Technical Report Documentation Page

1. Report No. FHWA/TX-08/0-5220-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle State of the Practice: Permeable Friction Courses		5. Report Date December 2007
		6. Performing Organization Code
7. Author(s) Christina Stanard, Rémi Candaele, Randall Charbeneau, Ph.D., P.E., and Michael Barrett, Ph.D., P.E., D.WRE		8. Performing Organization Report No. 0-5220-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 0-5220
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Technical Report September 1, 2006–August 31, 2007
		14. Sponsoring Agency Code

15. Supplementary Notes

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

16. Abstract

Permeable Friction Courses (PFC) are open-graded bituminous mixtures placed over an impervious base. The interconnected air voids allow rainwater to drain into the pavement thus providing a safer driving surface in wet weather and a filter for highway runoff.

This report summarizes the current state of the practice related to the hydraulic properties, water quality benefits, and maintenance of PFC based on literature from around the world. Porous pavements reduce pollutant concentrations in the highway runoff during the functional service life of the pavement, which ultimately results in the clogging of the pavement. This material accumulating in the pores was found to have high concentrations of pollutants, such as heavy metals. Pavement cleaning machines used in Europe to remove accumulated pollutants are described and usually found to maintain the function of the pavements. Existing research also includes measurements of hydraulic conductivity over time and from different pavements. In winter conditions, more maintenance is required for PFCs than for conventional pavements since the air voids change with ambient air temperature casing the PFC to freeze faster than conventional pavement. Other beneficial properties of PFCs, such as the friction coefficient and noise reduction ability, are also described.

This report also presents the results of a nationwide survey of DOTs conducted to document PFC use and maintenance in the U.S. The survey revealed minimal hydraulic testing, hydraulic design guidelines, and pavement maintenance by the DOTs. The cleaner stormwater runoff observed from PFC in several European studies has not been investigated by U.S. DOTs other than TxDOT.

17. Key Words	18. Distribution Statement
Permeable Friction Course, Open-Graded Friction Course, porous asphalt, stormwater, highway runoff treatment,	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	60	

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State of the Practice: Permeable Friction Courses

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CTR Technical Report:	0-5220-1
Report Date:	December 2007
Project:	0-5220
Project Title:	Investigation of Stormwater Quality Improvements Utilizing Permeable Pavement and/or the Porous Friction Course (PFC)
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

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

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Professional Engineer License State and Number: Texas No. 82582
P. E. Designation: Environmental

Acknowledgments

The authors would like to express their appreciation to the TxDOT Project Director, Gary Lantrip (Austin District), and Project Advisors: James Williams (AUS), Richard Izzo (CST), and James Bice (TCEQ). Without their assistance and ongoing support this innovative work on porous overlays would not be possible.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

Porous pavements are used throughout the world, most commonly in Europe and the United States. They are commonly referred to as porous asphalt, open-graded friction course (OGFC), or, in Texas, permeable friction course (PFC). PFCs are bituminous road mixtures that are applied over an impervious concrete or asphalt base. Porous pavements were first developed to improve road safety under wet conditions. The overlay allows rainwater to drain down through the pores in the asphalt and then flow over the impervious base and out to the edge of the pavement. The widely accepted advantages of PFC are the road safety improvements in wet conditions as well as the noise reduction from the roadway. The safety benefits during rain events include reduced hydroplaning, greater skid resistance at high speeds, less spray and light reflection from the roadway due to the improved drainage, and therefore, better visibility. In addition to these benefits, PFC has been found to reduce pollutant concentrations in stormwater runoff.

These advantages come with greater initial and maintenance costs and sometimes shorter service lives than conventional pavement. Cost-benefit analyses (van der Zwan, 1990) have shown that even with a greater yearly maintenance cost and shorter service life, the benefits outweigh the increased costs. Also, recent improvements in mix designs have increased the expected service life of these types of pavements. Other commonly noted disadvantages are reduced performance over time due to clogging of the pavement and the winter maintenance requirements.

This document includes a review of literature on porous asphalt from around the world as well as a survey of Departments of Transportation (DOTs). The literature review focuses on the hydraulic properties, water quality benefits, and common maintenance practices for porous pavements. Chapters Two through Five summarize the findings of this review. The review also includes some information on other aspects of PFC, such as noise reduction and friction coefficient. The purpose of these sections is only to alert the reader that is new to the subject of PFC about these other aspects and a comprehensive review of the literature related to these aspects is not provided. The majority of the cited articles are from online databases or journals. The search for articles focused on recent publications with relevant experiments and results or discussion.

Chapter Six presents the results of a nationwide DOT survey conducted to document PFC use and common practices of other DOTs, including hydraulic testing and design guidelines, maintenance practices, and any water quality benefits.

Chapter 2. Hydraulic Properties

2.1 Introduction

The hydraulic properties of porous asphalt are of great interest, because they are responsible for many of the benefits of the pavement. This chapter discusses hydraulic properties of PFC and common tests used to characterize these properties. Some properties are easily determined while others can be difficult to evaluate. When available, reported values of various properties are compiled in the following sections.

2.2 Hydraulic Measurements

The hydraulic properties of PFC depend on the porosity, layer thickness, mix design (aggregate grading), and roadway cross-section and slope. The porosity, or void content, is usually considered the largest influence on the drainage capacity of a porous pavement (Tan et al., 2004).

Permeability is a measure of a materials ability to transmit fluids. Measured values for permeability, hydraulic conductivity, and infiltration rate vary widely in the literature. While these terms are often used interchangeably, they do not represent the same quantity. In this paper, hydraulic conductivity is used as the permeability coefficient that relates the volumetric flux and the hydraulic gradient. Its units are length per time. Nearly every reported value is derived from a different test, thus preventing a direct comparison. However, the test methods do share some similarity in that many utilize a falling head apparatus to achieve a sense of the flow capacity of the pavement. The test documents the time required for a certain amount of water to drain into the pavement, which can be converted to a flow rate measurement. One problem with this test is that the water surfaces around the apparatus rather than flowing through the pavement. Thus, the data from such tests do not accurately represent a theoretical quantity.

Bear (1972) describes the methods commonly used in determining the hydraulic conductivity of a porous media. The experiments consist of characterizing the unsteady or steady flow in the vertical or horizontal direction through a cylindrical specimen with an instrument called a permeameter. The two types of permeameters can be distinguished.

The constant head permeameter applies a constant head loss ΔH over a porous media of height L, and cross-sectional area A. The discharge Q flows through the sample in a time period ΔT, and the hydraulic conductivity is computed according to Equation 1:

Equation 1

$$K = \frac{QL}{A\Delta H}$$

Several runs are necessary in order to reduce the uncertainty. In France, the standardized test consists of a constant head of 1.5 meters of water (Di Benedetto et al., 1996).

The falling head permeameter measures a percolation velocity (v_p) through a specimen of porous media of height L and cross section A. Initially, a standpipe of section a constrains the sample to a fixed volume of water V. The time T for the water level to drop in the standpipe from heights

H_i to H_f is recorded and the hydraulic conductivity is computed with Equation 2 (Terzaghi et al., 1996):

Equation 2

$$K = \frac{aL}{AT} \ln\left(\frac{H_i}{H_f}\right)$$

Experimental data is needed to calibrate both permeameters. Standardized diagrams for these two types of permeameters can be seen in Appendix A.

Isenring et al. (1990) discuss the testing apparatus used to measure the drainage potential of porous asphalt in Switzerland. The Institute for Transportation, Traffic, Highway, and Railway Engineering (IVT) of the Swiss Federal Institute of Technology developed the "IVT permeameter." A cylindrical tube with putty around the bottom is used to time how long it takes for 2.27 L of water to flow into the porous pavement, or "drainage potential." It is extremely similar to TxDOT's cylindrical field permeameter, specified in Tex-246 (TxDOT, 2004). The tested pavements had void contents ranging from 11 to 22% and layer thicknesses of 28 to 50 mm. The average measured value of new porous asphalt was 3.4 L/min.

Isenring et al. point out that a single point measurement does not represent the true flow rate because the porous mixture is not homogeneous. Nonetheless, it does allow for comparison of the porous asphalt over time. As expected, the project in Switzerland found that the drainage potential decreased with time at all of the testing locations. The greatest reduction in the results was found in the years directly following construction of the overlay. The measurements from multiple sites of two types of porous asphalt (maximum aggregate sizes of 10 mm and 16 mm) from this project are shown in Figure 1.

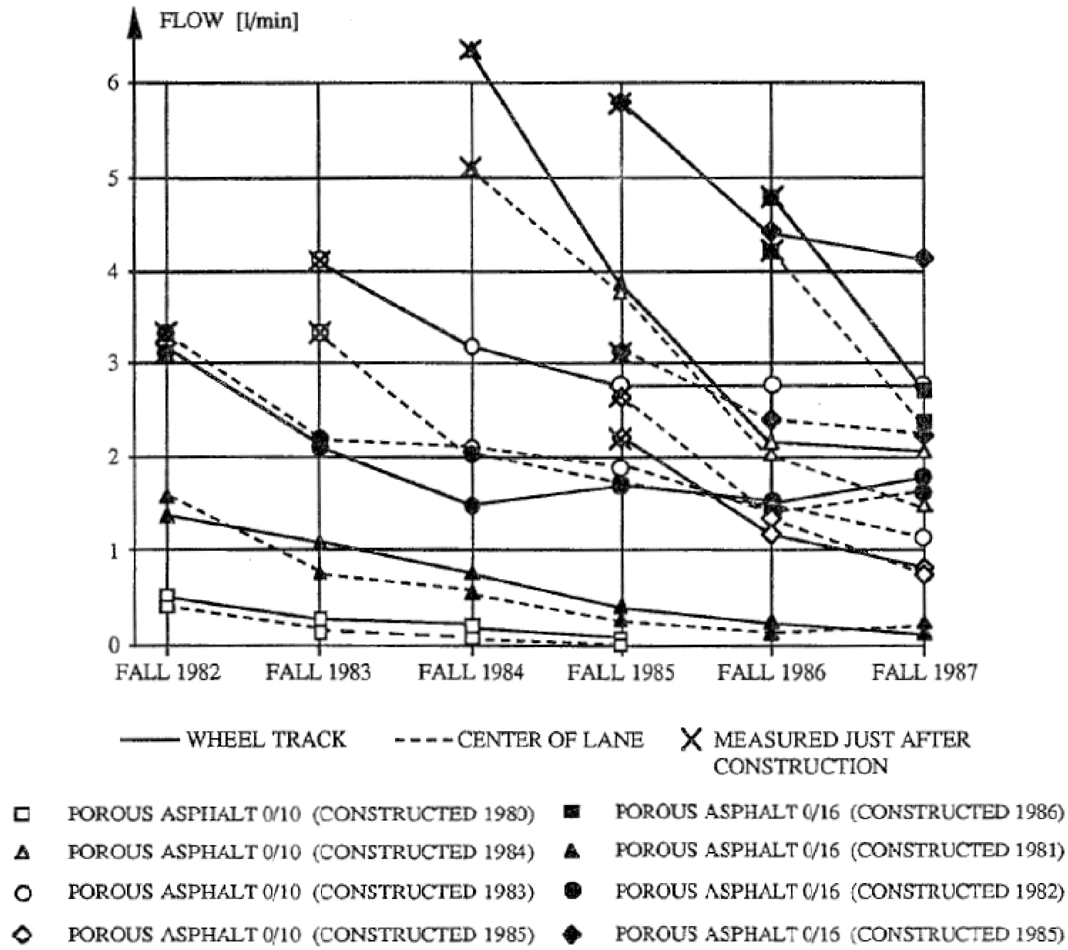

Figure 1 - Drainage potential over time (Isenring et al., 1990)

Ruiz et al. (1990) also perform similar testing on porous asphalt mixtures in Spain. Using an "LCS Drainometer," the time to drain 1.735 L of water is recorded. This test includes a large plate around the bottom of the tube in an effort to prevent the water from surfacing. The drainage time (T) is related to percent void content (H) by Equation 3, which was developed with laboratory tests.

