Technical Report Documentation Page

1. Report No. FHWA/TX-10/0-5836-1	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

SYNTHESIS OF CURRENT RESEARCH ON PERMEABLE FRICTION COURSES: PERFORMANCE, DESIGN, CONSTRUCTION, AND MAINTENANCE

5. Report Date

October 2009

Published: February 2010

6. Performing Organization Code

7. Author(s)

Kai-Wei Liu, Allex E. Alvarez, Amy Epps Martin, Terry Dossey, André Smit, and Cindy K. Estakhri

8. Performing Organization Report No.

Report 0-5836-1

9. Performing Organization Name and Address

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

Project 0-5836

12. Sponsoring Agency Name and Address

Texas Department of Transportation
Research and Technology Implementation Office
P. O. Box 5080
Austin, Texas 78763-5080

13. Type of Report and Period Covered

Technical Report:
August 2008–August 2009

14. Sponsoring Agency Code

15. Supplementary Notes

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

Project Title: Performance of Permeable Friction Courses (PFC) Pavements Over Time

URL: http://tti.tamu.edu/documents/0-5836-1.pdf

16. Abstract

Over the past several years, the Texas Department of Transportation (TxDOT) adopted the use of porous or permeable friction course (PFC) mixtures as a thin asphalt pavement surface layer to provide safety and environmental benefits. This type of mixture is defined in TxDOT Specification Item 342 as a surface course of a compacted permeable mixture of aggregate, asphalt binder, and additives mixed hot in a mixing plant.

Recent research addressed important design, construction, and maintenance issues associated with PFC, which has been increasingly employed by TxDOT. In order to complete the evaluation of this relatively new hot mix asphalt (HMA) concrete mixture type as a possible solution for improving pavement safety and reduction of pavement noise, performance will be tracked over time in this research project to assess benefits, cost, and changes in benefits. The main objective of this research project is to develop a database of PFC performance in terms of functionality (noise reduction effectiveness and permeability), durability (resistance to raveling and possibly rutting and cracking), and safety (skid resistance and accident history), in order to produce guidelines for design, construction, and maintenance of PFC mixtures.

This report includes a comprehensive and focused review of research conducted since 2004 related to the mix design, performance (i.e., functionality, durability, and safety), construction, and maintenance of surface courses using PFC.

17. Key Words

Porous Friction Courses, Open-Graded Friction Courses, Porous Asphalt, Mixture Design, Mixture Performance, Asphalt Mixture, Asphalt, Permeability, Noise Reduction, Maintenance, Construction, Durability, Safety

18. Distribution Statement

No restrictions. This document is available to the public through NTIS:
National Technical Information Service
Springfield, Virginia 22161
http://www.ntis.gov

19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 152	22. Price

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

SYNTHESIS OF CURRENT RESEARCH ON PERMEABLE FRICTION COURSES: PERFORMANCE, DESIGN, CONSTRUCTION, AND MAINTENANCE

by

Kai-Wei Liu
Graduate Student, Texas A&M University

Allex E. Alvarez
Graduate Research Assistant, Texas Transportation Institute

Amy Epps Martin
Associate Research Engineer, Texas Transportation Institute

Terry Dossey
Research Scientist, Center for Transportation Research

André Smit
Research Associate, Center for Transportation Research

and

Cindy K. Estakhri
Research Engineer, Texas Transportation Institute

Report 0-5836-1
Project 0-5836
Project Title: Performance of Permeable Friction Courses (PFC) Over Time

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

October 2009
Published: February 2010

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

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Amy Epps Martin, P.E. # 91053.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Texas Department of Transportation personnel for their support throughout this project. Special thanks are given to the TxDOT project committee: Robert Lee (project director), Feng Hong, Dar Hao Chen, John Wirth, and George Reeves for providing technical guidance and assistance.

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

Permeable or porous friction courses (PFC), a new generation open-graded friction courses (OGFCs) as defined by Texas Department of Transportation (TxDOT) in Item 342, have special gap-graded aggregate gradations that lead to a mixture containing a high percentage of air voids (AV) (at least 18 percent of total AV content). In fact, most international and national studies refer to this open structure mixture as porous asphalt (PA) or new generation open-graded friction courses; therefore, PFC and OGFCs mixtures will be termed PFC/OGFCs in this report in order to coincide with the majority of the literature.

Several researchers indicate PFC/OGFCs provide various advantages due to the high AV content and the large permeability, which improve traffic safety, fuel consumption, and reduce tire/pavement noise. The high AV content and the open structure enhance the effective drainage of water at the pavement surface, which can reduce hydroplaning, splash and spray, and glare under wet weather conditions as well as visibility during darkness and daylight. This property also improves wet skid resistance in comparison with dense-graded hot mix asphalt (DGHMA), since less water remains at the pavement surface. Moreover, PFC/OGFCs can reduce fuel consumption due to the promotion of smoothness and provide noise reduction in an expected range of 3 to 6 dB(A), which is important to minimize or control pavement noise levels especially in the urban area (*1, 2, 3*).

PFC/OGFCs can also pose some disadvantages, such as reduced performance, high construction costs, winter maintenance problems, and limited structural contribution. Reduced performance of PFC/OGFCs is associated with reduced durability and functionality (i.e., permeability and noise reduction effectiveness), due to raveling and clogging, respectively. Furthermore, construction costs per ton of PFC/OGFCs in the United States are much higher than DGHMA, and PFC/OGFCs have pavement surface lives that are less than the standard DGHMA. Winter maintenance is also considered a serious problem with frost and ice formation common, and frequent maintenance is required which leads to high maintenance costs. In addition, for pavement structure design, PFC/OGFCs materials are typically considered to have no or minimal structural contribution (*1, 2, 3*).

TxDOT Projects 0-5262 *Optimizing the Design of Permeable Friction Courses (PFC)*, 0-5185 *Noise Level Adjustments for Highway Pavements*, and 0-4834 *Cold-Weather*

Performance of New Generation OGFC addressed important design, construction, and maintenance issues associated with PFC/OGFCs mixtures over the past several years. In order to complete the evaluation of this relatively new mixture type as a possible solution for improving pavement safety and reduction of pavement noise, performance must be tracked over a multiyear period to assess benefits, costs, and changes in benefits over time.

This need for additional research motivated TxDOT Project 0-5836 *Performance of Permeable Friction Courses (PFC) Pavements over Time*. The main objective of this research project is to develop a database of PFC/OGFCs performance in terms of functionality (noise reduction effectiveness and permeability), durability (resistance to raveling and possibly rutting and cracking), and safety (skid resistance and accident history), in order to produce guidelines for design, construction, and maintenance of PFC/OGFCs mixtures.

This document represents the first interim research report (Technical Report 0-5836-1) and summarizes the results of Task 2 (Conduct Information Search) that was included in the work plan to conduct a comprehensive and focused review of research conducted since 2004 related to the design, construction, maintenance, and performance of surface courses using PFC/OGFCs. Therefore, it provides the necessary written information for use by TxDOT to guide the conduct of the research project and documents interim results for TxDOT and the research community.

The first part of this report describes PFC/OGFCs performance including functionality (noise reduction effectiveness and drainability), durability, and safety (skid resistance and accident rate). The second part presents the mixture design methodologies, the fundamental aspects involved in the construction process, and the primary considerations for maintenance of PFC/OGFCs mixtures. Next, section reports results of an ongoing online survey that was established in order to gain information from TxDOT districts on the use and experience in terms of performance and maintenance of PFC/OGFCs mixtures. Finally, the document concludes with a summary of information obtained from recent research regarding performance, design, construction, and maintenance of PFC/OGFCs and proposes some recommendations for future study.

2. PERFORMANCE

This chapter discusses the performance of PFC/OGFCs, including aspects related to functionality, durability, and safety. In addition, functionality includes both noise reduction effectiveness and drainability. Safety is described in terms of skid resistance.

2.1. FUNCTIONALITY

Noise reduction effectiveness and drainability are the main functional properties of PFC/OGFCs that justify using these mixtures as surface layers in asphalt pavements. These properties are subsequently discussed in separate sections.

2.1.1. Noise Reduction Effectiveness

First, noise measurements will be briefly described in this section followed by a comparison of noise measurements. Next, a summary of the following factors that influence pavement noise as well as related recent research conducted since 2004 are described in chronological order: pavement surface type, vehicle speed, layer thickness, texture and roughness of the pavement surface, air temperature, type of tire, age of pavement, traffic condition, nominal aggregate size, binder type, AV content, and aggregate gradation. After that, a synthesis is provided following the descriptions of the effects of each individual factor.

Noise Measurements

Standardized approaches for measuring traffic noise are needed to characterize the noise level from various pavement surface types. These approaches are generally divided into two categories: (1) wayside methods, such as the Statistical Pass-by (SPB) method which was defined by International Standards Organization (ISO) standard 11819-1 and the Controlled Pass-by method (CPB) which was introduced by the Federal Highway Administration (FHWA) manual "Measurement of Highway-Related Noise;" and (2) near-field methods such as the Close-Proximity (CPX) method that was defined by ISO standard 11819-2 and the Onboard Sound Intensity (OBSI) method that was developed by Donavan for the California Department of Transportation (CalTrans) (*4, 5*).

The Statistical Pass-by method measures the maximum A-weighted sound levels in the field according to a statistically significant number of pass-by vehicles at a specified wayside location and a specific speed. In the SPB method, microphones are placed at a defined distance of 7.5 m (25 ft) from the center of the travel line and at a height of 1.2 m (4 ft) above the pavement surface. It also requires measurements for automobiles, dual-axle heavy trucks, and multi-axle trucks. After the noise level of each individual pass-by vehicle and its speed is recorded, a regression line is used to calculate the relationship between the maximum A-weighted sound level and the logarithm of vehicle speed. According to this regression line, the average A-weighted vehicle sound level is determined. The reference speed is provided by ISO standard, and the statistical vehicle sound level data is analyzed to determine the statistical pass-by index (SPBI) in order to compare the noise level for different types of pavement surfaces (*5*).

The Controlled Pass-by method measures sound levels from automobiles and light trucks in the field at a designed test site. In this method, the vehicles drive past a microphone placed at a distance of 7.5 m (25 ft) from the centerline of the measured line and at a height of 1.2 m (4 ft) above the pavement surface. Then, the peak sound level is recorded by the microphone while the vehicles pass at specific speeds.

The Close-Proximity method measures the sound levels at or near the tire/pavement interface in the field. In the CPX method, microphones are located near the pavement surface in order to measure the sound pressure level. The microphones are placed at a defined distance of 20.3 cm (8 in) from the center of the tire and at a height of 19.2 cm (4 in) above the pavement surface. Since the microphones will measure the sound from all directions and the noise level needs to be measured quickly and directly at the tire/pavement interface, the microphones are either suspended in a free field or inside an acoustic chamber. The acoustic chamber method achieves some degree of isolation from higher frequency outside noise, but introduces errors at some frequencies due to modes formed by standing wave reflections inside the enclosure.

The Onboard Sound Intensity method developed by Donavan for CalTrans uses the industry-standard sound intensity measurement technique adapted for a moving vehicle to measure near-field noise levels. In the OBSI method, two locations for sound intensity probes are used: one is at the leading edge and the other is at the trailing edge of the tire-contact patch. The probe consists of two 2.54 cm (1 in) phase-matched microphones spaced 1.6 cm (0.6 in) apart. A jig is used to fasten the microphone assembly to the vehicle wheel. Microphones align the leading or trailing edge of the tire contact and are placed at a distance of 10 cm (4 in) perpendicular from the side of the tire and at a height of 7 cm (2.8 in) above the pavement surface (*5, 6*).

The FHWA Traffic Noise Model (TNM) versus Wayside Measurements

Wayside noise measurements are considered the most appropriate technique to evaluate the impact of traffic noise at any location where noise is objectionable, especially in urban areas. Therefore, wayside measurements are the standard when referring to traffic noise.

In 1998, the traffic noise model (TNM) was released for the first time by the FHWA. This program not only allows the modeling of the road geometry, condition, and traffic but also calculates the sound levels for receivers near the side of the road. The FHWA's TNM contains two options for OGFC and average pavements. An OGFC pavement option cannot be used to determine the need for noise barrier walls, while an average pavement option is used for this purpose for all pavements, which implies that all pavements offer equivalent acoustics.

In order to overturn the FHWA existing restrictions with regard to use of quieter pavement design for noise avoidance and abatement, Trevino and Dossey (*7*) conducted a study in 2008 to compare the wayside test and the TNM to demonstrate that not all pavements are acoustically equivalent. Wayside noise levels were measured on several PFC/OGFCs pavements in Texas, and TNM calculations were performed using both the average and OGFC options. Table 1 presents the results of the comparison between the wayside method and the TNM. Leq, (equivalent A-weighted noise level over time) was used for the wayside measurements as this is what the TNM model predicts.

Table 1. Wayside Tested Results and TNM Comparisons in Texas (*7*).

Roadway	District	Pass-by Test (Meter Average)	TNM ("Average")	TNM ("OGAC")	TNM "Average" - Pass-by (dBA)	TNM "OGAC" - Pass-by (dBA)
FM 620	Austin	70.3	75.0	73.4	4.8	3.2
IH-30	Dallas	78.2	80.6	79.0	2.4	0.8
SH 6	Waco	70.9	75.5	74.0	4.6	3.1
IH-35	Waco	77.0	81.1	79.5	4.1	2.5
IH-37 (CC1NB1)	C. Christi	75.4	78.9	77.2	3.6	1.9
IH-37 (CC2NB1)	C. Christi	73.4	76.2	74.5	2.8	1.1
IH-35	S. Antonio	78.4	81.4	79.8	3.0	1.4
US 281 (PFC1)	S. Antonio	73.9	79.5	77.9	5.6	3.9
US 290 (Yoakum 1)	Yoakum	70.4	74.0	72.5	3.6	2.1
US 290 (Yoakum 1)	Yoakum	69.5	74.8	73.3	5.3	3.8
IH-10 (Yoakum 6)	Yoakum	71.2	76.5	75.0	5.3	3.8
IH-10 (Yoakum 6)	Yoakum	72.8	77.2	75.8	4.4	3.0
IH-10 (Yoakum 5)	Yoakum	70.5	75.1	73.7	4.6	3.2
IH-10 (Yoakum 5)	Yoakum	69.8	76.0	74.5	6.2	4.7
IH-10 (Yoakum 5)	Yoakum	73.2	77.5	76.0	4.3	2.8
IH-10 (Yoakum 5)	Yoakum	72.4	77.7	76.2	5.3	3.8
US 281 (PFC1)	S. Antonio	74.5	79.7	78.1	5.2	3.6
US 281 (PFC1)	S. Antonio	73.7	79.0	77.4	5.3	3.7
SH 6	Waco	69.1	75.8	74.4	6.7	5.3
SH 6	Waco	66.7	75.0	73.5	8.3	6.8
Mean					4.8	3.2
Std. Deviation					1.4	1.4
C. of Variation (%)					29.2	44.5

The results showed that the actual measured noise levels were lower than the noise levels from the TNM, and the predicted noise levels using the OGFC pavement option were lower than the average pavement option. Moreover, the results from the average pavement option in the TNM over predicted noise levels by 5 dB(A), and the results of the OGFC pavement option in the TNM over predicted noise levels by 3 dB(A) when comparing to the actual noise levels. Based upon the findings, the authors concluded that PFC/OGFCs are quieter than both the predicted noise levels using the average and OGFC pavement options in the TNM program. The over prediction of 5 dB(A) is significant using the average pavement option, which should not be used for PFC/OGFCs, and the OGFC pavement option in the program should be adjusted to be a better predictor for PFC/OGFCs. Thus, the study provided evidence to remove the FHWA restrictions regarding the exclusive use of the average pavement option in the TNM. Moreover, the longer term noise reduction benefit of PFC/OGFCs is one of the goals of the current study.

2.1.1.1. Pavement Surface Type

Pavement surface type greatly influences tire/pavement noise. Therefore, many researchers have undertaken studies to explore the noise reduction effectiveness of different mixture types used on the pavement surface.

Danish Road Institute (2004)

The Danish Road Institute (*8*) developed and tested thin open layers as noise reduction pavements under Nordic conditions (without studded tires). Thin open courses are defined as an open structure only at the upper part of pavements with pores that have the depth less than the maximum size of the aggregates. The Danish Road Institute conducted research on pavement noise on PA (AC6), SMA (SMA6), and open thin layers (TP6) as a combination layer compared with DGHMA with 8 (AC8d) and 11 mm (0.43 in) (AC11d) aggregates (Table 2).

Table 2. Pavements Tested by the Danish Road Institute (*8*).

Type	***Aggregate Size***	***Bitumen***	***Approx. Thickness***
AC11 dense (reference)	11 mm (0.43 in)	70/100 (B85)	30 mm (1.18 in)
AC11 dense (reference)	8 mm (0.31 in)	70/100 (B85)	25 mm (0.98 in)
AC6 open	6 mm (0.24 in)	160/220 1.5% elastomer	20 mm (0.79 in)
SMA6	6 mm + 5/8 mm (0.24 in + 0.02 in)	70/100	20 mm (0.79 in)
TP 6k	6 mm (0.24 in)	100/150	17 mm (0.67 in)

Testing was performed in traffic traveling at 60 kph (37.5 mph), and noise measurements were carried out using the SPB method. Study results showed that the noise reduction of thin open layers is 2-3 dB(A) compared to DGHMA when the thin layers were 6 months old. The results of measured attenuation on different pavement surfaces relative to a DGHMA with 11 mm (0.43 in) aggregate were 0.8 dB(A) for a DGHMA with 8 mm (0.31 in) aggregate (AC8d), 1.8 dB(A) for SMA (SMA6), and 2.9 dB(A) for a open thin layer (TP6).

Colorado (2004)

The noise levels of HMA surfaces including DGHMA with fine- and coarse-gradation, PFC/OGFCs, Novachip, and SMA were assessed throughout Colorado state (*4*). All noise measurements were done at 96 kph (60 mph) using the CPX method. Table 3 presents the results of the noise levels on the HMA pavement surfaces. The results showed that the DGHMA with fine gradation produced noise levels of 0.4 dB(A) more than PFC/OGFCs, the DGHMA with coarse gradation produced noise levels of 5.7 dB(A) more than PFC/OGFCs, and the SMA produced noise levels of 1.2 dB(A) more than PFC/OGFCs.

Table 3. The Noise Levels for Different HMA Pavement Surfaces from Colorado DOT (*4*).

Type Mix	*Type*	*Year Constructed*	*Noise Level dB(A)*
SMA	19 mm (0.75 in)	2002	96.9
	12.5 mm (0.49 in)	2002	96.2
	19 mm (0.75 in)	2003	96.3
	Average		96.5
DGHMA (coarse gradation)	-	1997	100.6
	-	1998	101.2
	-	1999	101.4
	Average		101
DGHMA (fine gradation)	-	2003	95.6
	-	2002	96.1
	Average		95.7
Novachip	Type C	2003	95.1
		2002	98.9
	Average		97
PFC/OGFCs	-	2003	95.3

Indiana (2004)

The Indiana Department of Transportation (INDOT) (*9*) compared the pavement noise levels for PFC/OGFCs, SMA, and DGHMA mixtures. Table 4 shows the mix design of the three field test sections.

Table 4. Mix Design Parameters in Indiana DOT (9).

Gradation		***PFC/OGFCs***	***SMA***	***DGHMA***
12.5 mm (1/2 in)		100	100	100
9.5 mm (3/8 in)		83	84.7	94
4.75 mm (No. 4)		27.9	39.1	64.3
2.36 mm (No. 8)		12.5	26.9	46
1.18 mm (No. 16)		8.6	21	-
0.6 mm (No. 30)		6.0	17.7	17
0.3 mm (No. 50)		4.6	15	-
0.15 mm (No. 100)		3.3	13.3	-
0.075 mm (No. 200)		2.4	10.1	5.5
Parameter	PG Grade	76-22	76-22	76-22
	Pb, %	5.7	5.5	5.7
	Air Voids, %	23.1	4	4
	VMA, %	-	17.7	15.5
	Other	0.3% cellulose fiber	0.1% cellulose fiber	-

Note: PG: Performance Grade; Pb: asphalt content; VMA: voids in mineral aggregate

Both the CPB and the CPX methods were applied to measure the sound levels. The sound pressure levels using the CPB method were conducted at 80 and 110 kph (50 and 68 mph), and the noise pressure levels using the CPX method were conducted at 72 and 97 kph (45 and 60 mph). Table 5 presents the sound pressure levels by the CPB and the CPX methods. Based upon the testing results, the PFC/OGFCs produced the lowest tire/pavement noise levels, and the SMA produced the highest noise levels. The CPB method at 80 kph (50 mph) showed that the noise levels of DGHMA were 4.2 dB(A) higher than PFC/OGFCs, and the noise levels of SMA were 5.9 dB(A) higher than PFC/OGFCs. However, the CPX method at two different speeds showed that the DGHMA produced noise levels of 3.6 dB(A) more than PFC/OGFCs, and the SMA produced noise levels of 4.8 dB(A) more than PFC/OGFCs. Both the CPB and the CPX methods indicated that PFC/OGFCs exhibited the lowest levels compared with SMA and DGHMA pavement surfaces.

Table 5. The CPB and the CPX Sound Pressure Levels from Indiana DOT (*9*).

	CPB sound pressure levels, dB(A)		
Speed	***DGHMA***	***SMA***	***PFC/OGFCs***
80 kph (50 mph)	72.6	74.8	68.1
	75.2	75.5	70.1
	74.5	77	71.6
Average	74.1	75.8	69.9
110 kph (68 mph)	-	78.5	71.7
	-	80.5	74.3
	-	79.4	74.4
Average	-	79.5	73.5
	CPX sound pressure levels, dB(A)		
Speed	***DGHMA***	***SMA***	***PFC/OGFCs***
72 kph (45 mph)	93	94.2	89.7
97 kph (60 mph)	96.4	97.6	92.6

New Jersey (2005)

Bennert et al. (*10*) conducted pavement noise evaluations on different HMA pavement surfaces in New Jersey using the CPX method at speeds from 32.2 to 48.3 kph (25 to 30 mph) for automobiles and 56.3 to 72.4 kph (35 to 45 mph) for trucks. The HMA pavement surfaces were PFC/OGFCs with and without crumb rubber, DGHMA, SMA, Novachip, and microsurfacing. For comparison of the influence of pavement surface materials on the tire/pavement noise generation, the noise levels were evaluated at 96.5 kph (60 mph). The testing results showed that the PFC/OGFCs with crumb rubber produced the lowest tire/pavement noise levels; the SMA, microsurfacing, and Novachip produced louder noise levels; and the DGHMA produced the highest noise levels. The average values of measured noise levels at 96 kph (60 mph) on different pavement surfaces were 96.5 dB(A) for PFC/OGFCs with rubber, 97.9 dB(A) for PFC/OGFCs without rubber, 98.6 dB(A) for SMA, 98.7 dB(A) for microsurfacing, 98.8 dB(A) for Novachip, and 99.1 for DGHMA.

Bennert et al. (*11*) also used the CPX method at 96 kph (60 mph), comparing thin-lift HMA mixes with in-service DGHMA pavements in New Jersey. The thin-lift HMA mixes were constructed with PFC/OGFCs, Novachip, microsurfacing, and SMA. In comparing the thin-lift surfaces, the pavement noise results showed that the quietest pavement surfaces were PFC/OGFCs. The order of lowest noise to highest in the other thin-lift surfaces was: PFC/OGFCs, 9.5 mm (0.37 in)-SMA, microsurfacing, Novachip, and 12.5 mm (0.49 in)-SMA. Table 6 presents the results of tire/pavement noise levels from the CPX method.

Table 6. Tire/Pavement Noise Levels from the CPX Method in New Jersey (*11*).

Surface Type		***Location***	***Noise Level at 96 kph (60 mph), dB(A)***
AR-OGFCs		US-9N	96.8
		I-195W	96.2
MOGFCs		I-78E	97
		US-24	97.6
		I-195E	98.4
Novachip		I-195E	98.2
		I-78W	99.4
SMA	9.5 mm (0.37 in)	I-78W	98
	12.5 mm (0.49 in)	US-1	100.5
Microsurfacing		US-202S	98.8
		NJ-29	98.8
12.5 mm (0.49 in)-DGHMA		I-78E	97.1
		US-22W	98.5

Note: AR-OGFCs: asphalt rubber OGFCs; MOGFCs: modified asphalt binder OGFCs

Sweden (2005)

The Swedish National Road and Transport Research Institute (*12*) constructed and tested three PA surfaces for traffic noise reduction in Stockholm. The tested sections were constructed by rubber particle as aggregate with polyurethane containing 30 to 35 percent AV. Each section had an average thickness of 30 mm (1.18 in) layer under a mix of light and heavy traffic. Both the CPX and CPB methods were applied to measure the noise levels on the PA and DGHMA surfaces at a test speed of 50 kph (31.25 mph). The results indicated that the noise levels can be reduced at the range of 7 to 12 dB(A) by PA mixtures. Table 7 shows the results of noise levels from the CPX and CPB methods.

Table 7. Tire/Pavement Noise Levels from the CPX and CPB Methods in Sweden (*12*).

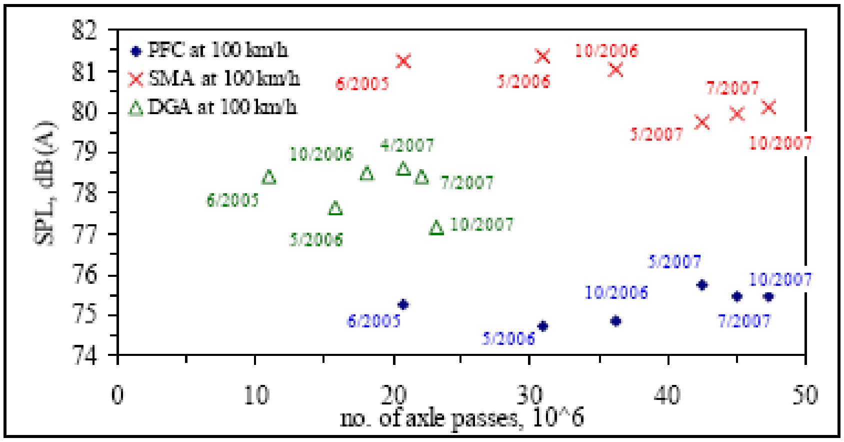
Surface Type	***Section***	***Noise Level (CPX), dB(A)***	***Noise Level (CPB), dB(A)***
PA	1	82	59
	2	85	63
	3	83	62
DGHMA		94	70

Asphalt Institute (2006)

The Asphalt Institute (*13*) indicated PFC/OGFCs surfaces generate lower noise levels than Portland cement concrete (PCC) surfaces. The PFC/OGFCs with crumb rubber reduced the pavement noise level by 4 dB(A) compared to PCC pavements in Arizona, and the average tire/pavement noise for all HMA sections was 4.3 dB(A) lower than the PCC pavements in Arkansas. The average noise reduction on all HMA pavements was 4.1 dB(A) lower than the average noise level for the PCC surfaces using the CPX method in New Jersey. The New Jersey study also found that the average sound pressure level of SMA surfaces was 3.6 dB(A) lower than the PCC surfaces.

Indiana (2008)

Kowalski et al. (*14*) monitored the pavement noise levels of three highway test sections with the SPB, CPB, and CPX methods at 100 kph (62 mph). The test sections were constructed with PFC/OGFCs, SMA, and DGHMA. Based on the results of measured tire/pavement noise levels, the SMA surface was the loudest pavement surface and the PFC/OGFCs surface was the quietest pavement surface. Figure 1 shows the noise levels of three pavement surfaces at a speed of 100 kph (62 mph).



SPL: Sound pressure level

Figure 1. Noise Levels at Speed 100 kph (62 mph) by the SPB Method in Indiana (*14*).

Texas (2008)

TxDOT (*7*), using the OBSI method at a vehicle speed of 96 kph (60 mph), measured pavement noise levels of several highway test sections in Texas. The tests in this project were conducted on PFC/OGFCs, DGHMA, and continuously reinforced concrete pavement (CRCP). The OBSI results of the PFC/OGFCs measurements are presented in Figure 2. In this figure, the findings showed that 58 percent of pavement noise levels were between 98 and 100 dB(A), 17 percent of them were below 98 dB(A), and 25 percent of them were above 100 dB(A). The average noise levels of PFC/OGFCs were 98.8 dB(A).

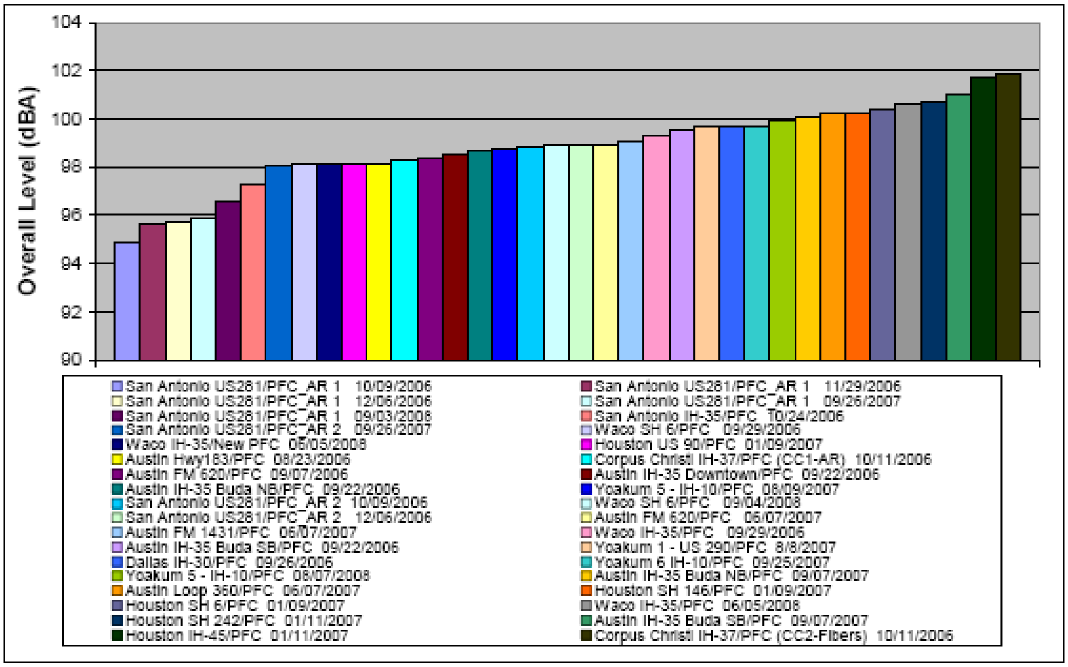


Figure 2. Noise Levels of PFC/OGFCs in Texas (*7*).

Figure 3 shows the OBSI measurements for PFC/OGFCs, DGHMA, and CRCP surfaces. In general, PFC/OGFCs were the quietest mixture type.

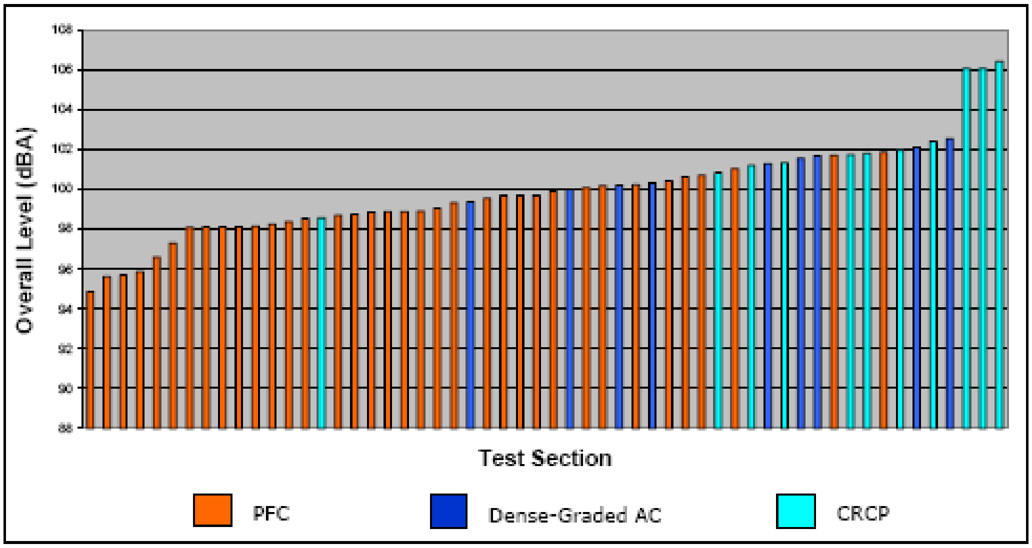


Figure 3. Noise Levels of PFC/OGFCs, DGHMA, and CRCP in Texas (*7*).

California (2008)

CalTrans (*15*) evaluated tire/pavement noise level on PFC/OGFCs with and without rubber, gap-graded HMA with rubber, and DGHMA using the OBSI method. For all tested sections, noise levels were measured at 96 kph (60 mph) in the range of eight years. The results indicated that the noise level of 25 percent of PFC/OGFCs mixtures without rubber was 104 dB(A), which provided noise reduction above 3 dB(A) as compared to DGHMA mixtures. On the entire set of sections, the PFC/OGFCs mixtures reduced noise level at the range of 1 to 4 dB(A) compared to DGHMA mixtures. The study also found that there was no major difference of noise levels between PFC/OGFCs with and without rubber across the age ranges.

2.1.1.2. Vehicle Speed

The tire/pavement noise levels of PFC/OGFCs can be influenced by the vehicle speed. Hence, researchers investigated the correlation between vehicle speed and tire/pavement noise levels to determine the traffic speed thresholds of vehicles for PFC/OGFCs pavement.

New Jersey (2005)

Bennert et al. (*10*) investigated the effect of vehicle speed on tire/pavement noise generation of various HMA and PCC surfaces with three different vehicle speeds. The HMA surfaces included DGHMA, PFC/OGFCs with and without crumb rubber, SMA, Novachip, and a microsurfacing slurry mix. Vehicle speeds at 88.5, 96.5, and 104.6 kph (55, 60, and 65 mph) were tested. Figure 4 shows the results from the vehicle speed analysis. For comparison of the effect of vehicle speed and tire/pavement noise levels, the noise gradient parameter (dB(A) per mph) was calculated.

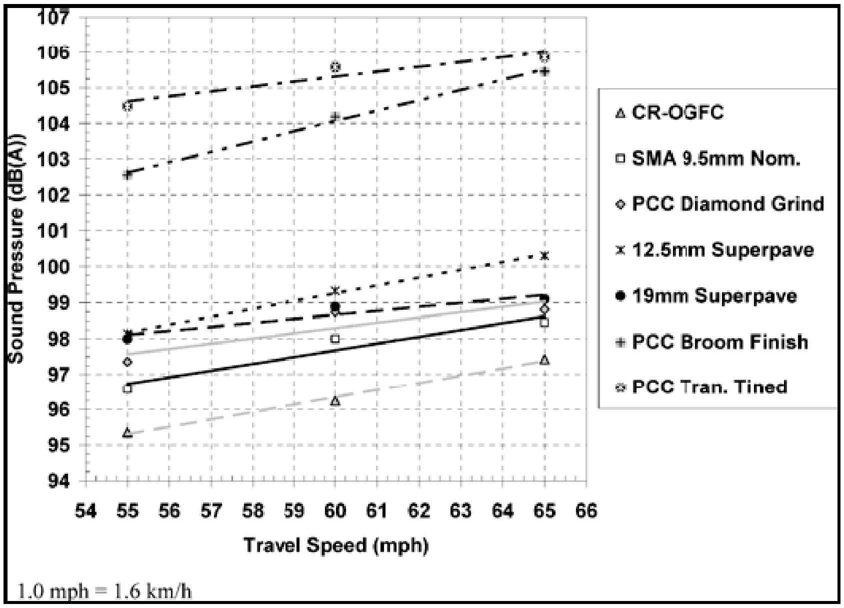


Figure 4. Effect of Vehicle Speed on Tire/Pavement Noise in New Jersey (*10*).

The noise gradient was calculated from Figure 4 and summarized in Table 8. The results of Table 8 indicate that Novachip had the lowest noise gradient, while microsurfacing had the highest noise gradient. The lower noise gradients of pavement surfaces would be less prone to an increase in the tire/pavement noise due to an increase in the vehicle speed. Based on the average value of noise gradient in Table 8, the HMA surfaces had a noise gradient equal to 0.12 dB(A) per kph (0.19 dB(A) per mph).

Table 8. Tire/Pavement Noise Gradient on Different Pavement Surfaces in New Jersey (*10*).

Surface Type	*# of Sections*	*Noise Gradient, dB(A) per kph (per mph)*
PFC/OGFCs	8	0.10 (0.16)
DGHMA	13	0.13 (0.20)
Novachip	1	0.09 (0.15)
SMA	7	0.11 (0.17)
Microsurfacing	2	0.18 (0.28)

Moreover, Bennert et al. (*11*) also investigated the effect of vehicle speed on tire/pavement noise generation by comparing thin-lift HMA mixes with in-service DGHMA and PCC pavements in New Jersey. Vehicle speeds at 88.5, 96.5, and 104.6 kph (55, 60, and 65 mph) were tested, and the thin-lift HMA mixes were constructed with PFC/OGFCs, Novachip, microsurfacing and SMA. The noise levels and gradients of different surface types are provided in Table 9.

Table 9. Tire/Pavement Noise Levels and Noise Gradients in New Jersey (*11*).

			Noise Level, dB(A)			*Noise Gradient, dB(A) per kph (per mph)*
Surface Type		*Location*	*88.5 kph (55 mph)*	*96.5 kph (60 mph)*	*104.6 kph (65 mph)*	
AR-OGFCs		US-9N	95.8	96.8	97.7	0.12 (0.19)
		I-195W	95.4	96.2	97.4	0.12 (0.20)
MOGFCs		I-78E	96.5	97	98.1	0.10 (0.16)
		US-24	-	97.6	-	-
		I-195E	97.4	98.4	99.2	0.11 (0.18)
Novachip		I-195E	97.7	98.2	99.2	0.09 (0.15)
		I-78W	-	99.4	-	-
SMA	9.5 mm (0.37 in)	I-78W	96.6	98	98.5	0.12 (0.19)
	12.5 mm (0.49 in)	US-1	-	100.5	-	-
Microsurfacing		US-202S	-	98.8	-	-
		NJ-29	97.4	98.8	100.4	0.19 (0.30)
12.5 mm (0.49 in)-DGHMA		I-78E	96.2	97.1	97.7	0.09 (0.15)
		US-22W	-	98.5	-	-

Note: AR-OGFCs: asphalt rubber PFC/OGFCs; MOGFCs: modified asphalt binder PFC/OGFCs

NCAT (2007)

As reported in NCAT Report 07-02 (*16*), sound intensity levels and sound pressure levels on both single and double layer structures constructed with fine- and coarse-PFC/OGFCs were measured. The study also investigated the influence of vehicle speed at 72 and 96 kph (45 and 60 mph) on tire/pavement noise levels. Five different pavement sections were tested, and the structures and mixtures are shown in Table 10.

Table 10. Structure and Mixtures of Five Pavement Sections Tested by NCAT (*16*).

Section (thickness)	***N5***	***N6***	***N7***	***N8***	***N9***
Layer 1 (31.75 m (1.25 in))	PFC/OGFCs	PFC/OGFCs	PFC/OGFCs	PA (coarse)	PA (coarse)
Layer 2 (31.75 mm (1.25 in))	DGHMA	PFC/OGFCs	PA (coarse)	PA (coarse)	DGHMA

Table 11 shows the mean value of sound pressure levels and sound intensity levels at vehicle speeds equal to 72 and 96 kph (45 and 60 mph). Both the sound pressure and intensity levels demonstrate that there is an average increase in noise level of 3 dB(A) when increasing the vehicle speed from 72 to 96 kph (45 mph to 60 mph). Moreover, sound intensity levels are between 1-2 dB(A) higher than sound pressure levels which provide a good correlation between sound pressure and intensity levels.

