| Sodium Sulfate | | - | 15 |
| Magnesium Sulfate | | - | 20 |
| Uncompacted Voids | AASHTO T326, Method A | 45 | - |

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

**b. Fine Aggregate.** Fine aggregate shall meet the requirements of Table 2. Soundness testing shall be conducted on each fine aggregate stockpile. Uncompacted voids and sand equivalency shall be conducted on the porous friction course blend used during design.

**Table 2: Fine Aggregate Requirements**

| Test | Method | Spec. Minimum | Spec. Maximum |
|---|---|---|---|
| Soundness (5Cycles), % | ASTM C88 | | |
| Sodium Sulfate | | - | 15 |
| Magnesium Sulfate | | - | 20 |
| Uncompacted Voids | ASTM C1252, Method A | 45 | - |
| Sand Equivalency | ASTM D2419 | 50 | - |

**402-2.2 FILLER**. If filler, in addition to that naturally present in the aggregate, is necessary, it shall meet the requirements of ASTM D 242. When mineral filler is required to be batched separately, hydrated lime in the amount of 1.5 percent maximum by weight of the total aggregate shall be batched as part of the added mineral filler. No additional compensation will be allowed the Contractor for furnishing and using hydrated lime or other approved mineral filler that may be required by this specification.

**402-2.3 BITUMINOUS MATERIAL**. Asphalt binders should be a Superpave performance grade (PG) meeting the requirements of AASHTO M320-04. Relatively high asphalt binder contents are required for PFC mixtures to ensure durability and, thus, minimize FOD potential. Because of the open-grading of the aggregate, a stiff asphalt binder is needed to ensure a durable mixture. The asphalt binder high temperature grade should be increased by two grades over the standard asphalt binder for the project location. Most asphalt binders utilized in PFC have been modified with either polymers or rubber.

*** * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ***

The contractor shall furnish vendor’s certified test reports for each lot of bituminous material shipped to the project. The venoder’s certified test report for the bituminous material can be used for acceptance or tested independently by the Engineer..

*** * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ***

**Samples shall be taken, however a minimum of one sample shall be tested by the Engineer to verify the submitted certification. Additional samples shall be tested if results are borderline or for any other reason. The initial test is recommended to be done early in the project.**

*** * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ***

**402-2.4 ANTI-STRIPPING AGENT.** Any anti-stripping agent or additive, if required, shall be heat stable, shall not change the asphalt cement viscosity beyond specifications, shall contain no harmful ingredients, shall be added in recommended proportion by approved method, and shall be a material approved by the Department of Transportation of the State in which the project is located.

**4.02-2.5 STABILIZING ADDITIVES:** Stabilizing additives are sometimes needed within PFC to prevent the draining of asphalt binder from the coarse aggregate skeleton during transportation and placement. Stabilizing additives such as cellulose fiber, mineral fiber, and asphalt binder modifers (e.g., polymers and rubber) have been used with success to minimize draindown potential. When using polymer or rubber as a stabilizer, the amount of additive added should be that amount necessary to meet the specified PG grade of the asphalt binder.

Cellulose fibers are typically added to a PFC mixture at a dosage rate of 0.3 percent by total mixture mass. Mineral fibers are typically added at a dosage rate of 0.4 percent of total mixture mass.

## COMPOSITION

**402-3.1 COMPOSITION OF MIXTURE**. The porous friction course shall be composed of aggregate, filler, bituminous material, anti-stripping agent and stabilizing additives.

**402-3.2 JOB MIX FORMULA**. No bituminous mixture shall be produced for payment until the Engineer has given written approval of the job mix formula. The job mix shall be prepared by a certified laboratory at the Contractor’s expense and shall remain in effect for the duration of the project. The job mix formula shall establish a single percentage of aggregate passing each required sieve size, a single percentage of bituminous material to be added to the aggregate, the amount of anti strip agent to be added (minimum of one half of one percent by weight), and a single temperature for the mixture as it is discharged into the hauling units. Silicone may be added to the mixture at a maximum rate of 1 ounce per 5,000 gallons of asphalt to facilitate laydown and rolling. Proper asphalt content shall be determined by mixing trial batches in the laboratory.