Equation 3

$$H = \frac{58.6}{T^{0.305}}$$

The drainometer test was conducted on porous mixes with void contents less than 20% and mixes with void contents greater than 20%. The mixes with the lower void content experienced a larger decrease in drainage capacity over time. Overlays with initial air voids of 16% and heavy traffic had clogged up after only two years according to the drain time. Other mixes totally clogged at different times up to nine years. Clogged overlays are defined as having a drainage time from the LCS drainometer greater than 600 seconds. The mixes with the void content above 20% had initial drainage times in the range of 15 to 25 seconds. These mixes had longer drainage times after many years of service but did not totally clog or deteriorate. After 9 years, drainage times were still under 300 seconds.

In Denmark, porous asphalt is characterized with a similar instrument called “Becker’s Tube” as described by Bendtsen et al. (2002). Measurements taken immediately after construction and over time, before and after cleaning, were compared to cleaning guidelines for Dutch porous asphalt surfaces from Van Leest et al. (1997), which are shown in Table 1. Once the outflow time gets too high, the porous asphalt is considered clogged and cannot be flushed clean.

Table 1 - Cleaning guidelines from Van Leest et al. (1997)

Degree of Clogging of Porous Asphalt	Outflow time (seconds)	Permeability Class
New	30	High
Partly Clogged	50	Medium
Clogged	75	Low

A study on pervious pavement in Germany by Stotz and Krauth (1994) evaluated the drainage capacity of a highway section based on the percentage of rainfall that ran off the highway. The porous asphalt was 40 mm thick with a porosity of 19%. Comparison of values in the summer and winter revealed that the infiltration rate was approximately 50% larger in the winter than in the summer. Because Germany has cold and damp winters, it is assumed that the greater conductivity is due to fewer losses from high temperatures and dry pavements.

The Georgia DOT uses open-graded friction course as the overlay on all interstate projects. Watson et al. (1998) compare the three different types of OGFC mix designs that have been developed by GDOT: conventional, modified, and European. The conventional mix has a maximum aggregate size of 9.5 mm, while the modified and European mixtures have a max aggregate size of 12.5 mm. The air voids percentage of the mixes ranges from 10-20%. A falling head permeameter is used by GDOT to determine the hydraulic conductivity of the mixes. The conventional mix had the smallest hydraulic conductivity of all of the mixes with an average value of 39 m/day. The European mix, with coarser gradation and largest thickness of 32 mm, had the greatest drainage capacity of approximately 100 m/day.

Birgisson et al. (2006) evaluated the use of OGFC in Florida. Field tests were performed to analyze the latest PFC design. A falling head permeameter was used to measure the hydraulic conductivity of test sections of porous pavement. Hydraulic conductivity tests in and between the wheel paths gave values of 0.81 cm/s and 0.74 cm/s respectively. The hydraulic conductivity was greater in the wheel path even only 2 months after construction. Part of the test section was repaved with lower design asphalt content and similar field tests were again performed two months later. The permeability of the PFC increased overall, and the permeability between the wheel paths was greater with a value of 1.27 cm/s.

Kandhal and Mallick (1999) compared four OGFC mixes with different gradations using Florida DOT's laboratory falling head permeameter. The results show that the mixes with the smallest percentage of fine aggregates (4.75 mm) have the largest hydraulic conductivity. The reported values are shown in Table 2. For comparison, the values found in the literature are presented in Table 3.

Table 2 - Summary of conductivity data from Kandhal and Mallick (1999)

Gradation (percent passing 4.75 mm sieve)	Hydraulic Conductivity (m/day)
15	117
25	88
30	28
40	21

Table 3 - Literature values for PFC characterization

Location	**Age of Pavement**	**Flowrate (Q)**	**Hydraulic Conductivity**	**Void Content**	**Layer Thickness**	**Max Agg. Size**	**Source**
Switzerland	Initial	3.4 L/s	-	11-22%	28-50 mm	10 mm	Isenring et al. 1990
Spain	Initial	-	-	>20%	40 mm	10 mm	Ruiz et al. 1990
Belgium	Design Spec	< 1.4 L/s	-	19-25%	40 mm	-	Van Heystraeten et al. 1990
Germany	3 years	-	17-40 mm/hr	19%	40 mm		Stotz and Krauth 1994
Netherlands	Design Spec	-	-	> 20%	50 mm	11 mm	Van der Zwan et al. 1990
Georgia	Design Spec	-	100 m/day	10-20%	30 mm	12.5 mm	Watson et al. 1998
Florida	2 months		1.2 cm/s		1.4"		Birgisson et al. 2006
Oregon	Design Spec	-	-		50 mm	19 mm	Moore et al. 2001
Florida	Design Spec	-	0.78 cm/s	18-22%	32 mm	10 mm	Bjorn et al. 2006

2.3 Porosity and Measurement Methods

As stated, the drainage capacity of PFC depends greatly on the porosity, or void content. Studies on different mix designs are used to improve the durability and strength of new mix designs, and also to decrease issues associated with clogging. Based on experiences with mixes with different void contents, a study in Spain (Ruiz et al., 1990) found that pavements with greater than 20% void content are more durable than ones with less than 20% void content.

Regimand et al. (2004) developed a method for evaluating air void contents for compacted materials. This method determines the effective air void (EAV) content of a porous sample, which is a subset of the total void content. The EAV content includes the voids that are accessible by water and other environmental fluids and excludes the portion of voids that will not be reached by liquid during the compacted material's use. The EAV parameter is beneficial because it strongly correlates to mixture permeability. To determine the EAV, a compacted material sample is encased in a sealant material of known weight and air is evacuated from the encasement. The vacuum-sealed material is weighed both in air and then under water. After weighing the sealed sample in water, the seal is opened to allow water to contact the compacted sample. This weight should also be recorded. Because the volume of the bag is non-negligible, the dimensions of both the sample and the sample in the bag should also be recorded. With these recorded values, Equation 4 can be used to calculate the EAV parameter.

Equation 4

$$EAV = \left(\frac{\rho_2 - \rho_1}{\rho_2} \right) \cdot 100$$

where ρ_1 = the density of the vacuum sealed compacted material sample
ρ_2 = the density of the vacuum sealed sample after opening the seal under water

Illustrations of the techniques and methods of measuring the EAV content of porous asphalt can be seen in Appendix B: Measuring EAV Content.

In 1999, researchers in Denmark used samples from test sections of porous asphalt surfacing to conduct porosity measurements with image analysis (Bendsten et al., 2002). The Danish Road Institute has been using the image analysis method since the early 1980s. This method of analyzing thin sections was developed to detect clogged pores sooner than would otherwise be possible. Other benefits of image analysis besides porosity and clogging of pores include the size of voids and their distribution. The surfaces of the plane sections are impregnated with a florescent epoxy that fills all of the void space in the section. Porous stones exposed in the thin sections are marked with black ink to avoid any confusion in the analysis. The void content number is determined by looking at the plane section under ultraviolet light. Bendsten et al. (2002) obtained air void contents of 0.182 to 0.224 depending on the size of the aggregates.

2.4 Thickness

Tan et al. (2004) discuss the drainage performance of porous asphalt to establish surface course design requirements. The performance depends on the properties of the asphalt and the longitudinal gradient and cross-slope of the roadway. Because water flows within the porous asphalt structure, the porous overlay must be designed with the different properties in mind. Specifically, the minimum thickness requirement must be substantial enough to avoid sheet flow on the roadway, which negates the safety benefits during rain events. The flow of water over the pavement surface is also known as the water film thickness (Anderson et al., 1998). The smaller the water film thickness is during a rain event, the greater the skid resistance and reduction in hydroplaning potential.

Tan et al. (2004) use a program to model the porous asphalt roadway to determine the effects of cross and longitudinal slopes on the drainage capacity. They found that the cross slope, longitudinal slope, pavement thickness, and width had significant effects on the drainage performance. They were able to develop charts to relate rainfall intensity and required asphalt thickness per width of pavement.

Ranieri (2002) also developed a model for porous pavements that can be used to determine the minimum design thickness. The model predicts the depth of water flowing in the pavement by relating the hydraulic conductivity to the geometric characteristics of the roadway and the rainfall intensity. The drainage capacity is assumed to depend on the porosity and the inclination of the impervious base. Ranieri developed a chart that can be used for pavement design to determine the thickness required to avoid surface runoff. Ranieri (2007) also developed a more detailed design to account for the assumptions used in his original model. He concludes that the hydraulic conductivity of the porous material is not a constant because it changes depending on the flow regime of the draining water. The drainage capacity of the PFC is found to be linearly proportional to the thickness. Ranieri provides design criteria equations with pavement slope, rainfall intensity, permeability, and thickness as variables.

Van der Zwan et al. (1990) review the use of porous asphalt in the Netherlands, where it was first used 30 years ago because of the large amount of precipitation that the Netherlands receives year-round. They use a greater normal thickness size of 50 mm to provide a high water storage capacity to accommodate the rainfall.

OGFC is also the preferred choice for highways in Oregon, according to Moore et al. (2001). The Oregon DOT also specifies a minimum thickness of 50 mm with a maximum aggregate size of 19 mm. Past experiences with anything less than 50 mm overlay thickness resulted in application and compaction problems.

2.5 Runoff Coefficient

The runoff coefficient as used in this report is the fraction of rainwater runoff that actually flows off of a drainage surface. The term “runoff coefficient” also is commonly applied to one of the terms in the rational equation. In this usage, it is a coefficient which relates runoff rate to rainfall intensity. Although the values for the different applications are similar, the values are not interchangeable and should not be confused.

Pagotto et al. (2000) determined runoff coefficients from conventional and porous asphalt over 1-year study periods and found a higher coefficient for PFC. PFC an average runoff coefficient of 0.98 compared to the 0.84 measured for conventional asphalt pavement at the same site before the overlay was installed. It was speculated that the increase is due to the reduction in spray behind vehicles, which can transport this water off the roadway and beyond the monitoring location.

2.6 Peak Damping

Pagotto et al. (2000) also investigated the effect of conventional and porous pavement on the hydraulic behavior of highway runoff. These experiments found that porous pavement had response times about twice as long as the conventional pavement under similar conditions. It was shown that the porous pavement had smaller peak discharges and longer total discharge time. These results are experimental and only the difference in response times was statistically significant.

