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IMPROVED POROUS FRICTION COURSES (PFC) ON ASPHALT AIRFIELD PAVEMENTS

Volume II: Summary of Research

for

AAPTP PROJECT 04-06

Submitted to

Airfield Asphalt Pavement Technology Program

By

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Draft Final Report

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Summary of Research

INTRODUCTION

The term porous friction course (PFC) in the US is used to describe an HMA having an open aggregate grading that is used as a wearing course. Porous friction courses 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 foreign object damage (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 these mixes over the last 10 to 15 years. 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

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.

Report Purpose and Organization

The Final Report for AAPTP 04-06 is divided into two volumes. Volume I of the Final Report provides documentation of all research results. Detailed discussions are provided on the advantages/disadvantages of using PFCs on airfield pavements, design of PFC mixes for airfield applications, production and construction of PFC mixes and maintenance of PFC pavement layers. Also, included within this Volume I of the Final Report are conclusions and recommendations for the use of PFC mixes on airfield pavements. For each of the conclusions and recommendations detailed, discussions are provided for justification. Because the end user for the research results will be practicing engineers, Volume II was developed to provide a concise summary of the best practices developed during the conduct of this research study.

This volume of the Final Report is divided into five primary sections. The first section summarizes the advantages and disadvantages of using PFCs for airfield pavements. The second section provides a summary of the mix design procedure recommended as part of the study. Also included are discussions on the desirable properties of PFC mixes and how they are related to mix design. These desirable properties were used to develop the recommended mix design method. The third and fourth sections discuss current practices for production/construction of PFC mixes. Finally, the conclusions and recommendations from this research project are provided.

ADVANTAGES AND DISADVANTAGES OF PFCS ON AIRFIELD PAVEMENTS

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 on the pavement surface. 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 yield a significant amount of surface texture on the pavement surface 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. The goal of PFC compaction is simply to seat the aggregates, not densify the mix to an impermeable compaction level. 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(2).

The primary disadvantages of using PFC layers are winter maintenance, potential 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 also identified as a problem with some PFC layers. 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.

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, the clogged PFCs still maintain their frictional properties because of the high amount 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.

MIX DESIGN FOR PFC USED ON 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. 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). One of the perceived disadvantages of PFCs is the occurrence of raveling; therefore, PFCs, should also be durable with minimal potential for raveling.

Improved frictional properties can be achieved by focusing on two characteristics of PFC mixtures. 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 (1).

The second characteristic is proper selection of aggregates. Aggregates with a significant amount of microtexture 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 (2) and 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.

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 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.

The potential areas for improvements in mix design and divided by the four steps in designing PFCs: materials selection, selection of design gradation; selection of optimum asphalt binder content and evaluation of moisture susceptibility. The following paragraphs describe potential improvements for the design of porous friction courses.

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.

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. Tables 1 and 2 summarize the recommended aggregate characteristics for PFCs used on airfields.

Table 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.

Table 2: Fine Aggregate Quality Requirements for PFC

Test	Method	Spec. Minimum	Spec. Maximum
Soundness (5Cycles), %	AASHTO T104		
Sodium Sulfate		-	15
Magnesium Sulfate		-	20
Uncompacted Voids	AASHTO T304, Method A	45	-
Sand Equivalency	AASHTO T176	50	-

The next material requiring selection is the asphalt binder. Current requirements for designing airfield PFC mixes are for using 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*. 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 for highway use in the 1930’s, neat (unmodified) asphalt binders were utilized. In 1992, Anderton (3) 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 (4, 5). Additionally, in most instances, these problems tended to accelerate quickly requiring immediate maintenance or complete removal (6).

Many of the past problems with PFCs can be traced to the selection of the asphalt binder. 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, generally termed as draindown (6). Because of the draindown issues, a typical remedy was to reduce mixing and compaction temperatures (4). 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 (7). 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 (4).

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 (5) 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 the National Center for Asphalt Technology (NCAT) (8,9,10) have shown that the use of modified asphalt binders that provide high stiffness at typical in-service pavement temperature helps provide increased durability. Anderton (3) has also showed that the addition of reclaimed rubber particles to the asphalt binder (i.e., increased viscosity) improved the performance of PFCs.

As discussed 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 (10). Figure 1 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 2 illustrates the results of laboratory durability testing at two different asphalt binder contents (10). The laboratory durability testing depicted in Figure 9 is the Cantabro Abrasion Test which is the most common laboratory durability test for PFCs. Figure 2 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.