The job mix formula shall be submitted to the Engineer at least [30] days prior to the start of paving and shall include:

**a.** Percent passing each sieve size and gradation requirements.
**b.** Percent of asphalt cement.
**c.** Asphalt viscosity.
**d.** Mixing temperature range.
**e.** Temperature of mix when discharged from the mixer.
**f.** Temperature viscosity relationship of the asphalt cement.
**g.** Percent of wear (LA abrasion).
**h.** Sand Equivalency for fine aggregate.
**i.** Uncompacted Voids in Coarse Aggregate
**j.** Uncompacted Voids in Fine Aggregate
**k.** Percent flat or elongated particles
**l.** Voids in Coarse aggregate for coarse aggregate fraction
m. Percent fibers

**n.** Voids in Coarse Aggregate for compacted mixture.
**o.** Air void content.
**p.** Anti-strip agent.

The Contractor shall submit samples to the Engineer, upon request, for job mix formula verification testing.

The combined aggregate shall be of such size that the percentage composition by weight, as determined by laboratory sieves, will conform to the gradation shown in Table3 when tested in accordance with ASTM C 136.

The gradations in Table 3 represent the limits, which determine the suitability of the aggregate for use from the source of supply. The aggregate, as finally selected, shall have a gradation within the limits designated in Table 3 and shall not vary from the low limit on one sieve to the high limit on the adjacent sieve, or vice versa, but shall be uniformly graded from coarse to fine.

**TABLE 3. AGGREGATE-POROUS FRICTION COURSE PERCENTAGE BY WEIGHT PASSING SIEVES**

| | % Passing, Maximum Aggregate Size | | Job-Mix (Production) |
|---|---|---|---|
| Sieve Size, mm | ½ in. (12.5 mm) PFC | ¾ in. (19mm) PFC | Tolerances** |
| ¾ in. | | 100 | --- |
| ½ in. | 100 | 80-95 | ± 5% |
| 3/8 in. | 80-95 | 40-70 | ± 5% |
| No. 4 | 20-40 | 15-30 | ± 5% |
| No. 8 | 10-25 | 8-20 | ± 2% |
| No. 30 | 4-10 | 4-10 | ± 2% |
| No. 200 | 2-5 | 2-5 | ± 0.1% |
| Bitumen | | | ± 0.2% |
| Temperature of Mix | | | ± 20°F |

** The gradation job mix tolerance limits will apply if they fall outside the master grading band in Table 2 except for the top two sieve sizes starting at the 100% passing band. These two sieve size bands shall also be additional limits for production.

The gradations shown are based on aggregates of uniform specific gravity. The percentages passing the various sieves will be subject to appropriate adjustments by the Engineer when aggregates of varying specific gravities are used. The adjustments to the job mix gradation curve should result in a curve of the same general shape as the median curve of the gradation band in Table 3 and fall within the gradation band.

The Asphalt Institutes Manual Series No. 2 (MS-2) contains a convenient procedure for "adjusting" the job mix gradation when aggregates of non uniform specific gravity are proposed for use.

For best performance, the PFC mixture must have a coarse aggregate skeleton with stone-on-stone contact. The coarse aggregate fraction of the blend is that portion of the total aggregate retained on the breakpoint sieve. The breakpoint sieve is defined as the finest (smallest) sieve to retain at least 10 percent of the aggregate gradation. The voids in coarse aggregate for the coarse aggregate fraction ($VCA_{DRC}$) is determined using ASTM C29. 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:

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

where,

$VCA_{DRC}$ = voids in coarse aggregate in dry-rodded condition
$\gamma_s$ = unit weight of the coarse aggregate fraction in the dry-rodded condition ($kg/m^3$),
$\gamma_w$ = 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.