Table 11. Sound Pressure and Intensity Levels on Five Sections Measured by NCAT (*16*).

Section	***Sound Pressure Level, dB(A)***		***Sound Intensity Level, dB(A)***	
	Vehicle Speed			
	72 kph (45 mph)	***96 kph (60 mph)***	***72 kph (45 mph)***	***96 kph (60 mph)***
N5	88.16	90.98	90.83	93.49
N6	86.96	90.16	88.76	91.35
N7	87.41	90.98	88.69	92.40
N8	91.80	95.19	93.56	97.28
N9	93.32	96.93	95.80	98.62

2.1.1.3. Layer Thickness

Noise characteristics of PFC/OGFCs are also dependent on thickness of the pavement layer. This factor affects the high frequency component of the pavement noise level (higher than 1200 Hz) (*4*).

NCAT (2007)

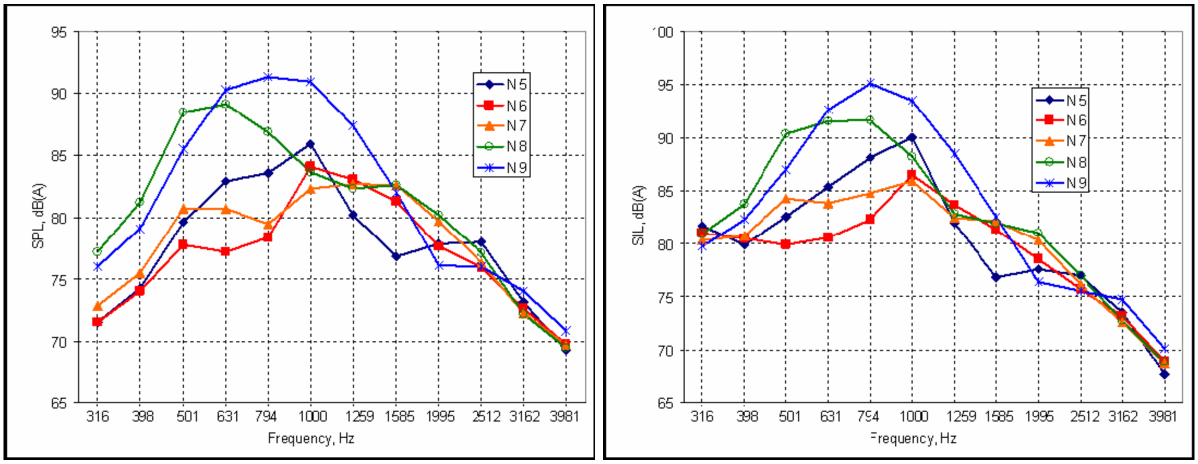
Smit and Waller (*17*) used OBSI and the CPX method to measure sound intensity levels and sound pressure levels on DGHMA, PFC/OGFCs, microsurfacing, and SMA mixtures. The results indicated that the noise levels were also influenced by layer thickness of the surface mixtures. Twelve different pavement sections were tested, and the structures and mixtures are shown in Table 12.

Table 12. Structures and Mixtures of 12 Pavement Sections Tested by NCAT (*17*).

Section	***N5 N6 N7***			***N8***	***N9***
Layer 1 (32 mm (1.26 in))	PFC/OGFCs	PFC/OGFCs	PFC/OGFCs	PA (coarse)	PA (coarse)
Layer 2 (32 mm (1.26 in))	DGHMA	PFC/OGFCs	PA (coarse)	PA (coarse)	DGHMA
Section	***S2 S4 S5***			***S6***	***S7***
Layer 1 (50 mm (1.97 in))	EAP	4.75mm (0.19 in)-DGHMA	9.5mm (0.37 in)-DGHMA	<4.75mm (0.19 in)-SMA	4.75mm (0.19 in) -SMA
Layer 2	Existing track				
Section S8		***S9***			
Layer 1 (50 mm (1.97 in))	9.5mm -SMA	Microsurfacing			
Layer 2	Existing track				

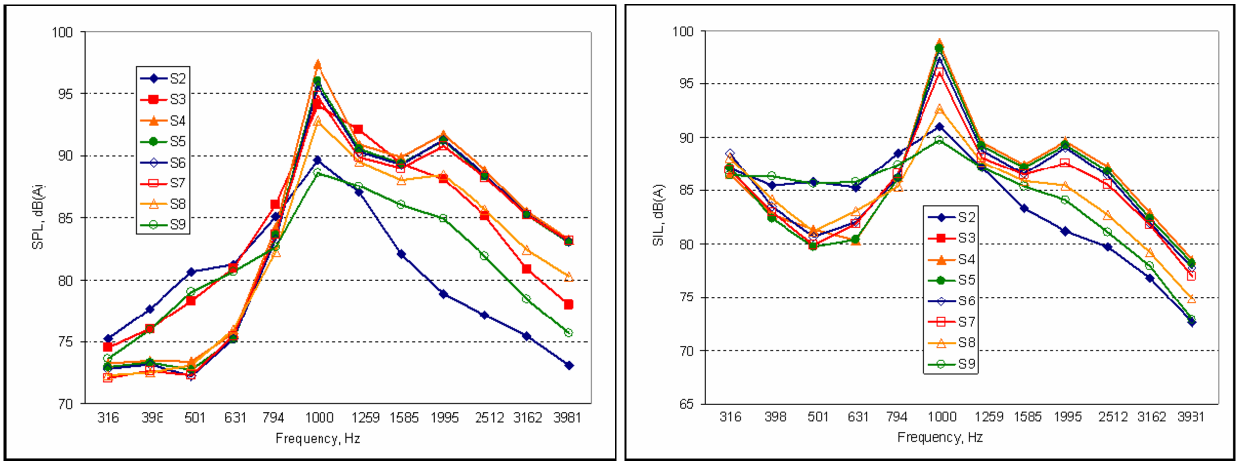
Note: EAP: the East Alabama asphalt plant (proprietary PFC/OGFCs)

Based on the results of OBSI and the CPX methods, the study illustrated that in general the thicker the layer, the lower the tire/pavement noise level. Figures 5 and 6 show the comparison of sound pressure and intensity levels on different pavement surfaces at a vehicle speed of 97 kph (60 mph).



Note: SPL: sound pressure level; SIL: sound intensity level

Figure 5. Comparison of Sound Pressure and Intensity Levels on PFC/OGFCs Surface Pavements from NCAT (*17*).



Note: SPL: sound pressure level; SIL: sound intensity level

Figure 6. Comparison of Sound Pressure and Intensity Levels on DGHMA, SMA, and Microsurfacing Surface Pavements from NCAT (*17*).

California (2008)

Ongel et al. (*6*) evaluated layer thickness as one of the variables affecting noise levels on four different surface pavement types: PFC/OGFCs with and without rubber, gap-graded HMA with rubber, and DGHMA. OBSI levels increased with an increase in surface layer thickness, and PFC/OGFCs had lower sound intensity levels compared to DGHMA. CalTrans (*15*) indicated that thickness did not affect the noise levels on PFC/OGFCs layers around 30 mm (1.18 in); however, increasing thickness may lower the noise levels for thickness above 50 mm (2 in), which may be less susceptible to clogging and to reduce their permeability.

2.1.1.4. Texture and Roughness of the Pavement Surface

One of the main characteristics of pavement surfaces pertaining to noise is texture. The texture of pavement surfaces can be divided into three categories: megatexture, macrotexture, and microtexture. Most research on tire/pavement noise has focused on the macrotexture and microtexture. The macrotexture is defined as surface asperities that range from 0.1 to 20 mm (0.004 to 0.79 in) in height and from 0.5 to 50 mm (0.02 to 1.97 in) in width, while the microtexture is defined as surface asperities that range from 0.001 to 0.5 mm ($3.94*10^{-5}$ to 0.02 in) in height with widths less than 0.5 mm (0.02 in). The function of macrotexture, which creates channels that water can escape from, is to provide a dry pavement surface to maintain high friction, while the function of microtexture is to provide high dry friction on the pavement surface. Rough texture increases the tire vibration, thus increasing the tire/pavement noise levels (*18, 19*).

NCAT (2007)

Smit and Waller (*17*) measured sound intensity levels and sound pressure levels on DGHMA, PFC/OGFCs, microsurfacing, and SMA mixtures. The sound pressure and intensity levels on different pavement surfaces at a vehicle speed of 97 kph (60 mph) were shown in Figures 5 and 6. Twelve different pavement sections were tested. Corresponding structures and mixtures were shown in Table 12. Figures 7 through 10 show the surface texture of the measured pavement surfaces. The scale of the figures indicates both 10 mm (0.39 in) and 25.4 mm (1 in) subdivision intervals. The apparent macrotexture on the DGHMA as well as the nominal aggregate size less than 4.75 mm (0.19 in) SMA and 4.75 mm (0.19 in) SMA is smooth, while the macrotexture on the proprietary PFC/OGFCs from the East Alabama asphalt plant (EAP), microsurfacing, and 9.5 mm (0.37 in) SMA surfaces is rough. In general, the results showed that the lower the macrotexture of the surface pavement the quieter the pavement. Too low a macrotexture, however, results in increase noise levels due to air pmping at tire/pavement interface.

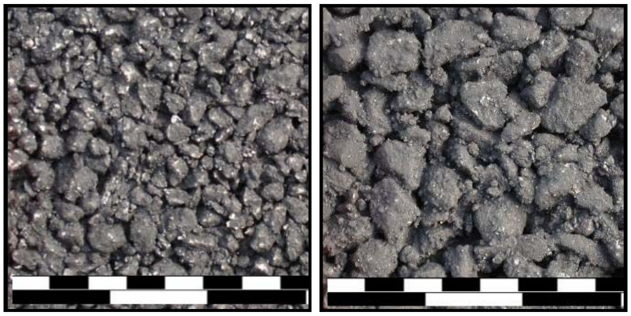


Figure 7. Surface Texture of PFC/OGFCs (left) and PA-coarse (right) Mixtures (*17*).

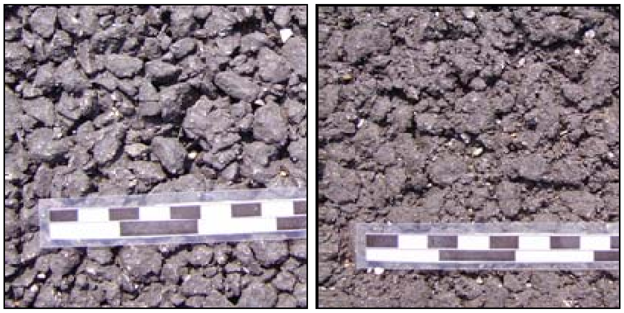


Figure 8. Surface Texture of EAP (left) and Microsurfacing (right) Mixtures (*17*).

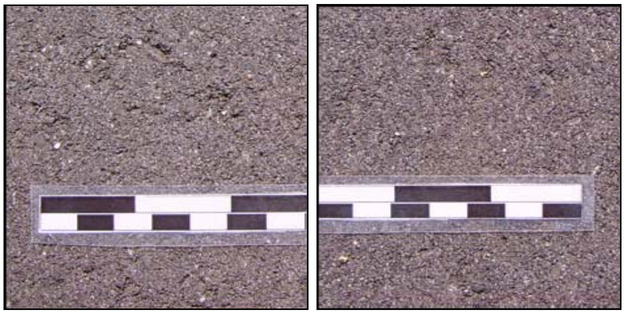


Figure 9. Surface Texture of 4.75 mm (0.19 in)-DGHMA (left) and 9.5 mm (0.37 in)-DGHMA (right) Mixtures (*17*).

Figure 10. Surface Texture of <4.75 mm (0.19 in)-SMA (left), 4.75 mm (0.19 in)-SMA and 9.5 mm (0.37 in)-SMA (right) Mixtures (*17*).

California (2008)

Ongel et al. (*6*) evaluated the effect of roughness and macrotexture of the surface layer on noise levels for four different types of surface pavements: PFC/OGFCs with and without rubber, gap-graded HMA with rubber, and DGHMA. Roughness was measured with the inertial laser profiler, and macrotexture was measured with the British pendulum tester. Noise levels increased with roughness and also increased with increasing macrotexture.

Spain (2008)

Miró et al. (*20*) conducted a study to determine the correlations between texture and noise levels in several test sections. All sections were constructed with three types of binders: bitumen with crumb rubber by the wet process (CRMB), the same bitumen with addition of crumb rubber by the dry process (CRMB+1% and CRMB+2%), and polymer-modified bitumen (PMB). Figure 11 shows the correlation between texture and noise level. For PMB mixtures, a texture increase resulted in an increase in the noise level, while a texture increase did not increase the noise level for crumb rubber mixtures by both wet and dry processes. However, for addition of crumb rubber by the dry process (CRMB+1% and CRMB+2%), the proportion of the increase in crumb rubber content leads to a decrease in texture.

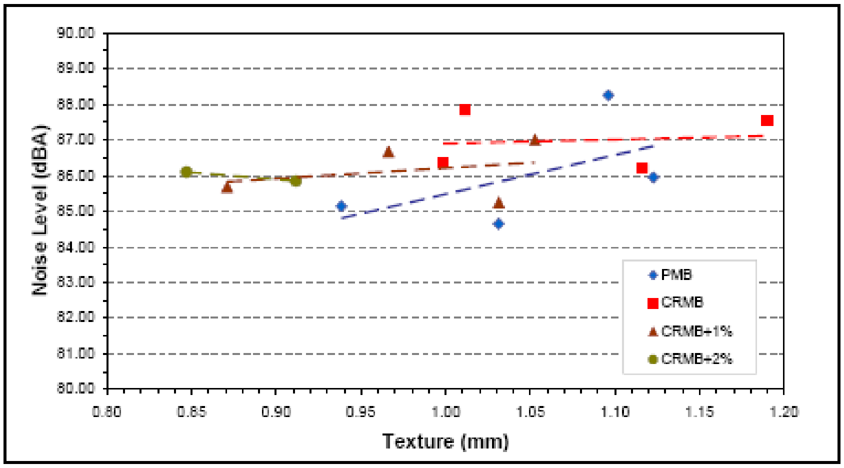


Figure 11. Correlation between Texture and Noise Level (*20*).

2.1.1.5. Air Temperature

Studies indicate that sound pressure levels can decrease with air temperature with a gradient ranging from -0.1 dB(A)/°C to -0.036 dB(A)/°C (*21*). As reported in NCHRP Report 630 (*22*), an increase of air temperature of about -8 °C (18 °F) results in a decrease of 1 dB(A) in the overall OBSI noise levels, which corresponding to 1 dB(A) decrease in noise level for a 9 °C (48.6 °F) increase in pavement temperature. Therefore, air temperature plays an important role affecting the tire/pavement noise levels especially in areas with a large daily temperature difference.

In 2007, Smit and Waller (*23*) investigated the influence of variations in air temperature on tire/pavement noise measurement. The sections, which included DGHMA, PFC/OGFCs, and SMA, were tested at different air temperature at 5 a.m. (10 °C [50 °F]), 9 a.m. (19 °C [66 °F]), 12 p.m. (26 °C [79 °F]), and 3 p.m. (30 °C [86 °F]). The study indicated that maximum differences in mean sound levels at different temperatures were about 1 dB(A), and that a temperature increase did not seem to result in a large change in the sound level. However, on most sections, the sound levels were higher at the lower temperature. Sound pressure levels were also more affected by temperature variations at frequencies above 1500 Hz, especially at temperatures below 21 °C (70 °F). Figure 12 shows the temperature and frequency influence on sound pressure levels.

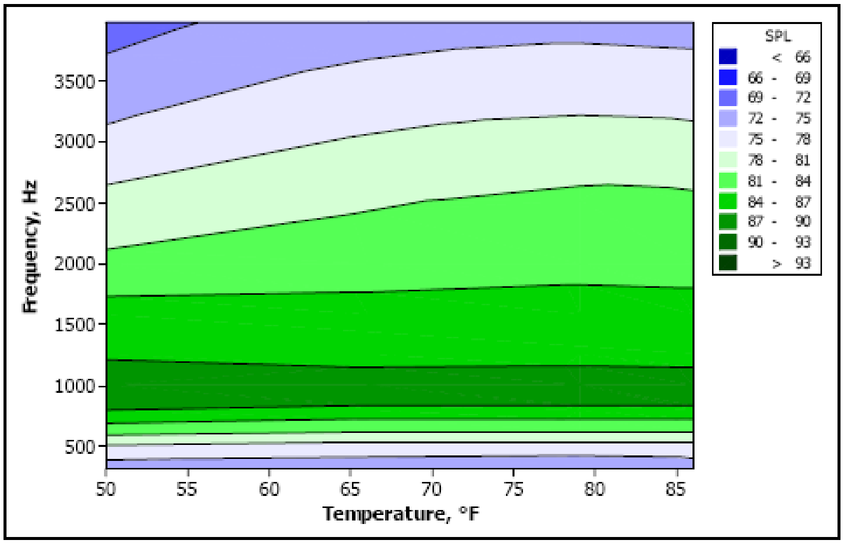


Figure 12. Temperature and Frequency Influence on Sound Pressure Levels (*23*).

As reported in NCAT Report 07-04 (*21*), the influence of air temperature on tire/pavement interface noise was investigated with the CPX and OBSI methods on DGHMA, PFC/OGFCs, and SMA pavement surfaces. Figure 13 shows box-plots of the sound pressure and sound intensity data with four air temperatures. Since there are no clear trends in Figure 13, the results suggested that temperature correction of measured sound levels is not necessary at temperatures from 10 °C to 30 °C (50 °F to 86 °F).

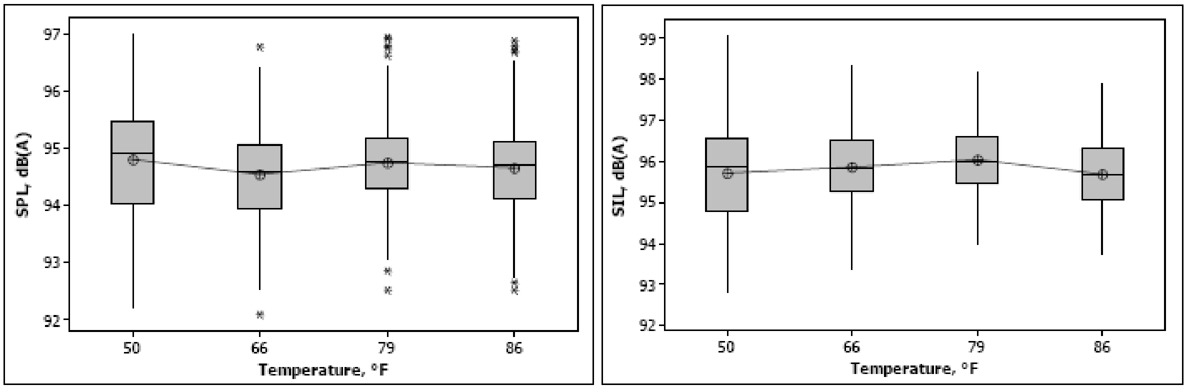


Figure 13. Box Plots of Sound Pressure Level (SPL) and Sound Intensity Level (SIL) vs. Air Temperature (*21*).

Sound intensity levels were also more affected by temperature variations at frequencies above 1500 Hz, especially at temperatures below 21 °C (70 °F). Figure 14 shows the influence of temperature and frequency on sound intensity levels.

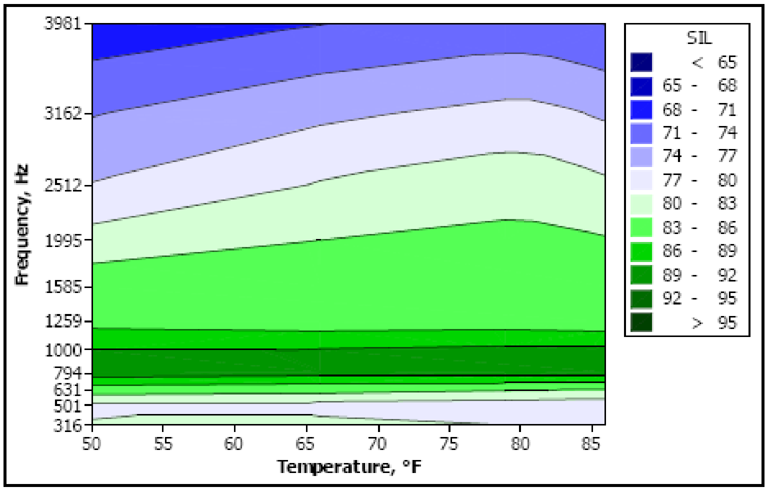


Figure 14. Influence of Temperature and Frequency on Sound Intensity Levels Measured by NCAT (*21*).

2.1.1.6. Type of Tire

Tires can adjust themselves to changes in the road surface and expand laterally due to their flexibility. These two kinds of distortions lead to a spatial reduction in the tire tread, which causes additional noise and an increase in tire/pavement noise levels. Since different tires have different stiffness, the influence of tire types on tire/pavement noise levels has been investigated.

NCAT (2007)

As indicated in NCAT Report 07-02 (*16*), the influence of tire types at 72 and 96 kph (45 and 60 mph) on tire/pavement noise pressure levels was evaluated. Three different tires were tested: the Goodyear Aquatread (GDYR), the Uniroyal Tiger Paw (UNIR), and the Michelin standard reference test tire (SRTT). Five different pavement sections (N5 to N9) were tested with the structures and mixtures shown in Table 10. Figure 15 illustrates the treads of each tire showing that the UNIR is similar to the SRTT. The treads of the SRTT are slightly wider. Tire inflation pressure of each tire was 2.11 kg/cm^2 (30 psi).

Figure 15. Tires Tested by NCAT from Left to Right Are GDYR, UNIR, and SRTT (*16*).

Table 13 summarizes the sound pressure levels on the five tested pavement surfaces at speeds of 72 and 96 kph (45 and 60 mph) with all three tires. The data indicate that the sound pressure levels with the GDYR tires are higher than those with the UNIR tires. The order of sound pressure levels with the three types of tires is GDYR, SRTT, and UNIR. The sound level at the tire/pavement noise from best to worst is N6 (the double layer OGFCs), N7, N5, N8, and N9 (the single layer coarse OGFCs) at both speeds of 72 and 96 kph (45 and 60 mph). These results showed that the type of tires can influence sound pressure levels on the same type of pavement surfaces.

Table 13. Sound Pressure Levels with Different Tires (*16*).

Tire	*Section*	*Sound Pressure Level, dB(A)*	
		72 kph (45 mph)	*96 kph (60 mph)*
GDYR	N5	89.56	92.18
	N6	88.06	91.46
	N7	88.40	92.31
	N8	92.60	95.93
	N9	94.58	98.00
UNIR	N5	87.37	89.66
	N6	86.82	89.25
	N7	87.45	90.19
	N8	92.28	94.74
	N9	92.99	95.65
SRTT	N5	89.26	91.11
	N6	87.47	89.78
	N7	88.11	90.45
	N8	91.72	94.90
	N9	94.12	97.13

Washington (2008)

Pierce et al. (*24*) examined three pavement sections, including PFC/OGFCs with rubber, PFC/OGFCs with styrene butadiene styrene (SBS), and DGHMA, using the OBSI method. The study investigated the effects of studded tires on sound intensity levels. A clear noise reduction happened outside of the wheel path (Figure 16), and the large increase of noise levels was attributed to studded tires.

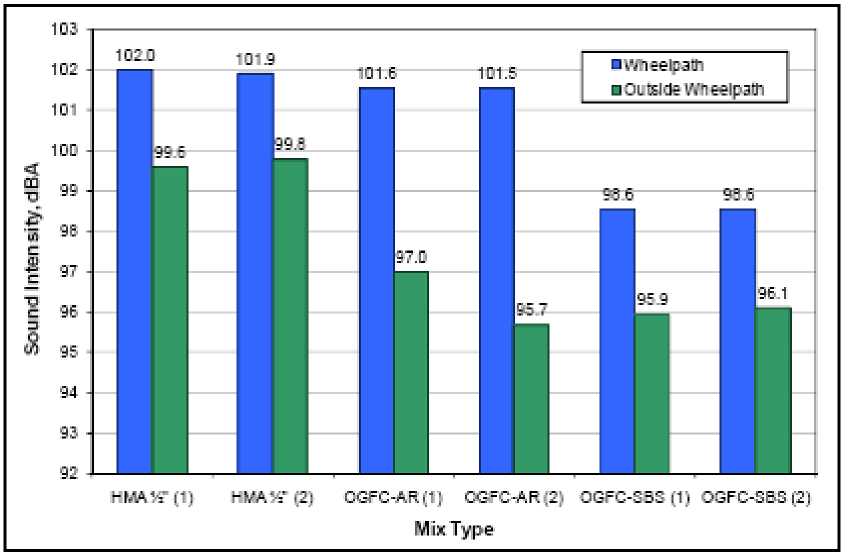


Figure 16. Sound Intensity Levels In/Outside of Wheelpath Measured in Washington (*24*).

Texas (2008)

Trevino et al. (*7*) compared the UNIR tire to the Michelin SRTT tire using identical vehicles equipped with each tire, testing both conventional asphalt sections and tined CRCP sections. Subsequent analysis found a mean difference of 0.6 dB(A) with a standard error of 0.16. This finding supports the NCAT and NCHRP conclusion that the difference is sufficiently negligible to justify most comparisons between data taken with the old and new standard test tires. The reference also provides a regression model calibrating measurements using the two tire types. It should be noted that although the composite A-weighted result is essentially interchangeable, the results vary slightly with the type of pavement tested (PCC vs. DGHMA), and more substantially in some of the individual frequency bands.

2.1.1.7. Age of Mixture

Colorado (2004)

Based on the study of different HMA surfaces (DGHMA, PFC/OGFCs, Novachip, and SMA), Hanson and James (*4*) concluded that the noise characteristics of HMA are dependent on the mixture age. Figure 17 presents the relationship between age and pavement noise measured by the CPX method. The authors indicated that the functionality in terms of noise reduction was lost with an increase of mixture age.

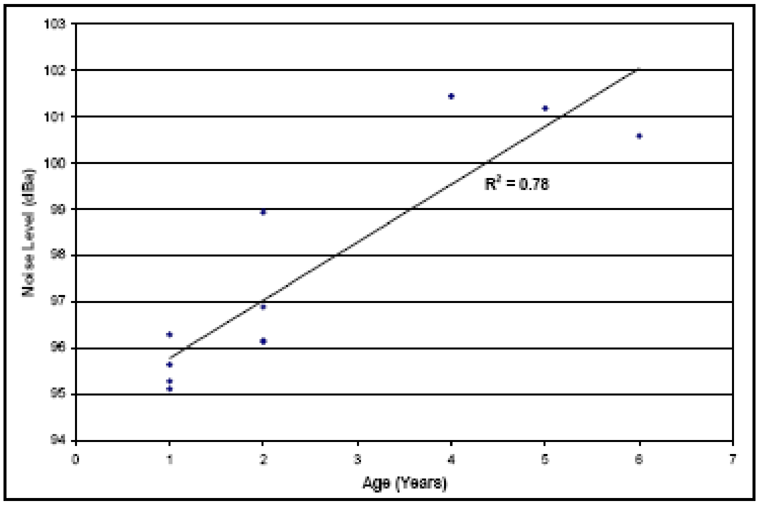
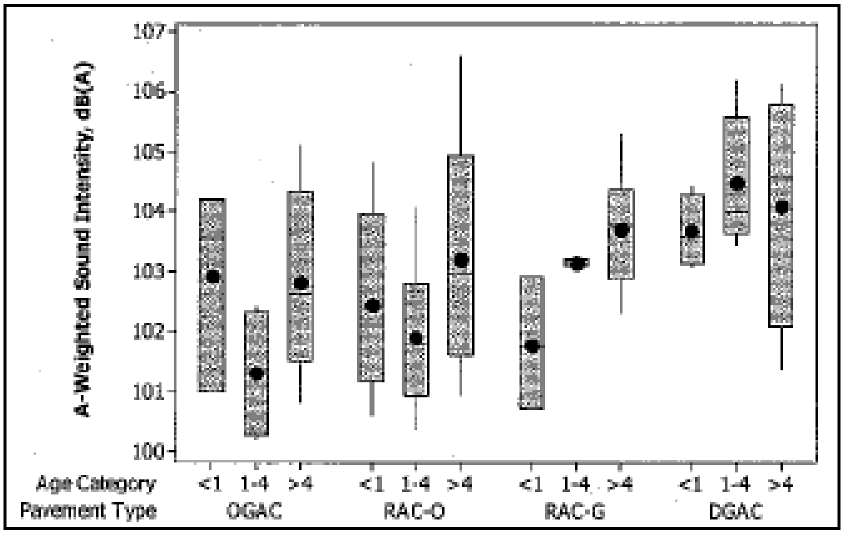


Figure 17. Relationship between Age and Noise Level for All HMA Mixtures Measured by Colorado DOT (*4*).

California (2008)

Ongel et al. (*6*) investigated the effects of age on the sound intensity levels of PFC/OGFCs with and without rubber, gap-graded HMA with rubber, and DGHMA in California. Figure 18 shows the sound intensity levels on different pavement surfaces at different ages. The DGHMA had higher sound levels than other pavements, and in general, sound intensity levels increased with age. PFC/OGFCs in 1-4 years of age reduced the noise level by 3 dB(A). Gap-graded HMA with rubber, however, behaved like DGHMA after only 4 years.

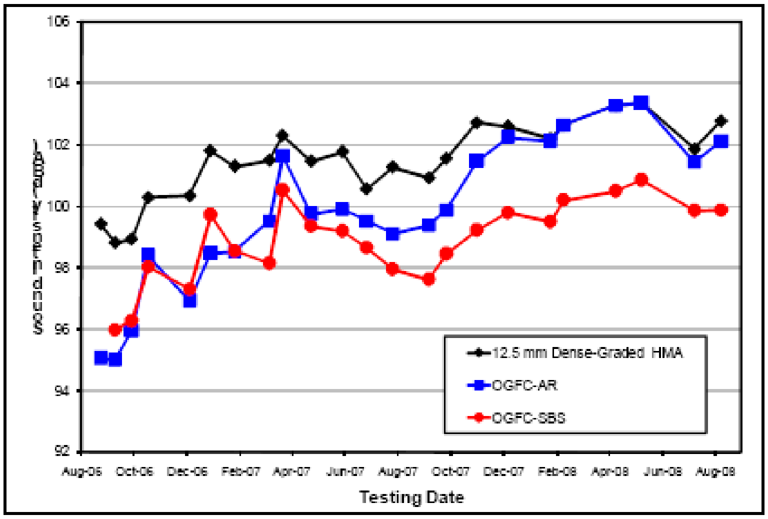


Note: OGAC: PFC/OGFCs without rubber; RAC-O: PFC/OGFCs with rubber; RAC-G: gap-graded HMA with rubber

Figure 18. Box Plot of SILs for Diverse Mixtures at Different Age in California (*6*).

Washington (2008)

Pierce et al. (*24*) investigated the effects of mixture age on the sound intensity levels on three pavement sections: PFC/OGFCs with rubber, PFC/OGFCs with styrene butadiene styrene (SBS), and DGHMA on a four-lane highway. Figure 19 shows the sound intensity levels for these three mixtures with time. All of the tested pavements got noisier, and the PFC/OGFCs with rubber acted like the DGHMA after only 1.5 years due to studded tire wear.

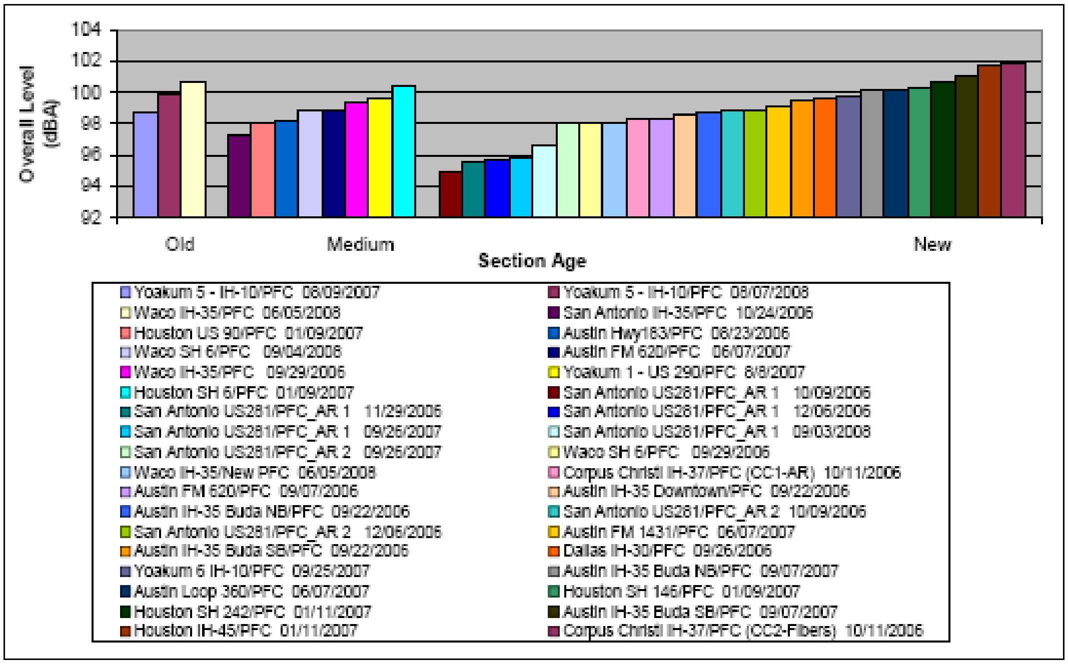


Note: OGFC-AR: PFC/OGFCs with rubber

Figure 19. Sound Intensity Level for Three Pavements with Time Measured in Washington (*24*).

Texas (2008)

The TxDOT (*7*) using the OBSI method at a vehicle speed of 96 kph (60 mph) measured the pavement noise levels of several highway test sections in Texas. The effects of pavement age on the sound intensity levels were also studied on PFC/OGFCs mixtures. The OBSI results determined at different ages for PFC/OGFCs mixtures are presented in Figure 20. The average noise levels of old pavements were 99.8 dB(A), the medium pavements were 98.9 dB(A), and the new pavements were 98.7 dB(A).



Note: Old: age>=5 years; Medium: 2<age<5 years; New: age<=2 years

Figure 20. OBSI Results Determined at Different Ages for PFC/OGFCs Mixtures in Texas (*7*).

The noise level of PFC/OGFCs mixtures seems to increase with age. Clogging and traffic compaction, and thus reduction in both the size and amount of AV, were probably the main reasons. However, the study indicated that the amount of clogging and the rate of compaction did not significantly diminish the capability of PFC/OGFCs to reduce pavement noise levels over the reasonable service life (normally considered to be between 6 and 8 years).

2.1.1.8. Traffic Condition

Traffic conditions may accelerate the rate of traffic compaction in HMA mixtures and increase the pavement noise levels. This section reports results of several studies that focused on the effect of traffic conditions on tire/pavement noise levels.

NCAT (2007)

As indicated in NCAT Report 07-02 (*16*), the influence of vehicle type on sound intensity levels on both single and double layer structures constructed with fine- and coarse-PFC/OGFCs were investigated. The pavements were tested at a speed of 72 kph (45 mph), and the noise levels of passenger vehicles with/without 90.6 kg (200 lbs) load and trucks were measured on five different pavement sections (Table 10). The results indicated that the sound intensity levels generally increased with the increasing weight of vehicles. Table 14 shows the sound intensity levels with different types of vehicles.

Table 14. Sound Intensity Levels with Different Vehicles (*16*).

Vehicle Type	*Section*	*Sound Intensity Level, dB(A)*
		72 kph (45 mph)
Passenger vehicle	N5	91.02
	N6	88.93
	N7	89.45
	N8	93.74
	N9	96.10
Passenger vehicle with 90.6 kg (200 lbs)	N5	91.35
	N6	88.99
	N7	89.41
	N8	93.89
	N9	95.91
Truck	N5	92.82
	N6	92.03
	N7	91.20
	N8	94.72
	N9	96.44

Indiana (2008)

Kowalski et al. (*14*) monitored the pavement noise levels of three highway test sections as well as the noise levels under different traffic conditions (passenger vehicle and heavy vehicle). The test sections were DGHMA, SMA, and PFC/OGFCs. The study assumed that an equal number of vehicles were driven in both directions, and the average truck had 4.5 axles. In addition, the sound pressure levels were tested at a speed of 100 kph (62 mph). The results from Figures 21 and 22, in general, show that the sound pressure level is about 75 dB(A) for passenger vehicles and about 86 dB(A) for heavy vehicles on the PFC/OGFCs section. On the SMA section, the sound pressure level is about 80 dB(A) for passenger vehicles and about 90 dB(A) for heavy vehicles. Sound pressure level also substantially increased with traffic volume after the initial noise measurement.

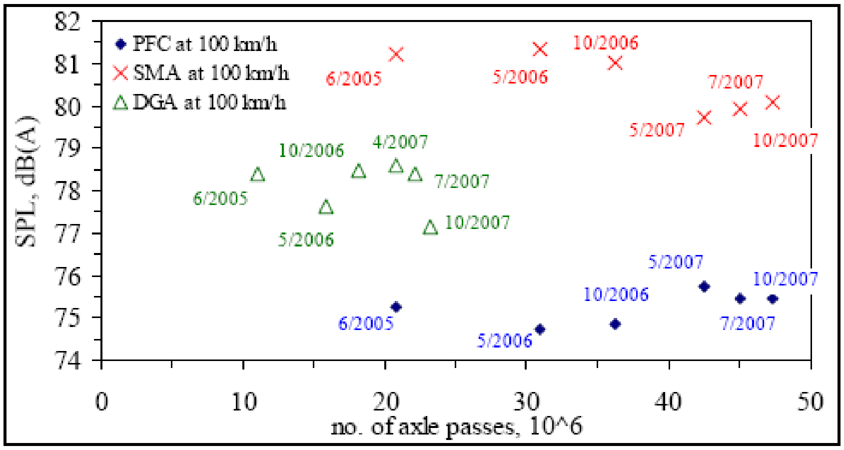


Figure 21. Noise Level with Traffic Volume for Passenger Vehicles at 100 kph (62 mph) Measured in Indiana (*14*).

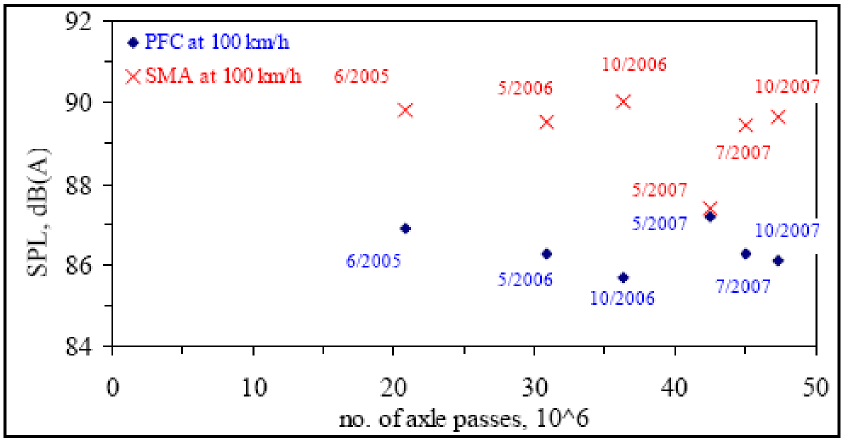


Figure 22. Noise Level with Traffic Volume for Heavy Vehicles at 100 kph (62 mph) Measured in Indiana (*14*).