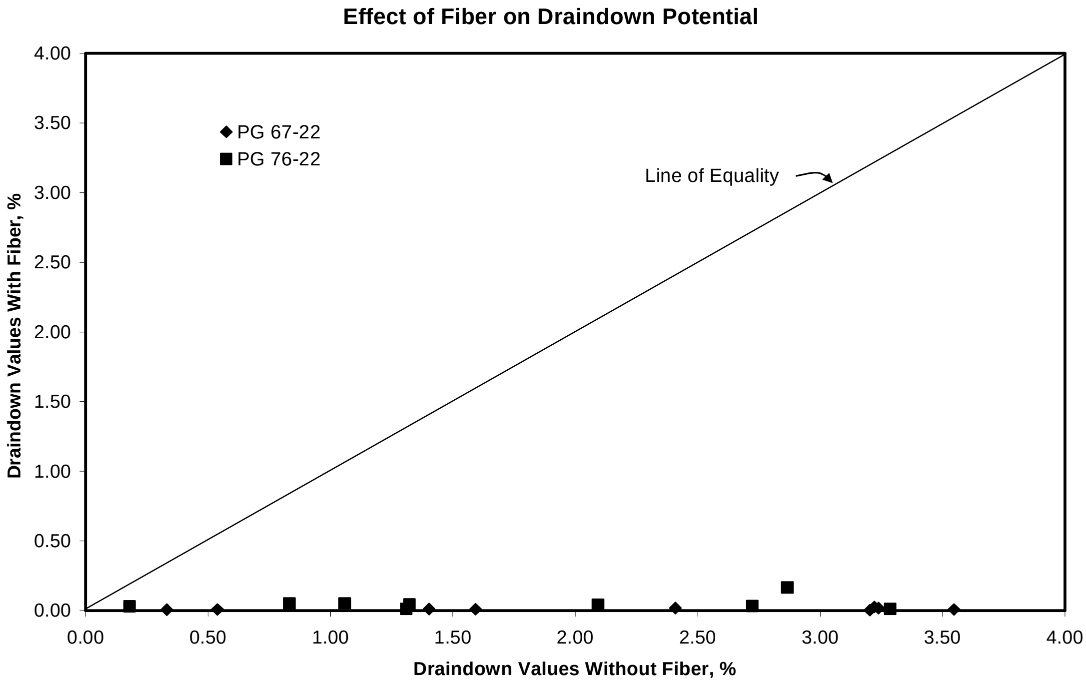

Figure 1: Effect Of Fiber on Draindown Potential (<u>10</u>)

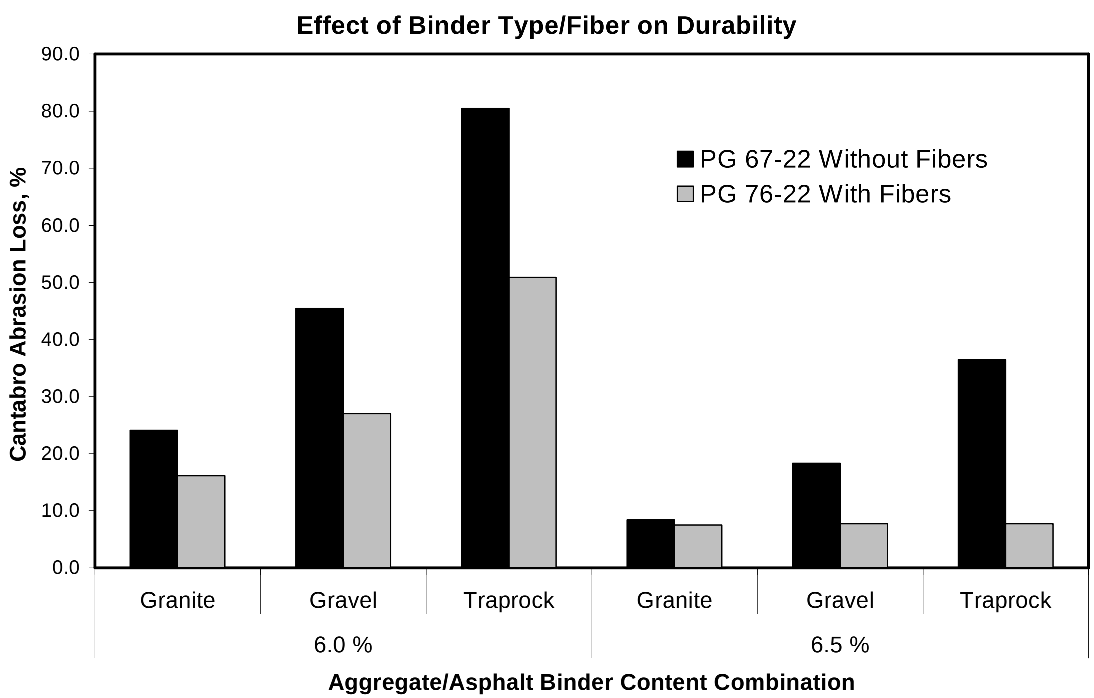

Figure 2: Effect of Asphalt Binder Type on Cantabro Abrasion Loss (<u>10</u>)

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.