Stotz and Krauth (1994) also proved that peak effluent flows were lower from the porous pavement. Ranchet (1995) found similar results from his comparison of porous asphalt and conventional pavement. Porous asphalt had longer runoff times of 12 to 23 hours. Hydrographs revealed that the peak flows from the porous asphalt ranged from 25% to 79% of the peak flow from conventional pavement.

Pagotto et al. (2000) found that higher volumes of water came from the porous asphalt than the conventional pavement as there were consistently higher runoff coefficients. This could be attributed to the decrease of water spray from the porous asphalt, and therefore less evaporation and wind losses.

Stotz and Krauth (1994) found the opposite that lower volumes of water came from the porous asphalt than the impermeable runoff volumes. Ranchet (1995) similarly found that porous asphalt had an average runoff volume reduction of 20%. These results could be the explanation for the reduced peak flows previously discussed.

Chapter 3. Water Quality Benefits

3.1 Introduction

While there is not a great amount of information on this subject, a few studies have discussed water quality benefits of porous asphalt. The porous pavement acts like a filter and decreases the pollutant concentration in the runoff (Pagotto et al., 2000). However, the filtered particles remain within the pores of the pavement until the pores are clogged or until the particles are pushed out or removed through vacuum cleaning. This aspect is one of great interest and requires further research.

3.2 Pollutant Reduction

Berbee et al. (1999) studied the effects of impervious and pervious asphalt in the Netherlands where polluted highway runoff is a problem. The study involved testing runoff samples from two highways with similar characteristics except that one was conventional (impervious) asphalt and the other had a porous asphalt overlay. The results showed that the pollutant concentrations in the runoff from porous asphalt were significantly lower than in the runoff from the impervious asphalt. The concentrations of the heavy metals (lead, copper, and zinc) in the porous asphalt runoff were much lower than in the runoff from impervious asphalt. The ranges of concentration values found in this study are compared in Table 4. The greatest pollutant reduction was the suspended solids concentration being reduced by a factor of 10.

Table 4 - Concentration range comparison from Berbee et al. (1999)

Pollutant	*units*	*Impervious*	*Pervious*
Suspended Solids	mg/L	153 - 354	2 - 70
Nitrogen, Kjeldahl, Total	mg/L	2 - 3	0.3 - 0.5
Chemical Oxygen Demand	mg/L	143 - 149	16 - 18
Chlorine	mg/L	< 1	< 1
Copper	µg/L	91 - 163	14 - 107
Lead	µg/L	51 - 106	2 - 22
Zinc	µg/L	225 - 493	18 - 133
Cadmium	µg/L	0.8 - 0.9	0.1

Berbee et al. (1999) also investigated the effect of particle settling in runoff from both types of asphalt. Settling provides significant reduction of heavy metal concentrations usually found in highway runoff. Due to the decrease in suspended solids in the porous asphalt runoff, settling had a greater effect on the runoff from impervious asphalt.

Pagotto et al. (2000) also studied the effects of different types of pavement on the quality of highway runoff. The site of the experiment was a section of a highway in France that originally had conventional pavement but was replaced with a porous asphalt surfacing. Keeping the parameters as constant as possible, the data collected over the different pavement time periods could be compared and any differences could be attributed to the type of asphalt. The datasets were compared for the same length time periods with similar total rainfall and with all other variables comparable as well. The results showed a significant reduction in total suspended solids (TSS) from a mean value of 46 mg/L to 8.7 mg/L (an 81% reduction). Total metals were all reduced: Pb by 78%, Cd by 69%, Zn by 66%, and Cu by 35%. The concentration values are shown in Table 5. All of these metals had high retention in the particulate form, which is expected because all of the metals, except for Cu, are present mainly in the particulate form. Some dissolved metals (Zn and Cd) were also reduced by about 60%. Hydrocarbons were reduced by 92%.

Table 5 - Concentration comparison from Pagotto et al. (2000)

Pollutant	*units*	*Impervious*	*Pervious*
Suspended Solids	mg/L	46	8.7
Nitrogen, Kjeldahl, Total	mg/L	2.1	1.2
Chemical Oxygen Demand	mg/L	80	80
NO3	mg/L	6.7	2.1
Chlorine	mg/L	18	16
Hydrocarbons, Total	mg/L	1.2	0.09
Copper	µg/L	30	20
Lead	µg/L	40	8.7
Zinc	µg/L	228	77
Cadmium	µg/L	0.88	0.28

Pagotto et al. (2000) assume that all of the removed solids and sediments are retained in the porous asphalt. The mechanisms for pollutant removal are discussed but not clearly understood. These mechanisms include filtration, adsorption onto the pavement (or materials in the pores of the pavement), and possibly biosorption or biodegradation.

Stotz and Krauth (1994) analyzed runoff from a section of porous asphalt in Germany to compare summer and winter pollutant concentrations. All pollutants, except lead and solid iron, had higher concentrations in the winter than in the summer. Some of these concentration increases could be attributed to winter maintenance procedures. As described by Legret and Pagotto (1999), these pollutants are considered “seasonal” and generally include suspended solids, chlorides, sulfates, and heavy metals from deicing salt.

Colandini et al. (1995) analyzed the clogging material of porous pavement to determine the pollutant concentrations and particle size distribution. The clogging material, consisting of mostly fine and course sand, was removed through a cleaning process of high-pressure water spray and immediate suction of the resulting sludge. The clogging material was found to have high concentrations of the heavy metals copper, zinc, cadmium, and especially lead. These concentrations reported in mg/kg are shown in Table 6.

Table 6 - Clogging material concentrations from Colandini et al. (1995)

Pollutant	Concentration by particle size (mg/kg)	
	less than 2mm	less than 125 µm
Lead	1258	1474
Copper	320	438
Cadmium	2.01	3.25
Zinc	796	975

This study also found that course particles were less contaminated than fine particles (sizes less than 40 µm). The fine particles represented 25% of the mass of clogging particles but contained 40-50% of the total heavy metal contents.

Ranchet (1995) studied the impact of porous pavements on water quality and quantity in France by monitoring an urban site and freeway site for a two-year period. The urban site had both porous pavement sections and impervious stone-matrix. Upon comparison to the impervious pavement, the porous pavement had pollutant reductions of lead by 87% and hydrocarbons by 43%. The other site consisted of a divided freeway with porous asphalt in one direction and conventional pavement on the other direction. The concentrations found at this site are compared in Table 7.

Table 7 - Concentration comparison from Ranchet (1995)

Pollutant	*units*	*Impervious*	*Pervious*
Suspended Solids	mg/L	61	57
Nitrogen, Kjeldahl, Total	mg/L	1.4	2.3
Hydrocarbons, Total	mg/L	3.2	1.7
Copper	µg/L	16	6
Lead	µg/L	< 2	< 1
Zinc	µg/L	190	63
Cadmium	µg/L	< 0.1	< 0.1

The greatest pollutant reductions were zinc, copper, and hydrocarbons. For this site, the orientation of the freeway must be considered as the wind blows across the highway and is likely to transfer pollutants from the impervious lanes onto the pervious asphalt pavement.

A stormwater quality study in Israel (Pacific Water Resources, 2004) was conducted over a 10-month period on a highway with sections of porous pavement located near populated areas. The highway has a channel that runs between the edge of the pavement and the barriers on the side of the road. The channel overflows into containment basins. The water quality monitoring sites were located at porous pavement runoff areas and traditional pavement areas for comparison. The samples were taken at the edge of pavement, top of the channel spillway, and the containment basin outlet. A comparison of TSS concentrations at the edge of pavement sampler and the channel spillway show a decrease in TSS over the spillway due to settling in the channel. Dissolved zinc and copper concentrations were similar at both locations. Due to particle settling, only dissolved species are accurately compared in this study. Upon comparison of washoff concentrations from both pavement types, there was not a significant reduction in concentrations from the porous pavement. This was attributed to the channel that runs next to the roadway and easily collects and transports sediment.

Another part of this study included road dirt accumulation comparisons and cleaning practice effects, which are also discussed in Chapter 3. The road dirt testing was performed by hand-vacuuming areas of pavement to collect the dirt in the pavement. While there was not much difference in the accumulated road dirt in the two types of pavement, there was a difference in the particle size distribution. Particles from porous pavement were coarser than particles on traditional pavement. As expected, runoff from cleaned pavements of both types had lower pollutant concentrations than pavements that were not cleaned. The statistical difference is not significant as the average values are only slightly lower, but the results suggest that cleaning the pavements reduced the frequency of high concentrations.

While all of these studies were conducted on roadways of different types and traffic loads, some trends are noticed. Overall, total suspended solids were reduced from the runoff from porous asphalt by up to a factor of 10. Heavy metals concentrations were also consistently lower from the porous asphalt. A summary of pollutant concentration ranges found in the literature is provided in Table 8.

Table 8 - Summary of literature data of pollutant concentrations in highway runoff

Pollutant	*units*	*Impervious*	*Pervious*
Suspended Solids	mg/L	46 - 354	2 - 70
Nitrogen, Kjeldahl, Total	mg/L	1.4 - 3.0	0.3 - 2.3
Chemical Oxygen Demand	mg/L	80 - 149	16 - 80
NO3	mg/L	6.7	2.1
Chlorine	mg/L	< 1 -18	< 1 - 16
Hydrocarbons, Total	mg/L	1.2 - 3.2	0.09 - 1.7
Copper	µg/L	16 - 163	6 - 107
Lead	µg/L	2 - 106	1 - 22
Zinc	µg/L	190 - 493	18 - 133
Cadmium	µg/L	0.8 - 0.9	0.1 - 0.28

Chapter 4. Maintenance

4.1 Introduction

The service life of porous asphalt depends not only on the deterioration of the overlay, but also the drainage capacity (Fwa et al., 1999). Only a few studies have been conducted on the long-term behavior of porous pavements; such studies are necessary to help determine the functional life of PFC. Because the pores in the overlay collect particles and are susceptible to clogging, some transportation authorities perform regular maintenance on the porous overlays (FHWA, 2005). This chapter discusses the causes of deterioration and commonly used maintenance procedures.

4.2 Causes of Deterioration

Graff (2006) discusses different aspects of asphalt pavement preservation, in particular the most common causes of deterioration. Asphalt is made from by-products of refining crude oil. Over the past few decades, overall asphalt quality has declined due to better refining of crude oil. To offset the decreasing quality of asphalt, it is now common to add materials to asphalt mixes in order to improve the properties of the asphalt.

According to Graff (2006), two main physical factors lead to the aging of asphalt: ultraviolet (UV) light and heat. The surface or the chip seal of overlay ages first because of its exposure to UV light and heat. Porous asphalt allows more light penetration, which results in faster aging than regular asphalt. The high temperature that porous asphalt is manufactured and placed under also contributes to a shorter service life.

All pavements are also subject to stresses that cause failure in the form of cracking or raveling. Thermal expansion causes internal stresses in porous asphalt because the coefficients of expansion are different for the aggregates and the asphalt. Traffic loading and expansive soils also cause internal stresses. As the asphalt ages, it cannot handle these stresses as well as new asphalt. Water in the pores of the pavement, combined with traffic loading and temperature changes, also creates extreme internal pressures on the pavement (Graff, 2006).