2.1.1.9. Nominal Aggregate Size

In the past few years, quiet pavement systems in Europe employed a reduction in nominal aggregate size in the pavement surface to decrease the noise level. In the United States, researchers also found that a noise reduction can be produced by a reduction in nominal aggregate size. CalTrans (*15*) recommended that the best approach to reduce noise is to use PFC/OGFCs with nominal aggregate size of 12.5 mm (0.5 in) instead of 9.5 mm (0.37 in).

New Jersey (2005)

Bennert et al. (*10*) investigated the effect of nominal aggregate size on the tire/pavement generation noise of both DGHMA and SMA in New Jersey. The DGHMA mixtures had nominal aggregate sizes that ranged from 9.5 to 19 mm (0.37 to 0.75 in), while the SMA mixes had nominal aggregate sizes of 9.5 and 12.5 mm (0.37 and 0.5 in). The tire/pavement noise levels for the DGHMA and SMA sections were measured by the CPX method at 96 kph (60 mph). Figures 23 and 24 show the noise pressure levels for the DGHMA and SMA test sections with different nominal aggregate sizes.

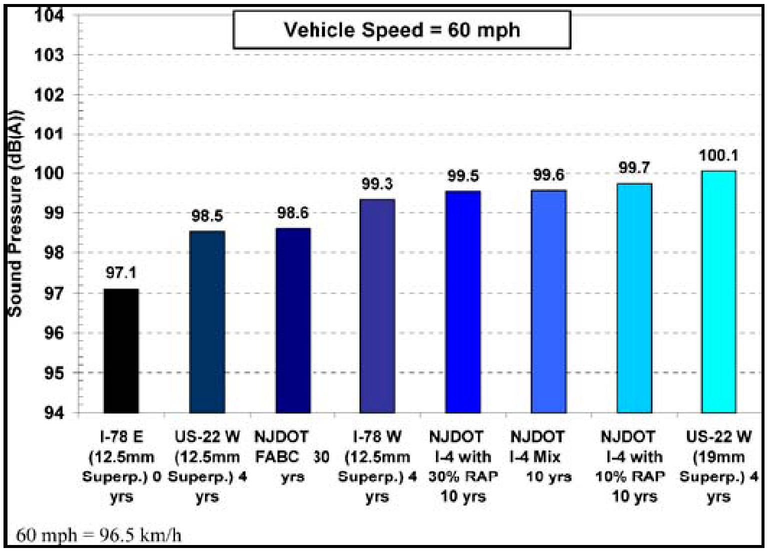


Figure 23. SPLs for DGHMA Sections Measured in New Jersey (*10*).

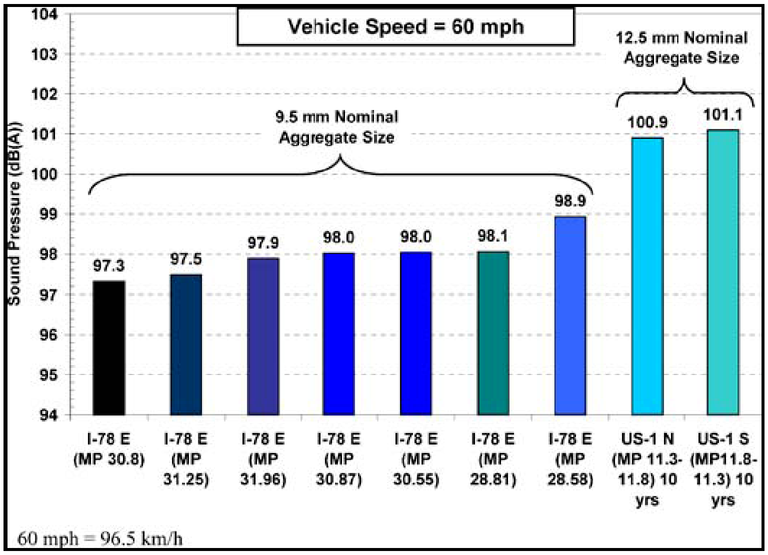


Figure 24. SPLs for SMA Sections Measured in New Jersey (*10*).

The results demonstrated that the nominal aggregate size of the HMA has an effect on pavement noise. The DGHMA sections showed that the nominal aggregate size of 12.5 mm (0.5 in) produced less noise than the 19 mm (0.75 in) nominal aggregate size DGHMA mixture, and the nominal aggregate size of 9.5 mm (0.375 in) in SMA sections had lower noise levels than the 12.5 mm (0.5 in) nominal aggregate size SMA mixture.

NCAT (2007)

As reported in NCAT Report 07-03 (*25*), the noise levels on DGHMA and SMA pavement surfaces with varying nominal maximum aggregate sizes were measured using OBSI and the CPX method. The DGHMA mixtures had nominal maximum aggregate sizes of 4.75 and 9.5 mm (No. 4 and 3/8 in), while the SMA mixtures had nominal maximum aggregate sizes which were less than 4.75 mm (No. 4), equal to 4.75 mm (No. 4), and equal to 9.5 mm (3/8 in). Table 15 presents the sound pressure levels and sound intensity levels for DGHMA and SMA with different nominal maximum aggregate size at 72 and 96 kph (45 and 60 mph). The results show that the noise levels decreased with the increasing nominal maximum aggregate sizes. Tire tread depth and weight of the vehicle may also be influencing factors.

Table 15. Sound Pressure and Intensity Levels for DGHMA and SMA Measured by NCAT (*25*).

Surface Type	***Nominal maximum Aggregate Size***	***Sound Pressure Level, dB(A)***		***Sound Intensity Level, dB(A)***	
		72 kph (45 mph)	***96 kph (60 mph)***	***72 kph (45 mph)***	***96 kph (60 mph)***
DGHMA	4.75 mm (No. 4)	93.8	100.4	94.9	101.0
	9.5 mm (3/8 in)	93.8	99.5	94.6	100.6
SMA	< 4.75 mm (< No. 4)	93.8	99.3	94.2	100.2
	2.2. mm (No. 4)	93.8	98.8	93.7	99.1
	9.5 mm (3/8 in)	92.5	97.1	92.8	97.5

2.1.1.10. Binder Type

Binder type appears to play an important role in the noise level reduction at the tire/pavement interface. Changing binder type can reduce traffic noise and save money by avoiding other costly noise-reduction alternatives.

In 2008, Miró et al. (*20*) conducted a study to determine the noise pressure levels at 50 kph (31.3 mph) after adding crumb rubber to gap-graded mixtures in several test sections in Spain. All sections were constructed with three types of binder: bitumen with crumb rubber by the wet process (CRMB), the same bitumen with crumb rubber by the dry process (CRMB+1% and CRMB+2%), and polymer-modified bitumen (PMB). When comparing noise levels for the CRMB, CRMB+1%, and CRMB+2% mixtures (Table 16), the noise pressure level decreased with increasing addition of crumb rubber by the dry process.

Table 16. Noise Level Measurements with Different Bitumen Types in Spain (*20*).

Bitumen Type	***Sound Pressure Level, dB(A)***
PMB	86.24
CRMB	88.15
CRMB+1%	87.04
CRMB+2%	86.80

2.1.1.11. Air Voids (AV) Content

The noise reduction effectiveness of PFC/OGFCs is dependent on the AV content in the mixture. This factor affects the high frequency component of the pavement noise level (higher than 1200 Hz) (*4*).

Colorado (2004)

The Colorado DOT (*4*) concluded that the noise characteristics of PFC/OGFCs are dependent on the AV content in the mixture based on a study that included four states (Alabama, Nevada, Arizona, and Colorado). The results indicate that as the AV content of the mixture increased, the noise levels decreased (Figure 25).

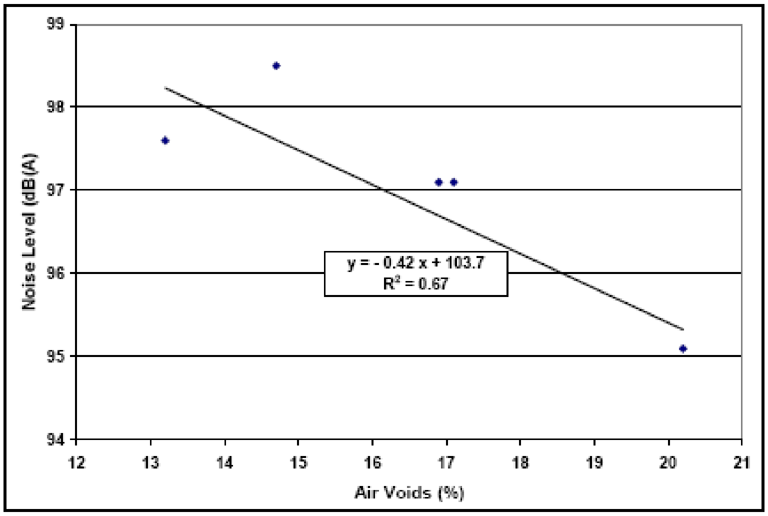
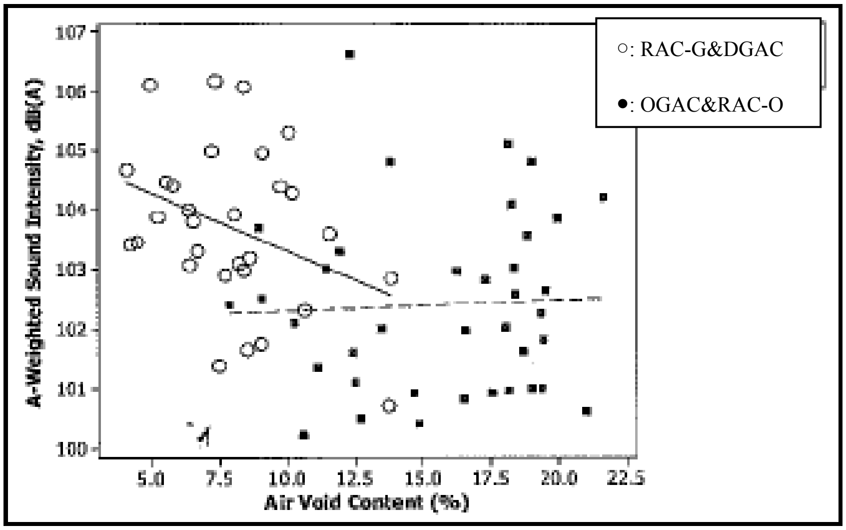


Figure 25. Effect of Air Voids Content on Noise Level Presented by Colorado DOT (*4*).

California (2008)

Ongel et al. (*6*) conducted a study to investigate the effects of AV content on the sound intensity levels of pavements constructed with PFC/OGFCs with and without rubber, gap-graded HMA with rubber, and DGHMA. As shown in Figure 26, the sound intensity level decreased with increasing AV content, although the linear correlation was limited.



Note: OGAC: PFC/OGFCs without rubber; RAC-O: PFC/OGFCs with rubber; RAC-G: gap-graded HMA with rubber

Figure 26. Sound Intensity Levels vs. Air Voids Content Measured in California (*6*).

The study also found that AV content has only a small effect on PFC/OGFCs due to the greater mean profile depth (MPD) for larger AV contents in OGFCs mixtures. MPD is the mean profile depth measured by Circular Texture Meter (CTM). The MPD was defined in ASTM E1845 and measured with the CTM in both the laboratory and the field. The CTM uses a laser displacement sensor to measure the surface profile of a circle 284 mm (11.2 in) in diameter or 892 mm (35 in) in circumference. CalTrans (*15*) indicated that the noise levels of OGFCs mixtures with AV content above 15 percent associated with high MPD values did not vary significantly with changes in AV.

2.1.1.12. Aggregate Gradation

The noise levels of PFC/OGFCs are also dependent on the aggregate gradation of the mixture. Aggregate gradation affects the low frequency component of the pavement noise level (lower than 800 Hz) (*4*).

Colorado (2004)

The Colorado DOT (*4*) concluded that the noise characteristics of PFC/OGFCs are dependent on the aggregate gradation of the mixture based on a study that included the states of Arizona, Nevada, Colorado, and Alabama. Table 17 presents the effect of aggregate gradation of

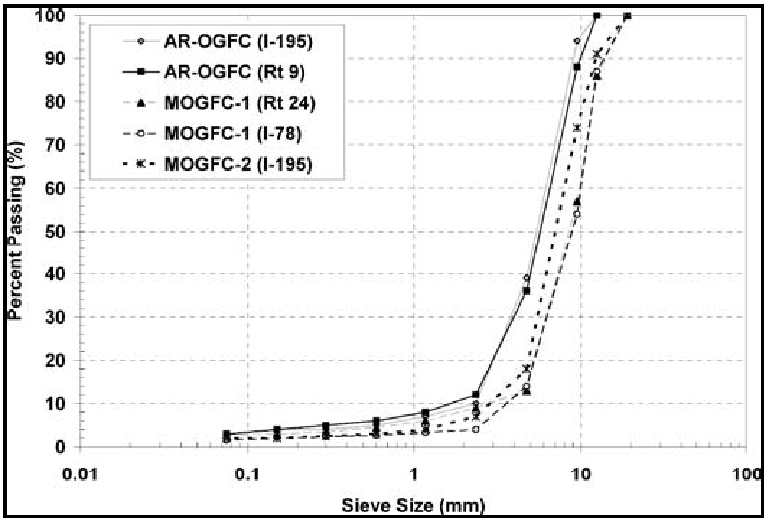
PFC/OGFCs on noise level in these states. The results indicated that when the percent aggregate retained on the 9.53 mm (3/8 in) sieve was reduced, the noise level decreased. Hence, as the aggregate gradation becomes finer, the noise level becomes lower.

Table 17. Aggregate Gradations of PFC/OGFCs in Four States Presented by Colorado DOT (*4*).

Gradation	*Arizona*	*Nevada*	*Colorado*	*Alabama*
19 mm (3/4 in)	-	-	100	100
12.5 mm (1/2 in)	-	100	98	89
9.5 mm (3/8 in)	100	95	64	56
4.75mm (No. 4)	38	45	11	14
2 mm (No. 8)	6	-	8	9
1.18 mm (No. 16)	-	11	6	-
0.75 mm (No. 200)	1.2	2	3.3	3.2
Average Noise Level, dB(A)	91.5	93.8	95.1	98.6

New Jersey (2005)

Bennert et al. (*10*) investigated the effect of aggregate gradation on the tire/pavement generation noise on PFC/OGFCs pavements with and without crumb rubber. Figure 27 presents the gradation of the different PFC/OGFCs studied, and Table 18 shows the noise level of each PFC/OGFCs.



Note: AR-OGFC: PFC/OGFCs with crumb rubber; MOGFC: PFC/OGFCs without crumb rubber

Figure 27. Gradation of Different PFC/OGFCs Studied in New Jersey (*10*).

Table 18. Noise Level of Different PFC/OGFCs Studied in New Jersey (*10*).

Surface Type	***Sound Pressure Level, dB(A)***
AR-OGFC (I-195)	96.2
AR-OGFC (Rt 9)	96.8
MOGFC-1 (Rt 24)	97.6
MOGFC-1 (I-78)	97.0
MOGFC-2 (I-195)	98.6

Two PFC/OGFCs with crumb rubber (AR-OGFC) had similar aggregate gradations (Figure 27), which explained why the noise levels are similar in Table 18. The noise levels for PFC/OGFCs without crumb rubber mixtures (MOGFC-1 and MOGFC-2), which are coarser in gradation, were higher than PFC/OGFCs with crumb rubber mixtures. Therefore, the finer aggregate gradation can reduce the tire/pavement generated noise.

2.1.1.13. Summary

Some researchers found that the thicker the PFC/OGFCs layer, the lower the noise levels at the tire/pavement interface (*17*), while other studies reported that noise levels increase with an increase in surface layer thickness (*6*). More research is needed to resolve this conflict. In addition, some studies speculated that the suction effect of the vehicle tires can clean and protect the pores from clogging at high vehicle speeds. However, there is no research that supports or concludes this. Hence, research on the suction effect of the vehicle tires on PFC/OGFCs mixtures is needed.

Some research indicates that the noise reduction effectiveness of PFC/OGFCs mixtures reduces in only a few years due to clogging of AV and traffic compaction. In addition, as reported in TxDOT Report 0-5185-3 in 2008 (*7*), there was a very slight increase in noise due to aging exposure but the amount was not practically significant over the reasonable service life (6 to 8 years) of the mixture. Therefore, a study separating age from traffic condition (in terms of volume or axle loadings) and factors causing clogging needs to be pursued.

Based upon recent literature (2004 to 2008), an overview of recent noise research is summarized in Table 19, including the agencies and date, pavement surface types, noise measurements, and factors included in each study. In addition, the noise levels on pavements can be either increased or decreased by various factors. Table 20 summarizes the effects of different factors on pavement noise.

Table 19. An Overview of Noise Research from 2004 to 2008.

Agency/Year	*Surface Types*	*Noise Measurements*	*Factors*
Danish Road Institute (2004)	PFC/OGFCs, SMA, open thin layers, DGHMA	SPB	Surface types
Colorado (2004)	PFC/OGFCs, SMA, DGHMA, Novachip	CPX	Surface types, aggregate gradation, AV, age
Indiana (2004)	PFC/OGFCs, SMA, DGHMA	CPB, CPX	Surface types
New Jersey (2005)	PFC/OGFCs, SMA, DGHMA, Novachip, Microsurfacing	CPX	Surface types, nominal aggregate size, vehicle speed, aggregate gradation
New Jersey (2005)	Thin-lift HMA, DGHMA	CPX	Surface types, vehicle speed
Sweden (2005)	PFC/OGFCs, DGHMA	CPX, CPB	Surface types
Asphalt Institute (2006)	OGFCs, SMA, HMA	CPX	Surface types
NCAT (2007)	PFC/OGFCs, SMA, DGHMA	CPX	Air temperature
NCAT (2007)	PFC/OGFCs, SMA, DGHMA, microsurfacing	OBSI, CPX	Layer thickness, macrotexture
NCAT (2007)	PFC/OGFCs	OBSI, CPX	Vehicle types, tire types, vehicle speed
NCAT (2007)	SMA, DGHMA, Microsurfacing	OBSI, CPX	Nominal maximum aggregate size
NCAT (2007)	PFC/OGFCs, SMA, DGHMA	OBSI, CPX	Air temperature
California (2008)	PFC/OGFCs, HMA(rubber/no rubber), DGHMA	OBSI	AV, age, roughness, texture, layer thickness , aggregate gradation, nominal aggregate size
Washington (2008)	PFC/OGFCs (rubber/ SBS), DGHMA	OBSI	Tire type, age
Indiana (2008)	PFC/OGFCs, SMA, DGHMA	SPB, CPB, CPX	Surface types, traffic conditions
Spin (2008)	PFC/OGFCs	CPX	Bitumen type, texture, skid resistance
Texas (2008)	PFC/OGFCs	OBSI, CPX	Surface types, age, tire type

Table 20. Summary of the Effect of Different Factors on Pavement Noise.

Factor Best	*Noise Reduction*
Surface type	PFC/OGFCs
Vehicle speed	Slow
Texture & Roughness	Decreased
Air temperature	High
Tire type	No studded tires
Traffic condition	Low volume
Nominal aggregate size	Small
Binder type	Crumb rubber modified
Air voids (AV)	High
Aggregate gradation	Fine

The best noise reduction with PFC/OGFCs is obtained at low volume traffic with slow speed, where studded tires are not allowed, in a high air temperature area. However, slow speeds may favor clogging of AV in the mixture. A decrease of pavement texture and roughness, small nominal aggregate size, high AV content, fine aggregate gradation, and the use of crumb rubber modified binder need to be considered as alternative parameters for selection of materials and mix design regarding the noise reduction effectiveness of PFC/OGFCs.

2.1.2. Drainability

The drainability conferred by an elevated connected AV content in PFC/OGFCs mixtures contributes to improved safety under wet weather conditions, and this is the main reason to use these mixtures as surface layers in the United States. At present, measurement of drainability is not directly included as part of the PFC/OGFCs mix design since specifying a minimum total AV content (i.e., 18 percent on specimens compacted using the Superpave Gyratory Compactor [SGC]) is considered an indirect indication of adequate permeability.

Recent research (*26*) concluded that obtaining a minimum value of either total AV content or permeability on SGC compacted specimens does not ensure adequate drainability of field-compacted PFC/OGFCs mixtures. Field drainability was measured, according to the Tex-246-F test procedure, in terms of the water flow value (WFV). The WFV is the time (expressed in seconds) required for a given water volume to flow through a PFC/OGFCs mixture using an outflow meter 152 mm in diameter. Results reported by Alvarez et al. (*27*) provided evidence as to the practical possibility of specifying a minimum requirement of permeability (e.g., 100 m/day [328.08 ft/day]) based on the field assessment of WFV. In addition, based on a modified version of the Kozeny-Carman equation proposed by Masad et al. (*28*), the expected value of permeability ($E[k]$) was recommended as an estimator to predict permeability for mix design and evaluation of PFC/OGFCs mixtures (*27*).

This section summarizes the following factors that influence mixture drainability and briefly describes related recent research conducted since 2004: binder content, compaction energy, aggregate gradation, maximum aggregate size, and determination of drainability.

2.1.2.1. Binder Content

As reported in NCHRP project 9-41 (*29*), Punith et al. (*30*) used a falling-head laboratory permeability test to evaluate the permeability of three different PFC/OGFCs mixtures (CRMB, 60/70 Pen-grade binder with fiber, and reclaimed polyethylene [RPEB]) at different binder contents. The authors indicated that an increase in asphalt binder content resulted in a lowering of AV content, and thus caused a reduction in permeability. The study concluded that an increase in asphalt content from 4.5 to 6.0 percent caused a drop of permeability from a value between 0.5 and 0.55 m^3/day (500 and 550 liters/day) to one between 0.4 and 0.425 m^3/day (400 to 425 liters/day).

2.1.2.2. Compaction Energy

Punith et al. (*30*) evaluated the permeability of three different PFC/OGFCs mixtures (CRMB, 60/70 Pen-grade binder with fiber, and reclaimed polyethylene (RPEB)) at different binder contents compacted with 25 and 50 blows per face by Marshall hammer. The 25 blows mixtures showed higher permeability than the 50 blows mixtures. Alvarez et al. (*31*) evaluated permeability of two PFC/OGFCs mixtures (PG and AR) compacted with 12 to 15 and 50 gyrations of the SGC. 12 to 15 gyrations of the SGC were required to achieve AV content values similar to those computed on corresponding road cores of the evaluated mixtures. The results indicated that the PG mixture reduced its water-permeability by approximately 80 percent when the number of gyrations was increased from 15 to 50.

2.1.2.3. Aggregate Gradation

Watson et al. (*32*) conducted a study in 2004 on drainability of PFC/OGFCs to evaluate the current criterion of 100 m/day permeability applied for mix design. The falling-head laboratory permeability test, which was adopted by Florida Department of Transportation (FDOT), was performed to measure permeability. All specimens were compacted at 50 gyrations with the SGC. The study indicated that an increase in permeability was achieved by making the aggregate gradation coarser, but it resulted in a great potential for durability problems. For the fine aggregate gradation, the current criterion of 100 m/day permeability was difficult to achieve. The authors found high variability (standard deviation of 22.8 m/day) in the permeability values measured.

2.1.2.4. Maximum Aggregate Size

In 2005, the Silvia project (*33*) reported drainability measurements for PA mixtures fabricated using different maximum aggregate sizes. Corresponding results were reported as percolation speed, expressed in cm/sec. The test results shown in Table 21 indicated that an increase in the maximum aggregate size of the gradation caused an increase in permeability.

Table 21. Permeability of PA in France (*29*).

Asphalt Type	***Class 1***		***Class 2***	
Max. Aggregate Size, mm (in)	6 (0.24)	10 (0.39)	6 (0.24)	10 (0.39)
Percolation Speed, cm/s (in/s)	0.6 (0.24)	0.8 (0.31)	0.9 (0.35)	1.2 (0.47)

2.1.2.5. Determination of Drainability

Determination of permeability in the laboratory is an important aspect that should be part of designing PFC/OGFCs mixtures. However, the measurement of permeability is not widely practiced, since it is indirectly integrated into most mixture design procedures by specifying a minimum AV content, which is considered to be representative of drainability. In the laboratory, permeability has been measured using permeameters with either falling head or constant head. The common approach to measure the drainage capacity of porous mixtures in the field is the determination of the time of discharge of a specific water volume. A unique modification of specifying a discharge rate for a specific volume of water in Europe is the Zarauz permeameter, where the water falls from a certain elevation and flows freely onto the pavement surface (*1*).

In 2008, Alvarez et al. (*27*) evaluated the suitability of the current approaches used to assess drainability of PFC/OGFCs mixtures and explored alternatives to improve this evaluation. In this research, laboratory evaluations were conducted using road cores as well as plant mixed-laboratory compacted (PMLC) specimens (or SGC specimens), produced using the SGC. Corresponding mixtures were obtained from nine PFC/OGFCs mixtures fabricated in the field and used in actual field projects. The mixtures included permitted evaluation of both binder types (AR and PG) used in Texas and corresponding aggregate gradations. The study focused on the assessment of the initial mixture drainability (as constructed) including permeability measurements conducted in the laboratory as well as determination of WFV used to assess field drainability right after construction. In the laboratory, falling head permeability tests were conducted in accordance with ASTM PS 129-01 to evaluate the drainability of road cores as well as PMLC specimens, and field assessments of WFV were conducted according to the Tex-246-F test procedure.

Based on the comparison of total AV content and laboratory-measured permeability for PG- and AR-mixtures (Figure 28), Alvarez et al. concluded that the linear relationship between total AV content and permeability values of SGC specimens cannot be employed for road cores extracted from mixtures produced by applying the current construction specifications for PFC/OGFCs mixtures. Although a linear relationship between total AV content and permeability values was shown for road cores of the AR mixtures, the slopes of the linear relationships obtained for these road cores and corresponding SGC specimens were not coincident.

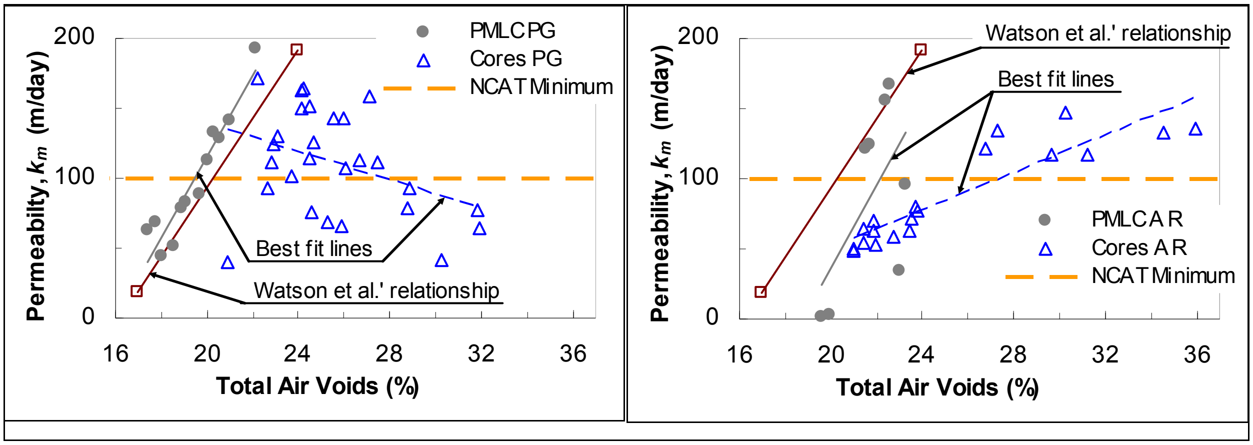


Figure 28. Comparison of Total Air Voids Content and Laboratory-Measured Permeability for (a) PG Mixtures and (b) AR Mixtures by Alvarez et al. (*27*).

In addition, the authors found that both the magnitude and variability in permeability values for SGC specimens and road cores provided additional evidence of the limitations encountered in predicting mixture drainability in the field based on permeability measurements conducted on laboratory (using SGC specimens). This conclusion was based on the comparison of road cores and SGC specimens in terms of (a) laboratory-measured permeability and (b) total AV content (Figure 29). In general, the road cores exhibited higher permeability values as compared to SGC specimens.

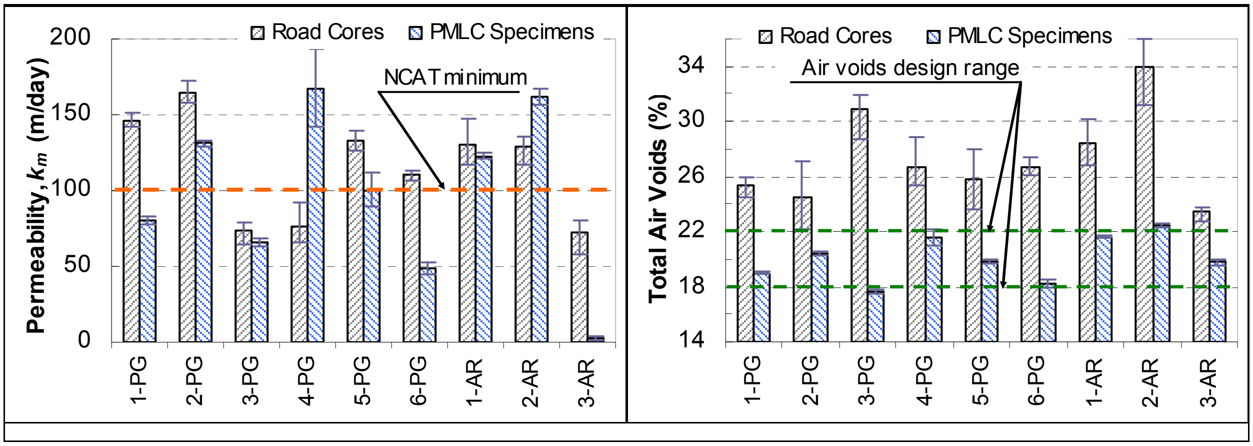


Figure 29. Comparison of Road Cores and SGC Specimens in Terms of (a) Laboratory-Measured Permeability and (b) Total Air Voids Content (*27*).

According to the results reported by Alvarez et al. (*27*), the authors evaluated the relationship of water-accessible AV content and laboratory-measured permeability, and the relationship of laboratory and field drainability. The first relationship indicated that water-accessible AV content may be adopted as a surrogate of the total AV content to indirectly assess the permeability of PFC/OGFCs mixtures, although improvements in the internal structure of SGC specimens are required before pursuing the determination of a useful relationship. The water-accessible AV content may better capture the content of AV directly associated with drainability, since it constitutes an indication of the proportion of AV that form connected pathways for transport of air and water through PFC/OGFCs mixtures (*27*). The relationship of laboratory-measured permeability and WFV presented by Alvarez et al. (Figure 30) showed that a maximum WFV of 21.5 and 13.3 seconds are required for PG and AR mixtures, respectively, to guarantee a minimum permeability value of 100 m/day. Although the WFV constitutes a practical parameter to verify the drainability of PFC/OGFCs mixtures in the field, it does not allow calculation of a fundamental property (e.g., permeability) to facilitate comparisons with other field or laboratory measurements.

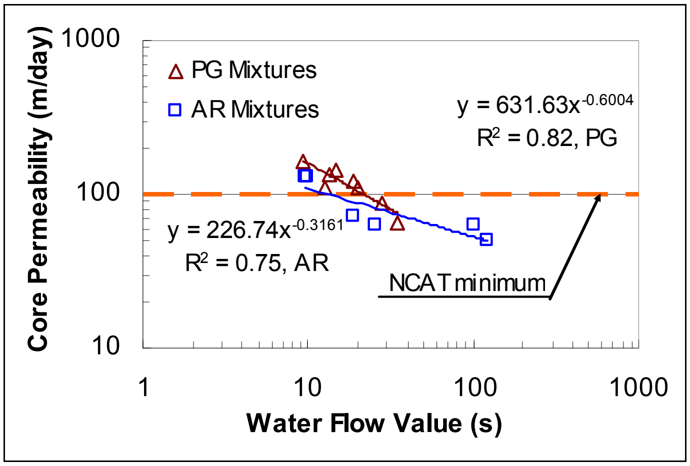


Figure 30. Relationship of Laboratory-Measured Permeability and Water Flow Value by Alvarez et al. (*27*).

Alvarez et al. (*27*) also computed the expected value of permeability, $E[k]$, using Equation (1), based on the equation modified by Masad et al. (*28*) (Equation (3)) from the Kozeny-Carman equation.

$$E[k] = A\overline{C} \times \left[\begin{array}{l} \left(\frac{\overline{n}^3}{(1-\overline{n})^2} \right) \left(\overline{D}_s^2 + \mathrm{var}(D_s) \right) + \left(\frac{3\overline{n}}{(1-\overline{n})^2} + \frac{6\overline{n}^2}{(1-\overline{n})^3} + \frac{3\overline{n}^3}{(1-\overline{n})^4} \right) \overline{D}_s^2 \times \mathrm{var}(n) + \\ \left(\frac{2\overline{n}^3}{(1-\overline{n})^3} + \frac{3\overline{n}^2}{(1-\overline{n})^2} \right) 2\overline{D}_s \times \mathrm{cov}(D_s, n) \end{array} \right] \quad (1)$$

where $\overline{n}$ is the average total AV content, var(n) is the variance of the distribution of total AV values (along the vertical axis of compacted specimens), var(D_s) corresponds to the variance of the distribution of aggregate-particle size, cov(D_s, n) is the covariance of the aggregate-particle size and the total AV content, and the constant A is defined as:

$$A = \left(1 + \frac{G_{sb}(P_b - P_{ba}(1-P_b))}{G_b(1-P_b)}\right)^{\frac{2}{3}} \frac{\gamma}{\mu} \tag{2}$$

where G_{sb} is the bulk specific gravity of the aggregate, P_b is the percent of asphalt content by total weight of the mix, P_{ba} is the percent of absorbed asphalt by weight of aggregate, G_b is the asphalt specific gravity, γ is the unit weight of the fluid (9.79 kN/m^3 for water at 20°C), and μ is the fluid viscosity (10^{-3} kg/m·s for water).

Equation (3) accounts for the effect of asphalt content in HMA by making use of an equivalent aggregate-particle diameter, which includes the average particle diameter coated with an average asphalt film thickness:

$$k_c = \frac{\overline{C}n^3}{(1-n)^2}\left[\overline{D}_s\left(1 + \frac{G_{sb}(P_b - P_{ba}(1-P_b))}{G_b(1-P_b)}\right)^{\frac{1}{3}}\right]^2 \frac{\gamma}{\mu} \tag{3}$$

where k_c is the calculated coefficient of permeability (or calculated permeability) in m/s, $\overline{C}$ is an empirical coefficient to include both the effect of the AV-shape factor and saturation, n is the total AV content, and $\overline{D}_s$ corresponds to the average aggregate-particle size.

The analysis conducted by Alvarez et al. (summarized in Figure 31) led to conclude that the expected value of permeability, $E[k]$, is a better estimator of laboratory-measured permeability (k_m) as compared to the calculated permeability (k_c) obtained from the deterministic evaluation of Equation (3).

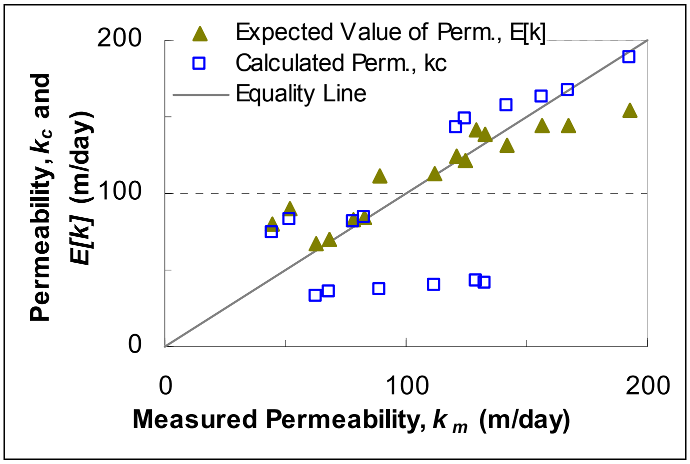


Figure 31. Comparison of Laboratory-Measured and Predicted Permeability (*27*).

2.1.2.6. Summary

An overview of recent research on drainability is summarized in Table 22, including the authors and date, pavement surface types, factors, and the effect of different factors on pavement drainability included in each study.

Table 22. An Overview of Drainability Research Conducted since 2004.

Author/Year	*Surface Type*	*Factor Best*	*Drainability*
Punith et al. (2004)	PFC/OGFCs	Binder content,	Low
		Compaction energy	Low
Watson et al. (2004)	PFC/OGFCs	Aggregate gradation	Coarse
SILVIA project (France) (2005)	PA	Maximum aggregate size	Large
Alvarez et al. (2008)	PFC/OGFCs	Compaction method (SGC- and field- compacted mixtures)	Assess with: WFV (field), expected value of permeability

Assessment of drainability of PFC/OGFCs mixtures is required to guarantee high initial drainability and to evaluate mixture performance by comparing the evolution of this parameter during the mixture functional life. Low binder content, coarse aggregate gradation, large maximum aggregate size, and low compaction effort can provide sufficient AV content (which is considered to be representative of drainability). However, decreasing the energy of compaction (in both the field and laboratory) to obtain a higher AV content is not recommended, since durability problems can arise in mixtures with incomplete compaction due to insufficient stone-on-stone contact in the coarse-granular skeleton. In addition, high permeability values should not be pursued by reducing the binder content below the minimum recommended values (e.g., 6 percent and 8 percent are specified by TxDOT, respectively, for PG and AR mixtures) required to ensure adequate mixture durability (*31*).

NCAT suggested a minimum value of permeability of 100 m/day (328.08 ft/day) for PFC/OGFCs mixtures if the main objective is to remove water from the pavement surface. However, if the main purpose of using PFC/OGFCs is noise reduction, a minimum permeability of 60 m/day (196.85 ft/day) was suggested (*1*). Although permeability is believed to be integrated in most PFC/OGFCs mix design procedures (by specifying a minimum total AV content), recent research suggested that this approach has limitations to ensure adequate drainability.

2.2. DURABILITY

Durability of PFC/OGFCs is an important aspect to evaluate when designing this type of HMA. At present, several agencies perform the mix design of PFC/OGFCs primarily by determining volumetric mixture properties. This current PFC/OGFCs design practice focuses on ensuring mixture functionality, based on a minimum total AV content, but there is a limited evaluation of durability in terms of the mixture resistance to disintegration (i.e., raveling) and susceptibility to moisture damage, which are still a concern for PFC/OGFCs performance (*34*). The Cantabro Loss test (Cantabro test), the Hamburg Wheel-Tracking test (HWTT), and the retained tensile strength ratio (TSR) were used in the past for assessing durability of PFC/OGFCs and PA. The TSR is used in Switzerland to design PA and was also proposed by NCAT to design PFC/OGFCs. The use of HWTT to evaluate permanent deformation of PA was reported by Denmark, and the Cantabro test is used to design PA mixtures in Australia, South Africa, and some European countries (*34*).

This section summarizes the following factors that influence PFC/OGFCs durability and briefly describes related recent research conducted since 2004: binder content, binder type and moisture susceptibility, and binder aging. The laboratory assessment of durability is also discussed in this section.

2.2.1. Binder Content

In 2004, Punith et al. (*30*) used the Cantabro test, which is an abrasion and impact test carried out in the Los Angeles (LA) abrasion machine, to analyze the resistance of compacted PFC/OGFCs to abrasion loss. The mixtures analyzed were CRMB, 60/70 Pen-grade binder with fiber, and reclaimed polyethylene binder (RPEB). The percentage abrasion loss (P) was calculated according to Equation (4). A value of 25 percent for the maximum permitted abrasion loss of freshly compacted specimens was recommended.

$$P = 100\frac{P_1 - P_2}{P_1} \tag{4}$$

where P_1 is the initial mass of compacted sample, and P_2 is the final mass of sample after operated for 300 revolutions in the LA abrasion machine at a rate of 30 to 33 rpm at 25 °C (77 °F).