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 will 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.

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 traffic 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 3 and 4 and provided in Table 3, are a compromise between the Item P-402 and UGFS-32 12 20 gradation requirements. 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. 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 4), 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.

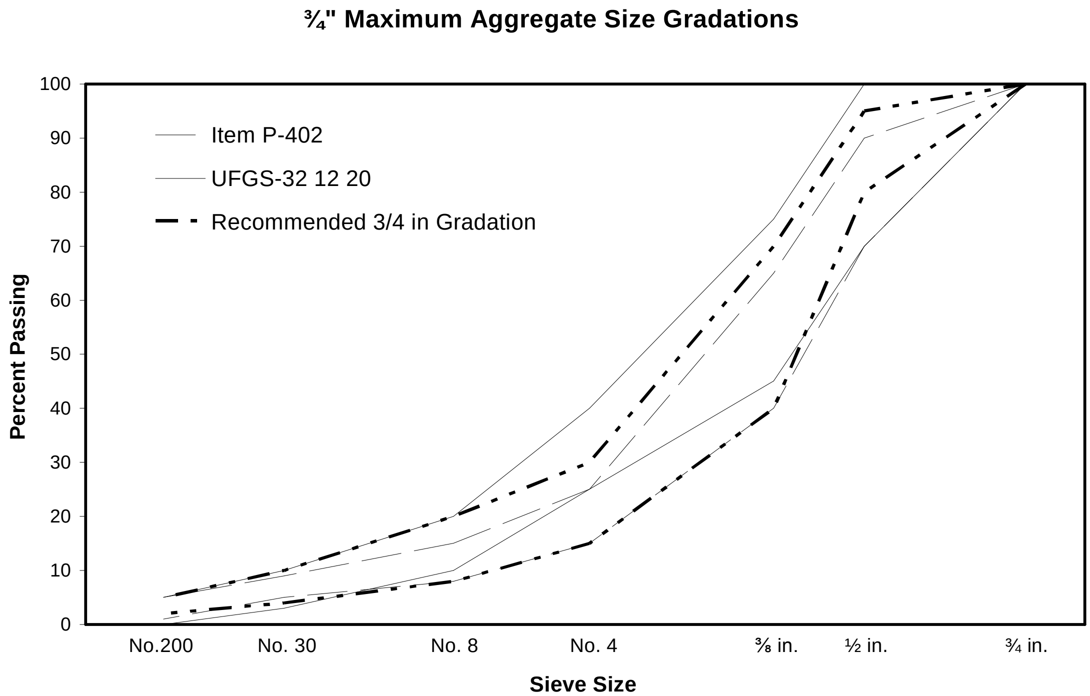

Figure 3: Recommended Gradation Band for ¾ in. Maximum Aggregate Size PFC

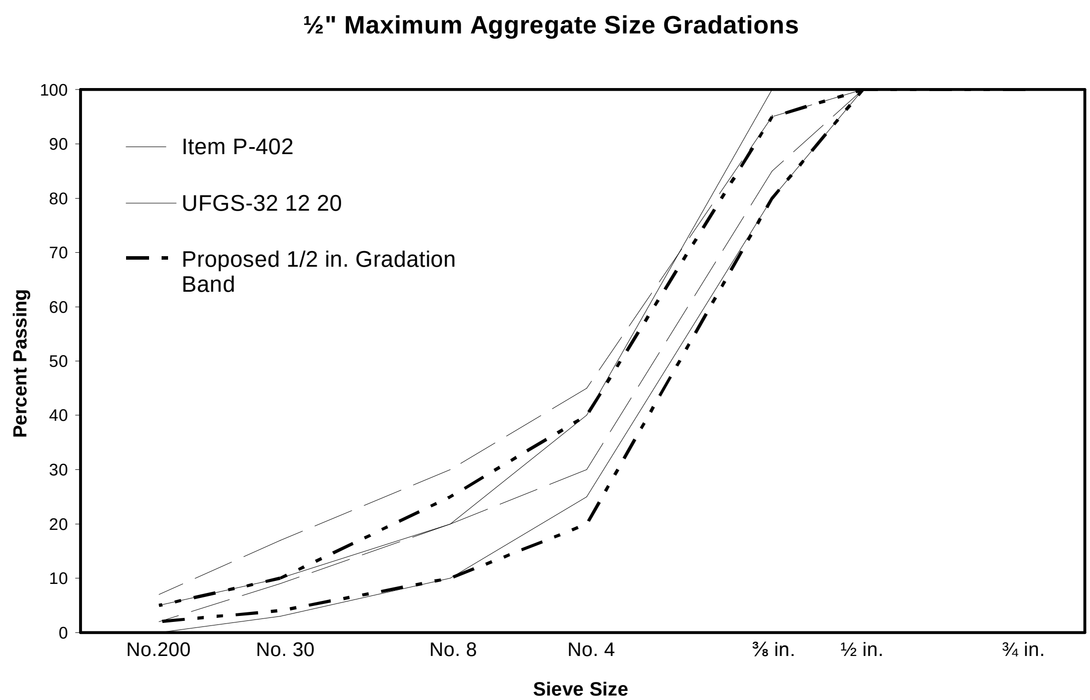

Figure 4: Recommended Gradation Band for ½ in. Maximum Aggregate Size PFC

Table 3: Recommended PFC Gradation Bands

Sieve	Proposed ¾ in. Max. Aggregate Size Gradation		Proposed ½ in. Max. Aggregate Size Gradation	
	Min.	Max.	Min.	Max.
¾ in.	100	100		
½ in.	80	95	100	100
⅜ in.	40	70	80	95
No. 4	15	30	20	40
No. 8	8	20	10	25
No. 30	4	10	4	10
No. 200	2	5	2	5

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.

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. Of the various methods, only the draindown basket method developed by NCAT currently has a national standard. The test method is provided in 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 asphalt binder content. Testing should be conducted 15°C above the anticipated mix production temperature at the plant (11).

The literature shows that the predominant test used to evaluate a minimum asphalt binder content (for durability) is the Cantabro Abrasion Loss test. As shown in Figure 2, 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. Within Europe and the US, the predominant compactive effort used in the past has been 50 blows per face of the Marshall hammer. 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 (8) of the Superpave gyratory compactor. This compactive effort is likely applicable to PFCs but may need further evaluation. A draft test method for the Cantabro Abrasion Loss test is provided in Appendix B of Volume I of the Final Report.

Based upon research conducted by Watson et al (9), 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. Since PFCs for airfield pavements are not specifically designed to remove large volumes of water from the pavement surface, a minimum air void content of 15 percent is appropriate.

The combination of draindown and Cantabro Abrasion testing and a minimum air void content requirement will allow for selection of optimum asphalt binder content. Optimum asphalt binder content should be selected at least 0.4 percent below the identified maximum asphalt binder content to account for production variability while also meeting the Cantabro Abrasion and air void requirements.