The minimum desired asphalt binder content for PFC mixtures is presented in Table 4. Values in this table reflect the minimum asphalt binder contents for PFCs. Table 4 illustrates that the minimum asphalt binder content for PFCs is based upon the combined bulk specific gravity of the aggregates used in the mix.

**Table 4: Minimum Asphalt Content Requirements for Aggregates with Varying Bulk Specific Gravities**

| 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 |

The mixing and compaction temperatures are determined in accordance with ASTM D6926, 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.

Specimens should be compacted at the established compaction temperature after laboratory short-term aging in accordance with AASHTO R30.  Laboratory samples of PFC are compacted using 50 revolutions of the Superpave gyratory compactor (SGC).

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.  Uncompacted samples are used to determine the theoretical maximum density, $G_{mm}$ (ASTM D2041).  Using $G_{mb,}$ $G_{mm}$ and $G_{ca,}$ percent air voids (VTM), and $VCA_{MIX}$ are calculated.  The VTM and $VCA_{MIX}$ are calculated as shown below.

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

$$VCA_{MIX} = 100 - \left( \frac{G_{mb} * P_{ca}}{G_{ca}} \right)$$

where:

$P_{ca}$ = percent of coarse aggregate in the mixture
$G_{sb}$ = combined bulk specific gravity of the total aggregate
$G_{ca}$ = bulk specific gravity of the coarse aggregate

Table 5 presents the requirements for PFC designs

**Table 5: PFC Mixture Specification for SGC Compacted Designs**

| Property | Requirement |
|---|---|
| Asphalt Binder, % | See Table 4 |
| Air Voids, % | 15 min. |
| Cantabro Loss % | 15 max. |
| $VCA_{MIX}$% | Less than $VCA_{DRC}$ |
| Tensile Strength Ratio | 0.70 min. |
| Draindown at Production Temperature, % | 0.30 max |

The Cantabro Abrasion test is used as a durability indicator during the design of PFC mixtures.  In this test, three PFC specimens compacted with 50 gyrations of the Superpave gyratory compactor are used to evaluate the durability of an PFC mixture at a given asphalt binder content.  To begin the test, the mass of each specimen is weighed to the nearest 0.1 gram.  A single test specimen is then placed in the Los Angeles Abrasion drum without the charge of steel spheres.  The Los Angeles Abrasion machine is operated for 300 revolutions at a speed of 30 to 33 rpm.  The test temperature is 25±5˚C.  After the 300 revolutions, the test specimen is removed from the drum and its mass determined to the nearest 0.1 gram.  The percentage of abrasion loss is calculated as follows:

$$PL = \frac{(P_1 - P_2)}{P_2} 100$$

where:

PL = percent loss
$P_1$ = mass of specimen prior to test, gram
$P_2$ = mass of specimen after 300 revolutions, gram

The average results from three specimens are reported as the Cantabro Abrasion Loss. Resistance to abrasion generally improves with an increase in asphalt binder content and/or the use of a stiffer asphalt binder.

The draindown sensitivity of the selected mixture is determined in accordance with ASTM D6390 except that a 2.36mm wire mesh basket should be used. Draindown testing is conducted at a temperature of 15˚C higher than the anticipated production temperature.

Moisture susceptibility of the selected mixture is determined using the modified Lottman method in accordance with ASTM D4867 with one freeze-thaw cycle. The ASTM D4867 method should be modified as follows: (a) PFC specimens should be compacted with 50 gyrations of the Superpave gyratory compactor at the selected 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.

The optimum bituminous content shall be one that meets all requirements of Table 5. The bituminous content of porous friction courses shall be expressed as a percentage of the total mix by weight and shall be approved by the Engineer on the basis of laboratory tests. The materials used in the mix design shall be the same as those used on the project.

The laboratory used to develop the job mix formula shall meet the requirements of ASTM D 3666. A certification signed by the lab manager of the laboratory stating that it meets these requirements shall be submitted to the Engineer prior to the start of construction. The certification shall contain as a minimum:

**a.** Qualifications of personnel; laboratory manager, supervising technician, and testing technicians.
**b.** A listing of equipment to be used in developing the job mix.
**c.** A copy of the laboratory's quality control system.
**d.** Evidence of participation in the AASHTO Materials Reference Laboratory (AMRL) program.

