

Optimize Application of Open Graded Friction Courses (OGFC) in Tennessee

Submitted to the Tennessee Department of Transportation
Research Development and Technology Program

Xiang Shu, Ph.D., P.E.

Baoshan Huang, Ph.D., P.E.

Weimin Song, Ph.D.

The University of Tennessee, Knoxville

Mbakisya A. Onyango, Ph.D.

The University of Tennessee at Chattanooga

August 2017

Technical Report Documentation Page

1. Report No. RES2013-34	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle <i>Optimize Application of Open Graded Friction Course (OGFC) in Tennessee</i>	5. Report Date March 2017		
	6. Performing Organization Code		
7. Author(s) Xiang Shu, Baoshan Huang, Weimin Song	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 Tennessee Department of Transportation James K. Polk Bldg., Suite 700 505 Deaderick Street, Suite 900 Nashville, TN 37243	13. Type of Report and Period Covered		
	14. Sponsoring Agency Code HFTS-16.4		
15. Supplementary Notes			
16. Abstract In this study, optimize application of open graded friction course (OGFC) was evaluated. Two types of OGFC (limestone and gravel), eight types of underlying layers and two types of tack coat were used. Cantabro loss test and permeability test were conducted, OGFC with limestone aggregate showed larger Contabro loss and larger permeability. The bonding property between OGFC and underlying layers were conducted by two test methods: direct shear strength test and direct shear fatigue test. In the direct shear strength test, shear strength and direct shear stiffness were recorded to evaluate the bonding property. In the direct shear test, the influence of temperature, tack coat application rate and the type of underlying layer were explored. The conventional 50% stiffness reduction method, ratio of dissipated energy change (RDEC) and cumulative dissipated energy were selected to analyze the fatigue performance. The interface characteristics between OGFC and underlying layer were analyzed and correlated with the shear performance between OGFC and underlying layer. The cohesive failure area, adhesive failure area and the non-contact area in the interface were determined. The cost-benefit of OGFC pavement was analyzed considering the accident rate in different weather condition. Compared analysis was made between OGFC pavement and the traditional dense asphalt pavement. A survey was conducted by the University of Tennessee to States Departments of Transportation to collect information on the state of OGFC in the US. The survey may provide help and guide in the application use of OGFC in Tennessee.			
17. Key Words OPEN-GRADED FRICTION COURSE; SHEAR STRENGTH; FATIGUE; UNDERLYING LAYER; INTERFACE CHARACTERISTICS; COST-BENEFIT		18. Distribution Statement No restriction. This document is available to the public from the sponsoring agency at the website https://www.tn.gov/	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages xxx	22. Price

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 #: 2013-34, Research Project Title: Optimize Application of Open Graded Friction Course (OGFC) in Tennessee.**

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

Optimize application of open-graded friction course (OGFC) was conducted in this study. Two types of OGFC (limestone and gravel), seven types of underlying layers (TLD, BM, BM2, SMA, D, CS64-22 and CS76-22) and two types of tack coat materials (anionic asphalt emulsion and ultrafuse tack coat) were selected in this study.

Cantabro loss test and permeability test of OGFC were conducted first. OGFC with limestone aggregate (OGFC1) showed larger Cantabro loss and permeability. To evaluate the bonding property between OGFC and underlying layer, the direct shear strength test and direct shear fatigue test were conducted. In the strength test, the shear strength and the direct shear stiffness were recorded. Texture depth is one important factor affecting the shear strength between OGFC and underlying layers. The larger the texture depth, the larger the interlock effect between OGFC and underlying layer, the larger the shear strength.

Besides the texture depth, temperature and tack coat application rate are also the influential factors affecting the shear strength between OGFC and underlying layer. At low to intermediate temperatures (0 °C to 25 °C), tack coat rate played a significant role in shear strength. However, at high temperature (50 °C), tack coat application rate did not cause significant change in shear strength. The optimal tack coat was not only affected by temperature, but also underlying layer. The effect of surface texture depth of underlying layer on shear strength was influenced by tack coat application rate, and vice versa. At low texture depth or low tack coat rate, the other factor became insignificant.

In the fatigue test, fatigue life, cumulative dissipated energy, and RDEC were used to analyze the fatigue behavior of the composite specimens. The contact area plays the key role in the shear fatigue performance. The larger the contact area, the better the shear fatigue performance. The underlying layer with finer aggregates gives larger contact area between OGFC and the underlying layer. In this study, the fatigue life of OGFC-TLD was longer than that of OGFC-BM. With the increase in tack coat dosage, the number of loading

cycle to failure decreased, which may be attributed to the lubricating effect of tack coat. The plateau value (PV) of OGFC-TLD was lower than that of OGFC-BM under the same

Because of the complicated interface between OGFC and the underlying layer, the effect of the interface characteristics on the shear performance between OGFC and underlying layer was further evaluated. Adhesive and cohesive failure types on the interfaces were identified. Non-contact area between OGFC and the underlying was obtained.

Besides the bonding performance, the cost-benefit analysis was conducted. OGFC mixtures provided excellent performance and maintained comparable performance level as traditional dense mixture. Although the unit cost (\$/m³) of OGFC was about 42% higher than traditional dense mixture, it was observed that the accident rate could be significantly and continuously reduced, especially in rainy days. For some sections, the reduction in rainy days could be as high as 77.8%, indicating the long-term benefit of improved surface drainage and friction. The cost-benefit analyses based on the ratio of accident rate reduction over cost demonstrated that OGFC was significantly cost-beneficial in improving driving safety and reducing accident rate especially in rainy days.

Meanwhile, a survey was conducted by the University of Tennessee to States Departments of Transportation to collect information on the state of OGFC in the US.

Table of Contents

CHAPTER 1 INTRODUCTION	1
1.1 Problem Statement	1
1.2 Objectives.....	2
1.3 Scope of Study	2
CHAPTER 2 LITERATURE REVIEW	3
2.1 Introduction	3
2.2 Background	4
2.3 Literature review on OGFC testing method	11
2.3.1 Durability test.....	11
2.3.2 Mixture functionality test	12
2.3.3 Test methods about the bonding property between OGFC and underlying layer.....	13
CHAPTER 3 RESEARCH METHODOLOGY	17
3.1 Materials.....	17
3.1.1 Open Graded Friction Course	17
3.1.2 Underlying Layer	18
3.1.3 Tack Coat.....	18
3.2 Laboratory Performance Tests.....	19
3.2.1 Cantabro Loss Test	20
3.2.2 Permeability Test.....	20
3.2.3 Direct Shear Test	22
3.2.4 Direct Shear Fatigue Test	24
3.3 Specimen Preparation.....	25
3.3.1 Cantabro Loss Test	25
3.3.2 Permeability Test.....	26
3.3.3 Direct Shear Test and Fatigue Test.....	26
CHAPTER 4 LABORATORY TEST RESULTS AND DISCUSSION.....	28
4.1 Cantabro Loss Test.....	28
4.2 Permeability Test.....	29
4.3 Direct Shear Test	31
4.3.1 Shear Test Result for Single Tack Coat Application Rate and Temperature	31
4.3.2 Shear Test Result for Different Tack Coat Application Rates and Temperatures	34
4.3.2.1 Materials.....	34
4.3.2.2 Laboratory tests	35
4.3.2.3 Results and discussion.....	37
4.3.2.4 Statistical analysis	46
4.3.2.5 Summary and conclusions.....	48
4.4 Shear Fatigue Test	49

4.4.1 Methodology	50
4.4.2 Experiment design.....	51
4.4.2.1 Presentation of the test device	51
4.4.2.2 Experimental program and loading condition	51
4.4.3 Results and discussion.....	53
4.4.3.1 Stiffness approach	53
4.4.3.2 Ratio of dissipated energy change (RDEC).....	55
4.4.3.3 Cumulative dissipated energy	58
4.4.3.4 Interface Characterization	60
4.4.4 Summary and Conclusions.....	63
CHAPTER 5 INFLUENCE OF INTERFACE CHARACTERISTICS ON THE SHEAR PERFORMANCE BETWEEN OPEN-GRADED FRICTION COURSE AND UNDERLYING LAYER	65
5.1 Introduction.....	65
5.2 Objective and Scope.....	68
5.3 Experiment Program	68
5.3.1 Materials.....	68
5.3.2 Specimen Preparation.....	69
5.3.3 Direct Shear Test	70
5.3.4 Texture Depth Test	72
5.4 Results and Discussion.....	73
5.4.1 Texture Depth.....	73
5.4.2 Shear Strength and Stiffness.....	73
5.4.3 Interface Characteristics.....	74
5.5 Summary and Conclusions.....	82
CAPTER 6 COST BENEFIT ANALYSIS.....	84
6.1 OGFC Projects in PMS	84
6.2 Cost Analysis.....	84
6.3 Cost-benefit analysis	85
6.4 Accident rate reduction	86
6.5 Cost-benefit.....	89
6.6 Conclusions.....	90
CHAPTER 7 SUMMARY OF DOT SURVEY RESPONSE.....	92
CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS	119
REFERENCE.....	123

Figures

Figure 2- 1 Current use of OGFC in USA (Putman, 2012).....	10
Figure 2- 2 (a) Specimen loading and measurement system (b) cracking mechanism (Chen, et al. 2012)	14
Figure 3- 1 Aggregate gradation of OGFC.....	17
Figure 3- 2 Aggregate gradation of underlying layers	18
Figure 3- 3 Anionic asphalt emulsion	19
Figure 3- 4 Ultrafuse tack coat.....	19
Figure 3- 5 Los Angeles Abrasion machine	20
Figure 3- 6 Permeability test setup and sample.....	22
Figure 3- 7 Shear test setup and sample	23
Figure 3- 8 Strength-displacement curve	24
Figure 3- 9 Typical RDEC vs. number of loading cycle	25
Figure 3- 10 Underlying layer sample.....	27
Figure 3- 11 Tack coat was applied on the upper surface of underlying layer	27
Figure 3- 12 Specimens for shear test and fatigue test.....	27
Figure 4- 1 Initial specimen and final specimen	28
Figure 4- 2 Result of Cantabro Loss test.....	29
Figure 4- 3 Time vs Head (OGFC-1)	29
Figure 4- 4 Time vs. Head (OGFC-2)	30
Figure 4- 5 Hydraulic gradient vs. Discharge velocity (OGFC-1).....	30
Figure 4- 6 Hydraulic gradient vs. Discharge velocity (OGFC-2).....	30
Figure 4- 7 Permeability test result	31
Figure 4- 8 Shear strength OGFC1- Anionic Asphalt Emulsion	32
Figure 4- 9 Shear strength OGFC1-Ultrafuse Tack Coat	32
Figure 4- 10 Shear strength OGFC2-Anionic Asphalt Emulsion	32
Figure 4- 11 Shear strength OGFC2-Ultrafuse Tack Coat	33
Figure 4- 12 Shear stiffness OGFC1-Anionic Asphalt Emulsion	33
Figure 4- 13 Shear stiffness OGFC1-Ultrafuse Tack Coat.....	33
Figure 4- 14 Shear stiffness OGFC2-Anionic Asphalt Emulsion	34
Figure 4- 15 Shear stiffness OGFC2-Ultrafuse Tack Coat.....	34
Figure 4- 16 Aggregate gradation.....	35
Figure 4- 17 Texture depth test.....	36
Figure 4- 18 Schematic of surface asperity deformation (Xie, et al. 2011).....	37
Figure 4- 19 Effect of temperature on shear strength (OGFC2-SMA).....	38
Figure 4- 20 Failure modes of composite specimens at different temperatures	38
Figure 4- 21 Effect of tack coat rate on shear strength for different underlying layers.....	40
Figure 4- 22 Effect of underlying layer on shear strength at different temperatures.....	42
Figure 4- 23 Texture depth results for different layers	42
Figure 4- 24 Effect of texture depth of underlying layer on shear strength at different temperatures	

.....	43
Figure 4- 25 Section combined by OGFC and TLD	44
Figure 4- 26 Section combined by OGFC and D	44
Figure 4- 27 Section combined by OGFC and SMA	45
Figure 4- 28 Interfaces of OGFC with different underlying layers	45
Figure 4- 29 Roughness of different underlying layers	46
Figure 4- 30 Relationship between texture depth and interface roughness	46
Figure 4- 31 Typical RDEC vs. number of loading cycle	50
Figure 4- 32 Shear fatigue test	51
Figure 4- 33 Aggregate gradation	52
Figure 4- 34 Evolution of stiffness of OGFC-TLD at 0.4 MPa	54
Figure 4- 35 Comparison of stiffness of OGFC-BM and OGFC-TLD at 0.4 MPa	54
Figure 4- 36 Fatigue life results based on 50% stiffness reduction method	55
Figure 4- 37 Load-displacement hysteresis loops	56
Figure 4- 38 RDEC vs. number of loading cycle	56
Figure 4- 39 PV results	57
Figure 4- 40 PV vs. fatigue life	58
Figure 4- 41 Fitting between PV and fatigue life	58
Figure 4- 42 Total dissipated energy	59
Figure 4- 43 Total dissipated energy vs. number of loading cycle to failure	60
Figure 4- 44 Failure OGFC surface (OGFC-BM)	61
Figure 4- 45 Failure OGFC surface (OGFC-TLD)	62
Figure 4- 46 Results of contact area	62
Figure 4- 47 Contact area vs. fatigue life at tack coat rate 0.15 l/m ²	63
Figure 4- 48 Contact area vs. fatigue life at tack coat rate 0.30 l/m ²	63
Figure 5- 1 Aggregate gradation	69
Figure 5- 2 Direct shear test set up	71
Figure 5- 3 Strength-displacement curve	71
Figure 5- 4 Texture depth test	72
Figure 5- 5 Texture depth result	73
Figure 5- 6 Shear strength result	74
Figure 5- 7 Shear stiffness result	74
Figure 5- 8 Original failure interface	75
Figure 5- 9 Adhesive failure	76
Figure 5- 10 Non-contact area	76
Figure 5- 11 Results of adhesive failure area	77
Figure 5- 12 Results of cohesive failure area	77
Figure 5- 13 Results of non-contact area	78
Figure 5- 14 Comparison between D/d and texture depth	81
Figure 5- 15 Texture depth vs. shear property	82
Figure 6- 1 Cost comparison of OGFC and D mixture: (a) cost unit: \$/m ³ ; (b) cost unit: \$/m ² ...	85

Figure 6- 2 Accident rate: (a) all weather; (b) wet weather.....	88
Figure 6- 3 Accident rate reduction: (a) all weather; (b) wet weather.....	89
Figure 6- 4 Cost-benefit analysis: (a) overall accident reduction relative to cost; (b) accident reduction in rainy days relative to cost.....	90
Figure 7- 1 States that responded to the survey.....	94
Figure 7- 2 Percent of responded states	95
Figure 7- 3 Percent of responded states and the use of OGFC.....	95
Figure 7- 4 Reasons to why the states are not using OGFC any more.....	96
Figure 7- 5 Other reasons that lead to no using OGFC	97
Figure 7- 6 Usage of OGFC in tons per year	98
Figure 7- 7 Usage of OGFC on Roads	98
Figure 7- 8 Usage of OGFC in tons per year	99
Figure 7- 9 Is the state having a preferred pavement structure?.....	103
Figure 7- 10 Cost Difference between OGFC and dense graded HMAC (in%)	106
Figure 7- 11 Materials used as the interlayer for OGFC	107
Figure 7- 12 Performance of OGFC, very poor being 0%	108
Figure 7- 13 Percent of states using stabilizing agent.....	109
Figure 7- 14 Types of additives used.....	109
Figure 7- 15 Performance of OGFC with additives	110
Figure 7- 16 Performance of OGFC with additives	111
Figure 7- 17 Potential concerns for using OGFC.....	113
Figure 7- 18 OGFC pavements flushed or cleaned.....	113
Figure 7- 19 OGFC pavement cleaning methods.....	114
Figure 7- 20 Width of OGFC layer	114
Figure 7- 21 Paved shoulder width	116

Tables

Table 2- 1 OGFC-AR mix design binder properties for the three projects (Anderson, et al. 2013)	5
Table 2- 2 OGFC-AR gradation properties for the three projects (Anderson, et al. 2013)	5
Table 2- 3 OGFC-SBS mix design binder properties for the three projects (Anderson, et al. 2013)	6
Table 2- 4 OGFC-SBS gradation properties for the three projects (Anderson, et al. 2013).....	6
Table 2- 5 Recommended OGFC aggregate gradations (FHWA, 1990, Kandhal, 2002).....	7
Table 2- 6 NCAT mix design criteria (Kandhal and Association 2002).....	9
Table 3- 1 Aggregate type and asphalt cement of OGFC	17
Table 3- 2 Asphalt cement of underlying layer	18
Table 3- 3 Sample information.....	26
Table 4- 1 Summary of the shear results	31
Table 4- 2 Asphalt cement (AC) and AC content.....	35
Table 4- 3 Three-way ANOVA results.....	47
Table 4- 4 Two-way ANOVA results with insignificant factors	48
Table 4- 5 Loading condition	53
Table 5- 1 OGFC and underlying layer material.....	69
Table 5- 2 Numbers of specimen of the shear test and texture depth test	72
Table 6- 1 List of the OGFC and non-OGFC sections	84
Table 7- 1 States Response to the Survey.....	92
Table 7- 2 Pavement structure and underlying layers	100
Table 7- 3 Number of years OGFC in operation	110
Table 7- 4 Potential concerns of using OGFC.....	112

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Open graded friction course (OGFC) is a special purpose mixture intended for higher internal air voids and better friction characteristics. OGFC mixtures consist of an open gradation, mostly of coarse size aggregate with little fines to ensure a higher content of connected air voids. The primary benefit of using OGFC is the improvement of wet weather skid resistance, reduction of potential for hydroplaning, reduction of water splash and spray, and reduction of night time wet pavement glare. Secondary benefits include better wet-night visibility of traffic lane stripes and pavement markers, and better wet weather (day and night) delineation between the traveled way and shoulders.

However, compared to conventional asphalt mixtures, OGFC is more prone to pavement distresses such as cracking and raveling, resulting in a shorter service life. Studies have shown that the performance of OGFC and its service life are affected by many factors, especially the underlying layer and the interface bond between OGFC and underlying layer. Since OGFC is highly expensive than ordinary asphalt mixtures, it is of great importance to improve its performance and to extend its service life.

The objective of the proposed research project is to investigate into the best potential combination of OGFC, interlayer bond, and underlying layer in Tennessee. The properties and performance of the potential candidates of the OGFC combination will be tested in the laboratory and field survey will be conducted on existing OGFC pavements in Tennessee.

This research will significantly benefit the economy of the State of Tennessee through selecting best OGFC mixtures in flexible pavement design:

- (1) OGFC pavements will last longer and perform better;
- (2) Improved wet weather driving environment;

- (2) Reduced frequency and severity of traffic accidents;
- (4) Increased public satisfaction through a better and safer driving environment.

1.2 Objectives

The objectives of the proposed research are

- (1) Identify potential candidate combinations of OGFC, interlayer, and underlying layer for laboratory evaluation.
- (2) Compare the properties and performance of different OGFC pavements through laboratory testing.

1.3 Scope of Study

The scope of the research work includes:

- To complete a synthesis of literature review and state DOT survey on the use of OGFC layer in pavement structures;
- To identify potential combinations of OGFC with associated interlayer and underlying layers for use in Tennessee;
- To conduct laboratory testing on the properties and performance of different OGFC combinations.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Open graded friction course (OGFC) is a thin layer of permeable asphalt placed on a dense graded asphalt pavement. It is a special purpose asphalt mixture, comprising of an open gradation, intended for higher internal air voids and better friction characteristics. The OGFC mixtures consist of mostly coarse size aggregates with little fines to ensure a higher content of connected air voids (Kandhal and Association 2002).

Benefits of using OGFC include: the improvement of wet weather skid resistance, reduced potential for hydroplaning, reduced water splash and spray, and reduced night time wet pavement glare. OGFC also provides better wet-night visibility of traffic lane stripes and pavement markers, and better wet weather (day and night) delineation between the traveled way and shoulders. Studies have shown that OGFC is more prone to pavement distresses such as cracking and raveling, resulting to a shorter service life as compared to conventional asphalt mixtures.

Factors affecting the performance of OGFC and its service life include the properties of the underlying layer and the interface bond between OGFC and underlying layer. Since OGFC is expensive than conventional asphalt mixture, it is important to improve its performance and to extend its service life. Polymer modified binder have been used to improve the performance of OGFC but it impacts the cost. The polymer modified asphalts provide thicker films on the aggregate particles which minimize potential oxidation and reduces the tendency of raveling, and improves the durability of OGFC (Kandhal and Association 2002).

2.2 Background

Open graded friction course (OGFC) was created from experimentation with plant seal mixes (PSMs) in the 1940's (Huber 2000). The seal mixes were to provide a better performing alternative to chip seals and it gained popularity across the United States in the 1970's in response to the FHWA's program to increase frictional resistance on roadways. Japan and European countries also began using OGFCs on their roadways at almost the same time (Kandhal and Association 2002).

In 1960's, the United Kingdom began using porous pavement in military airfield runways to avoid hydroplaning and skidding in wet weather (Hwee and Guwe 2004). After research into the advanced aging and hardening was conducted, the mix design changed to use higher binder contents with additives to prevent draindown. This improved mix design was then allowed on main roadways where the benefits were shown to outweigh the disadvantages (Nielsen 2006).

The use of porous asphalt in France began in 1976 and its use grew through 1990 when winter maintenance recommendations discouraged use. French research studies have determined that modified binder is necessary to help minimize raveling and draindown. It was also found that this pavement type should only be used on roadways with high design speeds (50 mph) (Nielsen 2006).

The Netherlands were introduced to porous asphalt in the early 1980's and by 1990, it was decided that the entire highway network was to be paved with porous asphalt. The OGFC pavements typically lasted 10-12 years with maintenance or rehabilitation being required due to raveling (Nielsen 2006).

In the United States, California was the first state to begin using OGFC. Their plant seal mixes were applied in a thin layer, used a smaller nominal aggregate size, and increased binder content as compared to traditional paving mixes. This provided similar benefits to the chip seals, but also resulted in reduced road noise, increased durability, and

a better ride quality (Kandhal and Association 2002).

Arizona Department of Transportation (ADOT) is a leader in the use of crumb rubber modified pavements for noise mitigation and helped in the development of the mix design for the OGFC-AR on the Lynnwood project (Anderson, et al. 2012, Anderson, et al. 2012, Anderson, et al. 2012, Anderson, et al. 2013). The OGFC-AR mixes for the Medina project and Bellevue project were done in-house but patterned after the ADOT design was used for Lynnwood project. One big difference on the Bellevue project was the use of lime as the anti-stripping additive. ADOT specifies hydrated lime for all of their HMA mixes. Table 2- 1 lists the percent of asphalt, grade of the asphalt binder, rubber content and anti-stripping additive used on the projects.