The results showed that the abrasion loss from the lowest to the highest was the RPEB, the CRMB, and the 60/70 Pen-grade binder with fiber. In general, an increase in asphalt content and decrease in AV content resulted in a decrease in abrasion loss. Alvarez et al. (*34*) evaluated the Cantabro loss values of PFC/OGFCs mixtures and suggested that PFC/OGFCs mixture resistance to disintegration is affected more by aggregate properties than by those of the asphalt.

2.2.2. Binder Type and Moisture Susceptibility

Watson et al. (*32*) used the fiber stabilizer instead of increasing binder grade to improve the resistance to draindown in 2004. The NCAT draindown test was applied to determine draindown for mixtures fabricated using three binder grades (PG 67-22, PG 76-22 polymer modified binder, and PG 76-34) and three aggregate types (granite, gravel, and traprock). The results showed that four percentage points draindown in specimens were reduced with fibers. In addition, the Cantabro test was performed to determine the differences in mixture resistance to disintegration for specimens compacted using two different methods, and between aged- and unaged-specimens. The specimens were compacted using both Marshall hammer and the SGC. The Marshall specimens were compacted to 50 blows per face, and the SGC specimens were compacted to 50 gyrations. The Cantabro test results indicated that there was no significant difference between aged- and unaged-Marshall specimens. The authors also mentioned that an increase in stiffness for the PG binder grade can reduce abrasion loss. The evaluation of moisture susceptibility was investigated in the study using the modified AASTO T283 method. Specimens were tested after 1, 2, and 5 freeze-thaw cycles. For specimens with PG 76-22 binder and fiber stabilizer, the results showed that there was no significant difference among specimens tested using these three conditioning processes. However, the time needed to perform a PFC/OGFCs mix design can be reduced by about two weeks by using 1 freeze-thaw cycle compared to the 5 freeze-thaw cycles. Therefore, one freeze-thaw cycle was recommended regarding time thrift.

2.2.3. Binder Aging

Alvarez et al. (*1*, *2*, *3*) indicated that regarding durability, raveling is the distress most frequently reported as the cause of failure in PFC/OGFCs mixtures. Raveling in PFC/OGFCs is often characterized by its rapid progress, which can disintegrate the layer within a few months or even a few weeks. This problem can be associated with aging binder (oxidation and hardening), binder softening generated by oil and fuel drippings, and inadequate compaction or insufficient asphalt content. The authors discussed several aspects where the field aging on PFC/OGFCs mixtures can be different from conventional DGHMA (*1*):

- PFC/OGFCs mixtures are placed on the pavement surface where, because of higher temperatures, oxidation rates will be higher than they are deeper in the pavement structure;
- PFC/OGFCs mixtures, because of their high permeability, might be expected to provide better access of oxygen to the binder, tending to increase oxidation rates;
- the thicker asphalt binder films in PFC/OGFCs mixtures will serve to reduce oxygen transport rates into the binder, thus slowing oxidation;
- the thicker binder films in PFC/OGFCs mixtures likely will favorably affect the impact of aging on durability differently from dense-graded, thin-film mixtures;
- fibers in some of the PFC/OGFCs binders may act to reinforce the binder film and minimize the effects of age hardening that lead to raveling; and
- the presence of lime in PG PFC/OGFCs mixtures may retard the effects of binder aging (*1*).

Analysis of asphalt binder recovered from field cores, taken at the time of mixture construction or within six months of construction, provided evidence of significant oxidative aging (beyond the unaged asphalt binder level) (*3*). However, long-term assessment was recommended to be able to determine a relationship of asphalt binder oxidation and PFC mixture performance.

2.2.4. Laboratory Assessment of Durability

In 2008, Alvarez et al. (*34*) conducted a study to recommend a durability test that can be included in PFC/OGFCs mix design to improve the determination of the optimum asphalt content (OAC) obtained based on volumetric properties.

The authors evaluated the Cantabro test, the HWTT and the Overlay test (OT) to determine the one most appropriate test for PFC/OGFCs mix design and laboratory performance evaluations. The Cantabro test was performed in both wet and dry conditions, the HWTT was performed in wet condition, and the OT was performed in dry condition. Table 23 presents the comparison of the durability tests in terms of the following criteria: (1) specimen preparation for testing, (2) specimen fabrication to meet specific total AV content ranges, (3) equipment availability in Texas, (4) testing time, and (5) variability in the test results.

Table 23. Comparison of Durability Test by Alvarez et al. (*34*).

Test, Testing Condition	Specimen Preparation for Testing	Variability of Total AV Content, COV	Availability of Equipment in Texas	Testing Time (hours)	Test Results Variability, COV
HWTT, wet	Saw trimming	0.030	Medium	5	0.02 to 0.57
OT, dry	Saw cutting, drying, final AV checking, and gluing	0.030	Low	2	0.22 to 1.17
Cantabro test, dry	Not required	0.016	High	0.3	0.07 to 0.36

Based on these criteria, the Cantabro test was recommended over the HWTT and the OT for evaluating PFC/OGFCs mixture durability. The high variability of the HWTT- and OT-results, defined in terms of the coefficient of variation, was the main factor restricting their application for PFC/OGFCs mix design and evaluation. Although the Cantabro test results exhibited smaller variability as compared to those of the HWTT and the OT, the trends and variability of the Cantabro test results (observed as the asphalt content was modified) prevented recommendation of this test as a definitive tool for selecting the OAC. Ultimately, the Cantabro test is a simple and quick test that may be useful as an initial screening tool for selecting material combinations to include in more advanced testing towards selection of the OAC. The authors also indicated that mixture resistance to disintegration was affected more by aggregate properties than by those of the asphalt based on the evaluation of the Cantabro loss values. Moreover, the Cantabro loss values showed a direct relationship with water-accessible AV content values, providing an indication of the importance of the volumetric properties on the durability of PFC/OGFCs mixtures.

2.2.5. Summary

An overview of recent research conducted since 2004 on PFC/OGFCs durability is summarized in Table 24, including the agencies and date, pavement surface types, durability measurements, and factors included in each study. In addition, mixture durability can either increase or decrease as a function of various factors. Table 25 summarizes the effects of different factors on PFC/OGFCs durability.

Table 24. An Overview of Durability Research Conducted since 2004.

Agency/Year	*Mixture Type*	*Durability Measurement*	*Factor*
Punith et al. (2004)	PFC/OGFCs	Cantabro test	Binder content
Watson et al. (2004)	PFC/OGFC	NCAT draindown test, Cantabro test, modified AASHTO T283	Binder type, moisture susceptibility
Alvarez et al. (2006, 2008)	PFC/OGFCs	Cantabro test, Hamburg Wheel-Tracking test, Overlay test	Binder aging, binder and aggregate type

Table 25. Summary of the Effect of Different Factors on Pavement Durability.

Factor	*Best Durability*
Binder content	High
Binder type	Polymer modified
Binder aging	Slow rate

In the United States, the draindown test and at some extent the Cantabro loss test (conducted in dry condition) are used to evaluate PFC/OGFCs mixture durability. TSR was also recommended to evaluate the moisture susceptibility of the mixture. High binder contents decrease abrasion loss and thus provide better durability. In order to evaluate mixture durability and susceptibility to moisture damage, the Cantabro loss test was found to be the most appropriate test currently available for PFC/OGFCs mix design and laboratory performance evaluations. However, the Cantabro test may not provide enough sensitivity to become a definitive tool for selecting the OAC of PFC/OGFCs mixtures.

2.3. SAFETY

In this section, pavement safety measurements will be briefly described followed by a comparison of safety measurements. Next, a summary of the following factors that influence pavement safety and related recent research performed since 2004 are described in chronological order: pavement surface type, vehicle speed, texture of the pavement surface, air temperature, traffic condition, binder type, and aggregate texture. After that, a synthesis is provided following the descriptions of the effects of each individual factor.

Safety Measurements

Skid resistance in the field is generally measured by the force required to slide a locked tire along a pavement surface. While measuring friction force between a tire and pavement surface, state-of-the-art friction testing applies a standard tire to pavement surfaces with controlled wheel slip. There are four main types of skid resistance measurements: locked wheel, sideway force, fixed slip, and variable slip.

The locked wheel method that is specified by the American Society for Testing and Materials (ASTM) E274 (*35*) is performed by a vehicle pulling a two-wheel trailer with standardized wheels locked in place. The relative velocity of the tire contact over the pavement surface is equal to the test vehicle speed at a constant speed of 64 kph (40 mph). The friction force is recorded, and the friction coefficient is calculated in terms of skid number (SN) or friction number (FN) using Equation (5).

$$SN = \frac{F}{W} \times 100 \tag{5}$$

where

F is the force required to pull the trailer (lb) and *W* is the weight of the trailer (lb).

Other types of measurements are the sideway force, fixed slip, and variable slip. A test wheel moving at an angle in relation to the direction of motion is used in the sideway force mode, and the sideway-force coefficient (SFC) is used to determine skid resistance. In the fixed or variable slip mode, the friction factor is a function of the slip of the rolling test wheel on the pavement surface.

The most common device widely used to assess skid resistance is the portable British pendulum tester (BPT), which is one of the simplest and cheapest instruments used in measuring friction characteristics of pavement surfaces. The BPT that is specified in ASTM E303 (*36*) is a dynamic pendulum impact-type tester with a pad of tire-tread rubber mounted at the end of a pendulum arm that slides over the pavement surface. The BPT is easy to handle both in the laboratory and in the field, but it only provides the measured friction property at a low speed. Moreover, the other type of tester is the dynamic friction tester (DFT) specified in ASTM E1911 (*37*). The DFT is a disc-rotating-type tester that measures the friction force between the pavement surface and three rubber pads attached to the disc. The disc touches the pavement surface at different speeds from 20 to 80 kph (12.5 to 50 mph) under a constant load to measure the skid resistance at any speed within this range. The DFT is affected by both the microtexture and macrotexture of the pavement surface.

In order to combine friction and texture measurements determined by different test methods, the International Friction Index (IFI) specified in ASTM E1960 (*38*) has been developed by collecting a wide range of friction data measured by several test methods on different pavement surfaces. Based on ASTM E1960 (*38*), two parameters are used in the IFI calibrated model: wet friction at 60 kph (F(60)) and the speed constant of wet pavement friction (S_p). F(60) and S_p are indications of (1) the average wet coefficient of friction experienced by a driver during a locked wheel slide at a speed of 60 kph (37.5 mph) and (2) dependence of the wet pavement friction on the sliding speed, respectively. The F(60) value for the locked wheel friction trailer using a smooth tire and rib tire at desired speeds are described in Equations (6) and (7), respectively, and the speed constant of wet pavement friction is shown in Equation (8).

$$F(60) = 0.045 + 0.925 \times 0.01 \times SN(64).e^{\frac{4}{S_P}} \text{; For Smooth Tire} \tag{6}$$

$$F(60) = -0.023 + 0.607 \times 0.01 \times SN(64).e^{\frac{4}{S_P}} + 0.098 \times MPD \text{; For Rib Tire} \tag{7}$$

$$S_P = 14.2 + 89.7MPD \tag{8}$$

where *SN*(64) is the skid number measured at test speed of 64 kph (37.5 mph) divided by 100.

Because the value of texture is not measured during friction measurement by a skid trailer, the IFI requires two separate measurements using Equations (6) to (8). The resulting F(60) and S_p parameters are reported as IFI (F(60), S_p).

2.3.1. Pavement Surface Type

Pavement surface type greatly influences pavement skid resistance. Therefore, many researchers have undertaken studies to determine the improvement in traffic safety obtained by using different mixture types at the pavement surface.

Indiana (2004)

The Indiana Department of Transportation (INDOT) (*9*) compared the pavement skid resistance for PFC/OGFCs, SMA, and DGHMA pavement surfaces. Table 4 shows the mix design of the three field test sections in INDOT study. The portable DFT was applied to measure the pavement friction. The pavement friction using the DFT was conducted at 20 kph (12.5 mph), and the DFT number was used with MPD to determine the wet friction number for each pavement surface (Equation (9)).

$$F(60) = 0.081 + 0.732 \times DFT_{20} \times e^{\frac{-40}{108.1 \times MPD - 1.3}} \tag{9}$$

Table 26 presents the pavement skid resistance by the DFT number and the wet friction value in INDOT study. Based upon the testing results, the SMA had a lower DFT number than the PFC/OGFCs or the DGHMA. The DFT at 20 kph (12.5 mph) showed that the pavement friction of DGHMA was 0.01 more than PFC/OGFCs, and the pavement friction of SMA was 0.14 less than PFC/OGFCs. The wet friction at 60 kph (37.5 mph) showed that the PFC/OGFCs had a much higher F(60) value, and the SMA had a F(60) value between those of the PFC/OGFCs and DGHMA. Both the DFT and the wet friction values indicated that PFC/OGFCs exhibited the highest skid resistance compared with SMA and DGHMA pavement surfaces.

Table 26. DFT Numbers and Wet Friction Values from Indiana DOT Study (*9*).

Surface Type	***DGHMA***	***SMA***	***PFC/OGFCs***
DFT_{20}	0.52	0.37	0.51
F(60)	0.19	0.28	0.36

Florida (2004)

The FDOT (*39*) conducted a study to measure the pavement skid resistance with the locked wheel tester at a vehicle speed of 64 kph (40 mph). The tested sections were randomly selected PFC/OGFCs and DGHMA pavements in Florida. The measured friction data were analyzed to determine the skid resistance in terms of FNs. The average value of measured FNs at 64 kph (40 mph) on PFC/OGFCs and DGHMA pavement surfaces were 38.8 for PFC/OGFCs and 42.3 for DGHMA.

New Jersey (2005)

Bennert et al. (*11*) used the locked wheel tester to determine the skid resistance in terms of SN at a vehicle speed of 64 kph (40 mph). The tested sections were DGHMA, PFC/OGFCs with and without crumb rubber, SMA, Novachip, and a microsurfacing slurry mixture in New Jersey. In comparing the thin-lift pavement surfaces (PFC/OGFCs, Novachip, SMA, and microsurfacing), the pavement SN results showed that the highest pavement SN was measured for PFC/OGFCs with crumb rubber. The rank order of highest SN to lowest in the other thin-lift pavement surfaces was: microsurfacing, modified PFC/OGFCs, Novachip, and SMA. Table 27 presents the results of testing on the different pavement surfaces in New Jersey.

Table 27. The SNs of the Different Pavement Surfaces in New Jersey (*9*).

Surface Type		***Location***	***SN at 64 kph (40 mph)***	***Average SN***
AR-OGFCs		US-9N	47.8	51.9
		I-195W	55.9	
MOGFCs		I-78E	47.9	48.0
		US-24	44.8	
		I-195E	51.2	
Novachip		I-195E	45.4	45.6
		I-78W	45.7	
SMA	9.5 mm (0.37 in)	I-78W	42.5	42.3
	12.5 mm (0.49 in)	US-1	42.0	
Microsurfacing		US-202S	49.6	49.4
		NJ-29	49.1	
12.5 mm (0.49 in)-DGHMA		I-78E	51.8	53.1
		US-22W	54.3	

Note: AR-OGFCs: asphalt rubber PFC/OGFCs; MOGFCs: modified asphalt binder PFC/OGFCs

Jordan (2005)

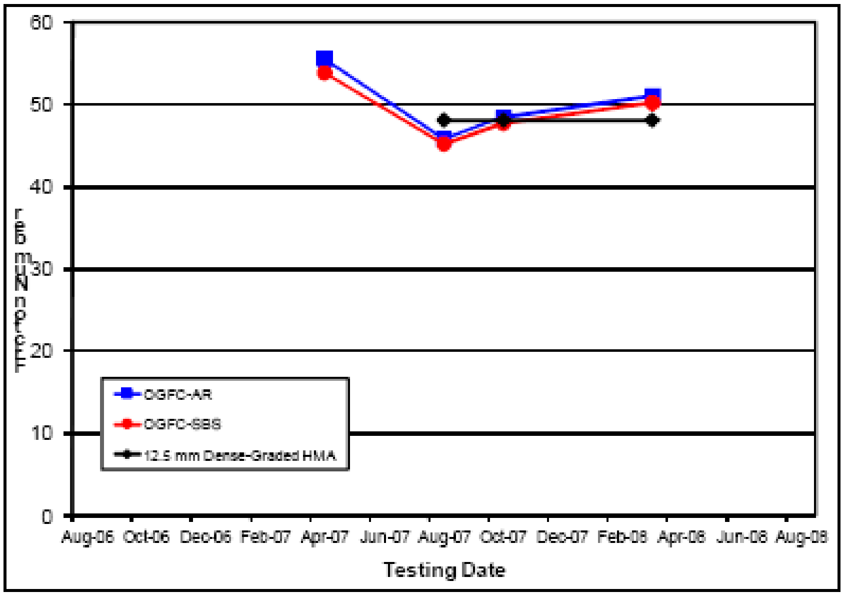
Asi (*40*) compared the skid resistance of different HMA using the BPT. The sections were tested on HMA with 30 percent slag, DGHMA designed using the Marshall method (or Marshall mixtures (0, 0.5, and 1.0 percent higher than OAC)), Superpave mixtures, and SMA. Table 28 summarizes corresponding results, expressed in terms of the British pendulum number (BPN). Based on the results, the HMA containing 30 percent slag had the highest BPN followed by Superpave mixtures, SMA, and Marshall mixtures. Moreover, an increase of asphalt content above the Marshall OAC decreased the skid resistance of the mixtures.

Table 28. Average BPN for Different Pavement Surfaces in Jordan (*40*).

Surface Type	***BPN***
Marshall	87.2
Marshall + 0.5%	81.3
Marshall + 1%	73.9
Superpave	95.7
SMA	92.4
30% slag	99.6

Washington (2008)

Pierce et al. (*24*) examined three pavement sections, which were PFC/OGFCs with rubber, PFC/OGFCs with styrene butadiene styrene (SBS), and DGHMA in Washington with the locked wheel tester. Figure 32 presents the FNs of all pavements tested in Washington. The FN results indicated that there was little difference in surface friction with FN values greater than 45 due to the use of the same aggregate source.



Note: y-axis: FN

Figure 32. FN for Different Pavement Surfaces in Washington (*24*).

Indiana (2008)

Kowalski et al. (*14*) measured the pavement skid resistance of three highway test sections with the DFT and the locked wheel tester. The measured highway test sections were DGHMA, SMA, and PFC/OGFCs in Indiana. The DFT and locked wheel tester were measured with smooth tires at vehicle speeds of 12.5 kph (20 mph) and 40 kph (64 mph), respectively. The average DFT values were 0.6 for PFC/OGFCs, 0.73 for SMA, and 0.42 for DGHMA. The SNs were 57 for PFC/OGFCs, 54 for SMA, and 27 for DGHMA. The wet friction numbers were calculated using DFT and MPD results. Table 29 shows the SNs, DFT, and wet friction numbers of the three pavements in Indiana.

Table 29. SN and DFT Values of the Tested Pavement Surfaces in Indiana (*14*).

Surface Type	***PFC/OGFCs***	***SMA***	***DGHMA***
SN_{64}	57	54	27
DFT_{20}	0.6	0.73	0.42
F(60)	0.41	0.46	0.24

Virginia (2004)

The Virginia Department of Transportation (*41*) assessed the skid resistance of five HMA sections with locked wheel testers. The tested mixtures were PFC/OGFCs, SMA, and DGHMA within a temperature range from -1 to -5 °C (30.2 to 23 °F), and the skid resistance was represented in terms of SN at a vehicle speed of 48 kph (30 mph). On average, the PFC/OGFCs had the highest SN_{30} (19.35) followed by SMA (17.31) and DGHMA (15.67).

2.3.2. Vehicle Speed

The Indiana Department of Transportation (INDOT) (*9*) investigated the effect of vehicle speed on the pavement skid resistance. The tested pavement surfaces were PFC/OGFCs, SMA, and DGHMA. The DFT values were evaluated at vehicle speeds of 20 kph (12 mph), 40 kph (24 mph), and 60 kph (36 mph). Table 30 shows the results from the vehicle speed analysis in Indiana.

Table 30. Average DFT Number at Different Vehicle Speed in Indiana (*9*).

Surface Type	***DFT***		
	20 kph (12 mph)	***40 kph (24 mph)***	***60 kph (36 mph)***
PFC/OGFCs	0.51	0.45	0.42
SMA	0.37	0.31	0.29
HMA	0.52	0.47	0.44

The results showed that the SMA had the lowest DFT value among the PFC/OGFCs and HMA at all speeds, and the friction values decreased as the speed increased on all tested mixtures.

2.3.3. Texture of the Pavement Surface

One of the main characteristics of pavement surfaces pertaining to safety is texture. The texture of pavement surfaces can be divided into three categories: megatexture, macrotexture, and microtexture. Most research on pavement safety focused on the macrotexture, which is defined as surface asperities that range from 0.1 to 20 mm (0.004 to 0.787 in) in height and from 0.5 to 50 mm (0.020 to 1.969 in) in width. The function of macrotexture is to provide a dry pavement surface in wet conditions with channels that water can escape from to maintain high friction, thus increasing pavement safety.

Indiana (2004)

The INDOT (*9*) compared the pavement skid resistance among PFC/OGFCs with 0.3 percent fiber, SMA with 0.1 percent fiber, and DGHMA pavement surfaces, and evaluated the effect of texture. The study also used the DFT and MPD to determine the wet friction of the three types of pavements. The results of the texture measurements and wet friction on the three types of pavements in INDOT study are summarized in Table 31.

Table 31. Results of MPD and F(60) on the Pavements from INDOT (*9*).

Surface Type	***PFC/OGFCs***	***SMA***	***HMA***
MPD, mm (in)	1.37 (0.05)	1.17 (0.05)	0.30 (0.01)
F(60)	0.36	0.28	0.19

Because of the mastic of asphalt binder and fibers, the texture of SMA with 0.1 percent fiber was lower than PFC/OGFCs with 0.3 percent fiber, as expected. In addition, the macrotexture of the pavement had a strong influence on skid resistance. The greater the MPD value, the higher the F(60) value.

Florida (2005)

FDOT (*42*) estimated the texture and friction characteristics of PFC/OGFCs and DGHMA in Florida. The MPD and FN were measured in order to transform to IFI value. The FN was tested with smooth and rib tires at a vehicle speed of 64 kph (40 mph), and the MPD was measured at vehicle speeds of 32, 64, and 96 kph (20, 40, and 60 mph) in order to calculate the speed constant. Table 32 presents the results of FN, MPD, and wet friction values for the different sections in FDOT study. The results demonstrated that there was no clear relationship between MPD and friction number or wet friction value. Macrotexture was found to be a poor predictor of overall pavement friction.

Table 32. FN, MPD, and Wet Friction for the Different Sections from FDOT (*42*).

Tested Section	FN_{40}		MPD, mm (in)			F(60)	
	Rib Tire	Smooth Tire	32 kph (20 mph)	64 kph (40 mph)	96 kph (60 mph)	Rib Tire	Smooth Tire
1	35.5	32.5	2.489 (0.098)	2.565 (0.101)	2.616 (0.103)	22.2	30.6
2	36.6	27.4	0.533 (0.021)	0.635 (0.025)	-	23.7	27.0
3	51.3	41.4	0.035 (0.001 in)	0.037 (0.001 in)	-	32.6	40.1
4	35.3	33.4	0.114 (0.004 in)	0.117 (0.005 in)	0.116	22.1	31.4
5	43.3	37.8	0.148 (0.006 in)	0.149 (0.006 in)	0.145	27.0	35.5

Spain (2008)

Miró et al. (*20*) conducted a study to determine the SFC after adding crumb rubber to gap-graded mixtures in several test sections. All sections were constructed with three types of binders that were bitumen with crumb rubber by the wet process, the same bitumen with the addition of crumb rubber by the dry process, and polymer-modified bitumen. The results obtained from this study included the correlations between texture and skid resistance. The results of texture and SFC are shown in Table 33. Compared to crumb rubber mixtures (CRMB), a decrease in texture leads to a slight increase of SFC.

Table 33. Texture and SFC for Tested Sections in Spain (*20*).

Binder Type	*PMB*	*CRMB*	*CRMB+1%*	*CRMB+2%*
Texture, mm	1.06	1.06	1.00	0.88
SFC, %	56.79	53.70	55.88	56.02

2.3.4. Air Temperature

In 2005, Bazlamit et al. (*43*) investigated the effects of temperature on the friction force developed at the tire/pavement interface with the BPT. Five different temperatures were measured in Ohio, and the pavement skid resistance was expressed in terms of BPN. The temperatures were recorded at 273, 283, 293, 303, and 313 K (32, 50, 68, 86, and 104 °F). Figure 33 shows the results of BPN versus temperature in Ohio.

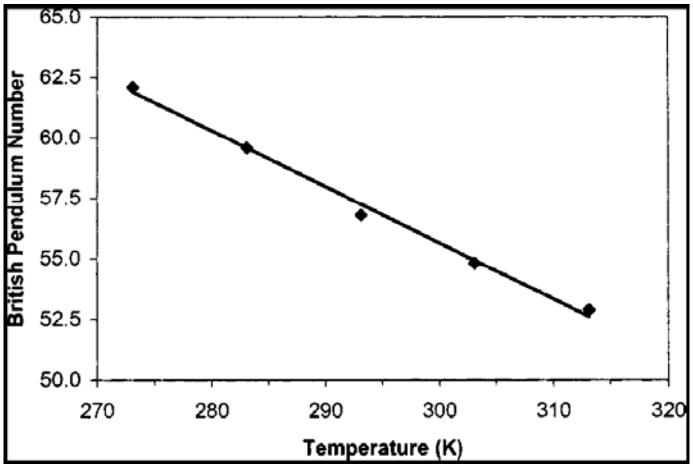


Figure 33. Linear Regression of BPN and Temperature for All Tested Sections in Ohio (*43*).

The results indicated that skid resistance decreased with increased temperature. From Figure 33, a linear curve fit (Equation (10)) was implemented for measured data.

$$BPN = 125.2508 - 0.232T \tag{10}$$

where T is the temperature in Kelvin.

Equation (10) can be used to correct comparisons between the BPNs obtained at different temperatures and also to relate the SN obtained at any arbitrary temperature by Equation (11).

$$SN = 0.862(BPN) - 9.69 \tag{11}$$

2.3.5. Traffic Condition

In 2008, Kowalski et al. (*14*) measured the pavement skid resistance of three highway test sections with the DFT and the locked wheel tester as well as the skid resistance under different traffic conditions (passenger vehicle and heavy vehicle). The sections included DGHMA, SMA, and PFC/OGFCs in Indiana. The study assumed an equal number of vehicles were driven in both directions, and the average truck had 4.5 axles. The results from Figures 34, 35, and 36, in general, showed that the friction values initially increased due to wearing-off of the binder on the pavement surface. After the initial increase, the friction values started to decrease and then stayed at a low level.

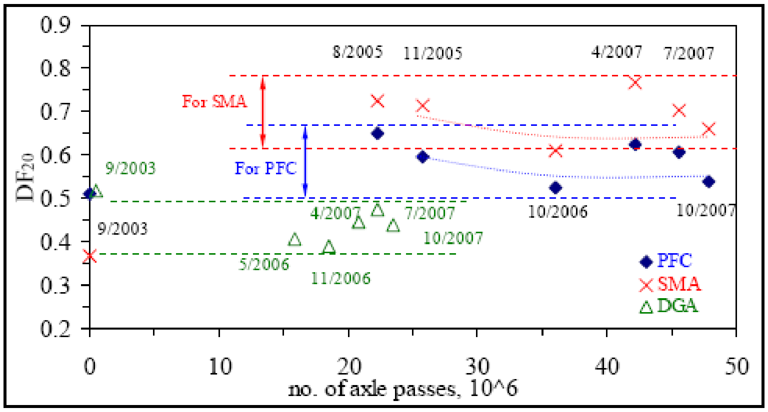


Figure 34. Changes in DFT Values as a Function of Traffic in Indiana (*14*).

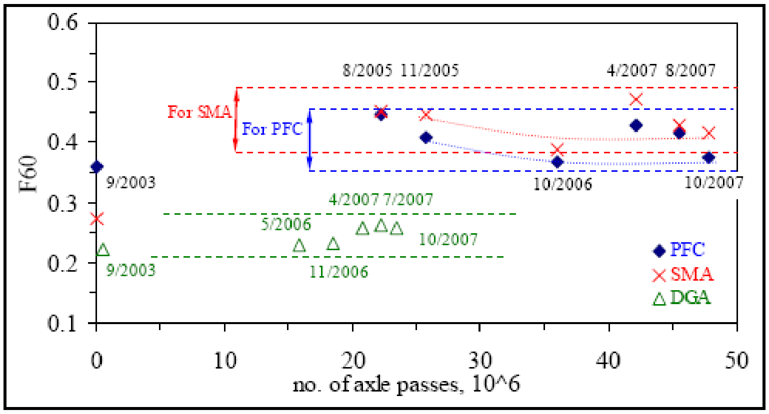


Figure 35. Changes in F(60) Values as a Function of Traffic in Indiana (*14*).

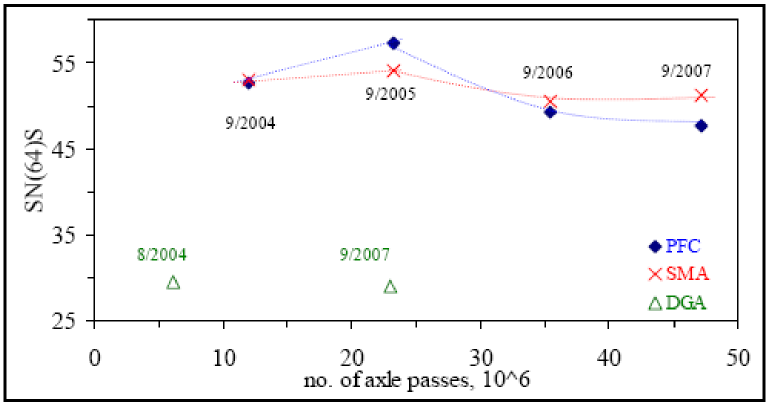


Figure 36. Changes in SN Values as a Function of Traffic in Indiana (*14*).

2.3.6. Binder Type

In 2008, Miró et al. (*20*) conducted a study to determine the SFC after adding crumb rubber to gap-graded mixtures in several test sections with sideway force testers. All sections were constructed with three types of binders: bitumen with crumb rubber by the wet process (CRMB), the same bitumen with the addition of crumb rubber by the dry process (CRMB+1% and CRMB+2%), and PMB. When comparing SFC for the CRMB, CRMB+1%, and CRMB+2% mixtures; the SFC increased with increasing addition of crumb rubber by the dry process versus the wet process. Table 34 summarizes the SFC results of mixtures constructed using different bitumen types in Spain.

Table 34. SFC Results of Different Bitumen Types in Spain (*20*).

Bitumen Type	*SFC, %*
PMB	56.79
CRMB	53.70
CRMB+1%	55.88
CRMB+2%	56.02

2.3.7. Aggregate Texture

In 2007, Luce et al. (*44*) conducted an experiment to determine the relationship between aggregate texture and pavement skid resistance with the locked wheel tester in Texas. The tested sections were constructed with three different aggregate types (quartzite, sandstone, and siliceous gravel) combined in DGHMA mixtures. Skid resistance can be affected by the change in aggregate texture due to polishing. The texture of quartzite aggregate before polishing was higher than sandstone, and siliceous gravel had the lowest texture. However, the results showed that the quartzite aggregate had the most rapid decrease in texture due to polishing as a function of time followed by sandstone and siliceous gravel. Table 35 presents the average SN of mixtures fabricated with the aggregates characterized.

Table 35. Average SN of Mixtures with Different Tested Aggregates in Texas (*44*).

Aggregate Type	*Average Mixture SN*
Quartzite	45.15
Sandstone	51.62
Siliceous Gravel	39.73

Based on the results in Table 35, the siliceous gravel mixtures had less skid resistance than the sandstone and quartzite mixtures because of the low aggregate texture.

2.3.8. Summary

An overview of research on safety performed since 2004 is summarized in Table 36, including the agencies and date, pavement surface types, skid resistance measurements, and factors included in each study. In addition, pavement skid resistance can either increase or decrease as a function of various factors. Table 37 summarizes the effects of different factors on pavement safety in terms of skid resistance.

Table 36. An Overview of Safety Research since 2004.

Agency/Year	*Surface Type*	*Skid Resistance Measurement*	*Factor*
Indiana (2004)	PFC/OGFCs, SMA, DGHMA	DFT, IFI	Surface type, vehicle speed, texture
Virginia (2004)	PFC/OGFCs, SMA, DGHMA	Locked wheel	Surface type
Florida (2004)	PFC/OGFCs, DGHMA	Locked wheel	Surface type
New Jersey (2005)	PFC/OGFCs, SMA, DGHMA, Novachip, Microsurfacing	Locked wheel	Surface type
Florida (2005)	PFC/OGFCs, DGHMA	Locked wheel, IFI	Texture
Jordan (2005)	HMA, SMA	BPT	Surface type
Ohio (2005)	HMA	BPT	Air temperature
Texas (2007)	DGHMA	Locked wheel	Aggregate texture
Washington (2008)	PFC/OGFCs (rubber/ SBS), DGHMA	Locked wheel	Surface type
Indiana (2008)	PFC/OGFCs, SMA, DGHMA	Locked wheel, DFT, IFI	Surface type, traffic condition
Spain (2008)	PFC/OGFCs	Sideway force	Binder type, texture

Table 37. Summary of the Effect of Different Factors on Pavement Safety.

Factor	*Best Skid Resistance*
Surface type	PFC/OGFCs
Vehicle speed	Slow
Pavement texture	Increased
Air temperature	Low
Traffic condition	Low volume
Binder type	Crumb rubber modified
Aggregate texture	High

The binder films present on the aggregate surfaces of PFC/OGFCs are abraded and removed from the surface of the mixture under repeated traffic loading but appear as a potential skid hazard when roads are opened to traffic directly after construction. After the initial abrasion of the binder film from the aggregate surfaces, repeated trafficking can further polish and reduce the microtexture of the aggregates and consequently the low-speed skid resistance of the surface. Polishing of the surface together with clogging and flushing of the PFC/OGFCs may further reduce the macrotexture offered by the surface over time that will reduce the high-speed skid resistance of the mixture.

The best skid resistance with PFC/OGFCs mixtures is obtained for low traffic volume with slow speed and at low air temperature. However, low traffic speeds may favor the rapid clogging of the mixture AV structure and lead to loss of the mixture functional properties (drainability and noise reduction effectiveness).

An increase of pavement texture, high aggregate texture, and the use of crumb rubber modified binder need to be considered as alternative parameters for selection of materials as well as the current mix design regarding the skid potential.

3. DESIGN, CONSTRUCTION, AND MAINTENANCE

This chapter summarizes recent advances in the mixture design method for PFC/OGFCs and the fundamental aspects involved in the construction process of these mixtures. The primary considerations for corresponding maintenance are also introduced.

3.1. MIXTURE DESIGN

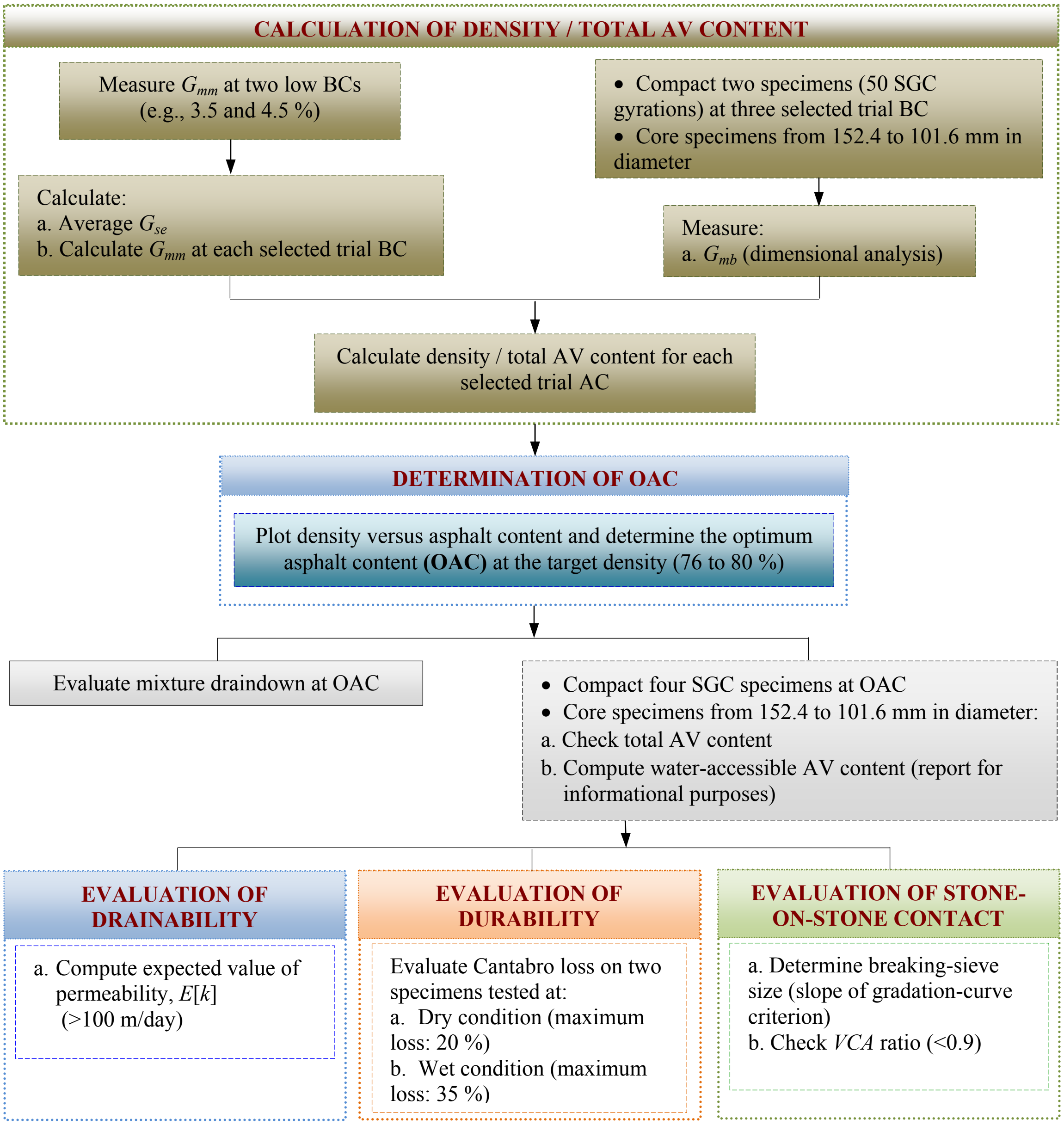
TxDOT Report 0-5262-1 (*1*) summarized the principles of the design methods used in some European countries that had the higher construction rates of PA mixtures. In addition, based on an overview of the design practices applied in the Unites States, the authors indicated that there were variants in the design method for PFC/OGFCs mixtures used by different state DOTs and various criteria were applied for determining the OAC.

A first effort for developing a standard mix design method for the new generation OGFC mixtures was conducted by NCAT in 2002 (*45*) and refined in 2003 (*46*) and 2004 (*32*). In addition, in 2004, ASTM released the Standard Practice for Open-Graded Friction Course (OGFC) Mix Design (designation D 7064-04) (*47*). Further research recently conducted at Texas A&M University led to recommendation of an improved mix design method for PFC/OGFCs mixtures (Figure 37) (*48*) based on the guidelines of the current method applied by TxDOT. Proposed modifications (indicated in Figure 37 by dashed-lined boxes) included improvements in the computation of volumetric properties and the assessment of drainability, durability, and stone-on-stone contact. Recommendations extracted from an analysis of the effects of densification in PFC/OGFCs mixtures as well as their internal structure were also integrated.