**402-3.3 TEST SECTION**. At least one full day prior to full production, the Contractor shall prepare a quantity of bituminous mixture according to the approved job mix formula. The amount of mixture should be sufficient to construct a test section at least 50 feet long and 20 feet wide, placed in two sections and of the same depth specified on the plans. The test area will be designated by the Engineer. The underlying pavement on which the test section is to be constructed shall be the same as the remainder of the course represented by the test section. The equipment to be used in construction of the test section shall be the same type and weight to be used on the remainder of the course represented by the test section. No bituminous mixture shall be produced for payment prior to successful placement of and acceptance of a test strip by the Engineer.

If the test section should prove to be unsatisfactory, the necessary adjustments to plant operation, and/or placement procedures shall be made. Additional test sections, as required, shall be constructed and evaluated for conformance to the specifications. When the test section does not conform to specification requirements the test section shall be removed and replaced at the Contractors expense. Full production shall not begin without approval of the Engineer. Test sections, which conform to specification requirements, shall be measured and paid in accordance with Paragraphs 402-5.1 and 402-6.1. The asphalt content may be adjusted by the Engineer during the test section and will be used as the target asphalt content.

## CONSTRUCTION METHODS

**402-4.1 WEATHER AND SEASONAL LIMITATIONS**. The porous friction course shall be constructed only on a dry surface when the atmospheric temperature is 50 F (10 C) and rising (at calm wind conditions) and when the weather is not foggy or rainy.

**402-4.2 BITUMINOUS MIXING PLANT**. Plants used for the preparation of bituminous mixtures shall conform to the requirements of ASTM D 995 with the following changes:

**a. Requirements for all Plants.**

**(1) Truck Scales.** The bituminous mixture shall be weighed on approved scales furnished by the Contractor, or on public scales at the Contractor’s expense. Such scales shall be inspected and sealed as often as the Engineer deems necessary to assure their accuracy. Scales shall conform to the requirements of Section 90.

**(2) Testing Laboratory.** The Contractor or producer shall provide laboratory facilities for control and acceptance testing functions during periods of mix production, sampling, and testing and whenever materials subject to the provisions of these specifications are being supplied or tested. The laboratory shall provide adequate equipment, space, and utilities as required for the performance of the specified tests.

**(3) Inspection of Plant.** The Engineer, or Engineer’s authorized representative, shall have access, at all times, to all parts of the plant for checking adequacy of equipment; inspecting operation of the plant; verifying weights, proportions, and materials properties; and checking the temperatures maintained in the preparation of the mixtures.

**(4) Storage Bins and Surge Bins.** Paragraph 3.9 of ASTM D 995 is deleted.

**402-4.3 HAULING EQUIPMENT**. Trucks used for hauling bituminous mixtures shall have tight, clean, smooth metal beds. Petroleum products shall not be used for coating truck beds. To prevent the mixture from adhering to them, the beds shall be lightly coated with an approved asphalt release agent. The truck beds shall be raised to drain any excess solution before loading the mixture in the trucks. Each truck shall have a suitable cover to protect the mixture from adverse weather. If conditions warrant, truck beds shall be insulated and covers shall be securely fastened so that the mixture will be delivered to the site at the specified temperature.

**402-4.4 BITUMINOUS PAVERS**. Bituminous pavers shall be self-contained, power-propelled units with an activated screed or strike-off assembly, heated if necessary, and shall be capable of spreading and finishing courses of bituminous plant-mix material which will meet the specified thickness, smoothness, and grade.

The paver shall have a receiving hopper of sufficient capacity to permit a uniform spreading operation. The hopper shall be equipped with a distribution system to place the mixture uniformly in front of the screed. The screed or strike-off assembly shall effectively produce a finished surface of the required smoothness and texture without tearing, shoving, or gouging the mixture.

The paver shall be capable of operating at forward speeds consistent with satisfactory laying of the mixture.

