Maintenance Strategies for Open-graded Friction Course (OGFC)

Submitted to the Tennessee Department of Transportation

Research Development and Technology Program

Baoshan Huang, Ph.D., P.E.
Xiang Shu, Ph.D., P.E.
Weimin Song, Ph.D.
Hongren Gong, Ph.D.

Department of Civil and Environmental Engineering
The University of Tennessee, Knoxville

August 2019

Technical Report Documentation Page

1. Report No.
RES2016-14

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Maintenance strategies for open-graded friction course (OGFC)

5. Report Date

6. Performing Organization Code

7. Author(s)
Baoshan Huang, Xiang Shu, Weimin Song, Hongren Gong

8. Performing Organization Report No.

9. Performing Organization Name and Address
The University of Tennessee
325 John D. Tickle Building
Knoxville, TN 37996

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Federal Highway Administration
Central Federal Lands Highway Division
12300 W. Dakota Avenue, Suite 210
Lakewood, CO 80228

13. Type of Report and Period Covered

14. Sponsoring Agency Code
HFTS-16.4

15. Supplementary Notes
COTR: First & Last name, FHWA CFLHD; Advisory Panel Members: List First & last names. This project was funded under the FHWA Federal Lands Highway Technology Deployment Initiatives and Partnership Program (TDIPP). Or the Coordinated Technology Implementation Program (CTIP).

16. Abstract

This report investigated the maintenance strategies for open-graded friction course (OGFC) in Tennessee. Three OGFC patching materials and the fog seal application were selected and laboratory tests were conducted to investigate their effectiveness and performance. In addition, the effectiveness of different maintenance treatments was investigated using the data derived from TDOT, other DOTs, and LTPP database. For the patching material, TDOT cold patching material was selected by considering the mechanical performance, permeability, adhesiveness, cohesion and economic efficiency. Although adding cement could slightly decrease the permeability, 3% cement content was suggested to add into the TDOT cold patching material to improve the indirect shear strength and moisture damage resistance. The application of fog seal decreased the permeability and the texture depth of OGFC. However, it could also significantly reduce the abrasion loss, indicating that the durability of OGFC pavement could be increased by this application. The reduced texture depth due to the fog seal treatment may be restored to certain extent by moving vehicles after opening to traffic. Based on the analyses on the LTPP data and the DOT survey response, recommendations on OGFC maintenance strategies were proposed to correct different distresses.

17. Key Words
open-graded friction course; TDOT cold patching material; fog seal; treatment methods; cracking; rutting; international roughness index

18. Distribution Statement
No restriction. This document is available to the public from the sponsoring agency at the website http://www.cflhd.gov.

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

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

DISCLAIMER

This research was funded through the State Research and Planning (SPR) Program by the Tennessee Department of Transportation and the Federal Highway Administration under RES #: 2016-14, Research Project Title: Maintenance Strategies for Open-graded Friction Course (OGFC).

This document is disseminated under the sponsorship of the Tennessee Department of Transportation and the United States Department of Transportation in the interest of information exchange. The State of Tennessee and the United States Government assume no liability of its contents or use thereof.

The contents of this report reflect the views of the author(s) who are solely responsible for the facts and accuracy of the material presented. The contents do not necessarily reflect the official views of the Tennessee Department of Transportation or the United States Department of Transportation.

Acknowledgements

We would like to begin by thanking the Tennessee Department of Transportation (TDOT) for funding this research project. We have continued to collaborate closely with regional engineers and local technicians at the TDOT Materials and Test Division and local asphalt plants. They have provided valuable support towards the fulfillment of the research objectives. Without their support, it would be impossible for us to finish this research project. We would also like to thank the administrative staff from the TDOT research office who have worked very closely with our research team and kept the whole project on the proposed schedule.

Executive Summary

This report investigated the maintenance strategies for open-graded friction course (OGFC) in Tennessee. To evaluate the current maintenance methods for OGFC, three OGFC patching materials were selected and laboratory tests were conducted. The fog seal application, as another maintenance method, was conducted in a test section in Tennessee, and laboratory tests were carried out to investigate the effectiveness and performance of this method. In addition, the effectiveness of different maintenance treatments was investigated using the data derived from TDOT, other DOTs, and Long-Term Pavement Performance (LTPP) database.

For the patching material, TDOT cold patching material was selected for OGFC pavement by considering the mechanical performance, permeability, adhesiveness, cohesion and economic efficiency. Although adding cement could slightly decrease the permeability, 3% cement content was suggested to add into the TDOT cold patching material to improve the indirect shear strength and moisture damage resistance.

The application of fog seal decreased the permeability and the texture depth of OGFC. However, it could also significantly reduce the abrasion loss, indicating that the durability of OGFC pavement could be increased by this application. The reduced texture depth caused by the fog seal application could be restored by a further abrasion test, indicating that the skid resistance of OGFC could initially be reduced due to the fog seal treatment, but it may be restored to certain extent by moving vehicles after opening to

traffic.

In Tennessee, because most of the OGFCs were paved within the recent three years (since 2016), an analysis of the data from the Pavement Management System (PMS) of TDOT indicated that the cracking probabilities were all at a low level. It also showed that the rut depth of OGFC was negligible (around 0.1 in). During the OGFC service life, the wheel path longitudinal cracking was generated and developed first, followed by the non-wheel path longitudinal cracking, fatigue cracking, transverse cracking, and block cracking. According to the data collected, the wheel path longitudinal cracking seemed to be the most critical factor to the durability of the OGFC sections.

The effectiveness of different maintenance treatments was investigated using the data derived from the LTPP database. In the US, overlaying with asphalt concrete (AC) or hot-mix recycled AC is the most commonly used treatment method in OGFC maintenance, which is also true for Tennessee. In Tennessee, the AC overlay treatment (T1) is generally applied in the eighth year of service. The treatment time of crack sealing (T5) is nearly the same as T1, and the treatment time of aggregate sealing and slurry sealing is in the third year of service. In general, the AC overlay (T1) decreased the occurrence of fatigue cracking, block cracking, wheel and non-wheel path longitudinal cracking, and international roughness index (IRI). As per the analyses on the LTPP data and the DOT survey response, recommendations on OGFC maintenance strategies were proposed to correct different issues, including raveling and crack sealing.

Table of Contents

List of Tables

List of Figures

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Open graded friction course (OGFC) is a thin layer of permeable asphalt placed on a dense graded asphalt pavement intended for quick drainage of rainwater and increased skid resistance, thus reducing traffic accidents and improving driving environment. Other benefits of OGFC include reducing traffic noise and urban heat island effect. Over the years, many state Departments of Transportation (DOTs) have adopted this pavement for these benefits.

With the wide application of OGFC in the U.S., good maintenance has become more and more important to maintain its function and performance. OGFC has different functions and properties than conventional dense graded asphalt mixtures and needs special maintenance strategies. According to a survey conducted by the UT research team and other previous surveys on OGFC (Cooley Jr et al., 2009), poor maintenance has resulted in short service life and poor performance of OGFC, preventing some state DOTs from continuing use of OGFC. Compared to conventional dense graded pavements, one of the big challenges for OGFC maintenance is fast formation of black ice during winter. This is because OGFC has a thermal conductivity that is 40% to 70% lower than dense graded asphalt mixtures and may have a temperature of 2 °C lower than dense graded pavement. Therefore, frost and ice will accumulate earlier, more quickly, and more frequently on

OGFC compared to other pavement surfaces. This indicates that conventional deicing chemicals and snow and ice removal methods for OGFC may not work as effectively as for dense graded pavements. New winter maintenance methods and strategies must be explored and secured for OGFC to ensure its performance during winter.

Like other state DOTs, TDOT has recently adopted OGFC as one of its standard pavement options for interstate resurfacing. It is anticipated that in the near future, this could also become one of TDOT's primary options for resurfacing other non-interstate high traffic or high-speed routes. As TDOT's network of highways paved with OGFC grows every year, its need for road maintenance methods is also growing. TDOT's oldest OGFC was placed in 2005 and will need to be preserved or repaired in the near future. Also, TDOT Operations' forces have expressed a need for improved methods for snow and ice removal on these porous pavements, where traditional methods are not as effective. Therefore, there is an urgent need to evaluate the current maintenance methods for OGFC pavements and to explore innovative maintenance methods and strategies so that OGFC performance can be maintained and service life extended. This study will benefit the TDOT in the following aspects:

(1) Provide TDOT best practices for pavement preservation/maintenance strategies of open-graded mixtures throughout the entire life of the treatment;
(2) Extend the service life of OGFC pavements;
(3) Help TDOT maintain a safe driving environment and economic efficiency;

(4) Increase public satisfaction through a better and safer driving environment.

1.2 Objectives

The objectives of the proposed research were:

- To identify best practices for OGFC pavement preservation/maintenance strategies through literature review and state DOT survey;
- To make recommendations for state specifications and operational guidelines to optimize the Department's open-graded pavement program;
- To evaluate potential methods for maintaining open-graded friction course mixtures during winter maintenance activities including anti/deicing strategies.

1.3 Scope of Study

The scope of the research work included:

- To complete a synthesis of literature review on OGFC preservation/maintenance methods and DOT survey on their practice of OGFC preservation/maintenance in the US, especially in the southeastern region;
- To evaluate the performance of different maintenance methods through field test section observation;
- To establish operational guidelines and make recommendations for OGFC preservation/maintenance strategies including type and timing of treatment;

- To recommend potential winter treatment methods for OGFC pavements including anti/deicing strategies.

1.4 Overview of the Final Report

The whole report is organized as follows: Chapter 1 gives a brief background of the project. Chapter 2 reviews the current maintenance methods for OGFC pavements. Chapter 3 presents the performance evaluation of different patching materials for OGFC. Chapter 4 evaluates the performance of OGFC treated with fog seal. Chapter 5 assesses the performance of the OGFC sections in Louisiana through data collected from the Pavement Management System (PMS) of Louisiana. Chapter 6 analyzes the effects of pre-treatment on the performance evolution of OGFC. Chapter 7 offers an evaluation of the field performance of OGFCs on a national scale using data extracted from the LTPP database. Chapter 8 summarizes the surveys sent out the DOTs in the U.S. The report concludes by summarizing the findings from the laboratory studies, field performance evaluations, and DOT surveys.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Open graded friction course (OGFC) is a thin permeable asphalt layer placed on the top of traditional dense graded asphalt pavement. OGFC mixtures designed for the requirement of stone-on-stone contact and high connected air voids content are a special type of hot mix asphalt (HMA) characterized by the use of high quality open-graded aggregate (Alvarez, Martin, & Estakhri, 2011; Huber, 2000; Kandhal & Mallick, 1998; R. B. Mallick, P. Kandhal, L. A. Cooley, & D. Watson, 2000). The stone-on-stone structure of coarse aggregate provides good resistance to permanent deformation, and the high air voids provides beneficial functional properties, such as drain-ability and noise reduction (Alvarez et al., 2011; Alvarez et al., 2006; Huber, 2000; R. B. Mallick et al., 2000).

Although advantages of OGFC are obvious, it is not free of disadvantages. As characterized by the high percentage air voids, asphalt binder is more likely to be oxidized, and as time goes on, the adhesion between binder and aggregate becomes disabled and raveling is more likely to happen. Clogging of the pores with time is another major problem with OGFC which significantly affects the functionality, such as water removal and noise reduction. Besides, for OGFC in severe cold area, maintenance in winter is a big challenge to meet. After water transforms into ice with the increasing volume, OGFC mixture is subject to high internal stress resulting in pavement cracking. Additionally, the thermal conductivity of OGFC is also different from the traditional HMA (Alvarez et al., 2006; King Jr, Kabir, Cooper Jr, & Abadie, 2013; Root, 2009). **Table 2-1** shows the problems encountered with porous friction course (Kandhal & Mallick, 1998; Nielsen, 2006).

The steadily increasing traffic on Tennessee highways requires a longer service life of OGFC than ever before. Maintenance is an essential procedure to ensure the functionality and longer service life of OGFC.

Table 2-1. Problems Encountered with Porous Friction Courses (Kandhal & Mallick, 1998; Nielsen, 2006)

	Agency	**Typical Problems Encountered**
International	Austria	Raveling
	Germany	Raveling
	France	Raveling
	The Netherlands	Raveling & Rapid Aging
	Spain	Raveling & Pore Clogging
	United Kingdom	Pore Clogging & Rapid Aging
United States	Alaska	Ice Removal
	Colorado	Stripping
	Hawaii	Raveling
	Idaho	Pore Clogging
	Iowa	Ice Removal
	Kansas	Ice Removal
	Louisiana	Raveling
	Maine	Ice Removal
	Maryland	Raveling
	South Dakota	Pore Clogging
	Tennessee	Stripping & Ice Removal
	Virginia	Stripping

2.2 Maintenance Methods

Maintenance of OGFC often includes general maintenance, winter maintenance and rehabilitation. This part covers only general maintenance and rehabilitation, and winter maintenance will be discussed in a later chapter.

2.2.1 General Maintenance

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

2.2.1.1 Cleaning clogged OGFC

The high porosity of OGFC is important to realize its benefits, such as noise reduction and water permeability, which also improves safety and driving comfort. However, it is inevitable that OGFC will be clogged by dirt and debris over time (D. Rogge & E. Hunt, 1999).

Previous studies point out that the clogging would begin from the top layer, which could protect the middle and the bottom of the pavement from clogging (Kevern, 2011). The National Cooperative Highway Research Program (NCHRP) Report 640 provided recommendations for addressing the clogging issues with asphalt permeable friction courses (Cooley Jr et al., 2009). Permeability on clogged OGFC sections can be restored using a combination of high-pressure water ranging from 860 kPa to 3,450 kPa (125 psi to 500 psi) and a vacuum to remove the debris. Isenring et al. stated that cleaning clogged

OGFC layers can be difficult. The research reported that cleaning techniques should begin while the layer is still permeable, and such regular maintenance could maintain permeability of the layer for a longer time period (Isenring, Koster, & Scazziga, 1990).

According to the experience from Portland cement pervious concrete pavement, clog cleaning maintenance can be achieved by standard street cleaning equipment containing a vacuum to remove particles from the surface (Ferguson, 2005). Figure 2-1 shows routine maintenance on pervious concrete in Olathe, Kansas. The stripping seen in the picture is from water used for dust control. It should be noted that the typical cleaning speed used for traditional pavement or curb and gutter applications does not allow enough time to completely clean debris from the OGFC surface pores.

Figure 2-1 Typical pavement cleaning operations

2.2.1.2 Preventive surface maintenance

It is expected that the asphalt binder of OGFC will get oxidized and become brittle after 10 to 15 years of service. In addition, the high porosity and the stone-stone structure of OGFC may precipitate raveling. Fog seal is a necessary method to reduce any raveling distress. The Asphalt Emulsion Manufacturers Association (AEMA) defines a fog seal as "a light spray application of dilute asphalt emulsion used primarily to seal an existing asphalt surface to reduce raveling and enrich dry and weathered surfaces" (Manual, 1997). Fog seals provide a thin film of neat asphalt binder at the surface and, therefore, are believed to extend the life of Porous Friction Courses (PFC) pavements (Rogge, 2002). The schematic of fog seal application is shown in Figure 2-2.

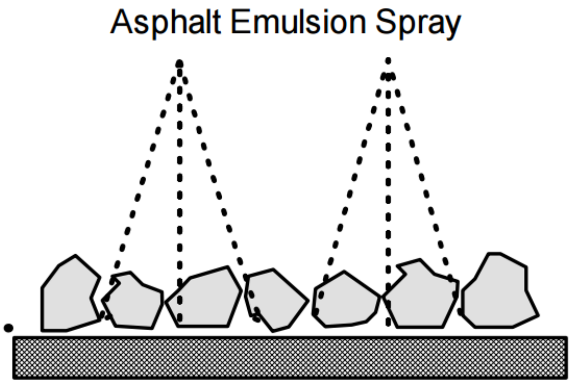


Figure 2-2 Schematic of fog seal application (Hicks & Holleran, 2002)

Previous studies (Rogge, 2002) showed that the application of fog seals reduces the permeability of PFC layers. Also, application of fog seals to PFC layers will reduce the frictional properties of PFC layers. However, friction increases significantly in the first month after application as the fog seal is worn away by traffic. Fog seals did not affect the macrotexture of PFC layers; therefore, the reduced potential for hydroplaning was maintained. Rogge (2002) concluded that the expected benefits of fog seals to prolong the life of PFC layers were not substantiated with quantitative studies. Additionally, he recommended that when it was acceptable to abandon the free draining characteristics of PFC layers and the pavement structure was sound, chip seals may be applied which are more expensive but can seal the surface better than fog seals (Rogge, 2002). Additionally, Oregon responded in the survey that they had concerns with the use of chip seals. These concerns were related to increased potentials for moisture damage in underlying layers. Wimsatt and Scullion (Wimsatt & Scullion, 2003) stated that it was standard practice by Texas DOT to use seal coats over distressed open-graded surfaces.

2.2.1.3 Corrective surface maintenance

When delamination occurs or a pothole forms, patch repair is needed. Regular HMA can be used when the patch is small and the permeability of OGFC will not be affected (Rogge, 2002). In the field, if HMA is used for patching, it is recommended that the patch should be diamond shaped and oriented so that the water can drain along the patch at 45-degree angles. An example of this is illustrated in the sketch in Figure 2-3. However, milling an area of this shape may be difficult depending on the equipment used. In addition, the grade and cross-slope of the pavement section should be considered when designing patches for OGFC as the water will flow downhill along the edge of a dense graded patch until it can flow laterally to the edge of pavement. Therefore, it is important that a patch does not extend continuously through a "valley" in the pavement section. When patching with an OGFC mix, a light emulsion tack coat (as opposed to a heavy tack) should be applied to the edge of the patch to not inhibit the drainage of the OGFC.

As for the cracking of OGFC, small cracks are usually invisible due to its textured surface. Once they become noticeable, they are significant and need to be sealed. Transverse cracks can be sealed using normal methods since the permeability of the pavement will not be affected. Longitudinally cracked areas are more troublesome because sealing the cracks will prevent drainage. One method of solving this problem is to mill the strip of pavement surrounding the longitudinal crack and replace with new OGFC. Rehabilitation is the only other solution if the severity of the crack becomes excessive (Dennis, 2007).

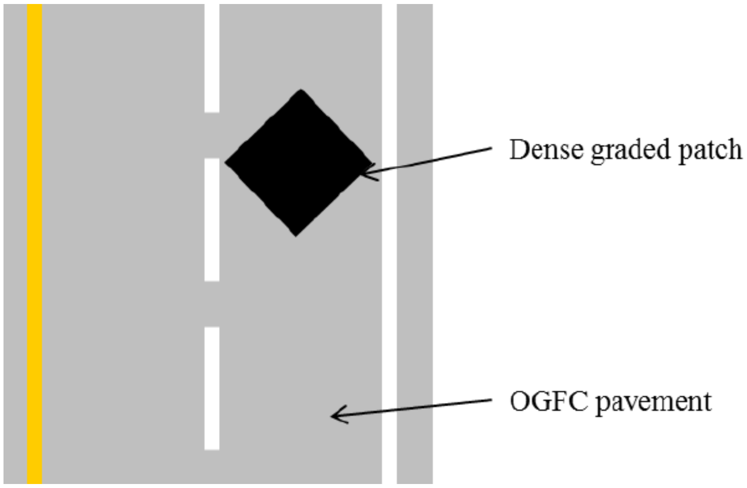


Figure 2-3 Schematic of a diamond shaped patching solution for an OGFC pavement (Putman, 2012)

2.2.2 Rehabilitation

An ideal set of technical actions for major rehabilitation of PFC has been defined by some DOTs (e.g., Florida and Georgia) as mill, recycle, then inlay. The same approach has been recommended in Oregon and reported as the favored approach in The Netherlands (Rogge, 2002). When inlaying PFC, one must avoid creating an impermeable vertical wall at the lower side of the inlay and, thus, the potential for ponding water.

General recommendations and actual practices for rehabilitation of PFC in the United States include milling and replacing of existing PFC with new PFC or any other asphalt mixture (Huber, 2000; Kandhal & Association, 2002). Direct placement of new dense-graded mix over porous mixture is not recommended because life of the new layer can be diminished by water accumulation inside the PFC. Experimental reports from Netherlands showed that recycled PFC kept approximately the same permeability, which has analogous durability to that of the new mixtures (Huber, 2000).

In the absence of raveling or delamination demanding rehabilitation, once PFC has lost its functionality (i.e., permeability and noise reduction) through clogging, the continued use of the pavement might still be permitted since it essentially behaves as a dense-graded mix with low permeability (Huber, 2000).

CHAPTER 3 LABORATORY PERFORMANCE EVALUATION OF OGFC PATCHING MATERIALS

3.1 Patching Materials

Three types of repair material were collected, and they can potentially be used to repair OGFC. They are TDOT cold patching material, EZ patch material, and Aquaphalt material. TDOT cold patching material and EZ patching material are coarser than Aquaphalt as shown in Figure 3-1.

(a) TDOT cold patching (b) EZ patching (c) Aquaphalt

Figure 3-1 Repair materials

3.2 Laboratory Performance Tests

The main distresses after patching in OGFC pavements generally include missing patch, edge disintegration, and void clogging. To investigate the resistance of patching materials to those distresses, four laboratory tests were performed. Adhesiveness and cohesion tests were conducted to evaluate the materials' adhesiveness to original OGFC pavement and internal cohesion, respectively. Moisture susceptibility including a freeze-thaw cycle was conducted to evaluate the freeze-thaw resistance of patching materials. The permeability test was conducted to investigate the permeability of the patching materials. Figure 3-2 shows the distresses and corresponding proposed laboratory tests.

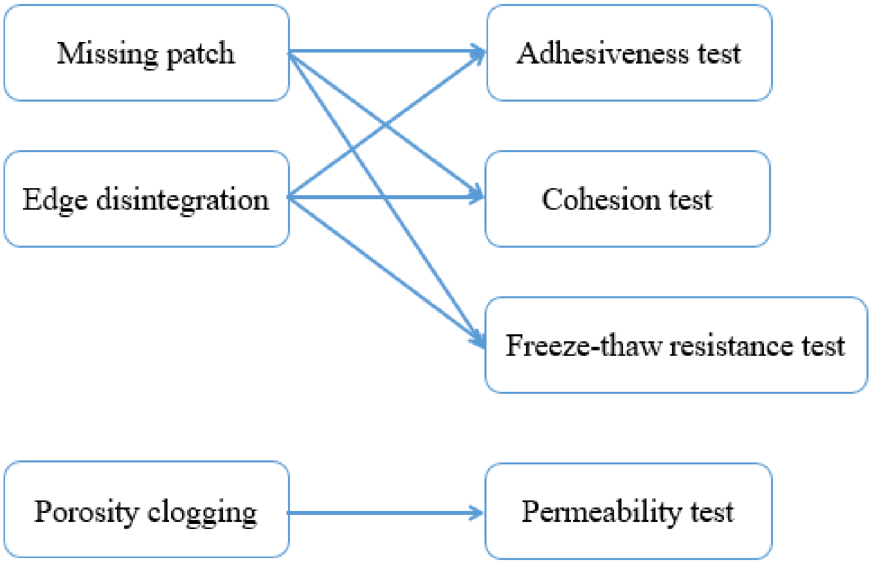


Figure 3-2 Distresses and lab tests

3.2.1 Adhesiveness Test

Adhesiveness is the bond between the patching mixture, the underlying pavement, and the sides of the pothole. Loss of adhesion usually causes edge disintegration and missing patch, which were the two main distresses observed in the field survey. For the traditional "throw-and-roll" pothole repair procedures, no tack coat was applied before patching. The adhesiveness of the patching materials plays a vital role in the bond between the patching material and original pavement. It is important to test the adhesiveness of different patching materials.

Several laboratory tests have been tried in an effort to produce a suitable procedure to evaluate the adhesiveness of patching materials. Anderson et al. (1988) proposed a shear test to evaluate the bonding strength of patching materials with old pavement, but the results were inconclusive. In another study, Virginia DOT evaluated different cold mix patching materials through coating, stripping, cohesion, adhesion and workability tests, and they recommended an adhesion test procedure for quality control of cold patching materials (Prowell & Franklin, 1996). This study adopted this method as follows: Loose mixture of 500 g was placed in a 100-mm diameter Marshall mold on top of compacted HMA with a thickness of 75-mm and compacted with 10 blows of a standard Marshall hammer. The compacted sample was extruded, and then inverted. The adhesion of the mixture was measured by the amount of time it took for the specimen to debond from the substrate HMA. The test was conducted at room temperature (25°C). Figure 3-3 shows the testing procedure.

Aquaphalt is a pre-mixed repair material, which reacts and hardens with solely water. Therefore, water curing is necessary for Aquaphalt. Before compaction, water was added in the loose mixture. An adhesiveness test was performed 15 mins after the compaction. Water accounted for 10% of the mass of the mixture. To make the comparative analysis, adhesiveness tests of all three patching materials were performed 15 mins after compaction.

(a) Weighing materials (b) Sample compaction

(c) Measuring the Time (d) Weighing the Remnants

Figure 3-3 Procedure of adhesiveness test

3.2.2 Cohesion Test

The cohesion test, also called the rolling sieve test, measures the cohesion or the bonding inside the materials. It was developed by the Ontario Ministry of Transportation to evaluate the cohesion and durability of stockpiled patching materials and then revised by AASHTO TP-44-94 (Maher, Gucunski, Yanko, & Petsi, 2001; Prowell & Franklin, 1996; Thomas & Anderson, 1986). In this study, the sealed loose cold mixes and the Marshall mold were put in a refrigerator at 4°C for 12 hours. A 1000 g cold-mix was then put into the mold and compacted 5 times on each side with the Marshall hammer. The extruded sample was placed in a 30.5 cm diameter full height sieve with 25.4 mm (1 in.) openings. A cover was placed on the sieve and the sieve was rolled back and forth on its side approximately 550 mm (22 in) for 20 cycles. Recommended test time for this test are approximately 20 seconds (Tam, 1987). The sieve remained in this position for ten seconds. Then, the material loss was calculated by weighing the material retained on the sieve. The percentage of materials retained on the sieve was calculated as a measure of cohesion of the mixture. A higher percentage indicates a more cohesive material. The Ontario Ministry of Transportation recommended a minimum percentage retained of 60% for adequate cohesion in a cold mix. One limitation of this test is that it only indicates the cohesion at low temperature. The pavement surface temperature could be much higher than 4°C even in winter with direct sunlight. Thus, in this study the test was performed at room temperature (25°C) with different compaction times to investigate the cohesion at moderate temperature. Figure 3-4 shows the testing procedure.