4.3 Clogging

Particles in the runoff are often collected by the pores of the pavement because porous asphalt allows surface runoff to flow within it. The particles are generally sand particles or debris released from tires (Fwa et al., 1999). The drainage capacity of the pavement is drastically affected by the clogging of the pores (Van Heystraeten and Moraux, 1990). Therefore, clogging of the pores will decrease the benefits of wet weather traction and noise reduction. Regular maintenance is often required to ensure adequate drainage capabilities over time.

In many locations, porous asphalt is only used on high-speed roadways to help avoid clogging problems. The tires push water into the voids and suck it back out as they drive over the surface. At high speeds, this helps to clean the pores at the surface. For this reason, it is not recommended to use porous asphalt on low-volume or slow-traffic roadways (Van Heystraeten and Moraux, 1990). Also, less traffic results in more debris on the roadway as there is not enough wind created by the cars to keep the roadway clean (NCHRP, 2000).

Fwa et al. (1999) performed laboratory testing on porous asphalt samples to evaluate the clogging potential. The testing involved manually clogging the porous samples with soil and measuring the permeability of the sample throughout the clogging process. The permeability coefficient (k) in this experiment was calculated with an equation based on Darcy's law. The results consistently showed that the permeability coefficient decreased quickly in the beginning of the test and then asymptotically approached a terminal value, as shown in Figure 2.

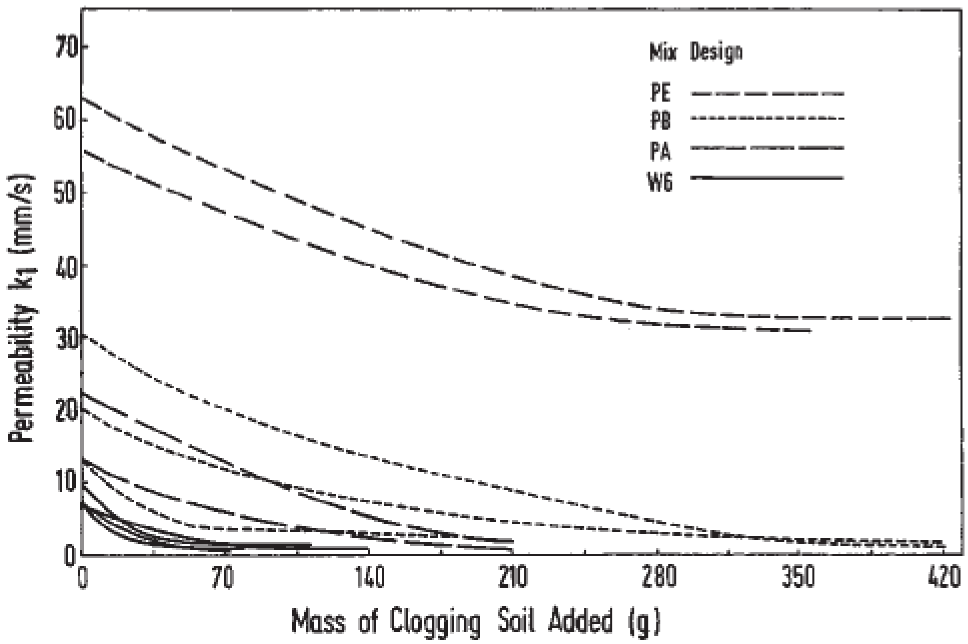

Figure 2 - Deterioration of permeability coefficient k (Fwa et al., 1999)

The curves for the deterioration of k are comparable with an average of 33 mm/s overall reduction of k from the different initial values. This information could be used in design to establish a required initial permeability depending on the expected terminal value.

According to NCHRP (2000), larger aggregate sizes are being specified because they create larger air voids. Larger voids are less likely to clog because they are cleaned by the pressure from traffic during rain events. Issues associated with clogging from de-icing materials in the winter are discussed in Section 4.6.

4.4 Cleaning Machines

Different techniques are used to clean porous pavement around the world. One major and recurrent technique is the use of cleaning machines.

The most common type of these cleaning machines spray water at high-pressures into the overlay and then vacuum out the resulting sludge. This process is referred to as "captive hydrology." According to Newcomb and Scofield (2004), pressure cleaning is recommended on fine-graded open-graded overlays in Europe once or twice a year. Bäckström and Bergstrom (2000) recommend cleaning the porous asphalt every 2 to 4 years with this high-pressure water cleaning.

The stormwater quality study in Israel (Pacific Water Resources, 2004) tested the performance of a cleaning machine that used the "captive hydrology" technique. The cleaning machine used in Israel was supplied by Netivey Hamifratz Ltd. (NH). It was tested on its pick-up performance by cleaning a test area with a known weight of soil applied over it. The NH machine was found to have very high pick-up performance of 99.7%.

A report from the Public Work Research Institute (PWRI, 2005) in Japan gives some insight on porous asphalt cleaning machines. The first types of machines developed in Japan, similar to ones in Europe, had to clean at very slow speeds (1 km/hr) and attempted to fully recover the pavement. The newer machines can run at greater speeds (10-20 km/hr) and are designed to be used more frequently to maintain the function of the pavement.

One machine, the "Spec-Keeper," sprays water into the pavement and creates high pressure air around the cleaning area to push the water back out of the pavement with the collected particles. The water and particles are then separated so the water can be reused. A schematic of the Spec-keeper's cleaning process is shown in Figure 3 and a picture of the machine is shown in Figure 4.

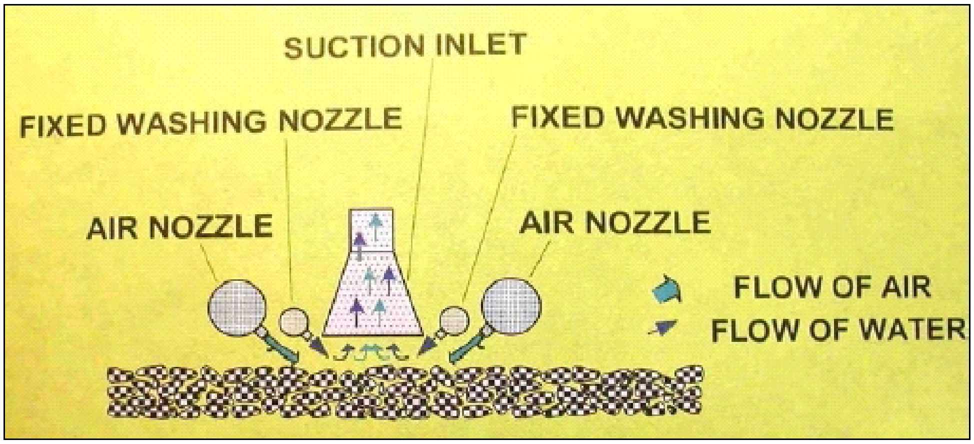

Figure 3 - The cleaning process of the Spec-Keeper cleaning machine (PWRI, 2005)

Figure 4 - The Spec-Keeper cleaning machine in Japan from PWRI (2005)

Another machine uses high-pressure air only to loosen the clogging particles. The particles are then vacuumed up. The machine blows air from both sides of the pavement and a vacuum in the middle collects the dirt and dust from the pavement. This machine runs at an average speed of 20 km/hr. Experiments on the frequency of use of this machine found that cleaning should be conducted as often as possible to maintain the most effective function of the pavement. The machine is shown in Figure 5.

Figure 5 - Cleaning machine with high-pressure air only from PWRI (2005)

Upon comparison of the different types of machines, the original slow-speed machines collected the most mass of particles per area and had to be used with the lowest frequency. However, the cleaning costs were much greater. The high-pressure water and air machines had lower efficiencies but were much more cost effective. An overview in effectiveness and costs of the three types of cleaning machines is given in Table 9.

Table 9 - Cleaning machine summary from Japan at PWRI (2005)

Cleaning Machine	Collected mass/cycle (g/m^2)	Frequency (times/year)	Cleaning Costs ($\$/m^2$)	Cleaning Costs ($\$/m^2/year$)
Conventional slow speed	100	3	8.55	25.65
High speed with high-pressure water	10	30	0.27	8.18
High-pressure air blow	6	50	0.10	4.96

A study was conducted by the Federal Highway Administration (FHWA, 2005) to learn more about common practices with noise-reducing pavements in European countries that have more experience with porous pavements. Different general and winter maintenance methods are used according to the policy priorities and environment conditions. In most countries, porous pavements are cleaned in order to maintain a certain acoustic ability (noise reduction) affected by clogging. A summary of each country's policy follows.

In Denmark, porous asphalt is cleaned with high-pressure water spray (125 psi) followed by vacuuming. Cleaning is performed three months after construction and then semiannually. Experience at the Danish Road Institute (DRI) has found that the pavement can become too clogged to clean effectively after two years if regular cleaning is not performed.

In the Netherlands, porous pavements are also cleaned semiannually with a captive hydrology cleaning machine. The Dutch have found that the noise reduction and drainage benefits are reduced immediately after cleaning because the clogging material is brought to the surface. However, after a short time these properties improve to an unknown extent. Porous pavements are not used in urban areas because of the problem with clogging and questioned effectiveness of cleaning.

Porous pavements in France are not cleaned as the French have found cleaning to be ineffective. The mixes are designed to avoid clogging and the expected service life is greater than ten years.

4.5 Fog Sealing

Fog sealing is a process where asphalt is sprayed onto an existing pavement surface. Fog seals are used to replace asphalt that has deteriorated at the surface due to weathering (NCHRP, 2000). They can also be used to stop the pavement from raveling or reduce aggregate loss. Fog seals are applied by spraying dilute asphalt emulsion over the surface of the pavement. The fresh application of asphalt can lengthen the service life of the pavement and even seal small cracks in the pavement. However, applying too much asphalt can result in slick pavement surfaces and tracking of excess asphalt (Caltrans, 2003). Fog seals reduce the air void content of open-graded pavements. Some transportation authorities apply fog seals every 3–5 years as a part of surface maintenance (NCHRP, 2000).

4.6 Winter Conditions

Winter maintenance is a commonly noted disadvantage of porous asphalt. A few studies on the performance of PFCs under winter conditions have been conducted.

Bäckström and Bergstrom (2000) studied drainage through porous asphalt in freezing temperatures and snowmelt conditions. Laboratory experiments were performed in a climate room to determine the infiltration rate through porous asphalt samples at cold temperatures. The results indicated that the infiltration rate decreased significantly at freezing temperatures and was nearly zero at -5ºC (23ºF). To simulate snowmelt conditions, periods of freezing temperatures were combined with rainfall. After a few days of these conditions, the infiltration rate decreased to about 90% of the initial infiltration rate.

Shao et al. (1994) developed a model to predict the state of porous asphalt pavement surfaces. The thermal properties of the porous overlay depend on the porosity of the mixture. A higher porosity, or more air voids, creates a faster thermal response of the asphalt to the ambient air temperatures as it is an open structure. The air in the pores insulates the mixture from heat from the road sub-layer or ground. Water is retained in the pores of the pavement after wet conditions and incoming heat from the sub-layer is first consumed by evaporation of this water. Therefore, the surface of the pavement reaches freezing temperatures faster and stays below freezing longer than conventional pavements. Porous asphalt studies discussed by van der Zwan et al. (1990) also found similar results. Experience in France (FHWA, 2005) found that porous pavements reached freezing temperatures about 30 minutes before conventional pavements.