Alternative methods for the computation of the inputs (G_{mm}: theoretical maximum specific gravity of the mixture and G_{mb}: bulk specific gravity of the mixture) required to compute mixture density (employed to determine the OAC) and corresponding total air content were proposed. The proposed methods correspond to a procedure to calculate G_{mm} (or calculated G_{mm}) at any binder content (e.g., selected trial binder content or OAC) and dimensional analysis to compute G_{mb} (*49*).

The method recommended to determine the calculated G_{mm} includes measuring G_{mm} at two low binder contents (3.5 percent and 4.5 percent were suggested) to determine the average

G_{se} of the aggregate, and then calculating G_{mm} at the selected binder content or at the OAC. Dimensional analysis to compute G_{mb} requires direct measurement of the specimen dimensions to calculate the total volume. Additional details on these computations are documented elsewhere (*49*).



Note: BC: binder content.

Figure 37. Improved Mix Design Method for PFC/OGFCs Mixtures (*48*).

Coring of SGC specimens, produced at both the trial binder contents and OAC, from 152.4 (6 in) to 101.6 mm (4 in) in diameter was included to minimize the horizontal heterogeneity of AV reported in research conducted by Alvarez et al. (*50*). This work also suggested the necessity of conducting further research to improve the comparison of the vertical distribution of AV for mixtures compacted in the laboratory (using the SGC) and in the field. Limitations in the outcomes of the current mix design method applied by TxDOT and in the improved mix design method are expected due to the referred to differences in the distribution of AV (*50*).

The changes in the procedures recommended to compute both G_{mm} and G_{mb} led to recommend modification of the density specification (from 78-82 percent to 76-80 percent) to ensure adequate drainability (*49*).

Computation of the water-accessible AV content was included. Alvarez et al. (*51*) reports additional details on the computation of this parameter, which was proposed as a surrogate of the total AV content for future mix design and evaluation (*49*). In addition, the water-accessible AV content showed strong linear correlation with the interconnected AV content (computed using X-ray Computed Tomography (X-ray CT) and image analysis techniques), which supports the convenience of further investigating the use of both AV contents in the laboratory and computational evaluation of PFC/OGFCs mixtures (*51*).

An evaluation of drainability based on the computation of the expected value of permeability, $E[k]$, was included. Details of this computation are presented in section 2.1.2.5 (Determination of Drainability) of this report.

A durability evaluation conducted by applying the Cantabro loss test in both dry- and wet-conditions was included. The Cantabro loss value obtained from the dry-condition test constitutes an indirect measurement of the mixture resistance to disintegration, and the value computed for the wet-condition test determines the moisture sensitivity of the mixture (*34*).

Verification of stone-on-stone contact was included to guarantee that a fully developed stone-on-stone contact condition is developed in the coarse aggregate fraction of the PFC/OGFCs mixtures. This condition is required to ensure adequate mixture resistance to both disintegration and permanent deformation (*31*). As recommended in previous research (*52*), determination of the breaking-sieve size (defined as the aggregate size that differentiates the fine- and coarse-aggregate fractions), can be conducted according to the slope of gradation-curve criterion, which suggest selecting the sieve size at which the slope of the gradation curve below this size begins to flatten out.

Future evaluation of field performance (including both functionality and durability) of mixtures fabricated as recommended in the improved mix design method was recommended for implementation and validation of this method (*48*).

3.2. CONSTRUCTION

The construction of PFC/OGFCs, in general, utilizes the current techniques applied to construct DGHMA with the same equipment. However, the construction of porous layers requires some special considerations throughout the process.

In this section, considerations of PFC/OGFCs construction are discussed including the following aspects: mixture production, mixture storage and transportation, surface profile, mixture placement, material compaction and joint construction, and mixture acceptance.

3.2.1. Mixture Production

This section summarizes the following mixture production considerations of PFC/OGFCs mixtures: aggregate moisture control, fibers, and mixing temperature.

3.2.1.1. Aggregate Moisture Control

As in the production of DGHMA, PFC/OGFCs mixture production requires special attention to aggregate moisture control. All of the moisture can be removed from the aggregate before discharging from the plant if the mixing time and temperature are controlled. Some states require the use of aggregate in a surface dry condition for PFC/OGFCs production (*53*), while other states require a minimum of two days reserve of aggregate (before mixture production starts) in the case of production with mobile plants. 2004 TxDOT specifications (Item 342) require that the mixture contain no more than 0.2 percent moisture by weight, which should ensure better control of mixing temperature. The British standard establishes 1 percent (by mass of the mixture at the required temperature) as the maximum moisture content for PA mixtures during construction (*54*).

3.2.1.2. Fibers

Drum and batch plants are both used successfully for addition of mineral and cellulose fibers when a PG 76-XX binder is specified (according to the current TxDOT specifications (*2*)). Conventional asphalt plants can be adapted to allow the incorporation of fibers with the installation of a fiber feed device and the use of modified binders as required for most PFC/OGFCs mixtures. In drum and batch plants, pelletized fibers and loose fibers are available for incorporation into the mixture.

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

In batch plants, bags of fiber can be added directly into the pugmill where the bags melt, and the fiber is distributed into the mixture. When using a batch plant to produce mixtures with mineral fibers or cellulose fibers, both the dry and the wet mixing time should be lengthened to augment fiber distribution. Drying time should also be increased, since lower temperatures are specified (compared with production temperatures of other mixtures), which leads to longer drying time for the aggregate, resulting in reduced plant production rates (*1, 2*).

3.2.1.3. Mixing Temperature

In order to prevent draindown of the binder and minimize binder component degradation, the mixing temperature should be limited to ensure that the mix reaches the roadway at a temperature that provides for ease of placement. TxDOT specifications (*2*) require that the maximum temperature not exceed 177 °C (350 °F) prior to shipping the mix from the plant and that the mixture shall not be placed at a temperature below 138 °C (280 °F). Arizona established a maximum mixing temperature of 175 °C (347 °F), and Oregon specified maximum plant temperatures of 175 °C (347 °F) and 160 °C (320 °F) for modified asphalt binder and unmodified asphalt binder, respectively (*1*). Spanish standards established a maximum temperature of 155 °C (311 °F) upon leaving a drum mix plant and 170 °C (338 °F) for production in batch plants (*1*). FHWA recommends keeping the binder viscosity in the range of 700 to 900 centistokes (1.08 to 1.39 in^2/s) to establish the mixing temperature considering the prevention of draindown issues. Table 38 presents the limits on the mixture temperature for any location in the plant for paving grade binder for PA in Europe (*55*).

Table 38. Temperature Limits for PA in Europe (*55*).

Penetration of binder, 1/10 mm	*Temperature, ºC (ºF)*
35/50	150-180 (302-356)
40/60	150-180 (302-356)
50/70	145-175 (293-347)
70/100	140-170 (284-338)
100/150	130-160 (266-320)
160/220	130-160 (266-320)
250/330	120-150 (248-302)

3.2.2. Mixture Storage and Transportation

Since PFC/OGFCs are prone to draindown, some state DOTs limit mixture storage and transportation times (with maximum periods of storage in the silo between 1 and 12 hours). FHWA suggested that the combined handling and hauling of PFC/OGFCs mixture should be limited to 40 miles or 1 hour. In Britain, a maximum period of 3 hours is specified as acceptable for the entire process between mixing, placement, and compaction (*1*). California DOT recommends PFC/OGFCs should not be stored in a silo for more than two hours (*56*). TxDOT requires that PFC/OGFCs mixtures not be stored for a period long enough to affect the quality of the mixture, nor in any case longer than 12 hours. Thus far, draindown of the binder has not been reported as a problem in the construction of PFC/OGFCs in Texas (*2*).

Tarps are necessary to avoid crusting of PFC/OGFCs mixtures during transportation. Although the use of tarps and insulated truck beds for PFC/OGFCs transportation are required by some state DOTs, TxDOT specifications (Item 342) does not require these. In Britain, double-sheeted insulated vehicles are required to transport PA mixtures (*57*). Truck beds should be prepared for transportation of rich PFC/OGFCs mixtures by using a full application of an asphalt release agent (particularly if polymer or rubber-modified binder is used).

3.2.3. Surface Profile

PFC/OGFCs should not be considered as a layer to correct profile distresses or any kind of structural distress. Before PFC/OGFCs placement, any edge clearing should be performed to prevent clogging of the mixture near the edge. Simultaneously, the pavement surface should be corrected to avoid zones that allow water accumulation (e.g., zones with permanent deformation) and adversely affect not only the PFC/OGFCs layer but also the underlying pavement layers. Lateral and longitudinal drainage of the underlying layer must be provided to guarantee adequate water discharge from the PFC/OGFCs. Due to the existence of flow into the PFC/OGFCs, it should be placed over an impermeable layer to prevent problems in underlying layers. In Britain, protection is provided for underlying layers by applying a tack or bond coat and specifying a minimum cross slope of 2.5 percent (*1, 2*). As reported in NCHRP project 9-41 (*29*), in France, a tack coat with 400 g/m^2 of residual binder was used to protect the porous layer and underlying layer, which are only in contact through the coarse aggregate of the PA (*33*). FHWA suggested application of asphalt emulsion (diluted 50 percent with water and applied at a rate of 0.23 to 0.45 liter/m^2 [0.05 to 0.10 gal/yd^2]) to seal the surface of underlying layers before PFC/OGFCs placement (*1, 2*), and TxDOT suggested application of asphalt emulsion at a rate of 0.36 to 0.45 liter/m^2 (0.08 to 0.1 gal/yd^2).

TxDOT (*2*) prefers the surface directly beneath the PFC/OGFCs to be a seal coat (also known as a chip seal), which not only ensures an impermeable membrane to protect the underlying layers from surface water intrusion but also helps to provide a good bond between the PFC/OGFCs and underlying surface. An adequate tack coat to bond the PFC/OGFCs to the underlying surface is also important. It can help to seal the surface from the intrusion of water from the surface. The tack coat, which should be uniform and applied at a rate between 0.04 and 0.10 gal/yd^2 residual asphalt, is described in TxDOT specifications (Item 342). If there is a new seal coat underneath the PFC/OGFCs, some agencies do not require a tack, although other agencies still required a tack on the new seal prior to placement of the PFC/OGFCs (*2*).

3.2.4. Mixture Placement

This section summarizes the following mixture placement considerations of PFC/OGFCs mixtures: paver operations and temperature.

3.2.4.1. Paver Operations

To produce a smooth surface, the paver should advance continuously with minimal stoppages. In the case of direct delivery from the truck to the paver, it is important to limit mixture delivery with cold lumps and avoid bumping the paver because surface depressions are more difficult to correct with PFC/OGFCs than with DGHMA. In addition, when asphalt pavers with extendible screeds are used, auger extensions are recommended to avoid irregular distribution of mixture between the center and the edge of the paver (*53*). The use of a hot screed in the asphalt paver is recommended to avoid pulling excessively on the material and diminish the necessity of raking, which can cause areas with lower AV content or more likely uneven void distribution across the pavement. In addition, raking can generate unsightly surface texture and poor aesthetics, which cannot be rolled out with compaction (*58*).

As reported in NCHRP project 9-41 (*29*), Wagner and Kim (*59*) used two pieces of equipment to construct a safety edge that was constructed as a tapered edge approximately 15.2 to 20.3 cm (6 to 8 in) in length. One piece of the equipment was developed by Georgia Department of Transportation (GDOT), and the other named Safety Edge Maker (SEM) was designed and built by TransTech Systems, Inc. These two pieces of equipment were a wedge that mounted onto a paver. The GDOT safety wedge mounted only onto the end gate of the paver screed, and the SEM can mount onto a variety of different pavers. The use of a safety edge may have benefit to PFC/OGFCs because these pavements are daylighted at the pavement edge. Since degradation of PFC/OGFCs mixtures is expected, a tapered pavement edge is recommended to provide safety to the traveling public. The study demonstrated that both pieces of equipment successfully constructed safety edges. The GDOT safety wedge created a safety edge from a dropoff of 0 to 15.2 cm (0 to 6 in). The SEM allowed the device to follow the wayside surface by using a self adjusting spring, and then setting the initial height and the taper to create the safety edge.

Initiation of mixture placement is recommended on the low side of the paving area to avoid accumulation of water (from the rollers or surface water) onto areas to be paved. It is desirable to minimize or even avoid mixture hand-working, but if handwork is necessary, it should be done with a wooden lute instead of metal-toothed rakes (*1*).

If the PFC/OGFC s mixture is to be placed in the main lanes only, thicker materials may require a taper to join the grade of the existing shoulder. If tapering is required, the Beaumont

District in TxDOT recommends the use of a special-type milling machine to mill in the tapers due to the workability difficulties in constructing a taper with the paver for this type of mix. The Yoakum District in TxDOT was able to construct the taper for the notched wedge joint. The smaller roller attached to the paver to roll the taper required a worker to constantly apply a release agent to minimize mixture pickup (*2*). Handwork on PFC/OGFCs mixtures is difficult to impossible. Experienced districts recommend staying away from crossovers and bridge ends when paving with PFC/OGFCs mixtures and instead paving these areas with DGHMA (*2*).

PFC/OGFCs are generally constructed using modified binders and is typically placed at lower thicknesses than DGHMA. Thin layers cool faster and allow less time for compaction. In the United States, PFC/OGFCs are commonly constructed in thin layers 20 to 25 mm (0.75 to 1 in) in thickness; whereas, in Europe, PA is typically constructed with a 40 to 50 mm (1.57 to 1.97 in) layer thickness (*49*). However, for the PFC/OGFCs in the United States, the typical layer thickness is 32 mm (1.25 in) (*32*). In Japan and some European countries, agencies are testing thicker two-layer PA to provide both noise reduction and safety. In this case, the top layer is about 25 to 30 mm (0.98- to 1.18-in) thick, and the bottom layer is about 40 to 50 mm (1.57 to 1.97 inch) (*60*). Figure 37 shows a two-layer PA mixture. The Japanese have developed the Multi-Asphalt Paver with the capability to simultaneously place both layers of the two-layer PA (*61*). In Britain, a nominal thickness of 50 mm (1.97 in) is specified to maximize sound attenuation, spray reduction life, water storage capacity, and compaction time of the PA mixture. The minimum paver discharge temperature is specified in terms of binder viscosity, with a limit of 5 Pa-s (0.104 lb s/feet^2) (*1*).

Figure 37. Double Layer PA Mixture (*62*).

3.2.4.2. Temperature

Monitoring the temperature of PFC/OGFCs as delivered to the roadway is important. Any cold spots will form lumps in the mix and must be removed. The use of a material transfer vehicle (MTV) to minimize the need to remove large chunks of mix is recommended by some TxDOT districts. Even with the MTV, there may still be small chunks of mix requiring removal and patching from the material. The windrow pickup process tends to exhibit more thermal segregation for PFC/OGFCs. Several TxDOT districts reported that while this process was used on hot, summer days, it should not be used for PFC/OGFCs mixtures on cooler days (*2*).

Acceptable paving conditions in the United States are commonly defined as a minimum air temperature of 15 °C (60 °F). Although this limit is used by most agencies, there are some exceptions. Florida, for example, requires a minimum air temperature of 8 °C (45 °F) (*53*). The British Manual of Contract Documents for Highway Works specified the maximum wind speed as part of its acceptable paving conditions (*57*). As reported in NCHRP project 9-41 (*29*), CalTrans (*56*) provided guidance on the relationship between ambient temperature and placement temperature shown in Table 39. CalTrans required a minimum ambient temperature of 8 °C (45 °F) for PFC/OGFCs placement. The guidelines also provided temperature limits for PFC/OGFCs, including minimum temperatures for rolling presented in Table 40.

Table 39. PFC/OGFCs Placement Temperatures Used by CalTrans (*29*).

Ambient Temperature	Binder Type	Placement Temperature
> 21°C (> 70 °F)	conventional asphalt	Rolling < 91°C (195 °F)
	polymer modified	Rolling > 121°C (250 °F)
	asphalt rubber	Initial breakdown compaction > 135 °C (275 °F) Final breakdown compaction > 121 °C (250 °F)
13 to 21°C (55 to 70 °F)	conventional asphalt	Rolling < 104°C (220 °F)
	polymer modified	Rolling > 121°C (250 °F)
	asphalt rubber	Initial breakdown compaction > 138 °C (280 °F) Final breakdown compaction > 127 °C (260 °F)
8 to 13 °C (45 to 55 °F)	polymer modified	Rolling > 121°C (250 °F)
< 8 °C (< 45 °F)	PFC/OGFCs should not be placed	

Table 40. OGFC Temperatures Limits Used by CalTrans (*29*).

Binder Type	*Min. Ambient T. °C (°F)*	*Min. Pavement T. °C (°F)*	*Max. Aggregate T. at Plant °C (°F)*	*Min. Breakdown Rolling T. °C (°F)*	*Min. Final Rolling T. °C (°F)*
Conventional (normal)	21 (70)	*	135 (275)	N/A	91 (195)
Conventional (cold T.)	13 (55)	*	135 (275)	N/A	104 (220)
Polymer Modifier	7 (45)	*	163 (325)	N/A	121 (250)
Asphalt rubber (normal)	18 (65)	18 (65)	163 (325)	135 (275)	121 (250)
Asphalt rubber (cold T.)	13 to 18 (55 to 65)	13 (55)	163 (325)	138 (280)	127 (260)

Note: *: critical temperature (the min. ambient temperature, min. pavement temperature, max. aggregate temperature at plant and the mixture laydown temperature range)

TxDOT required a minimum roadway temperature of 21 °C (70 °F). TxDOT specifications (Item 342) indicated that the mixture delivered to the paver not drop below 138 °C (280 °F) and thermal profiles are required for each sublot (*2*). The TxDOT Austin District personnel report that they prefer the mixture to be at 163°C (325 °F) as it is coming out of the trucks (*2*).

3.2.5. Material Compaction and Joint Construction

This section describes the considerations of material compaction and joint construction of PFC/OGFCs mixtures.

3.2.5.1. Material Compaction

Static steel-wheel rollers are required for the compaction of PFC/OGFCs mixtures. Typically, two to four passes (within the adequate range of temperature) with an 8- to 9-ton tandem roller are appropriate to complete the compaction process on thin layers (20 mm [0.78 in]). McDaniel and Thornton (*63*) used a MTV to construct PFC/OGFCs mixtures in Indiana. They found that one pass from each of two steel-wheel rollers was sufficient for compaction. CalTrans indicated that two complete coverages with a steel-wheel roller should be made for PFC/OGFCs compaction (*56*). Vibratory rollers, which will break down aggregates within the PFC/OGFCs, should not be used. Moreover, pneumatic tire rollers, which will pick up the PFC/OGFCs, should not be used either. FHWA recommends one or two passes of an 8- to 10-ton static steel-wheel roller to compact PFC/OGFCs (*1*). However, the Design Manual for Roads and Bridges (Britain) recommends application of at least five passes, but they typically use thicker (~50.8 mm [2 in]) layers (*1*). Heavier rollers (weighing more than 10 tons) should be avoided because they can lead to excessive aggregate breakage, and pneumatic rollers must not be used since their kneading action reduces the mixture drainage capacity by closing surface pores. Roller drums should be thoroughly moistened with a soap-and-water solution to prevent adhesion. Only water or an approved release agent may be used on rollers, tamps, and other compaction equipment.

The aggregate gradation of HMA has a far greater influence on aggregate degradation under compaction than alterations to the compaction energy *(64)*. PFC/OGFCs mixtures experience a greater amount of aggregate degradation after compaction compared to DGHMA. There should be a balance between achieving the needed compaction to ensure durability of the mixture without degrading the aggregate as well as providing a proper amount of compaction to achieve drainability.

In 2007, PFC sections were tested in the TxDOT Austin and Yoakum Districts to show how the field WFV changed with each roller pass and how two different mixes (both constructed under Item 342) behaved very differently (*2*). To ensure adequate drainability, the field WFV did not exceed 20 seconds. For the mixtures in the TxDOT Austin District, the WFV of 20 seconds corresponded to a compaction effort of not more than four passes. For the mixtures in the TxDOT Yoakum District, the field WFV did not change significantly after the first two passes. Field WFV versus field compaction effort is shown in Figure 38, and mixture differences are shown in Table 41.

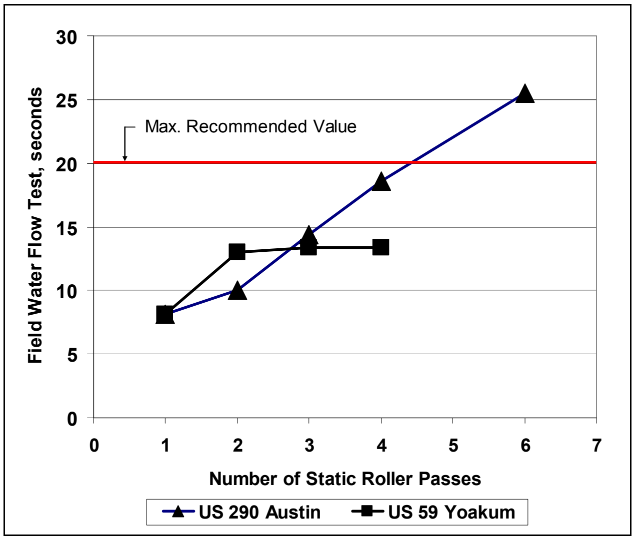


Figure 38. Field WFV vs. Field Compaction Effort (*2*).

Table 41. Mixture Designs Used in Yoakum and Austin, Texas (*2*).

Gradation	*US 59 Yoakum Mix, % pass*	*US 290 Austin Mix, % pass*
3/4 in	100.0	100.0
1/2 in	84.5	99.7
3/8 in	52.8	75.7
No. 4	6.6	7.9
No. 8	4.2	1.1
No. 200	2.4	0.6
Binder Type, Content	PG 76-22S, 6.0%	Asphalt Rubber, 8.3%

Care should also be exercised to minimize the amount of roller overlap which often occurs in the center of the material. This results in the center of the material receiving more compaction than the outside edges and is not a problem for DGHMA. Additional compaction due to roller overlap in the center of the PFC/OGFCs for the mixtures in the TxDOT Austin District could restrict the lateral flow of water through the mix.

One of the requirements implemented by the TxDOT Houston District is that only one roller pass is allowed (i.e., rollers are not permitted to back up). This requires two rollers operating in tandem to achieve one full coverage of the mixture. WFV for this mixture after one roller pass was about 10 seconds. In addition, stopping the roller on the mixture for an extended length of time may leave a roller mark (*2*).

3.2.5.2. Joint Construction

Longitudinal and transverse joints in PFC/OGFCs require special treatment since they are more difficult to construct than those in DGHMA. Transverse joints should be minimized as much as possible, but where required, they can be formed by using lumber fastened to the underlying surface before placing the joint. This kind of joint does not require the application of additional binder prior to placement of new mixture. On the other hand, when a sawn joint is required, a scarce amount of binder (i.e., asphalt emulsion) should be applied to improve adhesion. This kind of joint should be minimized with the realization that the applied binder does not have the purpose of sealing the joint as in DGHMA (*1*).

Longitudinal joints should always be located outside the wheel paths. Most TxDOT districts use a conventional butt joint, though the TxDOT Yoakum District has successfully constructed the notched wedge joint (*2*). Longitudinal joints for PFC/OGFCs should be constructed in much the same manner as for DGHMA. There are four steps to correctly constructing a longitudinal joint (*2*) (Figure 39):

(1) Properly compact the unsupported edge of lane 1.
(2) Properly overlap the mix from lane 2 to lane 1.
(3) Do not rake the joint.
(4) Locate rollers at the proper location when compacting the joint.

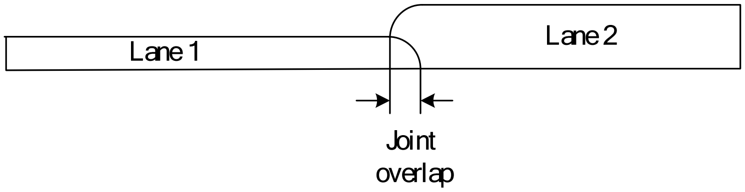


Figure 39. Longitudinal Joint Schematic.

The edge of the steel-wheel drum should extend over the unsupported edge of the lane paved first by 15 cm (6 in). This will prevent shear loading, which can occur at the edge of the drum and can cause the mix to move transversely. Secondly, when the mixture from lane 2 is placed over the top of the compacted mixture from lane 1, the thickness of the mixture as placed needs to account for "roll down" during compaction. For DGHMA, this is typically about 6.35 mm (0.25 in) per 25.4 mm (1-in) thick material. For example, to obtain a 25.4 mm (1-in) thick compacted material, the mixture should be about 31.75 mm (1.25-in) thick prior to compaction. The amount of "roll down" that will occur for a PFC/OGFCs mixture is much less, about 2.54 mm (0.1 in) of roll down per inch of compacted material thickness. There should be very little transverse overlap of the mixture from lane 2 to lane 1, less than 25.4 mm (1 in). No raking should be performed at the joint and is not necessary if the proper vertical and horizontal overlap is achieved. Finally, to compact the joint, the most efficient location is to place the rollers on the hot side of the material with 152.4 mm (6 in) extended over the joint (*2*).

Joint adhesives or tack coats are sometimes placed on the longitudinal unsupported material edge to improve the bond to the subsequent lane at the joint interface of DGHMA. This practice should be avoided for PFC/OGFCs mixtures since additional binder at the joint interface could reduce the permeability and interfere with the lateral movement of water.

3.2.6. Mixture Acceptance

Even though specified density in the field is not currently required, adequate compaction is necessary since low-density zones are prone to raveling. However, too much compaction can affect the mixture's permeability. The practice in most agencies for mixture approval is based on the evaluation of binder content and gradation and the execution of visual inspection of the mixture after compaction to evaluate (qualitatively but not quantitatively) the density, material variability, and segregation (*1*). TxDOT accepts the mixture based on aggregate gradation, laboratory-molded density, binder content, draindown, boil test, and a thermal profile. In addition, the engineer may take samples or cores from suspect areas to determine recovered asphalt properties. Corrective action is also required if there are any surface irregularities such as segregation, rutting, raveling, flushing, fat spots, material slippage, color, texture, roller marks, tears, gouges, streaks, or uncoated aggregate particles (*2*). Essentially, all agencies, including TxDOT, specify a minimum smoothness *(53)*.

In Spain, the acceptance criterion corresponds to the determination of the mean AV content (for which a maximum difference of 2 percent in comparison with the reference AV content is required.) In England, a specified hydraulic conductivity of the material is required and is evaluated in the field before any traffic is permitted (*1*). Recent research (*31*) on PFC/OGFCs suggested that the field density requirement for PFC/OGFCs corresponding to the

OAC, computed during the mix design, may be used as reference to define the equilibrium density.

3.3. MAINTENANCE

Since maintenance cannot be performed in the same way as for conventional DGHMA, it is a fundamental aspect to consider in any project involving PFC/OGFCs. PFC/OGFCs mixtures may exhibit the following distress modes: shear failures in high stress areas, cracking due to fatigue, cracking due to reflection from below, raveling due to oxidation and hardening of the binder, raveling due to softened binder from oil and fuel drippings, raveling due to lack of compaction or low asphalt content, delamination due to improper tack coat application as well as rich- and dry-asphalt spots due to draindown of binder during transportation and placement (*56*).

TxDOT PFC/OGFCs mixtures that are designed and placed under Item 342 are relatively new (less than 5 years old) and, thus far, have performed well with little to no maintenance required (*2*). No rutting was observed on any of the in-place mixtures assessed in TxDOT Project 0-5262 (*2, 3*), and many of the PFC/OGFCs are under very heavy traffic. Some minimal cracking has been observed, which appears to be a reflection of underlying cracks. Longer-term performance concerns for PFC/OGFCs are with regards to raveling and delamination, though there is little evidence of these failure modes in the current mixtures to date. One of the original Item 342 PFC/OGFCs was placed on IH-35 just north of San Antonio. This mixture started to exhibit some isolated performance problems at about 4 years of age. Small isolated areas in the wheel paths were exhibiting signs of delamination or raveling or both (*2*). This project (0-5836) will evaluate long-term performance of PFC/OGFCs.

The first part of this section reviews the main issues associated with winter maintenance in PFC/OGFCs materials. Next, surface maintenance is discussed, followed by a summary of current rehabilitation practices for PFC/OGFCs.

3.3.1. Winter Maintenance

In general, PFC/OGFCs mixtures exhibit lower thermal conductivity and reduced heat capacity compared with DGHMA. Elevated AV contents in PFC/OGFCs reduce the flow rate of heat through the material. In fact, the thermal conductivity of PFC/OGFCs can be only 40 to

70 percent of the magnitude of that for DGHMA, making PFC/OGFCs operate as an "insulating course" at the surface *(1)*.

As a result of these thermal properties, the surface of a PFC/OGFCs can exhibit temperatures -17 to -16 °C (2 to 4 °F) lower than the surface temperature of adjacent DGHMA, producing earlier and more frequent frost and ice formation *(45, 53)*. Longer periods under such conditions, compared with DGHMA, are thus expected. The occurrence of this phenomenon has been identified in Europe, in the United States, and specifically in Texas. Thus, the time to reach adequate pavement friction values after ice formation has occurred is longer in porous pavement (*53)*. In fact, formation of black ice and extended frozen periods are currently considered the main problems associated with PFC/OGFCs maintenance in the United States. Consequently, PFC/OGFCs require specific winter maintenance practices. For example, in addition to conventional practices for winter maintenance, the use of pavement condition sensors, meteorological instrumentation, and connecting hardware and software is suggested to monitor the road system and support the decision process involving when and how to treat a PFC/OGFCs surface *(2)*.

More salt (or deicing agents) and more frequent applications than on DGHMA are required to perform winter maintenance on PFC/OGFCs *(53, 65, 66)*. As reported in NCHRP project 9-41 (*29*), researchers in the Netherlands recommended average rate for spreading road salt (Table 42) for winter maintenance (*67*). The study found that too much salt placed on PFC/OGFCs under dry conditions led to slipperiness, and the salt froze when temperatures dropped below -15 °C (5 °F); instead, calcium chloride was applied on the pavement surface. In New Jersey, agencies used liquid magnesium chloride for deicing successfully on PFC/OGFC pavements (*11*). Researchers mentioned that pretreatment with liquid magnesium chloride on PFC/OGFCs surfaces can avoid icing. However, if the liquid magnesium chloride is applied after the PFC/OGFCs are frozen, then the liquid magnesium chloride washes off the pavement surface. In Texas, deicing agents are currently considered the most effective winter treatment, followed by liquid deicer agents and sand. However, the FHWA recommends developing snow and ice control using chemical deicers and plowing and avoiding the use of abrasive materials to improve traction. Spreading of sand to enhance friction and hasten deicing contributes to the clogging of voids, causing a decrease in drainage and noise reduction effectiveness, which are considered two of the main PFC/OGFCs advantages *(2)*.

Table 42. Spreading Rate Recommended by the Netherlands (*29*).

Condition	*Dry Salt, g/m^2*	*Prewetted Salt, g/m^2*
Preventative (before a problem exists)	-	7(1)
Fog moisture	10	7
Icing	15-20	7-10
Glazed frost(2)	20	15
Snow (after removel with plows)(3)	20	-

Note:

(1) On PFC, 14 g/m^2 is used (two application of 7 g/m^2)
(2) When the glazed frost situation stays for several hours, 20-40 g/m^2 dry salt should be used.
(3) Precautionary treatment: 15-20 g/m^2 pre-wetted salt.

Since the deicer can flow into a PFC/OGFCs instead of remaining at the surface, Oregon DOT has suggested research on organic deicers with higher viscosity and electrostatic charge technology (similar to that employed in emulsified asphalt) to improve bonding of deicers on the surface *(65)*. In Europe, agencies use calcium magnesium mixtures as a deicing agent, which can stay on the porous surface and not drain into PA pavements (*68*).

In Texas, severe weather events are generally confined to the northern section of the state. It is in these areas that TxDOT district personnel must prepare for winter maintenance strategies for PFC/OGFCs pavements *(69)*.

From the literature and the current practice of TxDOT districts, anti-icing procedures may produce the best result to combat black ice, freezing rain, and light snow events *(69)*. Anti-icing procedures involve a combination of liquid, dry solid, and prewetted chemicals applied at the appropriate times, taking into consideration temperature, the amount of moisture, and traffic conditions. De-icing procedures should be reserved for events in which ice and snow have already bonded (*2*).

Sand should only be used in emergency situations where quick friction is needed, for instance, during a surprise ice or snow event *(69)*. The use of other materials may be used to generate the needed friction. Table 43 shows a plan for anti-icing and de-icing operations suggested by the FHWA in a black ice event *(70)*.

Table 43. Weather Event: Frost or Black Ice *(2)*.

Pavement Temp. Range and Trend and Relation to Dew Point	**Traffic Condition**	**Initial Operation**			**Subsequent Operations**			**Comments**
		Maint. action	**Dry chemical spread rate, kg/lane-km (lb/lane-mi)**		**Maint. action**	**Dry chemical spread rate, kg/lane-km (lb/lane-mi)**		
			liquid	**solid or prewetted solid**		**liquid**	**solid or prewetted solid**	
Above 0°C (32°F), steady or rising	Any level	None, see comments			None, see comments			Monitor pavement temperature closely; begin treatment if temperature starts to fall to 0°C (32°F) or below and is at or below dew point
-2 to 2°C (28 to 35°F), remaining in range or falling to 0°C (32°F) or below, *and* equal to or below dew point	Traffic rate less than 100 vehicles per h	Apply prewetted solid chemical		7-18 (25-65)	Reapply prewetted solid chemical as needed		7-18 (25-65)	1) Monitor pavement closely; if pavement becomes wet or if thin ice forms, reapply chemical at higher indicated rate 2) Do not apply liquid chemical on ice so thick that the pavement can not be seen
	Traffic rate greater than 100 vehicles per h	Apply liquid or prewetted solid chemical	7-18 (25-65)	7-18 (25-65)	Reapply liquid or prewetted solid chemical as needed	11-32 (40-115)	7-18 (25-65)	
-7 to -2°C (20 to 28°F), remaining in range, *and* equal to or below dew point	Any level	Apply liquid or prewetted solid chemical	18-36 (65-130)	18-36 (65-130)	Reapply liquid or prewetted solid chemical when needed	18-36 (65-130)	18-36 (65-130)	1) Monitor pavement closely; if thin ice forms, reapply chemical at higher indicated rate 2) Applications will need to be more frequent at higher levels of condensation; if traffic volumes are not enough to disperse condensation, it may be necessary to increase frequency 3) It is not advisable to apply a liquid chemical at the indicated spread rate when the pavement temperature drops below -5°C (23°F)
-10 to -7°C (15 to 20°F), remaining in range, *and* equal to or below dew point	Any level	Apply prewetted solid chemical		36-55 (130-200)	Reapply prewetted solid chemical when needed		36-55 (130-200)	1) Monitor pavement closely; if thin ice forms, reapply chemical at higher indicated rate 2) Applications will need to be more frequent at higher levels of condensation; if traffic volumes are not enough to disperse condensation, it may be necessary to increase frequency
Below -10°C (15°F), steady or falling	Any level	Apply abrasives			Apply abrasives as needed			It is not recommended that chemicals be applied in this temperature range

Notes:
Timing: (1) Conduct initial operation in advance of freezing. Apply liquid chemical up to 3 hrs in advance. Use longer advance times in this range to effect drying when traffic volume is low. Apply prewetted solid 1 to 2 hrs in advance. (2) In the absence of precipitation, liquid chemical at 75 lb/lane-mi has been successful in preventing bridge deck icing when placed up to 4 days before freezing on higher volume roads and 7 days before on lower volume roads.

3.3.2. Surface Maintenance

According to a survey conducted as part of the National Cooperative Highway Research Program (NCHRP) Synthesis 284 (2), there are no reports in the United States on the application of major maintenance for PFC/OGFCs. From 17 states that reported their use, only New Mexico, Wyoming, South Carolina, and Oregon employ fog seals to perform preventive maintenance. Although quantitative information about the significance of these treatments is not available, it is expected that fog seals extend the life of porous mixtures since they provide a small film of unaged asphalt at the surface *(65)*. The FHWA in 1990 recommended fog seal application in two passes (at a rate of 0.05 gal/yd^2 for each pass) using a 50 percent dilution of asphalt emulsion without any rejuvenating agents *(2)*.

Research in Oregon regarding permeability reduction and changes in pavement friction on certain PFC/OGFCs pavements generated by fog seals concluded that the mixtures still retain porosity and keep the rough texture related to its capability to reduce the potential for hydroplaning *(65)*. However, quantitative conclusions regarding the changes in these parameters are not included. A decrease in pavement friction was noticed immediately after fog seal application, but during the first month, it increased considerably by traffic action.

Snowplow blade abrasion has considerable effects on the durability of traffic markings on PFC/OGFCs. Thermoplastic markings or even some fragments of mixture impregnated with thermoplastic can be displaced when steel snowplow blades are used for winter maintenance. Field trials in Rhode Island showed the lack of durability of the permanent inlaid traffic marking tape on modified PFC/OGFCs under such conditions. Therefore, Rhode Island recommended suspension of its use until corrections can be implemented to improve its durability. Rhode Island further reported that recessed thermoplastic traffic markings proved cost effective in comparison with non-recessed thermoplastic markings. Although recessed thermoplastic traffic markings showed lower snowplow blade damage, fully and semi-recessed markings installed in a tangent highway test section failed to maintain the recommended minimum retroreflectivity in wet night conditions *(2)*.

Highway agencies in British Columbia, South Carolina, and Maryland reported that thermoplastic marking material was the most appropriate for PFC/OGFCs applications *(53)*. The British limit the use of pavement markings with thermoplastic materials to certain directional signs and arrows, considering that in PFC/OGFCs the marking material has more opportunity to flow downward into the mixture *(2)*.

Cleaning of PFC/OGFCs in the United States is not common practice (*1*). High-pressure washing is currently quite expensive and of questionable value. Current maintenance activities in Denmark include cleaning of the voids by high-pressure water and air suction twice a year as a strategy that combines the construction of two-layer drainage asphalt and cleaning in order to maintain porosity during the pavement lifetime *(71)*. On the other hand, Japan is applying the "function maintenance" concept that comprises more frequent cleaning operations with only partial debris removal during each cleaning *(61)*.

3.3.3. Corrective Maintenance

Mill and inlay using PFC/OGFCs was recommended (*2*) in Oregon to repair PFC/OGFCs when the quantities of material were enough to justify these activities. FHWA advises consideration of the area and the drainage continuity. Thus, when the area to be repaired is small and the flow around the patch can be ensured, DGHMA is recommended for patching. Otherwise, the zone should be repaired by using PFC/OGFCs mixture when larger areas of patching are involved (*1*). In 2000, the use of DGHMA to repair delaminated areas and potholes was indicated by all states in the United States that reported the utilization of PFC/OGFCs. Only the Wyoming DOT reported crack filling, and according to their experience, drainage problems can result from crack sealing, since water flow inside the material is diminished *(53)*. In Britain, the use of PFC/OGFCs or open-graded macadam is recommended to repair both small and large potholes. The use of dense bitumen macadam is permitted, if necessary, but its replacement by permeable mixture is recommended. Finally, the application of hot-rolled asphalt is limited for repairing small areas (i.e., 45.72 x 45.72 cm [18 x 18 in]) *(72)*.

To diminish the wheel impact on the patch joint and facilitate the flow of water around a DGHMA patch, rotation of the patch to 45 degrees to provide a diamond shape is recommended. Alternatively, the execution of machine patch, blade patch, or screed patch may be used (*65*).