(a) Prepare specimens (b) Rolling sieve (c) Percent of retained

Figure 3-4 Procedure of cohesion test

3.2.3 Moisture Susceptibility Test

Statistical analyses indicated that the times of freeze-thaw cycling was a significant factor for the deterioration of pothole patching. Freeze-thaw resistance, which is the capability of the patching mixture to withstand the expansion of ice resulting from freeze-thaw cycles, plays a vital role in the durability of patching mixture.

According to ASTM D4867, the moisture susceptibility test with a freeze-thaw cycling was conducted to evaluate the freeze-thaw resistance of patching materials. The fresh loose cold mix using cutback asphalt could not be compacted into specimens. In order to add stability to the mixture and simulate field conditions after several months of traffic, the cold mixtures were cured and aged before compaction in an oven at 60 °C for 96 hours (Chatterjee, White, Smit, Prozzi, & Prozzi, 2006). After curing, the cold and hot mixes were heated to 100°C and 135°C respectively to prepare 100-mm diameter Marshall specimens. For moisture susceptibility tests, specimens are usually compacted to a void content between 6 to 8 %. Chatterjee at al. (2006) found that some cold mix patching material can have 10% air content even with 200 gyration times. To simulate the actual compaction of repeated wheel loads in the field, specimens were compacted for 50 blows on each side. The air content of TDOT cold patching, EZ patching and Aquaphalt after compaction were 10.7%, 8.1% and 3.7%, respectively. The saturations were controlled between 70% and 80% as recommended by ASTM D4867. Table 3-1 summarizes the average air voids and saturation of each mixture. In Table 3-1, the saturation of Aquaphalt was 29%, because the mixture was very dense and no further saturation could be conducted.

Table 3-1. Air Void and Saturation of the Patching Materials

	TDOT patching	**EZ patching**	**Aquaphalt**
Air Void (%)	10.7	8.1	3.7
Saturation (%)	74	77	29

In accordance with ASTM D4867, the partially saturated specimens were then wrapped with two layers of plastic film, sealed into a leak-proof plastic bag, placed into a freezer at −7 °C for 20 h and then eventually immersed in a water bath at 60 °C for 24 h. During the test, the TDOT cold patching and EZ patching specimens could not withstand the 60 °C water bath and collapsed shortly after being submerged in the hot water. The low high-temperature stability was probably caused by the high air void and low viscosity. The air voids of TDOT cold patching and EZ patching were 10.7% and 8.1% respectively, much higher than that of Aquaphalt. At similar saturation level, specimens with higher air voids had higher void pressure generated by the expansion of water in the freeze-thaw cycle. Even after curing at 60°C for 96 hours, the viscosity of these cutback asphalt cold mixes might be still lower than that of the traditional HMA, and the low viscosity and cohesion caused insufficient strength of the specimen. It seemed the traditional 60°C did not apply for these cold patching mixtures. In addition, the pavement surface temperature in winter season in Tennessee is not likely to be as high as 60 °C. In the revised procedure, the water bath was changed to 25°C.

An MTS machine was utilized to test the indirect tensile strength (IDT) of both dry and conditioned specimens. The indirect tensile strength (IDT) and tensile strength ratio (TSR) can be calculated by using equation (1) and (2).

$$S_t = 2P / \pi t D \tag{1}$$

Where, S_t = tensile strength (psi);

P = maximum load (lbf);

t = specimen height immediately before tensile test (in.);

D = specimen diameter (in.).

$$TSR = (S_{tm} / S_{td})100 \tag{2}$$

Where, TSR = tensile strength ratio (%);

S_{tm} = average tensile strength of the moisture conditioned subset (psi);

S_{td} = average tensile strength of the dry subset (psi).

3.2.4 Permeability Test

Permeability is an important parameter of a pervious mixture since the material is designed to perform as a drainage layer in pavement structures. Due to the high porosity and the interconnected air voids path, Darcy's law for laminar flow is no longer applicable for pervious mixtures. In this study, a permeability measurement device and method developed by Huang et al. (Huang, Mohammad, & Chris Abadie, 1999) for drainable asphalt mixtures (similar to pervious concrete in function) were used. Figure 3-5 shows the specimen and device for the permeability tests.

Pressure transducer installed gives accurate readings of the hydraulic head difference during the test. Automatic data acquisition makes continuous reading possible during a falling head test so that the test can be conducted even at very high flow rate, such as in OGFC. The specimen is placed in an aluminum cell. Between the cell and the specimen is an anti-scratch rubber membrane that is clamped tightly at both ends of the cylindrical cell. A vacuum is applied between the membrane and the cell to facilitate the installation of the specimen. During the test, a confining pressure of up to 103.5kPa is applied on the membrane to prevent short-circuiting from the specimen's side. The top reservoir tube has a diameter of 57 mm and a length of 914 mm. The cylindrical specimen has a diameter of 152 mm and a height of 76 mm.

In this test, the falling head method was used. From the study of Huang et al. (Huang et al., 1999), hydraulic head difference vs. time curve obtained from the two pressure transducers is expressed as:

$$h = a_0 + a_1 t + a_2 t^2 \tag{3}$$

where, a_0, a_1 and a_2 are regression coefficients.

Then, differentiate equation is expressed as,

$$\frac{dh}{dt} = a_1 + 2a_2 t \tag{4}$$

where, α_1 and α_2 are regression coefficients for differential equation of head and time. Therefore, the discharge velocity is expressed as:

$$v = \frac{dQ}{A_2 dt} = \frac{A_1}{A_2}\frac{dh}{dt} = \frac{r_1^2}{r_2^2}\frac{dh}{dt} \tag{5}$$

where, Q is the rate of flow, A_1 and A_2 are the cross section areas of upper cylindrical reservoir and the specimen, r_1 and r_2 are the corresponding radius of upper cylindrical reservoir and the specimen.

Figure 3-5 Permeability test setup and sample

3.3 Performance Test Results

3.3.1 Adhesiveness Test

Figure 3-6 shows the adhesion time of different mixes. The adhesion times of the original group and the cured group were consistent (except TDOT cold patching). Since the high temperature accelerated the volatilization of the dilution in the mixture, cured cold mixes had much higher adhesiveness than the original cold mixes, so in this study, the adhesion time after curing improved significantly. Curing has no effect on the adhesion property of EZ patch. For Aquaphalt, the adhesion time before and after curing was the longest among three materials; however, the process of curing did not show any effect on the adhesive property.

Figure 3-7 shows the weight of the materials remained on the bottom of the pile after the test. It seems that very little TDOT cold patching and EZ patching materials remained in contrast to the Aquaphalt materials.

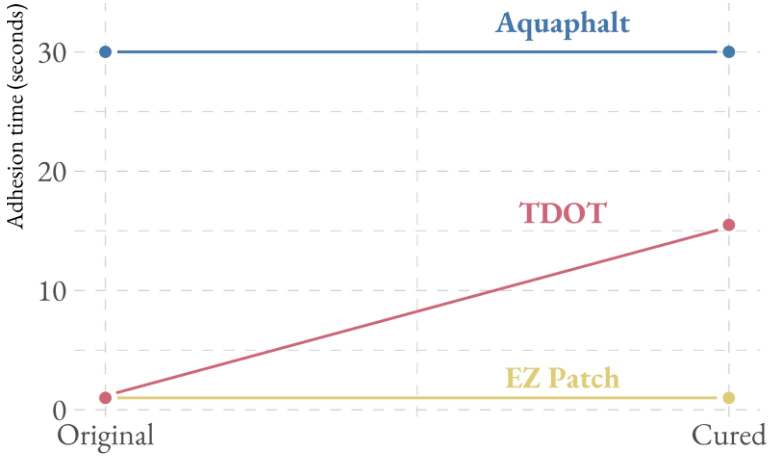


Figure 3-6 Comparison of repair materials in original and cured HMA

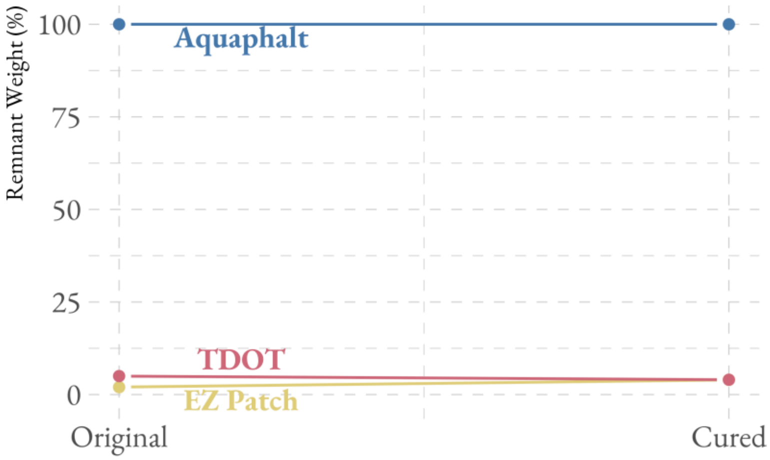


Figure 3-7 Remnant weights of patching materials

3.3.2 Cohesion Test

Figure 3-8 shows the cohesion test results expressed as the percentage of materials retained on the 25mm sieve. Generally, Aquaphalt had the highest percentage of material retained, followed by the TDOT cold patching then the EZ patching.

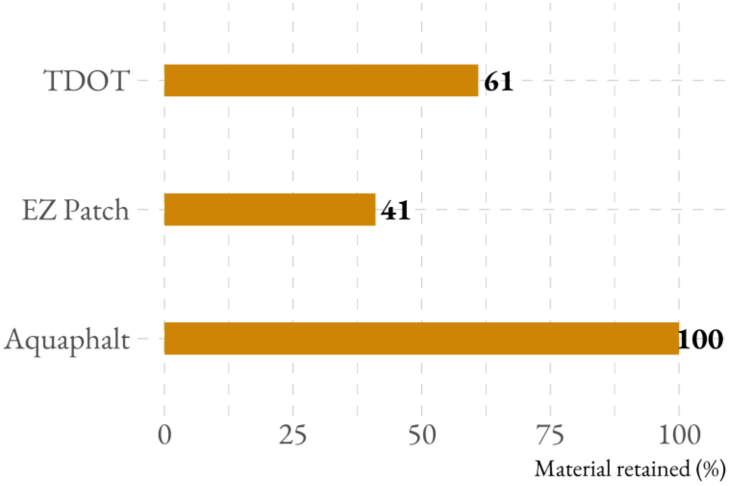


Figure 3-8 Results of cohesion test

The tested specimens can be classified into good, moderate and poor conditions as shown in Figure 3-9. A good specimen had little materials loss, whereas a moderate specimen had some material loss but still maintained its geometric shape. A poor specimen basically fell apart during the test and usually had less than 60% of material retained. During the test, the EZ patch specimens tested at 25°C were classified as poor condition after testing.

(a) Good (a) Moderate (c) Poor

Figure 3-9 Cohesion test samples

3.3.3 Moisture Susceptibility Test

Figure 3-10 shows the indirect tensile strength of mixtures before and after the freeze-thaw cycle. As indicated, Aquaphalt had highest indirect tensile strength among the three-cold mixes, followed by TDOT cold patching then EZ Patch, mainly because the air voids of TDOT cold patching and EZ patching are higher than that of Aquaphalt. Figure 3-11 shows the TSR test results of different mixes. EZ patching shows the highest TSR value. However, its indirect tensile strengths before and after curing were the smallest of the three materials.

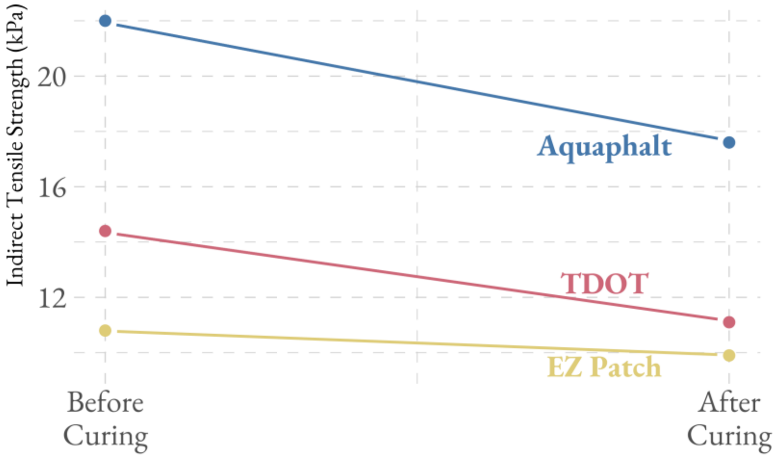


Figure 3-10 Indirect tensile strengths before and after freeze-thaw cycle

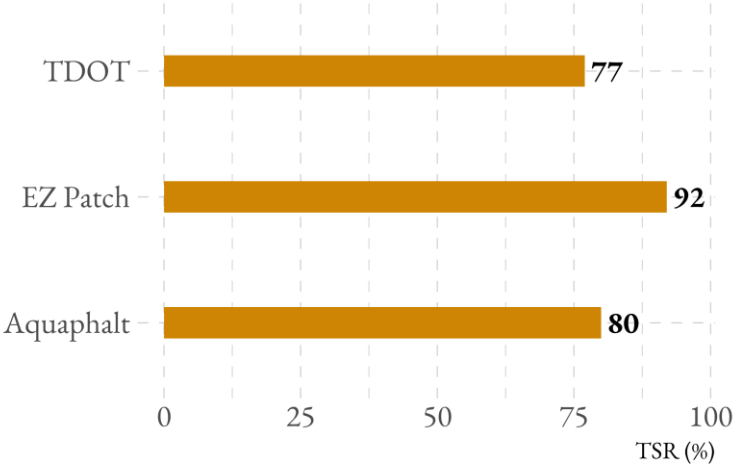


Figure 3-11 TSR of different mixes

3.3.4 Permeability Test

Figure 3-12 shows the permeability test results of the three patching materials. It seems that although Aquaphalt shows the best adhesiveness property, cohesion property and the largest indirect tensile strength, the permeability value is zero. Therefore, Aquapahlt may not be a suited patching material for OGFC in terms of permeability.

For TDOT cold patching and EZ patching, the permeability showed just a slight difference.

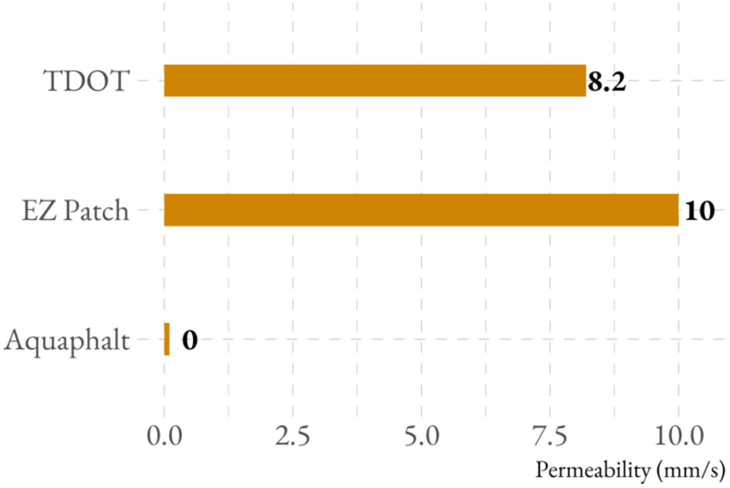


Figure 3-12 Permeability test result

3.4 Selection of Patching Material based on test results

The laboratory tests of the performance of different patching materials gave the following conclusions:

- TDOT cold patching material and Aquaphalt showed a sufficient adhesiveness.
- Cohesion test results showed that Aquaphalt presented the best cohesion performance, followed by TDOT cold patching then EZ patching.
- EZ patching material showed the best freeze-thaw resistance ability.
- Permeability test results showed that TDOT cold patching material and EZ patching material presented similar results. Aquaphalt was nearly waterproof, indicating that it may not be used as OGFC patching material in terms of permeability.

Based on the permeability results, TDOT cold patching material and EZ patching material may be used as the patching materials in OGFC pavement to ensure the adequate permeability. However, the mediocre adhesiveness performance of EZ patching material may restrict its application in OGFC maintenance. In addition, compared to TDOT cold patching material, EZ patching material is expensive. Therefore, TDOT cold patching material was selected as the patching material for the next portion of this study. Compared to the other two patching materials, one disadvantage of TDOT cold patching material is its lower TSR value, which may later transform into high moisture susceptibility. To overcome this issue and further improve its mechanical performance, TDOT cold patching material was modified by adding fast setting cement. Then, indirect shear strength tests, freeze-thaw tests, and permeability tests were conducted again on the modified patching material as discussed in the following portion.

3.5 Tests of the Modified TDOT Patching Material

Fast setting cement in this study satisfies the requirements of ASTM C1600/C1600M, which was used to modify the TDOT cold patching material to improve the strength and moisture damage resistance. To identify the optimum dosage, cement was manually mixed with patching material in mass content of 0%, 3%, 6% and 9%. The moisture susceptibility test and permeability test were conducted using the same procedure shown in Section 3.2.

3.5.1 Moisture Susceptibility Test

Figure 3-13 shows the indirect tensile strength of the three types of samples. It can be observed that adding cement could increase the tensile strength, and the effect is especially significant for 3% and 6% cement addition. The strength increase may be caused by the cement hydration, which increased the bonding strength between asphalt and aggregates. When comparing the dry and freeze-thaw condition, the samples after the freeze-thaw damage did not experience the strength loss except the sample without cement, indicating that cement could increase the freeze-thaw damage resistance.

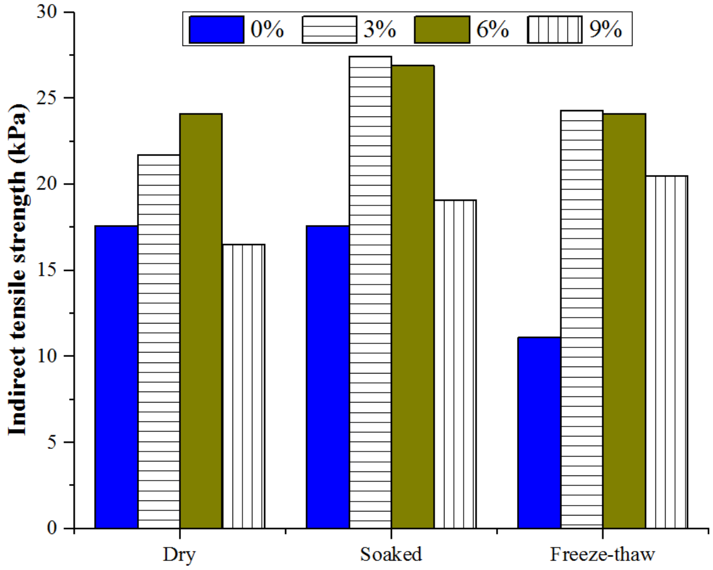


Figure 3-13 Indirect tensile strength

Figure 3-14 shows the results of the TSR, which has been commonly employed as indicator for susceptibility. It can be clearly observed that adding cement could significantly improve the moisture damage. Adding 3% of cement can improve the TSR value from 62% to 83% for the specimens after the freeze-thaw damage, whereas adding more cement will not further increase the TSR value significantly. Weighing the gained tensile strength by adding more cement and the extra cost caused, 3% of cement was proposed to add into patching material to improve its performance.

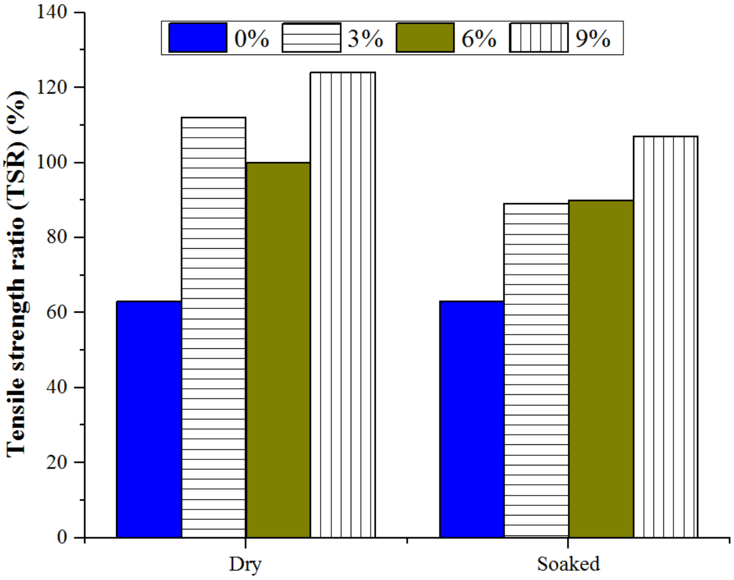


Figure 3-14 Tensile strength ratio

3.5.2 Permeability Test

A series of permeability tests were conducted for the soaked specimens. As shown in Figure 3-15, adding 3% of cement only negligibly reduces the permeability (< 3%), while adding 6% of cement causes around 10% of reduction in permeability. For the patching material modified by adding 9% of cement, the permeability decreased up to 25%.

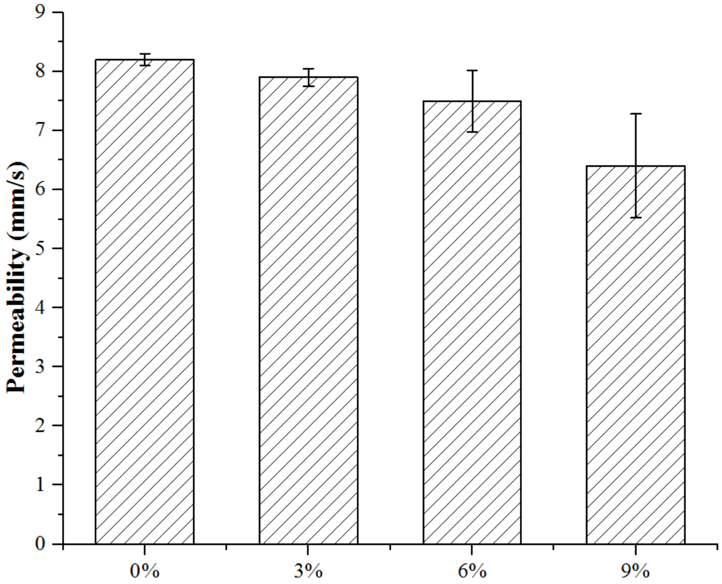


Figure 3-15 Permeability test results

3.6 Conclusions

In this section a series of performance tests on three types of patching materials were conducted to investigate the performance of adhesiveness, cohesion, moisture susceptibility, and permeability. Following conclusions were drawn based on the test results:

- Three patching materials, TDOT cold patching material, Aquaphalt, and EZ patching material, showed varied performance characteristics during the performance tests.
- TDOT cold patching material was recommended as the preferred patching material in OGFC pavement by considering the performance in mechanical, permeability, adhesiveness, and cohesion.

- 3% of cement content was suggested to add into the TDOT cold patching material to improve the indirect shear strength and moisture damage resistance.
- In modifying the TDOT cold patching material, when less than 6% of cement was added, the resulting patching materials had less than 10% of reduction in permeability. Beyond 6% of cement, the modified patching materials could experience a significant reduction in permeability and may cause clogging of the OGFC surface.

CHAPTER 4 LABORATORY PERFORMANCE EVALUATION OF OGFC TREATED WITH FOG SEAL

4.1 Introduction

OGFC is a special type of asphalt mixture characterized by the use of high quality open-graded aggregate to obtain: (1) high air void content and (2) coarse granular skeleton that develops stone-on-stone contact (Song, Shu, Huang, & Woods, 2015, 2016). As shown in Figure 4-1, because of these structure characteristics, OGFC provides many benefits including rapid water drainage, noise reduction, improved skid-resistance, better visibility in rainy days, and reduced urban heat island effect (Alvarez et al., 2011; Alvarez et al., 2006; Huber, 2000; R. B. Mallick et al., 2000).

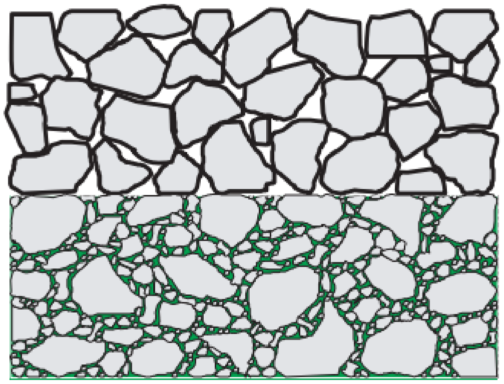


Figure 4-1 Illustration of OGFC pavement with dense HMA base (J.-S. Chen & Huang, 2010)

Despite these benefits, there are also challenges concerning the use and maintenance of OGFC. Raveling, cracking, and stripping are the common forms of distress on OGFC pavements (Cooley Jr et al., 2009; Kline, 2010).

Raveling is defined as the loss of aggregates at the surface of pavement caused by repeated abrasion from traffic and often aggravates with the exposure to moisture (Hernandez-Saenz, Caro, Arámbula-Mercado, & Martin, 2016). Raveling in OGFC pavements can spread rapidly and accelerate the appearance of other distresses that degrade the pavement condition, and thereby increases maintenance cost and affects the pavement serviceability (Cooley Jr et al., 2009; Kline, 2010). Many factors have been reported to associate with raveling, such as binder aging, moisture damage, and insufficient binder content.