The "Icebreak Model" developed by Shao et al. (1994) was validated against actual temperature measurements at a site in England. The model successfully predicted 90% of the occurrences of below freezing temperatures at the pavement surface. Predicting freezing temperatures of the porous road surface would allow highway authorities to react in time and take appropriate actions. Therefore, road safety would not be compromised in winter conditions.

The pores in the pavement also affect the application of salt for de-icing in the wintertime as a portion of the salt will simply run into the pavement. This problem can be dealt with by increasing the frequency of salt applications on the roadway and also using wet salt instead of dry salt (Van der Zwan et al., 1990).

A survey of DOT districts in Texas found that sand is the most commonly used material even though it causes clogging of the pavement. Anti-icing chemical agents, instead of de-icing agents, are the most effective winter maintenance procedure in these districts. Pre-wetted salts and chemicals are effective if they are applied at the right time (Yildirim et al., 2006).

Pre-wetted salt is the most effective form of salt application for winter maintenance of porous asphalt in Europe. This type of salt application will stick to the porous surface instead of draining into the pavement and clogging the internal pores. This allows it to be useful for more reasonable periods of time. Many users expect that the winter maintenance on the porous asphalt will require twice as much salt as the original dense-graded asphalt (Newcomb, 2004).

Camomilla et al. (1990) advise using almost three times the amount of salt used for conventional pavements to prevent icy conditions on roadways in Italy. Snowplow efforts are most effective shortly after snowfall, before the snow penetrates the pores. Because the snowplows push some snow into the pores, which can easily freeze, salt application is especially important following the snowplows. Experiences in Oregon also reveal that PFC should not be used in areas where snowplows are frequently used because they often damage the surface (Moore et al. 2001).

In Denmark, the DRI uses a wetted-salt solution with calcium chloride to allow an even distribution of the solution. Experience has found that porous asphalt winter maintenance increases the salt use by 50%. The DRI also recommends avoiding short sections of porous asphalt as the change in pavement type can startle drivers and make maintenance changes difficult. (FHWA, 2005)

In Italy, highway runoff of salt brine is an environmental concern, and therefore, a combination of magnesium and calcium is used for winter maintenance on the porous pavements (FHWA, 2005).

The Switzerland summary of porous asphalt performance in winter conditions by Isenring et al. (1990) found that porous asphalt did not behave worse than conventional pavements. They concluded that any disadvantages of porous asphalt in the winter can be avoided by intensive winter maintenance. The same conclusions were drawn from porous asphalt use in Belgium (Van Heystraeten and Moraux, 1990).

Chapter 5. Miscellaneous Properties

5.1 Introduction

An overview of other properties of porous asphalt that are not directly related to this research project as discussed in this chapter.

5.2 Friction Coefficient

When the water from rainstorms is able to drain through the pores of the pavement, the friction coefficient between the pavement and vehicle tires is increased (Watson et al., 1998).

Skid properties were tested in a Switzerland study described by Isenring et al. (1990). Skidding properties of porous asphalt at high speeds were much better than conventional pavements because of greater skid resistance. This is due to the high macro-texture (large pores) of PFC, which is important at high speeds. There was less skid resistance at lower speeds because the micro-texture is lacking. The skid properties of PFCs are considered a benefit because skid resistance is critical at high speeds and not nearly as much at low speeds. Skidding properties were lower immediately after construction than after a year. This is caused by the binder coating on the surface aggregates that wears off after some use—approximately one year.

Research conducted in the Netherlands described by Van der Zwan et al. (1990) confirmed that better skid resistance in the rain generally decreases the number of accidents on the roadway. Even though porous asphalt has been found to have an overall lower skid resistance in dry conditions than conventional pavement, the skid resistance is high enough in these conditions that it not disadvantageous.

5.3 Noise Reduction

Noise reduction is a widely accepted advantage of PFC and in some locations, such as cities in Europe, it is the reason for implementation. Noise reduction is a very complex, multi-faceted subject that is very difficult to adequately/clearly address in a few paragraphs. Consequently, the reader is directed to reports by Trevino and Dossey (2006) and Trevino-Frias and Dossey (2007). These reports include descriptions of work done by other U.S. DOTs as well as several western European countries in the area of noise reduction.

5.4 Mix Design

The main components of PFC design are selection of materials, gradation, compaction, and binder. The Federal Highway Administration developed an original mix design for PFC in 1974, and since then DOTs have modified or developed their own mix designs.

Commonly reported performance problems in the past include draindown, raveling, and short service lives. Draindown is when the binder separates from the aggregates during transportation or in-place from high temperatures. According to NCHRP (2000), raveling is the most typical failure, which occurs when the asphalt binder becomes brittle. Raveling usually occurs quickly, within a couple months, which is not much time to prepare a new overlay. In recent years, improving the durability of PFCs has been the focus of many studies, resulting in better materials and mix designs. Modified asphalt binders make the mix stronger to avoid raveling and increase service life (NCHRP, 2000).

Kandhal and Mallick (1999) recommend a “new generation” mix design based on laboratory experiments that tested the draindown, permeability, rutting, and moisture susceptibility of PFC samples. They recommend no more than 20% passing the 4.75 mm sieve to achieve a strong yet permeable mix. Using polymer-modified binders and adding fibers to the mix minimizes draindown of the binder, abrasion loss and rutting, and therefore increases the durability of the PFC. These modifications also decrease susceptibility to moisture problems, which makes them especially helpful in cold climates.

Open-graded large stone asphalt mixtures are more durable and stronger than conventional OGFC (Mohammad et al. 2000). “Large stone” is defined as having maximum aggregate sizes from 25 to 63 mm. Laboratory testing of a large stone mixture with 37.5 mm maximum aggregate size found that the stone-on-stone contact created with large aggregates provides more strength in the pavement.

Two-layer OGFC or porous asphalt is comprised of a course bottom layer and a smaller stone mix in the upper layer. As defined by Kandhal (2004), the lower layer aggregates range from 16 to 22 mm, while the upper layer ranges from 5 to 8 mm. This configuration helps to prevent the overlay from clogging during its service life.

Chapter 6. Survey of DOTs

6.1 Introduction

In an effort to better understand the common practices associated with porous asphalt, a survey was conducted on DOTs in the United States. The results are summarized in the following sections.

6.2 National Survey

The survey was distributed to state DOTs and some international agencies via electronic mail. The survey covered the hydraulic design, testing, maintenance, and water quality benefits of PFC overlays. The purpose of the survey was to collect information on the design of PFC and current practices of transportation authorities. The survey specifically covered PFC (or OGFC) overlays used on roadways with an impervious base. Forty-six state DOTs responded to the survey. The survey consisted of five questions about PFC use; the responses to each question are discussed here.

6.3 PFC Use

Out of the 46 state DOTs that responded to the survey, 17 (37 %) states currently use PFC on a regular basis. Eight (17 %) more states are currently testing PFC by evaluating test sections over certain time periods. The remaining 21 (46 %) state do not currently use PFC. Of these states, eight (17 %) have used PFC in the past and have discontinued its use due to poor performance. Figure 6 is a map of the states categorized according to their PFC use.

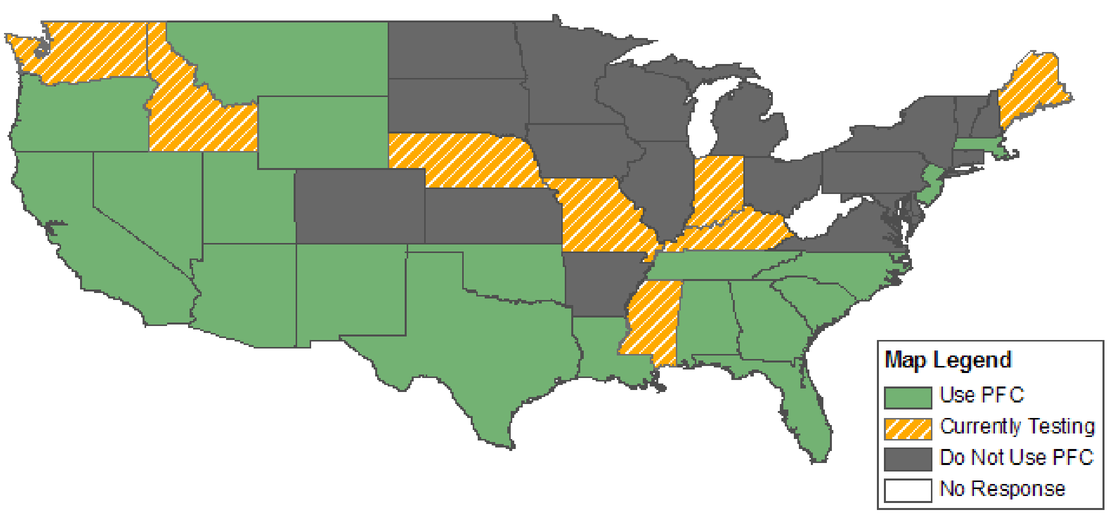

Figure 6 - Survey Results on PFC Use

The state DOTs currently using or testing sections of PFC mentioned noise reduction, safety benefits (reduced water spray), and increased friction as reasons for use or study. The state DOTs that no longer use PFC most commonly noted issues associated with cold climates, such as icing problems, increased maintenance requirements, and raveling due to icy conditions.

6.4 Hydraulic Testing

Only one state performs a hydraulic test of the porous asphalt. Mississippi DOT conducts a falling head permeability test on their test section at approximately one-year intervals for research purposes. This DOT also tests the pavement with an in-house, laboratory falling head method to ensure adequate permeability before installation. The hydraulic conductivity must exceed 30 meters/day. None of the other state DOTs perform any direct hydraulic testing.

6.5 Hydraulic Design Guidelines

Most states do not have any specific hydraulic design guidelines. Most of the DOTs mentioned the gradation, air void percentage, normal pavement cross slope, and compaction limitations as the only design guidelines used. The Tennessee DOT follows the guidelines in the National Asphalt Pavement Associations publication IS-115, "The Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses." The Oregon DOT mentioned the following guidelines: ensure that proper slopes are maintained for drainage, do not pave over the top of an OGFC, and ensure no "dams or bathtubs" are created that would block the drainage path of the OGFC. The South Carolina DOT increases the pavement thickness when paving sections with multiple lanes to ensure drainage through the OGFC.

6.6 Maintenance

Out of the 46 state DOTs, only one state (Idaho) had performed maintenance with a vacuum truck. The Idaho DOT no longer uses the vacuum truck because they found it to be inefficient.

Most states use the PFC only on high-speed and high-volume roads where the traffic is effective in keeping the pavement relatively clean. Some states mentioned that the pavement eventually does clog, become less effective, and must be replaced. Other states stated that cleaning was not necessary because the roads are resurfaced after about six years anyway.