Table 2- 1 OGFC-AR mix design binder properties for the three projects (Anderson, et al. 2013)

Project	Asphalt Content (%)	Binder Grade	Rubber Content (%)	Anti-Stripping Additive and (%)
Lynnwood	9.2	PG64-22	22.0	ARR-MAZ 6500 (0.50)
Medina	8.8	PG64-22	23.5	ARR-MAZ 6500 (0.25)
Bellevue	9.4	PG64-22	20.0	Hydrated Lime (1.0)
Average	9.1		21.8	

Table 2- 2 OGFC-AR gradation properties for the three projects (Anderson, et al. 2013)

Project-Pit Source	Sieve Size			
	3/8	#4	#8	#200
Lynnwood – B-335	100	34	8	1.5
Medina – B-335	100	31	8	1.6
Bellevue – A-189	100	35	8	1.9
Average	100	33	8	1.7

All of the OGFC-SBS mixes were designed in-house using the drain down test to

determine the optimum percent of asphalt. The first OGFC-SBS mix design for Lynnwood was done with guidance provided by the National Center for Asphalt Technology (NCAT), an asphalt industry supported research facility located on the campus of Auburn University in Auburn, Alabama. Fibers were added to help prevent drain down. Liquid anti-strip additives were used on Lynnwood and Medina with hydrated lime used on Bellevue. Table 2- 3 and Table 2- 4 below summarize the binder and gradation properties of the mix designs for the projects.

Table 2- 3 OGFC-SBS mix design binder properties for the three projects (Anderson, et al. 2013)

Project	Asphalt Content (%)	Binder Grade	Rubber Content (%)	Anti-Stripping Additive and (%)
Lynnwood	8.3	PG70-22	3.4 ± 1	ARR-MAZ 6500 (0.25)
Medina	8.8	PG70-22	3.4 ± 1	ARR-MAZ 6500 (0.25)
Bellevue	8.6	PG70-22	3.4 ± 1	Hydrated Lime (1.0)
Average	8.6		3.4 ± 1	

Table 2- 4 OGFC-SBS gradation properties for the three projects (Anderson, et al. 2013)

Project-Pit Source	Sieve Size			
	3/8	#4	#8	#200
Lynnwood – B-335	100	37	10	2.1
Medina – B-335	100	36	12	2.3
Bellevue – A-189	100	38	12	2.0
Average	100	37	11	2.1

It shows that, the mix designs for the OGFC-AR and OGFC-SBS sections were very similar for the three projects with only slight variations in asphalt content, crumb rubber content and aggregate gradation. The largest dissimilarity was the use of hydrated lime on the I-405 project.

The first FHWA open graded mix design procedure was published in 1974 (Watson, et al. 2003). This design procedure was modified in 1980, and again in 1990. This procedure specifies materials, gradation, optimum binder content, mix temperature, and resistance to effects of water (FHWA 1990). The aggregate should be a high-quality aggregate with the gradation included in Table 2- 5 while the binder and additives are based on local conditions. The binder content is determined using the predominant aggregate size and oil absorbance testing. A draindown test is then used to determine the mixing temperature and measured by a visual inspection. A moisture resistance test is also required with at least 50% retained strength (FHWA 1990).

Table 2- 5 Recommended OGFC aggregate gradations (FHWA, 1990, Kandhal, 2002)

Sieve Size	FHWA Gradation Percentage Passing	NCAT Gradation Percentage Passing
3/4 inch (19 mm)	-	100
1/2 inch (12.5 mm)	100	85 – 100
3/8 inch (9.5 mm)	95 – 100	55 – 75
#4 (4.75 mm)	30 – 50	10 – 25
#8 (2.36 mm)	5 – 15	5 – 10
#200 (0.075 mm)	2 – 5	2 – 4

It is believed that the first widely used OGFC mix design was developed by FHWA in 1974. This design procedure was modified twice, first in 1980 and then again in 1990 (King Jr, et al. 2013). The FHWA mix design was based on the evaluation of the surface capacity (determined by oil absorbency test) of the predominant aggregate fraction corresponding to the materials that passed through a 3/8-in. sieve and retained on a No. 4 sieve. Additionally, a draindown test was required to determine the optimum mixing temperature along with a moisture resistance test (King Jr, et al. 2013).

Studies have shown that OGFC is more prone to pavement distresses such as cracking and raveling, resulting to a shorter service life as compared to conventional asphalt mixtures. Many states experienced durability problems from the altered plant seal mixes and hence stopped the use of OGFC in 1980's. However, some states tried to improve the mix designs and continued its use. The improvements included (1) using polymer modified binders and fiber additives to stabilize the mix and decrease binder drain down; (2) increased binder content and air voids; and (3) specifying more durable aggregates.

Factors affecting the performance of OGFC and its service life include the properties of the underlying layer and the interface bond between OGFC and underlying layer. Since OGFC is expensive than conventional asphalt mixture, it is important to improve its performance and to extend its service life. Polymer modified binder have been used to improve the performance of OGFC but it impacts the cost. The polymer modified asphalts provide thicker films on the aggregate particles which minimize potential oxidation and reduces the tendency of reveling, and improves the durability of OGFC (Kandhal and Association 2002).

The use and performance of open graded friction courses is highly variable across the US. In 1998, The National Center for Asphalt Technology (NCAT) conducted a survey of transportation departments to evaluate the use, performance, design and construction methods of OGFC. Among other things, the survey results indicated that 38% of the respondent states had discontinued the use of OGFC on their roadways, and 8% had never used this pavement type at all. The estimated service life was found to be between 8 and 12 years with good to very good durability and surface friction performance (Kandhal and Mallick 1998).

In 2000, NCAT published a new generation OGFC mix design based on research in response to the OGFC experiences in the US and Europe (Mallick, et al. 2000). There are three primary components in the mix design. The first characteristic is material selection.

A strong and durable aggregate should be chosen with recommended LA abrasion values of 30% or less. The aggregate should also be crushed, have minimal flat and elongated particles, and low absorption values. The binder type recommended is two grades higher than typically used in the area and should be polymer modified. Fibers are also recommended for strength and durability. The second component is gradation. A recommended gradation is shown in Table 5 above, but it is chosen by comparing the voids in coarse aggregate (VCA) of the mix to the VCA of the aggregate alone and the air voids of the mix. This ensures stone-on-stone contact of the aggregate particles and permeability. The final component is choosing the optimum binder content. The optimum binder content is determined by a series of tests on specimens compacted with a gyratory compactor. The mixture properties tested include air voids, abrasion on aged and un-aged specimens, binder draindown, and moisture susceptibility (Kandhal and Association 2002). The requirements are summarized in Table 2- 6 below.

Table 2- 6 NCAT mix design criteria (Kandhal and Association 2002)

Criteria	Recommended Value
Air Voids	Minimum 18%
Unaged Cantabro Abrasion	Maximum 20%
Aged Cantabro Abrasion	Maximum 30%
Asphalt Binder Draindown	Maximum 0.3%
Tensile Strength Ratio	Minimum 80%

Based on the experience gained in the U.S., Europe, and internal research, NCAT proposed a new OGFC mix design procedure in 2000. This mix-design method included an assessment of both functionality (permeability) and durability. There were four primary components in this new mix design: material selection, selection of design gradation, determining optimum binder content, and lastly, evaluation for moisture susceptibility. The

mix design recommended a coarser aggregate gradation than the typical ones used in the past. A strong and durable aggregate with LA abrasion values of 30 percent or less was recommended. The aggregate should also be crushed, have minimal flat and elongated particles, and be low in absorption. The criteria for binder selection should be regulated by environment, traffic, and expected functional purposes of the pavement. In general, polymer-modified binders were recommended with a desired addition of fiber stabilizer to resist draindown.

In 2009, Cooley et. al conducted a survey as part of NCHRP Project 09-41 and the results are reported in NCHRP Report 640 (Cooley, et al. 2009). The survey was distributed to highway agencies in the US and around the world and included questions related to general use, structural design, mix design, construction practices, maintenance and rehabilitation, and performance. Responses were received from 32 states plus four Canadian provinces, Austria, and Japan. The report showed that the use of this type of mix was limited to the southeastern states and California. 75% of responded said the OGFC is commonly used on higher speed roadways such as urban freeways, and 50% of respondents use it in rural primary highways (Cooley, et al. 2009).

The survey conducted in 2012 by Putman indicates that 61% of responded states use OGFC. Figure 2- 1 is the map that shows states that use OGFC by 2012.

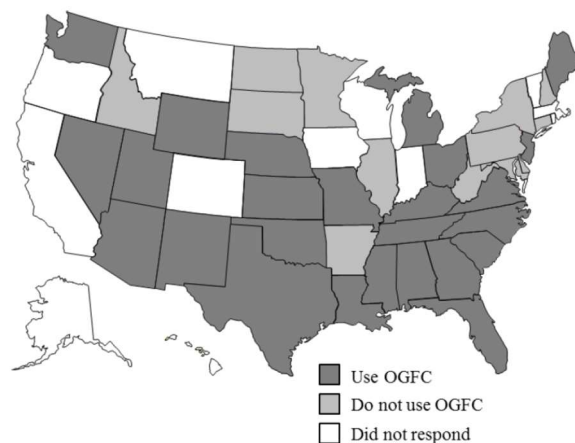


Figure 2- 1 Current use of OGFC in USA (Putman, 2012)

There is little or no evidence/on the literature that discusses layers underlying the OGFC layer. The questionnaires are expected to capture this information.

2.3 Literature review on OGFC testing method

2.3.1 Durability test

The Cantabro test is widely used as an index of the PFC mixture resistance to disintegration (i.e., resistance to raveling (Jimenez and Perez 1990, Ruiz, et al. 1990)). Dry and wet condition specimens both can be used in the test. The moisture conditioned test was introduced as a way to evaluate aggregate–asphalt combinations with poor adhesion, and the effect of low-quality fillers, which were identified as responsible for accelerated mixture deterioration (Ruiz, et al. 1990), and the Cantabro loss value had good correlation to field performance (i.e., mixture resistance to raveling). However, in 2006 Nielsen (Nielsen 2006) indicated the lack of direct correlation with field performance of PA in particular for mixtures fabricated using polymer modified asphalt binders.

Besides Cantabro test, approaches used to evaluate durability in OGFC include the Overlay test (OT), the Hamburg Wheel-Tracking test (HWTT). Denmark reported the use of HWTT to evaluate permanent deformation of PA. Besides, the Overlay test (OT) (Tex-248-F) (Zhou and Scullion 2005, Zhou and Scullion 2006) were also used to characterize the mixture durability in terms of cracking life (number of cycles).

Moisture susceptibility is also one of the most important aspects of durability of OGFC. The moisture susceptibility of PFC mixes was evaluated by two approaches: (1) retained tensile strength or tensile strength ratio (TSR) method (Putman 2012), and (2) the wet abrasion loss (WAL) method (Sabita 1995).

To evaluate the fatigue properties of asphalt mixture, flow number test, asphalt pavement analyzer (APA), beam fatigue test, French wheel tracker, Hamburg wheel tracker,

and loaded wheel fatigue test are all used by many people.

Besides methods above, in Nielsen (Nielsen 2006) suggested the following methods to evaluate the durability performance: Cyclic Shear Test, Rotating Surface Abrasion Test, Cyclic Tensile Test, and Nynäs immersion wheel-tracking test. Poulikakos and Partl (Poulikakos and Partl 2009) proposed application of a refined version of the coaxial shear test, an axial cyclic loading system, to successfully characterize moisture susceptibility in terms of fatigue damage in PA in both wet (under water immersion) and dry conditions.

2.3.2 Mixture functionality test

Drainability and noise reduction effectiveness are two indexes used to evaluate the mixture functionality of OGFC. In general, current mix design procedures do not directly integrate assessment of properties associated with functionality (Alvarez, et al. 2006).

Permeability, also called hydraulic-conductivity (Suresha, et al. 2009) is considered as one of the major indicators of the performance-life of PFC mixes (Huber 2000). Current approaches suggested for PFC mix design to evaluate drainability (using gyratory-compacted specimens) include: (1) achieving a target total air void (AV) content as an indirect indication of permeability and (2) direct measurement of permeability in the laboratory (Alvarez, et al. 2009).

Previous studies reported the use of both falling head (Watson, et al. 2004) and constant head-parameters (Hassan and Taha 2002) with different technical characteristics to measure permeability of PFC mixtures. On the basis of previous research (International 2010, Kandhal and Association 2002, Mallick, et al. 2000), permeability values of at least 100 m/day were recommended for acceptable performance. Mallick, R. B. et al. (2010) evaluated the permeability of OGFC, ANOVA showed that the compaction level (MC), aggregate gradation (G) and the interaction between compaction level and gradation (MC*G) is the most significant factor influencing the permeability.

Allex E. Alvarez et.al (Alvarez, et al. 2009) suggested that approaches above are

not effective in ensuring adequate drainability in field-compacted mixtures and suggested alternative methods: (1) the water-accessible AV content can be used as a surrogate of the total AV content to indirectly assess permeability and (2) the water flow value (outflow time) can be applied to evaluate the field drainability of PFC mixtures. Papers (Alvarez, et al. 2009, Watson, et al. 2003) also made the research about the water-accessible air voids.

For the noise reduction, although there is no standard for it in the mix design, research for it has been made extensively (Biligiri 2013, Liu, et al. 2010, Trevino and Dossey 2006). Factors such as AV content, aggregate, traffic speed, layer thickness and asphalt binder type all influence the noise reduction properties of OGFC (Kowalski, et al. 2009, Miró, et al. 2009, Smit and Waller 2007). Future research should fully use X-ray CT and image analysis techniques to further characterize PFC mixtures and identify the mixture parameters that should be integrated to optimize the noise reduction effectiveness.

2.3.3 Test methods about the bonding property between OGFC and underlying layer

FHWA suggested application of asphalt emulsion (diluted 50 percent with water and applied at a rate of 0.05 to 0.10 gallons per square yard) to seal the surface of underlying layers before OGFC placement (FHWA 1990).

Hongren Gong (Gong 2013) made the research on stress analysis and compaction of double layered asphalt pavement, results showed that the shear strength of the interface increased compared with conventional methods.

To evaluate the effect of conventional tack coat and polymer-modified asphalt emulsion (PMAE) on the characteristics of the interface between OGFC and conventional dense graded mixture, Yu Chen et.al (Chen, et al. 2012) took the composite specimen interface cracking (CSIC) tests, as Figure 2- 2 shows. The total number of cycles to failure and the damage rate are two evaluation indexes used in this test.

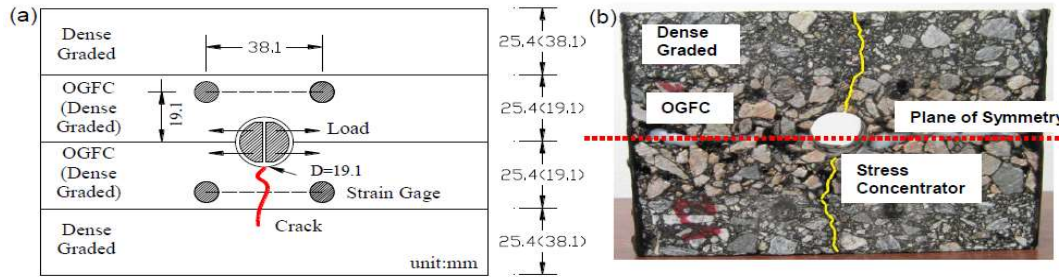


Figure 2- 2 (a) Specimen loading and measurement system (b) cracking mechanism
(Chen, et al. 2012)

By using CSIC method, Yu Chen et.al (Chen, et al. 2013) evaluated the effect of asphalt rubber membrane interlayer (ARMI) on pavement reflective cracking properties, results showed that ARMI not only cannot retard reflective cracking, also reduced reflective cracking resistance. However, Ogundipe, O. M.et al. (Ogundipe, et al. 2013) concluded that the potential of stress absorbing membrane interlayers (SAMIs) to delay crack growth depends on many factors, such as the SAMI stiffness and thickness, the overlay thickness, the load level and temperature.

With the increased application of OGFC, many studies have been conducted to evaluate its performance (Mallick, et al. 2000, Suresha, et al. 2009). One of the major factors that affect the performance of OGFC is the adhesion between OGFC and its underlying layer because bonding properties between pavement layers are vital to ensure all layers behave as a monolith system, which can reduce the pavement distresses and increase the service life.

Many researchers have evaluated the factors that affect the bonding properties between different asphalt pavement layers, including tack coat, mixture type, temperature, surface characteristics. However, these studies are conducted mostly for conventional pavement layers. Little has been done on the bonding between OGFC and its underlying layer. Influence of tack coat dosage was investigated by (Mohammad, et al. 2002, Raposeiras, et al. 2012) and concluded that there exists an optimal tack coat dosage at which the shear strength reaches the maximum value. However, it is controversial (Collop,

et al. 2009, Gong 2013). Tack coat type was also one of the factors that influence the bonding properties of pavement layers and different types of tack coat result in different bonding properties (Mohammad, et al. 2002, West, et al. 2005). Some researchers also took into account breaking time of tack coat in their studies of bonding properties of pavement layers (Chen and Huang 2010, Tashman, et al. 2008).

Asphalt mixture type plays an important role in the bonding strength between pavement layers. West et al. (West, et al. 2005) evaluated the bonding properties of fine and coarse-graded mixtures and found that the shear strength of fine-graded mixture with a 4.75-mm nominal maximum aggregate size (NMAS) is larger than that of coarse-graded mixture with a 19-mm NMAS. Chen et al. (Chen and Huang 2010) tested the bonding strength of the specimens combined by dense-graded asphalt concrete (DGAC), stone matrix asphalt (SMA), and porous asphalt concrete (PAC). Their results showed that DGAC-DGAC (upper layer-lower layer) system generally has the best bonding performance, followed by the PAC-DGAC and PAC-SMA systems. They attributed the different performance to the difference in the adhesion of different systems. Raposeiras et al. (Raposeiras, et al. 2012) investigated the influence of surface macro-texture of asphalt mixtures on the adhesion between pavement layers and found that a rough texture of 0.17 mm gives the maximum shear strength in their study. Raab et al. (Raab, et al. 2012) evaluated the interlock of aggregates between pavement layers by using steel balls with different diameters. Their results showed that the highest shear strength is reached for the combination of small/big, where good interlocking between the steel balls was observed.

Temperature is another important factor that affects the bond between different pavement layers, which has been investigated by many researchers (Chen, et al. 2013, Miró, et al. 2005, Mohammad, et al. 2002, Raab, et al. 2012, West, et al. 2005). Generally, as temperature goes up, shear strength decreases because tack coat binder becomes less stiff with the increase in temperature.

The shear fatigue behavior between pavement layers has also been studied

(Boudabbous, et al. 2013, Diakhaté, et al. 2011, Li and Yu 2013, Li, et al. 2014). Tack coat and temperature are two important factors affecting the fatigue properties between pavement layers (Li, et al. 2014). Power law equations are used to describe the relationship between stress level and fatigue life for direct shear test and oblique shear test (Diakhaté, et al. 2011, Li, et al. 2014). Li et al. (Li and Yu 2013) concluded that epoxy tack coat gives a remarkably superior shear fatigue performance than styrene- butadiene-styrene-modified asphalt and emulsified asphalt tack coat.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Materials

3.1.1 Open Graded Friction Course

Two types open graded friction course (OGFC) were selected. The aggregate type and asphalt cement content is shown in Table 3- 1. The aggregate gradation of OGFC is shown in Figure 3- 1.

Table 3- 1 Aggregate type and asphalt cement of OGFC

Mixture Property	OGFC-1	OGFC-2
Aggregate Type	Limestone	Gravel
Asphalt PG Grade	76-22	76-22
AC Content	6.4%	7.5%

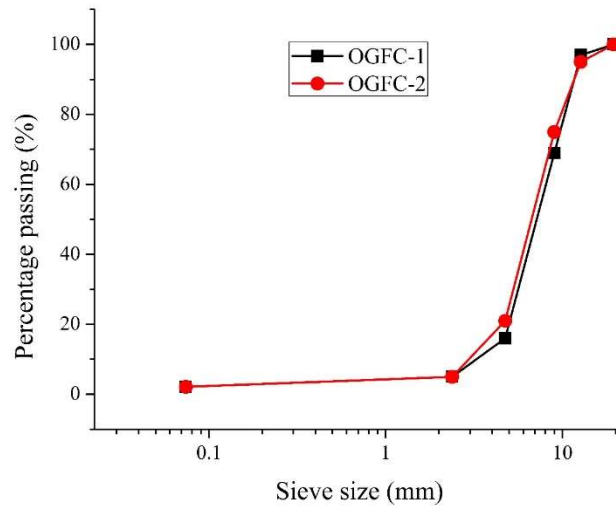


Figure 3- 1 Aggregate gradation of OGFC

3.1.2 Underlying Layer

Seven types of underlying layer asphalt mixture (TLD, D, BM, BM2, CS64-22, CS76-22 and SMA) were employed, of all the underlying mixture, SMA were not used in Tennessee, in this study SMA was picked up from Georgia Department of Transportation. The aggregate gradation and asphalt cement content of CS76-22 and CS64-22 are the same.

Table 3- 2 Asphalt cement of underlying layer

Mixture Property	TLD	D	SMA	BM2	BM	CS64-22	CS76-22
Asphalt PG Grade	76-22	70-22	76-22	64-22	64-22	64-22	76-22
AC Content	6.20%	6.00%	6.30%	5.00%	4.20%	6.50%	6.50%

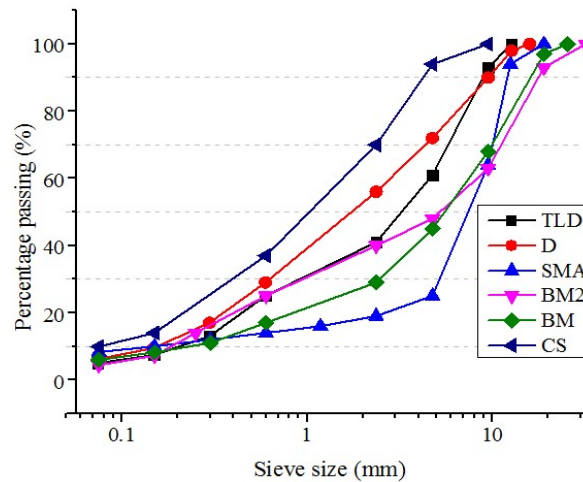


Figure 3- 2 Aggregate gradation of underlying layers

3.1.3 Tack Coat

Two types of tack coat were employed in this study: anionic asphalt emulsion and ultrafuse tack coat. Two tack coats were used in the shear test, anionic asphalt emulsion and ultrafuse tack coat. Anionic asphalt emulsion can be applied at ambient temperature (Figure 3- 3). Ultrafuse (UF) handles similarly to a PG asphalt, but require additional heat and/or heating time to obtain the same level of flowability that you would observe with a

PG 67-22, it is typically applied at 375 degrees F in the field, so when it was used for lab test, it was also applied at 375 degrees F (Figure 3- 4).