To retard raveling developing, the fog seal has been a typical treatment. Fog seals are placed primarily to seal the pavement, inhibit raveling, enrich the aged asphalt binder, and provide some pavement edge-shoulder delineation. Fog seals are a light application of diluted asphalt emulsion directly on the pavement surface with no aggregate. Fog seals have been used as one of the preventative maintenance techniques for many years (Prapaitrakul, Freeman, & Glover, 2005). The purpose of fog sealing is to improve aggregate retention, rejuvenate the existing binder, and thus extend the pavement service life (Johanns & Craig, 2002). In general, fog seals are composed of asphalt emulsion, water, and rejuvenator, in which the rejuvenator agent is used to revitalize the aged asphalt and thus extend the service life of pavements. To seal off the surface, fog seals must penetrate the voids of the pavement surface. Therefore, the viscosity of fog seals is usually very low so that it does not break before penetrating the surface voids. However, due to the unique structural characteristics of OGFC, concerns have been raised on applying fog sealing to treat the surface of OGFC pavements. Although fog sealing provides some benefits, the issues accompanied also demand close attention. Fog seals may fill the surface voids and decrease the permeability of OGFC (Prapaitrakul et al., 2005). On the other hand, fog seals may temporarily reduce the surface friction of OGFC and hence impair driving safety (Estakhri & Agarwal, 1991). To optimize the performance of fog seals on OGFC, a better understanding of its application procedures is necessary.

4.2 Experimental Program

4.2.1 Materials and core samples

In this study, the fog seals selected for OGFC treatment was a cationic asphalt emulsion containing a rejuvenator agent, which can potentially replace water on the surface of aggregates or aged asphalt films, and thus enhance the durability of OGFC (Prapaitrakul et al., 2005; Shatnawi & Toepfer, 2003).

A test section at the eastbound of I-40 in west Tennessee was selected as the field project. The thickness of the original OGFC layer was approximately 3.2 cm (1.25 in). A total of 24 cores with a diameter of 15.2 cm were taken before and after applying the fog seals, with 12 from the pavement shoulder and 12 from the traffic lane, as shown in Figure 4-2. The length of the section treated with fog sealing was about 300 m. On the pavement shoulder, two different application rates (0.59 l/m^2 and 0.36 l/m^2) were used, while only one was used on the traffic lane (0.45 l/m^2). Figure 4-3 schematically shows the application of fog seal and the locations of the cores. Figure 4-4 shows the OGFC pavements before and after the fog sealing treatment. It was around 1.5 hours between the fog sealing treatment and coring to let the asphalt emulsion break adequately.

Figure 4-2 OGFC cores with and without fog seal treatment

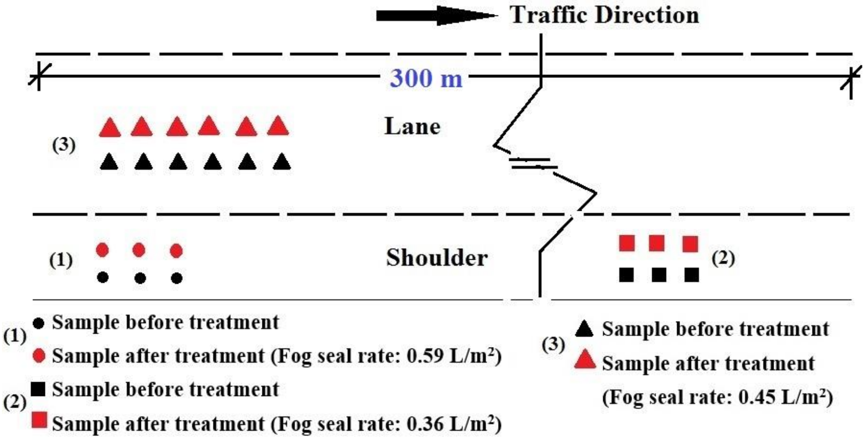


Figure 4-3 Schematic diagram of fog seal application and core locations

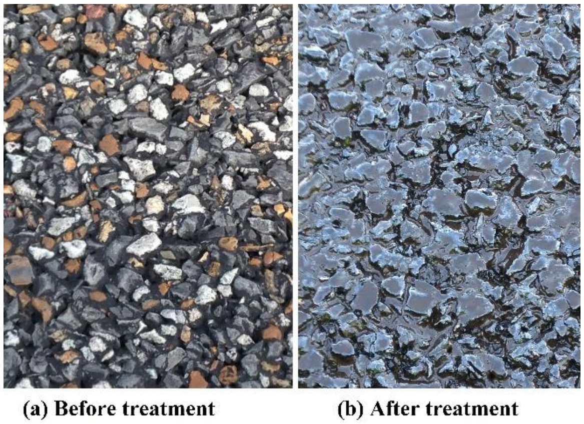

(a) Before treatment (b) After treatment

Figure 4-4 OGFC pavements before and after fog seal treatment

4.2.2 Permeability Test

High permeability is an important function of OGFC, which allows water to drain off the pavement surface quickly, and thus significantly improves drivers' visibility in rainy days. Because the OGFC layer of the field project was only 3.2 cm thick and highly porous, it is hard to maintain the integrity of the OGFC layer when cutting cores. To avoid this issue, a new permeability test was developed (Figure 4-5 and Figure 4-6). During the test, the upper part of an OGFC specimen with a thickness of 2.2 cm was sealed by a membrane and the rest was left open for water flow. A plastic tube with a length of 87 cm was used to provide water head. The time required for the water in the standpipe to drop from the top to the bottom was recorded and then used to calculate the permeability.

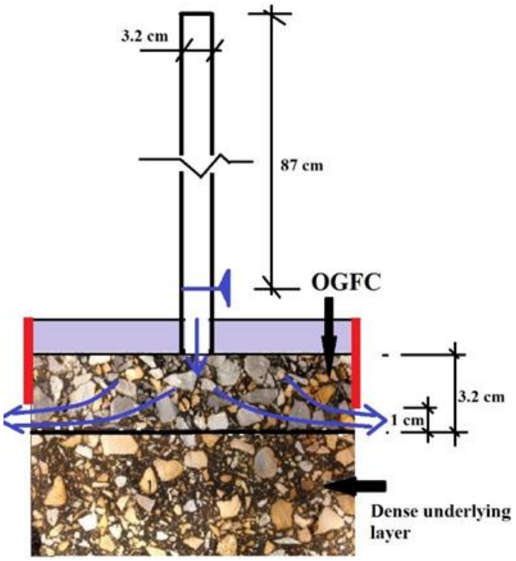


Figure 4-5 Schematic diagram of the permeability test

Figure 4-6 Permeability test setup

4.2.3 Texture Depth Test

Texture depth is an essential parameter to OGFC due to its direct relation to skid-resistance performance, which especially affects driving safety on rainy days. A bigger percent of air void allows faster water drainage while a higher macrotexture depth increases skid resistance, which leads to improved traffic safety under wet weather (Roque, Koh, Chen, Sun, & Lopp, 2009). In this project, the macrotexture depths of the OGFC surface were tested using the sand patch method as per ASTM E 965 (Figure 4-7). The average surface macrotexture depth is the ratio of a known volume of sand material to the total area covered. The method is suitable for the bituminous surface course and the concrete pavement surface with a texture depth greater than 0.25 mm. The test was conducted in triplicate.

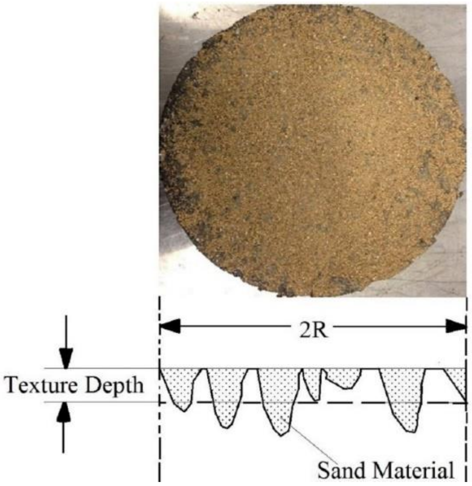
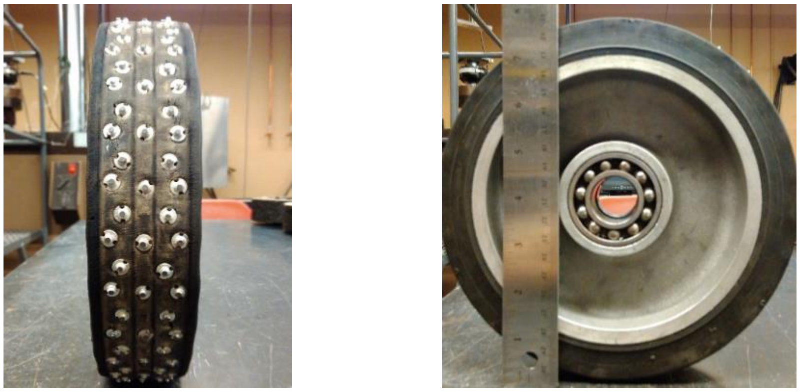


Figure 4-7 Texture depth test setup (Song et al., 2015)

4.2.4 Loaded Wheel Abrasion Test

The loaded wheel tester (LWT) is a device originally designed to evaluate the rutting susceptibility of asphalt mixtures by rolling a small loaded wheel device repeatedly across a prepared asphalt mixture sample (Collins, Shami, & Lai, 1996). This equipment can also be used to evaluate the rutting, fatigue, moisture susceptibility, and stripping of pavements. There are several types of LWT, among which the Asphalt Pavement Analyzer (APA) is most widely used (Cooley, Kandhal, Buchanan, Fee, & Epps, 2000). The APA provides controllable wheel loads and contact pressures to simulate field conditions (Kandhal & Cooley, 2003; Skok, Johnson, & Turk, 2002), and thus can be used to test the abrasion durability of OGFC under traffic loads. Previous studies from the research team have successfully demonstrated the efficacy of the equipment on evaluating the abrasion resistance of pervious concretes (Dong, Wu, Huang, Shu, & Wang, 2012; Wu, Huang, Shu, & Dong, 2010), with a load of 890 N on each wheel to provide the impacting and abrasive forces on specimens.

In this study, APA was utilized to measure the abrasion resistance of OGFC cores before and after applying fog sealing. To make the abrasion loss more significant, steel studs (2 mm in diameter and 3 mm in height) were embedded into the originally smooth rubber surface, as shown in Figure 4-8. The introduction of studs can better simulate the tires' abrasion action on the surface of OGFC pavements, and thus more realistically simulate the raveling failure of OGFC pavements.



(a) Side view (b) Front View

Figure 4-8 Studded rubber wheels for abrasion test

Through the APA, the repeated wheel loads were applied to the cores by two moveable loaded wheels (Figure 4-9). Prior to testing, the original cores taken from the field were cut to fit into the specimen holder, which has a dimension of 75 mm in height and 152.4 mm in diameter. Before weighing the samples, the surfaces of the OGFC cores were cleaned by a steel brush to remove loose aggregate particles. Subsequently, the samples were placed into the APA and subjected to 12000 cycles of repeated loads at a frequency of 2 cycles/second. A wheel load of 800 N was applied to provide a sufficient impacting and abrasive force to the specimens, which was chosen through multiple trial tests. The weight loss after the LWT abrasion testing was used to evaluate the effect of the fog seal treatment, which was calculated as a percentage using Eq. (1):

$$WL = \frac{W_1 - W_2}{W_1} \times 100 \tag{1}$$

where WL = weight loss (%); W_1 = initial sample weight (g); W_2 = final sample weight (g).

Figure 4-9 LWT abrasion test

4.3 Discussion of Results

4.3.1 Permeability Test

Figure 4-10 shows the results of the permeability test in boxplots. When applying no fog seal, the permeability time of the cores taken from the lane was lower than that of the cores from the shoulder, indicating that fast-moving traffic helped keep the pores from clogging with debris (Program, Highway, Officials, & Advanced Asphalt Technologies, 2011; Zoorob, Collop, & Brown, 2002). It also revealed that the pores in the shoulder had concerns of clogging over the long term. The test results also showed that applying fog seals decreased the permeability for both the lane and the shoulder. As the application rate of the fog seals increased, the permeability time slightly increased for the cores obtained from the shoulder, indicating that more pores were clogged due to more residual asphalt from the fog seal application.

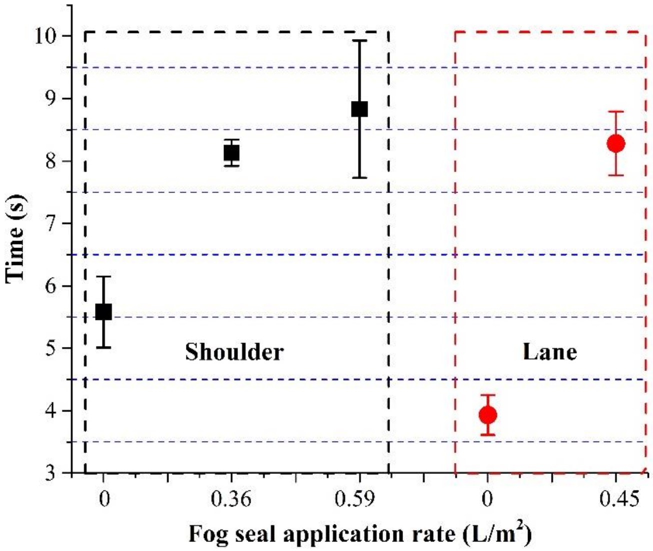


Figure 4-10 Results of the permeability test

4.3.2 Texture Depth Test

Figure 4-11 shows the macrotexture depths of the cores. The average macrotexture depths of OGFC in the shoulder and the traffic lane were 0.308 mm and 0.357 mm respectively before the fog seal application, which agreed well with the values found in the literature (Flintsch, de León, McGhee, & AI-Qadi, 2003; Wang & Flintsch, 2007). As shown in Figure 4-11, fog seals decrease the macrotexture depth as both the cores from the traffic lane and the shoulder indicate. As the rate of application increased, a further reduction in the macrotexture depth was observed for the cores obtained at the shoulder.

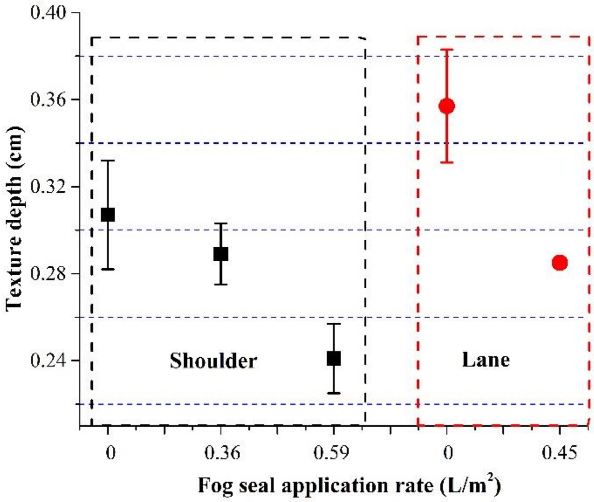


Figure 4-11 Texture depth results

4.3.3 Loaded Wheel Abrasion Test

Figure 4-12 shows the specimens after the LWT abrasion test, and Figure 4-13 presents the results of the loaded wheel abrasion test. Clearly, when applying no fog seal, the abrasion loss was about 0.8% for the shoulder, and the fog seals used significantly reduced the abrasion loss. In the traffic lane, when applying fog seals at a rate of 0.45 l/m^2, the abrasion loss was only about 0.5%, while the average abrasion loss reached 1% for samples without fog seal. The weight loss due to abrasion was reduced by about 50% after applying the fog seal.

Specimens without fog seal **Specimens with fog seal**

Figure 4-12 Cores after loaded wheel abrasion test

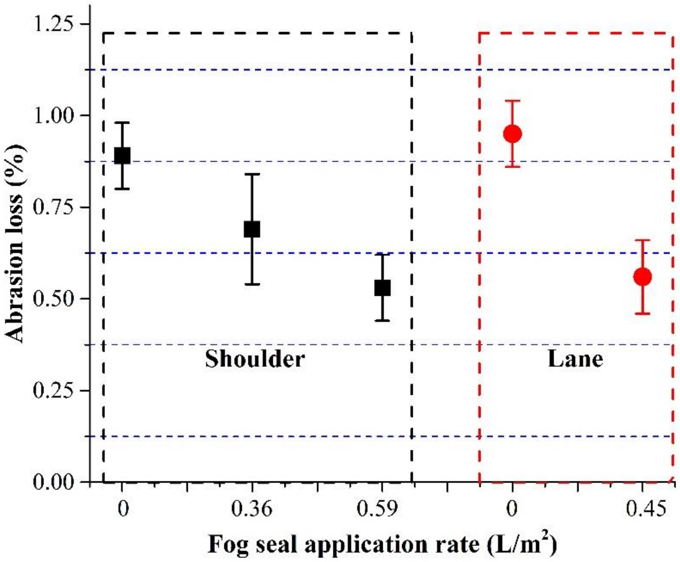


Figure 4-13 Results of loaded wheel abrasion test

4.3.4 Texture Depth after Abrasion Test

After the LWT abrasion test, the macrotexture depth of the cores with fog seal was measured again to evaluate the effect of traffic on pavement texture depth. Figure 4-14 compares the texture depth before and after the LWT abrasion test. It can be seen that the texture depth increased after the LWT abrasion test, indicating that the reduced texture depth of OGFC due to applying fog seals could be restored by abrasion. This situation also implies that although fog sealing reduced skid resistance of OGFC pavement, it could be restored by moving vehicles after opening to traffic.

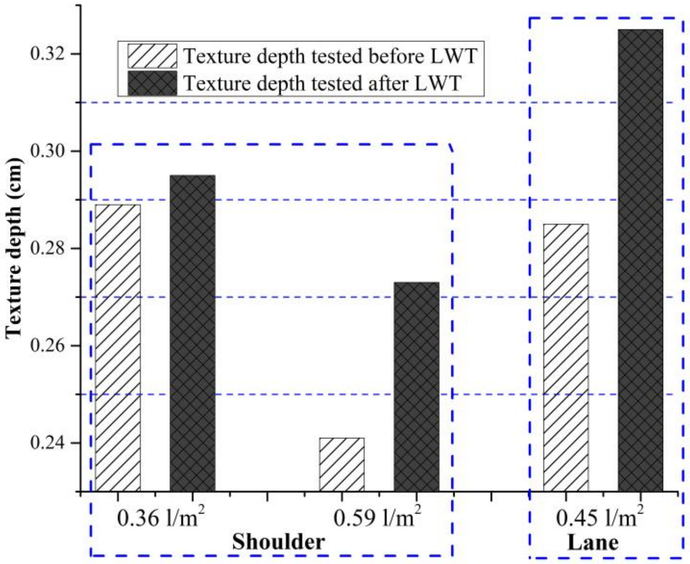


Figure 4-14 Comparison of texture depth before and after abrasion test

4.4 Conclusions

In this chapter, multiple laboratory tests were conducted to evaluate the effect of fog sealing on the performance of OGFC pavements. Before and after fog sealing, core samples were taken from both the traffic lane and the shoulder of the field project. The permeability test, the texture depth test, and the loaded wheel abrasion test were performed to compare the performance of OGFC pavements before and after fog sealing. Based on the results of laboratory tests, the following observations were made:

- When using no fog seal, the cores obtained from the traffic lane had higher permeability than those from the shoulder. Applying fog seal decreased the permeability for both the lane and the shoulder. Increasing the fog seal application rate would further reduce the permeability.
- Fog seals decreased the macrotexture depth of cores from both the lane and the shoulder. As the fog seal application rate increased, a further reduction in the macrotexture depth was observed.
- The application of fog seal significantly reduced the abrasion loss, indicating that it could increase the durability of OGFC pavement. The abrasion loss was reduced by about 50% for the cores in the traffic lane after fog sealing.
- After the abrasion test, the reduced macrotexture depth of samples with fog sealing was partially restored, indicating that although fog sealing decreased the skid resistance of OGFC, it could be partially restored after opening to traffic.
- The tests conducted primarily focused on the laboratory performance of fog seal treated OGFC cores. More studies on evaluating the field performance of OGFC pavements using fog sealing are recommended, which will help better understand the effects of fog sealing on OGFC maintenance.

CHAPTER 5 PERFORMANCE EVOLUTION OF OGFC PAVEMENT BASED ON FIELD DATA

In this chapter, the performance data of OGFC pavements were collected and analyzed from previous studies conducted by TDOT and other state highway agencies.

5.1 Data Analysis from Other DOTs and Agencies

5.1.1 Friction Measurement

The OGFC pavement friction data were collected in I-20, US 61, and US 171 by researchers in Louisiana Transportation Research Center (LTRC) (Abadie, 2013). Correspondingly, the friction was also measured on SMA pavements (I-10) and Superpave pavements (US 190 and US 171). Project information about the six test sections was shown in **Table 5-1**, and Figure 5-1 shows the friction numbers of the six test sections. Overall, as can be observed from Figure 5-1, OGFC shows a higher friction number than the dense-graded counterparts. Among them, the OGFC section in I-20 has the highest friction number even after 5 years of service.

Table 5-1. Information of the six test sections

Test section	Mix type	Length (miles)	Year constructed	Year tested	Traffic records	
					ADT (year)	Percent of truck
I-20	OGFC	5.6	2005	2010	38,000 (2010)	18
US 61	OGFC	5.6	2007	2010	25,500 (2010)	13
US 171	OGFC	4.3	2009	2010	7,650 (2010)	12
I-10	SMA	3.7	2009	2010	32,341 (2010)	17
US 190	Superpave	4.7	2008	2010	17,200 (2010)	14
US 171	Superpave	6.5	2009	2010	9,140 (2010)	6

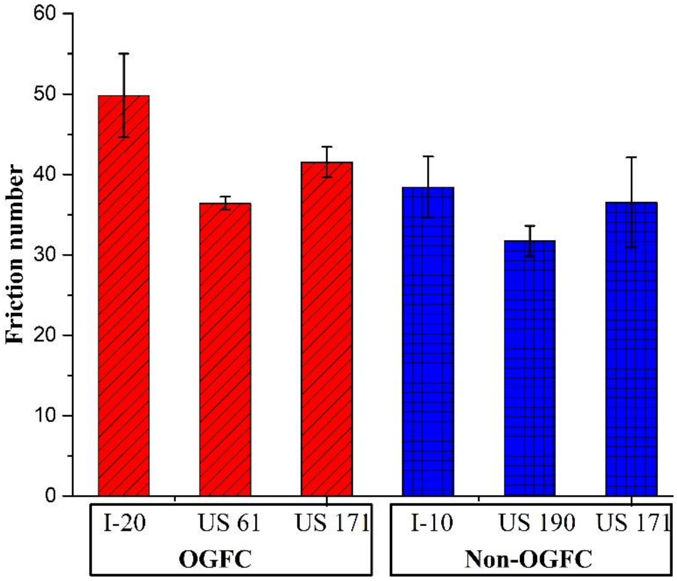


Figure 5-1 Friction number of six sections

The texture depth of OGFC (PFC) was recorded in I-74 east of Indianapolis (McDaniel, 2010). The long-term performance of OGFC was compared with the SMA and dense graded hot-mix asphalt (DGHMA). From Figure 5-2, it can be observed that the texture depth of OGFC was larger than those of SMA and DGHMA. In addition, the texture depth of OGFC did not change significantly after more than three years of service.

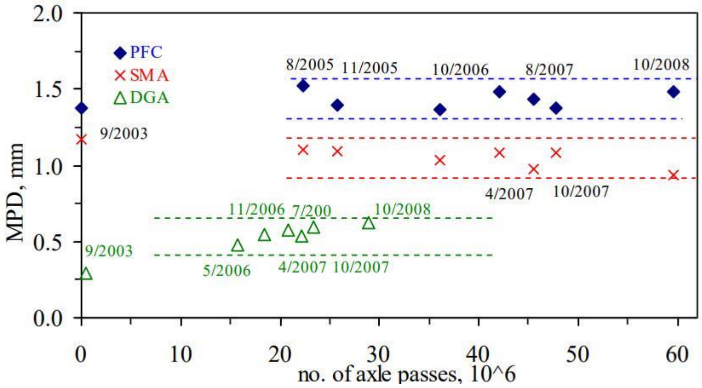


Figure 5-2 Change in texture depth, MPD: mean profile depth, in mm.

5.1.2 Rutting, International Roughness Index (IRI), and Random Cracking

In Louisiana, the rutting, IRI, and random cracking data of OGFC were collected from PMS (Abadie, 2013). To compare the performance of sections with/without an OGFC layer, the data associated with early Louisiana Superpave roadways were collected from five Interstates (15,000–60,000 ADT) and four US routes (8,000–25,000 ADT, constructed in the late 1990s) (Kabir, Icenogle, King Jr, & Abadie, 2011). Since the construction and survey data for the OGFC and Superpave pavements were different, to show the developing trend of performance clearer, the performance indices (rut depth, IRI, and cracking) were plotted according to the same service time. Figure 5-3 shows the rutting development of OGFC, and the Interstate and US route trends were drawn using the Superpave data only. It was observed that the overall rutting performance of OGFCs was considerably better than those of the Superpave US routes.

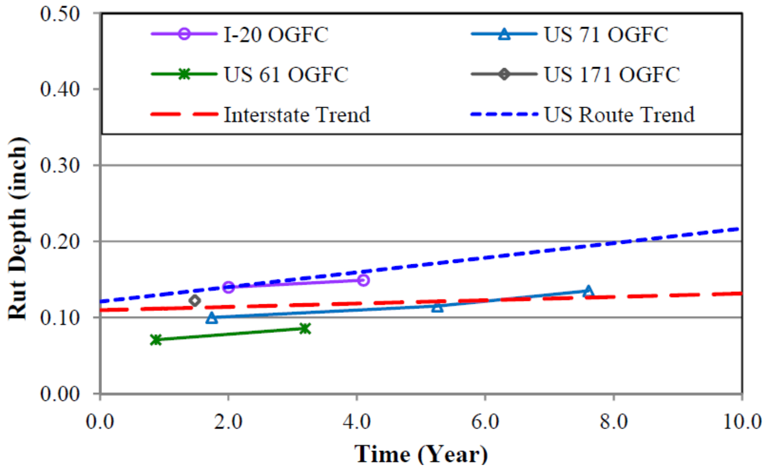


Figure 5-3 Rut depth

Figure 5-4 illustrates the developing curves of IRI. As shown below, the developing trend of the IRI of OGFC sections is similar to those of the Superpave sections. I-20 OGFC showed a slightly lower IRI value than those of the state routes, while higher IRI values were found in the OGFC section at US 71.