The Nebraska Department of Roads fog seals its porous pavements to prevent raveling and have found that fog sealing does notably decrease the permeability of the pavement. New Mexico DOT also applies fog seals. Maintenance in the form of patching is usually done with dense-graded asphalt and not an open-grade mix. South Carolina DOT noted that the dense-graded asphalt patches block drainage in some situations.

Winter maintenance is a commonly noted issue. Most states try to avoid sand and use a liquid deicer instead, which must be applied more often than conventional salt. Plowing can damage the pavement, as can studded tires.

6.7 Water Quality

None of the state DOTs have studied or determined any water quality benefits. The Oklahoma DOT observed cleaner run-off but did not measure or document anything. A few DOTs showed interest in water quality benefits from PFC and have discussed potential research on this topic.

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Appendix A: Permeameters

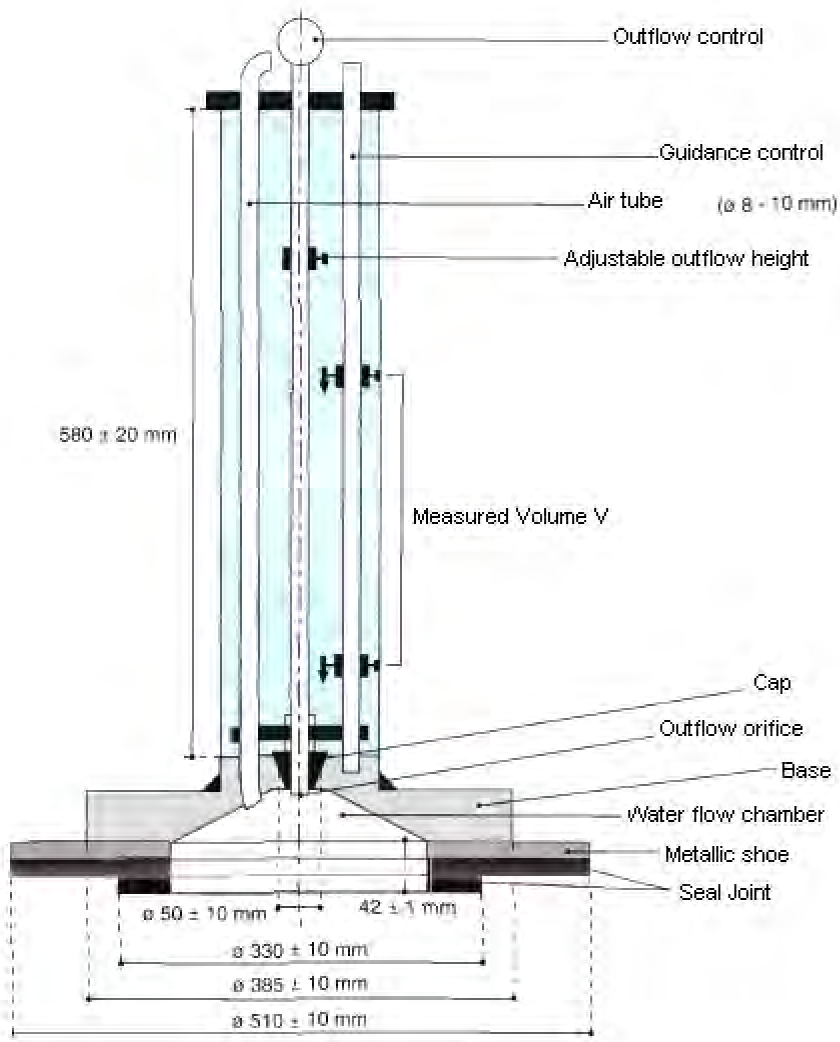

Figure A1: In-Situ Field Permeameter (Di Benedetto et al., 1996)

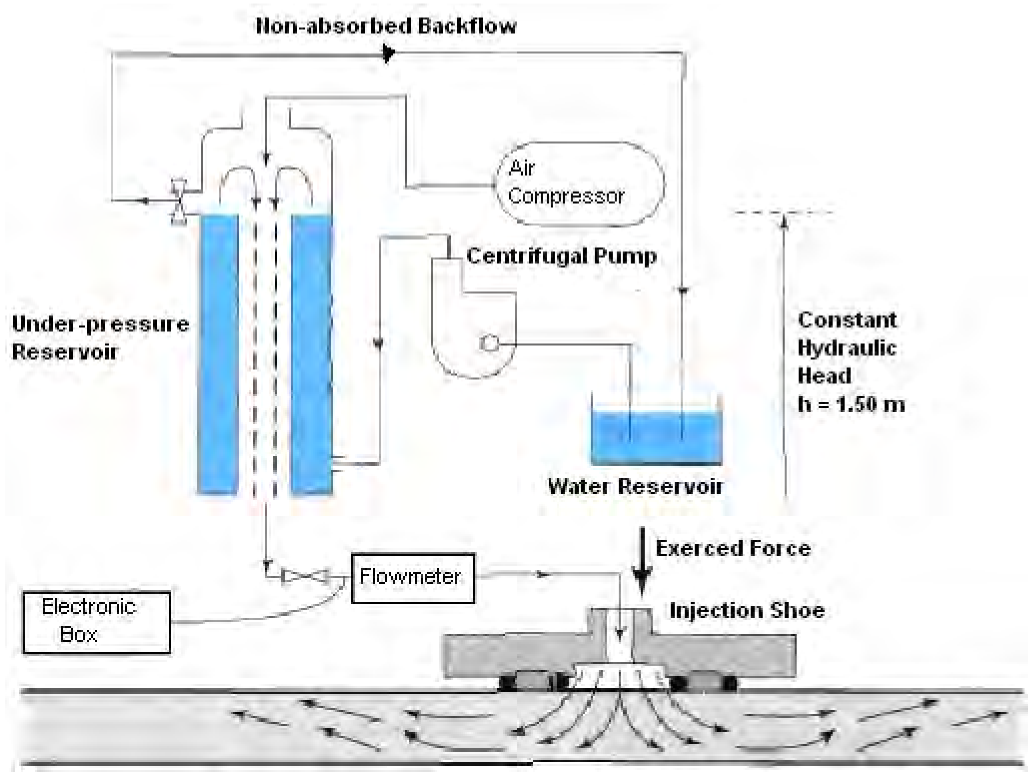

Figure A2: Constant Head—Automatic Permeameter (Di Benedetto et al., 1996)

Appendix B: Measuring EAV Content

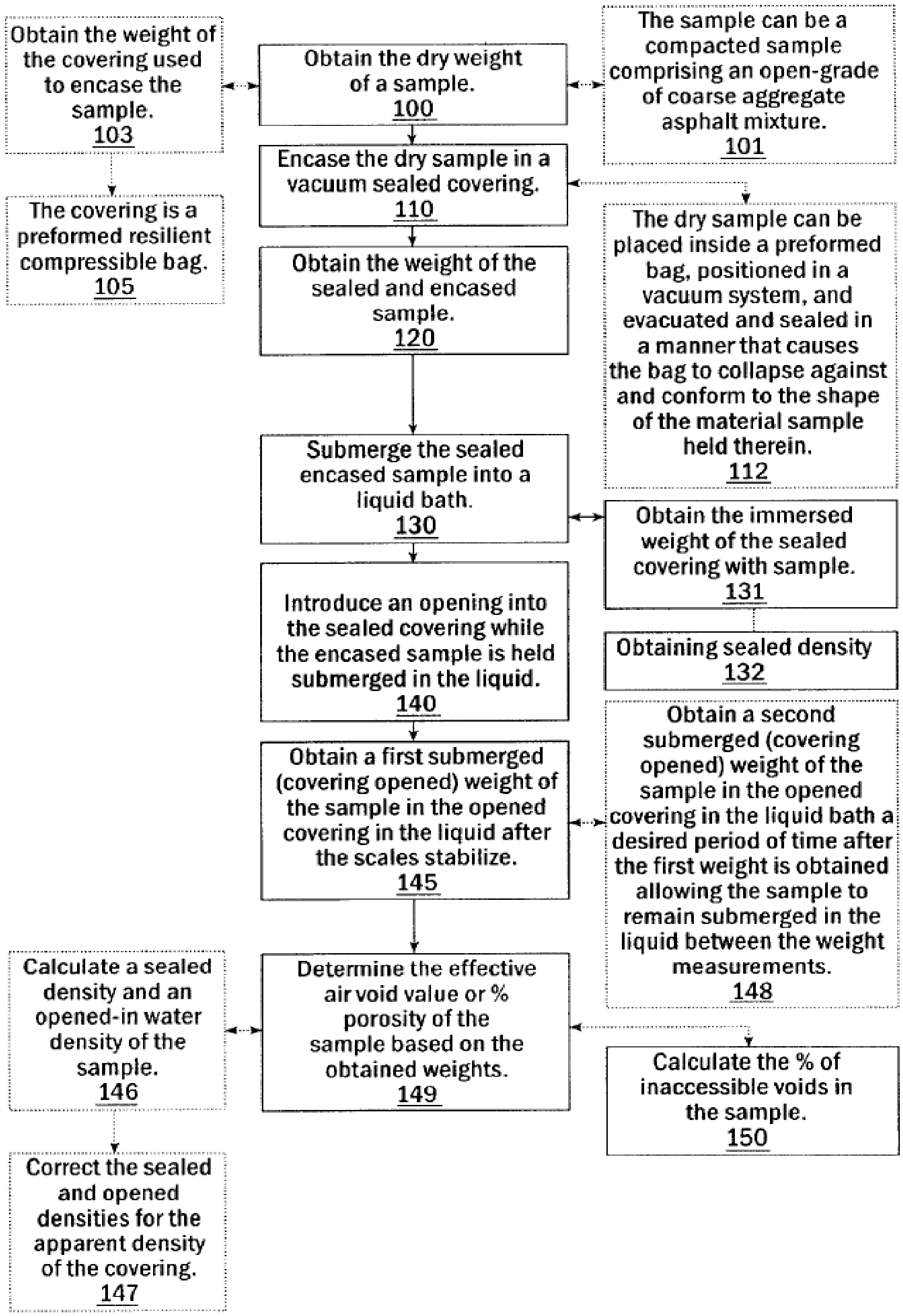

Figure B1: Determination of the EAV content according to Regimand et al. (2003)