3.3.4. Rehabilitation

An ideal set of technical actions for major rehabilitation of PFC/OGFCs has been defined by some DOTs (e.g., Florida and Georgia) as mill, recycle, and inlay (*1*). The same approach has been recommended in Oregon and reported as the favored approach in the Netherlands *(65)*. When inlaying PFC/OGFCs, one must avoid creating an impermeable vertical wall at the lower side of the inlay and, thus, the potential for ponding water. In the absence of raveling or delamination demanding rehabilitation, once the PFC/OGFCs has lost its functionality by clogging, its service might still be permitted since it essentially behaves as a DGHMA with low permeability *(53)*.

General recommendations and actual practices for rehabilitation of PFC/OGFCs in the United States include milling and replacing of existing PFC/OGFCs with new PFC/OGFCs or any other asphalt mixture *(2)*. However, this conventional milling operation is an expensive proposition. GDOT (*73*) suggested that the micro-milling technique using much finer teeth on the milling drum can solve this problem. A micro-milling operation not only produces a finer and smoother milled surface texture but also mills out only the existing PFC/OGFCs layers. Hence, use of micro-milling operation resulted in savings when compared with the conventional milling operation. Direct placement of new DGHMA over porous mixture is not recommended because life of the new layer can be diminished by water accumulation inside the PFC/OGFCs. For rehabilitating failed or aged PFC/OGFCs pavements, CalTrans only allows removal and replacement (*56*). The results reported by the Silvia project indicated that both hot-mix and cold-mix recycling are options for rehabilitation of PA (*68*). Hot-mix recycling takes reclaimed PA with new asphalt through a hot mix production, and cold-mix recycling used reclaimed PA with new asphalt and/or recycling agents to produce cold base mixtures. In general, hot-mix recycling is recommended for rehabilitation of PA in Europe. Experimental reports from the Netherlands showed that recycled PA kept approximately the same permeability, and its durability (evaluated by the Cantabro test) is similar to that of a new mixture *(53)*.

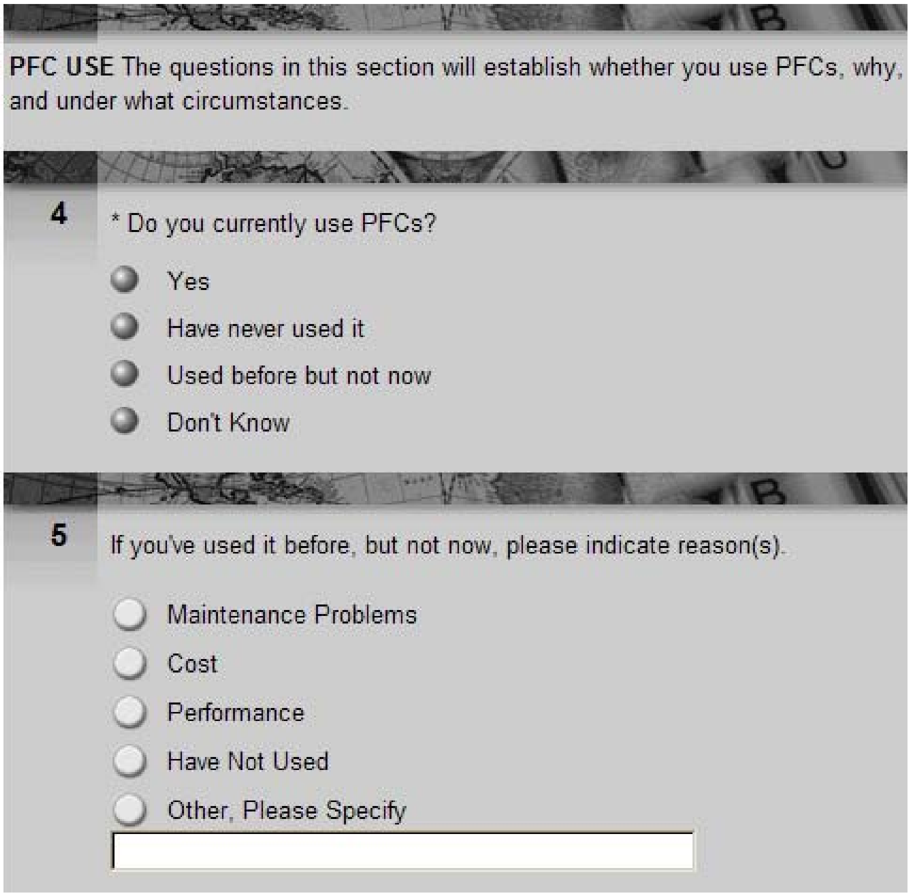
4. SURVEY

TxDOT Project 0-4834 *Cold-Weather Performance of New Generation OGFC* was a two-year project that investigated winter performance and maintenance issues of PFC/OGFCs pavements in Texas. The project included the following aspects:

- national and statewide surveys of practice comprising sections for use, performance, cost, maintenance, and other
- laboratory results for permeability and abrasion,
- a methodology for remote detection of icing, and
- recommendations for construction and maintenance based on geographic location.

TxDOT Project 0-4834 not only documents Texas's and other states history with PFC/OGFCs but establishes an initial reference point that can serve as a benchmark for performance of older PFC/OGFCs. Under this previous project, an online survey was conducted to determine the state of the practice with PFC/OGFCs pavements. The survey was initially sent to the TxDOT districts, and then subsequently to all 50 states to determine national experience with these pavements. Fifty-six questions were asked from the following five broad topics: (1) use or non-use of these pavements, (2) performance issues, (3) cost, (4) maintenance issues, and (5) other.

Under TxDOT Project 0-5836, an online survey was conducted to gather information concerning changes in performance and maintenance noted nationally and in Texas for PFC/OGFCs mixtures after aging in terms of time and traffic. Simultaneously, the existing data from TxDOT Project 0-4834 will serve as a baseline to evaluate changes in experience with PFC/OGFCs. The objective of this online survey is to gain information from TxDOT districts on the use and experience in terms of performance and maintenance with PFC/OGFCs pavements. Thirty questions will be asked from the following five broad topics: (1) use or non-use of PFC/OGFCs pavements, (2) performance issues, (3) cost, (4) maintenance and rehabilitation issues, and (5) other. Figure 40 shows the convenience of the online survey format, as seen by the user.



PFC USE The questions in this section will establish whether you use PFCs, why, and under what circumstances.

4 * Do you currently use PFCs?

● Yes
● Have never used it
● Used before but not now
● Don't Know

5 If you've used it before, but not now, please indicate reason(s).

○ Maintenance Problems
○ Cost
○ Performance
○ Have Not Used
○ Other, Please Specify

Figure 40. Online Survey Presentation.

The survey was sent to the 25 TxDOT districts, and a subsequent survey response follow up is being used to obtain a maximum response rate from 98 TxDOT contacts. In this section, five broad topics are briefly introduced, respectively, and samples of the responses obtained so far from this survey are summarized. In addition, a copy of the questions as seen by the user is presented in the Appendix.

4.1. USE OR NON-USE OF PFC/OGFCs

The questionnaire included six questions related to PFC/OGFCs use. If PFC/OGFCs were not used or used before, but not now, five reasons were listed to identify agencies' decisions. These five reasons included:

- maintenance problem,
- cost,

- performance,
- have not used, and
- other.

If PFC/OGFCs were selected for use, nine reasons for use were listed with the option of ranking from 1 to 9, with 1 being the most prevalent reason for PFC/OGFCs use. These nine reasons included:

- reduced splash and spray,
- skid resistance,
- noise,
- durability,
- smoothness,
- traffic level,
- environment,
- cost, and
- other.

The main advantages and disadvantages in the use of PFC/OGFCs mixtures in respondents' districts are also asked in the questionnaire. Seven possible advantages were listed with the option of ranking from 1 to 7, with 1 being the greatest advantage. The seven possible advantages included:

- improved wet weather skid resistance,
- improved driver visibility on wet pavement (reduced spray),
- improved road marking visibility during wet weather,
- noise reduction,
- durability,
- cost, and
- other.

Seven possible disadvantages were listed with the option of ranking from 1 to 7, with 1 being the biggest disadvantage. The seven possible disadvantages included:

- initial or construction cost,
- winter maintenance problems,

- durability,
- performance,
- rehabilitation,
- general maintenance, and
- other.

According to 34 responses so far, 22 currently use PFC/OGFCs, six have never used PFC/OGFCs, and six used PFC/OGFCs before but not now. The reasons for discontinuing the use of PFC/OGFCs are maintenance problems (8 percent), cost (17 percent), and performance problems (8 percent). One respondent replied that PFC/OGFCs were used to fix bleeding surface in his district.

In terms of traffic volumes for PFC/OGFCs, 43 percent respondents use the mixture in medium traffic volumes, 93 percent respondents use the mixture in high traffic volumes, and 7 percent respondents do not use it.

In terms of criteria for the use of PFC/OGFCs, the rankings 1 through 4 were considered to be the significant factors in order to use PFC/OGFCs mixtures. The rankings 1 through 4 were calculated in Figure 41. The highest ranking is reduced splash and spray followed by durability, skid resistance and noise, cost, smoothness, traffic level, and environment, as ranked by the respondents.

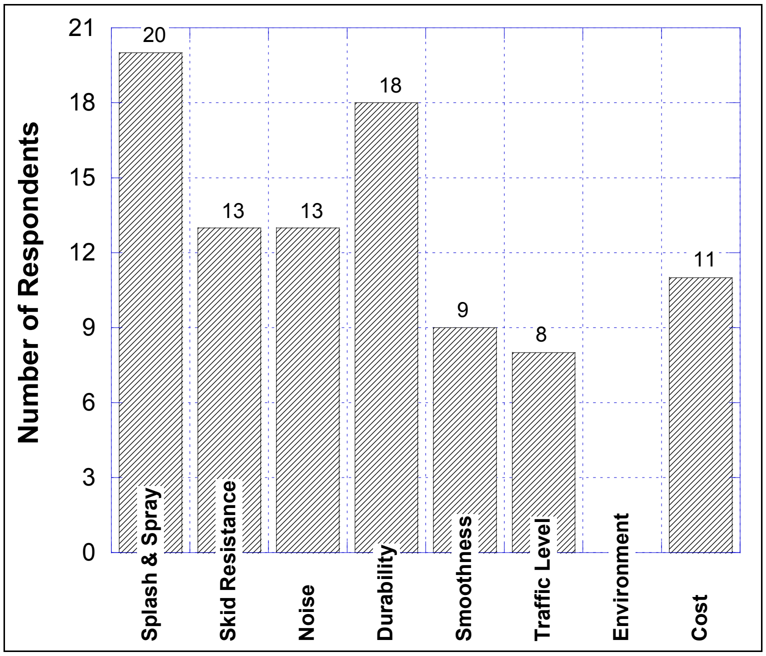


Figure 41. Criteria for Use of PFC/OGFCs.

In terms of advantage for the use of PFC/OGFCs, the rankings 1 through 3 were considered to be the significant factors. The rankings 1 through 3 were calculated in Figure 42. Improved driver visibility is the most cited advantage ranked by respondents followed by improved wet skid resistance, improved road marking visibility on wet pavement, durability, noise reduction, and cost.

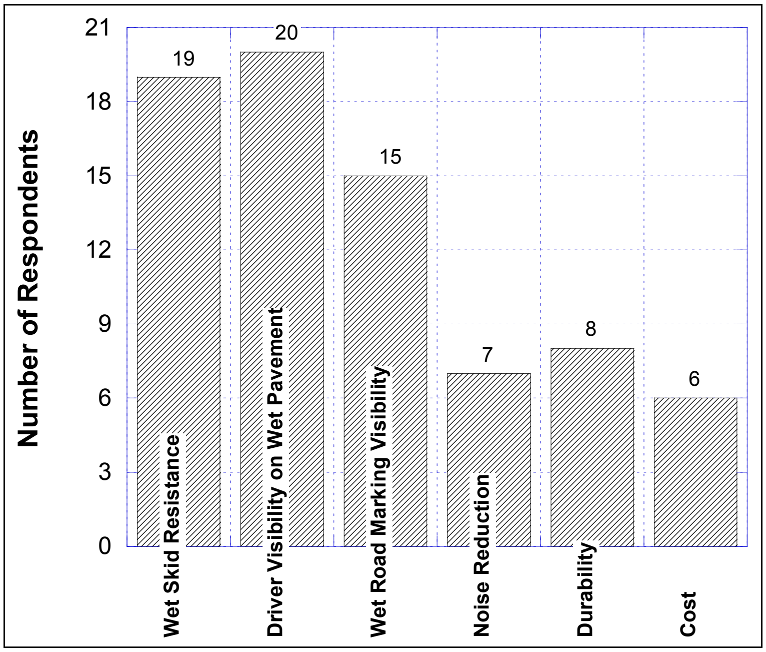


Figure 42. Advantages of Using PFC/OGFCs.

In terms of disadvantage for the use of PFC/OGFCs, the rankings 1 through 3 were considered to be the significant. The rankings 1 through 3 were calculated in Figure 43. Rehabilitation is the biggest disadvantage ranked by respondents followed by initial or construction cost, general maintenance, winter maintenance, durability, and performance.

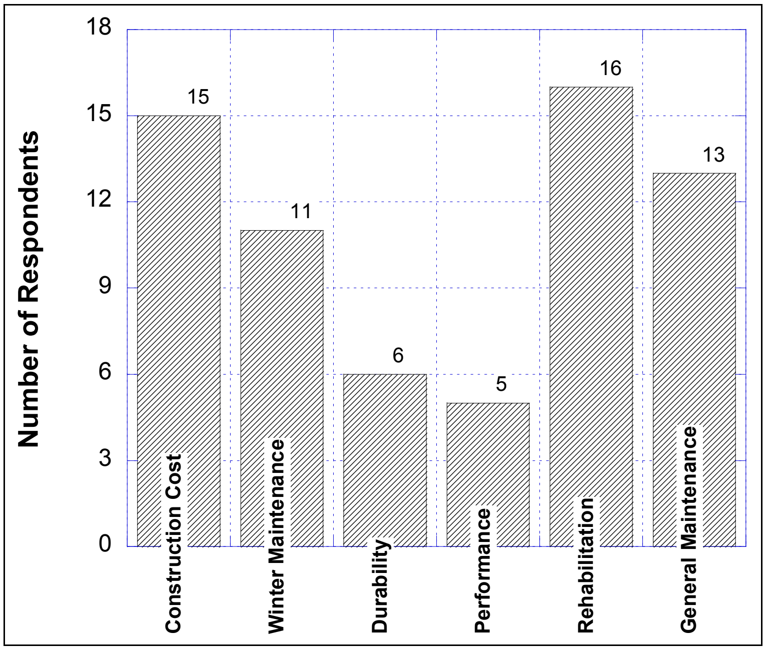


Figure 43. Disadvantages of Using PFC/OGFCs.

4.2. PERFORMANCE

The questionnaire asked respondents to estimate the average typical service life of PFC/OGFCs by choosing among the following five categories: fewer than 6 years, 6-8 years, 8-10 years, 10-12 years, and more than 12 years. Then, the first year PFC/OGFCs performance was rated in terms of three indices, including:

- improved safety,
- functionality, and
- durability.

These indices were listed with the option of a 5-point scale from 1 to 5, with 5 being the excellent and 1 being the poor performance. Moreover, these indices included six questions related to the PFC performance including:

- splash and spray,
- noise,
- permeability,
- raveling,
- cracking, and

- rutting.

According to 25 responses so far, 11 indicated that PFC/OGFCs had a service life of between 8 to 10 years, seven between 6 to 8 years, three between 10 to 12 years, two more than 12 years, and two fewer than 6 years.

In terms of the first year performance of PFC/OGFCs rated by respondents, the majority of rankings were either excellent or very good. Only one respondent rated raveling as fair, and one respondent ranked rutting as fair. Twenty-three respondents rated splash and spray as excellent, three as good, and no respondents rated it below good. The averages of all the rankings were calculated in Figure 44. Splash and spray was rated the highest with the average performance indices followed by permeability, noise, rutting, raveling, and cracking.

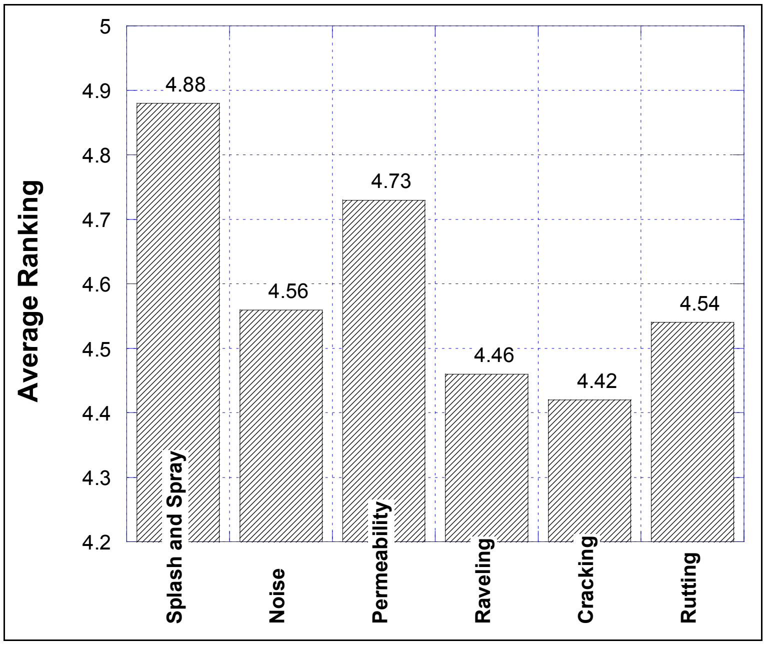


Figure 44. Performance Index of PFC/OGFCs.

4.3. COST

Typically, the cost of the PFC/OGFCs material in place is more expensive than the equivalent thickness of a conventional Type C or D surface mixture. One question with four options was presented in the questionnaire to identify the approximately relative cost of the material in place compared to DGHMA, and then whether a seal coat was applied prior to application of the PFC/OGFCs was asked.

According to 26 responses so far, seventeen indicated that the PFC/OGFCs were 15 percent more expensive, four indicated that they were more than 30 percent more expensive, three indicated that they were less expensive, and two indicated that they were roughly the same in terms of cost. Moreover, 77 percent of the respondents applied a seal coat prior to application of the PFC/OGFCs. One respondent noted that durability was improved using both hot rubber underseal and asphalt rubber PFC in his district although it cost more.

4.4. MAINTENANCE AND REHABILITATION

The questionnaire ranked six maintenance challenges experienced with PFC/OGFCs pavements from 1 to 6, with 1 being the most significant problem. The six possible challenges are listed below.

- pushing, shoving, and tearing;
- patching of potholes;
- slippage cracks;
- striping difficulties;
- hazardous liquid spills; and
- other.

Among all respondents, nine mentioned that patching of potholes was the biggest maintenance challenge for PFC/OGFCs, four indicated that hazardous liquid spills was the biggest, and one mentioned that slippage cracks was the biggest. In addition, 32 percent of respondents stated that hazardous spills needed to be addressed on PFC/OGFCs in their districts. However, one respondent stated that crumb rubber modified PFC/OGFCs have no maintenance problems in his district, and one other respondent replied that there were no maintenance problems except reflective cracking in his district.

In terms of materials used to patch PFC/OGFCs, 62 percent respondents indicated that regular hot or cold patching mixtures were used to patch PFC/OGFCs, 21 percent used special porous mixtures, and 8 percent did not patch.

According to 25 responses, 17 respondents indicated that in Texas no special maintenance activities were used on PFC/OGFCs pavements in their areas, four used patching of potholes, and two used fog seals to maintain the surface condition of PFC/OGFCs pavements. One respondent mentioned that fog seal was never used in his district for stripping. Furthermore, 72 percent of respondents did not observe a decrease in the rate of accidents on PFC/OGFCs pavements. However, one respondent noted that the rate of accidents was reduced but increased in freezing ice storms.

In terms of permeability, 12 out of 25 respondents indicated that permeability of PFC/OGFCs was never measured after construction. Ten respondents stated that permeability was measured when the PFC/OGFCs was constructed. Of those who measured permeability, 11 respondents used the Texas water flow test to measure permeability, and no respondents followed the NCAT procedure for the measurement of permeability.

In terms of rehabilitation, respondents were asked to supply the method and the determination of rehabilitation of PFC/OGFCs used in their districts. Sixteen out of 26 respondents stated that milling was used for rehabilitation, and three respondents used seal coat as a rehabilitation option. In one respondent's district, PFC/OGFCs were milled and replaced with hot rubber underseal and asphalt rubber PFC/OGFCs. In addition, of those who have experience on PFC rehabilitation, 10 respondents stated that potholes were the reason for rehabilitation of PFC/OGFCs in their districts, 10 indicated that cracking was the reason, nine mentioned that raveling/stone loss was the reason, five stated that life cycle was the reason, and three rehabilitated PFC/OGFCs due to clogging.

4.5. OTHER

The questionnaire listed five questions about mostly concerning material properties of the PFC/OGFCs pavements, with the option of identifying other material properties not listed. The following issues were asked in the questionnaire:

- the percentage of projects using PG binder with lime and filler compared to asphalt rubber,
- the performance of asphalt rubber compared to PG mixtures,
- the most impact of asphalt rubber mixtures on performance,
- the type of binder generally used as a tack coat, and
- the application rate of tack coat (gal/yd^2).

Thirty-three percent of respondents stated that over 75 percent projects used PG binder with lime and filler compared to asphalt rubber. Eleven out of 24 respondents reported that the performance of asphalt rubber mixtures were better than PG mixtures, and 84 percent respondents indicated that asphalt rubber mixtures affected PFC/OGFCs performance in terms of durability. One respondent replied that the most impact of asphalt rubber PFC/OGFCs was longevity.

Twelve respondents reported that emulsion was generally used as a tack coat. According to twelve respondents, the most common specified application rate of tack coat was 0.05 to 0.07 gal/yd^2.

Odessa district recommend that the use of both a hot rubber underseal and asphalt rubber PFC/OGFCs improved durability and provided a long life time in excess of 10 years in Odessa. The combination of a hot rubber underseal and asphalt rubber PFC/OGFCs was milled and replaced with the same mixtures, and it can even be used in curb and gutter sections for noise reduction and ridding quality.

5. SUMMARY AND RECOMMENDATIONS

This chapter presents a summary of information obtained from recent research regarding performance, mixture design, maintenance, and construction of PFC/OGFCs and proposes some recommendations for future research.

5.1. PERFORMANCE

PFC/OGFCs performance includes functionality, durability, and safety. Whereas functionality includes noise reduction effectiveness and drainability/permeability, safety is described in terms of skid resistance.

5.1.1. Functionality

This section presents a summary of the use of PFC/OGFCs in terms of functionality (noise reduction effectiveness and drainability), including an overview of recent research on noise and drainability.

Noise Reduction Effectiveness

It has been widely observed that use of PFC/OGFCs result in noise reduction at the tire/pavement-interface noise. When tires are rolling over a pavement surface, air in the tire treads is compressed between the tire and the pavement and is then released as the tires continue to roll, creating a noise. However, when tires are rolling over a PFC/OGFCs pavement surface, air in the tire treads is able to escape laterally through the pores of the PFC/OGFCs. Therefore, the tire/pavement generated noise can be reduced. Since the overall traffic noise output is dominated by tire/pavement noise on the highway, PFC/OGFCs have a significant effect on reduction of overall traffic noise.

Many researchers have undertaken studies to determine the influence of different factors on the noise reduction effectiveness using different mixture types. The following conclusions were generally offered:

- Compared to all types of HMA pavement surfaces, PFC/OGFCs have the lowest tire/pavement noise level.

- Tire/pavement noise levels increase with increasing vehicle speed, and the noise gradient of PFC/OGFCs is around 0.17 dB(A) per mph.
- Lower texture and roughness of the pavement surface lead to quieter pavements.
- The sound level is more influenced by air temperature at frequencies below 1500 Hz and at temperatures below 21 °C (70 °F).
- The type of tires influence sound levels on the same type of pavement due to the tire treads, with studded tires producing more noise at the tire/pavement interface.
- The noise reduction effectiveness of PFC/OGFCs may decrease as the pavement ages.
- The sound level increases with traffic volume due to an acceleration of pavement consolidation.
- PFC/OGFCs with small maximum aggregate size generate lower noise levels.
- The noise level can be reduced by increasing the addition of crumb rubber.
- An increase in the total AV content of the mixture result in a decrease in noise levels.

Numerous studies have been conducted to determine comparative noise levels on different pavement surface types, such as PFC/OGFCs, SMA, and DGHMA. In general, the noise reduction on PFC/OGFCs pavement surfaces in the United States is from 3 to 9 dB(A) and up to 10 dB(A) in Europe (*74*). General conclusions from international and national studies are given in Tables 44 and 45, respectively. The information reported in these tables led to conclude that the levels of pavement noise reduction are dissimilar due to different factors. Thereby, more research that isolates factors from environmental conditions and mixture parameters needs to be pursued.

Table 44. Summary of HMA Noise Studies: International Studies (*24, 75, 76*).

	Pavement Noise Reduction, dB(A) vs. DGHMA			
Agency/Year	*PFC/OGFCs*	*SMA*	*Thin open layers*	*PCC*
Netherlands (1989)	2.5-3.2 (w/ crumb rubber)			
Italy (1990)	3.0			
Germany (1990)	4.0-5.0			
Sweden (1990)	3.5-4.5			
France (1990)	3.0-5.0			
Netherlands (1990)	3.0			
Nordic Countries (1990)	3.0-5.0			
Belgium (1990)	2.0-3.0			
Switzerland (1990)	1.5-5.0 (function of speed)			
United Kingdom (1990)	4.0-5.0			
Germany (1991, 1998)		2.0-2.5		
Danish Road Institute (1992)	4.0			
World Road Association (1993)	1.5-3.0			4.0
United Kingdom (1993)	6.0-7.0 (vs. PCC)			
Belgium (1994)	7.5 (vs. PCC)			3.4
United Kingdom (1997)	2.5-5.0			
Italy (1998)		7.0		
British Columbia, Canada (1999)	3.5-4.0			
Australia (2001)	2.0-3.0			
Danish Road Institute (2004)			2.0-3.0	
Sweden (2005)	7.0-12.0			
Spain (2008)	1.0 (w/ crumb rubber by dry process vs. wet process)			

Table 45. Summary of HMA Noise Studies: National Studies (*24, 75*).

	Pavement Noise Reduction, dB(A) vs. DGHMA		
Agency/Year	***PFC/OGFCs***	***SMA***	***PCC***
FHWA (1975)	2.0		1.0
Minnesota (1979,1987, 1995)	High		
Maryland (1990)	2.3-3.6 (vs. PCC)		
Wisconsin (1993)		1.0	
Maryland (1994)		1.0	
Oregon (1994)	5.7-7.8 (vs. PCC)		
New Jersey (1994)		2.1; 4.1 (vs. PCC)	2.0
U.S. Department of Transportation (1995)	1.5		3.0
Wisconsin (1997)			2.0-5.0
Ohio (2000)	3.0-4.0	-1.0	
Michigan (2000, 2001)		4.0	4.0-5.0
Washington (2001)	3.0-4.0		
Michigan (2002)		0.5	0.1-2.0
California (2002)	4.0-6.0		
National Asphalt Pavement Association (2002)	2.0		
Texas (2003)	14 (vs. PCC)		
Colorado (2004)		0.2 (vs. PFC/OGFCs)	
NCAT (2004)	4.0	2.0	3.0
Indiana (2004)	4.0; 5.0 (vs. SMA)		
Asphalt Institute (2005)	1.0-4.0	-1.0	
Asphalt Institute (2006)	4.0 (vs. PCC)		
Indiana (2008)	High	Low	
California (2008)	1.0 to 4.0		
Texas (2008)	2.0-3.0		

Based upon recent literature (2004 to 2008), the noise levels on pavements can be either increased or decreased by various factors. The best noise reduction with PFC/OGFCs is obtained for low volume- and slow speed-traffic (the minimum speed recommended for PA in Europe is 48 kph [30 mph]) where studded tires are not allowed, in a high air temperature area. A decrease of pavement texture and roughness, small nominal aggregate size, high AV content, fine aggregate gradation, and the use of crumb rubber modified binder need to be considered as alternative parameters for selection of materials and the PFC/OGFCs mix design regarding the noise reduction.

Drainability/Permeability

Assessment of drainability of PFC/OGFCs mixtures is required to guarantee high initial drainability and to evaluate mixture performance by comparing the evolution of this parameter during the mixture functional life. The common approach to measure the drainage capacity of porous mixtures in the field is the determination of the time of discharge of a specific water volume. In the laboratory, permeability has been measured using permeameters with either falling head or constant head.

Research has been used to investigate the influence of different factors on drainability. The following conclusions were generally offered:

- An increase in asphalt content causes a decrease of permeability.
- Reduction of the compaction energy produces PFC/OGFCs mixtures with higher permeability since the total AV content increases. However, increase permeability should not be obtained on the basis of producing low density PFC/OGFCs mixtures because durability problems can arise.
- An increase in permeability can be achieved by making the aggregate gradation coarser.
- An increase in the maximum aggregate size causes an increase in permeability.
- The water –accessible AV content can be used to indirectly assess permeability with better results than those obtained based on total AV content values.

Low binder content, coarse aggregate gradation, large maximum aggregate size, and low compaction effort can provide sufficient AV content which is considered to be representative of drainability. However, decreasing the energy of compaction (in both the field and laboratory) to obtain a higher total AV content is not recommended, since durability problems can arise in mixtures with incomplete compaction due to insufficient stone-on-stone contact in the coarse-granular skeleton. High permeability values can be pursued by reducing the binder content; however, in order to ensure adequate mixture durability, TxDOT specified the minimum binder content for both PG and AR PFC/OGFCs mixtures. Although permeability is believed to be integrated in most PFC/OGFCs mix design procedures (by specifying a minimum AV content), recent research suggested that this approach has limitations to ensure adequate drainability.

5.1.2. Durability

Raveling is the distress most frequently reported as the cause of failure in PFC/OGFCs mixtures. The service life of PFC/OGFCs is variable and can range from 5 to 10 years. The factor that most influences PFC/OGFCs mixture durability is the type of binder used. However, recent research suggested that PFC/OGFCs (*34*) and PA (*77*) durability is affected more by aggregate properties than by those of the asphalt.

The majority of agencies reporting successful application of PFC/OGFCs at present are using modified binders. Research has been used to investigate the influence of different factors on durability. The following conclusion was generally offered: an increase in asphalt content and decrease in total AV content resulted in a decrease in abrasion loss.

In the United States, the draindown test and the Cantabro loss test in dry condition are used to evaluate mixture durability. TSR is used to evaluate the mixture for moisture susceptibility. In order to evaluate mixture durability and susceptibility to moisture damage, the Cantabro loss test is the most appropriate test currently available for PFC/OGFCs mix design and laboratory performance evaluations. However, the Cantabro test may not provide enough sensitivity to become a definitive tool for selecting the OAC of PFC/OGFCs mixtures.

5.1.3. Safety

It has been widely observed that PFC/OGFCs result in skid resistance improvement at the tire/pavement interface as compared to DGHMA. Because of the high correlation between skid resistance and accident rates, road engineers consider pavement skid resistance an important property for designing HMA. For example, when using a high skid resistance mixture, a 54 percent reduction in wet weather accidents and a 29 percent reduction in overall accidents were shown by Luce et al. (*44*).

Numerous studies have been conducted to determine comparative skid resistance levels on different pavement surface types, such as PFC/OGFCs, SMA, and DGHMA. An increase in average friction from 0.4 to 0.55 results in a 63 percent decrease in wet weather accidents was stated by some studies. In addition, the wet weather accidents were decreased by 71 percent in intersections and 54 percent on highways by the improvement in pavement skid resistance in a TxDOT study (*4*). In addition, many researchers have undertaken studies to determine the influence of different factors on the safety improvement provided by different types of HMA. The following conclusions were generally offered:

- Compared to all types of HMA pavement surfaces, PFC/OGFCs have the highest pavement skid resistance.
- Pavement skid resistance increases with decreasing vehicle speed.
- In general, lower texture of the pavement surface led to lower pavement skid resistance.
- The skid resistance increases as the air temperature decreases.
- The pavement skid resistance initially increases due to wearing-off of the binder on the pavement surface. After the initial increase, the skid resistance decreases with increasing traffic volume.
- The skid resistance can be increased by adding crumb rubber.
- A high aggregate texture level can improve mixture skid resistance.

The best skid resistance with PFC/OGFCs is obtained in pavements with low volume, slow speed traffic, constructed in a low air temperature area. High aggregate texture, an increase of mixture texture, and the use of crumb rubber modified asphalt binder need to be considered as alternative parameters for selection of materials and mix design regarding the skid potential.

Based on the literature review of research conducted since 2004, Table 46 presents the different factor levels for the different performance aspects to achieve balance of desired properties for the best PFC/OGFCs mixtures.

Table 46. Summary of Factor Levels for the Different PFC/OGFCs Performance Aspects.

Property		***Functionality***		***Durability***	***Safety***
		Noise	***Drainability***		
Mixture texture and roughness	High				X
	Low	X			
Asphalt binder type	Modified	X		X	X
	Unmodified				
AV content	High	X	X		X
	Low			X	
Aggregate gradation	Fine				
	Coarse		X		X
Binder content	High			X	
	Low		X		X
Compaction effort	High			X	
	Low	X	X		
Maximum aggregate size	Large		X		X
	Small	X			
Binder aging	Fast				
	Slow			X	
Aggregate texture	High			X	X
	Low				
Vehicle speed	Fast		X		
	Slow	X			X
Air temperature	High	X			
	Low				X
Tire type	Studded				
	No studded	X			
Traffic condition	High				
	Low	X			X
Assessment		OBSI	Water-accessible AV content, Expected value of permeability	Cantabro loss test	FN, SFC, BPT, DFT, IFI

5.2. MIXTURE DESIGN

The current TxDOT PFC/OGFCs mix design method specifies a minimum total AV content of 18 percent to guarantee PFC/OGFCs functionality, but there is no durability test included in this approach to assess compacted PFC/OGFCs mixtures. Figure 37 showed an improved mix design method proposed for PFC/OGFCs mixtures. This method is based on the guidelines of the current mix design method applied by TxDOT and the recommendations presented by Alvarez (*48*) to enhance the determination of volumetric properties (density, total

AV content, and water-accessible AV content) and the evaluation of drainability, durability, and stone-on-stone contact of PFC/OGFCs mixtures.

5.3. CONSTRUCTION

Construction of PFC/OGFCs utilizes the current techniques applied to construct DGHMA. However, construction of porous layers requires some special considerations throughout the process as summarized below.

5.3.1. Mixture Production

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

5.3.2. Mixture Storage and Transportation

Since PFC/OGFCs are prone to draindown, limits on mixture storage and transportation time should be required. Tarps are necessary to avoid crusting of the PFC/OGFCs mixture during transportation. Although TxDOT specifications (Item 342) do not require insulated truck beds for PFC/OGFCs transportation, some state DOTs are already applying it. Preparation of truck beds by using a full application of an asphalt release agent is recommended for transportation of rich PFC/OGFCs mixtures particularly if polymer or rubber-modified binder is used.

5.3.3. Surface Profile

Since PFC/OGFCs are not layers to correct profile distresses or any kind of structural distress, the underlying surface should exhibit adequate conditions before PFC/OGFCs placement. Besides, lateral and longitudinal drainage of the underlying layer must be provided to ensure adequate water discharge from the PFC/OGFCs. In addition, placement of PFC/OGFCs over an impermeable layer is recommended to prevent problems in underlying layers. In Texas, road engineers prefer the surface directly beneath the PFC/OGFCs to be a seal coat (also known as a chip seal) and use an adequate tack coat to bond the PFC/OGFCs to the underlying surface, which can help to seal the surface from the intrusion of water from the surface.

5.3.4. Mixture Placement

PFC/OGFCs smoothness is highly dependent on constructive practices; surface depressions are more difficult to correct with PFC/OGFCs than with DGHMA. The use of a safety edge may have benefit to PFC/OGFCs because these pavements are daylighted at the pavement edge. Furthermore, the use of modified binders and the construction of PFC/OGFCs in thin layers demand special attention to placement and compaction temperatures. Acceptable paving conditions in the United States are commonly defined as a minimum air temperature of 15 °C (60 °F), but it slightly varies in different states.

5.3.5. Material Compaction and Joint Construction

Compaction of PFC/OGFCs mixtures is typically performed using static steel-wheel rollers; 8- to 9-ton tandem rollers are appropriate to complete the compaction process on thin layers. Vibratory rollers, which break down aggregates within the PFC/OGFCs, and pneumatic-tired rollers, which reduce the mixture drainage capacity by closing surface pores, are not used for PFC/OGFCs compaction. Keeping a maximum distance of 15 m (50 ft) between the roller and the paver is strongly recommended. Some TTI researchers used the Field Water Flow Test (Tex-246-F) to set the roller pattern and to verify that the compacted mixture has adequate drainability.

Longitudinal and transverse joints in PFC/OGFCs require special treatment since they are more difficult to construct than those in DGHMA. Longitudinal joints should always be located outside the wheel paths, and avoidance of longitudinal cold joints is always preferred.

5.3.6. Mixture Acceptance

The practice in most agencies for mixture approval is based on the evaluation of binder content, gradation, and visual inspection after compaction to evaluate the density, material variability, and segregation. Adequate compaction is necessary to prevent raveling. Although specified density in the field is not currently required, recent research recommended inclusion of a density specification for PFC/OGFCs construction. The density corresponding to the OAC may be used as reference to define the density that should be required in the field. In general, all agencies specify a minimum smoothness for mixture acceptance.

5.4. MAINTENANCE

Since maintenance cannot be performed in the same way as for conventional DGHMA, it is a fundamental aspect to consider in any project involving PFC/OGFCs. Maintenance of porous layers requires some special practices as summarized below.

5.4.1. Winter Maintenance

Earlier and more frequent frost and ice formation is a result of the particular open-graded mixtures' thermal properties. In fact, formation of black ice and extended frozen periods are currently considered the main problems associated with PFC/OGFCs maintenance in the United States. Consequently, PFC/OGFCs require specific winter maintenance practices such as more salt (or deicing agents) and more frequent applications than on DGHMA, and greater control in the homogeneous supply of deicing chemical.

The spreading of sand to enhance friction and hasten deicing is not recommended except in emergency situations where quick friction is needed because it contributes to the clogging of voids. Anti-icing procedures produce the best result to combat black ice, freezing rain, and light snow events, and de-icing procedures should be reserved for events in which ice and snow have already bonded.

5.4.2. Surface Maintenance

Although some states using PFC/OGFCs apply fog seals to perform preventive surface maintenance, there are no reports in the United States on the application of surface maintenance for PFC/OGFCs. Cleaning of PFC/OGFCs in the United States is not common practice. However, in some European countries and Japan, different techniques are applied to maintain porosity during the pavement's lifetime. These countries are also testing two-layer PA in order to maximize mixture functionality.

5.4.3. Corrective Maintenance

The use of DGHMA to repair delaminated areas and potholes was indicated by all states in the United States that reported the utilization of PFC/OGFCs in 2000. Crack filling may generate drainage problems since water flow inside the mixture is diminished.

5.4.4. Rehabilitation

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

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

5.5. RECOMMENDATIONS

The following recommendations can be drawn from literature (published since 2004) that was reviewed.