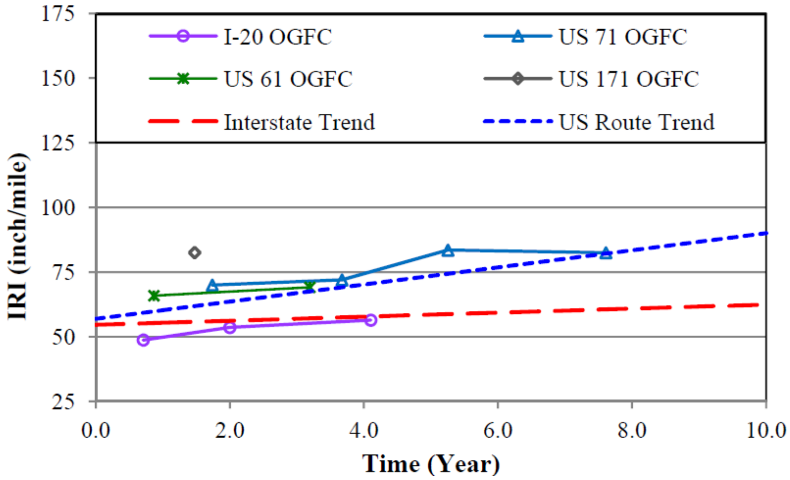


Figure 5-4 International roughness index (IRI)

The cracking data presented in Figure 5-5 represent a combination of longitudinal and transverse cracks (Kabir et al., 2011). The number of cracks in I-20 was larger than that of the Interstate trend, whereas the number of cracks in US 71 OGFC was significantly lower than that of the US route trend. The number of cracks in US 171 OGFC at the first service year were significantly larger than other test sections, which could most probably be due to construction quality variation. When considering rutting, IRI, and cracking, OGFC was found to have comparable performances with conventional Superpave mixtures.

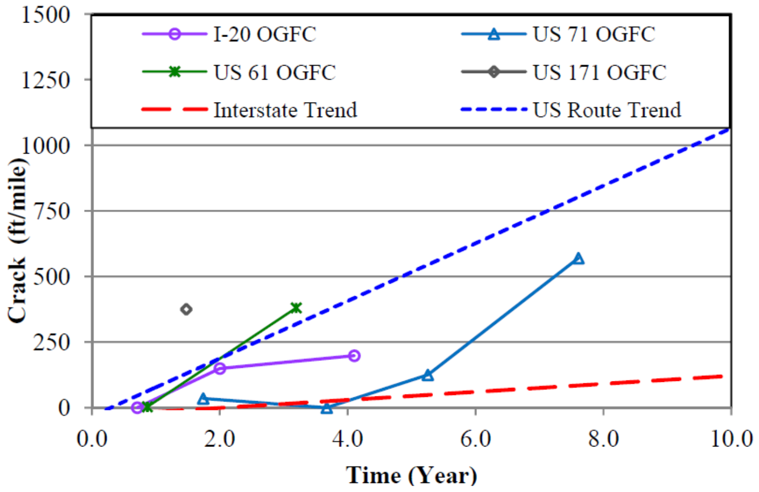


Figure 5-5 Random cracking

5.1.3 Accident rates

To investigate the effects of OGFC on traffic safety, the research team collected the accident rate data from the states of North Carolina and Louisiana.

(1) North Carolina

As reported by Durante and Johns, after 1.5 years of service compared to previous 3 years of service without OGFC (Durante & Johns, 2014), the following observations were reached:

- 14% decrease in total crashes
- 72% decrease in wet crashes
- 16% decrease in lane departure crashes
- 75% decrease in lane departure wet crashes

(2) Louisiana

The data from Louisiana were collected over a whole period of five years before and after the construction of OGFCs in US 71, I-20, US 61 and US 171 (Abadie, 2013). Based on the analysis, the following observations were made:

- US 71

  100%/year accident reduction in wet weather

  90%/year accident reduction in all weather conditions

- I-20

  76%/year accident reduction in wet weather

  42%/year accident reduction in all weather conditions

- US 61

  No reduction in wet weather and all weather conditions

- US 171

  57%/year accident reduction in wet weather

  No reduction in all weather conditions

5.1.4 Changes in Level of Noise

The changes of noise were recorded in a segment of I-74 locating in the east of Indianapolis (McDaniel 2010). It can be observed from Figure 5-6 that the OGFC (PFC) pavement had a lower level of noise in contrast to the SMA and DGHMA pavements. For the OGFC pavement, the sound pressure level (SPL) value slightly increased from June 2005 to Aug. 2008.

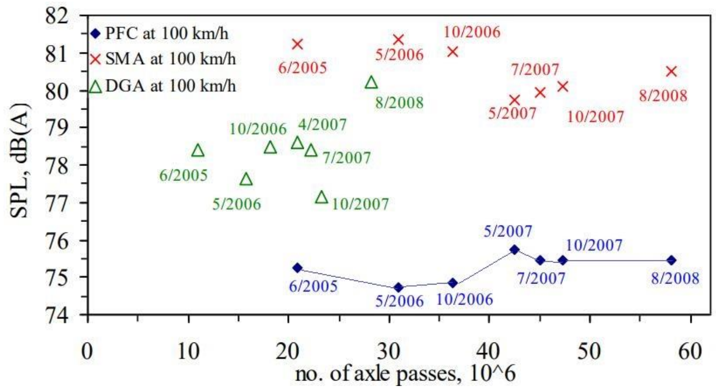


Figure 5-6 Change in noise

5.2 IRI, PDI and FN Analysis in Tennessee

Four OGFC projects in Tennessee were selected for the analysis. The performance indicators selected including IRI, pavement distress index (PDI), and friction number (FN). The Pavement Serviceability Index (PSI) was not considered as it can be directly calculated from IRI. Typically, the higher the IRI value, the worse the pavement performance can be. Usually, an intact pavement surface has IRI value around 60 in/mile (Varadhan, 2004). PDI reflects the combined severity level of multiple pavement distresses, such as cracks, rutting, and potholes. The PDI value ranges from 0 to 5, with five (5) as the best condition and 0 as the worst condition.

In addition, the friction number was used to evaluate the effect of OGFC on skid resistance. Typically, when the friction number is greater than 35, the skid resistance is considered as good. Unlike the common performance data, TDOT does not collect the friction number for cost reasons as a pavement performance index at a network level for the PMS, but some friction data at the project level could be found. Among the four investigated projects, two projects have access to the historical data of friction numbers.

The IRI data was shown in Figure 5-7. The horizontal axis in the figure is the service time of pavement. Negative values on the axis mean the years before the OGFC treatment and positive values indicate the years after treatment. It should be noted that the performance data corresponding to year 0 could be measured either before or after the treatment. It can be seen that the IRI clearly decreases after the OGFC treatment except for Section 3. Taking Section 4 as an example, the IRI before the treatment was above 60 inch/mile, whereas it was below 40 inch/mile after the treatment. For Section 3, the IRI was maintained between 40 and 50 inch/mile and the performance improvement was indiscernible. It can be concluded that for most OGFC pavements, the roughness performance was improved after the treatment. All OGFC pavements maintained an excellent level of roughness for five years of service.

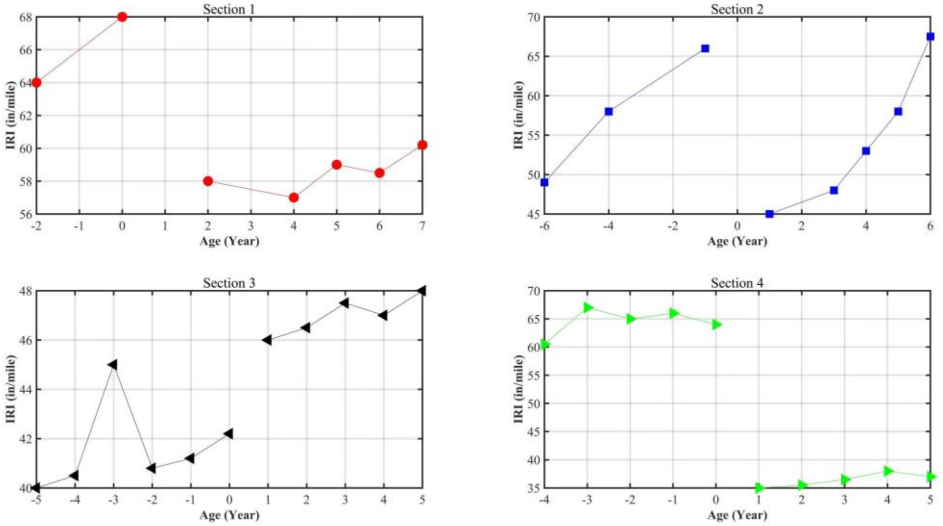


Figure 5-7 IRI of four sections

The development of PDI before and after OGFC paving was shown in Figure 5-8. According to the definition of PDI, a value of 5 indicates an intact pavement, while 0 indicates an entirely damaged pavement. As seen in Figure 5-8, the PDI values of all four OGFC sections were greater than 4 throughout their service periods after the treatment, and no discernible distress was observed.

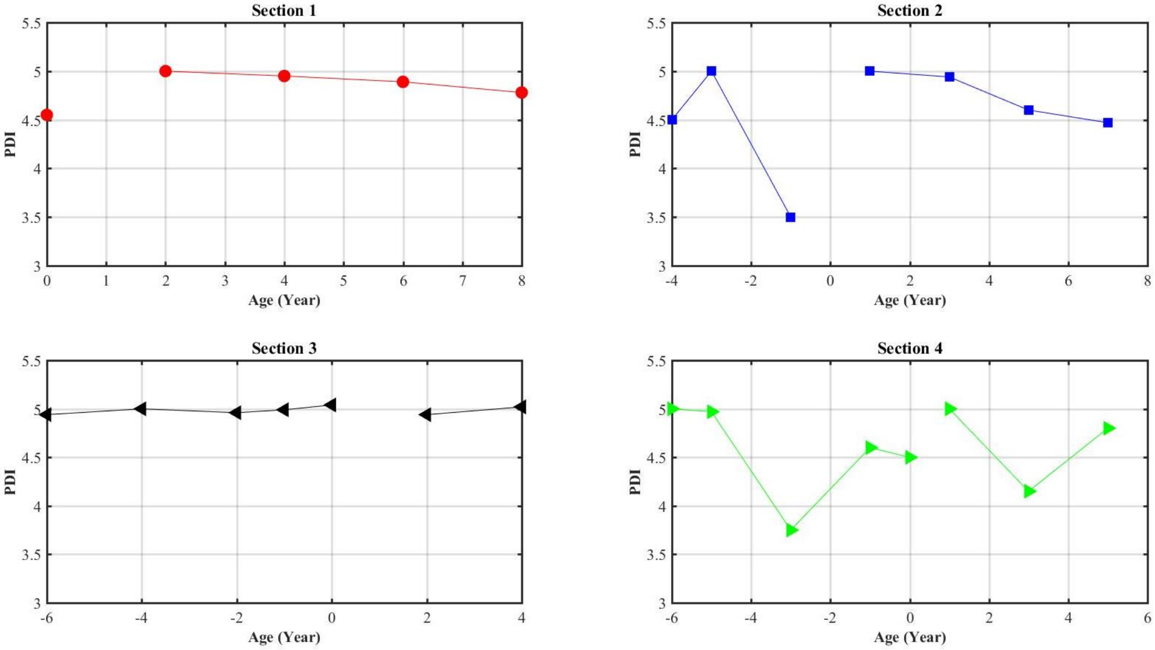


Figure 5-8 PDI of four sections

The friction numbers of Sections 1 and 4 were shown in Figure 5-9. It can be observed that the friction numbers were both greater than 35 after the treatment, indicating a good level of skid resistance for the two sections. Recent literature also revealed that the friction numbers of OGFCs are generally larger than that of the non-OGFC pavements (X. Chen, Zhu, Dong, & Huang, 2017).

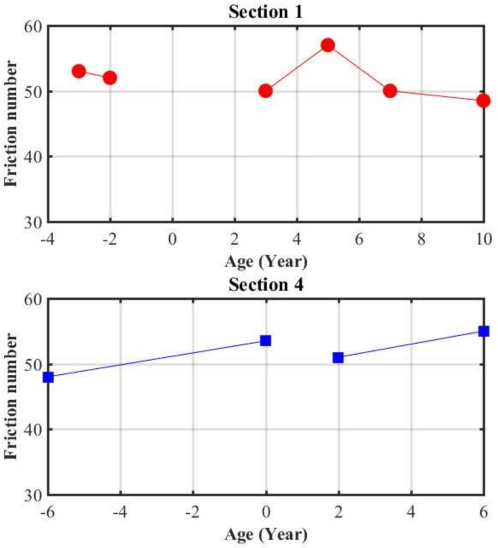


Figure 5-9 Friction number of two sections

5.3 Conclusions

The OGFC performance data from Tennessee and other state highway agencies were collected and analyzed. Several conclusions were drawn based on the analysis in this Chapter.

- OGFC pavement usually provides better friction resistance than SMA and DGHMA.
- When considering rut depth, IRI, and cracking, the OGFC sections provided comparable performance to their DGHMA counterparts.
- The accident rate and noise level observed on the OGFC sections were considerably lower than the conventional DGHMA pavements.

CHAPTER 6 EFFECTS OF PRE-TREATMENT CONDITIONS ON THE PERFORMANCE OF OGFC IN TENNESSEE

6.1 Introduction

OGFC is a special type of thin layer HMA placing on the traditional dense asphalt pavement (Song et al., 2015, 2016). The main structural feature of OGFC is its larger porosity than the traditional dense-graded asphalt. ASTM D 7064 suggests the minimal air void content in OGFC should be 18%. Because of this special structural characteristic, OGFC brings numerous benefits in terms of economy, safety, and environment (Alvarez et al., 2006). However, it also has some shortcomings, such as prone to raveling and cracking (Kline, 2010; Nielsen, 2006). Due to the high air void contents in OGFC, premium asphalt binder and aggregate are generally needed to ensure the acceptable quality of OGFC, which may lead to a higher unit cost of OGFC.

X. Chen et al. (2017) conducted cost-benefit and performance effectiveness analyses concerning the use of OGFC. Although the cost of OGFC was 42% higher than that of a dense mixture, the cost-benefit analyses based on the ratio of accident rate reduction over cost demonstrated that OGFC was significantly more cost-beneficial in improving driving safety and reducing accident rate in rainy days.

Under the traffic and environmental influences, pavements gradually degrade during service. Many forms of pavement distress will occur, such as cracking, rutting, layer debonding, etc. Pavement maintenance helps keep and extend the service life of pavements. The concept of present serviceability index (PSI) was introduced in the 1960s (Carey Jr & Irick, 1960; Hveem & Carmany, 1949). The PSI has become a standard metric evaluating the pavement serviceability for many state highway agencies. Figure 6-1 gives the development curve of PSI and the effects of maintenance or rehabilitation events on PSI. It shows that the maintenance activities help restore pavement performance and extend the pavement durability.

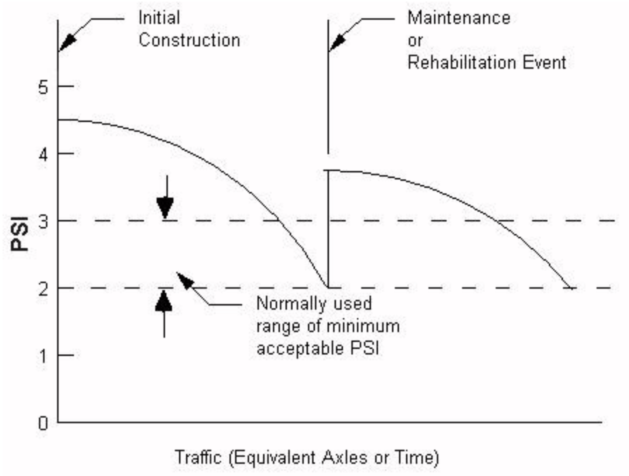


Figure 6-1 Concept of pavement serviceability index (Hveem & Carmany, 1949)

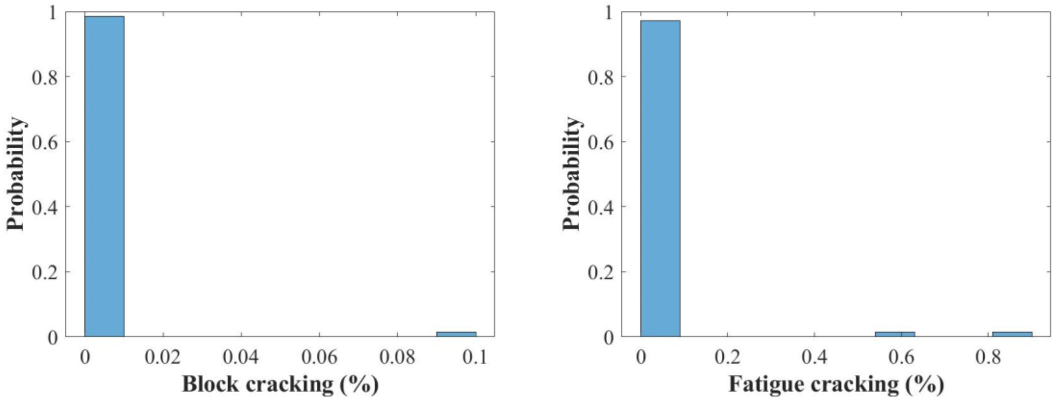
The timing for applying maintenance is critical, as it closely related to satisfactory pavement serviceability and cost-effectiveness. Hence, understanding the current distress condition of OGFC pavement is generally the first step for determining optimal maintenance strategies and timing of application.

In this chapter, the pavement distresses in OGFC pavements were first analyzed for 25 OGFC projects, then the influence of pre-treatment conditions on the service life of OGFCs was investigated.

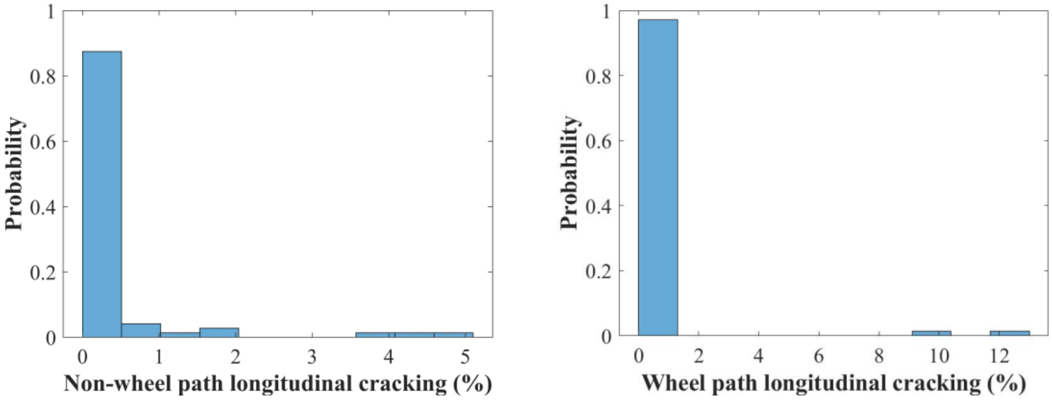
6.2 Data Collection and Distress Analysis

TDOT is responsible for the management of Interstate and State Route pavements. The interstate pavements are surveyed every year while the state routes are surveyed every two years. The collected pavement condition data are recorded in PMS.

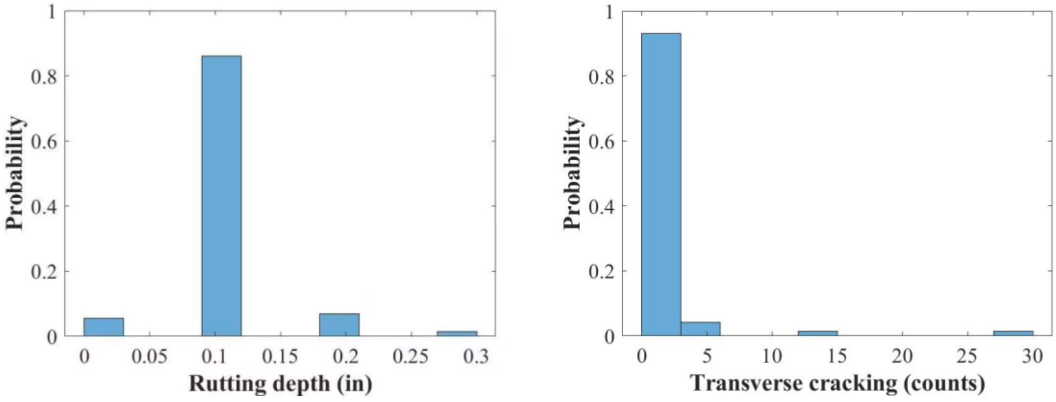
A total of 25 OGFC projects were selected in this part. The pavement distresses, including block cracking, fatigue cracking, longitudinal cracking, transverse cracking, and rut depth, were selected for analysis. Studies have shown that the condition before applying a treatment is essential to its future performance (Dong & Huang, 2011; Gong, Dong, Huang, & Jia, 2015; Mamlouk & Dosa, 2014). Figure 6-2 illustrates the distribution of the pre-treatment pavement distresses for the 25 projects. It should be noted that Figure 6-2 shows only the current distress condition of OGFCs although the construction dates of these OGFC pavements vary. Because most of the 25 OGFC pavements were constructed within the recent three years, the cracking probabilities were all at a low level while the rut depth was around 0.1 in.



(a) Block cracking (b) Fatigue cracking



(c) Longitudinal cracking (no lane) (d) Longitudinal cracking (lane)



(e) Rut depth (f) Transverse cracking

Figure 6-2 Distribution of pre-treatment conditions

Table 6-1 lists the summary statistics for pre-treatment pavement distresses. It shows that the median values of fatigue cracking, longitudinal cracking, block cracking and transverse cracking were all zero, indicating that most of the OGFC sections were free of cracking.

Table 6-1. Statistical Summary of pre-treatment conditions

Summary	Pre-treatment condition					
	Rut depth (in)	Fatigue (%)	Long. WP (%)	Block (%)	Trans. (count)	Long NWP (%)
Average	0.1	2.44	1.5	3.87	3.42	4.17
Standard deviation	0.05	7.89	3.88	20.77	9.57	9.44
Min	0	0	0	0	0	0
Max	0.32	100	88	95	98	68
Med	0.09	0	0	0	0	0
25%	0.09	0	0	0	0	0
90%	0.15	6	3	0	13	12

Notes: WP-wheel path; NWP-non-wheel path

The rut depth development and PSI are illustrated in Figure 6-3 and Figure 6-4, respectively. It can be observed that the rut depth before the 6th year was negligible. After six years of service, the rut depth increased rapidly. Since the rut depth, along with the roughness (IRI), is a primary contributing factor of PSI, there was an overall downward trend for PSI.

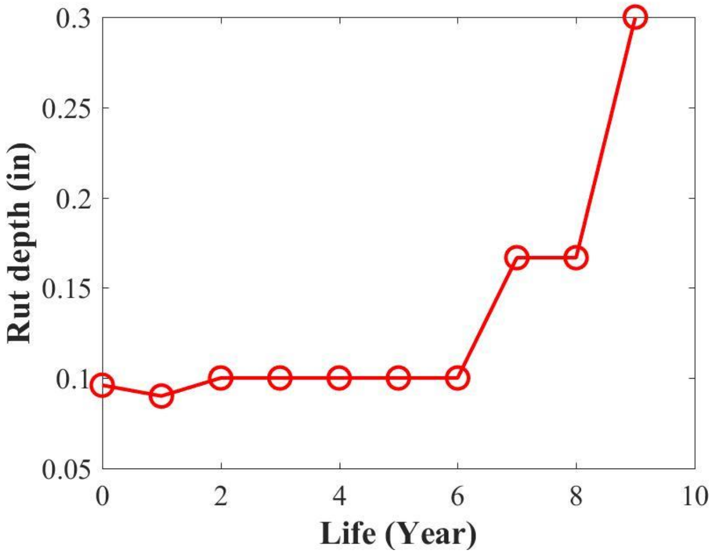


Figure 6-3 Development of rut depth

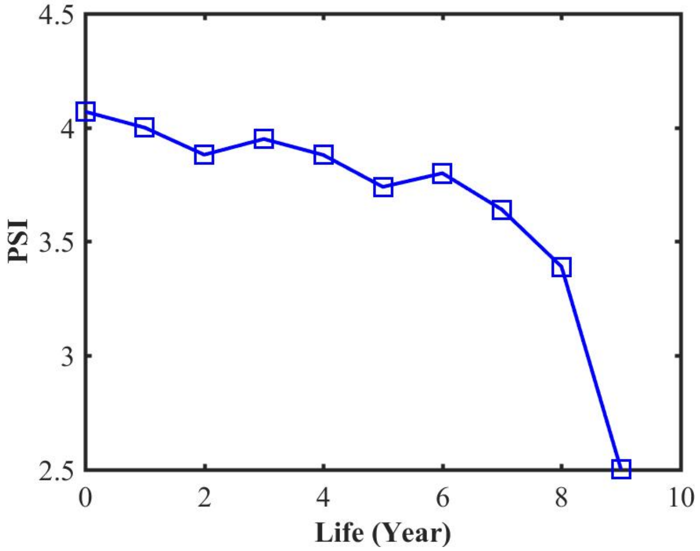


Figure 6-4 Pavement serviceability index

6.3 Effect of Pre-treatment Distress on Pavement Life

Survival analysis has been a popular statistical method to determine the time to a specific event, such as the failure of pavement as per a chosen threshold (e.g., 10% of alligator cracking). Figure 6-5 shows the survival curves of different types of cracking. In

Figure 6-5, the horizontal axis represents the pavement age (life), while the vertical axis represents the survival rate, which is the ratio of survived sections over the total number of sections. It should be noted that because of the limited samples, the analysis was based on data collected in the first three years. It can be observed clearly that with the increase of pavement age, the survival rate decreased, which is in accordance with the general assumption that the pavement ages satisfy the Weibull distribution (Balla, 2010).