Figure 3- 3 Anionic asphalt emulsion



Figure 3- 4 Ultrafuse tack coat

3.2 Laboratory Performance Tests

The following laboratory performance tests were conducted to determine the abrasion resist property, permeability of OGFC and the bonding property between OGFC and different underlying layers.

- Cantabro loss test
- Permeability test
- Direct shear test

- Direct shear fatigue test

3.2.1 Cantabro Loss Test

This test measures the breakdown of compacted specimens utilizing the Los Angeles Abrasion machine (Figure 3- 5), which represents the anti-abrasion property of OGFC. The percent of weight loss (Cantabro loss) is an indication of OGFC durability and relates to the quantity and quality of the asphalt binder. The percentage of weight loss is measured and reported.

Calculate the Cantabro Loss:

$$CL = \frac{A-B}{A} \times 100 \quad (3-1)$$

where:

CL-Cantabro Loss, %;

A-Initial weight of test specimen;

B-Final weight of test specimen.



Figure 3- 5 Los Angeles Abrasion machine

3.2.2 Permeability Test

Permeability is an important parameter of pervious concrete since the material is designed to perform as 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 concrete. In this study, a permeability measurement device and method developed by Huang et al. (Huang, et al. 1999) for drainable asphalt mixture (similar to pervious concrete in function) were used. Figure 3- 6 shows the specimen and device for permeability test.

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 paper of Huang et al. (Huang, et al. 1999), hydraulic head difference vs. time curve obtained from the two pressure transducers:

$$h = a_0 + a_1 t + a_2 t^2 \quad (3-2)$$

where, a_0 , a_1 and a_2 are regression coefficients.

Then, differentiate equation,

$$\frac{dh}{dt} = \alpha_1 + \alpha_2 t \quad (3-3)$$

where α_1 and α_2 are regression coefficients for differential equation of head and time.

Therefore, the discharge velocity is expressed as:

$$v = \frac{dQ}{dt} = \frac{A_1}{A_2} \frac{dh}{dt} = \frac{r_1^2}{r_2^2} \frac{dh}{dt} \quad (3-4)$$

where A_1 , A_2 , r_1 , r_2 are the cross-section areas and radius of upper cylindrical

reservoir and the specimen.



Figure 3- 6 Permeability test setup and sample

3.2.3 Direct Shear Test

Bonding property is vital to the property of the pavement. To ensure that OGFC layer and its underlying layer are well bonded to behave as a monolith system, it is essential to evaluate the bonding properties between OGFC and its underlying layer.

Amount of pioneer work has been performed to explore the methods to evaluate the bonding property between pavement layers. Tensile test was employed very early to characterize the bonding property (Deysarkar 2004, Litzka, et al. 1994, Mohammad, et al. 2009, Tschegg, et al. 1995), but it needs very good adhesion between asphalt mixture and test machine to ensure the damage occurred in the interface. Torque test can also be used to evaluate the bonding property (Collop, et al. 2011, MENT 1998), similar with the tensile test, this method also requires good adhesion between mixture surface with the test machine. Shear test is the most commonly used method to evaluate the interlaminar bonding property (Chen and Huang 2010, Collop, et al. 2009, Diakhaté, et al. 2011, Li, et al. 2014, Miró, et al. 2005, Raab, et al. 2012, Raposeiras, et al. 2012), this method is easy to perform and straightforward.

In this report, direct shear test will be taken, test equipment and samples are as shown below (Figure 3- 7). The direct shear fatigue device includes four semi-circular steel rings. It is installed to a MTS machine to apply shear force in vertical direction.



Figure 3- 7 Shear test setup and sample

To evaluate the shear property of the structure combined by OGFC and interlayer, two parameters - shear strength and shear stiffness were selected.

Shear strength:

$$S = F/A \quad (3-5)$$

Where: F is the shear force, A is the area of the shear interface.

Besides the shear strength, another parameter used in the present study to characterize the bonding property between OGFC and interlayer is interface stiffness (Figure 3- 8). The interface stiffness is defined by Goodman's constitutive law, as follows (Canestrari et al. 2005):

$$\tau = k\varepsilon \quad (3-6)$$

Where, τ = interface shear stress (kPa);
 ε = displacement within the interface (cm);
 k = interface stiffness (kPa/cm).

The interface stiffness is computed by dividing the peak stress by the displacement at failure from the stress-displacement curve (Figure 3- 8).

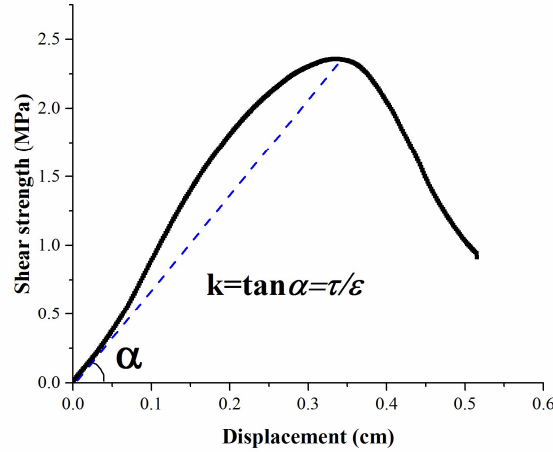


Figure 3- 8 Strength-displacement curve

3.2.4 Direct Shear Fatigue Test

The test device for fatigue test is the same as the shear strength test. By applying cycle load, the deformation response can be obtained.

- 50% stiffness reduction method

To determine the number of loading cycle to failure, a 50% stiffness reduction method is generally employed, which means failure happens when 50% initial stiffness reduction is reached (Diakhaté, et al. 2011, Hicks, et al. 1993, Roberts, et al. 1996, Williams 1998, Wu, et al. 2013).

- Ratio of dissipated energy change (RDEC)

RDEC can be demonstrated by equation (3-7)

$$RDEC(i) = \frac{|w_j - w_i|}{(j-i)w_j} \quad (3-7)$$

where i and j denote respectively the i th and j th cycles, w_i is the dissipated energy at cycle i , and w_j the dissipated energy at cycle j .

A typical curve depicted by RDEC as a function of loading cycles (Figure 3- 9) can be easily divided into three stages. There is a constant percentage of input energy being

turned into fatigue damage in stage II, which offers an indication of the fatigue performance called Plateau Value (PV).

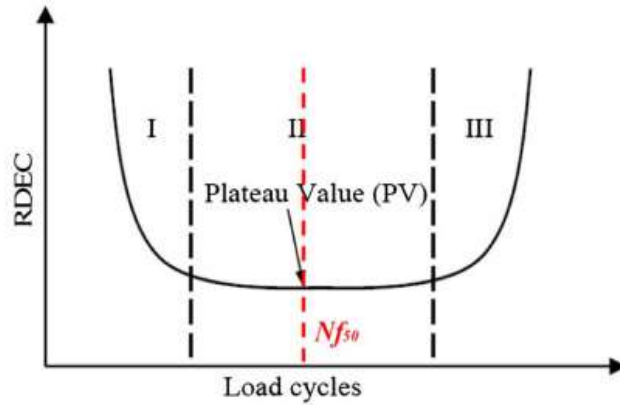


Figure 3- 9 Typical RDEC vs. number of loading cycle

- Cumulative dissipated energy

After the calculation of the dissipated energy at given cycles, in this study dissipated energy was calculated every 50 cycles, by linear interpolation, dissipated energy of all loading cycles can be generated. The total dissipated energy can be further obtained. Relationship between the total cumulative dissipated energy and fatigue life can be then examined.

3.3 Specimen Preparation

3.3.1 Cantabro Loss Test

Specimen was made by two types of OGFC mixture. Gyratory compaction and Marshall compaction were employed to the compaction of the specimens. The information of the specimen is shown in Table 3- 3. The size for Cantabro loss test is 2.5x4, after the Gyratory compaction, the sample was cored to the targeted size. The test was conducted in triplicate.

Table 3- 3 Sample information

Compaction mode	Size (depth x diameter) (in)	Air void
Gyratory	2.5x6	18%
Marshall	2.5x4	18%

3.3.2 Permeability Test

Specimen was compacted by Gyratory method. Specimen size is 2 inches and 6 inches in height and diameter respectively, air void of the specimen is 18%. The permeability test was conducted in triplicate.

3.3.3 Direct Shear Test and Fatigue Test

Two-layered composite specimens with a 150-mm diameter were used in the study for the laboratory direct shear testing. They were compacted using the Superpave gyratory compactor (SGC). The underlying layer was first compacted to a height of 50 mm. After the bottom layer was extruded and cooled down to ambient temperature, tack coat was evenly applied to its surface (Figure 3- 11). Underlying layer for shear test is TLD, D, SMA, BM, BM2, CS64-22 and CS76-22. Underlying layer for the fatigue test is TLD and BM2. The specimen was left for 30 minutes before the upper OGFC layer of 32 mm was compacted to its top surface. The composite specimen was name as OGFC1-TLD, in which OGFC1 represents the upper layer and TLD represents the underlying layer, the other composites were named in the same way. The test was conducted in triplicate.



Figure 3- 10 Underlying layer sample



Figure 3- 11 Tack coat was applied on the upper surface of underlying layer



Figure 3- 12 Specimens for shear test and fatigue test

CHAPTER 4 LABORATORY TEST RESULTS AND DISCUSSION

4.1 Cantabro Loss Test

In this test, Cantabro Loss test of two kind of OGFC materials (OGFC-1 and OGFC-2) were both performed in Marshall compaction and Gyratory compaction. Figure 4- 1 shows the initial specimen and final specimen. Figure 4- 2 shows the result of Cantabro Loss test of the two OGFC materials. Test result shows that Cantabro loss of OGFC-2 is bigger than that of OGFC-1 but all the values are around 20%.

From Part 3.1, there is litter difference in the aggregate gradation between the two OGFC, but the asphalt binder content showed great difference (7.5% vs. 6.4%). In this study, OGFC-1 with larger asphalt content showed smaller Cantabro loss, which indicates asphalt content plays a positive role in the abrasion resistance.

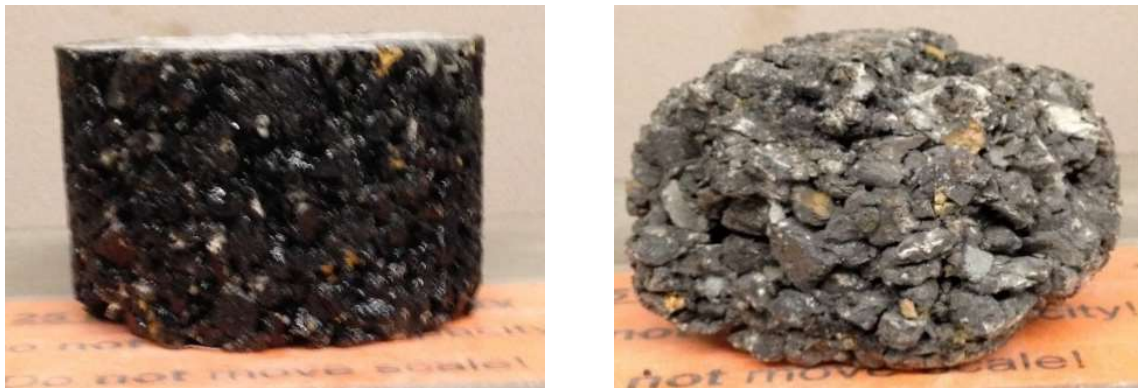


Figure 4- 1 Initial specimen and final specimen

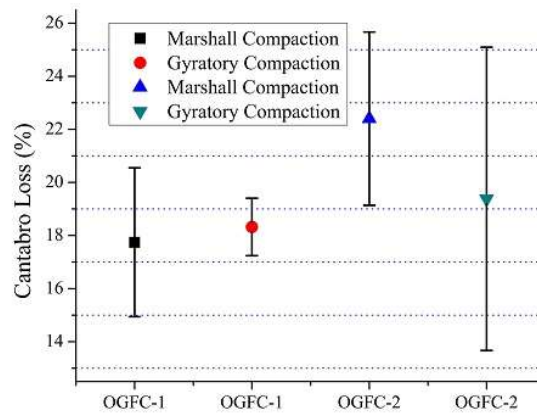


Figure 4- 2 Result of Cantabro Loss test

4.2 Permeability Test

In this study, a permeability measurement device and method developed by Huang et al. (Huang, et al. 1999) for drainable asphalt mixture (similar to pervious concrete in function) were used. Permeability test was conducted according the procedure in Part 3.2.2.

Figure 4- 3 to Figure 4- 6 presents the result of one sample of OGFC-1 and OGFC-2. The relationship between hydraulic gradient and discharge velocity are $v=4.9938i^{0.5846}$ and $v = 7.0862i^{0.5858}$, so the K' are 4.9938m/s and 7.0862 mm/s. The final result of the permeability test is shown as Figure 4- 7, OGFC-2 presents better permeability.

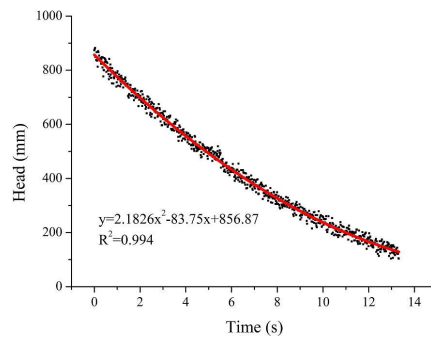


Figure 4- 3 Time vs Head (OGFC-1)

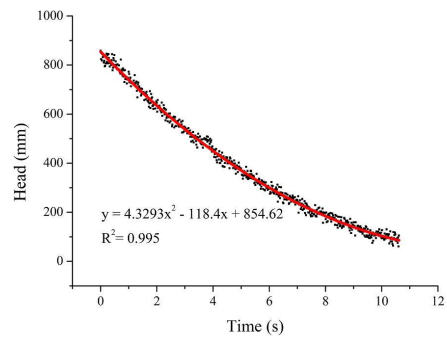


Figure 4- 4 Time vs. Head (OGFC-2)

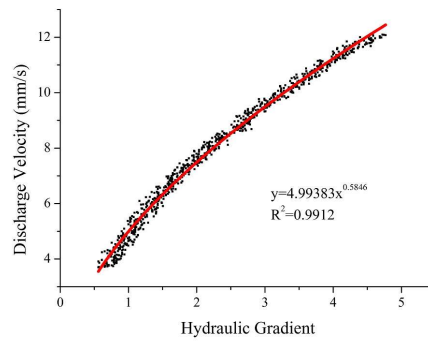


Figure 4- 5 Hydraulic gradient vs. Discharge velocity (OGFC-1)

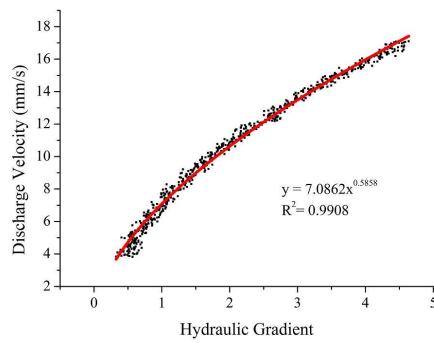


Figure 4- 6 Hydraulic gradient vs. Discharge velocity (OGFC-2)

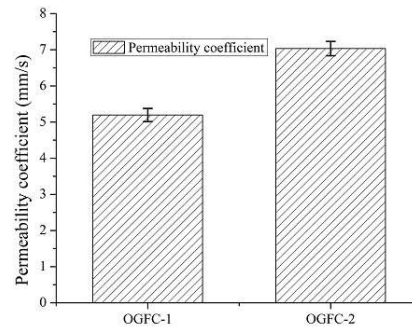


Figure 4- 7 Permeability test result

4.3 Direct Shear Test

4.3.1 Shear Test Result for Single Tack Coat Application Rate and Temperature

Two types of OGFC and seven underlying layer asphalt mixture (TLD, D, BM, BM2, SMA, CS76-22 and CS64-22). Tack coat application rate is 0.07 gallon/yd². Sample preparation was according to Part 3.3.3. Shear test was conducted based on Part 3.2.3.

Figure 4- 8 to Figure 4- 15 show the shear performance of the structure combined by OGFC and interlayers with two tack coats.

Table 4- 1 Summary of the shear results

	Shear strength ranking	Shear stiffness ranking
OGFC1-Anionic	SMA>TLD>BM2>CS76-22 >BM>D>CS64-22	BM2>SMA>BM>TLD> CS64-22>CS76-22>D
OGFC2-Anionic	SMA>BM2>TLD>CS76-22>CS64- 22>BM>D	BM2>SMA>BM>CS76- 22>CS64-22>D>TLD
OGFC1-Ultrafuse	BM2>SMA>BM>CS76-22>CS64- 22>D>TLD	BM2>TLD>CS64-22>CS76- 22>BM>SMA>D
OGFC2- Ultrafuse	SMA>BM2>BM>TLD>CS76- 22>CS64-22>D	SMA>BM>BM2>CS76- 22>CS64-22>TLD>D

Based on the results of shear strength and stiffness, the interlayer materials of SMA, BM2, BM appeared to show better bonding properties with the gravel and limestone OGFC than other interlayer materials.

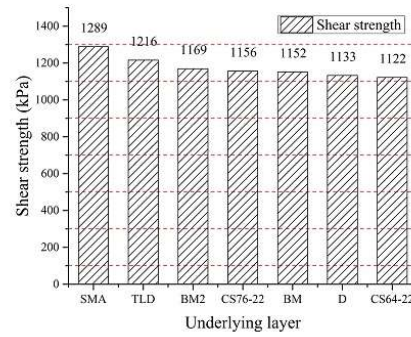


Figure 4- 8 Shear strength OGFC1- Anionic Asphalt Emulsion

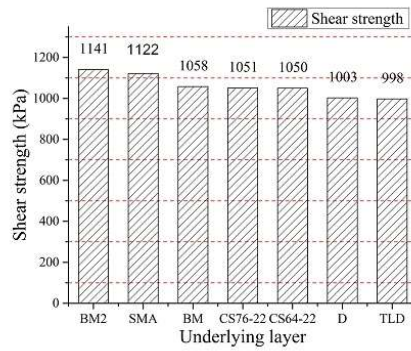


Figure 4- 9 Shear strength OGFC1-Ultrafuse Tack Coat

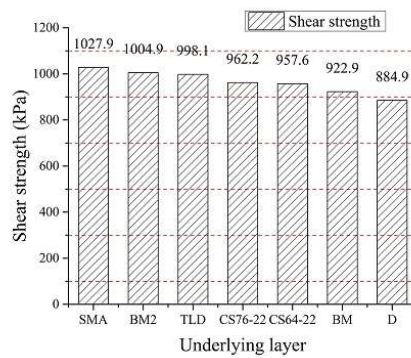


Figure 4- 10 Shear strength OGFC2-Anionic Asphalt Emulsion

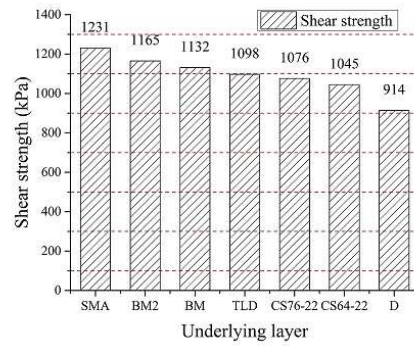


Figure 4- 11 Shear strength OGFC2-Ultrafuse Tack Coat

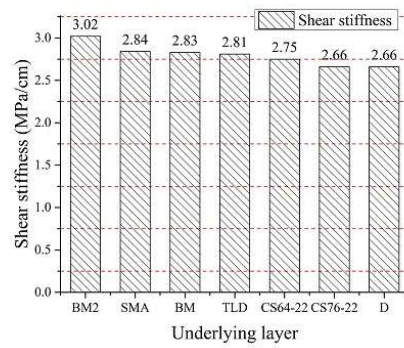


Figure 4- 12 Shear stiffness OGFC1-Anionic Asphalt Emulsion

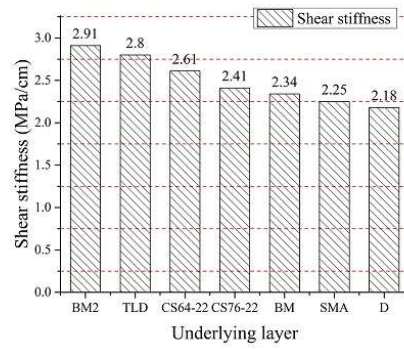


Figure 4- 13 Shear stiffness OGFC1-Ultrafuse Tack Coat

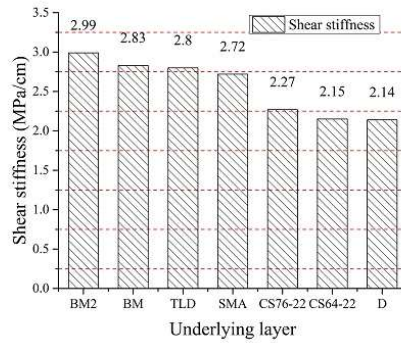


Figure 4- 14 Shear stiffness OGFC2-Anionic Asphalt Emulsion

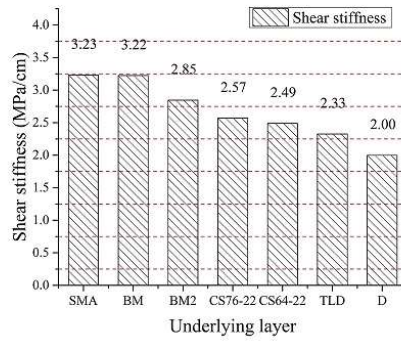


Figure 4- 15 Shear stiffness OGFC2-Ultrafuse Tack Coat

4.3.2 Shear Test Result for Different Tack Coat Application Rates and Temperatures

4.3.2.1 Materials

OGFC2 and TLD, D, SMA were employed in this part research. Figure 4- 16 shows the aggregate gradation of the four asphalt mixtures. The nominal maximum aggregate size (NMAS) was 12.5 mm, 9.5 mm, 9.5 mm and 12.5 mm, respectively, for OGFC, D, TLD, and SMA mixture. The tack coat material is a polymerized emulsion commonly used by the Tennessee Department of Transportation (TDOT).