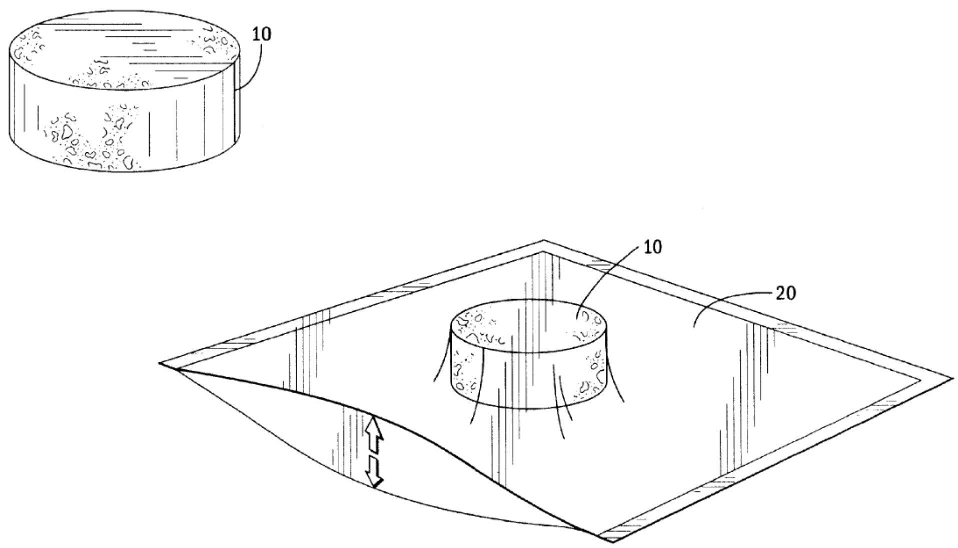

Figure B2: Sample and its plastic bag (Regimand et al., 2004)

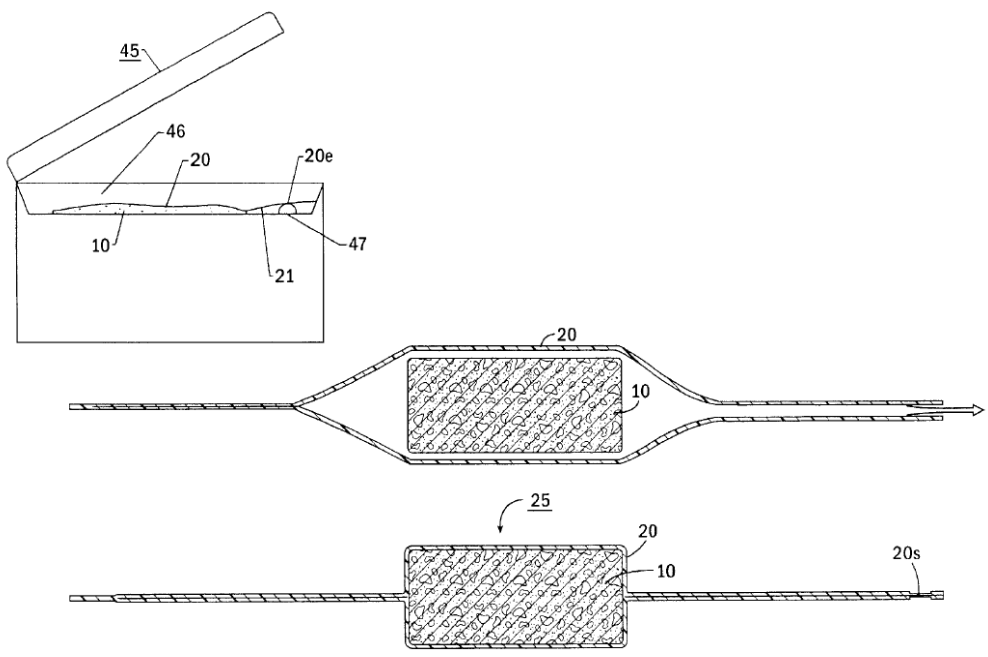

Figure B3: Core-lock air vacuum and the core sealed in plastic bag (Regimand et al., 2004)

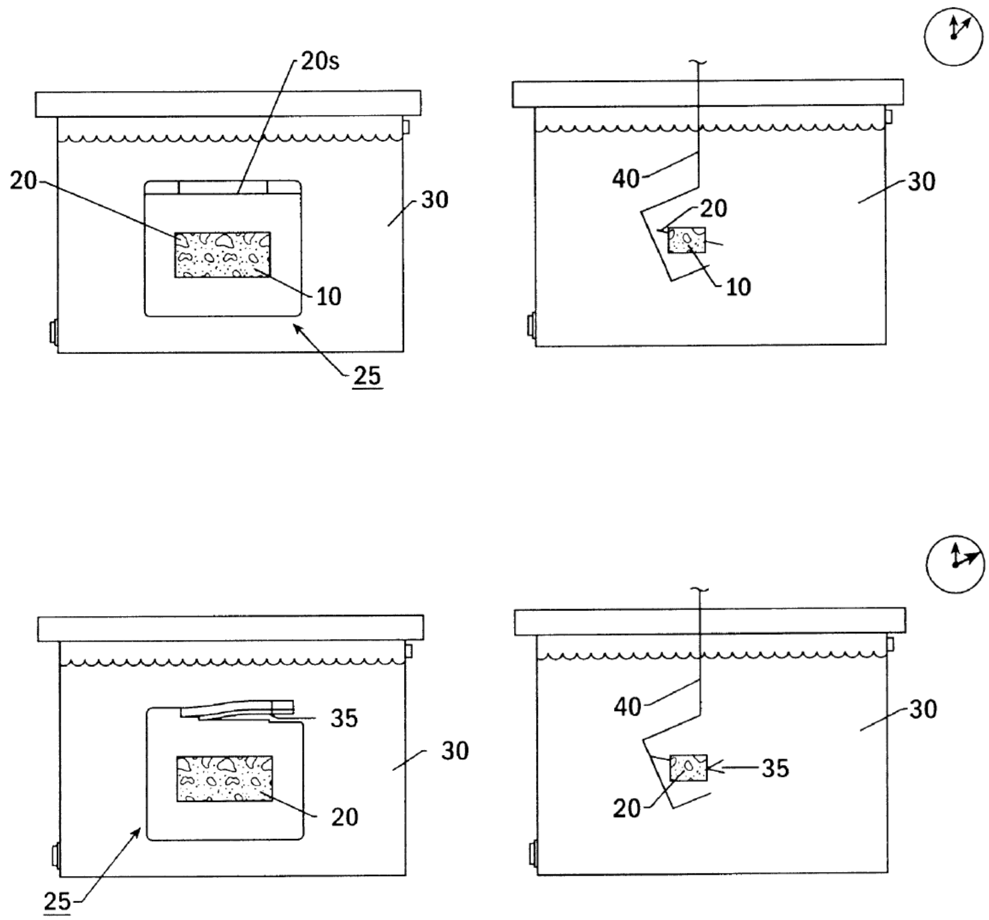

Figure B4: Measuring the weights of the core with and without the plastic bag (Regimand et al., 2004)

Appendix C: DOT Survey Responses

Table C1: DOT Survey Responses

STATE DOT	Use PFC?		Hydraulic Testing?		Hydraulic Design Guidelines?	Pavement Cleaning?		WQ Benefits	Other Comments
Alabama	YES	OGFC with polymer and fiber	NO	Target design air voids 20 – 25 %. Minimum air voids 15%. No direct hydraulic testing.	NONE	NONE	used on high speed roads, so traffic should clean the surface	NO	
Alaska	NO		N/A		N/A	N/A		N/A	
Arizona		No response							
Arkansas	NO		N/A		N/A	N/A		N/A	
California	YES	OGFC in 3/8", 1/2" and 1" maximum aggregate sizes	NO		NONE	NONE	We do not "clean" the OGFC surfaces. Like everyone else, we do get some "plugging" of the voids, but have not found any successful way to eliminate or correct this problem.	NO	Caltrans environmental starting WQ testing next year
Colorado	NO	We did place a test section using rubberized OGFC on I-70 a few years ago and the test section exhibited severe safety problems in the form of icing. Because of the safety issues, the test section was removed shortly after being placed.	N/A		N/A	N/A		N/A	
Connecticut	NO	We had used OGFC in the past but have discontinued its use for the last 9-10 years. No experience with PFC.	NO		NONE	NONE		NO	
Delaware	NO	We have used permeable asphalt treated base courses under our concrete pavement to act as collector systems for the water through the pavements.	N/A		N/A	N/A		N/A	

STATE DOT	Use PFC?		Hydraulic Testing?		Hydraulic Design Guidelines?		Pavement Cleaning?		WQ Benefits	Other Comments
Florida	YES	FDOT uses an open graded friction course on our high speed, multi-lane roadways. We call it FC-5 and it is 3/4" thick and is placed on top of an impermeable structural asphalt layer.	NO	The aggregate types, mix gradation, lay down temperature and asphalt content are checked. From experience, we know that this gradation will have good spray and hydroplaning reduction properties.	NONE		NONE	None, other than removal when cracking and/or ravelling gets severe.	NO	
Georgia	YES		NO	Permeability test could have been used	NONE	We designed OGFC or PEM (PFC) mix with air voids criteria in a range between 18% to 24%, which provided sufficient porous interconnected air voids to drain water quickly.	NONE	We only place OGFC/PEM on highways with traveling speed greater than 55 mph, which typically provide suction and therefore self-clean action on the pavement. Yes, the OGFC/PEM pavement air voids still closed up and became less effective over time.	NO	The primary reason to use OGFC/PEM is to increase invisibility during raining days, and reduce noise when driving.
Hawaii	NO		N/A		N/A		N/A		N/A	
Idaho	ONE	only one location in Idaho that uses this kind of surface. It is a long steep grade with several curves on a relatively high volume roadway.	NO	The surface is visually monitored by maintenance personnel.	NONE	it would be selected based on engineering judgement. The aggregate gradation is the AASHTO recommended standard gradation for open graded friction course.	TRIED	Vacuum trucks may have been tried however this is considered inefficient. Liquid deicers are preferred to prevent clogging. Friction is significantly reduced when sand is used.	NO	Lack of success with liquid deicers when temp gets too low. Also, once there is an established snow floor on OGFC, it takes longer for ice to melt than with dense graded HMA.
Illinois	NO		N/A		N/A		N/A		N/A	
Indiana	TESTING	one field trial of PFC that is currently being evaluated for long-term performance. It was placed in 2003. INDOT does not routinely use these mixes	NO	Attempts have been made to use field falling head permeability since the time of construction, but the pavement is so permeable and the surface is so open that reliable measurements have not been possible -- we cannot get a good seal at the surface and the water drains away too fast.	NONE	Design was based on air voids only (greater than 20%) and density was controlled int he field by limiting the number of roller passes (only enough to seat the aggregate -- same number of passes as used on adjacent SMA section).	NONE	Trial is on an interstate and traffic appears to be effective to date in keeping the pavement relatively clean	NO	Purpose of study is noise and safety
Iowa	NO		N/A		N/A		N/A		N/A	
Kansas	NO	Did km test section 2 years ago	NO		NONE		NONE		NO	