It can be seen from Figure 6-5 that the block cracking showed the highest survival rate, followed by the transverse cracking then the fatigue cracking. The wheel path longitudinal cracking showed the lowest survival rate at the end of three service years, which may be due to the fact that the traffic loads degraded the OGFC surface and accelerated the longitudinal cracking process. From Figure 6-5, it can also be inferred that after the paving of OGFC, the longitudinal cracking was generated first mainly due to the traffic loads, which would critically affect the pavement serviceability. After certain years of service, under the coupled influences from traffic and environment, the fatigue cracking, the block cracking, and the transverse cracking were generated.

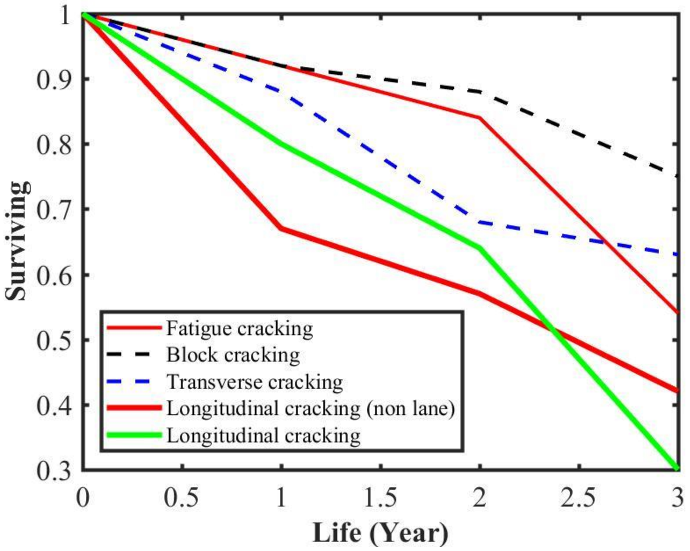


Figure 6-5 Comparison of survival curves of different types of distress (cracking)

6.4 Conclusions

This chapter presented analyses of the distress data collected from 25 OGFC projects in Tennessee. The effects of pre-treatment distress conditions on OGFC life were investigated. Based on the analysis results, the following observations were made:

- As most of the OGFCs were paved within the recent three years, the cracking probabilities were all at a low level. The rut depth of OGFC was around 0.1 in.
- According to the survival analysis, the wheel path longitudinal cracking was generated and developed first, followed by the non-wheel path longitudinal cracking, the fatigue cracking, the transverse cracking, and the block cracking. It is the longitudinal cracking affecting the durability of OGFC pavements the most.

CHAPTER 7 FIELD EFFECTIVENESS EVALUATION OF PREVENTATIVE MAINTENANCE TREATMENTS USING LTPP DATABASE

7.1 Introduction

It has been more than 70 years since OGFC's first use in California in 1944 (Huber, 2000). In 2000, a new generation of OGFC mix design method was developed by the National Center for Asphalt Technology (NCAT) with the consideration of both functionality and durability (R. Mallick, P. Kandhal, L. A. Cooley, & D. Watson, 2000). Because of its numerous benefits in terms of economy, safety, and environment (Alvarez et al., 2006), OGFC has been attracting extensive attention nowadays. Although OGFC receives wide acceptance in the U.S., researchers and engineers have still been struggling to maintain it cost-effectively. A previous survey has shown that various forms of distress affected the serviceability of OGFC pavements. OGFC has a higher porosity in contrast with conventional dense graded asphalt mixtures, which makes its mechanical behavior more complicated under the coupled effects from traffic loading and environmental factors (Song et al., 2015; Song, Shu, Huang, & Woods, 2017).

Applying appropriate maintenance treatments at the right time can extend the service life of pavements. Rehabilitation and pavement preservation represent the majority of pavement maintenance activities in the US. To maximize the benefits or effectiveness of pavement intervention with limited funds, many state highway agencies adopted the concept of preventive maintenance (PM). The basic concept of PM is to apply periodic and inexpensive treatments rather than the high-cost rehabilitation (Dong & Huang, 2011; Gong et al., 2015; Mamlouk & Dosa, 2014). Preventive maintenance is mainly used to prevent distress development and reduce the rate of damage development. The identification of appropriate type and timing of preventive treatment is the base of efficient preventive maintenance practice. The selection of preventive treatment is often based on experience and local practice specific to a region or district within a public highway agency.

A good source for pavement maintenance and performance data is the **long-term pavement performance** (LTPP) program, which has monitored more than 2,400 pavement test sections in the US and Canada (Dong & Huang, 2011). The specific pavement study 3 (SPS-3) of LTPP was designed in 1990 to evaluate the effectiveness of maintenance activities and to determine the optimum timing for applying treatments for flexible pavements. The commonly used indicators in the preventive maintenance analysis include roughness, friction, and surface distress condition.

Many studies have been conducted on the preventive maintenance of dense-graded asphalt pavements. Gong et al. (2015) analyzed the effectiveness of treatments (thin HMA overlay, chip seal, slurry seal, and crack seal) using LTPP SPS-3 data. Their study showed that the thin overlay and the chip seal were effective in mitigating the fatigue cracking. In a project of the National Cooperative Highway Research Program (NCHRP), Peshkin et al. (Peshkin, Hoerner, & Zimmerman, 2004) proposed an approach to quantify the optimal time of applying preventive maintenance treatment, thus to extend the pavement life the longest at the lowest cost. Dong et al. (2011) investigated the treatment effectiveness by using the data collected from the Highway Pavement Management Application (HPMA) and LTPP database and showed that HMA overlay had the highest effectiveness. However, there have been few studies of preventive maintenance activities on OGFC pavement so far.

In this chapter, OGFC maintenance and performance data were retrieved from the LTPP database to analyze the effects of PM treatments (including crack sealing, sand seal, slurry seal, and fog seal) on OGFC pavements. The appropriate treatment timing was also determined according to the LTPP data.

7.2 Data Collection

All the data used in this chapter was extracted from the LTPP database (http://www.infopave.com). The performance data were obtained from the monitoring module (Monitoring.mdb) in the LTPP database. The cracking, IRI, and rutting were obtained from tables MON_DIS_AC_REV, MON_HSS_PROFILE_SECTION, and MON_RUT_DEPTH_POINT, respectively. The length of each LTPP test section is 0.1

mile (500ft).

An exploration of the pavement structures and maintenance records in the LTPP database revealed that there had a total of 353 sections containing an OGFC layer. Among these 353 OGFC sections, only 305 sections were asphalt pavements and the remaining 24 sections were rigid pavements overlaid with asphalt concrete (AC). In addition, within the 305 AC pavement sections, several sections have no complete maintenance records. Therefore, these sections were excluded from further analyses. The sections were distributed across a total of 24 states covering all of the four climatic regions. Figure 7-1 gives the locations of the LTPP AC pavements sections with an OGFC.

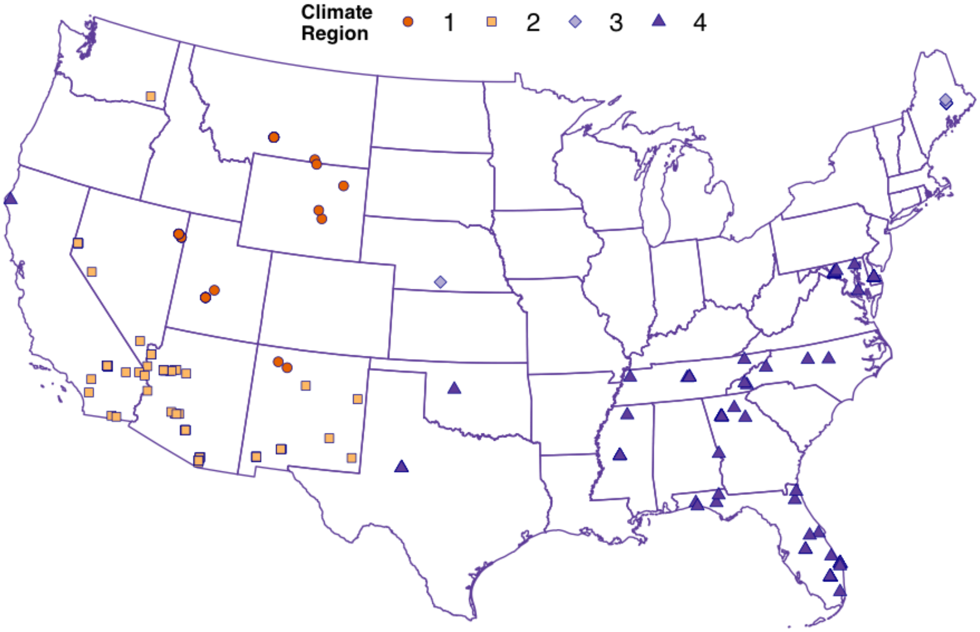


Figure 7-1 Locations of the LTPP sections containing an OGFC. Climatic region: 1-dry, freeze; 2-dry, non-freeze; 3-wetfreeze; 4-wet, non-freeze.

Figure 7-2 depicts the number of sections in each of the climatic regions. As indicated, most of the sections were located in the warm regions such as the wet, non-freeze (climatic region 4) and the dry, non-freeze (climatic region 2) regions. Relatively fewer sections were found in the wet-freeze region (climatic region 3), in which only 18 sections were identified. A possible reason for the less frequent use of OGFC at the wet-freeze region (climatic region 3) is that the severer snow and ice conditions in this region complicate the winter maintenance practice and thus reduce or even counteract the potential benefits of OGFC.

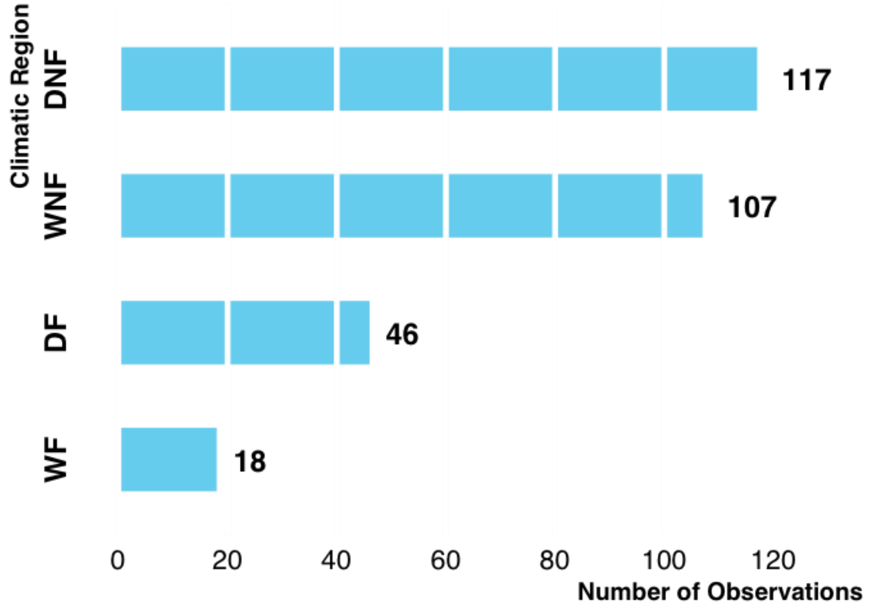


Figure 7-2 Distribution of sections by climatic region. Climatic region: DF-dry, freeze; DNF-dry, non-freeze; WF-wet, freeze; WNF-wet, non-freeze.

With the LTPP sections containing an OGFC layer collected, the types of strategies to maintain OGFC pavements were analyzed. Figure 7-3 presents the commonly used treatments on OGFC in the US.

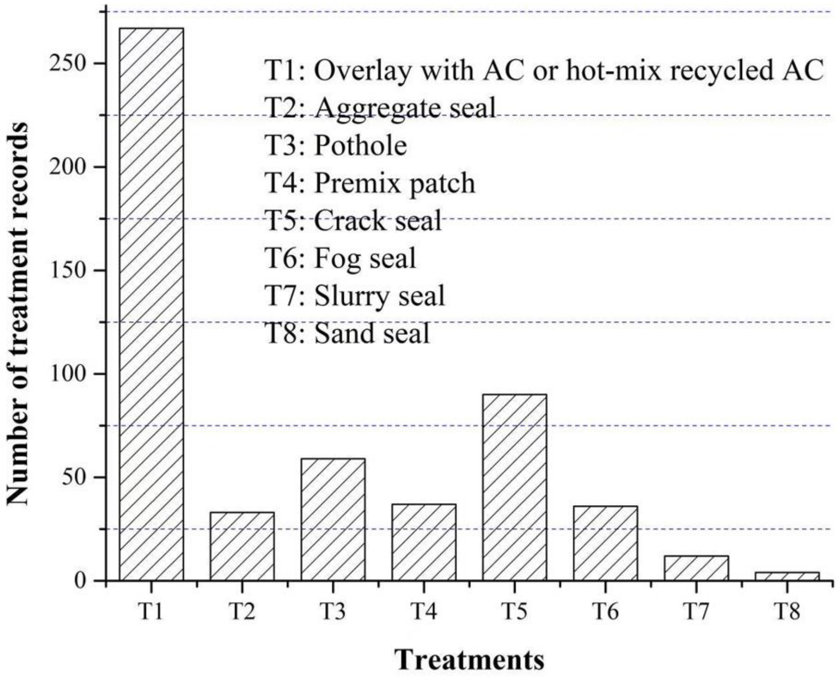


Figure 7-3 Treatments for OGFC in US

The following is a brief description of the treatments presented in Figure 7-3:

- Overlay with AC or hot-mix recycled AC (T1): this treatment includes milling the existing surface and then filling with hot-mix asphalt mixture. This type of treatment has been a common practice to rehabilitate damaged OGFCs. From Figure 7-3, it can be observed that this method is the most common method to maintain OGFC pavements. However, once rehabilitated with conventional DGHMA, the benefits of OGFC are eliminated as well, such as faster drainage, better surface friction, noise reduction. In this regard, this report omitted analyses of the effectiveness of overlay.

- Aggregate sealing (T2): also called chip seal coating, is a pavement surface treatment that combines one or more layer(s) of asphalt with one or more layer(s) of fine aggregates.
- Pothole patching (T3): This patching generally uses cold mix asphalt by hand spreading and is compacted with the truck.
- Premix patching (T4): It patches OGFC with premix AC and is compacted using a pave roller.
- Crack seal (T5): The primary purpose of crack sealing is to prevent the intrusion of moisture through existing cracks by filling cracks with an adhesive sealant.
- Fog seal (T6): The primary purpose of fog seals is to improve aggregate retention, rejuvenate the aged binder, and thus extend the pavement service life. A fog seal is typically a light spray application of dilute asphalt emulsion, and a rejuvenator agent is generally included.
- Slurry seal (T7): The primary purpose of slurry sealing is to seal less severe surface cracks, waterproof the pavement surface, and improve skid resistance. Unlike the sand seal, a slurry seal is applied as a mixture.
- Sand seal (T8): The primary purpose of sand seals is to enrich weathered pavements and fill fine cracks on the pavement surface. A sand seal is a sprayed application of asphalt emulsion followed by a covering of clean sand or fine aggregate. The sand can provide additional skid resistance to the pavement while also inhibit raveling.

7.3 Verification of gradation of OGFC

In 1998, Kandhal and Mallick (1998) conducted a survey on the state of practice regarding the performance of OGFCs. In their report, the recommended gradations of different states were provided. To verify the gradations of OGFCs included in the LTPP database, the research team plotted the gradation curves in their study against those from different sections of the LTPP database. Figure 7-4 through 7-6 give the comparisons for this purpose. Although the requirements of different states vary drastically, the sections in the LTPP claimed to have used OGFC can actually meet the gradation requirements of some states.

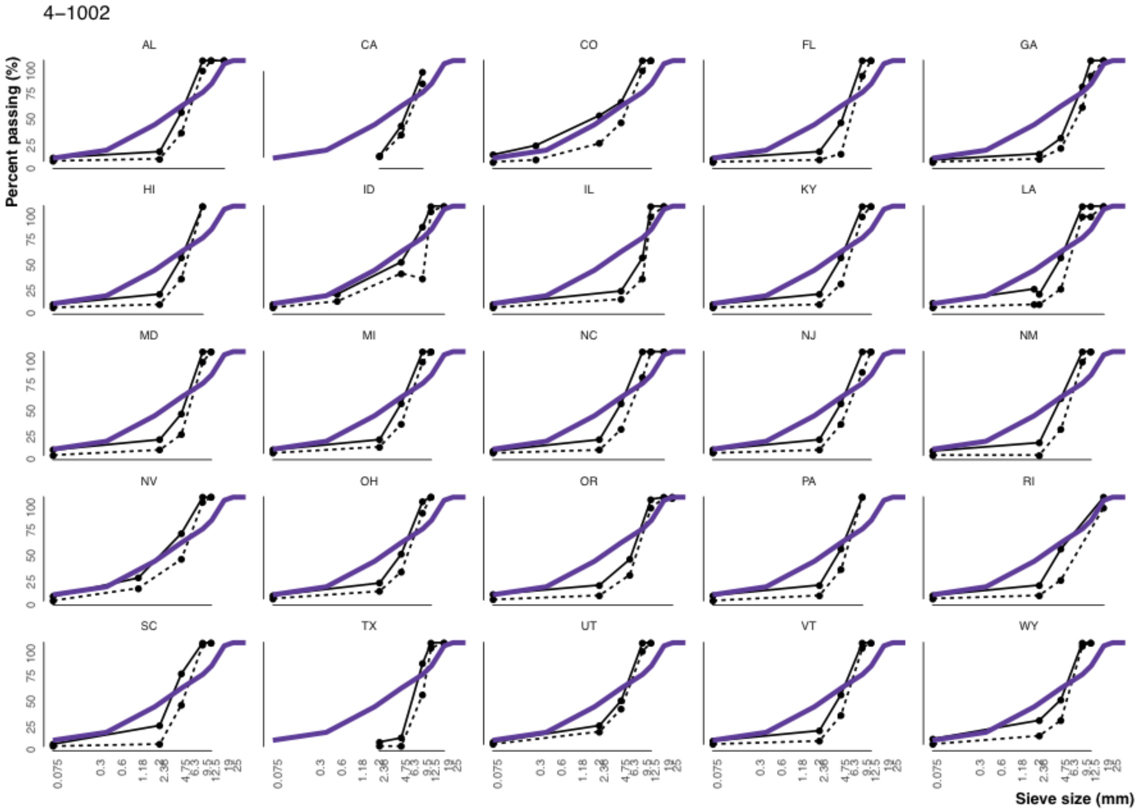


Figure 7-4 Gradation curves for OGFCs in Arizona (4-1002)

According to the gradation requirements of Colorado (CO), Idaho (ID) and Nevada (NV), the OGFC used in section 4-1002 (Arizona) satisfied these requirements and was indeed an open-graded mixture.

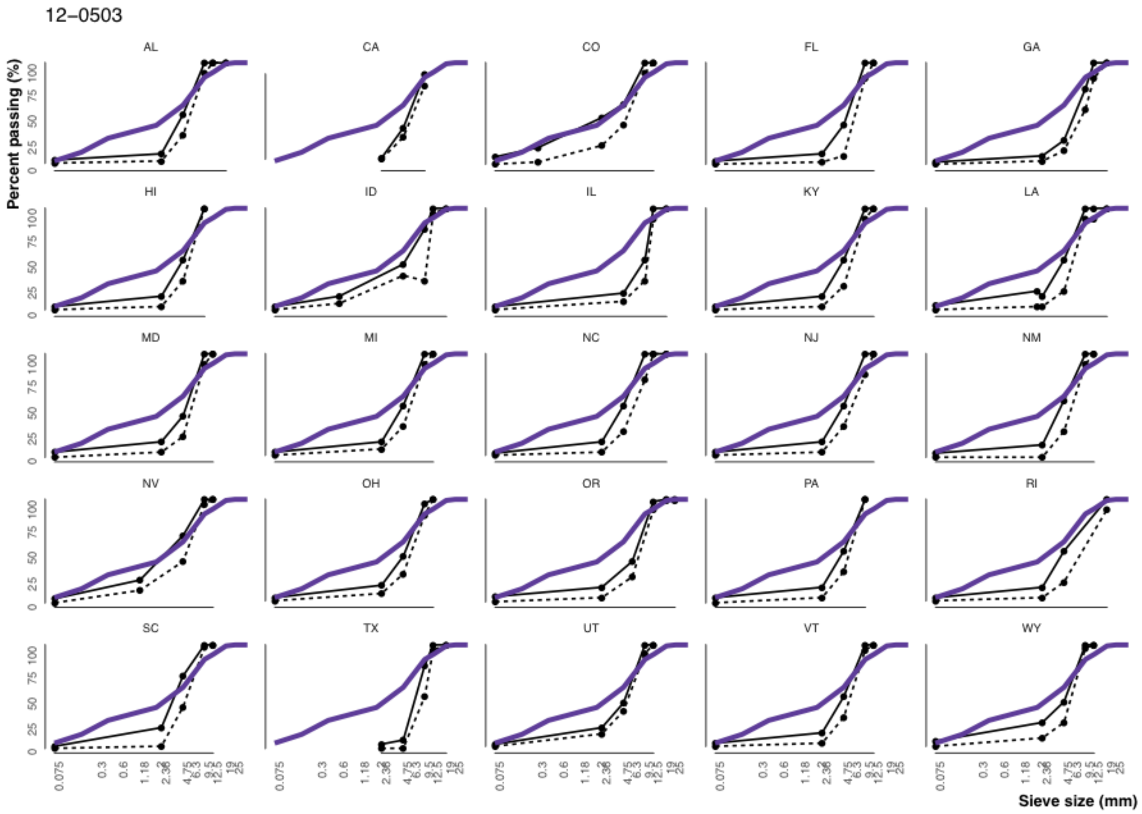


Figure 7-5 Gradation curves for OGFCs in Florida (12-0503)

Figure 7-5 shows the gradation curve of the OGFC used in section 12-0503. Seemingly, it does not match well with the requirements of Florida (FL); however, it is in the allowable ranges of Colorado (CO) and Nevada (NV).

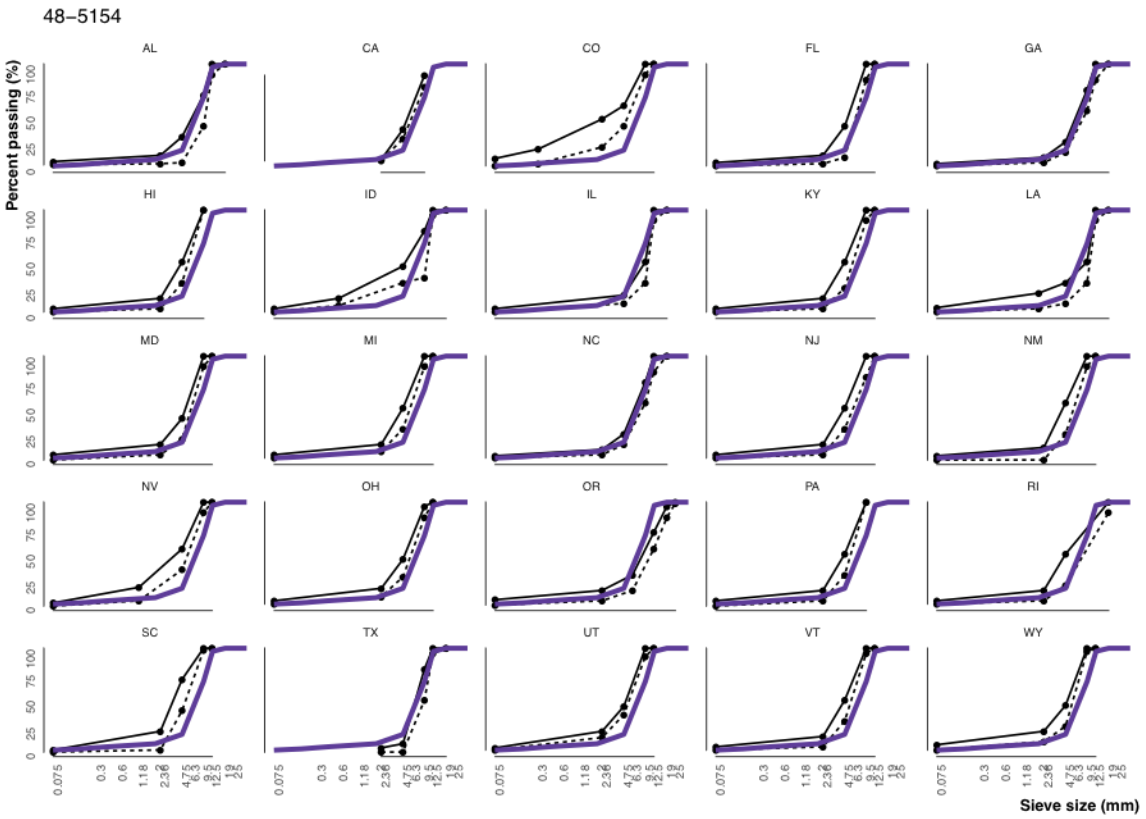


Figure 7-6 Gradation curves for OGFCs in Texas (48-5154)

For the OGFC used in section 48-5154 located in Texas, its gradation curve matches well with almost all of the 20 states.

The engineering properties of materials are critical to the performance of OGFC, including abrasion, angularity, particle shape, soundness, cleanliness, and absorption. Another crucial factor in material design is the selection of aggregation gradation, which is vital to establish adequate stone-to-stone contact to minimize rutting, sufficient air voids to ensure proper functionality of the mixture. Figure 7-7 presents the gradation limits in different states. **Table 7-1** summarizes the allowable boundary values for different sieve opening size, which may also be used as a reference for the OGFC design practices in

Tennessee.