Another area that would improve the design of PFC is the evaluation of stone-on-stone contact. 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 ASTM C29, *Bulk Density ("Unit Weight") and Voids in Aggregate*. 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 (9). 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 (11). This evaluation at the selected optimum asphalt binder content will help ensure a stable layer of PFC.

Of the methods to evaluate the moisture susceptibility of the designed PFC discussed previously, the tensile strength ratio, as defined in ASTM D4867, *Effect of Moisture on Asphalt Concrete Paving Mixtures*, 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 (4).

PRODUCTION AND CONSTRUCTION OF PFC MIXES FOR AIRFIELD PAVEMENTS

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 (4). 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 (11) 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)" (1).

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 (12). Low moisture contents and low moisture content variability will allow for easier control of mixing temperature (7).

A PFC mixture must contain a high percentage of coarse aggregate in order to provide the desired high air void contents and, thus, benefits related to permeability. Since the coarse aggregate gradation can have a tremendous effect on the quality of the PFC mixture produced, 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 (12).

Porous friction course mixtures may require that some type of modifier be used in order to enhance binder properties. 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. 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 5: 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.

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. 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.

Both cellulose and mineral fibers have been used as stabilizers in PFC mixture production. Dosage rates vary, but typically the rates are 0.3 percent for cellulose and 0.4 percent for mineral fiber, by total mixture mass (4). 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 (11). Therefore, the bags can be added directly to the pugmill during each dry mix cycle. When the bags melt, only the fiber remains. Another method for addition of fibers into a batch plant or drum-mix 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 6). The fluffed fiber next enters an auger system which conditions the material to a known density. The fiber is then metered by the machine into the production process at the appropriate time. These machines can meter in the proper amount of fiber by mass or blow in a known volume (4). 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 (Figure 7). It is imperative that fibers be captured by the asphalt binder before being exposed to the high velocity gases in the drum. If the fiber gets into the gas stream, it will enter the dust control system of the plant (4).