Table 4- 2 Asphalt cement (AC) and AC content

Mixture Property	OGFC	Underlying Layer		
		D	TLD	SMA
Aggregate Type	Limestone	Gravel	Gravel	Granite
Asphalt PG grade	PG 76-22	PG 70-22	PG 76-22	PG 76-22
AC Content	6.4%	6.0%	6.2%	6.3%

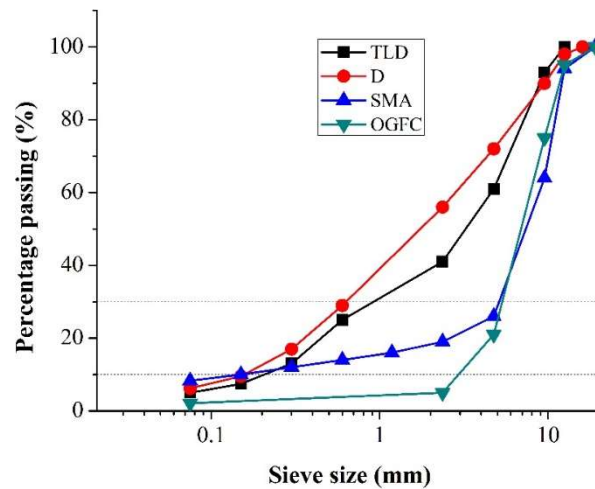


Figure 4- 16 Aggregate gradation

4.3.2.2 Laboratory tests

- **Texture depth test**

To investigate the effect of the surface characteristics of underlying layer on the friction between OGFC layer and underlying layer and thus on the interface shear strength, the underlying layer was tested for its surface texture depth using the sand patch method in accordance with ASTM E 965 (Figure 4- 17). The surface texture depth is the ratio of a known volume of sand material evenly spread on a pavement surface to the total area covered. The method is suitable for bituminous surface course and concrete pavement surface with texture depth greater than 0.25 mm. The test was conducted in triplicate.

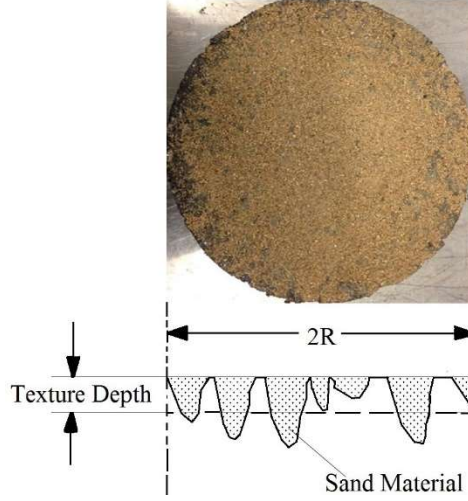


Figure 4- 17 Texture depth test

- **Direct shear test**

Direct shear test was conducted following the procedure in Part 3.2.3.

- **Interface roughness test**

To measure the interface roughness between OGFC and underlying layer, the average surface roughness, R_a , was introduced. Figure 4- 18 shows the schematic of a surface asperity deformation (Xie, et al. 2011). A horizontal line is drawn through the interface to make sure that Eq. (4-1) is satisfied. Then, the interface roughness can be determined using Eq. (4-2).

$$\int_0^L \delta dx = 0 \quad (4-1)$$

$$R_a = \frac{1}{L} \int_0^L |\delta| dx \quad (4-2)$$

Where, δ is the distance from this line to the surface nodes, and L represents the length of surface asperity after a certain deformation (Becker 1998, Li, et al. 2011, Li, et al. 2013).

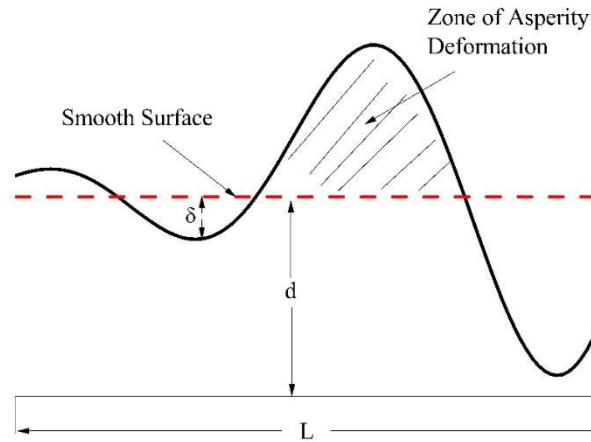


Figure 4- 18 Schematic of surface asperity deformation (Xie, et al. 2011)

4.3.2.3 Results and discussion

- **Direct shear test**

Effect of temperature

Figure 4- 19 shows the effect of temperature on the bonding shear strength of the OGFC-SMA composite specimens with or without tack coat. It clearly shows that temperature had a significant effect on the shear strength. With the increase in temperature from, the shear strength drastically decreased from approximately 2300 kPa to around 300 kPa, which can be attributed to the fact that the stiff asphalt material changed dramatically to a soft material when temperature increased from 0°C to 50°C due to its viscoelastic nature.

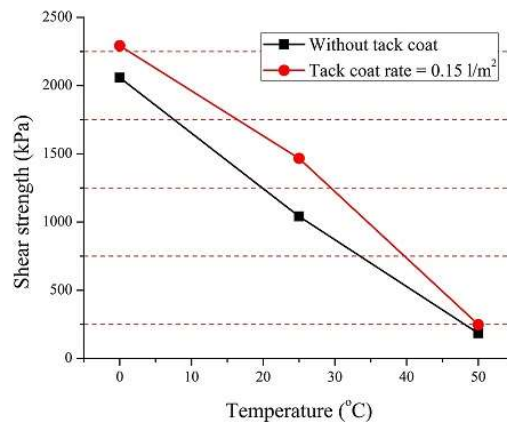


Figure 4- 19 Effect of temperature on shear strength (OGFC2-SMA)

The effect of temperature can also be seen from the failure mode of the composite specimens (Figure 4- 20). At 0°C, the specimens exhibited a brittle failure with the failure plane passing through the OGFC layer (Figure 4- 20 a). With the increase in temperature, the specimens gradually showed a plastic failure with an increased deformation because the peak load was reached (Figure 4- 20 b and c).

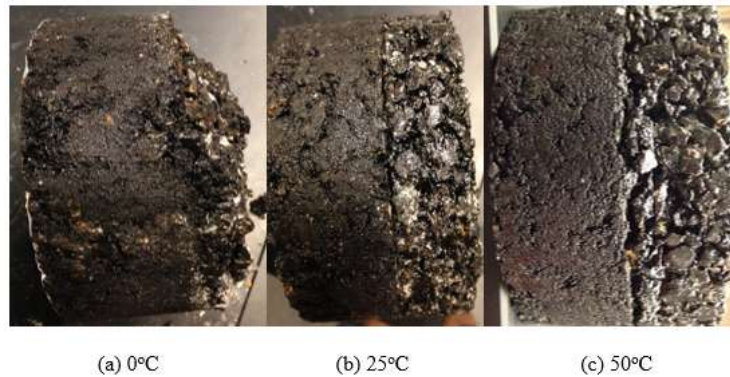


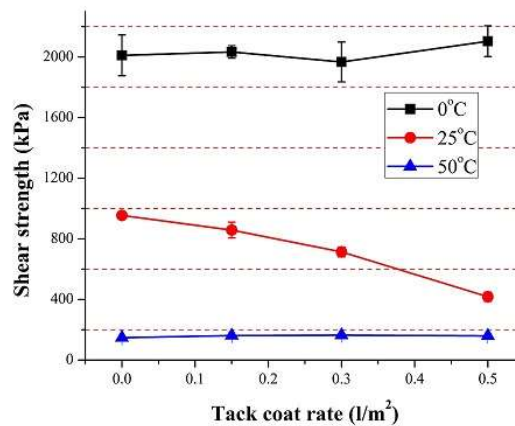
Figure 4- 20 Failure modes of composite specimens at different temperatures

Effect of tack coat application rate

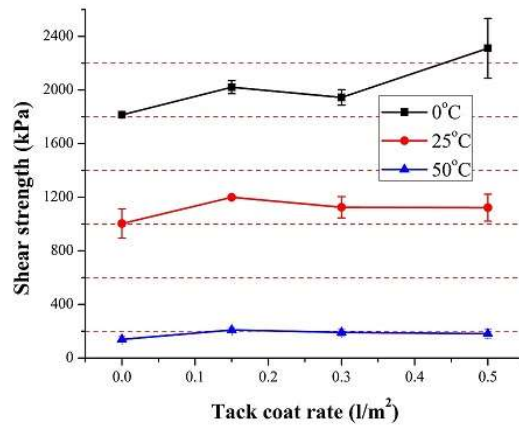
Figure 4- 21 shows the effect of tack coat application rate on the shear strength between OGFC and different underlying layers at different temperatures. Obviously, the effect of tack coat rate was affected by other factors, such as test temperature and type of

underlying materials. At low to intermediate temperatures (0 to 25°C), tack coat rate played a significant role in the shear strength. However, at higher temperature (50°C), change in tack coat application rate did not cause significant change in shear strength. This can be attributed to the low viscosity of asphalt material at high temperatures, which could not improve the friction between OGFC and underlying layer even with increased tack coat dosages.

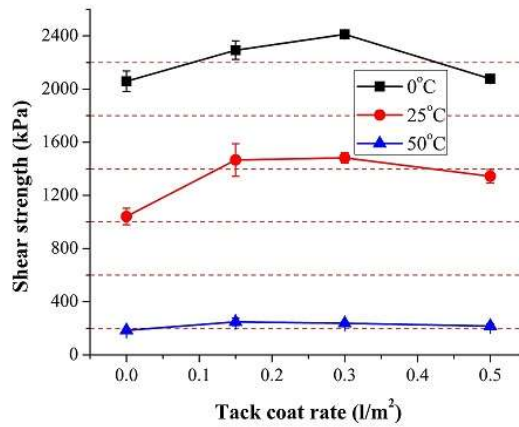
At low to high temperatures, usually there appeared to an optimal tack coat application rate, at which the specimens reached the peak shear strength. However, the presence of optimal tack coat rate was also influenced by type of underlying layer and temperature. For example, Figure 4- 21 shows that the shear strength of the OGFC-D specimens was not significantly affected by change in tack coat rate at 0°C and decreased with the increase in tack coat rate. This phenomenon can be explained by the low interface roughness between OGFC and D mixture. The low interface roughness did not significantly contribute to shear strength and made asphalt bonding between the two layers the dominant factor in controlling shear strength at 0°C, which explained the increase in tack coat application did not improve the shear strength. At 25°C, the low interface roughness even turned tack coat into a lubricant instead of the anticipated bonding agent. The more the tack coat was applied, the lower the shear strength.



(a) D



(b) TLD



(c) SMA

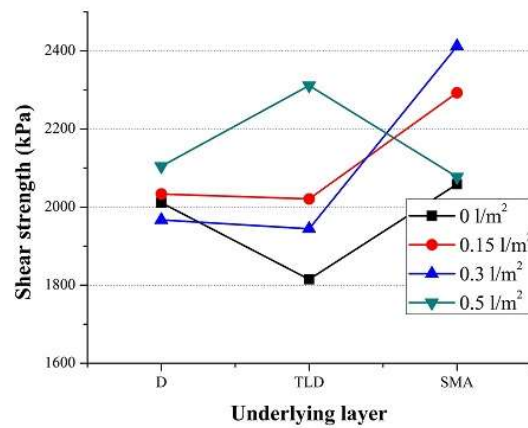
Figure 4- 21 Effect of tack coat rate on shear strength for different underlying layers

Effect of underlying layer

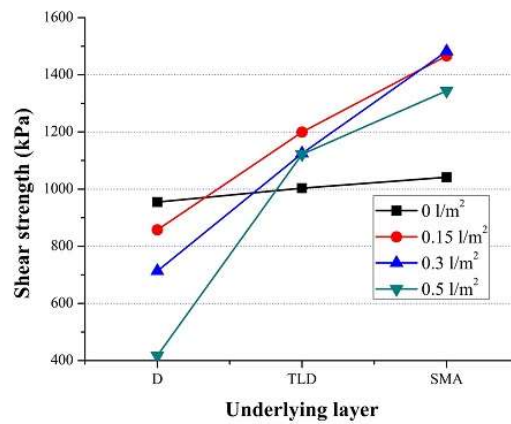
Figure 4- 22 shows the effect of underlying layer on the shear strength at different temperatures. Underlying layers showed a clear trend in shear strength development: Among the three underlying materials, the OGFC-SMA combination usually exhibited the higher shear strength, followed by the OGFC-TLD combination, whereas the OGFC-D combination gave the lowest shear strength. This trend clearly can be attributed to the interlocking between OGFC and different underlying layers, which indicated that SMA provided the strongest interlocking between OGFC and underlying layer and D mixture

gave the weakest interlocking.

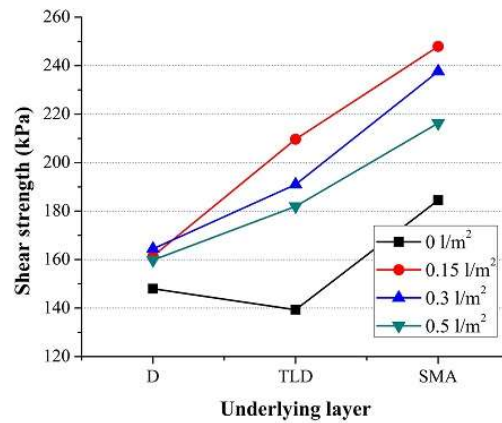
Figure 4- 22 (a) also shows that this trend was also affected by test temperature and tack coat rate. At low temperature (0°C), the trend was not so clear as that of intermediate to high temperatures (25°C to 50°C), which indicated that the high stiffness and strength of asphalt made its viscous bonding the dominant factor and the interface interlock/friction less important one in controlling shear strength.



(a) 0°C



(b) 25°C



(c) 50°C

Figure 4- 22 Effect of underlying layer on shear strength at different temperatures

- **Surface texture depth results**

Figure 4- 23 presents the surface texture depth results of the different underlying layers. Among the three underlying materials, SMA gave the highest texture depth and D mixture gave the lowest value, with the TLD's texture depth in between. The higher the texture depth, a stronger interlocking can be created between OGFC and underlying layer, indicating a higher friction resistance and higher shear strength. This can be clearly seen from Figure 4- 24 (b) and Figure 4- 24 (c) that higher texture depth usually led to a higher shear strength at intermediate and high temperature.

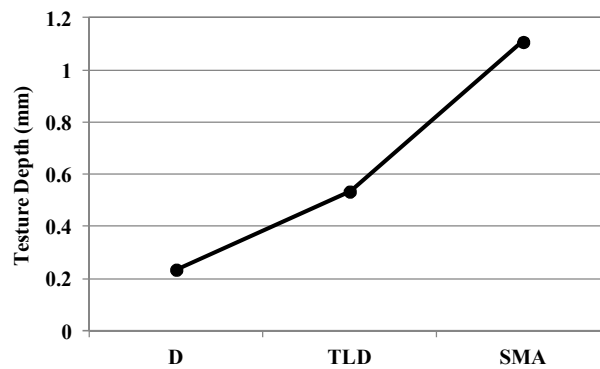
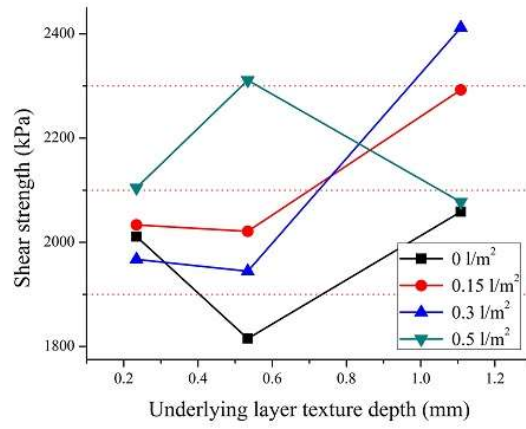
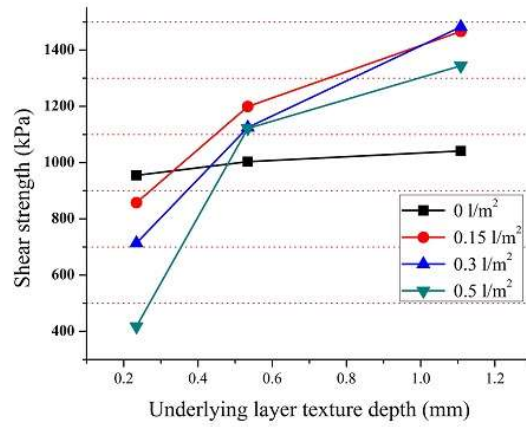


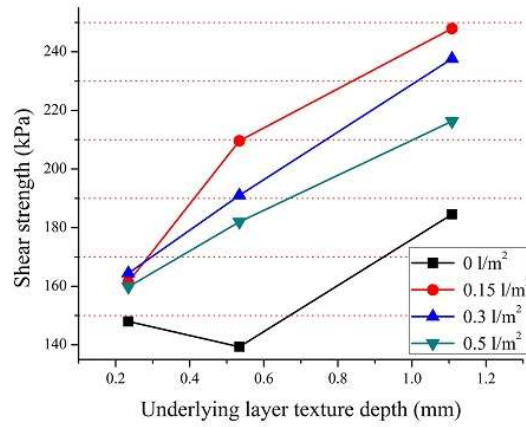
Figure 4- 23 Texture depth results for different layers



(a) 0°C



(b) 25°C



(c) 50°C

Figure 4- 24 Effect of texture depth of underlying layer on shear strength at different temperatures

- **Interface roughness results**

Figure 4- 25 through Figure 4- 27 show the sections of asphalt specimens cut in the middle. The red line delineates the interface between OGFC and underlying layer. Figure 4- 28 depicts just the interfaces for the three different combinations of OGFC and underlying layer.



Figure 4- 25 Section combined by OGFC and TLD



Figure 4- 26 Section combined by OGFC and D

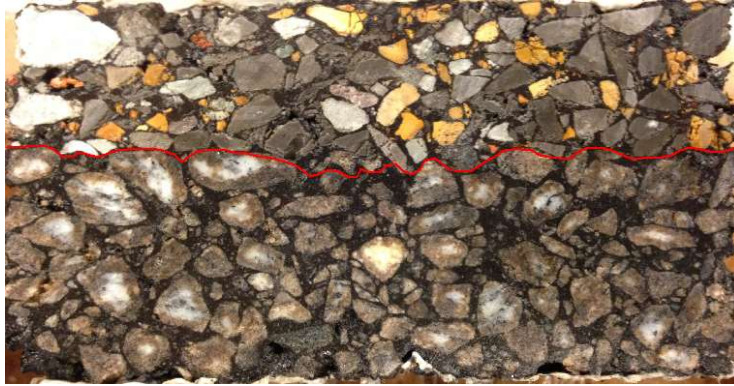


Figure 4- 27 Section combined by OGFC and SMA

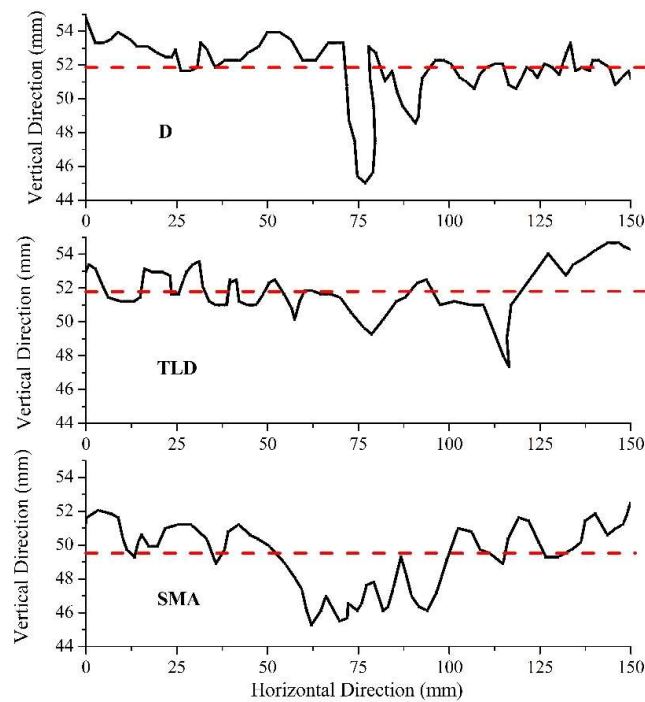


Figure 4- 28 Interfaces of OGFC with different underlying layers

Figure 4- 29 shows the interface roughness results. It can be seen that the combination of OGFC and SMA had the highest interface roughness followed by the OGFC-TLD combination. The OGFC-D combination had the lowest roughness. Figure 4- 30 shows the correlation between the surface texture depth and the interface roughness of different combinations. It shows that the two parameters had a strong correlation.

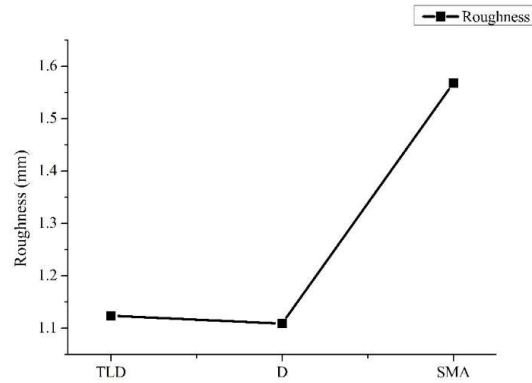


Figure 4- 29 Roughness of different underlying layers

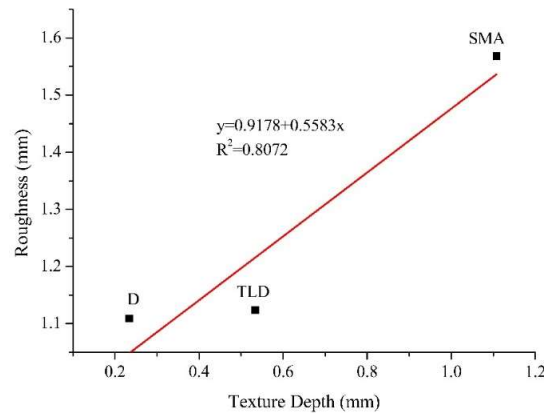


Figure 4- 30 Relationship between texture depth and interface roughness

4.3.2.4 Statistical analysis

Three-way and two-way Analyses of Variance (ANOVA) were performed to analyze the importance of the factors on their effects on the shear strength. In the three-way ANOVA analysis, shear strength was treated as the response variable and temperature, different underlying layer in terms of the surface texture depth, and tack coat application rate as factors. In the two-way analyses, two of the three factors were treated as variables while the third one kept as constant. The purpose of the two-way analyses was to investigate the effects of two factors when the third one was kept constant.