Table 7-1. OGFC gradation limits in different states, percent passing

Sieve Size (mm)	Min (%)	Mean (%)	Max (%)
0.075	0	3.35	9
0.3	3	10.00	18
0.6	8	11.50	15
1.18	5	14.25	22
2	5	12.50	20
2.36	0	11.31	47
4.75	0	34.62	70
6.3	15	27.50	40
9.5	30	84.68	100
12.5	55	95.54	100
19	85	97.69	100
25	99	99.50	100

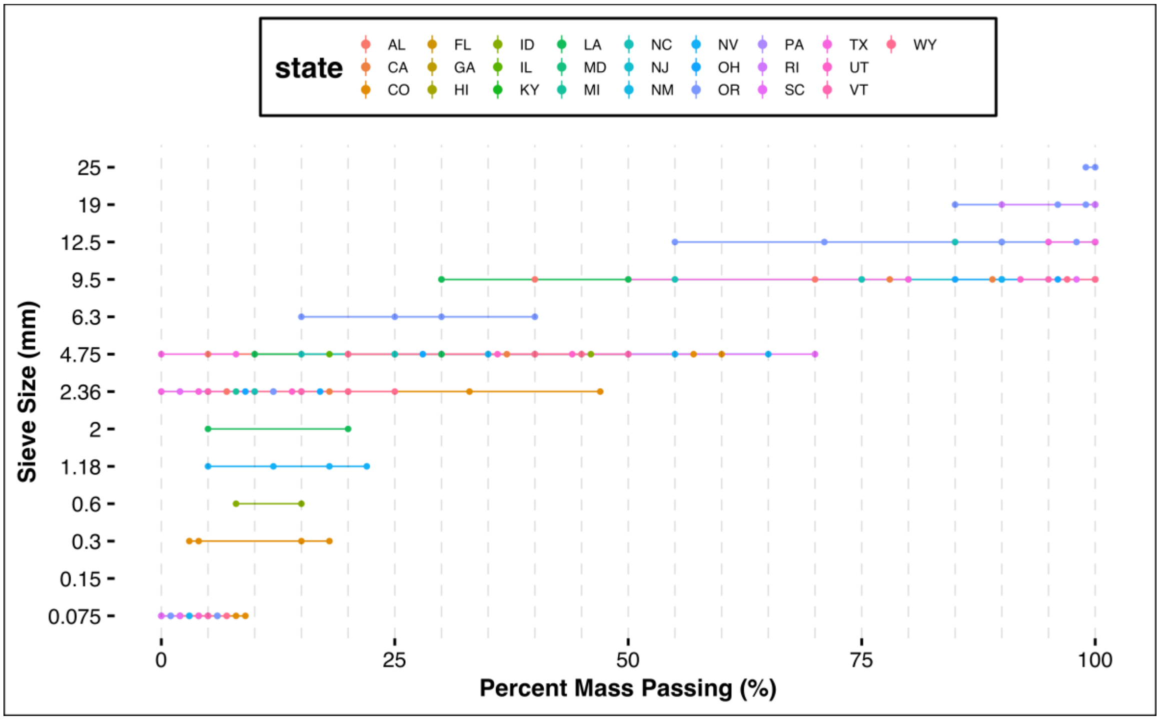


Figure 7-7 Limits of percent passing for sizes of sieve openings in different states.

7.4 Distress Analysis

In this report, the IRI, rutting, fatigue cracking, block cracking, wheel path longitudinal cracking, and non-wheel path longitudinal cracking were selected as the performance indicators of pre-treatment and post-treatment conditions.

- Cracking

  Data on cracking were very limited in the LTPP database. Comparisons were made between the pre-treatment data and the post-treatment data. Only the data for sections with crack seals and fog seals were analyzed, as there was only a limited amount of data for sand seals and slurry seals. The pre-treatment data were the last measurements before treating the pavement, and the post-treatment data were the first measurements after treating the pavement. The pre-treatment and post-treatment data were mainly obtained from an interval of shorter than two years before/after treating the sections.

- IRI and rutting

  The effectiveness of the treatments according to IRI and rutting was characterized through a weighted average index (WD). The index was calculated using the following equation:

$$WD = \frac{\sum_{i=0}^{n-1} (D_i + D_{i+1}) \times P_{i+1}}{2(P_n - P_1)}$$

where WD is the weighted distress value (e.g. area of fatigue cracking) over the total survey period; i is the survey number ($i = 0$ is the initial distress level immediately after the treatment); D_i is the distress value measured at the i^{th} survey; P_{i+1} is the period (in years) between survey i and survey $i+1$; n is the total number of surveys on the section.

Besides WD, the parameter 'IRI drop' was also used to evaluate the effectiveness of maintenance treatments. IRI drop is defined as the difference between the last measurement of IRI before a treatment and the first measurement after a treatment. 'IRI drop < 0' means an increase in IRI after the treatment, indicating negative results of the treatment. 'IRI drop >0' means a decrease in IRI after the treatment, indicating positive results of the treatment.

7.5 Results and Discussion

7.5.1 Times of Preventive Maintenance

Figure 7-8 shows the treatment time of seven preventative treatments used in the US. The boundaries of the box present lower and upper quartiles and the middle line is the median. **Table 7-2** shows the average treatment times and the number of sections. It should be noted that the numbers of samples were very limited for slurry seal and sand seal treatments. Therefore, the treatment times of slurry seal and sand seal may not be as accurate as those for crack seal and fog seal.

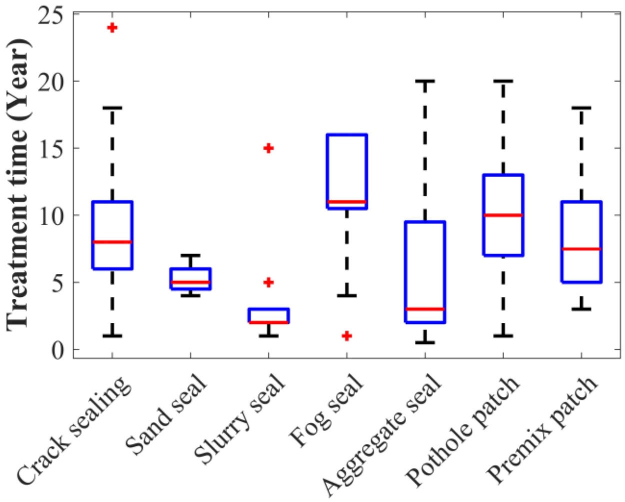


Figure 7-8 Box plots of treatment time

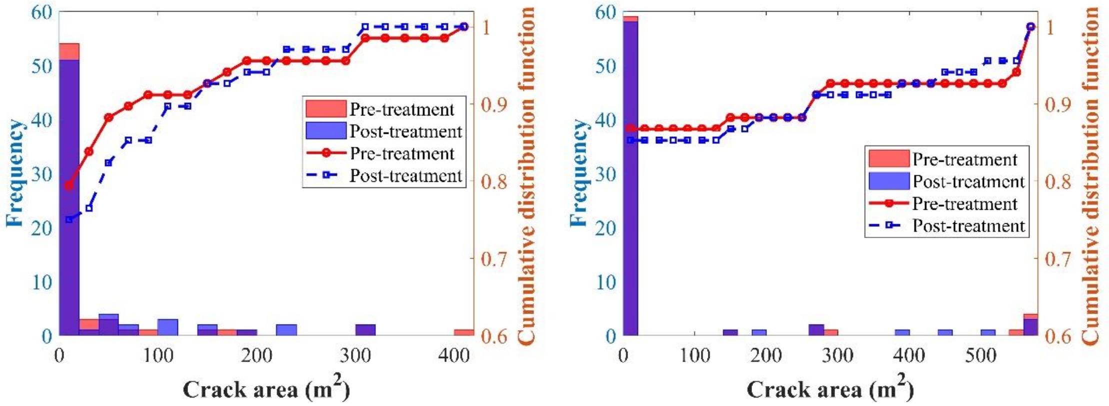
Table 7-2. Treatment times of various treatments

Treatment	Treatment time (year)	Number of sections
Crack seal	8.40±4.51	88
Sand seal	5.25±1.26	4
Slurry seal	3.70±4.11	10
Fog seal	11.53±4.27	36
Aggregate seal	5.77±5.46	24
Pothole patch	10.14±4.85	53
Premix patch	8.07±3.79	30

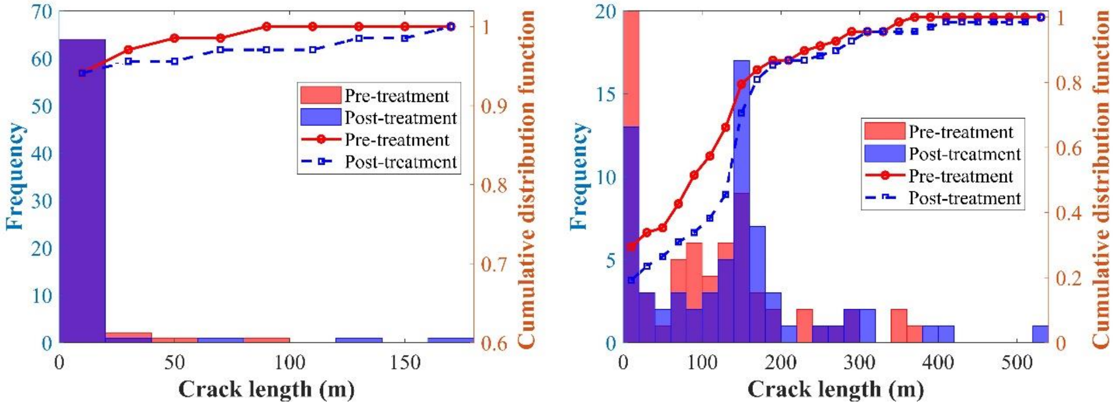
7.5.2 Cracking

The effects of preventive treatments on cracking were analyzed by comparing the cracking data before and after the treatment. The pretreatment condition of a section was defined as the performance measurement before a maintenance action was applied, whereas the post-treatment condition was the first measurement right after the application of the maintenance. It should be noted that the time between the maintenance action and the first performance measurement after it can vary among sites. Figure 7-9 through 7-13 show the cracking histograms and the corresponding cumulative frequency curves before and after a section received a preventive treatment. This part included no analysis of sand sealing and slurry sealing due to lack of data.

In Figure 7-9, the fatigue cracking and block cracking differ indiscernibly before and after the crack seal treatment. For the wheel path longitudinal cracking or non-wheel path longitudinal cracking, the crack seal treatment retarded the development of shorter cracks, while increasing longer cracks.



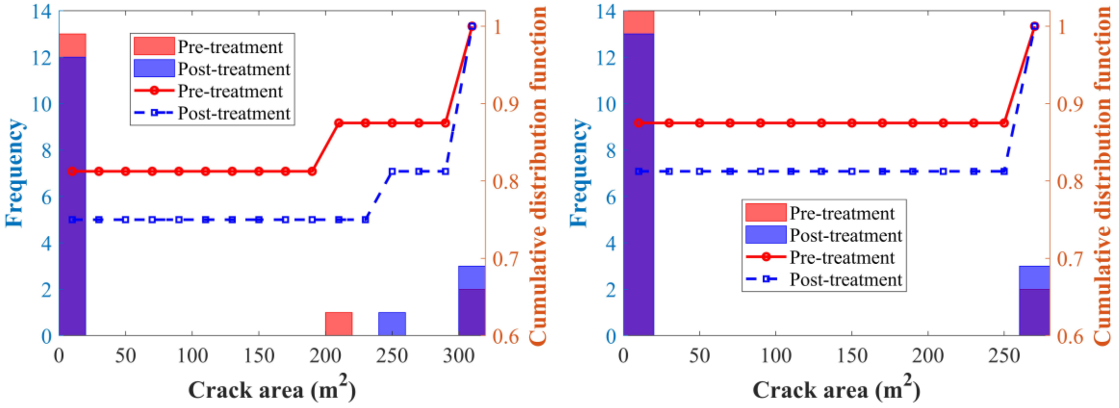
(a) Fatigue crack (b) Block crack



(c) Wheel path longitudinal cracking (d) Non-wheel path longitudinal cracking

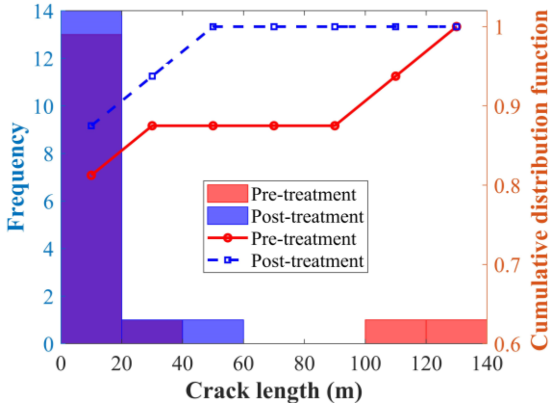
Figure 7-9 Cracking distributions before and after crack seal treatment

As shown in Figure 7-10, for fatigue cracking and block cracking, the fog seal was effective only when the cracked area was relatively small (< 42% lane area). As to the non-wheel path longitudinal cracking, the fog seal seemed to be efficient as the longer cracks of this type (>100 m) were fixed, although more shorter ones showed up. However, it should be noticed that the number of sections with performance observations of this treatment type was limited, and thus more data are needed to further validate the findings reached herein.



(a) Fatigue crack

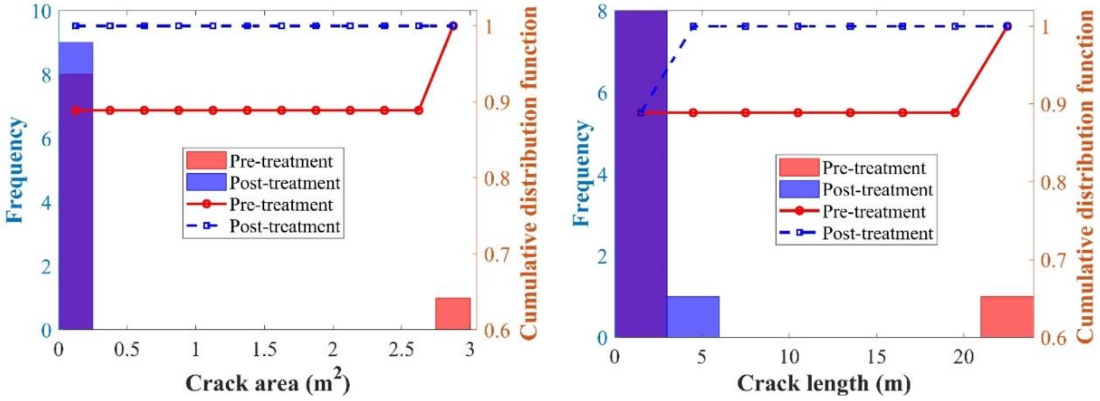
(b) Block crack



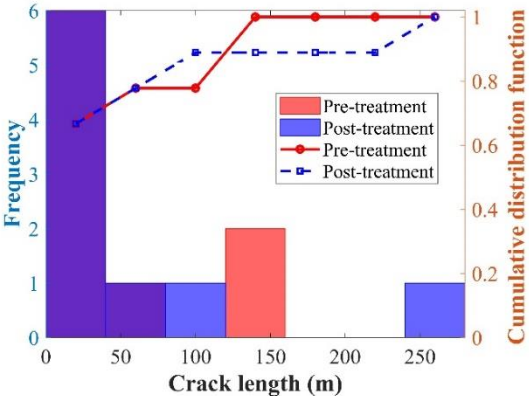
(c) Non-wheel path longitudinal cracking

Figure 7-10 Cracking distributions before and after fog seal treatment

As shown in Figure 7-11, the aggregate sealing (chip sealing) treatment decreased the occurrence of the fatigue crack even when the cracked area was large. It also decreased the occurrence of wheel path longitudinal cracking over the long-term. For the non-wheel path longitudinal cracking, however, no obvious difference was observed before and after the treatment. The results indicate that the aggregate sealing had advantages in decreasing fatigue cracks and the wheel path longitudinal cracking.



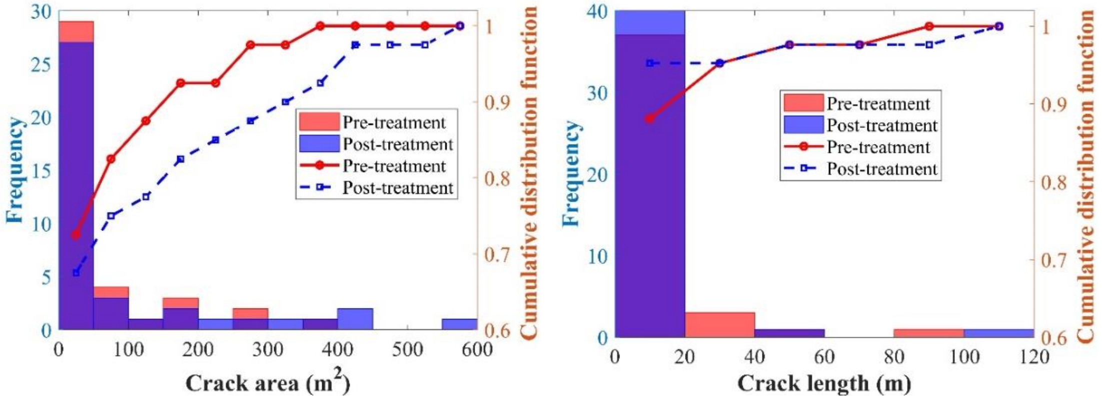
(a) Fatigue crack (b) Wheel path longitudinal cracking



(c) Non-wheel path longitudinal cracking

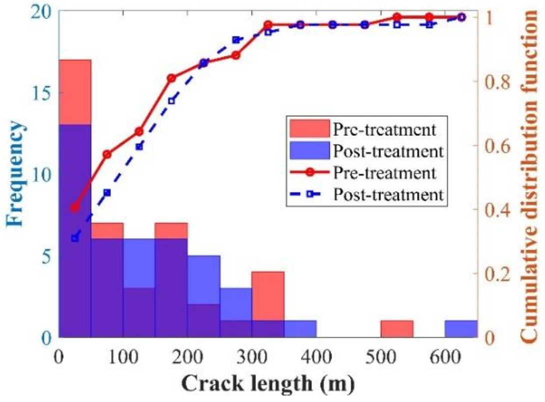
Figure 7-11 Cracking distributions before and after aggregate seal

In Figure 7-12, the frequency of pothole patching increases with the occurrence of larger areas of fatigue cracking. This indicates that as fatigue cracks accumulate and interconnect, with the coupled action of dynamic water pressure and traffic loading, they can further turn into potholes. Since patches are to fix localized defects, for the wheel and non-wheel path longitudinal cracking, the data differ insignificantly before and after applying the patch.



(a) Fatigue crack

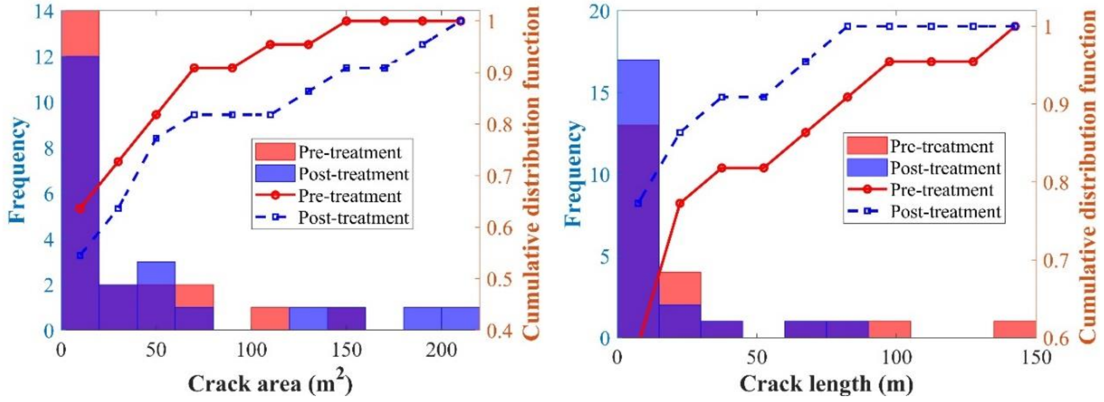
(b) Wheel path longitudinal cracking



(c) Non-wheel path longitudinal cracking

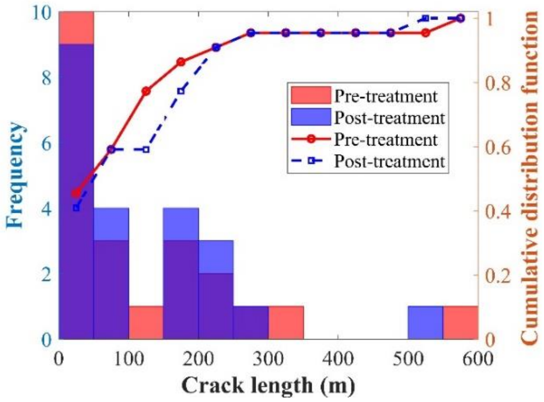
Figure 7-12 Cracking distributions before and after pothole patching

In Figure 7-13, the frequency of premix patches accompanies with the occurrence of larger areas of fatigue cracking, while the occurrence of wheel path longitudinal cracking does not follow such a trend. The data of non-wheel path longitudinal cracking before and after the treatment do not show any obvious difference.



(a) Fatigue crack

(b) Wheel path longitudinal cracking



(c) Non-wheel path longitudinal cracking

Figure 7-13 Cracking distributions before and after premix patching

7.5.3 Weighted Average IRI

Figure 7-14 illustrates the box plot of the weighted average IRI values. It can be seen that the median value of IRI for the premix patching was significantly larger than the others, indicating that the effect of premix patching was negative in the maintaining of international roughness. The median values of crack sealing, slurry seal and aggregate seal were very close, and these values were lower than the others, indicating that the crack sealing, the slurry seal and the aggregate seal were more effective in mitigating IRI in the survey period.

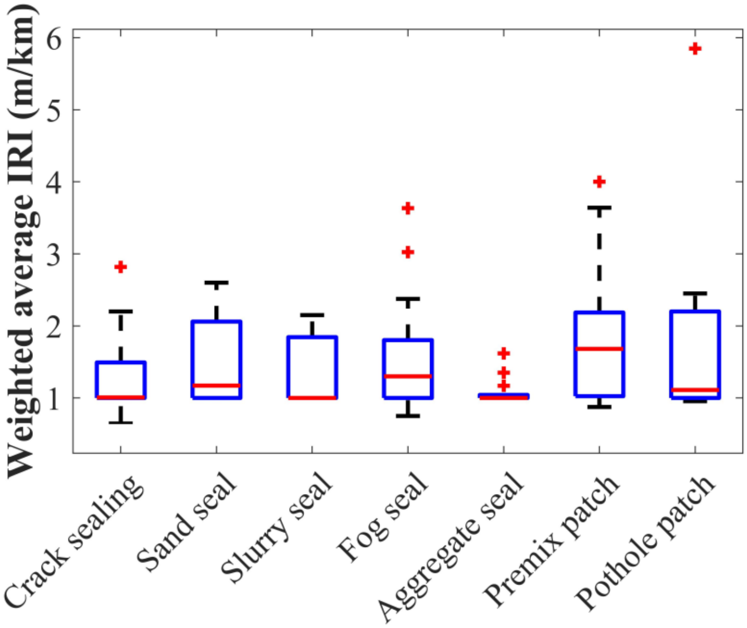


Figure 7-14 Weighted average IRI

Figure 7-15 shows the IRI drop for the seven treatments. The IRI drop is defined as the IRI before the treatment minus the IRI after the treatment. As indicated, the median values were all around the line of zero, except for the premix patching. The seven treatment methods generally helped to reduce the IRI. It should be noted that some data of the slurry seal were above zero, and the IRI drop data after crack sealing and pothole patching were more scattered.

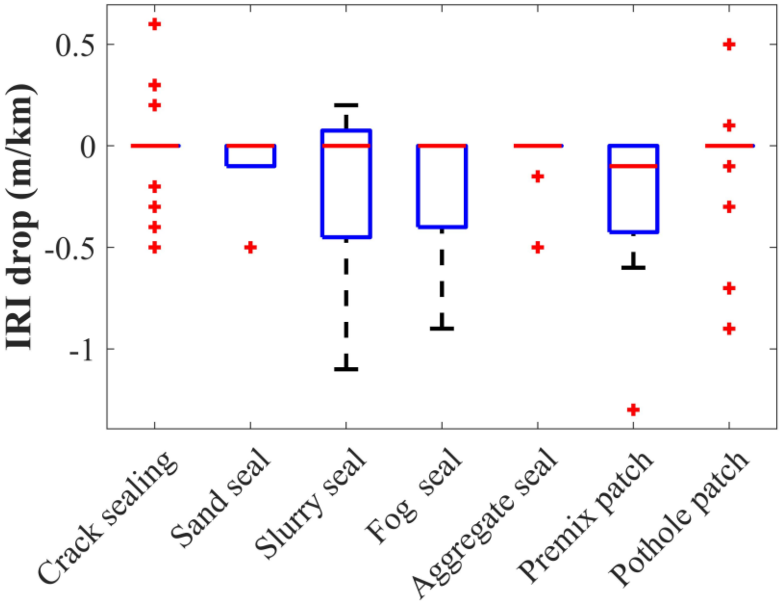


Figure 7-15 IRI drop

7.5.4 Weighted Average Rut

Figure 7-16 illustrates the weighted average rutting depth for the collected OGFC sections. According to their median values (the bars in the box plots), there exist differences among the four types of preventive maintenance treatments. Especially, sections received fog sealing had less rutting. However, it is hard to find any statistically discernable differences among the four types of preventive maintenance methods.