Pavers shall be equipped with an automatic grade control system capable of maintaining the screed elevation as specified herein. The control system shall be automatically activated from either a reference line or surface through a system of mechanical sensors or sensor-directed mechanisms or devices that will maintain the paver screed at a predetermined transverse slope and at the proper elevation to obtain the required surface.

The controls shall be capable of working in conjunction with any of the following attachments:

**a.** Ski-Type device of not less than 30 feet in length or as directed by the Engineer.
**b.** Taut stringline (wire) set to grade.
**c.** Short ski or shoe.
**d.** Laser controls.

The controls shall be so arranged that independent longitudinal grade controls can be operated simultaneously on both sides of the machine or independently on either side. The electronic controls shall be arranged so that the machine can be controlled automatically, semi-automatically, or manually.

The automatic equipment shall be capable of controlling the grade to within plus or minus one-eighth inch and the transverse slope to within plus or minus one tenth of one percent from the controlling grade.

The machine shall be equipped with a spirit level or other type of slope indicator that will continuously indicate the average transverse slope of the screen. Curvature of spirit level tubes shall be as required to produce a bubble movement of not less than one-eighth inch for each one-tenth of one percent change in the transverse slope.

The paving machine shall be capable of being equipped with an infrared joint heater if directed by the Engineer. The output of infrared energy shall be in the one to six micron range. Converters shall be arranged end to end directly over the joint to be heated in sufficient numbers to continuously produce, when in operation, a minimum of 240,000 BTU per hour. The joint heater shall be positioned not more than one inch above the pavement to be heated and in front of the paver screed and shall be fully adjustable. Heaters will be required to be in operation at all times.

**402-4.5 ROLLERS**. Rollers shall be steel wheel. Split drum rollers are not acceptable. They shall be in good condition, capable of reversing without backlash, and operating at slow speeds to avoid displacement of the bituminous mixture. The wheels shall be equipped with adjustable scrapers and sprinkling apparatuses using a water soluble asphalt release agent, approved by the engineer, to prevent the bituminous mixture from sticking to the wheels. The number, type, and weight of rollers shall be sufficient to compact the mixture without detrimentally affecting the material.

**402-4.6 PREPARATION OF MINERAL AGGREGATE**. The aggregate for the mixture shall be dried and heated at the central mixing plant before entering the mixer. When introduced into the mixer, the combined aggregate moisture content (weighted according to the composition of the blend) shall be less than 0.25 percent for aggregate blends with water absorption of 2.5 percent or less and less than 0.50 percent for aggregate blends with water absorption greater than 2.5 percent. Water absorption of aggregates shall be determined by ASTM C 127 and C 128. The water absorption for the aggregate blend shall be the weighted average of the absorption values for the coarse aggregate retained on the No. 4 sieve (4.75 mm) and the fine aggregate passing the No. 4 sieve (4.75 mm). The water content test will be conducted in accordance with ASTM C 566. In no case shall the moisture content be such that foaming of the mixture occurs prior to placement. At the time of mixing, the temperature of the aggregate shall be within the range specified in the job mix formula. The maximum temperature and rate of heating shall be such that no damage occurs to the aggregates. Particular care shall be taken so that aggregates high in calcium or magnesium content are not damaged by overheating. The aggregate shall be screened to specified sizes and conveyed in separate bins ready for mixing with bituminous material.

**402-4.7 PREPARATION OF BITUMINOUS MIXTURE**. The bituminous mixture shall be prepared in a central mixing plant. The mixture shall be prepared at the temperature designated by the mix design.

The dry aggregate shall be combined in the plant using the proportionate amounts of each aggregate size required to meet the specified gradation. The quantity of aggregate for each batch shall be determined, measured, and conveyed into the mixer.

The quantity of bituminous material for each batch or the calibrated amount for continuous mixers shall be determined by the certified laboratory that prepared the mix design. It shall be measured by weight and introduced into the mixer within the temperature range specified in the job mix formula. For batch mixers, all aggregates shall be in the mixer before the bitumen material is added. In no case shall the temperature of the aggregate be more than 25°F above the temperature of the bituminous material. Mixing shall continue until all particles are coated uniformly. In no case shall the bituminous mixture be stored in storage silos or surge bins.