- The performance of pavement surfaces focus on the entire lifetime of the pavement. Therefore, the functional life of PFC/OGFCs pavements will be monitored and measured over a long period of time in this project. A longer-term evaluation of PFC/OGFCs mixtures is required to assist road engineers in determining if PFC/OGFCs can perform as well under different conditions (e.g., climate, traffic) as compared to their initial performance.
- This report determined the factors that affect PFC/OGFCs functionality (noise and drainability), durability, and safety; and the performance of PFC/OGFCs currently used in Texas will be evaluated in this project with respect to these factors.
- Some researchers found that the thicker the PFC layer thickness, the lower the noise levels at the tire/pavement interface, while other studies reported that noise levels

increase with an increase in surface layer thickness. However, if layer thickness and total AV content are considered together, a noise reduction of about 3-5 dB(A) can be achieved with 25 percent total AV content for a thickness of 40 mm (0.16 inch) (*78*). Therefore, more research is needed to isolate layer thickness and total AV content.

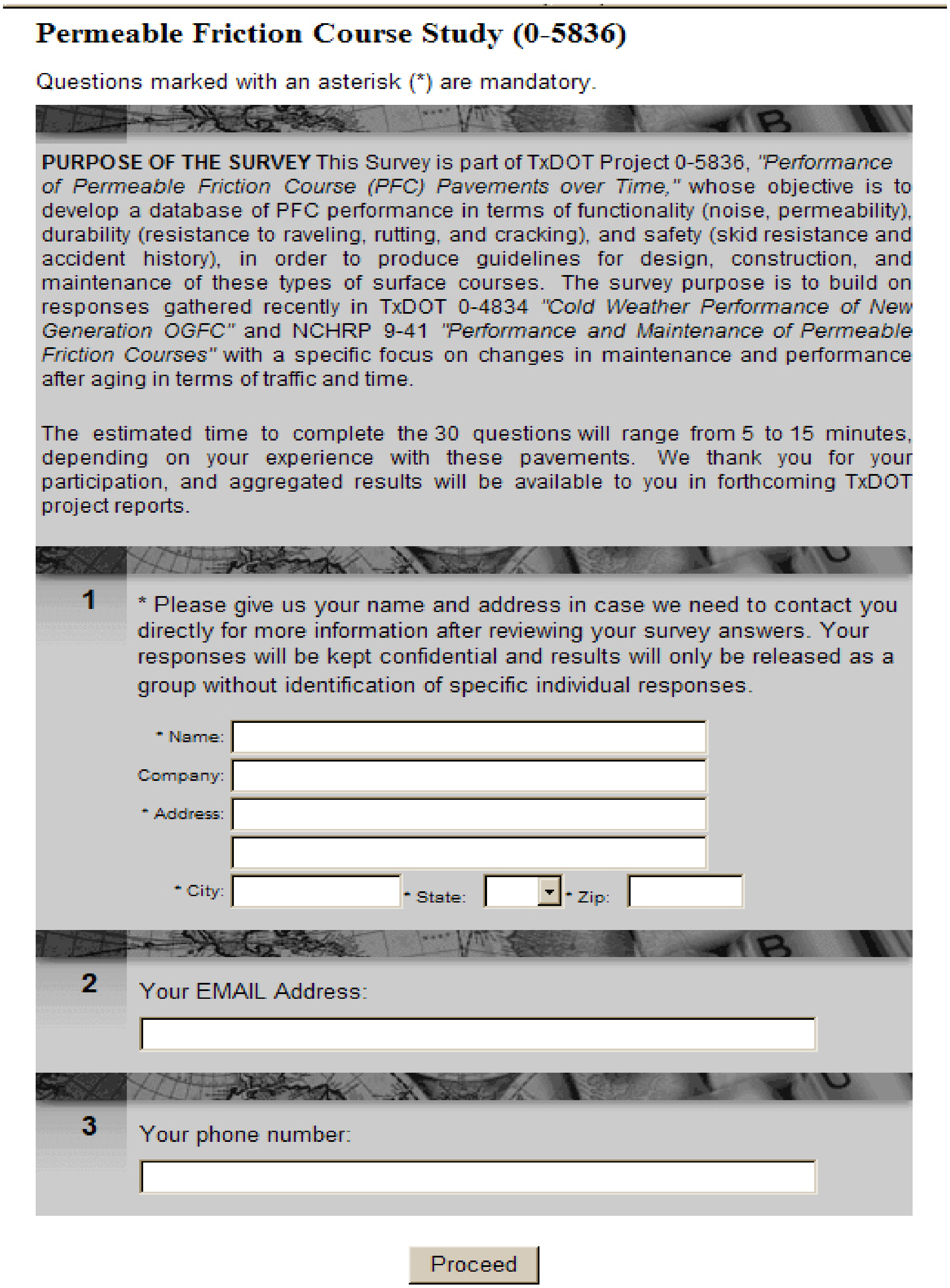
- Some studies speculated that the suction effect of vehicle tires rolling at high speed can clean and protect the pores from clogging. However, there is no research that supports or concludes this. Hence, research on the suction effect of the vehicle tires on PFC/OGFCs mixtures is needed.
- Some research indicates that the noise reduction effectiveness of PFC/OGFCs pavement surfaces may reduce due to clogging of AV in only a few years. However, as indicated in TxDOT Report 0-5185-3 in 2008, there was a very slight increase in noise due to aging exposure but the amount was not practically significant over the reasonable service life (6 to 8 years) of the pavement. Therefore, a study separating age from traffic condition in terms of volume or axle loadings and factors causing clogging needs to be pursued.
- The use of crumb rubber reduces the noise levels and generally produces higher binder contents. The AR mixtures can allocate more asphalt binder than PG mixtures and contain 20 percent total AV content. Therefore, the correlation between the amount of crumb rubber used in PFC/OGFCs mixtures and aggregate gradation might be evaluated in the future.
- Some research indicated that DGHMA provides more skid resistance than PFC/OGFCs, while other research reports that the skid numbers for PFC/OGFCs are higher than DGHMA. For further compare mixture types, test sections should be constructed under the same conditions that may affect the pavement skid resistance.
- Many studies used macrotexture to predict skid resistance on HMA pavements and advocated that an increase in macrotexture results in an increase in skid resistance. However, some researchers found that macrotexture is a poor predictor of pavement skid resistance. In order to further explore, the macrotexture needs to be measured in a separate relationship for open-graded surfaces, gap-graded surfaces, and dense-graded surfaces.

- Some research indicated that as the aggregate gradation becomes finer, the noise level decreases. However, CalTrans (*29*) indicated that noise levels can be reduced with coarser gradation and increasing AV content. Hence, more research can be investigated in order to solve the conflict.
- Researchers found that the pavement skid resistance is related to two main properties of the pavement, microtexture and macrotexture. Most research focused more on macrotexture than microtexture. Microtexture is mainly dependent on aggregate shape characteristics and mineralogy. Since microtexture can be determined by aggregate texture, abrasion resistance, and petrography of aggregates; a model may be developed to predict skid resistance of a pavement surface as a function of aggregate properties and mixture properties under various conditions.
- Since PFC/OGFCs maintenance activities cannot be performed in the same way as for DGHMA, to use a new technology to monitor in real time the road system and support the decision process involving when and how to treat a PFC/OGFCs surface needs more research in order to improve the maintenance process.
- Pavement texture and roughness includes contributions from aggregate texture, aggregate gradation, pavement wear, and pavement finishing technology. Low pavement texture and roughness reduce the pavement noise level but provide low skid resistance. Hence, more research is needed in order to achieve balance of desired properties between noise and safety aspects for the best PFC/OGFCs mixtures.
- An increase in asphalt content that will decrease the total AV content will result in a decrease in abrasion loss but will provide low drainability. Therefore, asphalt content needs to be modified to maintain suitable permeability in order to prevent durability problems. In order to better define the OAC, the balance of AV content to achieve the equilibrium which requires optimization of the aggregate gradation needs more evaluation.
- Within the frame of the 4-year project, AV clogging rate, service life, and corresponding actions to extend the service life of PFC/OGFCs mixtures in the field will be investigated for the selected field sections. In addition, field performance (including functionality and durability) of PFC/OGFCs mixtures will also be evaluated

using non-destructive testing and laboratory evaluation of field cores to further improve the mix design method for these mixtures.

- The current approaches used to evaluate drainability in PFC/OGFCs mixtures are based on either achieving a minimum total AV content or measuring permeability on laboratory-compacted specimens. For some sections, this project may evaluate the relationship among water-accessible AV content, field-measured permeability, and laboratory-measured permeability. Moreover, this project will address the relationship for WFV of laboratory and field drainability, and evaluate if WFV can be used to assess the drainability of PFC/OGFCs mixtures both in the laboratory and in the field.
- The expected value of permeability, E[k], determined using a modified version of the Kozeny-Carman equation, was recommended to analytically predict permeability for PFC/OGFCs mix design and evaluation purposes. For some sections, this project may further evaluate differences in the internal structure of laboratory- and field-compacted PFC/OGFCs mixtures in order to improve E[k] as an estimation of permeability in both the laboratory and field.
- The relationship between laboratory-measured permeability and water-accessible AV content values determined for SGC specimens preliminarily indicate that this AV content may be used as a surrogate of the total AV content to indirectly evaluate permeability in PFC/OGFCs mixtures. However, additional research is required to determine if the same conclusion is sustained for field-compacted mixtures (i.e., evaluation of road cores) and to improve the comparison of the internal structure of field- and laboratory-compacted PFC/OGFCs mixtures before pursuing the determination of the relationship based on water-accessible AV content.
- Based on the variables affecting performance (noise reduction effectiveness, drainability, durability, and safety) of PFC/OGFCs mixtures in this report, this project will select representative PFC/OGFCs materials in Texas, corresponding field sections and laboratory evaluation for a performance monitoring experiment, and then develop a PFC/OGFCs performance database associated with mix design, construction, and maintenance guidelines.

APPENDIX



Permeable Friction Course Study (0-5836)

Questions marked with an asterisk (*) are mandatory.

PURPOSE OF THE SURVEY This Survey is part of TxDOT Project 0-5836, *"Performance of Permeable Friction Course (PFC) Pavements over Time,"* whose objective is to develop a database of PFC performance in terms of functionality (noise, permeability), durability (resistance to raveling, rutting, and cracking), and safety (skid resistance and accident history), in order to produce guidelines for design, construction, and maintenance of these types of surface courses. The survey purpose is to build on responses gathered recently in TxDOT 0-4834 *"Cold Weather Performance of New Generation OGFC"* and NCHRP 9-41 *"Performance and Maintenance of Permeable Friction Courses"* with a specific focus on changes in maintenance and performance after aging in terms of traffic and time.

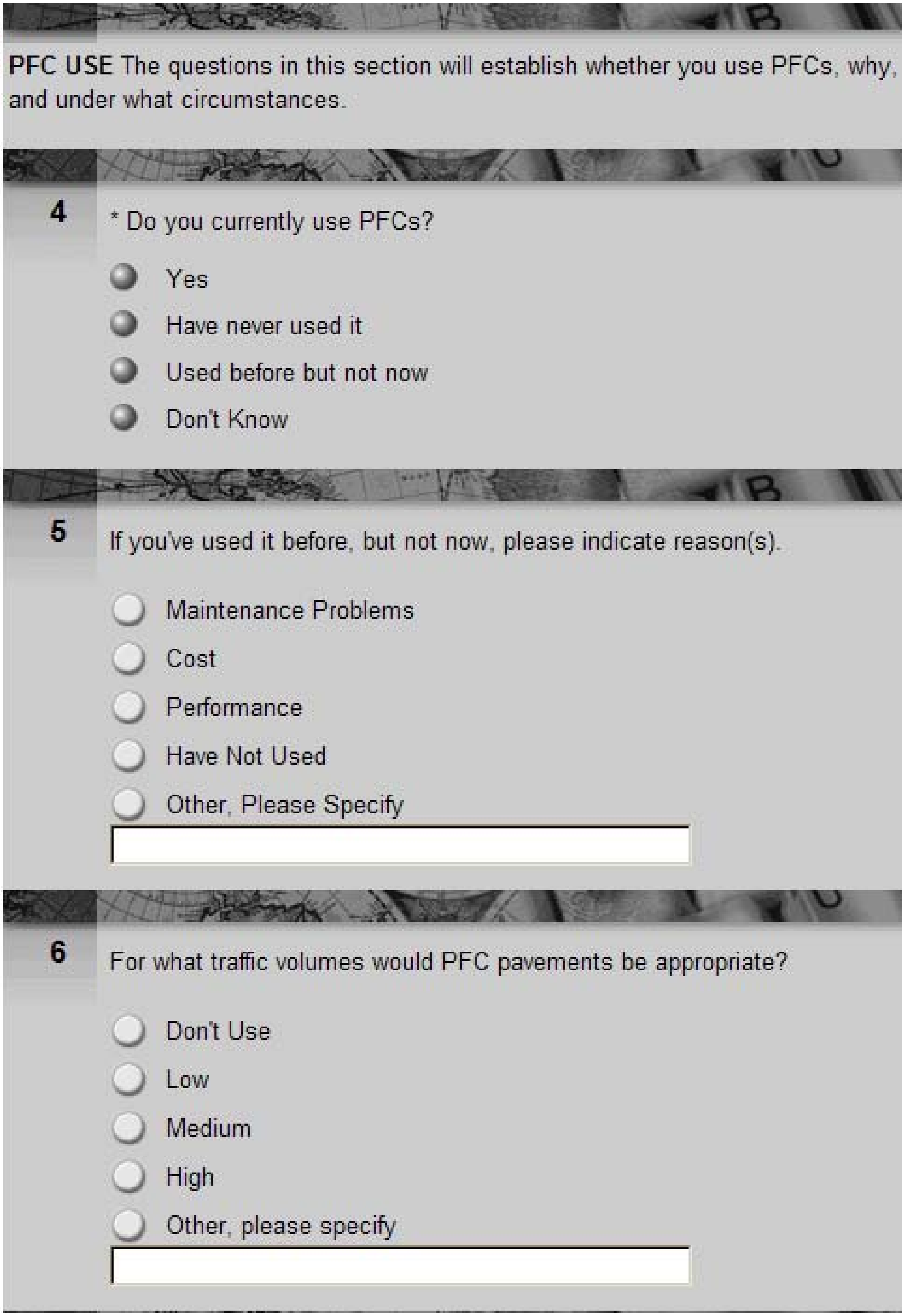
The estimated time to complete the 30 questions will range from 5 to 15 minutes, depending on your experience with these pavements. We thank you for your participation, and aggregated results will be available to you in forthcoming TxDOT project reports.

1 * Please give us your name and address in case we need to contact you directly for more information after reviewing your survey answers. Your responses will be kept confidential and results will only be released as a group without identification of specific individual responses.

* Name:
Company:
* Address:
* City: * State: * Zip:

2 Your EMAIL Address:

3 Your phone number:



PFC USE The questions in this section will establish whether you use PFCs, why, and under what circumstances.

4 * Do you currently use PFCs?

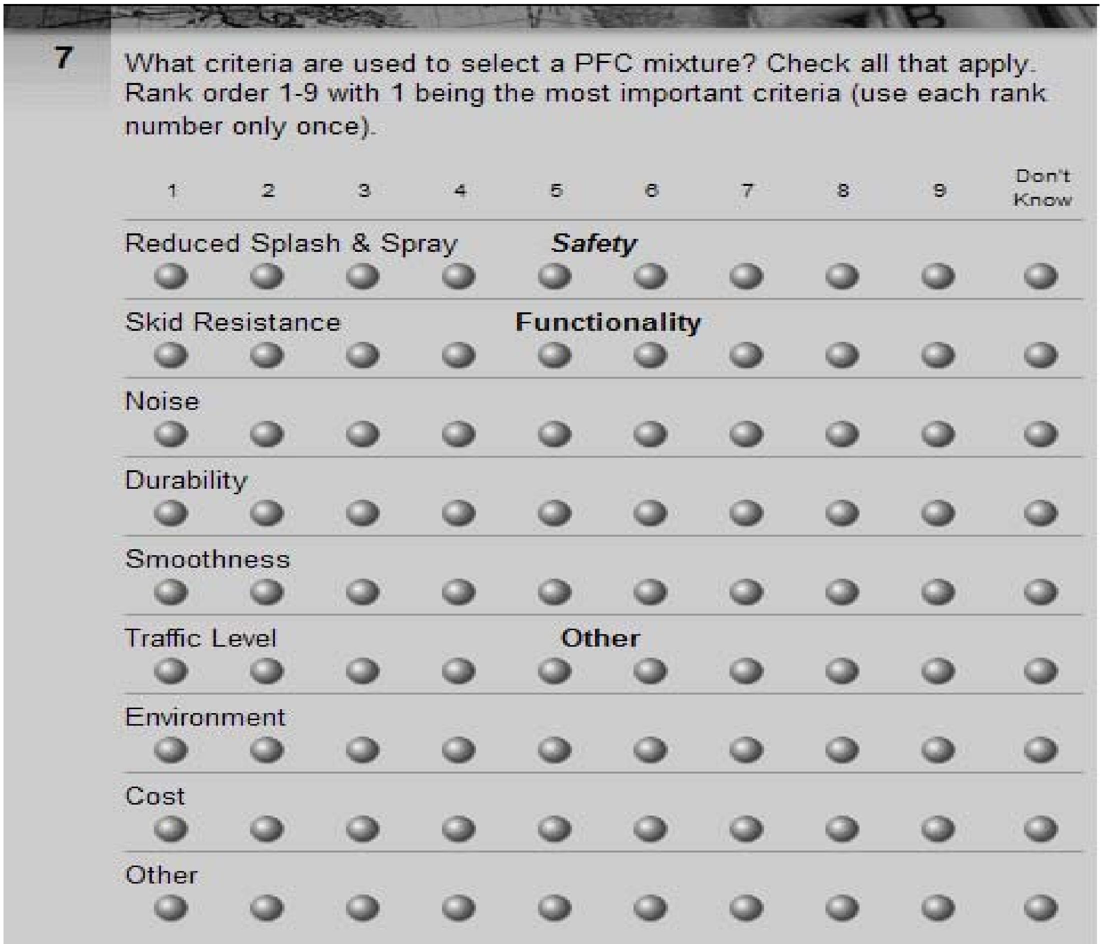
○ Yes
○ Have never used it
○ Used before but not now
○ Don't Know

5 If you've used it before, but not now, please indicate reason(s).

○ Maintenance Problems
○ Cost
○ Performance
○ Have Not Used
○ Other, Please Specify

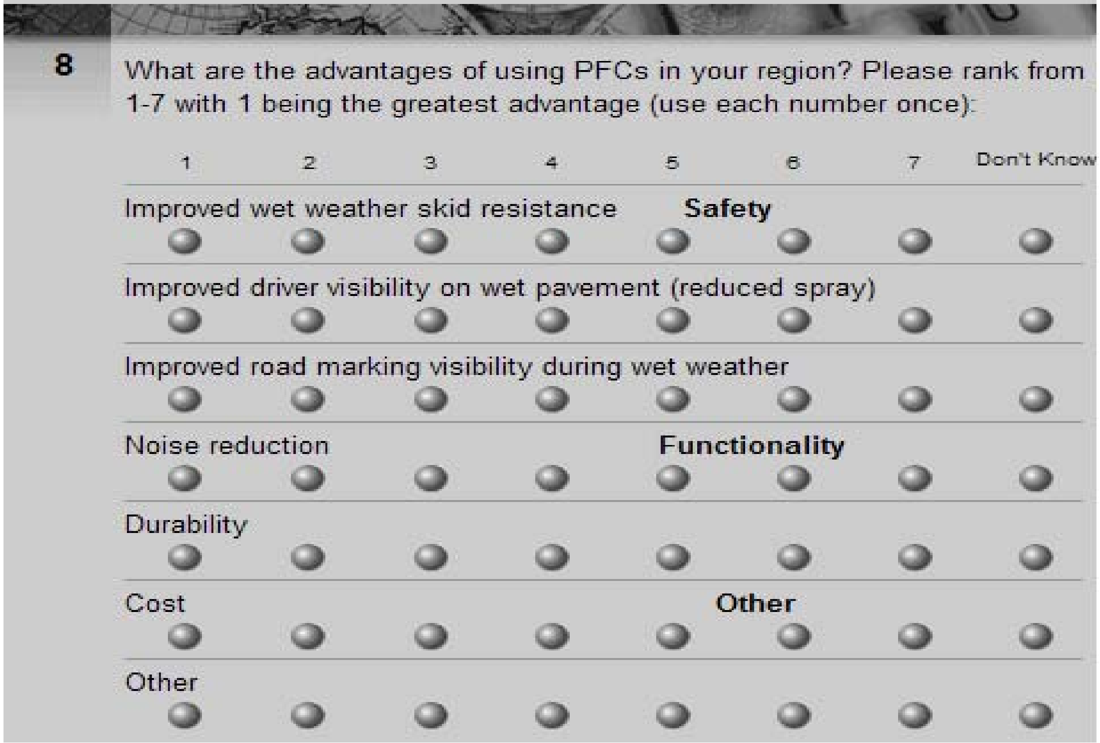
6 For what traffic volumes would PFC pavements be appropriate?

○ Don't Use
○ Low
○ Medium
○ High
○ Other, please specify



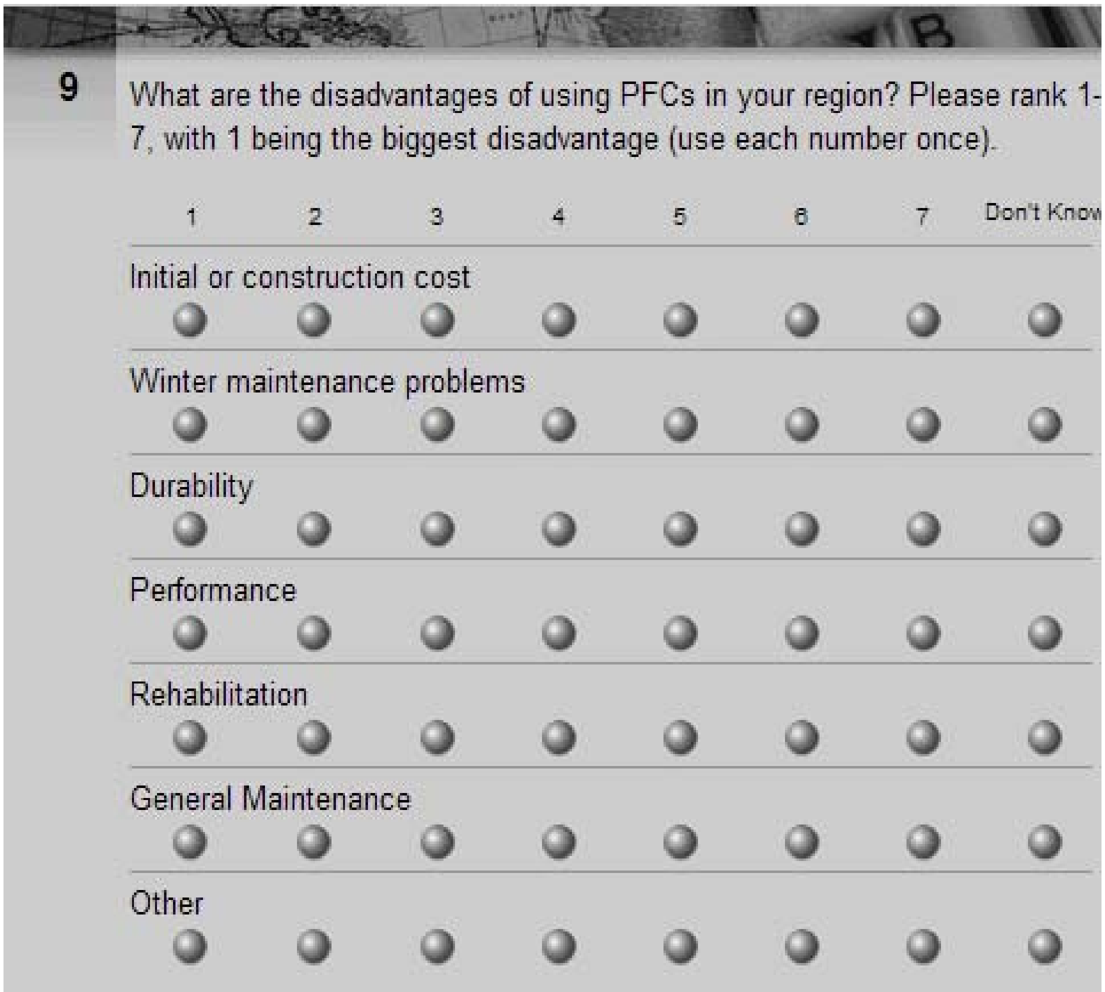
7 What criteria are used to select a PFC mixture? Check all that apply. Rank order 1-9 with 1 being the most important criteria (use each rank number only once).

	1	2	3	4	5	6	7	8	9	Don't Know
Reduced Splash & Spray ***Safety***	○	○	○	○	○	○	○	○	○	○
Skid Resistance **Functionality**	○	○	○	○	○	○	○	○	○	○
Noise	○	○	○	○	○	○	○	○	○	○
Durability	○	○	○	○	○	○	○	○	○	○
Smoothness	○	○	○	○	○	○	○	○	○	○
Traffic Level **Other**	○	○	○	○	○	○	○	○	○	○
Environment	○	○	○	○	○	○	○	○	○	○
Cost	○	○	○	○	○	○	○	○	○	○
Other	○	○	○	○	○	○	○	○	○	○



8 What are the advantages of using PFCs in your region? Please rank from 1-7 with 1 being the greatest advantage (use each number once):

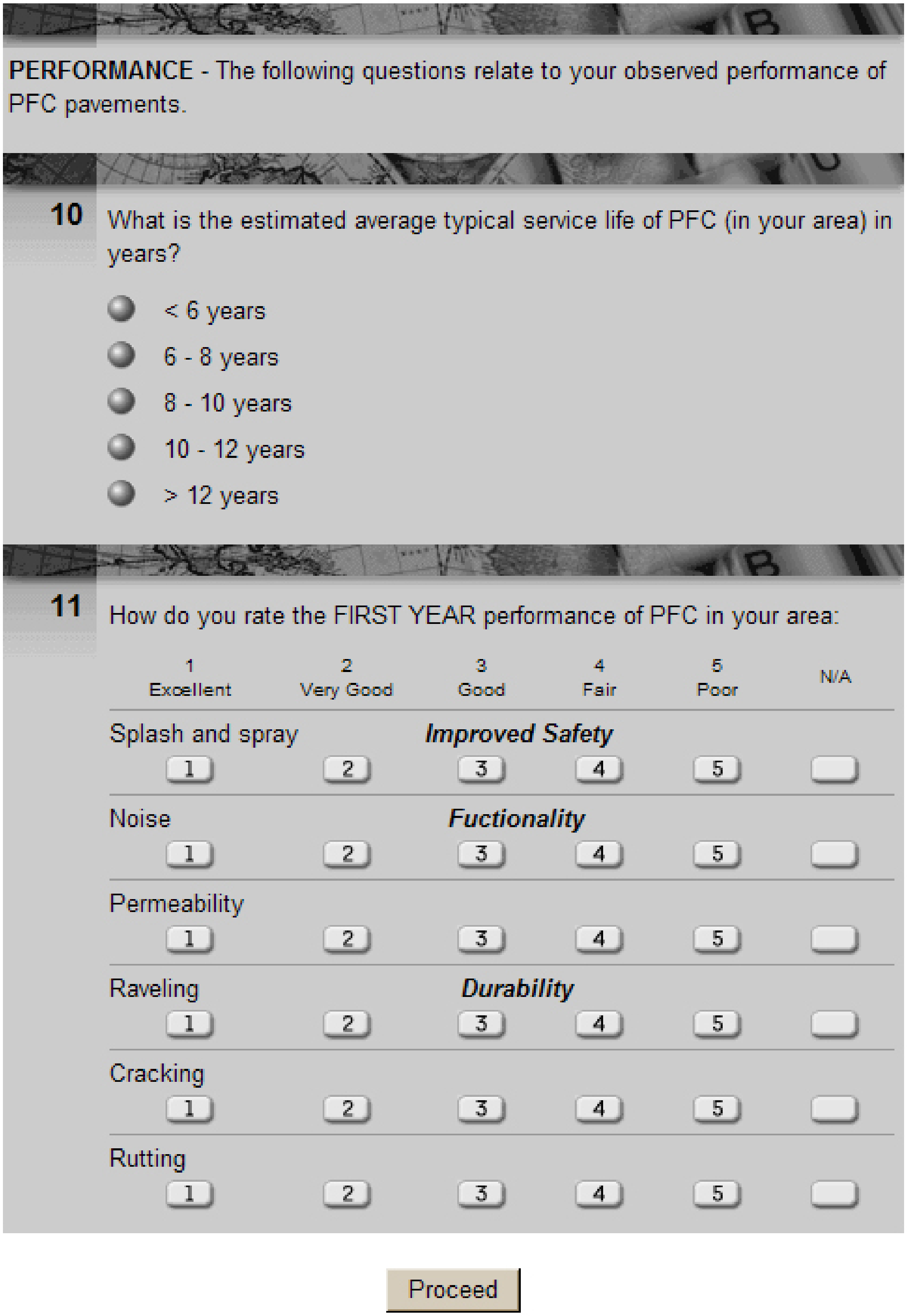
	1	2	3	4	5	6	7	Don't Know
Improved wet weather skid resistance **Safety**	○	○	○	○	○	○	○	○
Improved driver visibility on wet pavement (reduced spray)	○	○	○	○	○	○	○	○
Improved road marking visibility during wet weather	○	○	○	○	○	○	○	○
Noise reduction **Functionality**	○	○	○	○	○	○	○	○
Durability	○	○	○	○	○	○	○	○
Cost **Other**	○	○	○	○	○	○	○	○
Other	○	○	○	○	○	○	○	○



9 What are the disadvantages of using PFCs in your region? Please rank 1-7, with 1 being the biggest disadvantage (use each number once).

	1	2	3	4	5	6	7	Don't Know
Initial or construction cost	○	○	○	○	○	○	○	○
Winter maintenance problems	○	○	○	○	○	○	○	○
Durability	○	○	○	○	○	○	○	○
Performance	○	○	○	○	○	○	○	○
Rehabilitation	○	○	○	○	○	○	○	○
General Maintenance	○	○	○	○	○	○	○	○
Other	○	○	○	○	○	○	○	○

Permeable Friction Course Study (0-5836)



PERFORMANCE - The following questions relate to your observed performance of PFC pavements.

10 What is the estimated average typical service life of PFC (in your area) in years?

○ < 6 years

○ 6 - 8 years

○ 8 - 10 years

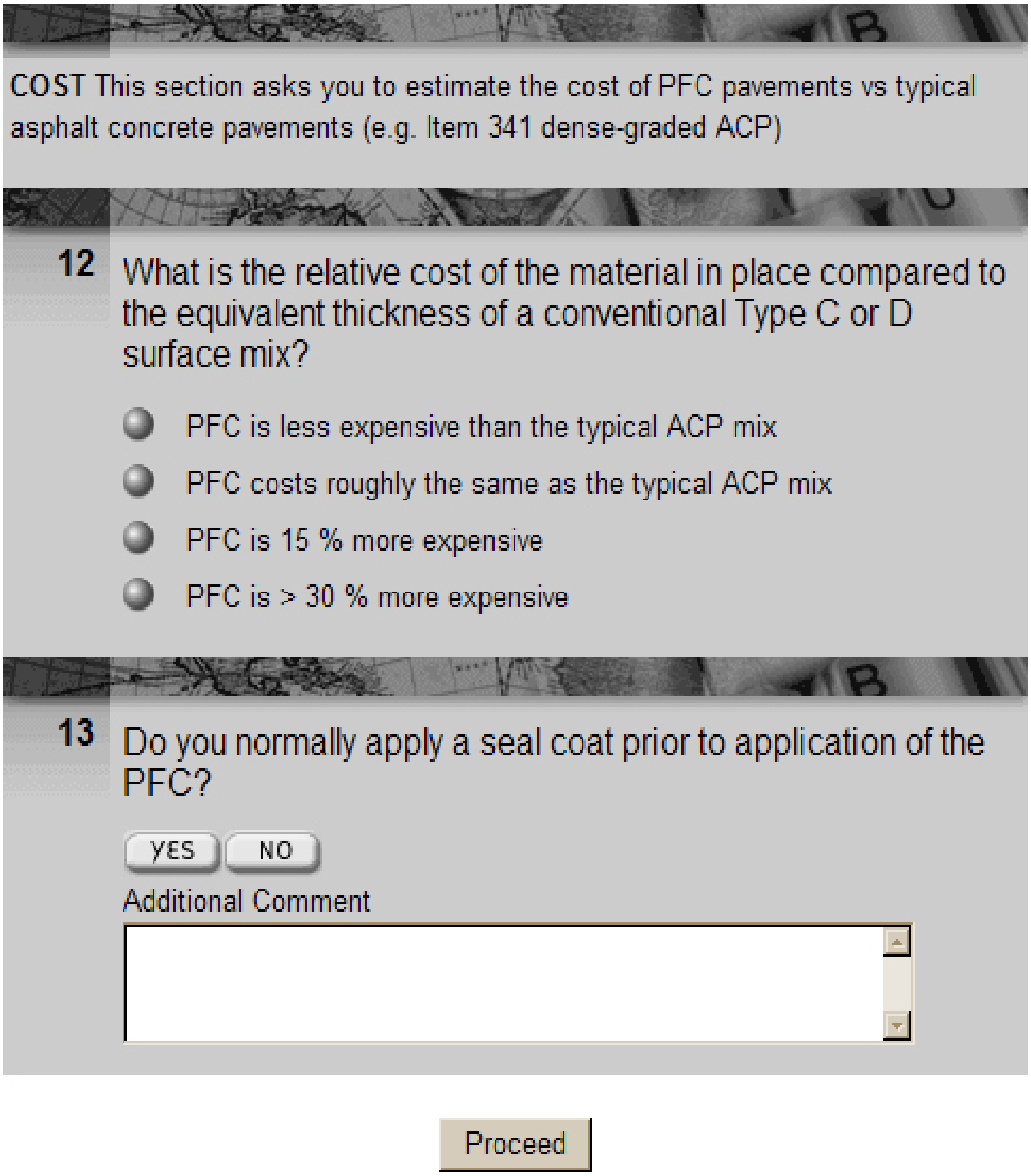
○ 10 - 12 years

○ > 12 years

11 How do you rate the FIRST YEAR performance of PFC in your area:

	1 Excellent	2 Very Good	3 Good	4 Fair	5 Poor	N/A
Splash and spray — ***Improved Safety***	1	2	3	4	5	☐
Noise — ***Fuctionality***	1	2	3	4	5	☐
Permeability	1	2	3	4	5	☐
Raveling — ***Durability***	1	2	3	4	5	☐
Cracking	1	2	3	4	5	☐
Rutting	1	2	3	4	5	☐

Permeable Friction Course Study (0-5836)



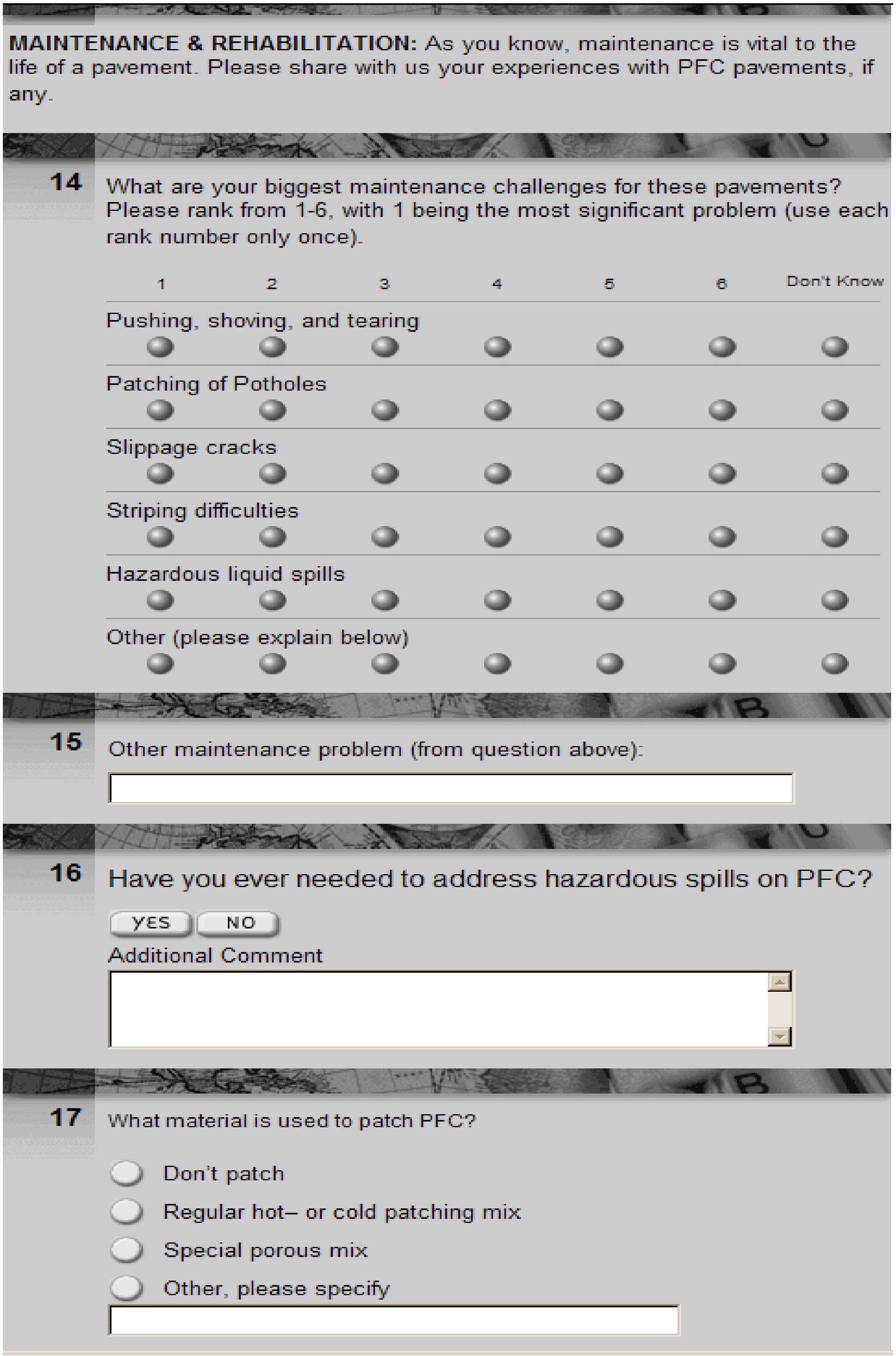
COST This section asks you to estimate the cost of PFC pavements vs typical asphalt concrete pavements (e.g. Item 341 dense-graded ACP)

12 What is the relative cost of the material in place compared to the equivalent thickness of a conventional Type C or D surface mix?

- ○ PFC is less expensive than the typical ACP mix
- ○ PFC costs roughly the same as the typical ACP mix
- ○ PFC is 15 % more expensive
- ○ PFC is > 30 % more expensive

13 Do you normally apply a seal coat prior to application of the PFC?

Additional Comment



MAINTENANCE & REHABILITATION: As you know, maintenance is vital to the life of a pavement. Please share with us your experiences with PFC pavements, if any.

14 What are your biggest maintenance challenges for these pavements? Please rank from 1-6, with 1 being the most significant problem (use each rank number only once).