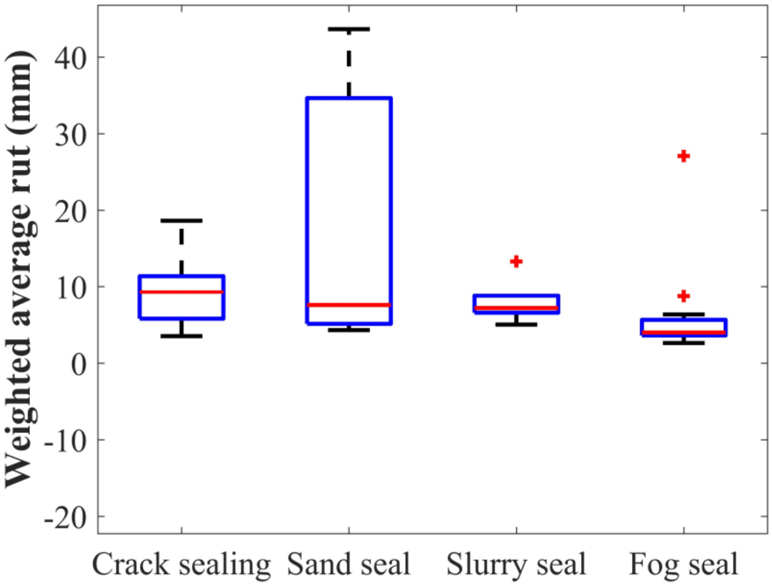


Figure 7-16 Weighted average rut

7.5.5 Maintenance Analysis in Tennessee

Among all the OGFC sections in the LTPP database, nine are located in Tennessee. The data for these nine sections were analyzed specifically for the effectiveness of treatment strategies.

7.5.5.1 Times of treatments in Tennessee

Figure 7-17 presents the time interval and frequency of the maintenance strategies employed in Tennessee. It can be observed that the treatment T1 (AC overlay) was most commonly used, followed by T5 (crack sealing). There were only two records of aggregate sealing, pothole patching, premix patching, and slurry seal, respectively. AC overlay treatment (T1) was generally applied after eight years of service. The treatment time of crack sealing (T5) was nearly the same as T1. The treatment time of aggregate sealing and slurry seal was usually in the third year. It should be noted that the results are obtained based on the data currently available in the LTPP database, as the amount of data is very limited, the result may need to verify further.

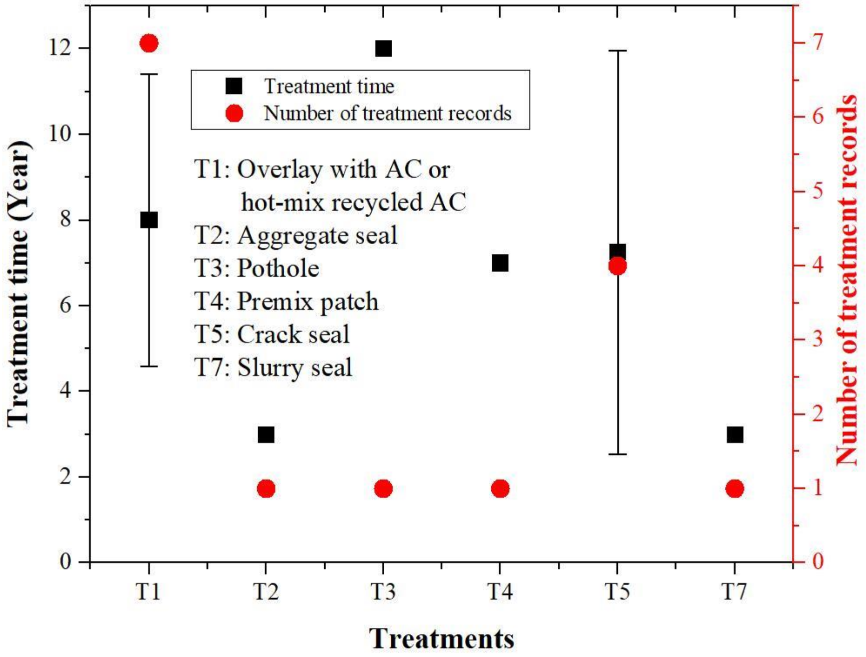
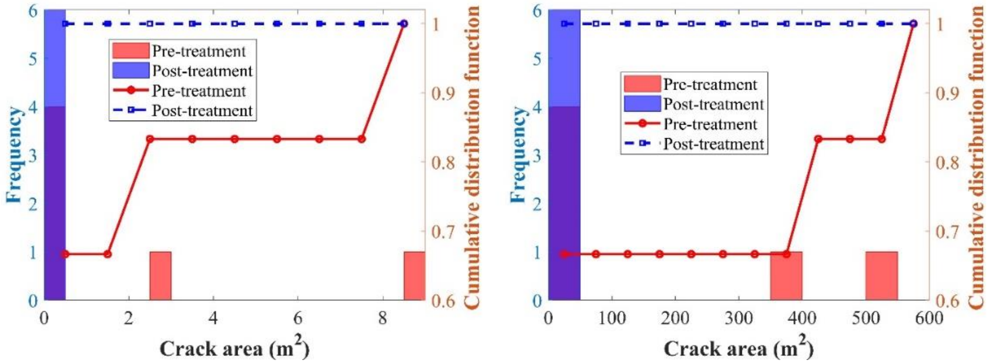


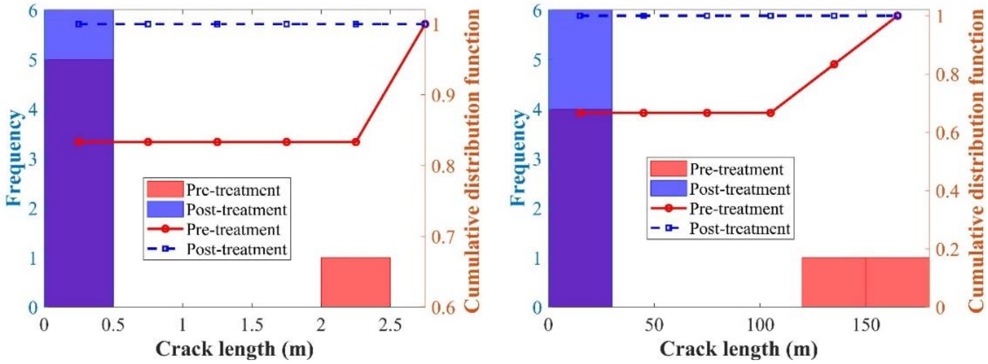
Figure 7-17 Treatments in Tennessee

7.5.5.2 Cracking in Tennessee

Figure 7-18 shows the cracking distributions before and after the application of DGHMA overlay (treatment T1). As expected, the DGHMA overlay treatment decreased the occurrence of fatigue crack, block crack, wheel and non-wheel path longitudinal cracking. It is caused by the fact that the structure of DGHMA overlay is different with OGFC. Typically, DGHMA is more durable than OGFC.



(a) Fatigue crack (b) Block crack

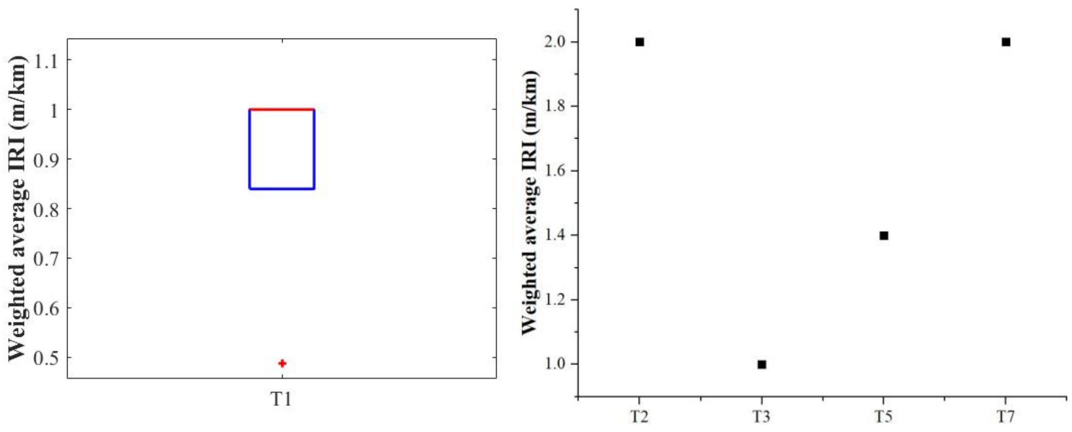


(c) Wheel path longitudinal cracking (d) Non-wheel path longitudinal cracking

Figure 7-18 Cracking distributions before and after T1

7.5.5.3 IRI in Tennessee

The weight averaged IRI of the OGFC sections in Tennessee is shown in Figure 7-19. The result of T1 is presented by a box plot, while the mean values of the weight averaged IRI for the other treatments are given in Figure 7-18 (b). It can be observed that the weight averaged IRI values of T1 and T3 were comparatively smaller, indicating that T2, T5, and T7 (aggregate sealing, crack sealing, and slurry seal) could maintain the roughness as well as the friction of OGFC better.



(a) T1 treatment (b) Other treatments

Figure 7-19 Weighted average IRI in Tennessee

Figure 7-20 gives the IRI drop of DGHMA overlay (T1). It should be noted that the results of other treatments were not presented because of the lack of useful data. The AC overlay treatment could usually decrease the IRI because of the material difference between DGHMA and OGFC. The positive value of IRI drop confirmed that the AC overlay treatment decreased IRI.

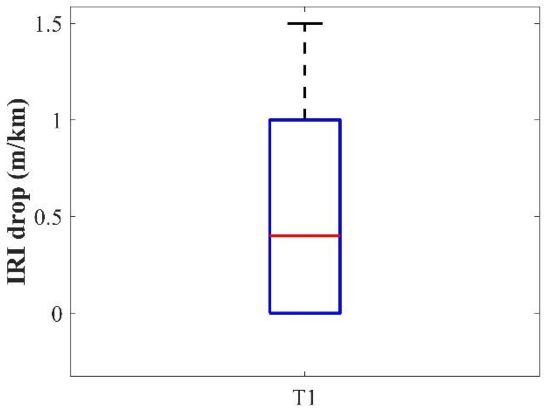


Figure 7-20 IRI drop. The IRI is dropped if the post-treatment IRI is smaller than the pre-treatment one.

7.6 Conclusions

In this chapter, the LTPP data were utilized to determine the application of different OGFC preventive maintenance treatments and their effectiveness. The maintenance records and performance data were analyzed for seven commonly used preventive maintenance treatments. The treatments analyzed were: crack sealing, sand seal, slurry seal, fog seal, aggregate seal, pothole patch, and premix patch. Four types of pavement distress were selected as the performance indicators, including roughness, rutting, fatigue cracking, wheel path longitudinal cracking and non-wheel path longitudinal cracking. Based on the analysis, the following conclusions were drawn:

- In the US, the AC overlay is the most commonly used treatment method for maintaining OGFC pavements.
- The treatment times of crack sealing, sand seal, slurry seal, fog seal, aggregate seal, pothole patch, and premix patch for OGFC were determined to be 8.40, 5.25, 3.70, 11.53, 5.77, 10.14 and 8.07 years, respectively.
- The crack sealing and fog sealing did not improve crack resistance of OGFC for fatigue cracking and block cracking, while the fog seal was beneficial to decrease non-wheel path longitudinal cracking. The aggregate sealing provided benefits in reducing the potential of fatigue cracking and wheel path longitudinal cracking.
- The crack sealing, slurry sealing, and aggregate sealing (chip sealing) were more effective in mitigating IRI over the years in the survey period. The premix patching

negatively affected the roughness of OGFC pavements. After maintenance, the seven treatments generally reduced the IRI, while the IRI drop data after crack sealing and pothole patching were more scattered.

- According to the sections in Tennessee, the AC overlay treatment (T1) is the most commonly used preservative method, which was generally applied in the eighth year of service. The treatment time of crack sealing (T5) was almost the same as T1, and the treatment time of aggregate sealing and slurry sealing typically occurred in the third year of service.
- Based on the performance data of Tennessee, the AC overlay (T1) decreased the occurrence of fatigue cracking, block cracking, wheel and non-wheel path longitudinal cracking, and IRI. However, it should be noted that the observations made were based on analyzing limited data; for more reliable and comprehensive results, it is suggested to evaluate a larger dataset that covers a longer time window of data in the future.

CHAPTER 8 SUMMARY OF DOT SURVEY RESPONSE AND RECOMMENDATIONS FOR OGFC MAINTENANCE

This chapter summarized the responses from the DOT survey about the current practice of maintenance strategies for OGFC. Based on the analyses of the LTPP data and the DOT survey responses, recommendations on guidelines for maintaining OGFC pavement in Tennessee were made to improve the OGFC performance.

8.1 Summary of DOT Survey Response

The survey was sent to 50 states in the US, and 30 responses were received. The detailed DOT survey results are provided in the Appendix. Among the 30 responded states, a total of 16 states currently have OGFC pavements in service. Among the states that don’t use OGFC extensively, some states have some sections of OGFC, such as Indiana. Also, some states may have used OGFC before but have stopped using it now.

For all the listed types of OGFC distresses, raveling was the most common distress (27%), while other distress forms were also common, such as pore clogging (10%), rutting (10%) and delamination (12%).

According to the survey, the fog seal treatment is most commonly used to deal with raveling. It is also used by many states to perform preventative maintenance. It has been shown that the fog seal can extend the life of porous mixtures since it provides a small film of unaged asphalt at the surface (D. Rogge & E. A. Hunt, 1999). FHWA recommends the fog seal application with two passes (at a rate of 0.05 gal/yd^2 for each pass) using a 50% dilution of asphalt emulsion without any rejuvenating agents (FHWA, 1990).

The cleaning of OGFC in the US is not a common practice. Most states don't take any measures to prevent the pore clogging of OGFC. Some studies show that for OGFC used in interstate and high-level roads, the fast moving traffic can help keep the pores of OGFC from being clogged with debris (Advanced Asphalt Technologies, 2011).

DGHMA is most commonly used for repairing potholes in OGFC. New Mexico uses proprietary cold mixes QPR and UPM for pothole repair. In Arizona, UPM material or cold patching are used, while Florida uses OGFC material as permanent patches. Another survey showed that Texas used a proprietary OGFC patching mix for small patches, but for large patches they still used DGHMA (Cooley Jr et al., 2009). For interstates with significant patching required, Georgia usually replaced it with new OGFC through milling and complete replacement (Cooley Jr et al., 2009).

According to the survey, 9~12 years is the common service life for OGFC before rehabilitation is conducted. One former survey (Cooley Jr et al., 2009) showed that the life of OGFC ranged from less than six years to as high as 15 years based on various factors, such as traffic volume, climate, etc.

8.2 Recommendations for Improving Performance of OGFC and Its Maintenance

Based on the results from the DOT survey and existing studies, the following provides the measures frequently applied to address the typical issues with OGFC:

- Approaches for correcting **raveling**: according to the results from the survey, 75% of the states used fog seal, while some states applied the removal and replacement, and others used a mixture with an increased optimum binder content. Many states reported that the fog sealing had a negative impact on the permeability of the OGFC. FHWA recommended applying fog seals in two passes at the rate of 0.05 gallon/yard^2 for each pass.
- **Clogging**: cleaning with a fire hose or high-pressure cleaner;
- **Ice removal induced damage**: when significantly damaged, using removal-and-replacement.
- **Stripping**: patching with bituminous concrete; liquid antistrips in limestone mixtures and hydrated lime in granite; fog seal.
- **Pothole**: patching with a DGHMA is typically used. According to FHWA, DGHMA mixture is more appropriate when the patching area is relatively small (less than 18 in. by 18 in.). Otherwise, the area should be repaired by using an OGFC mixture to consider drainage continuity. For TDOT’s cold patching material, adding 3% cement is suggested to improve the indirect shear strength and moisture damage

resistance.

- **Rutting**: patching is typically used. Some used polymer or rubber-modified PG 76-22 or a higher-grade asphalt binder.
- **Delamination**: removal-and-replacement is most frequently used. Some suggested using a chip seal or a thin overlay
- **Load-related distress**: removal-and-replacement is typically engaged.
- **Time of maintenance**: most of the agencies conduct maintenance during spring and summer.

For the rehabilitation of OGFC, most states followed the action set of milling, recycling, then inlaying. It is noted that when inlaying the OGFC, cautions should be taken to avoid the creation of an impermeable vertical wall at the lower side of the inlay, which may cause potential ponding water. When rehabilitation is needed, most states adopt the practice of milling and replacing the existing OGFC with new OGFC; many agencies advise against the application of new DGHMA mixture over the damaged old OGFC layer.

8.3 Recommendations for Winter Maintenance Practice

Winter maintenance of OGFCs needs to be carefully considered because snow and ice accumulate differently on OGFC pavements than on traditional pavements (Yildirim, Dossey, Fults, & Trevino, 2006). Due to its higher air voids, OGFC does not insulate like pavement with DGHMA. Typically, its temperature is about two Celsius degrees lower than pavements using DGHMA, thus resulting in earlier and more frequent frost and ice formation (Estakhri, Alvarez, & Martin, 2008). In addition, after frost and ice are formed in an OGFC, it stays freezing longer compared with regular DGHMA pavements, thus leading to a longer period with inadequate pavement friction.

Therefore, OGFC requires specific winter maintenance practices. In general, winter maintenance techniques for OGFC include liquid de-icing agent, anti-icing agent, sanding, snow plowing, and advisory signs. Unlike the de-icing agent which attempts to remove ice or snow already on the road surface, the anti-icing agent prevents ice or snow from forming on the road surface. Typically, ice or snow on OGFC pavements is more difficult to deal with, as more factors are to be considered when applying anti-icing procedures, such as temperature, the amount of moisture, and traffic conditions. In addition to these conventional practices, according to a study in Texas, it was suggested that pavement condition sensors, meteorological instrumentation, and connecting hardware and software should be used to monitor the road system and support the decision process involving winter maintenance practices (Estakhri, Alvarez, & Martin, 2008).

Based on previous studies, especially the practice of TxDOT, the liquid de-icing agents are currently considered as the most effective winter treatment. The anti-icing agents may produce the best result to combat black ice, freezing rain, and light snow events. However, de-icing procedures generally do not maintain safe road conditions compared with anti-icing procedures, since de-icing procedures are reserved for events when ice and snow have already bonded (Putman, 2012). Also, more de-icing agents (or salt) and more frequent applications than on dense graded mixes are required to perform winter maintenance on OGFC, since the deicer can flow into the OGFC instead of remaining at the surface. Previous studies in Europe have shown that OGFCs require 25 to 50% more salt than regular DGHMA or even higher. In the DOT survey response, when asking about what measures are taken for winter maintenance of OGFC, one response also suggested that additional salting was required due to a migration of salt into the open pores.

Sanding procedures should only be used in emergent situations where significantly higher friction is needed. This is mainly because small sand particles will get into the pores of OGFC, which then cause clogging and reduce the draining benefits of OGFC. In the DOT survey, when asking about what measures are taken for winter maintenance of OGFC, one response indicated that they had eliminated the use of a sand/salt mixture, and primarily used brine or salt only for winter maintenance now.

An OGFC surface is prone to damages incurred by the snowplow blade. Therefore, snow plowing needs to be done carefully, and it is important to give special and repeated training to drivers of snowplows and spreaders. A response in the DOT survey suggested using specialty snowplow blades to consider the wearing of the snowplow blades.

For the winter maintenance to be effective, the timing of application is crucial. In general, it requires more accurate weather information, flexible de-icing operations, more flexible choices of chemicals to handle different conditions. To achieve effective OGFC winter maintenance, TxDOT suggests using a pavement temperature management system with real-time pavement temperature along with moisture measurements, so that the prediction of potential future hazardous conditions on the OGFC surface is feasible (Root, 2009).

8.4 Conclusions

In this chapter, the responses from the DOT survey about the current practice of maintenance strategies for OGFC were summarized. According to the analyses on the LTPP data and the DOT survey response, recommendations on guidelines for maintaining OGFC pavement were made to correct different distresses. In particular, the winter maintenance of OGFCs needs to be carefully considered because snow and ice accumulate differently on OGFC pavements than on traditional pavements. Conventional winter maintenance techniques for OGFC were analyzed and the pavement temperature management system was suggested to assist in developing effective OGFC winter maintenance strategies. It should be noted that a few of the questions in the survey did not acquire enough responses to reach generalized findings as shown in the appendix. Also, a follow-up study is recommended to get more detail on the vague responses in the survey.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

For OGFC pavements, there is an urgent need to evaluate current maintenance methods and to explore innovative maintenance methods and strategies, so that OGFC performance can be maintained and its service life can be extended. This project identified current and potential practices for OGFC pavement preservation/maintenance strategies in Tennessee and other states, and laboratory tests, field tests and, data analyses were conducted for this purpose. This project will benefit the TDOT by providing best practices for OGFC pavement preservation/maintenance strategies, extending the service life of OGFC pavements; and maintaining a safe driving environment and economic efficiency. The main conclusions are summarized as follows:

- Laboratory tests were conducted on the selection of OGFC patching materials. The adhesiveness, cohesion, moisture susceptibility, and permeability performance were investigated on TDOT cold patching material, Aquaphalt, and EZ patching material. Because of its mechanical, permeability, adhesiveness, and cohesion performance, the TDOT cold patching material was recommended as the patching material for OGFC pavement. Adding cement could slightly decrease the permeability of patching material. However, dosing 3% of cement into TDOT cold patching material was suggested to improve its indirect shear strength and moisture damage resistance.

- The fog sealing treatment was applied in an OGFC pavement section of the eastbound I-40 in west Tennessee. Samples were cored from both the traffic lane and the shoulder in the field before and after the treatment. Applying fog seals decreased the permeability of the lane and the shoulder. As the application rate of fog sealing increased, the permeability was further reduced. The fog seal treatment also decreased the texture depth of the traffic lane and the shoulder. The application of fog seal could significantly reduce the abrasion loss, which was reduced by about 50% in the traffic lane, indicating that it could increase the durability of OGFC pavement. The reduced texture depth caused by fog sealing could be restored by a further abrasion test, indicating that the skid resistance of OGFC could initially be reduced due to fog sealing, but it may then be restored to a certain extent by moving vehicles after opening to traffic.
- The OGFC performance data from TDOT and other DOTs or agencies were collected and analyzed. The results showed that OGFC pavements provided better friction properties than SMA and DGHMA. When considering rut depth, IRI, and cracking, OGFC provided comparable performances with conventional dense-graded mixtures. Additionally, the accident rate and noise

level of OGFC pavements were significantly lower than their DGHMA counterparts.

- In Tennessee, because most of the OGFCs were paved within the recent three years, very few cracks were observed. The rut depth of OGFC was around 0.1 in, and most sections of OGFC were free of cracking. During the OGFC service life, the longitudinal cracking in lanes was generated and developed first, followed by the longitudinal cracking (non-lane), the fatigue cracking, the transverse cracking, and the block cracking. It is the longitudinal cracking affecting the durability of OGFC pavement the most.
- The effectiveness of different maintenance treatments was investigated using the data retrieved from the LTPP database. In the US, overlaying with dense-grade hot-mix asphalt or hot-mix recycled asphalt mixture is most commonly used to maintain OGFC pavements. The treatment times of crack sealing, sand sealing, slurry sealing, fog sealing, aggregate sealing, pothole patch, and premix patch on OGFC were determined to be 8.40, 5.25, 3.70, 11.53, 5.77, 10.14, and 8.07 years, respectively.
- The crack sealing and fog sealing did not noticeably improve crack resistance according to the fatigue cracking and block cracking data, while fog sealing was effective in retarding the development of non-wheel path longitudinal

cracking. The aggregate sealing was beneficial in reducing fatigue cracking and wheel path longitudinal cracking.

- The crack sealing, slurry sealing, and aggregate sealing were more effective in mitigating IRI over the years in the survey period. The premix patching had adverse effects on maintaining pavement smoothness (IRI). After the treatments, the seven treatments generally helped to reduce IRI, while the IRI drop data after crack sealing and pothole patching were more scattered.
- In Tennessee, the AC overlay treatment (T1) was the most commonly used method, which was generally applied in the eighth year of service. The treatment time of crack sealing (T5) was nearly the same as T1, and the treatment time of aggregate sealing and slurry seal was in the third year of service. In general, the AC overlay (T1) decreased the occurrence of fatigue cracking, block cracking, wheel and non-wheel path longitudinal cracking, and IRI.
- In this study, the responses from DOT survey about maintenance strategies for OGFC were summarized. Based on the analyses on the LTPP data and the DOT survey responses, strategies for OGFC maintaining were recommended to address the typical issues with OGFC. In addition, based on previous studies, conventional winter maintenance techniques for OGFC were briefly discussed.

Limitations and Recommendations

On the basis of the conclusions obtained in this study, the following recommendations can be made:

- The tests conducted in this study primarily focused on the laboratory performance of fog sealing treated OGFC cores. More studies on evaluating the field performance of OGFC pavements using fog sealing are recommended, which will help better understand the effects of fog sealing on OGFC maintenance.
- Special actions should be given to winter maintenance of OGFCs, as snow and ice accumulate differently on OGFC pavements than on traditional ones. The pavement temperature management system is suggested to promote effective OGFC winter maintenance, and an in-depth investigation of OGFC winter maintenance in Tennessee is recommended in the future.
- The distress data collected in Tennessee were from limited projects, and most of the projects were paved within the recent three years. The conclusiveness of findings in this study needs to be verified with more monitoring data in the future.
- A few of the questions in the survey did not acquire enough responses to reach generalized findings as shown in the appendix. A follow-up study is recommended to clarify some specific measures in certain states and to include OGFC winter maintenance in the future.

REFERENCE

Abadie, C. (2013). Evaluation of open graded friction course (OGFC) mixtures. *FHWA/LA. 13, 513*

Advanced Asphalt Technologies, L. (2011). *A Manual for Design of Hot Mix Asphalt with Commentary* (Vol. 673): Transportation Research Board.