**402-4.8 TRANSPORTATION AND DELIVERY OF THE MIXTURE**. The mixture shall be placed at a temperature appropriate for the properties of the asphalt binder. Loads shall be sent from the plant so that all spreading and compacting of the mixture may be accomplished during daylight hours. Excessive waiting or delay of haul trucks at the job site shall not be allowed and mix supplied at temperatures outside the specified range will not be accepted. Bleeding and rich spots resulting from segregation during transportation shall not be accepted.

**402-4.9 SPREADING AND LAYING**. Immediately before placing the porous friction course, the underlying course shall be cleared of all loose or deleterious material with power blowers, power brooms, or hand brooms as directed. A tack coat conforming to Item P-603 Bituminous Tack Coat shall be placed on all existing surfaces for bonding the PFC to the existing surface. Placement of the PFC must be delayed until the tack coat has properly cured.

The mixture shall be deposited from haul units directly into the laydown machine hopper and placed in a continuous operation.

Hauling over material already placed shall not be permitted until the material has been thoroughly compacted and allowed to cure for a period of at least 12 hours.

**402-4.10 COMPACTION OF MIXTURE**. After spreading, rolling shall be done immediately. Two or four passes, at the discretion of the Engineer, with a steel wheel roller weighing no more than 10 tons, shall be made for compaction. Care should be taken to avoid over rolling or rolling when material is too cool. To prevent adhesion of the mixture to the roller, the wheels shall be kept properly moistened using a water soluble asphalt release agent approved by the engineer. Rolling operations shall be conducted in such a manner that shoving or distortion will not develop. The amount of rolling shall be limited to only that necessary for compacting the porous friction course and bonding it to the underlying surface course. Any mixture, which becomes loose, broken, mixed with dirt, or in any way defective, shall be removed and replaced with fresh mixture and immediately compacted to conform to the surrounding area. Such rework shall be done at the Contractor's expense. Spreading of the mixture shall be done carefully with particular attention given to making the operation as continuous as possible. Hand working shall be kept to an absolute minimum.

**402-4.11 JOINTS**. The formation of all joints shall be made in such a manner as to ensure a continuous bond between old and new sections of the course. Bituminous material should not be placed on longitudinal joints. All joints shall present the same texture, density, and smoothness as other sections of the course.

The roller shall not pass over the unprotected end of the freshly laid mixture except when necessary to form a transverse joint. When necessary to form a transverse joint, it shall be made by means of placing a bulkhead or by tapering the course, in which case the edge shall be cut back to its full depth and width on a straight line to expose vertical face. In both methods all contact surfaces shall be given a tack coat of bituminous material before placing any fresh mixture against the joint.

Longitudinal joints which are irregular, damaged, or otherwise defective shall be cut back to expose a clean, sound surface for the full depth of the course. The longitudinal joint shall offset that in the existing course by at least 1 foot (30 cm).

**402-4.12 SHAPING EDGES**. While the surface is being compacted and finished, the Contractor shall carefully shape the longitudinal outside edges of the PFC to a vertical face at the established edge. When transitioning from PFC to existing pavement, transverse edges shall be constructed with a finer graded bituminous mixture.

*** * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ***

**Edge lips shall not exceed 3-inches; however, they are preferred to be less than 1.5-inches. This may be a problem on projects that have excessive surface irregularities.**

*** * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ***

**402-4.13 SURFACE TESTS**. The Contractor is responsible for supplying an acceptable metal 12-foot straight edge. After completion of final rolling, the finished surface shall be tested with the 12-foot straightedge and shall not vary more than 1/4 inch. The 12-foot straight edge shall be applied parallel with and at right angles to the runway centerline in a pattern that includes longitudinal and transverse joints. The 12-foot straightedge shall be advanced approximately 1/2 its length in the line of measurement. Areas of the porous friction course exceeding the specified tolerances shall be removed, as directed by the Engineer, and replaced with new material at the Contractor's expense. The Engineer shall immediately notify the Contractor of such unsatisfactory visual defects such as non-uniform texture, roller marks, bleeding of bituminous material, cracking and shoving of the mixture during rolling operations. Areas of the porous friction course, which possess such defects, shall be removed, as directed by the Engineer, and replaced with new material at the Contractors expense. Skin patching or hand working shall not be permitted.