STATE DOT	Use PFC?		Hydraulic Testing?		Hydraulic Design Guidelines?		Pavement Cleaning?		WQ Benefits	Other Comments
Kentucky	TESTING	Kentucky specifies OGFC very, very infrequently (only a couple in the past ten years). Our recent experience is insufficient to provide meaningful responses to your questions.								
Louisiana	YES	A few projects…	NO		NONE	just have to follow mix design and compaction guidelines	NONE	the projects are all new	NO	
Maine	TESTING	Not on a regular basis. We do have some test sites for ogfc's (NovaChip) over existing concrete pavements. The ogfc test sites are performing quite well after a year or so of service. We plan on expanding the use of ogfc's in specific areas.	NO		NONE		NONE		NO	
Maryland	NO	OGFCs were used significantly in MD in the late 80's and early 90's to reduce tire spray and reduce road noise. However, a few bad icy winters coupled with poor selection of material application resulted in network wide failures for the material in high profile locations. We have not used OGFC since because of the bad experience despite the need for this type of mix in our list of potential rehabilitation strategies.	N/A		N/A		N/A		N/A	
Massachusetts	YES	We are currently looking into using Stone Matrix Asphalton controlled access highways and interstates where we use open gradedmixes.	NO	Our experience with drainage across the pavement has been good. Being a snow state there has been concern that during the winter due to snow and ice operations that the roadway clogs and poses a potential for ice to form. This is not the case. Skidding accidents on the non open graded roads are three times as high. Today, we only use OGFC on major roadways.	NONE	other than normal cross slope	NO	Flushing action occurs on its own. We no longer use thermoplastic pavement markings with OGFC's. The thin asphalt coating on the OGFC bled downward and weakened the thin layer <1" of OGFC when the thermoplastic lines were installed. We no longer use these and switched to epoxy paint lines. Also	NO	Our roadways drainage studies have shown that water quality is not out of the normal slightly hydrocarbons and metals. We are seriously considering using more SMA mixes. The benefits, while slightly more

STATE DOT	**Use PFC?**		**Hydraulic Testing?**		**Hydraulic Design Guidelines?**		**Pavement Cleaning?**		**WQ Benefits**	**Other Comments**
				However we are developing pilot projects with the SMA pavements. They appear to wear much better than OGFC's but do cost somewhat more ($5-6 a ton).				we now userecessed pavement markers and no longer see the widespread damage to the pavement especially from plow blades used in snow removal operations.		money, are resistance to rutting, longer wear and good drainage. However, there may be a learning curve and start up costs for paving contractors.
Michigan	NO	our last OGFC project was in the 80's	NO		NONE		NO		NO	
Minnesota	NO	It was tried in Minnesota years ago but did not perform well, probably due to the climate.	N/A		N/A		N/A		N/A	
Mississippi	TESTING	One mile test section of OGFC this summer.	YES	For research purposes, we will conduct in-field falling head permeability testing on the installed pavement at approximately 1 year intervals.	YES	For design purposes, we require the laboratory permeability to exceed 30 meters/day based on the falling head method. We use an in-house test method to determine lab permeability.	NO	OGFC will only be placed on high volume roads. It is our belief that traffic will prevent the pavement from "clogging" up.	NO	
Missouri	TESTING	To date we have only constructed one OGFC overlay (a little over a year ago). The primary reason we have not made this a standard treatment is the concern over potential 'black ice' in a wet-freeze State like Missouri. In addition to this concern is the short effective duration of drainage, before the void system becomes plugged with fine debris, that has been recorded in other States and countries.	NO		NONE		NO		NO	
Montana	YES	MDT just recently began trying OGFC again after a moratorium. We always chip seal after overlaying or reconstruction. For a few high traffic roads we are using the OGFC instead of a chip seal to see how effective it is in providing friction, reducing noise,	NO		NONE		NO		NO	MDT used OGFC more extensively in the late 1980's and early 1990's. The OGFC performed OK, but after 8 years or so the OGFC would fail all at once. Failure consisted of the OGFC stripping

STATE DOT	Use PFC?		Hydraulic Testing?	Hydraulic Design Guidelines?		Pavement Cleaning?		WQ Benefits	Other Comments
		and reducing water spray.							and coming off of the roadway, resulting in a rough ride. Since these failures were sudden and required having to mill/fill the OGFC, MDT placed a moratorium to not use OGFC at all.
Nebraska	TESTING	Yes, we have used OGFC on a few projects as research projects. We generally use OGFC to reduce noise.	NO	NONE		NO	We have experienced some raveling. We fog seal these projects regularly to stop them from raveling. However, fog sealing reduces the pavement permeability.	NO	
Nevada	YES	NDOT routinely uses an open graded friction course (OGFC) on our high volume highways. This is done to improve frictional characteristics and improve traffic safety. Our OGFC is actually fairly dense, with only about 15% voids.	NO	NONE	We clearly recognize that the OGFC provides benefit in reducing hydroplaning during rain/runoff events, and it can help eliminate splash effects and sheet flow across pavement during light to (perhaps) moderate flows. However, we don't design the OGFC around any hydraulic parameters, such as ability to handle a given rate of rainfall or flow. Cross slope is obviously the primary design parameter in adequately dealing with runoff. Our mix designs for OGFC are created to achieve desired levels of friction, and for the durability of this layer as a wearing course.	NO	We do the standard sweeping, patching as/when required (we don't patch with an open grade mix), and we also do fog seals to help extend pavement life. As a desert state we have lots of fine blowing sand and we use salt/sand in winter maintenance, and all of this material tends to fill in the pore space of an OGFC. Our infrequent high flow events undoubtedly clear out some of this debris, but we make no effort in this regard.	NO	
New Hampshire	NO		N/A	N/A		N/A		N/A	
New Jersey	YES	NJDOT uses MOGFC as a HMA overlay for noise and water spray reduction	NO	NONE		NO	NJDOT relies on traffic flushing the fines out of the pavement	NO	NJDOT Maintenance crews are aware of the location of porous pavements and apply extra winter event chemicals

STATE DOT	Use PFC?		Hydraulic Testing?	Hydraulic Design Guidelines?	Pavement Cleaning?		WQ Benefits	Other Comments
								appropriately.
New Mexico	YES		NO	NONE	YES	Fog sealing	NO	
New York	NO		N/A	N/A	N/A		N/A	
North Carolina	YES	polymer modified OGFC -NCDOT uses the same general specification as Georgia and Oregon	NO	NONE	NONE	While we do understand that maintenance should be done to clean the pavement, I am unaware of any being done. We caution division maintenance forces that they cannot use sand during freezing events and that the pavements must be pretreated with salt brine in advance of freezing rain, etc. If this is not done, these pavements ice up and create a new hazard. That issue has caused a hesitation to use OGFC in the mountain areas where they have many freeze thaw cycles each year.	NO	
North Dakota	NO	We are considering placing a OGFC on a project to determine the performance in our climate but have not to date.	N/A	N/A	N/A		N/A	
Ohio	NO	Ohio DOT no longer uses OGFC. I was used by only one District in the past. They have discontinued its use due to the heavy salt usage required during the winter months.	NO	NONE	NONE		NO	

STATE DOT	Use PFC?		Hydraulic Testing?	Hydraulic Design Guidelines?		Pavement Cleaning?		WQ Benefits	Other Comments
Oklahoma	YES	used both OGFC & PFC mixes	NO	NONE		NONE		NO	There have been some observations that indicate somewhat of a filtering benefit of the PFC overlays in terms of run-off purity- Nothing measured or documented though.
Oregon	YES	ODOT use OFGC and have specifications for a 3/4" and a 1/2" open graded. The 3/4" design is used 98% of the time, both are also placed in 2" lifts.	NO	YES	The only hydraulic design guidelines are not to pave over the top of an OGFC, ensure proper slopes are maintain for drainage, ensure no "dams or bathtubs" are created which will block the drainage path of the OGFC.	NONE	If any patching needs to occur a dense graded is typically used.	NONE	
Pennsylvania	NO	PENNDOT had an experimental (test) done with porous asphalt overlays and it did not meet the criteria due to the weather. Water got into the pores and there was freezing in the winter that created skid resistant. We are using Superpave Asphalt Mixture (Hot Mix Asphalt) on the pavement.	N/A	N/A		N/A		N/A	
Rhode Island		No response							

STATE DOT	**Use PFC?**		**Hydraulic Testing?**		**Hydraulic Design Guidelines?**		**Pavement Cleaning?**		**WQ Benefits**	**Other Comments**
South Carolina	YES		NO	The hydraulic behavior is not tested or considered an acceptance parameter.	NONE	we have increased the OGFC thickness when paving sections with multiple lanes across which the water must drain.	NONE	At this time, we do not have any maintenance procedures for cleaning, although we have discussed them. The main problem with maintenance comes from damage caused by spills or other accidents that damage the pavement. Our maintenance forces are unable to replace the OGFC and end up patching with dense graded asphalts that can block drainage in some situations.	NO	we have discussed potential research on WQ benefits with the University of South Carolina on this topic.
South Dakota	NO		N/A		N/A		N/A		N/A	
Tennessee	YES	We recently let our first Interstate OGFC project in over 20 years. We have let one state route project in each of 2005 and 2006.	NO	We design the mix in accordance with NAPA publication IS-115, which should insure the proper gradation.	YES	NAPA publication IS-115	NONE		NO	
Utah	YES	We call it Open Graded Surface Course, OGSC	NO	We have not performed any hydraulic testing on these mixes in over 20 years. Most of our justification these days is based on driving during a rainstorm and seeking the difference behind a windshield. The OGSC is used for splash/spray as opposed to drainiage. We typically do not have signficant rainstorms in our climate.	NO	Our specifications for OGSC, based on gradation, lead to a VMA of low 20s for the mix. This has worked well for us in practical application.	NO	Sweeping is performed along road edges regularly (monthly or so in urban areas), but not for the purpose of addressing the porosity of the OGSC. I don't know of any particular maintenance problems. We typically resurface our roads about every 6 to 8 years, placing a new OGSC on the roadway.	NO	
Vermont	NO	considering it in the future	N/A		N/A		N/A		N/A	

STATE DOT	Use PFC?		Hydraulic Testing?		Hydraulic Design Guidelines?	Pavement Cleaning?		WQ Benefits	Other Comments
Virginia	NO	VDOT has not used PFC or OGFC for many years. Next Spring/Summer, we hope to place a section in Northern Virginia. I primary goal is tire pavement interaction noise reduction with improved friction being a secondary goal.	NO	Since the focus of next year's project will be noise, that will be our primary testing focus - not hydraulics. We will be testing skid resistance and surface texture.					
Washington	TESTING	WSDOT put a moratorium on OGFC back in the early 1990's due to the severe raveling that occurred due to studded tire damage. However, with recent improvements in the design and modified asphalts, we have currently placed two projects that we will evaluate over at least the next five years. One project was placed August 2006 and the second project was placed July 2007. Both projects will evaluate OGFC modified with asphalt rubber, OGFC modified with SBS, and our standard 1/2 inch HMA.	NO		NONE	NONE	It only lasts 4-6 years so we don't think we need to clean it.	NO	Potentially this will be included in our third test section which will be constructed in summer 2009.
West Virginia		No response							
Wisconsin	NO	WisDOT does not currently use OGFC or PFC.	N/A		N/A	N/A		N/A	

STATE DOT	Use PFC?		Hydraulic Testing?	Hydraulic Design Guidelines?	Pavement Cleaning?	WQ Benefits	Other Comments
Wyoming	YES	Commonly use OGFC, but have no plans for a PFC. Have concerns with plugging due to sanding materials. Our specification for OGFC percentage passing: 3/8" _ 97-100, #4 _ 25 - 45, #8 _ 10-25, #200 _ 2-7. (Finer sized)	NO	NONE	NONE	NO	Perform lock wheel friction testing every other year.
Washington, DC	NO		N/A	N/A	N/A	N/A	

Table C2. DOT Survey Contacts

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