Table 4- 3 presents the three-way ANOVA results. The effects of the surface texture depth of underlying layer, temperature, and tack coat application rate, as well as their

interactions were all significant at the 95% confidence interval. Of the three factors, temperature was the most significant factor followed by the surface texture depth of underlying layer.

Table 4- 3 Three-way ANOVA results

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Texture	160795.3	2	80397.6	35.38	0
Temp	8755375.6	2	4377687.8	1926.42	0
Tack coat	23062.4	3	7687.5	3.38	0.0285
Texture*Temp	161279.3	4	40319.8	17.74	0
Texture*Tack coat	72428.2	6	12071.4	5.31	0.0005
Temp*Tack coat	45418.1	6	7569.7	3.33	0.0103
Texture*Temp*Tack coat	78685.4	12	6557.1	2.89	0.0069
Error	81807.9	36	2272.4		
Total	9378852.2	71			

Although all three factors were significant in the three-way ANOVA analysis, some of the factors became insignificant when one of the factors were maintained constant. Table 4- 4 presents the two-way ANOVA results showing the insignificant factors. At other circumstances, both factors in the two-way ANOVA were significant. Table 4 shows that without application of tack coat, the influence of surface texture depth of underlying layer became less important and insignificant. This is due to the fact that the friction between OGFC and underlying layer is attributed to the combination of tack coat and interface roughness. The interface roughness cannot contribute significantly to shear strength in the absence of tack coat. At low test temperature (0°C), asphalt binder became so stiff and its contribution to shear strength so strong that the effects of roughens and tack coat on shear strength were significantly reduced and both factors became insignificant. At high temperature (50°C), asphalt became so soft that change in tack coat application rate wouldn't result in significant change in shear strength, indicating that tack coat application rate became an insignificant factor. At low surface texture depth of 0.234 mm, tack coat application rate became an insignificant factor, indicating that the influence of tack coat was significantly reduced by the low interface roughness.

Table 4- 4 Two-way ANOVA results with insignificant factors

Third factor	Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Tack coat application rate = 0 l/m ²	Texture	6231.5	2	3115.7	1.33	0.3107
	Temp	1976671	2	988335.6	423.47	0
Temperature = 0°C	Texture	13224.6	2	6612.3	1.37	0.2916
	Tack coat	35408.6	3	11802.7	2.44	0.1146
Temperature = 50°C	Texture	2503.18	2	1251.59	5.37	0.0216
	Tack coat	1628.54	3	542.85	2.33	0.1262
Surface texture depth = 0.234 mm	Temperature	3032979	2	1516489	828.46	0
	Tack coat	16163.4	3	5387.81	2.94	0.0761

4.3.2.5 Summary and conclusions

A laboratory experiment was conducted to investigate the effects of temperature, tack coat dosage and underlying layer mixture type on the shear strength between the OGFC layer and underlying layer. The surface texture depth of the underlying layer and the interface roughness between OGFC and underlying layer were also measured to reflect the effect of interface characteristics on the shear strength. Based on the test results, the following conclusions can be drawn:

- The three factors considered in the study, underlying layer mixture type, temperature, and tack coat application rate, all significantly contributed to the shear strength between OGFC and underlying layers with temperature as the most significant factor followed by surface texture depth of underlying layer.
- Temperature affected the shear strength by changing the stiffness of asphalt binder. At low temperatures, asphalt was so stiff that the effects of both tack coat rate and surface texture depth of underlying became less significant.
- With the increase in temperature from low to high, the failure mode of the shear between OGFC and underlying layer changed from brittle to plastic.
- At intermediate to high temperatures, surface texture depth of underlying layer played a significant role in shear strength, indicating that selection of appropriate underlying layer with adequate roughness with OGFC is important to the bonding properties between OGFC and underlying layer.

- The effect of surface texture depth of underlying layer on shear strength was influenced by tack coat application rate, and vice versa. At low texture depth or low tack coat rate, the other factor became insignificant.
- The surface texture depth of underlying layer was found to be indicative of the interface roughness which correlated well with shear strength. Usually, the higher the surface texture depth, the higher the shear strength between OGFC and underlying layer.
- Interlocking effect between OGFC and underlying layers makes a positive effect on the bonding property between OGFC and underlying layers. The higher the interface roughness, the higher the shear strength.
- The interface roughness between OGFC and underlying layer was measured and correlated well with the surface texture depth of underlying layer.

4.4 Shear Fatigue Test

The objective of the study was to evaluate the shear fatigue performance of the composite specimen consisting of OGFC and different underlying layers through laboratory testing. Two types of dense graded asphalt mixture were used as the underlying layer, combined with one gravel OGFC to make the two-layered composite specimens. Direct shear fatigue test was performed to obtain their fatigue properties. The conventional 50% stiffness reduction method, the cumulative dissipated energy and ratio of dissipated energy ratio from energy approach were employed to analyze the fatigue behavior. The interface characteristics were tested and further related to the fatigue properties of the composite specimens.

4.4.1 Methodology

- 50% stiffness reduction method

To determine the number of loading cycle to failure, a 50% stiffness reduction method is generally employed, which means failure happens when 50% initial stiffness reduction is reached (Diakhaté, et al. 2011, Hicks, et al. 1993, Roberts, et al. 1996, Williams 1998, Wu, et al. 2013).

- Ratio of dissipated energy change (RDEC)

RDEC can be demonstrated by equation (4-3).

$$RDEC(i) = \frac{|w_j - w_i|}{(j-i)w_j} \quad (4-3)$$

where i and j denote respectively the i th and j th cycles, w_i is the dissipated energy at cycle i , and w_j the dissipated energy at cycle j .

A typical curve depicted by RDEC as a function of loading cycles (Figure 4- 31) can be easily divided into three stages. There is a constant percentage of input energy being turned into fatigue damage in stage II , which offers an indication of the fatigue performance called Plateau Value (PV).

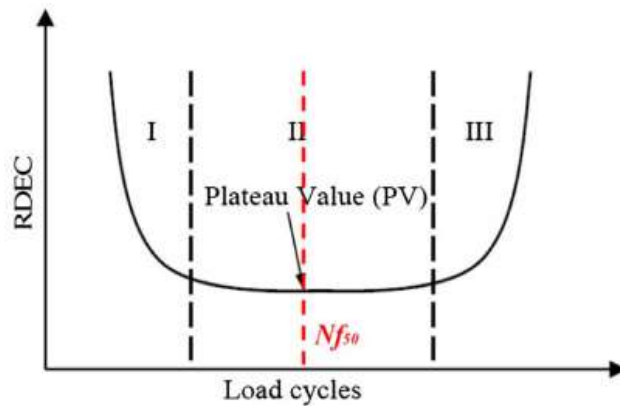


Figure 4- 31 Typical RDEC vs. number of loading cycle

- Cumulative dissipated energy

After the calculation of the dissipated energy at given cycles, in this study dissipated energy was calculated every 50 cycles, by linear interpolation, dissipated energy of all loading cycles can be generated. The total dissipated energy can be further obtained. Relationship between the total cumulative dissipated energy and fatigue life can be then examined.

4.4.2 Experiment design

4.4.2.1 Presentation of the test device

The direct shear fatigue device includes four semi-circular steel rings, as Figure 4-32 shows. It is installed to one MTS machine to apply shear force in vertical direction. In each cycle, both the shear force and displacement values are recorded at the frequency pre-set.

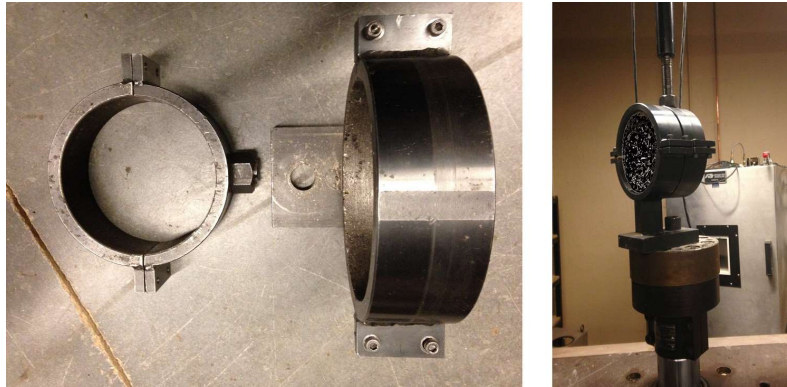


Figure 4- 32 Shear fatigue test

4.4.2.2 Experimental program and loading condition

Two type of dense asphalt mixture were selected as the underlying layer material, named as BM ad TLD2, which are commonly used in Tennessee. The aggregate gradation of the three asphalt mixture is shown as Figure 4- 33. The nominal top size of the aggregate of OGFC, BM and TLD is 19mm, 25mm and 12.5mm respectively. Detailed information of the asphalt mixtures is in Part 3.1.

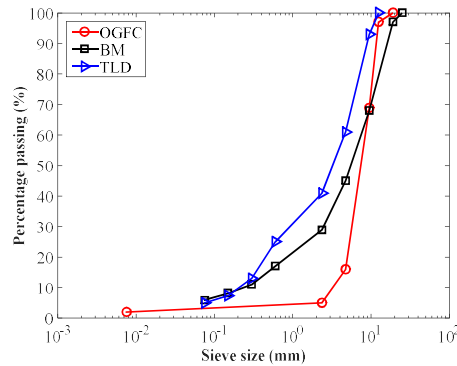


Figure 4- 33 Aggregate gradation

Test specimens are composed of two layers with diameter 150 mm, the bottom layer is underlying layer which is BM and TLD, the upper layer is OGFC, structures are named as BM-OGFC and TLD-OGFC. The height of underlying layer is 2 inches, and the height of OGFC is 1.25 inch, which is based on the experience of Tennessee Department of Transportation (TDOT). Firstly, the underlying layer was compacted by gyratory compactor, then the SGC specimen was extruded, after it cooled to ambient temperature, tack coat material was evenly applied to the surface of the underlying layer specimen at the required tack coat dosage. 30 minutes later, the specimen was put into the gyratory mold with the tack coat surface upwards, and then the loose mix of OGFC was put into the mold for further compaction. The compression pressure is 600 kPa and the compaction temperature of OGFC is 145°C. OGFC was compacted to 18% air voids, while BM and TLD were associated with 4% air voids.

By using stress-controlled model, frequency rate 10 Hz was selected in the fatigue test, with a sine form, and the test temperature was set at 20°C. The loading situation is shown in

Table 4- 5. The test was conducted in triplicate.

Table 4- 5 Loading condition

Underlying layer	Stress (MPa)	Frequency (Hz)	Tack coat residual application rate (L/m ²)
TLD	0.4	10	0
BM			0.15
	0.8		0.30
			0.50

4.4.3 Results and discussion

4.4.3.1 Stiffness approach

The results of the stiffness with respect to OGFC-TLD at stress 0.4 MPa is presented in Figure 4- 34. It can be observed clearly stiffness modulus showed identical ranking order for OGFC-TLD at four different tack coat application rates. Two stages can be clearly divided into two main stages. In stage I, stiffness modulus decreased slightly, which may be tied to damage extension (appearance of micro-cracking). During the stage II, the interface shear stiffness modulus decreased quickly, which implied both the coalescence and rapid propagation of macroscopic cracks at the interface. At the first stage, the stiffness decrease rate became larger as the tack coat application rate increased, which indicates tack coat decreased the interaction between OGFC and TLD and made an effect of lubrication to some extent instead of bonding agent.

The stiffness comparison between OGFC-TLD and OGFC-BM is plotted as Figure 4- 35 at tack coat application rate 0.15 l/m² and 0.30 l/m². The maximum shear stiffness modulus of OGFC-BM is lower than that of OGFC-TLD, and in the first stage the stiffness decrease rate of OGFC-BM was larger than that of OGFC-TLD at the same tack coat rate, which indicates OGFC-TLD presented better shear fatigue behavior than OGFC-BM.

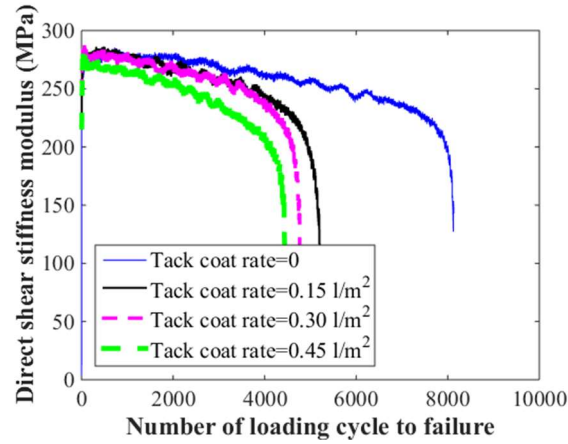


Figure 4- 34 Evolution of stiffness of OGFC-TLD at 0.4 MPa

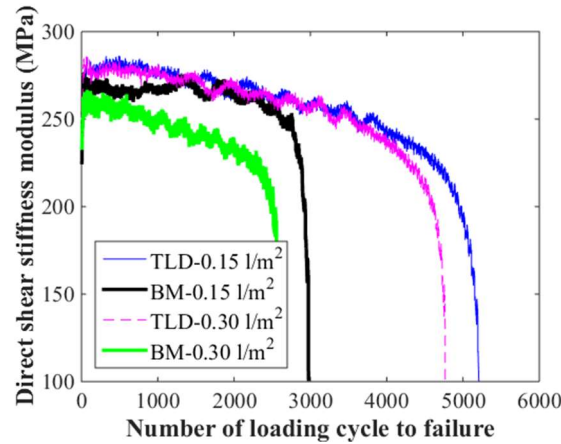


Figure 4- 35 Comparison of stiffness of OGFC-BM and OGFC-TLD at 0.4 MPa

The fatigue life of OGFC with two different underlying layers was determined according to the 50% stiffness reduction method. Figure 4- 36 shows the fatigue life of OGFC-BM and OGFC-TLD at different stress levels and different tack coat dosages. As tack coat application rate increased, the number of loading cycle to failure generally decreased. This may be caused by the lubricating effect of tack coat instead of the anticipated bonding effect. At the same tack coat application rate, OGFC-TLD appeared to have a longer fatigue life than OGFC-BM.

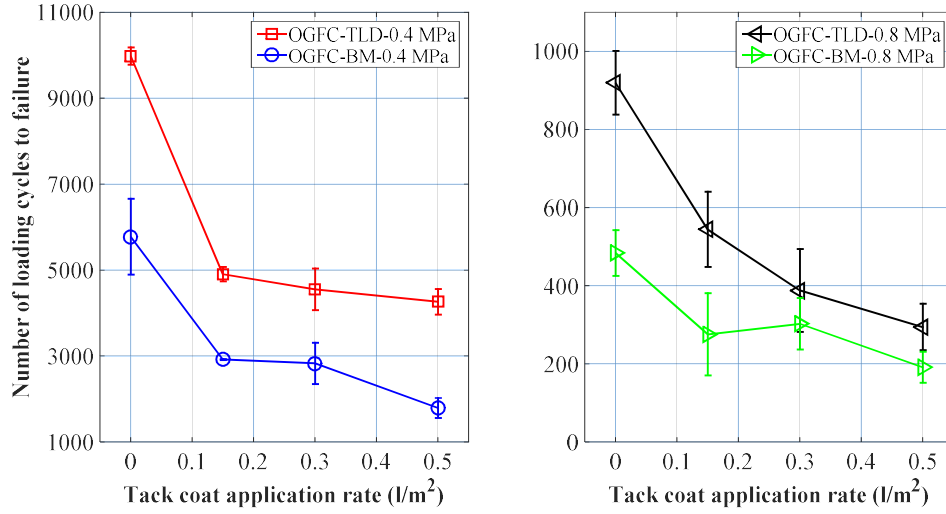


Figure 4- 36 Fatigue life results based on 50% stiffness reduction method

4.4.3.2 Ratio of dissipated energy change (RDEC)

Figure 4- 37 shows the load vs. displacement hysteresis loops of the first, 100th, 9000th, and 10000th loading cycles of OGFC-TLD at the shear stress of 0.4MPa for the specimens without tack coat applied. Because of viscoelastic nature, the maximum load of the first loop did not reach the predetermined load level. Figure 4- 37 reveals that during the first several cycles, the dissipated energy increased significantly, and then dissipated energy became stable and showed a slight increase, which indicates that fatigue damage developed gradually (appearance of micro cracking). During the last several cycles, the dissipated energy showed a great increase again, implying that significant damage was occurring, leading to the failure of the specimen. The significant damage in the last phase was caused by both the coalescence and rapid propagation of macroscopic cracks at the interface.

RDEC was obtained according to Equation (1). The plateau value (PV) was used to analyze the fatigue behavior. Figure 4- 38 presents the evolution of RDEC of OGFC-BM with the loading cycles at 0.4 MPa without tack coat applied. Three stages can be clearly observed from Figure 4- 38.

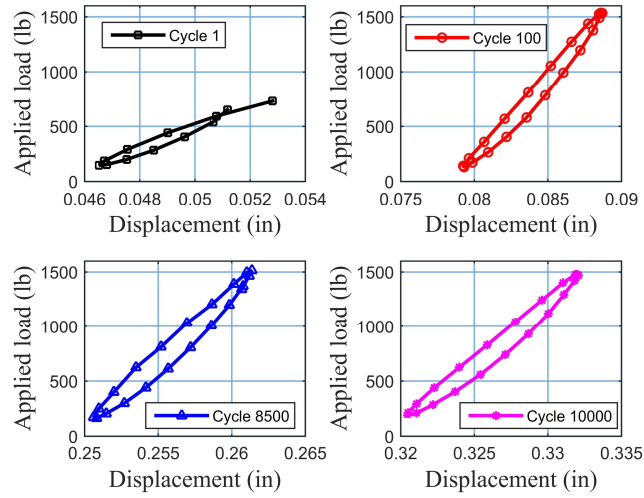


Figure 4- 37 Load-displacement hysteresis loops

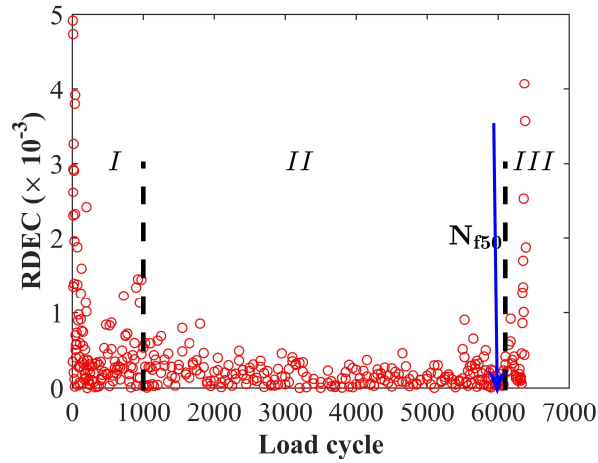


Figure 4- 38 RDEC vs. number of loading cycle

Figure 4- 39 shows the change of PV with tack coat dosage and Figure 4- 40 shows the relationship between PV and fatigue life. Generally, as the tack coat dosage increased, OGFC-BM and OGFC-TLD both experienced an increase in PV. As is known, the lower the PV, the lower the percentage of input energy being turned into damage, the better the fatigue performance. The relationship between PV and fatigue life shown in Figure 4- 40 further validated this phenomenon. This also indicates that OGFC-BM and OGFC-TLD with a lower PV would show the best fatigue performance when tack coat was not applied.

At the same tack coat dosage, OGFC-BM showed a higher PV than OGFC-TLD, indicating that OGFC-TLD would perform better than OGFC-BM in terms of fatigue performance. The PV results were generally consistent with the fatigue life determined according to the conventional 50% stiffness reduction method. The relationship between N_{f50} and PV is plotted in Figure 4- 41. It can be seen that a power law equation could be used to describe the relationship between PV and N_{f50} . This relationship is consistent with the findings of other researchers (Shen and Carpenter 2006, Wu, et al. 2013). The power function obtained in this study is shown as Equation (2). It can be seen that the power law equation was independent of the underlying layer material and tack coat application rate.

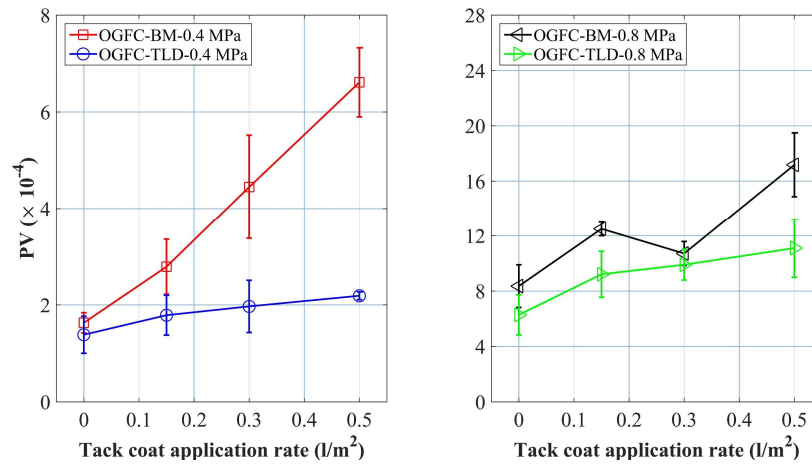


Figure 4- 39 PV results

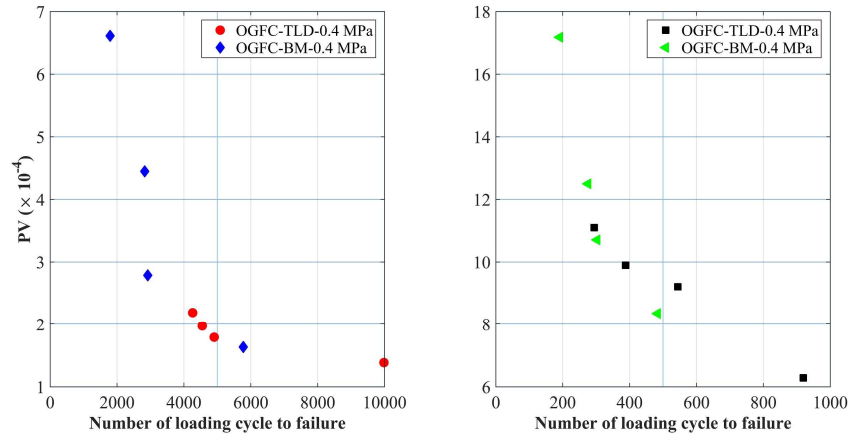


Figure 4- 40 PV vs. fatigue life

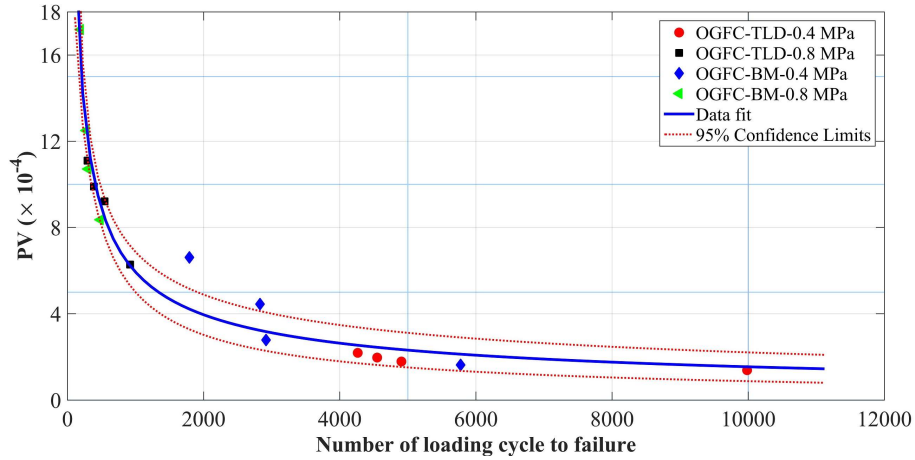


Figure 4- 41 Fitting between PV and fatigue life

$$PV = 0.0336N_{f50}^{-0.585} \quad (R^2 = 0.954) \quad (4-4)$$

4.4.3.3 Cumulative dissipated energy

The cumulative dissipated energy of OGFC-BM and OGFC-TLD was obtained at each loading cycle. The total dissipated energy was plotted against the tack coat dosage and shown in Figure 4- 42 for both stress levels. Figure 4- 42 indicates that OGFC-TLD released a higher cumulative dissipated energy than OGFC-BM at all tack coat dosages when fatigue failure happened. For both OGFC-TLD and OGFC-BM, when tack coat

dosage increased, the total dissipated energy decreased at both 0.4MPa and 0.8MPa stress levels.