	1	2	3	4	5	6	Don't Know
Pushing, shoving, and tearing	○	○	○	○	○	○	○
Patching of Potholes	○	○	○	○	○	○	○
Slippage cracks	○	○	○	○	○	○	○
Striping difficulties	○	○	○	○	○	○	○
Hazardous liquid spills	○	○	○	○	○	○	○
Other (please explain below)	○	○	○	○	○	○	○

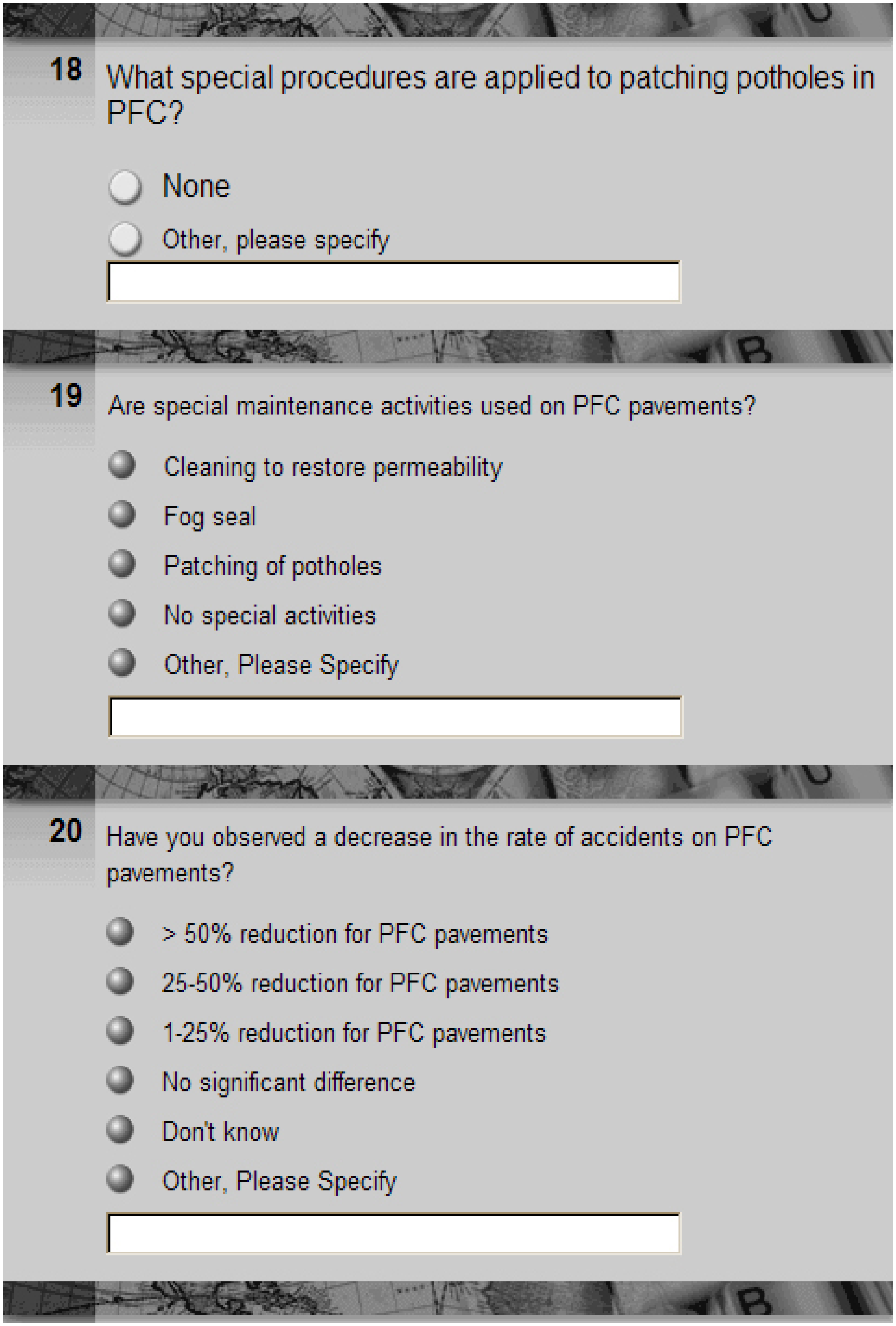
15 Other maintenance problem (from question above):

16 Have you ever needed to address hazardous spills on PFC?

Additional Comment

17 What material is used to patch PFC?

- ○ Don't patch
- ○ Regular hot– or cold patching mix
- ○ Special porous mix
- ○ Other, please specify



18 What special procedures are applied to patching potholes in PFC?

○ None

○ Other, please specify

19 Are special maintenance activities used on PFC pavements?

○ Cleaning to restore permeability

○ Fog seal

○ Patching of potholes

○ No special activities

○ Other, Please Specify

20 Have you observed a decrease in the rate of accidents on PFC pavements?

○ > 50% reduction for PFC pavements

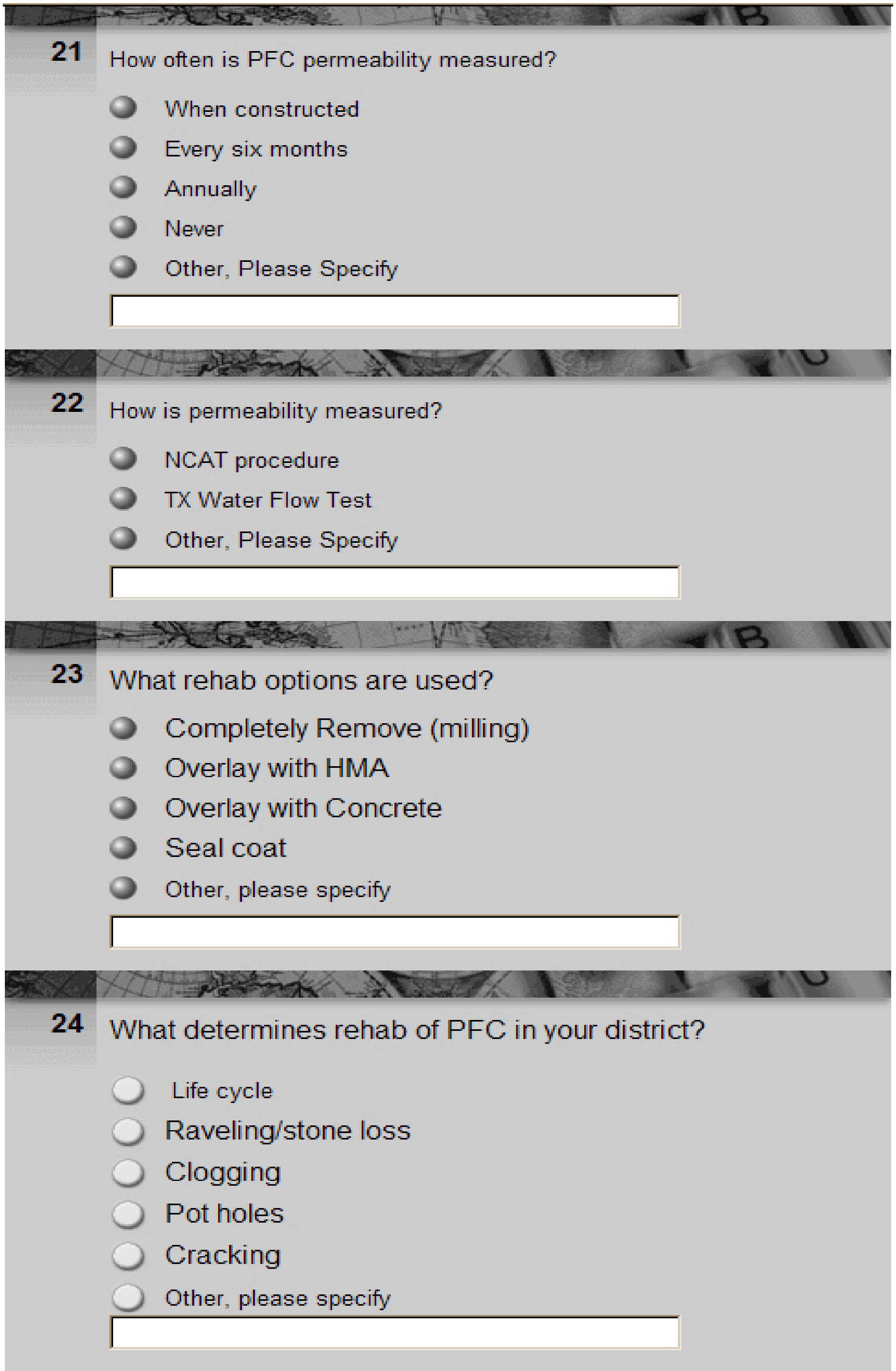
○ 25-50% reduction for PFC pavements

○ 1-25% reduction for PFC pavements

○ No significant difference

○ Don't know

○ Other, Please Specify



21 How often is PFC permeability measured?

- ○ When constructed
- ○ Every six months
- ○ Annually
- ○ Never
- ○ Other, Please Specify

22 How is permeability measured?

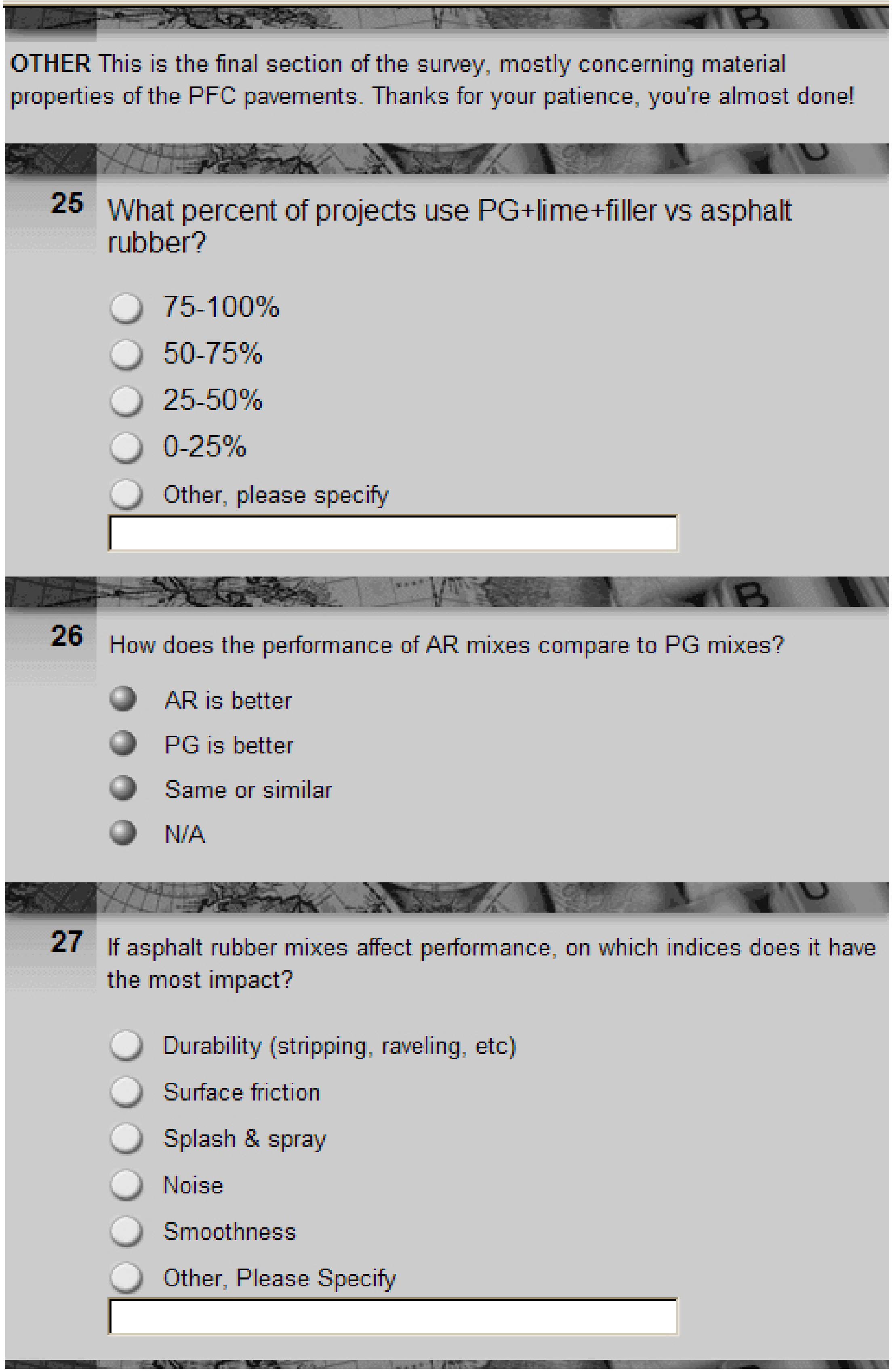
- ○ NCAT procedure
- ○ TX Water Flow Test
- ○ Other, Please Specify

23 What rehab options are used?

- ○ Completely Remove (milling)
- ○ Overlay with HMA
- ○ Overlay with Concrete
- ○ Seal coat
- ○ Other, please specify

24 What determines rehab of PFC in your district?

- ○ Life cycle
- ○ Raveling/stone loss
- ○ Clogging
- ○ Pot holes
- ○ Cracking
- ○ Other, please specify



OTHER This is the final section of the survey, mostly concerning material properties of the PFC pavements. Thanks for your patience, you're almost done!

25 What percent of projects use PG+lime+filler vs asphalt rubber?

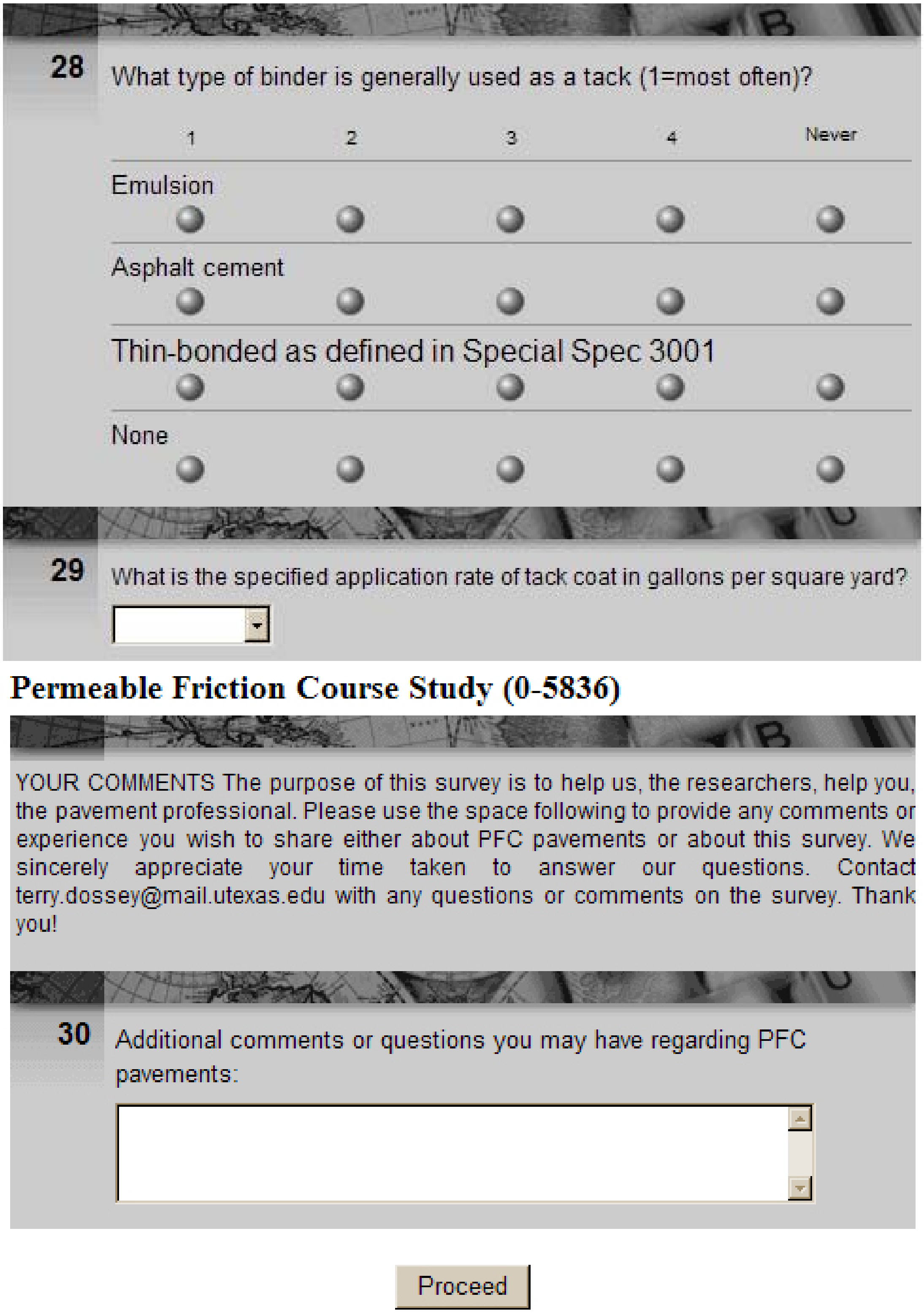
○ 75-100%
○ 50-75%
○ 25-50%
○ 0-25%
○ Other, please specify

26 How does the performance of AR mixes compare to PG mixes?

● AR is better
● PG is better
● Same or similar
● N/A

27 If asphalt rubber mixes affect performance, on which indices does it have the most impact?

○ Durability (stripping, raveling, etc)
○ Surface friction
○ Splash & spray
○ Noise
○ Smoothness
○ Other, Please Specify



28 What type of binder is generally used as a tack (1=most often)?

	1	2	3	4	Never
Emulsion	○	○	○	○	○
Asphalt cement	○	○	○	○	○
Thin-bonded as defined in Special Spec 3001	○	○	○	○	○
None	○	○	○	○	○

29 What is the specified application rate of tack coat in gallons per square yard?

Permeable Friction Course Study (0-5836)

YOUR COMMENTS The purpose of this survey is to help us, the researchers, help you, the pavement professional. Please use the space following to provide any comments or experience you wish to share either about PFC pavements or about this survey. We sincerely appreciate your time taken to answer our questions. Contact terry.dossey@mail.utexas.edu with any questions or comments on the survey. Thank you!

30 Additional comments or questions you may have regarding PFC pavements:

REFERENCES

1. Alvarez, A.E., A. Epps Martin, C. K. Estakhri, J. W. Button, C.J. Glover, and S. H. Jung, *Synthesis of Current Practice on the Design, Construction, and Maintenance of Porous Friction Courses.* Report No. 0-5262-1, Texas Transportation Institute, Texas A&M University, College Station, TX, 2006.
2. Estakhri, C.K., A. E. Alvarez, and A. Epps Martin, *Guidelines on Construction and Maintenance of Porous Friction Courses in Texas.* Report No. 0-5262-2, Texas Transportation Institute, Texas A&M University, College Station, TX, 2008.
3. Alvarez, A.E., A. Epps Martin, C. K. Estakhri, J. W. Button, C.J. Glover, N. Prapaitrakul, and Z. Krause, *Evaluation and Recommended Improvements for Mix Design of Permeable Friction Courses.* Report No. 0-5262-3, Texas Transportation Institute, Texas A&M University, College Station, TX, 2007.
4. Hanson, D. I., and R. S. James, *Colorado DOT Tire/Pavement Noise Study*. Report No. CDOT-DTD-R-2004-5, National Center for Asphalt Technology, Auburn University, Auburn, AL, 2004.
5. Trevino, M., and T. Dossey, *A Research Plan for Measuring Noise Levels in Highway Pavements in Texas*. Report No. 0-5185, Center for Transportation Research, University of Texas at Austin, Austin, TX, 2006.
6. Ongel, A., E. Kohler, and J. Harvey, Principal Components Regression of Onboard Sound Intensity Levels. *Journal of Transportation Engineering*, Vol. 134, No. 11, November 1, 2008.
7. Trevino, M. and T. Dossey, *Noise Measurements of Highway Pavement in Texas.* Report No. 0-5185-3, Center for Transportation, The University of Texas at Austin, April, 2009.
8. Bendtsen, H., and B. Andersen, *Thin Open Layers as Noise Reducing Pavements*. Report 135, Danish Road Institute, Road Directorate, Ministry of Transport-Denmark, 2004.
9. McDaniel, R. S., W. D. Thornton, and J. G. Dominguez, *Field Evaluation of Porous Asphalt Pavement*. Report No. SQDH 2004-3, North Central Superpave Center, Purdue University, West Lafayette, IN, 2004.

10. Bennert, T., D. Hanson, A. Maher, and N. Vitillo, Influence of Pavement Surface Type on Tire/Pavement Generated Noise. *Journal of Testing and Evaluation*, Mar. 2005, Vol. 33, No. 2.
11. Bennert, T., F. Fee, E. Sheehy, A. Jumikis, and R. Sauber, Comparison of Thin-Lift Hot-Mix Asphalt Surface Course Mixes in New Jersey. *Transportation Research Record*, n 1929, p 59-68, 2005.
12. Sandberg, U. and B. Kalman, *The Poroelastic Road Surface-Results of an Experiment in Stockholm*. SILVIA-VTI-006-00-WP4-030605, Sustainable Road Surfaces for Traffic Noise Control, European Commission, 2005.
13. Anon. Noise-Reducing Pavements Get Loud Acclaim in the United States and Europe. *Asphalt Institute*, Fall 2006, Vol. 21, No. 3, p 36-38.
14. Kowalski, K., R. S. McDaniel, A. Shah, and J. Olek, *Long Term Monitoring of the Noise and Frictional Properties of PFC, SMA and DGA Pavements*. Transportation Research Record, 88th Annual Meeting CD ROM, Paper No. 09-2742, 2009.
15. Ongel, A., J. T. Harvey, E. Kohler, Q. Lu, and B. D. Steven, I*nvestigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Type: First- and Secind- Year Results*, Research Report: UCPRC-RR-2007-03, Caltrans Division of Research and Innovation, 2008.
16. Smit, A. F., and B. Waller, *Sound Pressure and Intensity Evaluations of Low Noise Pavement Structures with Open-Graded Asphalt Mixtures*. NCAT Report 07-02, National Center for Asphalt Technology, Auburn University, Auburn, AL, 2007.
17. Smit, A. F., and B. Waller, Evaluation of OBSI for Measuring Tire-Pavement Noise. Conference paper Noise Conference 2007 October 22-24, Reno, Nevada, 2007.
18. Anfosso-Lèdèe, F. and M. T. Do, Geometric Descriptors of Road Surface Texture in Relation to Tire-Road Noise. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1806, TRB, Transportation Research Board of the Academies, Washington, D.C., 2002, p 160-167.

19. Herman, L., J. Withers, and E. Pinckney, Surfacing Retexture to Reduce Tire-Road Noise for Existing Concrete Pavements. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1983, Transportation Research Board of the Academies, Washington, D.C., 2006, p 51-58.
20. Miró, R., F. Pèrez-Jimènez, A. H. Martînez, O. Reyes-Qrtiz, S. E. Paje, and M. Bueno, *Effect of Using Crumb Rubber Bituminous Mixes on Functional Characteristics of Road Pavements*. Transportation Research Record, 88th Annual Meeting CD ROM, Paper No. 09-0776, 2009.
21. Smit, A. F., and B. Waller, *Air Temperature Influence on Close Proximity Sound Pressure and Intensity Measurements on HMA Pavements*. NCAT Report 07-04, National Center for Asphalt Technology, Auburn University, Auburn, AL, 2007.
22. Donavan, P. R. and D. M. Lodico, *Measuring Tire/pavement Noise at the Source*, NCHRP Report 630, Project 1-44, Transportation Research Board, Washington, DC, 2009.
23. Smit, A. F., and B. Waller, *Air Temperature Influence on Near-Field Tire-Pavement Noise*. Transportation Research Record, 87th Annual Meeting CD ROM, Paper No. 08-0389, 2008.
24. Pierce, L. M., J. P. Mahoney, S. Muench, H. J. Munden, M. Waters, and J. Uhlmeyer, *Quieter HMA Pavements in Washington State*. Transportation Research Record, 88th Annual Meeting CD ROM, Paper No. 09-2205, 2009.
25. Smit, A. F., and B. Waller, *Sound Pressure and Intensity Evaluations of Low Noise Pavement Structures with Dense-Graded and Stone Matrix Asphalt Mixtures*. NCAT Report 07-03, National Center for Asphalt Technology, Auburn University, Auburn, AL, 2007.
26. Alvarez, A.E. and A. Epps Martin, *Permeable Friction Course Mixtures are Different.* 2009: p. Submitted for publication, March 2009.
27. Alvarez, A.E., A. Epps Martin, and C. Estakhri, *Drainability of Permeable Friction Course Mixtures.* 2008: p. Submitted for publication in the Journal of Materials in Civil Engineering, ASCE, December 2008.
28. Masad, E., A. Al-Omari, and R. Lytton, *Simple Method for Predicting Laboratory and Field Permeability of Hot-Mix Asphalt.* Transportation Research Record, 2006. 1970: p. 55-63.

29. Cooler Jr., L. A., *Performance and Maintenance of Permeable Friction Courses; Vol. III Annotated Literature Review*. NCHRP Project 9-41, Burns Cooley Dennis, Inc., Transportation Research Board, Washington, D.C., 2009.
30. Punith, V. S., S. N. Suresha, A. Veeraragavan, S. Raju, and S. Bose, *Characterization of Polymer and Fiber-Modified Porous Asphalt mixtures*. TRB 2004 Annual Meeting CD-ROM, Transportation Research Board, National Research Council, Washington, D.C., 2004.
31. Alvarez, A. E., A. Epps Martin, and C. Estakhri, *Effects of Densification on Permeable Friction Course Mixtures*, Journal of Testing and Evaluation, Vol. 37, No 1, 2009, pp. 11-20.
32. Watson, D. E., L. A. Cooley Jr., K. A. Moore, and K. Williams, *Laboratory Performance Testing of Open-Graded Friction Course Mixtures*, Transportation Research Record, Vol. 1891, 2004, pp. 40-47.
33. Brousseaud, Y. and F. Anfosso-Le̕de̕e, Review of Existing Low Noise Pavement Solutions in France. SILVIA-LCPC-011-01-WP4-310505, Sustainable Road Surfaces for Traffic Noise Control, European Commission, May 2005.
34. Alvarez, A.E., A. E. Martin, C. Estakhri, and R. Izzo, *Evaluation of Durability Tests for Permeable Friction Course Mixtures.* International Journal of Pavement Engineering, Published on-line on February 2009.
35. ASTM Standard Test Method E 274-97, Skid Resistance of Pavements Using a Full-Scale Tire, *Annual Book of ASTM Standards*, Vol. 4.03, ASTM International, West Conshohocken, PA 2004.
36. ASTM Standard Test Method E 303, Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA 1993.
37. ASTM Standard Test Method E 1911-98, Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester, *Annual Book of ASTM Standards*, Vol. 4.03, ASTM International, West Conshohocken, PA 2004
38. ASTM Standard Test Method E 1960-03, Standard Practice for Calculating International Friction Index of a pavement surface, *Annual Book of ASTM Standards*, Vol. 4.03, ASTM International, West Conshohocken, PA 2004.
39. Choubane, B., C. R. Holzschuher, and S. Gokhale, Precision of Locked-Wheel Testers for

Measurement of Roadway Surface Friction Characteristics. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1869, TRB, Transportation Research Board of the Academies, Washington, D.C., 2004, p 145-151.

40. Asi, I. M., Evaluating Skid Resistance of Different Asphalt Concrete Mixes. *Building and Environment*, Vol. 42, P 325-329, 2007.
41. Flintsch, G. W., *Assessment of the Performance of Several Roadway Mixes under Rain, Snow, and Winter Maintenance Activities*. Report VTRC 04-CR18, Virginia Department of Transportation, University of Virginia, Charlottesville, VA, 2004.
42. Jackson, N. M., B. Choubane, C. Holzschuher, and S. Gokhale, Measuring Pavement Friction Characteristics at Variable Speeds for Added Safety. *Journal of ASTM International,* Vol. 2, No. 10, 2005.
43. Bazlamit, S. M. and F. Reza, Changes in Asphalt Pavement Friction Components and Adjustment of Skid Number for Temperature. *Journal of Transportation Engineering,* Vol. 131, No. 6, p 470-476, 2005.
44. Lucy, A., E. Mahmoud, E. Masad, and A. Chowdhury, Relationship of Aggregate Microtexture to Asphalt Pavement Skid Resistance. *Journal of Testing and Evaluation,* Vol. 35, No. 6, 2007.
45. Kandhal, P., *Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses*. Information series 115. National Asphalt Pavement Association (NAPA), Lanham, MD, 2002.
46. Watson, D. E., K. A. Moore, K. Williams, and L. A. Cooley, Refinement of New-Generation Open-Graded Friction Course Mix Design, In *Transportation Research Record: Journal of the Transportation Research Board*, No 1832, TRB, National Research Council, Washington, D.C., 2003, pp. 78-85.
47. American Standard of Testing Materials (ASTM), *Standard Practice for Open-Graded Friction Course (OGFC) Mix Design*, ASTM Designation: D 7064-04, ASTM International, West Conshochocken, PA, 2006, p. 940.
48. Alvarez, A.E. 2009. Improving Mix Design and Construction of Permeable Friction Course Mixtures. *Ph.D. Dissertation*, Texas A&M University, College Station, TX.
49. Alvarez, A. E., A. Epps Martin, C. Estakhri, and R. Izzo, *Determination of Volumetric*

Properties for Permeable Friction Course Mixtures, Journal of Testing and Evaluation, Vol. 37, No 1, 2009, pp. 1-10.

50. Alvarez, A. E., A. Epps Martin, and C. Estakhri, *Internal Structure of Compacted Permeable Friction Course Mixture*, Submitted for publication in the Construction and Building Materials journal, August 2009.
51. Alvarez, A. E., A. Epps Martin, and C. Estakhri, *Connected Air Voids Content in Permeable Friction Course Mixtures*, Journal of Testing and Evaluation, Vol. 37, No 3, 2009, pp. 254-263.
52. Alvarez, A. E., E. Mahmoud, A. Epps Martin, and E. Masad, *Stone-on-Stone Contact of Permeable Friction Course Mixtures,* Submitted for publication in the Journal of Materials in Civil Engineering, ASCE, September 2009.
53. Huber, G., Performance Survey on Open-Graded Friction Course Mixes. Synthesis of Highway Practice 284. TRB, National Research Council, Washington., D.C., 2000.
54. British Standards Institute (BSI)., *Coated Macadam (Asphalt Concrete) for Roads and Other Paved Areas – Part 1: Specification for Constituent Materials and for Mixtures.* BS 4987-1:2005. 2005.
55. Provisional European Standard, pr EN13108-7, Bituminous Mixtures Material Specifications Part 7–Porous Asphalt (PA). 2001.
56. *Open Grade Friction Course Usage Guide. California Department of Transportation, Division of Engineering Services, Materials Engineering and Testing Services-MS #5,* Sacramento, California, February 2006.
57. *Manual of Contract Documents for Highway Works, Volume 1. Specification for Highway Works, Series 900, Road Pavements – Bituminous Bound Materials.* United Kingdom, 2005.
58. Texas Department of Transportation. 5*00-C Asphalt Test Procedures Manual.* Austin, TX, 2004.
59. Wagner, C. and Y. S. Kim. *Field Construction of a Safe Pavement Edge: Minimizing the Effects of Shoulder Dropoff.* TRB 2005 Annual Meeting CD-ROM. Transportation Research Board. National Research Council. Washington, D.C. 2005.
60. Newcomb, D., and L. Scofield, Quiet Pavements Raise the Roof in Europe. *Hot Mix Asphalt Technology*, September-October, 2004, p 22-28.

61. Sandberg, U., and Y. Masuyama, *Japanese Machines for Laying and Cleaning Double–Layer Porous Asphalt–Observations from a Study Tour.* Report Produced by Direction of Rijkswaterstaat-DWW, Co-Sponsored by Chalmers University of Technology DWW/IPG, order number 64520946, 2005.

62. van Bochove, G. G. Porous Asphalt (two-layered) – Optimizing and Testing. In Procedures, 2nd Eurasphalt & Eurobitume Congress Barcelona 2000 – Proc.0229.uk. 2000.

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

64. Airey, G., A. Hunter, A. Collup, *The Effect of Asphalt Mixture Gradation and Compaction Energy on Aggregate Degradation.* Unpublished Draft Manuscript, University of Nottingham, Nottingham, United Kingdom, 2005.

65. Rogge, D., *Development of Maintenance Practices for Oregon F-Mix.* Publication FHWA-OR-RD-02-09. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2002.

66. Bredahl, C., *Construction of Two-Layer Porous Pavements*. Danish Road Institute. 2005. European Experience Quiet Asphalt 2005 Symposium.

67. Van Doorn, R., *Winter Maintenance in the Netherlands. Ministry of Transportation*, Public Work and Water Management, Compiled from COST 344 Snow and Ice Control on European Road and Bridges Task Group 3, Best Practice, 2002.

68. Pucher, E., J. Litzka, J. Haberl, and J. Girard. *Report on Recycling of Porous Asphalt in Comparison with Dense Asphalt*. SILVIA-036-01-WP3-260204, Sustainable Road Surfaces for Traffic Noise Control, European Commission, 2004.

69. Yildirim, Y., T. Dossery, K. Fults, and M. Trevino, *Winter Maintenance Issues Associated with New Generation with New Generation Open-Graded Friction Courses.* Center for Transportation Research, The University of Texas at Austin, Austin, Texas, 2006.

70. Federal Highway Administration (FHWA), *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel.* U.S. Army Cold Regions Research and Engineering Laboratory Corps of Engineers. Hanover, New Hampshire.

71. Danish Road Institute. *Noise Reducing Pavements–State of the Art in Denmark*. Report 141.

DRI, Road Directorate, Ministry of Transport–Denmark, 2005.

72. The Highways Agency, The Scottish Office Development Department, The Welsh Office Swyddfa Gymreig, The Department of the Environment for Northern Ireland. *Design Manual for Roads and Bridge, Volume 7: Pavement Design and Maintenance Bituminous Surfacing Materials and Techniques.* 1999.
73. Lai, J., *Assessing Techniques and Performance of Thin PEM Overlay on Micro-milled Surface*. Second Interim Technical Report, Office of Materials and Research, Georgia Department of Transportation, 2008.
74. Donavan, P. R., *Comparative Measurement of Tire/Pavement Noise in Europe and the United States*, Illingworth & Rodkin, Inc, 2005.
75. Kandhal, P., Asphalt Pavements Mitigate Tire/Pavement Noise. *Hot Mix Asphalt Technology*, March-April, 2004, pp. 22-31.
76. Yeo, E. R., J. Favaloro, and P. Mousley, An Australian Perspective on the Functional Durability of Open Graded Asphalt Surfacing. *Australian Meteorological Magazine*, Austria, 2001.
77. Molenaar, A.A.A., Meerkerk, A.J.J., Miradi, M. and van der Steen, T., 2006. Performance of Porous Asphalt Concrete. *In Annual Meeting and Technical Sessions, Association of Asphalt Paving Technologist. CD-ROM*, 1-42.
78. Sandberg, U. and J. A. Ejsmont, *Tyre/Road Noise Reference Book*, 2002.
79. Cooper, S. B., C. Abadie, and L. N. Mohammad, *Evaluation of Open-Graded Friction Course Mixture*. Report No. 04-1TA, Louisiana Transportation Research Center, Baton Rouge, LA, 2004.
80. Shatanawi, K. M., B. J. Putman, C. Thodesen, and S. N. Amirkhanian, *The Effects of Crumb Rubber Particles on Asphalt Pavement Traffic Noise Absorption*. Transportation Research Record, 88th Annual Meeting CD ROM, Paper No. 09-3197, 2009.
81. Rymer, B., and P. R. Donavan, *California Applications and Experiences Using the OBSI Method*. Transportation Research Record, 88th Annual Meeting CD ROM, Paper No. 09-3579, 2009.

82. Donavan, P. R., and D. M. Lodico, *Estimation of Vehicle Passby Noise Emission Levels Based on Onboard Sound Intensity Level of Tire/Pavement Noise*. Transportation Research Record, 88th Annual Meeting CD ROM, Paper No. 09-3561, 2009.
83. Lodico, D. M., and P. R. Donavan, *Evaluation of Test Variables for Onboard Sound Intensity (OBSI) Measurements*. Transportation Research Record, 88th Annual Meeting CD ROM, Paper No. 09-3261, 2009.
84. Jones, W., QUIET PAVEMENT — Coming to a Highway Near You. *Asphalt, The Magazine of the Asphalt Institute,* Summer 2005, p 24-25.
85. Kropp, W., K. Larsson, F. Wullens, P. Andersson, and F. X. Bѐcot, The Generation of Tire/Road Noise- Mechanisms and Models. Proceedings of the Tenth International Congress on Sound and Vibration, p 4289-4301, 2003, Proceedings of the Tenth International Congress on Sound and Vibration.
86. Kuemmel, D. A., R. C. Sonntag, J. Crovetti, and Y. Becker, *Noise and Texture on PCC Pavements-Results of a Multi-State Study*. Wisconsin Report SPR 08-99, June, 2000.
87. Landsberger, B. J., J. DeMoss, and M. McNerney, Effects of Air and Road Surface Temperature on Tire Pavement Noise on an ISO 10844 Surface. Proceedings-the 2001 Noise and Vibration Conference, Traverse City, Michigan, 2001.
88. Sandberg, U., Road Surface for Reduction of Tire Noise Emission. Proceedings-International Conference on Noise Control Engineering, v 2, p 517-520, 1979.
89. Cai, X. H., Master's Thesis: *Effect of Pavement Types and Ages on Traffic Noise Characteristics*, Department of Civil Engineering, Feng Chia University, Taichung, Taiwan, 2007.
90. Smit, A. F., *Synthesis of NCAT Low-Noise HMA Studies*. NCAT Report 08-01, National Center for Asphalt Technology, Auburn University, Auburn, AL, 2008.
91. Herman, L. A., M. J. Ambroziak, and E. Pinckney, Investigation of Tire-Road Noise Levels for Ohio Pavement Types. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1702, TRB, Transportation Research Board of the Academies, Washington, D.C., 2000, p 57-62.
92. Fickes, M., The Asphalt Rubber Phenomenon. *Hot Mix Asphalt Technology*, July-August, 2003, pp. 20-23.

93. Kandhal, P. S., How Asphalt Pavements Mitigate Tire-Pavement Noise. Better Roads, v 73, n 11, p S16-S22, November 2003.
94. Ogle, T. W., R. L. Wayson, and W. Lindeman, Effect of Vehicle Speed on Sound Frequency Spectra. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1559-03, TRB, Transportation Research Board of the Academies, Washington, D.C., 1996, p 14-25.
95. Kuemmel, D. A., J. R. Jaeckel, A. Satanovsky, S. F. Shober, and M. M. Dobersek, Noise Characteristics of Pavement Surface Texture in Wisconsin. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1544-04, TRB, Transportation Research Board of the Academies, Washington, D.C., 1996, p 24-35.
96. Crocker, M. J., D. Hanson, Z. Li, R. Karjatkar, and K. S. Vissamraju, Measurement of Acoustical and Mechanical Properties of Porous Road Surface and Tire and Road Noise. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1891, TRB, Transportation Research Board of the Academies, Washington, D.C., 2004, p 16-22.
97. Bèrengier, M., and G. Licitra, *Traffic Noise and Road Surfaces: a-State-of-the-Art*. Acta Acustica united with Acustica, v 89, n SUPP., p S81, May/June 2003.
98. Descornet, G., *Low-Noise Road Surfaces: European State of the Art*. Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions, v 74, p 1059-1083, 2005.
99. Trevino, M. and T. Dossey, *Preliminary Findings from Noise Testing on PFC Pavements in Texas.* Report No. 0-5185-2, Center for Transportation, The University of Texas at Austin, April, 2007.
100. Texas Department of Transportation. *200-F Bituminous Test Procedures Manual.* Austin, TX, 2004.
101. Yildirim, Y., T. Dossey, K. Fults, and M. Trevino, *Winter Maintenance Issues Associated with New Generation Open-Grade Friction Courses.* Report No. 0-4834-1, Center for Transportation Research, The University of Texas at Austin, TX, 2006.