Figure 6: Fiber Pugmill-Type Dispersion System

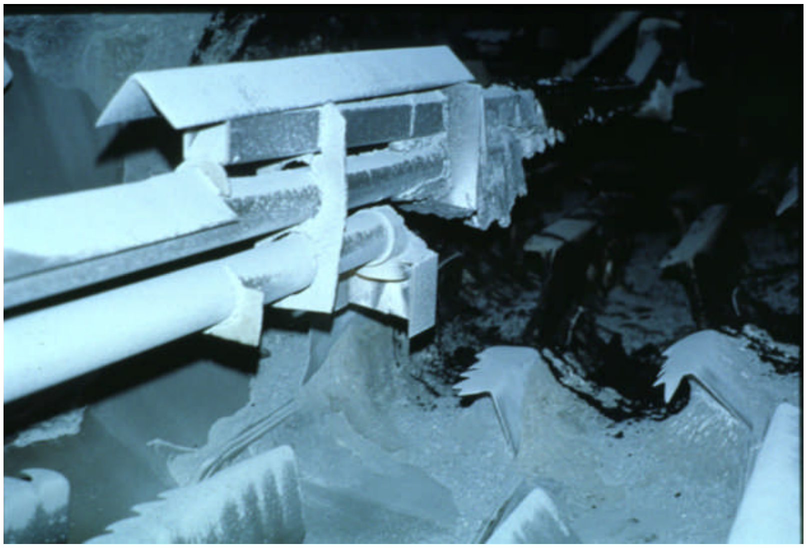
Figure 7: Fiber Injection Point in a Drier-Drum Plant

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. 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. Variations in the amount of additive can have a detrimental impact on the finished pavement. Stabilizing additive manufacturers will usually assist the hot mix producer in setting up, calibrating, and monitoring the stabilizing additive system.

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 and 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.

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 the silo overnight. 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.

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

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) (13,14). 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 (14). 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 (15).

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 (15). 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. 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.

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.

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.

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 minimize 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.

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 one to two complete coverage of the mat in static mode to compact a thin lift (20 mm or ¾ in) PFC.

No minimum density is recommended for PFC. 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 (16). 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. Vibratory rollers should not be used on PFC mainlines. 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. The vibration of the roller may break aggregate and/or force the mortar to the surface of the mat. Pneumatic-tired rollers are not recommended for use on PFC. The rubber tires tend to pick up the mortar causing surface deficiencies.

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.

MAINTENANCE OF PFC AIRFIELD PAVEMENTS

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 (4, 17) has been conducted and published in the US and Europe concerning general and winter maintenance of PFC highway pavement layers. 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 is discussed here.

General maintenance consists of cleaning clogged PFC; removal of rubber buildup; preventive surface maintenance; corrective surface maintenance; and rehabilitation. Porous friction course may gradually be choked and partially lose its permeability (4). Therefore, frequent cleaning may be necessary. A high pressure cleaner, has been found to be most effective based on permeability tests after cleaning in Switzerland (18). A piece of equipment was recently reported on at the meeting of the International Conference on Asphalt Pavements held in Copenhagen, Denmark (19). A high-pressure water blast (860 kPa or 125 psi) followed by a vacuum to remove the solids and water is used in Denmark. Experienced contractors with specialized equipment do such work.

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. 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 shot blast or sandblast PFC mixtures without filling some voids with sand. It is also quite possible that shot blasting and sandblasting may be too harsh for 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. It is unclear whether the chemicals will harm the asphalt-rubber binder contained within some PFCs.

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 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 (20).

Occasionally, the PFC airfield pavement will require repair of delaminated areas and/or 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 (20). 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 (20). 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 PFC airfield pavement can also develop transverse and longitudinal cracks while in service. 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. Again, only a light tack coat should be applied to the vertical faces of the existing pavement.

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 (6). 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 (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 may have a temperature of 2° C lower than dense asphalt pavement. 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 (7). "Preventive salting" of the PFC at the right time is important as practiced in Britain (21). 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 (22). 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 (22). According to experience in Netherlands (23) 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 (24). 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 (15). 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 of Volume I of the Final Report.

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 and 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 from debris. 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.

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