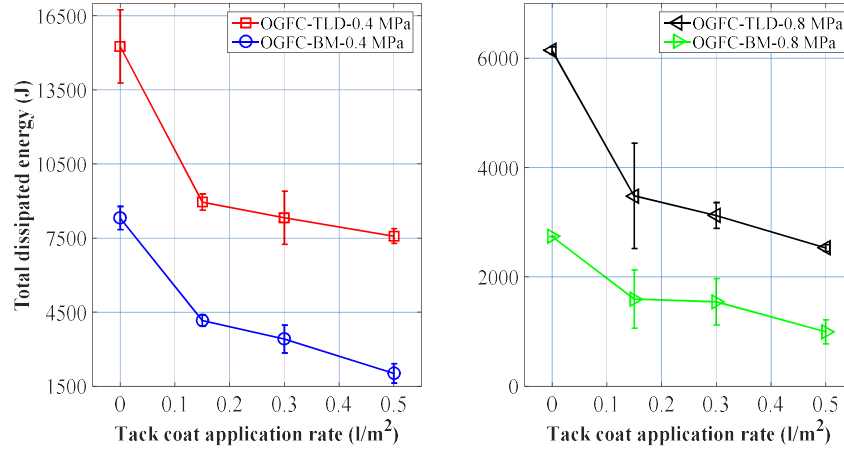


Figure 4- 42 Total dissipated energy

To further examine the relationship between the cumulative dissipated energy (W_{Nf}) and the fatigue life determined according to the 50% stiffness reduction method (N_{f50}), W_{Nf} was plotted against N_{f50} in Figure 4- 43 for OGFC-TLD and OGFC-BM. The relationship between W_{Nf} and N_{f50} was plotted in Figure 4- 43. Power law equations were fitted to explore the relationship. It is found that there exists a good correlation between W_{Nf} and N_{f50} for TLD-OGFC, but the R^2 value of BM-OGFC was a litter lower. With all the data used in the regression, the R^2 value of Equation (5) was 0.816, indicating that power law relationship between total cumulative dissipated energy and fatigue life was independent of tack coat application rate, but dependent on the underlying layer material. This is generally in agreement with the findings from other researchers (Carpenter and Jansen 1997, Van Dijk, et al. 1972). But further research is still needed in the future for the relationship between W_{Nf} and N_{f50} considering the variables of underlying layer and tack coat application rate.

$$W_{Nf_TLD} = 151.77N_{f50}^{0.489} \quad (R^2 = 0.907) \quad (4-5)$$

$$W_{Nf_BM} = 16.12N_{f50}^{0.707} \quad (R^2 = 0.797) \quad (4-6)$$

$$W_{All} = 30.82N_{f50}^{0.661} \quad (R^2 = 0.816) \quad (4-7)$$

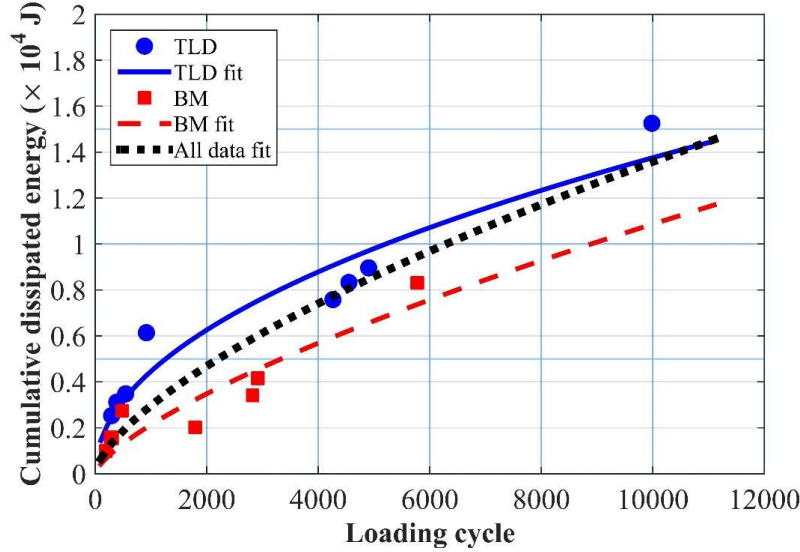


Figure 4- 43 Total dissipated energy vs. number of loading cycle to failure

4.4.3.4 Interface Characterization

Interface characteristics between OGFC and its underlying layer play an important role in interlayer bonding (Chen and Huang 2010). The contact area between OGFC and the underlying layer is vital to ensure a good bonding between different layers. Figure 4-44 and Figure 4- 45 show the bottom surface photographs of OGFC compacted on BM and TLD after shear fatigue failure. The left pictures are original pictures after failure and the right ones are those after image processing of binarization. A binary image is a digital image that has only two possible values for each pixel: 0 or 1.

In the original picture, some of the darkest spots can be clearly differentiated from others. The darkest spots represent the asphalt binder of OGFC, where there were voids and thus no contact area between OGFC and the underlying layer. Using image binarization, the dark areas could be identified and removed from the total area. Thus, the contact area between OGFC and its underlying layer could be calculated.

Figure 4- 46 shows the results of the contact area between OGFC and the underlying

at tack coat application rates 0.15 l/m^2 and 0.30 l/m^2 . It clearly shows that the contact area between OGFC and TLD was larger than that of OGFC-BM. The contact area at the tack coat rate of 0.30 l/m^2 was also found to be larger than that at 0.15 l/m^2 , which may be attributed to the fact that as more tack coat was applied, more tack coat filled the voids at the interface after the compaction of OGFC.

Figure 4- 47 and Figure 4- 48 present the relationship between fatigue life and contact area at the tack coat rates of 0.15 l/m^2 and 0.30 l/m^2 respectively. It can be clearly seen that at the same tack coat rate, the fatigue life of the specimens increased with the increase in the contact area between the two pavement layers. Although the tack coat rate of 0.30 l/m^2 resulted in a higher contact area than 0.15 l/m^2 , the higher rate also increased the lubricating effect, leading to a compromised fatigue life than 0.15 l/m^2 .

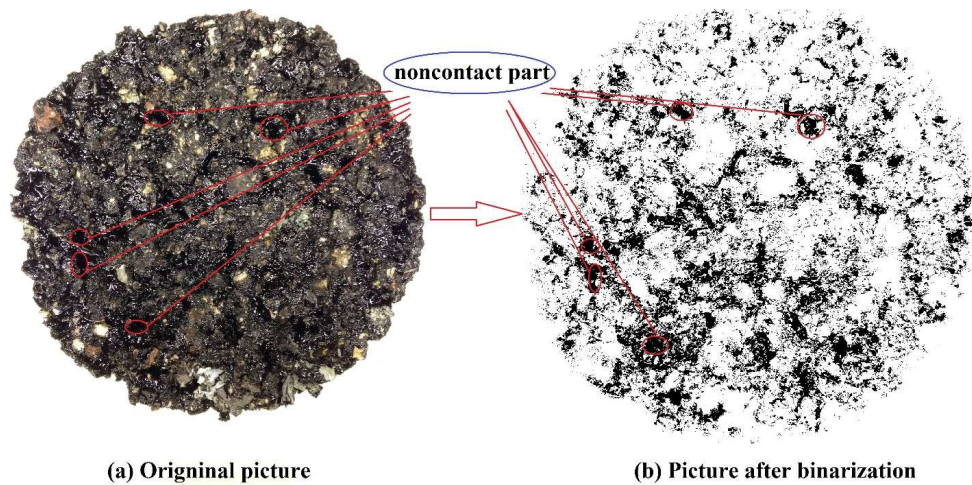


Figure 4- 44 Failure OGFC surface (OGFC-BM)

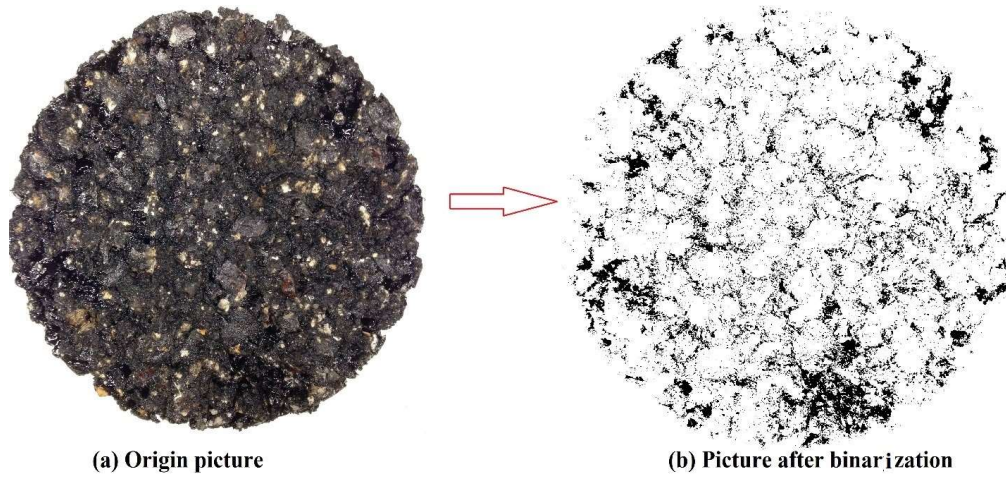


Figure 4- 45 Failure OGFC surface (OGFC-TLD)

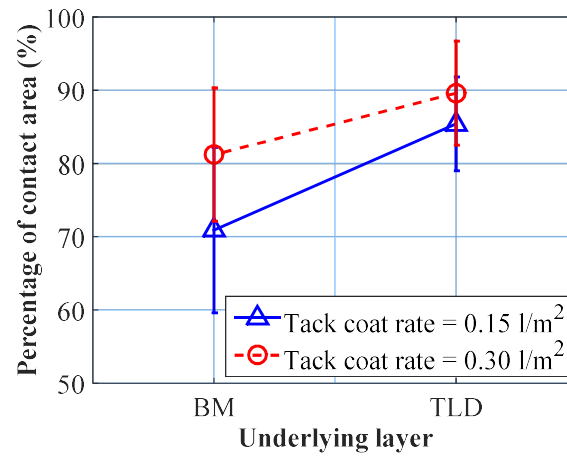


Figure 4- 46 Results of contact area

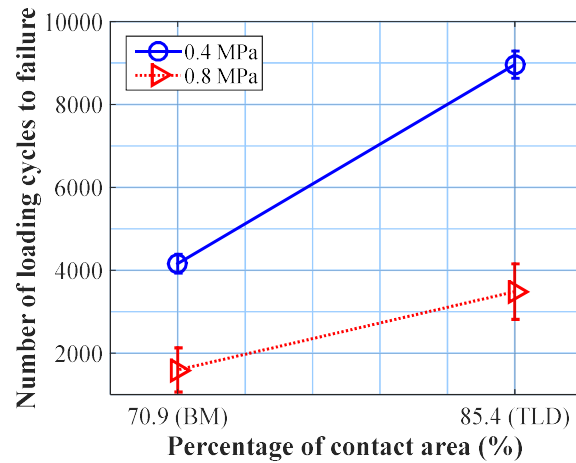


Figure 4- 47 Contact area vs. fatigue life at tack coat rate 0.15 l/m²

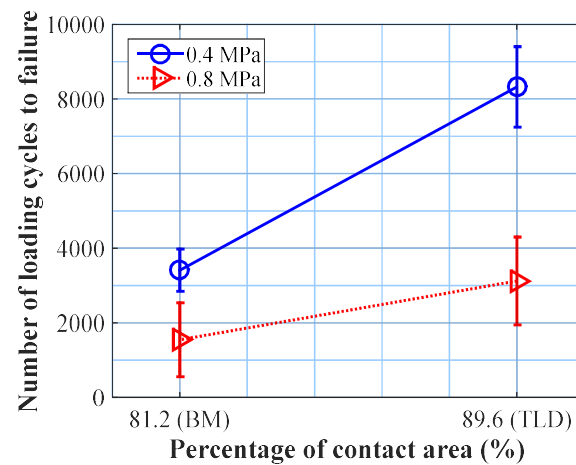


Figure 4- 48 Contact area vs. fatigue life at tack coat rate 0.30 l/m²

4.4.4 Summary and Conclusions

This study evaluated the laboratory shear fatigue performance of OGFC combined with different underlying layers (BM and TLD). Fatigue life, cumulative dissipated energy, and RDEC were used to analyze the fatigue behavior of the composite specimens. The contact area between OGFC and its underlying layer were tested and correlated to the fatigue performance. Based on the results and analyses, the following conclusions can be drawn:

- The fatigue life of OGFC-TLD was longer than that of OGFC-BM. With the increase in tack coat dosage, the number of loading cycle to failure decreased, which may be attributed to the lubricating effect of tack coat.
- The plateau value (PV) of OGFC-TLD was lower than that of OGFC-BM under the same loading condition, leading to a better fatigue performance of OGFC-TLD. In addition, with the increase in tack coat dosage, PV increased for both OGFC-TLD and OGFC-BM, implying a degraded fatigue performance because more dissipated energy was turned to fatigue damage. Power law relationship was found to exist between PV and fatigue life, which was independent of the underlying layer type and tack coat dosage rate.
- The total dissipated energy of OGFC-TLD was larger than that of OGFC-BM at same stress and same tack coat dosage. As tack coat dosage increased, total dissipated energy decreased. There existed a power law relationship between cumulative dissipated energy and fatigue life, which was independent of tack coat application rate, but dependent on underlying layer material.
- The OGFC-TLD interface contact area was larger than that of OGFC-BM, leading to a better fatigue performance of OGFC-TLD.
- The plateau value failure criterion appeared effective for evaluating the shear fatigue performance of multilayer structures.

CHAPTER 5 INFLUENCE OF INTERFACE CHARACTERISTICS ON THE SHEAR PERFORMANCE BETWEEN OPEN-GRADED FRICTION COURSE AND UNDERLYING LAYER

5.1 Introduction

Open-graded friction course (OGFC) is a thin asphalt pavement layer placed on the traditional dense asphalt concrete. Because of its numerous benefits in terms of economy, safety and environment (Alvarez et al. 2006), OGFC attracts extensive attention nowadays. Although OGFC has many advantages, some types of distress may also occur, such as raveling, stripping, pore clogging, and pothole (Kline 2010; Nielsen 2006; Putman 2012). The performance of OGFC pavements is not only related to the properties of OGFC, such as binder and aggregate gradation, but also the bonding between OGFC and its underlying layer. Like traditional dense asphalt pavements, debonding between OGFC and underlying layer is one common type of distress occurring in OGFC pavements (Kline 2010; Nielsen 2006; Song et al. 2016). To meet the durability requirement in pavement design, it is vital to evaluate the bonding properties between OGFC and underlying layer to ensure that the pavement serves as a monolith system.

For traditional dense asphalt mixture pavements, pioneering work has been done to explore the factors influencing the bonding strength between pavement layers (Canestrari et al. 2005; Chen and Huang 2010; Collop et al. 2009; Mohammad et al. 2002; Raab et al. 2012; Raab and Partl 2009; Raposeiras et al. 2012; Tashman et al. 2008; West et al. 2005). Some studies have shown that the bonding performance degrades as temperature increases

within a certain temperature range and asphalt becomes soft (Al-Qadi et al. 2012; Canestrari et al. 2005; Chen and Huang 2010; Mohammad et al. 2002; West et al. 2005). Research on bonding properties between OGFC and different underlying layers showed similar phenomenon (Song et al. 2016). Tack coat application rate is one important factor for pavement layer bonding (Mohammad et al. 2002; Raab and Partl 2009; Raposeiras et al. 2012). In the construction of OGFC, a tack coat material is also commonly used to ensure an adequate bonding between OGFC and the underlying layer (Abadie 2013; Kandhal and Mallick 1998). Besides providing the bonding between OGFC and underlying layer, the tack coat layer could also be used as the waterproofing layer which protects the underlying layer from the water damage (Estakhri et al. 2008). Some researchers (Mohammad et al. 2002; Raposeiras et al. 2012) concluded that there existed an optimal tack coat application rate at which the maximum shear strength can be obtained. However, other researchers indicated that better shear strength values can be obtained without tack coat application (Collop et al. 2009; Song et al. 2016). Shear strength is also affected by other factors, such as interface characteristics and temperature (Song et al. 2016). Some other factors, including tack coat type (Mohammad et al. 2002; West et al. 2005) and tack coat breaking time (Chen and Huang 2010; Tashman et al. 2008) were also evaluated.

Chen and Huang (2010) compared the bonding between dense graded asphalt concrete (DGAC), porous asphalt concrete (PAC), and stone matrix asphalt (SMA) and ranked their shear strengths in the following order: DGAC-DGAC > PAC-DGAC > PAC-SMA, because the contact of DGAC-DGAC was more pronounced. Al-Qadi et al. (2012) found that the nominal maximum aggregate size (NMAS) affects the shear strength through its effect on the aggregate interlock in the interface. By using ideal spherical aggregates, Raab et al. (2012) concluded that the aggregate combination s/b (small aggregate in the upper layer and big aggregate in the underlying layer) leads to the best shear strength, which is attributed to the higher adhesive strength caused by better aggregate interlock between the two layers. However, cohesive strength was not considered in their study

(Raab et al. 2012).

Regarding the interface characteristics, tack-coat application rate depends on the texture depth of the underlying layer surface for traditional dense asphalt pavement (Mrawira and Damude 1999; West et al. 2005). Song et al. (2016) found that texture depth of underlying layer plays a significant role in the bonding between OGFC and underlying layer. As texture depth increases, the shear strength increases as well at the optimal tack coat application rate. Other researchers found similar trends (Al-Qadi et al. 2012). Santagata et al. (2008) reported that a larger texture depth of underlying layer leads to a higher surface roughness, which provides a higher shear resistance. By milling the surface of underlying layer, a better shear resistance can be obtained in contrast with specimens with non-milled surface (Tashman et al. 2006; West et al. 2005).

Cracking is one major cause resulting in the deterioration of asphalt pavement. Aggregate gradation, binder, and aggregate shape all play an important role in asphalt concrete fracture behavior (Pirmohammad and Ayatollahi 2015; Sadd et al. 2004). Adhesive failure and cohesive failure are two failure types occurring in asphalt mixture. Adhesive failure is the failure state that the stone surface is separated completely without binder coating on, and the cohesive failure is the failure state that failure occurs in the binder and there is still asphalt binder remaining on the aggregate after fracture (Mo et al. 2011). The de-bonding between pavement layers can also be regarded as a fracture behavior. Identifying the adhesive failure condition and the cohesive failure condition is of vital importance to the bonding performance. On the other side, because OGFC is a porous asphalt mixture with high air voids (Kandhal and Mallick 1998; Song et al. 2016), the interface between OGFC and the underlying layer is more complicated than traditional pavements and the interface characteristics are very important for a better understanding of the shear behavior between OGFC and the underlying layer.

5.2 Objective and Scope

The objective of this study was to investigate the effects of interface characteristics and tack coat on the shear properties of the composite specimens consisting of OGFC and one of the two different underlying layers (called BM and TLD in Tennessee) through laboratory testing. Both adhesive failure and cohesive failure of the interfaces were analyzed and the non-contact area of the interface was also measured. Adhesive failure, cohesive failure and non-contact area were correlated with the shear properties. The surface texture depth of the underlying layers was also measured and correlated to the shear properties.

5.3 Experiment Program

5.3.1 Materials

One type of gravel OGFC and two types of dense graded asphalt mixture (called BM and TLD in Tennessee) were selected as the upper layer and underlying layer, respectively. BM (Base Mixture) is a base layer material, while TLD (Thin Layer D Mixture) is a surface mixture according to the specifications of the Tennessee Department of Transportation (TDOT). The aggregates of BM are coarser than the aggregates in TLD. Table 5- 1 presents the material information of OGFC, TLD and BM mixtures. The asphalt binder of OGFC was PG 76-22, and polymer modified binder was used in OGFC. Figure 5- 1 shows the aggregate gradation of the three mixtures. The nominal maximum aggregate size (NMAS) was 9.5 mm, 19 mm, and 12.5 mm, respectively, for TLD, BM and OGFC. The tack coat material is an anionic slow-setting asphalt emulsion (SS-1) that contains less than 2.0% emulsifying agent, the viscosity of the tack coat is 40 cSt at 25 ° C, satisfying the specification requirement of the Tennessee Department of Transportation (TDOT). In

this study, five tack coat application rates were selected, that is 0, 0.15 l/m², 0.30 l/m², 0.45 l/m² and 0.60 l/m². All the tack coat application rates were based on the residual rate.