Alvarez, A. E., Martin, A. E., & Estakhri, C. (2011). A review of mix design and evaluation research for permeable friction course mixtures. *Construction and Building Materials, 25*(3), 1159-1166

Alvarez, A. E., Martin, A. E., Estakhri, C. K., Button, J. W., Glover, C. J., & Jung, S. H. (2006). *Synthesis of current practice on the design, construction, and maintenance of porous friction courses*.

Balla, C. K. (2010). Prediction of remaining service life of pavements

Carey Jr, W. N., & Irick, P. E. (1960). The pavement serviceability-performance concept. *Highway Research Board Bulletin*(250)

Chatterjee, S., White, R. P., Smit, A., Prozzi, J., & Prozzi, J. A. (2006). *Development of mix design and testing procedures for cold patching mixtures*.

Chen, J.-S., & Huang, C.-C. (2010). Effect of surface characteristics on bonding properties of bituminous tack coat. *Transportation Research Record: Journal of the Transportation Research Board*(2180), 142-149

Chen, X., Zhu, H., Dong, Q., & Huang, B. (2017). Case study: performance effectiveness and cost-benefit analyses of open-graded friction course pavements in Tennessee. *International Journal of Pavement Engineering, 18*(11), 957-970

Collins, R., Shami, H., & Lai, J. (1996). Use of Georgia loaded wheel tester to evaluate rutting of asphalt samples prepared by Superpave gyratory compactor. *Transportation Research Record: Journal of the Transportation Research Board*(1545), 161-168

Cooley Jr, L. A., Brumfield, J. W., Mallick, R. B., Mogawer, W. S., Partl, M. N., Poulikakos, L. D., & Hicks, G. (2009). *Construction and maintenance practices for permeable friction courses*.

Cooley, L., Kandhal, P. S., Buchanan, M. S., Fee, F., & Epps, A. (2000). *Loaded wheel testers in the United States: State of the practice*: Transportation Research Board, National Research Council.

Dennis, B. C. (2007). Inc. Improved Porous Friction Courses (PFC) on Airfield Pavements–Volume I. Airfield Asphalt Pavement Technology Program Project 04-06.

Dong, Q., & Huang, B. (2011). Evaluation of effectiveness and cost-effectiveness of asphalt pavement rehabilitations utilizing LTPP data. *Journal of Transportation Engineering, 138*(6), 681-689

Dong, Q., Wu, H., Huang, B., Shu, X., & Wang, K. (2012). Investigation into laboratory abrasion test methods for pervious concrete. *Journal of Materials in Civil Engineering, 25*(7), 886-892

Durante, C., & Johns, C. (2014). *Maintenance of OGFC pavements - The North Carolina experience (https://pavementvideo.s3.amazonaws.com/2014_MPPP/PDF/43%20-%20Maintenance%20of%20OGFC%20Pavements%20-%20Jones.pdf)*.

Estakhri, C. K., & Agarwal, H. (1991). *Effectiveness of fog seals and rejuvenators for bituminous pavement surfaces*: Texas Transportation Institute, Texas A & M University.

Estakhri, C. K., Alvarez, A. E., & Martin, A. E. (2008). Guidelines on construction and maintenance of porous friction courses in Texas

Ferguson, B. K. (2005). *Porous pavements*: CRC Press.

FHWA. (1990). *Open-Grade Friction Courses FHWA Mix Design Method - Technical Advisory T 5040.31*. Washington D.C.: U. S. D. o. T. Federal Highway Administration.

Flintsch, G., de León, E., McGhee, K., & AI-Qadi, I. (2003). Pavement surface macrotexture measurement and applications. *Transportation Research Record: Journal of the Transportation Research Board*(1860), 168-177

Gong, H., Dong, Q., Huang, B., & Jia, X. (2015). Effectiveness analyses of flexible pavement preventive maintenance treatments with LTPP SPS-3 experiment data. *Journal of Transportation Engineering, 142*(2), 04015045

Hernandez-Saenz, M. A., Caro, S., Arámbula-Mercado, E., & Martin, A. E. (2016). Mix design, performance and maintenance of Permeable Friction Courses (PFC) in the United States: State of the Art. *Construction and Building Materials, 111*, 358-367

Hicks, R., & Holleran, G. (2002). Purpose and Use of Fog Seals and Rejuvenators: Sealer Binder Workshop, Foundation For Pavement Preservation, Federal Highway Administration.

Huang, B., Mohammad, L. N., & Chris Abadie, P. (1999). Fundamentals of Permeability in Aspbalt Mixtures *The Annual Meeting of the Association of Asphalt Paving Technologist*.

Huber, G. (2000). *Performance survey on open-graded friction course mixes* (Vol. 284): Transportation Research Board.

Hveem, F., & Carmany, R. (1949). The factors underlying the rational design of pavements *Highway Research Board Proceedings* (Vol. 28).

Isenring, T., Koster, H., & Scazziga, I. (1990). Experiences with porous asphalt in Switzerland. *Transportation Research Record*(1265)

Johanns, M., & Craig, J. (2002). Pavement maintenance manual. *Nebraska: Department of Road*, 5-10

Kabir, M., Icenogle, P., King Jr, W., & Abadie, C. (2011). Performance of Superpave Projects in Louisiana. *Transportation Research Record: Journal of the Transportation Research Board*(2207), 16-24

Kandhal, P. S., & Association, N. A. P. (2002). *Design, construction, and maintenance of open-graded asphalt friction courses*: National Asphalt Pavement Association.

Kandhal, P. S., & Cooley, L. A. (2003). *Accelerated laboratory rutting tests: Evaluation of the asphalt pavement analyzer*: Transportation Research Board.

Kandhal, P. S., & Mallick, R. B. (1998). Open-Graded Asphalt Friction Course: State of the Practice. *National Center for Asphalt Technology Report*(98-7)

Kevern, J. T. (2011). Operation and maintenance of pervious concrete pavements *Transportation Research Board Annual Meetings* (pp. 23-27).

King Jr, W., Kabir, S., Cooper Jr, S. B., & Abadie, C. (2013). *Evaluation of open graded friction course (OGFC) mixtures*.

Kline, L. C. (2010). *Comparison of open graded friction course mix design methods currently used in the United States.* Clemson University.

Maher, A., Gucunski, N., Yanko, W., & Petsi, F. (2001). *Evaluation of pothole patching materials*.

Mallick, R., Kandhal, P., Cooley, L. A., & Watson, D. (2000). Design Construction and Performance of New-

Generation Open-Graded Friction Courses. *Asphalt Paving Technology, 69*, 391-423

Mallick, R. B., Kandhal, P., Cooley, L. A., & Watson, D. (2000). Design, construction, and performance of new-generation open-graded friction courses. *Asphalt Paving Technology, 69*, 391-423

Mamlouk, M. S., & Dosa, M. (2014). Verification of effectiveness of chip seal as a pavement preventive maintenance treatment using LTPP data. *International Journal of Pavement Engineering, 15*(10), 879-888

Manual, A. B. A. E. (1997). Manual Series No. 19. *Asphalt Emulsion*

McDaniel, R. (2010). *Performance and maintenance of OGFC surfaces (https://engineering.purdue.edu/NCSC/services/2010%20Presentations/Performance%20and%20Maintenance%20of%20OGFC%20Surfaces.pdf)*.

Nielsen, C. B. (2006). *Durability of porous asphalt: International experience*.

Peshkin, D. G., Hoerner, T. E., & Zimmerman, K. A. (2004). *Optimal timing of pavement preventive maintenance treatment applications* (Vol. 523): Transportation Research Board.

Prapaitrakul, N., Freeman, T., & Glover, C. J. (2005). *Analyze existing fog seal asphalts and additives: Literature review*.

Program, N. C. H. R., Highway, A. A. o. S., Officials, T., & Advanced Asphalt Technologies, L. (2011). *A Manual for Design of Hot Mix Asphalt with Commentary* (Vol. 673): Transportation Research Board.

Prowell, B. D., & Franklin, A. G. (1996). Evaluation of cold mixes for winter pothole repair. *Transportation research record, 1529*(1), 76-85

Putman, B. J. (2012). Evaluation of Open-Graded Friction Courses: Construction, Maintenance, and Performance. *Rep. No. FHWA-SC-12-04, Clemson Univ., South Carolina Dept. of Transportation*

Rogge, D. (2002). Development of maintenance practices for Oregon F-mix: final report

Rogge, D., & Hunt, E. (1999). Development of maintenance practices for Oregon F-mix: interim report

Rogge, D., & Hunt, E. A. (1999). *Development of maintenance practices for Oregon F-Mix*.

Root, R. E. (2009). *Investigation of the use of open-graded friction courses in Wisconsin*.

Roque, R., Koh, C., Chen, Y., Sun, X., & Lopp, G. (2009). Introduction of fracture resistance to the design and evaluation of open graded friction courses in Florida

Shatnawi, S., & Toepfer, B. (2003). Fog Seal Guidelines. *Office of Flexible Pavement Materials, Sacramento (CA)*, 20

Skok, E. L., Johnson, E. N., & Turk, A. (2002). Asphalt pavement analyzer (APA) evaluation

Song, W., Shu, X., Huang, B., & Woods, M. (2015). Factors affecting shear strength between open-graded friction course and underlying layer. *Construction and Building Materials, 101*, 527-535

Song, W., Shu, X., Huang, B., & Woods, M. (2016). Laboratory investigation of interlayer shear fatigue performance between open-graded friction course and underlying layer. *Construction and Building Materials, 115*, 381-389

Song, W., Shu, X., Huang, B., & Woods, M. (2017). Influence of interface characteristics on the shear performance between open-graded friction course and underlying layer. *Journal of Materials in Civil Engineering, 29*(8), 04017077

Tam, K. K. (1987). *New Methods for Testing Workability and Cohesion of Cold Patching Material*: Ontario Ministry of Transportation, Engineering Materials Office.

Thomas, H. R., & Anderson, D. A. (1986). Pothole repair: you can't afford not to do it right. *Transportation Research Record*(1102)

Varadhan, A. (2004). *Evaluation of open-graded and bonded friction course for Florida.* University of Florida.

Wang, H., & Flintsch, G. W. (2007). Investigation of Short-and Long-Term Variations of Pavement Surface Characteristics at the Virginia Smart Road *Transportation Research Board 86th Annual Meeting*.

Wimsatt, A., & Scullion, T. (2003). Selecting Rehabilitation Strategies for Flexible Pavements in Texas *Transportation Research Board 82nd Annual Meeting. Washington DC, USA*.

Wu, H., Huang, B., Shu, X., & Dong, Q. (2010). Laboratory evaluation of abrasion resistance of Portland cement pervious concrete. *Journal of Materials in Civil Engineering, 23*(5), 697-702

Yildirim, Y., Dossey, T., Fults, K. W., & Trevino, M. (2006). *Winter maintenance issues associated with new generation open-graded friction courses*.

Zoorob, S., Collop, A., & Brown, S. (2002). Performance of Bituminous and Hydraulic materials in Pavements

APPENDIX A: DOT SURVEY RESPONSE

The University of Tennessee

Maintenance Strategies for Open-graded Friction Course (OGFC)

Open graded friction course (OGFC) is a thin layer of permeable asphalt placed on a dense graded asphalt pavement. Proper maintenance of OGFC is critical to keep its functionality and to extend its service life. This questionnaire is prepared jointly by the University of Tennessee-Knoxville (UTK) and the Tennessee Department of Transportation (TDOT), with the aim to identify the best practices for OGFC pavement preservation/maintenance strategies to TDOT as well as other state DOTs.

1. Do you currently use OGFC in your state?

   a. Yes

   b. No

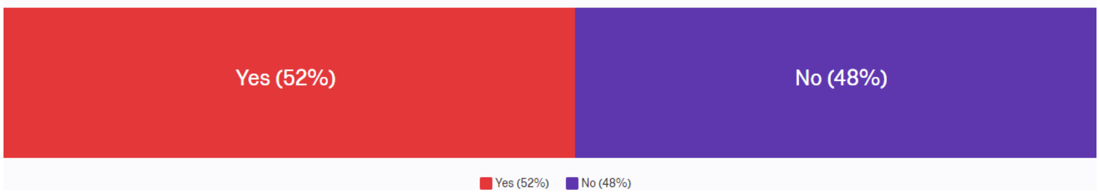


Figure A-1 Number of states using OGFC

2. How many years after OGFC in service is the first-time maintenance conducted?

a. < 3

b. 3~5

c. 6~8

d. >9

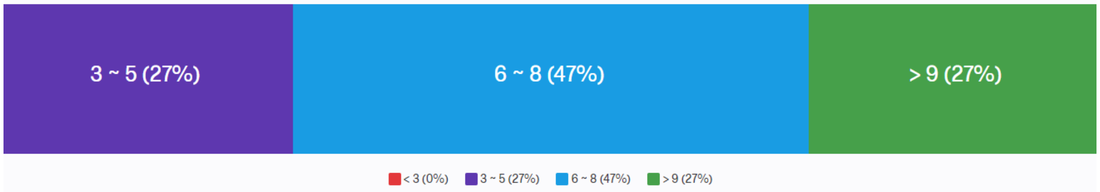


Figure A-2 OGFC first maintenance

3. What distresses do encounter with OGFC pavements? (Multiple choice)

a. Raveling

b. Pore clogging

c. Ice removal damage

d. Stripping

e. Rutting

f. Delamination

g. Load related cracking

h. Weather related cracking

i. Transverse cracking

j. Other distresses

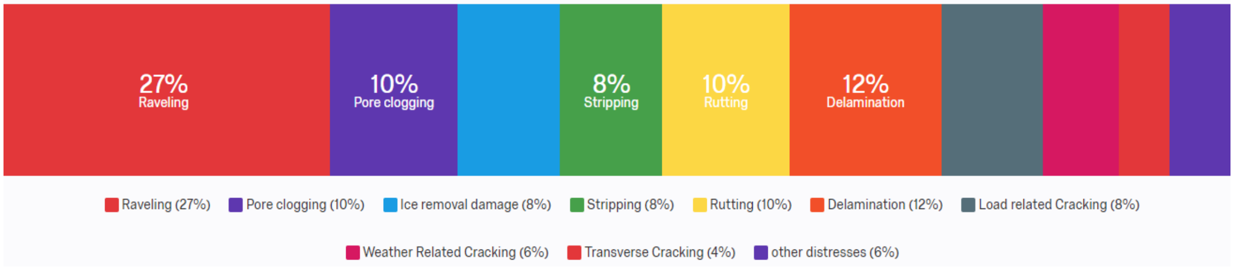


Figure A-3 OGFC distresses

4. If the answer to Q3 includes j. (Other distresses), what are the distresses?

- Raveling is most prominent at initial paving joint
- Increased salt usage due to residual displacement
- Potholes
- Occasional bleeding, not common.
- Not very often we see the above distresses
- Longitudinal cracking at joints

5. What measures are taken to deal with raveling?

a. Fog seal treatment

b. Chip seal treatment

c. Other treatment methods (please list below)

- Patching
- Currently none, removal and replacement
- Increase the optimum binder content recently

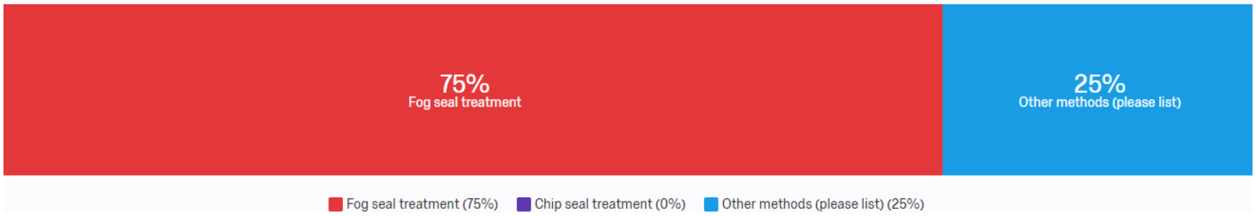


Figure A-4 Measures taken to deal with raveling

6. If fog seal treatment is conducted to deal with raveling in Q5, what is the type of fog seal material? (please list)

- We are looking into beginning a program to place a rejuvinating fog seal on all routes over 5 years and continue a cycle.
- SS-1 asphalt
- SS-1
- Rejuvinating fog seal - implementing our first project for this.
- Polymer modified emulsion
- Emulsified Asphalt (CRS-2P)
- CSS-1, TRMSS
- CSS 1p or CQS 1p mostly.

7. What effects do the treatment methods in Q5 have on OGFC performance (permeability, texture depth, skid resistance, durability …)? (please list)

- Where there is rutting and surface coat loss, we replace with traditional hot mix bituminous concrete.

- Permeability and some longevity.
- Nothing that we have quantified. The permeability was probably decreased a little when we increased the optimum AC content.
- No effect on permeability has been shown. We understand that there is a reduction in skid resistance for the first few days of application
- Hopefully will reduce raveling and only temporarily reduce skid resistance.
- Durability

8. What measures are taken to deal with pore clogging?

a. Cleaning OGFC with a fire hose

b. Cleaning OGFC with a high pressure cleaner

c. Cleaning OGFC with specially cleaning vehicle

d. Other methods (please list)

<u>Sweeper, which is not always successful</u>

e. None

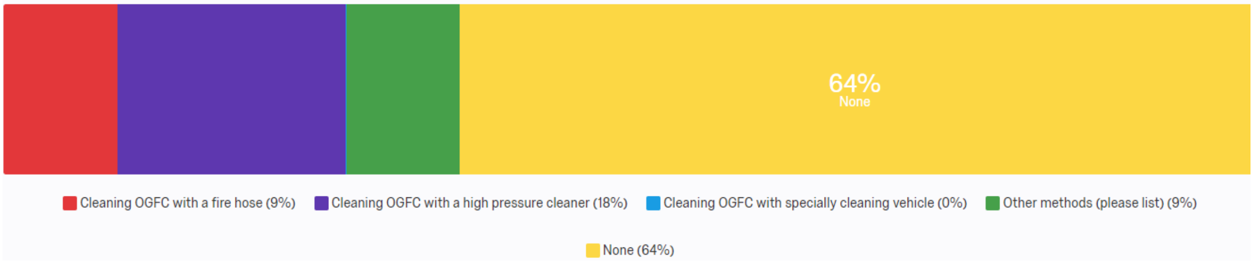


Figure A-5 Measures taken to deal with pore clogging

9. What measures are taken to deal with ice removal damage? (please list)

- N/A
- Patching with bituminous concrete.
- Not many. If significantly damaged, we provide a new wearing course.
- Ice is not a problem in our State where OGFC is used.
- None that we know of at this point, we have witnessed some enhanced degradation.
- None

10. What measures are taken to deal with stripping? (please list)

- N/A
- Patching with bituminous concrete.
- Investigate to determine the cause of failure, then depending how severe generally the pavement needs to be removed and replaced after correction of any subsurface drainage issues.
- We require liquid antistrips in limestone mixtures and hydrated lime in granite mixtures.
- Fogging
- None, but fog seal should help with that
- None

11. What measures are taken to deal with rutting? (please list)

- N/A
- Patching with bituminous concrete.
- Don’t see a lot of rutting in NM. Depending on how bad we may do some micro milling and chip seal or other wearing course.
- Modified (polymer or rubber) PG 76-22 or higher binder grade

12. What measures are taken to deal with delamination? (please list)

- Patching with bituminous concrete.
- Patching and then mill & replace.
- Hasn't been an issue, although we have recently increased the required tack spread rate for all mixtures.
- Remove and replace
- None
- None, other than improved construction practices. Bad areas are patched with a dense hot mix product.

13. What measures are taken to deal with load related cracking? (please list)

- N/A
- Crack seal when available.

- Really depending on the severity but sometimes we can get away with an HIR and overlay. If the subgrade is intact. Otherwise we get in there and repair the failure.
- All OGFCs contain mineral or cellulose fibers to increase the AC content. All OGFCs contain rubber or polymer modified binders with a PG 76-22 or higher grade
- Remove and replace
- Crack sealing

14. What measures are taken to deal with weather related cracking? (please list)

- N/A
- Patching with bituminous concrete.
- Patching and then mill & replace.
- Environmental cracking is usually dealt with crack seal or fog seal.
- Not an issue in our State where OGFC is used.
- Rehabilitation every 10-12 years.
- Crack sealing

15. What measures are taken to deal with the transverse cracking? (please list)

- N/A
- Patching with bituminous concrete.

- Depends of the severity.
- None specifically for OGFC
- Rehabilitation every 10-12 years
- None, but we are looking into crack sealing for transverse cracks
- Crack sealing

16. What measures are taken for winter maintenance of OGFC? (please list)

- Salt and cinders
- Not an issue in our State
- None
- We are discouraging the use of brine application verses rock salt application.
- Eliminated the use of placement of a sand/salt mixture. Primarily use applications of brine or salt only for winter maintenance.
- Plow blade wear considerations (specialty plow blades) and additional salting if residual is loss due to salt migration into the open grade.

17. If stripping, rutting and cracking are encountered, what measures are taken to deal with these problems? (please list)

- Depends of the severity, but probably a mill and inlay or maybe heater scarification.
- The area would be removed and replaced.

- Rehabilitation every 10-12 years
- None
- Once performance is deteriorated, it is milled off and replaced.
- Removal
- Repairs, maintenance with traditional measures.

18. In what season of a year is OGFC maintenance usually conducted?

a. Spring

b. Summer

c. Autumn

d. Winter

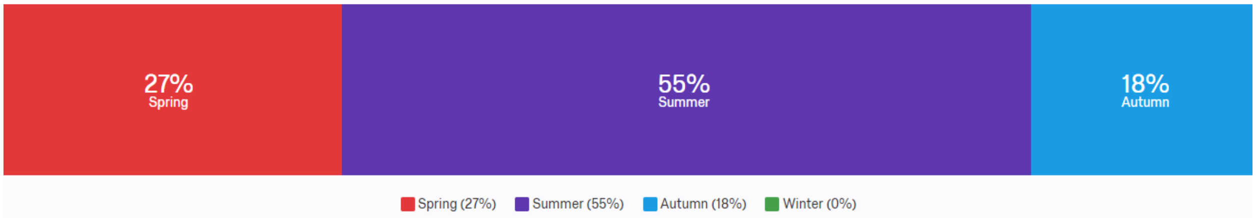


Figure A-6 Time for OGFC maintenance conduct

19. If potholes appear, what kind of repair material is used for the repair?

a. Dense graded HMA mix

b. OGFC

c. Other mixtures (please list below)

QPR, UPM (NM)

UPM material or cold patch (AZ)

OGFC for permanent patches. Sometimes a dense graded mix is utilized temporarily. (FL)

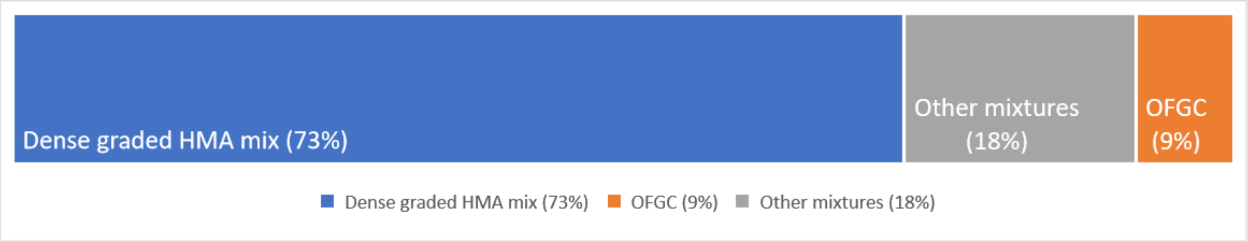


Figure A-7 Materials used for the pothole repair

20. Is rehabilitation ever conducted on OGFC surface layer?

a. Yes

b. No

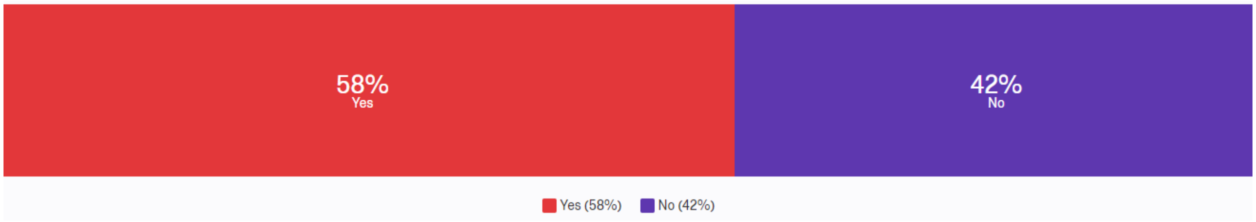


Figure A-8 Rehabilitation

21. If the answer to Q13 is Yes, how many years after OGFC in service is rehabilitation conducted?

a. < 5

b. 5~8

c. 9~12

d. > 12

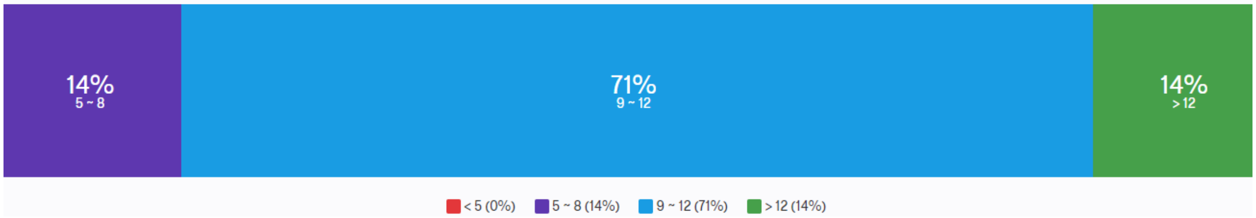


Figure A-9 Number of years for rehabilitation conduct

22. If preservation treatments are used to deal with OGFC distress, how is the performance of this preservation measured and monitored? (please list)

- Measured by the Lane Mile, monitored by performance.
- N/A
- Field Visits
- We do not have a good way to measure the increased service life.
- We are just beginning to use a fog seal application.
- Not in our program but applications being considered.