**402-4.14 ACCEPTANCE SAMPLING AND TESTING OF BITUMINOUS MATERIAL AND AGGREGATE.** The Engineer, at no cost to the Contractor, shall perform all acceptance sampling and testing. The testing laboratory performing the testing shall meet the requirements of ASTM D 3666.

Samples of the PFC mixture shall be taken at the point of discharge in hauling units and tested to control uniformity in bituminous content and gradation. Samples shall also be taken and tested to evaluate draindown in accordance with ASTM XXX. Samples shall be taken in accordance with ASTM D 979 and prepared in accordance with ASTM D 2172 or ASTM D 6307. One sample shall be taken from each lot on a random basis in accordance with procedures contained in ASTM D 3665. A lot shall consist of 1,000 tons or 1/2 day’s production, whichever is less. Should the average bituminous content for any two consecutive lots not fall within job mix tolerances under 402-3.1, the Contractor shall cease production until such out-of-tolerance conditions have been remedied. Any material, placed after the contractor has been informed of two consecutive failing tests, shall be rejected and removed at the Contractor's expense. Aggregate from each hot bin or aggregate feed shall be sampled on a random basis and tested for gradation analysis in accordance with ASTM C 136. One sample shall be taken on a random basis in accordance with ASTM D 3665 for each lot. A lot shall consist of 500 tons or 1/4 day’s production, whichever is less. If any two consecutive samples fail to meet the tolerances of the job mix formula gradation, the Contractor shall cease plant production until such out-of tolerance conditions have been remedied. Any material, placed after the contractor has been informed of two consecutive failing tests, shall be rejected and removed at the Contractor's expense.

The Engineer will notify the Contractor of unsatisfactory visual defects in the completed bituminous friction course such as non-uniform texture, roller marks, bleeding of bituminous material, cracking and shoving of the mixture during the roller operations, or nonconformance to the surface smoothness criteria specified. Unsatisfactory bituminous friction course shall be removed and replaced at the Contractor's expense as directed by the Engineer.

**402-4.15 BITUMINOUS AND AGGREGATE MATERIAL (CONTRACTOR’S RESPONSIBILITY)**. Samples of the bituminous and aggregate materials that the Contractor proposes to use, together with a statement of their source and character, shall be submitted for approval prior to use. The Contractor shall require the manufacturer or producer of the bituminous and aggregate materials to furnish material subject to this and all other pertinent requirements of the contract. Only those materials that have been tested and approved for the intended use shall be acceptable.

The Contractor shall furnish the vendor’s certified test reports for each carload or equivalent of bituminous material shipped to the project. The report shall be delivered to the Engineer before permission is granted to use the material. The vendor’s certified test report for the bituminous material shall not be interpreted as a basis for final acceptance. All test reports shall be subject to verification by testing sample materials received for use on the project.

**402-4.16 PROTECTION OF PAVEMENT**. After final rolling, no vehicular traffic of any kind shall be permitted on the pavement until it has cured at least 12 hours or unless otherwise authorized by the Engineer. Newly constructed pavement areas shall not be opened to aircraft traffic until 24 hours after completion or unless otherwise authorized by the Engineer.

## METHOD OF MEASUREMENT

**402-5.1** Porous friction course shall be measured by the number of **[square yards (square meters)][tons (kg)]** of mixture used in the accepted work.