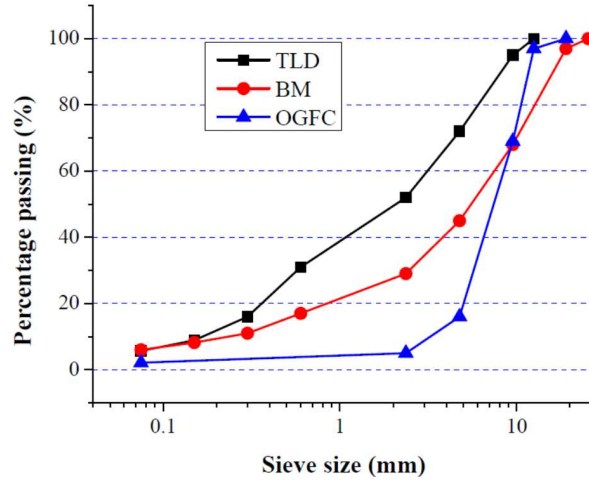


Figure 5- 1 Aggregate gradation

Table 5- 1 OGFC and underlying layer material

Mixture property	OGFC	Underlying layer	
		TLD	BM
Asphalt PG grade	PG 76-22	PG 64-22	PG 64-22
AC content	6.4%	6.2%	4.2%
Aggregate type	Gravel	Limestone	Limestone

5.3.2 Specimen Preparation

The size of the cylindrical specimens for texture depth test was 150 mm in diameter and 50.8 mm in height. The test specimens for the shear test were compacted in two layers with a 150 mm diameter. The upper layer was OGFC and the underlying layer was either BM or TLD. The heights of the upper and underlying layers were 50.8 mm and 31.8 mm,

respectively. The thicknesses of the specimens were determined according to the specifications of the Tennessee Department of Transportation (TDOT). All test specimens were compacted using a Superpave gyratory compactor (SGC).

To fabricate the two-layer shear test specimens, the underlying layer (BM or TLD) was first compacted, and then extruded. After the underlying layer cooled down to ambient temperature (20 °C), tack coat material was uniformly applied on the surface of the underlying layer. After curing about 30 minutes, the loose OGFC mixture was compacted on the top of underlying layer using SGC. The compressive pressure was 600 kPa and the compaction temperature of OGFC was 145 °C. OGFC was compacted to approximately an air void content of 18%, while BM and TLD to approximately 4%. The bulk specific gravities (G_{mb}) of BM, TLD and OGFC are $2.16 \times 10^3 \text{ kg/m}^3$, $2.11 \times 10^3 \text{ kg/m}^3$ and $1.84 \times 10^3 \text{ kg/m}^3$, respectively. The specimens were conditioned at ambient temperature (20 °C) for 24 hours before the texture depth test and shear test were conducted.

5.3.3 Direct Shear Test

Many shear test devices have been developed to test the bonding properties between different pavement layers, such as the Layer-Parallel Direct Shear (LPDS) tester (Leutner 1979), and the Laboratorio de Caminos de Barcelona (LCB) shear tester (Miró Recasens et al. 2003). LCB test was conducted without normal stress applied. Besides, the direct shear test with a normal load (Chen and Huang 2010; Romanoschi and Metcalf 2002), and a shear device developed by Mohammad et al. (2002) were also commonly utilized. In this study, the direct shear test was conducted with no normal load applied. The direct shear device consists of four semi-circular steel rings (Figure 5- 2) and it is simple and easy to use. It was mounted to an MTS machine. The shear force was applied in the vertical direction. Load and displacement were recorded simultaneously. The direct shear load rate was 50 mm/min.

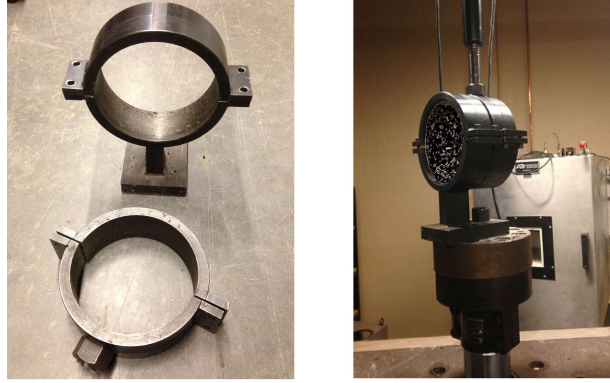


Figure 5- 2 Direct shear test set up

The number of the specimens of the shear test was shown in Table 5- 2. The direct shear test was conducted in triplicate. Figure 5- 3 presents the typical shear strength-displacement curve. Besides of the shear strength, interface shear stiffness was also used in the present study to characterize the bonding properties between OGFC and interlayer (Fig. 3). The interface stiffness is defined according to the Goodman's constitutive law as follows (Canestrari et al. 2005):

$$k = \tau / \varepsilon \quad (5-1)$$

Where, τ = interface shear stress (MPa); ε = displacement within the interface (cm); k = interface stiffness (MPa/cm).

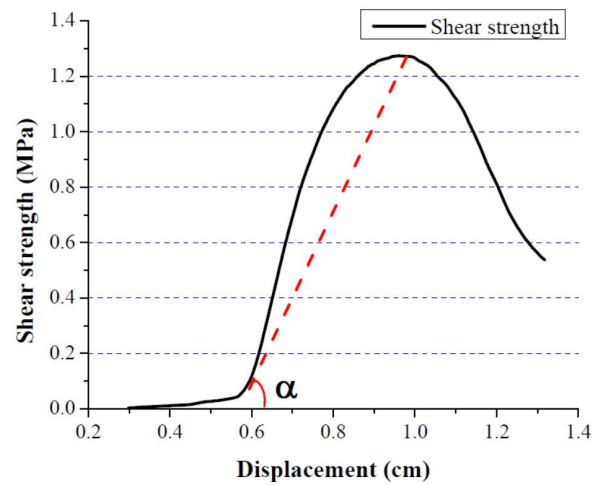


Figure 5- 3 Strength-displacement curve

Table 5- 2 Numbers of specimen of the shear test and texture depth test

	Specimen	Number of specimen
Shear test	OGFC-TLD	3
	OGFC-BM	3
Texture depth test	OGFC	3

5.3.4 Texture Depth Test

Conventional sand patch method was employed to conduct the texture depth test in accordance with ASTM E 965 (Figure 5- 4). The volumetric approach was employed to measure the pavement texture depth. The surface texture depth is the ratio of the volume of sand divided by the surface area. This test method can give reasonable results for asphalt and concrete pavements surface with texture depth greater than 0.25 mm. Sand patch texture depth test was performed in triplicate.

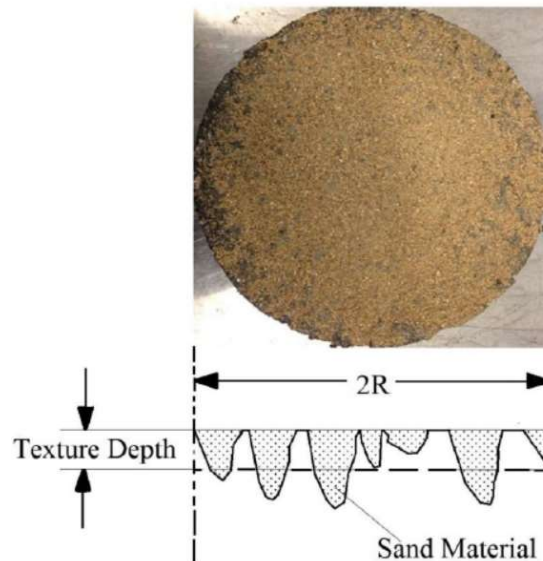


Figure 5- 4 Texture depth test

5.4 Results and Discussion

5.4.1 Texture Depth

The texture depth results of TLD and BM are shown in Figure 5- 5. The texture depth of BM was larger than that of TLD, which can be attributed to its coarser aggregate gradation.

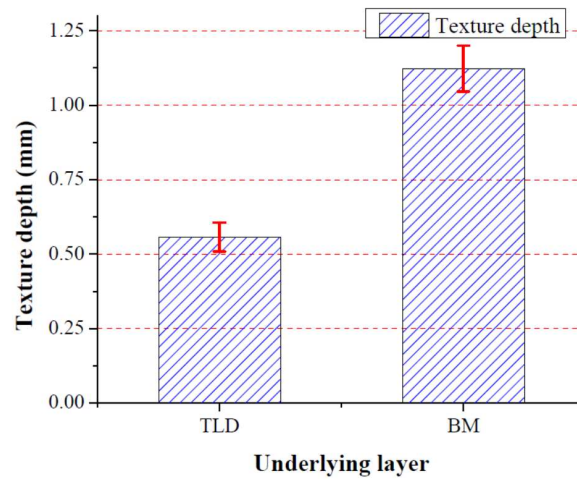


Figure 5- 5 Texture depth result

5.4.2 Shear Strength and Stiffness

Figure 5- 6 and Figure 5- 7 show the shear strength and stiffness results. As can be seen from Figure 5- 6 and Figure 5- 7, there existed an optimal tack coat application rate for OGFC-TLD and OGFC-BM, respectively, at which the peak shear strength and peak shear stiffness were obtained. The optimal tack coat application rate was 0.15 l/m^2 and 0.30 l/m^2 for OGFC-TLD and OGFC-BM, respectively. BM showed a higher texture depth, indicating that it had a larger surface area than TLD. To achieve the same tack coat film thickness, optimal tack coat application rate of OGFC-BM was larger than that of OGFC-TLD. The peak shear strength of OGFC-BM was higher than that of TLD-OGFC, which may be contributed to its higher surface roughness (Song et al. 2016). At low tack coat application rates of 0 and 0.15 l/m^2 , shear strength of OGFC-TLD was larger than that of

OGFC-BM. At high tack coat application rates of 0.30 l/m^2 , 0.45 l/m^2 and 0.60 l/m^2 , the shear strength of OGFC-BM became larger than that of OGFC-TLD. The trend of the change of shear stiffness with tack coat was similar to that of the shear strength.

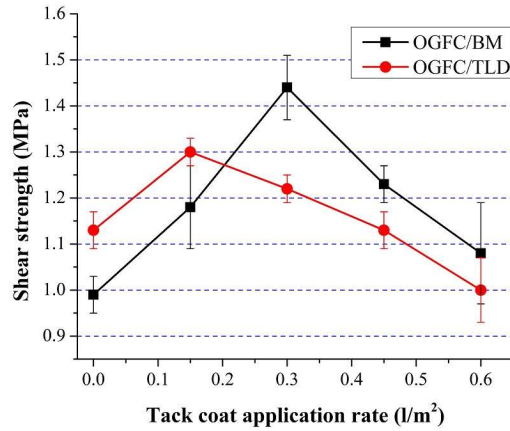


Figure 5- 6 Shear strength result

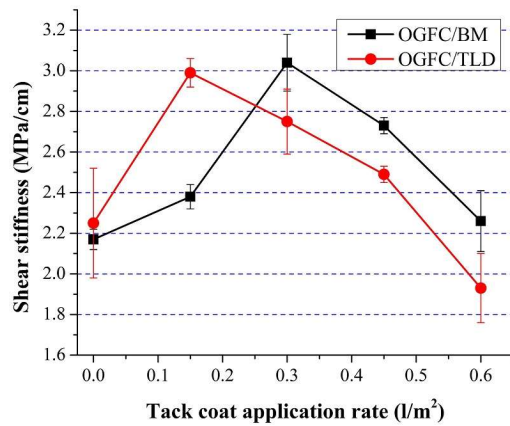


Figure 5- 7 Shear stiffness result

5.4.3 Interface Characteristics

Figure 5- 8 shows the pictures of the original failure interface of TLD and BM. Three areas can be clearly seen: adhesive failure, cohesive failure, and non-contact area. Adhesive failure is the failure state in which the stone surface is completely separated without binder coating on, and the cohesive failure is the one in which failure occurs in the

binder and there is still asphalt binder remaining on the aggregate after failure (Mo et al. 2011). The non-contact area between OGFC and the underlying layer was actually the voids which showed the darkest color, i.e., the color of asphalt binder.

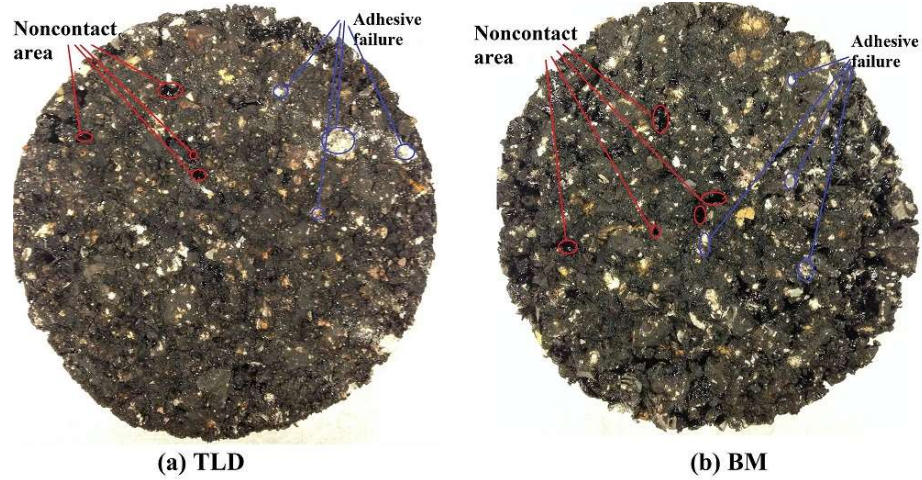


Figure 5- 8 Original failure interface

Image binarization was used to process the failed interface images. Image binarization is a process that transfers the original image into the binary image which just shows two colors, usually black and white. A binary image is a digital image that has only two possible values for each pixel: 0 or 1. By using an appropriate setting, the adhesive failure and non-contact part can be separated, and the cohesive failure can be obtained as well. The white area in Figure 5- 9 represents the adhesive failure and the black part in Figure 5- 10 represents the non-contact area of OGFC-TLD and OGFC-BM, respectively.

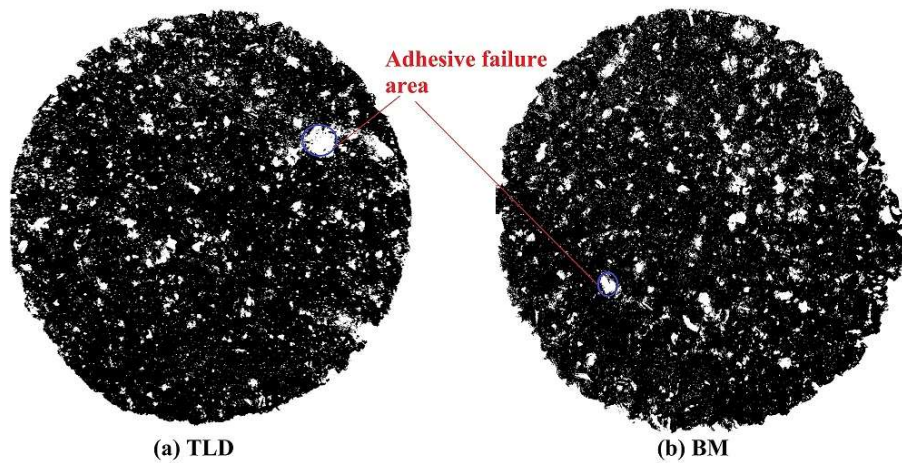


Figure 5- 9 Adhesive failure

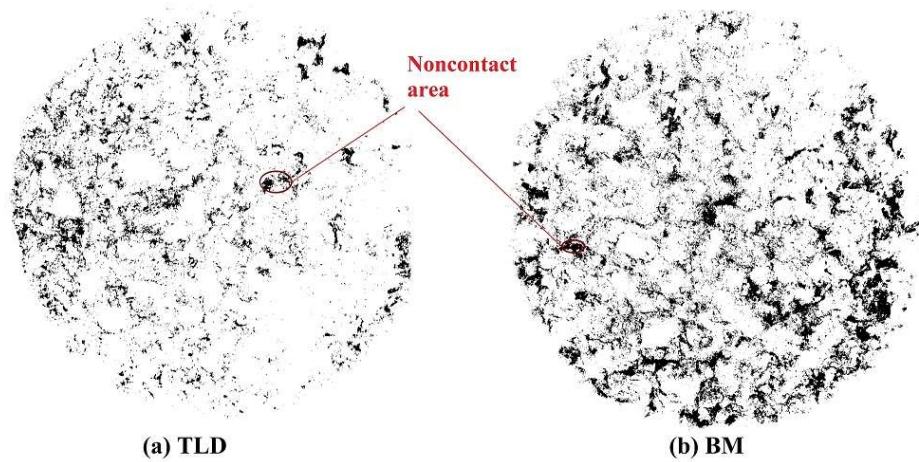


Figure 5- 10 Non-contact area

The results of adhesive failure area, cohesive area, and non-contact area are shown in Figure 5- 11Figure 5- 12Figure 5- 13. As the tack coat application rate increased, the tack coat thickness increased as well. Therefore, when other conditions were kept constant, the cohesive failure was easier to occur and the adhesive failure area decreased for both OGFC-TLD and OGFC-BM. From Figure 5- 11, it can be observed there were no significant differences in the adhesive failure area between OGFC-TLD and OGFC-BM at the same tack coat application rate. As the tack coat application rate increased, the cohesive area increased and the non-contact area decreased, which can be attributed to the fact that there

was more tack coat filling the voids, causing the contact area increased. At the same tack coat application rate, the cohesive area of TLD was larger than that of BM and the non-contact area of TLD was lower than that of BM.

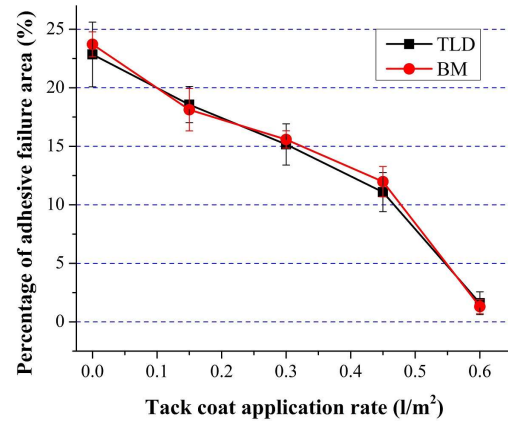


Figure 5- 11 Results of adhesive failure area

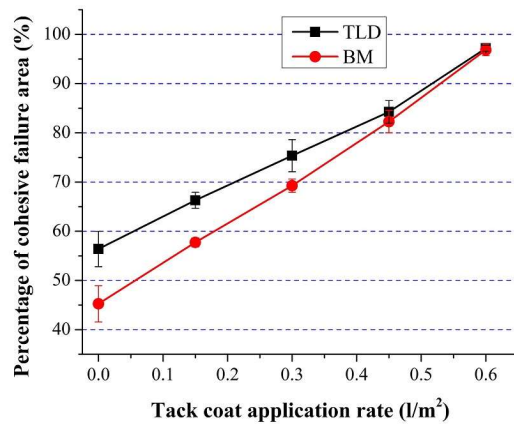


Figure 5- 12 Results of cohesive failure area

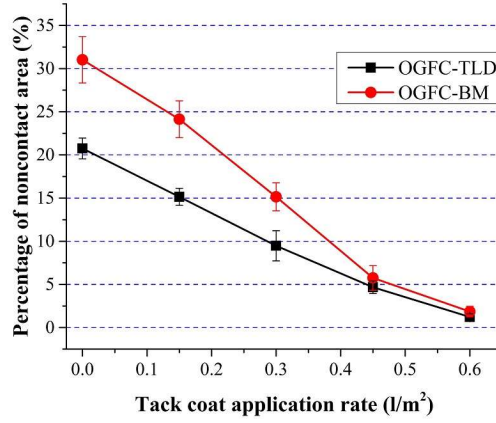


Figure 5- 13 Results of non-contact area

In this study, the total shear force which is needed to overcome the interfacial bond can be divided into two parts: force to overcome the adhesive bonds (F_{adhesive}) and the force to overcome the cohesive bonds (F_{cohesive}).

The cohesive failure is a binder failure itself. Therefore, F_{cohesive} is related to the cohesive failure area and the bonding property of the binder. The cohesive failure binder may be tack coat binder or the asphalt binder, to simplify the analysis, the binder properties of the tack coat and the asphalt binder were considered the same. Therefore, the ratios (R_{cohesive}) of the shear force to overcome the cohesive bonds (F_{cohesive}) of OGFC-TLD to that of OGFC-BM were:

$$R_{\text{cohesive}} = \frac{F_{\text{cohesive_TLD}}}{F_{\text{cohesive_BM}}} = \frac{\tau_{\text{cohesive_TLD}}}{\tau_{\text{cohesive_BM}}} \cdot \frac{A_{\text{cohesive_TLD}}}{A_{\text{cohesive_BM}}} = \frac{A_{\text{cohesive_TLD}}}{A_{\text{cohesive_BM}}} = \begin{Bmatrix} 1.246 \\ 1.148 \\ 1.088 \\ 1.024 \\ 1.004 \end{Bmatrix} \quad (5-2)$$

Where, $F_{\text{cohesive_TLD}}$ is the shear force of OGFC-TLD to overcome the cohesive bonds, $\tau_{\text{cohesive_TLD}}$ is the binder bonding strength of the binder, $A_{\text{cohesive_TLD}}$ is the cohesive failure area of OGFC-TLD, the meanings are the same for OGFC-BM.

The F_{cohesive} ratios were 1.246, 1.148, 1.088, 1.024, and 1.004, respectively, for tack coat application rate from 0 to 0.60 l/m². As the tack coat application rate increased, the ratio decreased and all the five ratios were greater than 1. This is because the cohesive

failure area of OGFC-TLD was larger than that of OGFC-BM at each tack coat application rate, and as the tack coat application rate increased, the difference in cohesive area between OGFC-TLD and OGFC-BM decreased.

The shear force to overcome the adhesive bonds not only relates to the adhesive failure area, but also the surface roughness (Raab et al. 2012). In their study on the bonding of ideal materials with a single graded aggregate in the upper and the underlying layers, Raab et al. (2012) showed that the adhesive shear load can be expressed as the following equation:

$$F_{adhesive} = A_{adhesive} C \left(\frac{D}{d} \right) \quad (5-3)$$

Where, $F_{adhesive}$ is the shear force to over come the adhesive bonds, $A_{adhesive}$ the adhesive failure area, d is the aggregate size of the upper layer (OGFC), D is the aggregate size of the underlying layer, C is a constant, D/d is a parameter that can be used to represent the interface roughness.

In this study, the upper layer mixture was open-graded and the underlying layer dense-graded. To simplify the analysis, the aggregate size was regarded as the mean value of all the aggregate sizes with the consideration of their volume fraction. In addition, from Fig. 11 the adhesive failure area between OGFC-TLD and OGFC-BM was nearly the same at each different tack coat application rate.