Only the areas of the porous friction course meeting the following thickness requirements shall be measured for payment:

To determine the thickness of the finished PFC, the Engineer shall take one core sample, not less than 2 inches (5 cm) in diameter, at random from each unit of the completed PFC area. A unit of the completed area shall be one paving lane wide by 1,000 feet (304 m) long. The last unit in any one paving lane shall include any remaining length in addition to the 1,000 feet (304 m).

When the measurement of any core is more than the maximum or less than the minimum allowable thickness, as shown in Table 6, additional cores shall be taken at 20-foot intervals (6 m) (parallel to and at right angles to the runway centerline) until the completed PFC is within such maximum or minimum thickness for the subunit being tested. Out-of-tolerance areas shall be deducted from the total **[square yards (square meters)][tons (kg)]** PFC for payment. If, in the Engineer's judgment, such out of tolerance areas warrant removal, the PFC shall be removed and the underlying course shall be cleaned (ready for reconstruction), all at the Contractor's expense.

**TABLE6. ALLOWABLE FINISHED PFC THICKNESS**

| | Nominal | | Maximum | | Minimum | |
|---|---|---|---|---|---|---|
| | in. | mm | in. | mm | in. | mm |
| 3/4 in. aggregate | 1.0 | 25 | 1.50 | 37 | 0.75 | 19 |
| 1/2 in. aggregate | 0.75 | 19 | 1.25 | 32 | 0.50 | 12 |

## BASIS OF PAYMENT

**402-6.1** Payment shall be made at the respective contract prices per **[square yard (square meter)][ton (kg)]** for porous friction course and per **[gallon (liter)][ton (kg)]** for bituminous material. The prices shall be full compensation for furnishing all materials; for all preparation and storage of materials; for cleaning the existing surface; for mixing, hauling, placing, and compacting the mixture (including initial test section); and for all tools, equipment, and incidentals necessary to complete each item. No separate payment is included in the contract for furnishing and batching mineral filler, or anti-stripping agents, should such items be required.

Rehabilitation of the existing pavement surface and the tack coat shall be measured and paid for at their respective contract prices.

Payment will be made under:
Item P-402-6.1 Porous Friction Course—**[per square yard (square meter)][ton (kg)]**
Item P-402-6.2 Bituminous material—**[per gallon (liter)][ton (kg)]**

## TESTING REQUIREMENTS

ASTM C29 Bulk Density ("Unit Weight") and Vods in Aggregate
ASTM C 88 Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
ASTM C 127 Density, Specific Gravity, and Absorption of Coarse Aggregates
ASTM C 128 Density, Specific Gravity, and Absorption of Fine Aggregate
ASTM C 131 Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine
ASTM C 136 Sieve Analysis of Fine and Coarse Aggregates
ASTM C 566 Total Evaporable Moisture Content of Aggregate by Drying

ASTM C1252 Uncompacted Void Content of Fine Aggregate (As Influenced by Particle Shape, Surface Texture and Grading)
ASTM D 979 Sampling Bituminous Paving Mixtures
ASTM D 995 Mixing Plants for Hot-Mixed Hot-Laid Bituminous Paving Mixtures
ASTM D 2172 Quantitative Extraction of Bitumen from Bituminous Paving Mixtures
ASTM D2041 Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
ASTM D2419 Sand Equivalent Value of Soils and Fine Aggregates
ASTM D 3665 Random Sampling of Paving Materials
ASTM D 3666 Minimum Requirements for Agencies Testing and Inspecting Bituminous Paving Materials
ASTM D4867 Effect of Moisture on Asphalt Concrete Paving Materials
ASTM D 4791 Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate
ASTM D 6307 Standard Test Method for Asphalt Content of Hot Mix Asphalt by Ignition Method
ASTM D6390 Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures
ASTM D6926 Preparation of Bituminous Speciments Using Marshall Apparatus
AASHTO R30 Mixture conditioning of Hot-Mix Asphalt
AASHTO T326 Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture and Grading

## MATERIAL REQUIREMENTS

ASTM D 242 Mineral Filler for Bituminous Paving Mixtures
AASHTO M320 Performance-Graded Asphalt Binder

## END OF ITEM P-402