Therefore, the ratios ($R_{adhesive}$) of the shear force to overcome the adhesive bonds of OGFC-TLD to that of OGFC-BM was

$$R_{adhesive} = \frac{F_{adhesive_TLD}}{F_{adhesive_BM}} = \frac{\tau_{adhesive_TLD}}{\tau_{adhesive_BM}} \cdot \frac{A_{adhesive_TLD}}{A_{adhesive_BM}} = \frac{D'_{TLD}}{D_{BM}} = \frac{\sum_{i=1}^n \varphi_i \cdot D_{TLD_i}}{\sum_{j=1}^m \varphi_j \cdot D_{BM_j}} = \frac{1}{2.34} \quad (5-4)$$

Where, $F_{adhesive_TLD}$ is the shear force of OGFC-TLD to overcome the cohesive bonds, $\tau_{adhesive_TLD}$ is the bonding strength between the binder and the aggregate, $A_{adhesive_TLD}$ is the cohesive failure area of OGFC-TLD, the meanings are the same for OGFC-BM, D'_{TLD} is the mean

value of the aggregate sizes of TLD, D'_{BM} is the mean value of the aggregate sizes of BM, D_{TLD_i} is the aggregate size at sieve i , ϕ_i is the volume fraction of aggregate of size D_{TLD_i} , D_{BM_j} and ϕ_j are of the same meanings as TLD.

From Figure 5- 6 and Figure 5- 7, the optimal tack coat application rates for OGFC-TLD and OGFC-BM were 0.15 l/m^2 and 0.30 l/m^2 . At the optimal tack coat application rate, the shear strength and shear stiffness of OGFC-BM were larger than that of OGFC-TLD. At the optimal tack coat application rate, the cohesive failure area percentage of OGFC-TLD and OGFC-BM was 66% and 69%, the cohesive failure area difference was very slight. Therefore, there was just slight difference in the shear force to overcome the cohesive bonding. It can be concluded that at the optimal tack coat application rate, it was the shear force to overcome the adhesive bonding (F_{adhesive}) that made the shear strength and shear stiffness of OGFC-BM larger than that of OGFC-TLD. The adhesive failure area percentage of OGFC-TLD was nearly the same with that of OGFC-BM at the optimal tack coat application rate (18% vs. 16%), according to Eq. (3), it can be concluded that it was the surface roughness (D/d) that made the shear force to overcome the adhesive bonding of OGFC-BM larger than that of OGFC-TLD.

At low tack coat application rates (0 and 0.15 l/m^2), the shear strength of OGFC-TLD was larger than that of OGFC-BM. From Figure 5- 12, it can be observed that the cohesive failure area of OGFC-TLD was larger than that of OGFC-BM. According to equation (2), the shear load to overcome the cohesive bonding between OGFC and TLD was larger than that of OGFC and BM. From equation (4), although the adhesive bonding of OGFC-BM was larger than that of OGFC-TLD, the combination of the cohesive bonding and adhesive bonding made the shear strength of OGFC-TLD larger than that of OGFC-BM at low tack coat application rates.

Because the texture depth can also be treated as one parameter characterizing the surface roughness, the texture depth was compared to (D/d) and the result is shown in Figure 5- 14. Although the calculated D/d was not identical with the texture depth for both

TLD and BM, the ranking of the two underlying layers was the same, indicating that both parameters were highly correlated and can be used as an indicator representative of surface roughness.

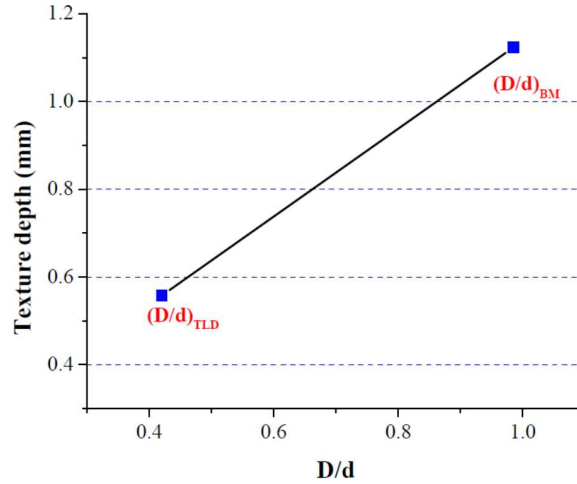


Figure 5- 14 Comparison between D/d and texture depth

Figure 5- 15 shows that as the texture depth increased, the maximum shear strength and shear stiffness increased as well, indicating the surface texture depth can be selected as an indicator of the shear strength and shear stiffness. It can also be seen from Figure 5- 6 and Figure 5- 7, the optimal tack coat application rates for OGFC-TLD and OGFC-BM were 0.15 l/m^2 and 0.30 l/m^2 , respectively, indicating that with the increase in texture depth, more tack coat was needed to achieve the optimal tack coat application rate. Because BM had a rougher surface than TLD, OGFC-BM showed a higher optimal tack coat application rate than OGFC-TLD.

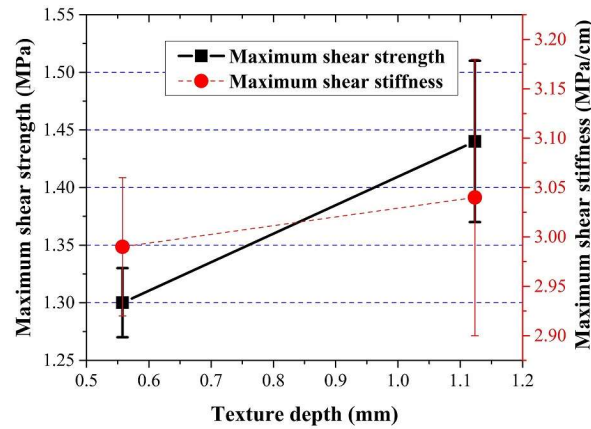


Figure 5- 15 Texture depth vs. shear property

5.5 Summary and Conclusions

This study investigated the shear bonding properties and interface characteristics between OGFC and two underlying layers at five different tack coat application rates. Shear strength and shear stiffness were employed to characterize the shear bonding properties. Texture depth was tested to evaluate the surface roughness of underlying layers. By assessing the adhesive failure, cohesive failure and non-contact area between OGFC and the underlying layer, this paper presents a new approach for analyzing the shear behavior between OGFC and the underlying layer. Adhesive failure, cohesive failure, and non-contact area at the failed interfaces were identified and correlated to the shear strength and shear stiffness. The following conclusions can be drawn:

- There existed an optimal tack coat application rate, at which the peak strength and peak stiffness could be achieved. The optimal tack coat application rates of OGFC-TLD and OGFC-BM were 0.15 l/m^2 and 0.30 l/m^2 , respectively.
- With the increase in texture depth, the maximum shear strength and shear stiffness also increased. Because BM had a larger texture depth than TLD. OGFC-BM

showed a higher shear strength and a higher shear stiffness than OGFC-TLD at the optimal tack coat application rate.

- There were no obvious differences in the adhesive failure area between OGFC-TLD and OGFC-BM. The cohesive failure area ranking was OGFC-TLD > OGFC-BM and the non-contact area ranking OGFC-TLD < OGFC-BM. With the increase in tack coat, the adhesive failure area and the non-contact area decreased and the cohesive failure increased.
- The ratio of the shear force to overcome the adhesive bonding (F_{adhesive}) of OGFC-BM to that of OGFC-TLD was 2.34. The ratio of the shear force to overcome the cohesive bonding (F_{cohesive}) of OGFC-TLD to that of OGFC-BM was a little higher than 1. As tack coat application rate increased, the ratio of the shear force to overcome the cohesive bonding (F_{cohesive}) decreased.
- At the optimal tack coat application rates for OGFC-TLD and OGFC-BM, the shear force to overcome the cohesive bonding was nearly the same, it was the shear force to overcome the adhesive bonding that made the shear strength and shear stiffness of OGFC-BM larger than that of OGFC-TLD. Because the adhesive failure area was nearly the same between OGFC-BM and OGFC-TLD, it can be concluded that it was the surface roughness that made the shear performance of OGFC-BM better than OGFC-TLD, indicating the aggregate gradations of OGFC and underlying layer play the important role in the shear behavior in OGFC pavement.
- As the texture depth increased, the roughness parameter D/d also increased.

CAPTER 6 COST BENEFIT ANALYSIS

6.1 OGFC Projects in PMS

The historical pavement maintenance records were investigated and it was found that there have been more than forty OGFC projects applied or initiated in Tennessee. Among these projects, the earliest one was completed in 2005 and a large number of them are just completed or still under construction. The pavement performance was inspected every year on interstates and every two years on state routes in Tennessee. In order to investigate the long-term performance, the OGFC sections that have been serving for more than four years were selected. As listed in Table 6- 1, four OGFC sections were selected. The adjacent non-OGFC pavement sections were investigated for performance and benefit comparisons.

Table 6- 1 List of the OGFC and non-OGFC sections

Section number	OGFC section		Non-OGFC section		Annual daily traffic (AADT)
	Length (mile)	Completion date	Length (mile)	Completion date	
1	11.69	Nov. 2005	4.3	June 2006	21744
2	6.06	Nov. 2006	5	Mar. 2002	7025
3	2.10	Aug. 2008	2	2005	62546
4	8.38	Oct. 2008	2	2007	107727

6.2 Cost Analysis

The total cost of a pavement maintenance project usually contains five aspects, including material, preparation, management, pavement marking and other items. An investigation indicates that the material cost is approximately 75-88% of the total cost and can be used to represent the cost of different treatments (Dong et al., 2013). Therefore, only the material cost was taken into consideration. Considering the great variation of asphalt

price, the historical asphalt bidding price in the past five years was utilized to calculate the material cost. The cost of the dense graded “D-mix”, which is the most commonly used asphalt surface layer mixture in Tennessee, was also calculated for comparison purpose. By investigating the bidding price data of more than 35 projects, the average unit cost (\$/m³) of OGFC and D-mix was calculated and shown in Figure 6- 1. It can be seen from Figure 6- 1 that the cost of OGFC mixture was about 42% higher than that of the traditional dense mixture.

On the other hand, Timm and Vargas-Nordbeck (2012) concluded that OGFCs required 12% thickness increase in order to achieve the same pavement structural number as the non-OGFC sections. The conventional thickness of D-mix is 1.25 inches. Thus, the thickness of OGFC should be 1.4 inches to achieve equivalent structural number. Considering the different thickness of OGFC and D-mix, the average cost per unit area (\$/m²) was calculated and shown in Figure 6- 1(b). It can be seen that, to achieve the same structural capacity, the cost of OGFC was about 59% higher than that of dense mixture.

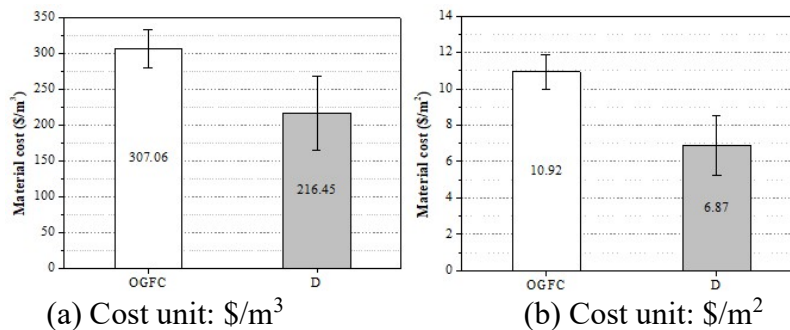


Figure 6- 1 Cost comparison of OGFC and D mixture: (a) cost unit: \$/m³; (b) cost unit: \$/m²

6.3 Cost-benefit analysis

Since the unit cost of OGFC is more expensive than that of traditional dense mix, it is necessary to take the cost and benefit into consideration to evaluate its sustainability.

Besides the improved performance, OGFC mixture can also improve skid resistance, improve driving safety, reduce noise and etc. In Washington, due to the short duration of noise mitigation properties and high life-cycle cost, it is not recommended to use OGFC (Anderson et al. 2008). Therefore, it is of great importance to analyze the cost-effectiveness of those extraordinary benefits relative to the high cost of OGFC. If the performance of OGFC maintained at a comparable level as non-OGFC and its cost-benefit was also fairly high, it would be more persuasive to promote OGFC.

The cost-benefit calculation could be incremental cost-benefit ratio (Willan et al. 1996), the ratio of benefit to cost (Irfan et al. 2005), the product of roughness increase and cost (Dong et al. 2011) and etc. The ratio of benefit to cost as shown in Eq. (6-1) was utilized as the cost-benefit index in this study.

$$CB\ index = \frac{Benefit}{Cost} \quad (6-1)$$

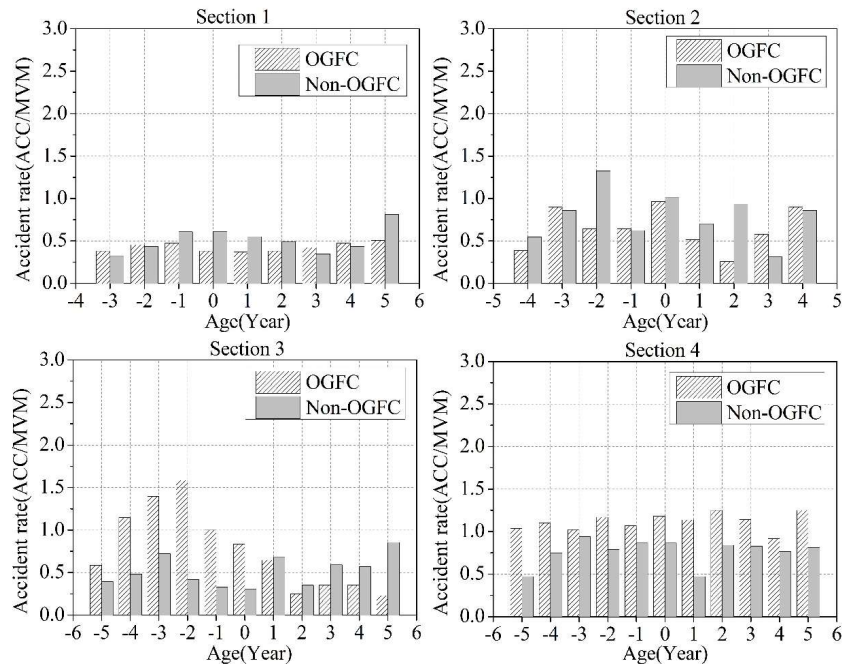
Here, Benefit is the accident rate reduction; Cost is the cost of OGFC or dense mixture calculated above.

6.4 Accident rate reduction

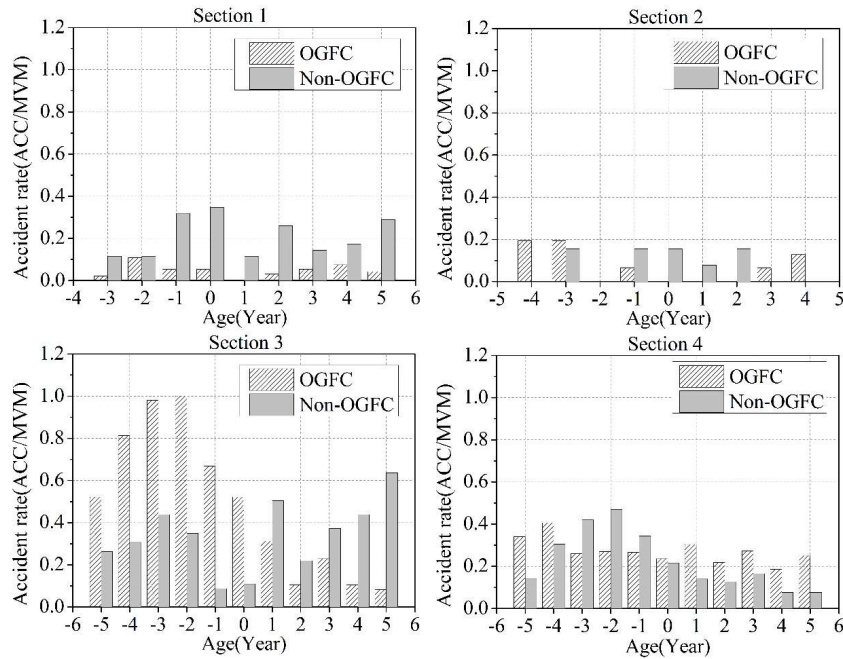
The overall accident rate and accident rate in rainy days of the OGFC and non-OGFC sections before and after the treatments are exhibited in Figure 6- 2. In Figure 6- 2 (a), it can be seen that the accident rate of section 2 and 3 decreased after the placement of OGFC. For instance, two years before the OGFC treatment, the accident rate of section 3 was as high as 1.59 ACC/MVM. After the treatment, the accident rate began to reduce and five years later the rate dropped to 0.23 ACC/MVM, showing a significant reduction. Compared with the non-OGFC sections, the accident rates of OGFC sections were lower especially for section 3. Its accident rates were much higher than the adjacent non-OGFC before the placement, but were lower than or comparable with those of the non-OGFC section. Unlike section 2 and 3, the accident rate reduction of section 1 and 4 was slight. Their accident rates were greater when compared with the adjacent non-OGFCs. The high accident rates could be caused by other influence factors such as the traffic markings, lanes,

intersections and severe climates.

Figure 6- 2 (b) shows clear accident rate reduction in rainy weather after the OGFC treatment. The reduction was significant for section 3. Before the OGFC placement, the accident rate in rainy days was as high as 1.00 ACC/MVM while after five years it decreased to 0.08 ACC/MVM. Section 2 even had no accidents in rainy days for several years. For section 4, although the reduction was not obvious and immediate, there were accident rate reduction at the age of 2 and 4 years. For section 1, 2 and 3, the accident rate of OGFCs were lower than those of non-OGFCs. For instance, before the OGFC treatment, the accident rate of section 3 was six times as that of its adjacent section. After the OGFC treatment, its accident rate decreased and it was finally smaller than the non-OGFC. However, for section 4, although there was overall accident rate reduction, its accident rate still wasn't lower than the non-OGFC. As explained above, other influence factors such as the traffic markings, lanes, intersections and severe climates might cause the high accident rate on the OGFC section.



(a) All Weather



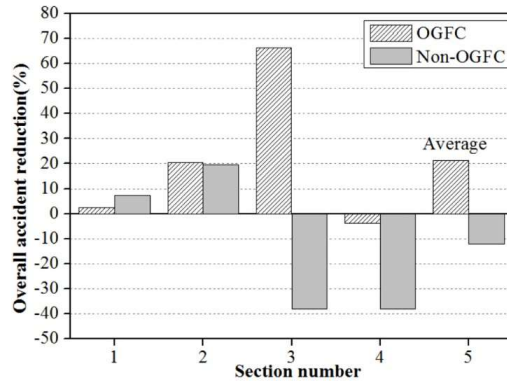
(b) Wet Weather

Figure 6- 2 Accident rate: (a) all weather; (b) wet weather

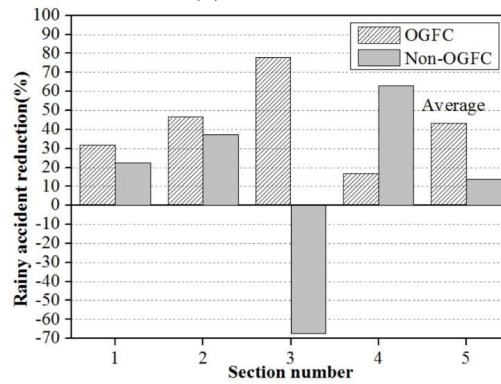
To quantify accident rate reduction before and after the OGFC treatment, the average accident rate and its reduction was calculated and shown in Figure 6-2. The overall accident rate reductions (%) of the four sections were positive except for section 4. The reduction was as high as 66.4% for section 3. For section 4, both the overall accident rate reductions of the OGFC and non-OGFC section were negative and the accident rate increase might be caused by other factors as discussed above. However, the accident rate reduction of section 4 in rainy days was positive with the value of 17% indicating the effect of OGFC on improving pavement safety in wet weather. The accident rate of all the sections in rainy days have decreased after OGFC treatment and the reduction of section 3 was as high as 77.8%. Further, it should be noted that the reductions in rainy days for all sections were greater than the overall accident rate reduction.

Compared to the non-OGFC sections, three of the four OGFC sections provided greater accident rate reduction especially in rainy days. For instance, the accident rate of non-OGFC section 3 increased in rainy days while the accident rate of their adjacent OGFC sections decreased by 77.8%. The fifth column in Figure 6- 3 (a) and Figure 6- 3 (b) was the average accident rate reduction of OGFC and non-OGFC. The reduction on OGFCs was significantly higher than that on the non-OGFCs especially in rainy days and the

average reduction difference was about 30%.



(a) All Weather



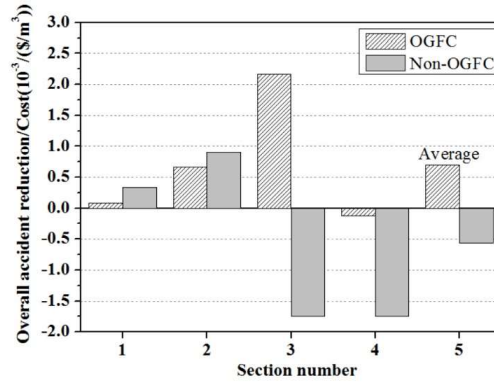
(b) Wet Weather

Figure 6- 3 Accident rate reduction: (a) all weather; (b) wet weather

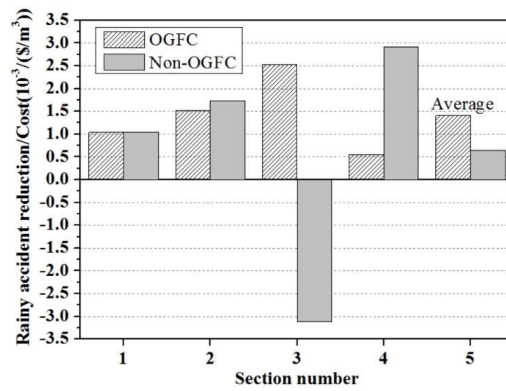
6.5 Cost-benefit

Considering OGFC's benefit on improving traffic safety, a question concerned by both engineers and public is whether it is worth to use the expensive OGFC. Therefore, it is necessary to evaluate the cost-benefit of OGFC, indicated as the ratio of accident rate reduction over cost. By using Eq. (6-1), the results were obtained and exhibited in Figure 6- 4. It should be noted that the fifth column in Figure 6- 4 (a) and Figure 6- 4 (b) is the average cost-benefit ratio. It can be observed from Figure 6- 4 that, the cost-benefit ratios of three of the four OGFC sections were higher than their adjacent non-OGFC sections. The average column illustrated more obviously that OGFC demonstrated higher cost-benefit ratio than non-OGFC. In addition, the average ratio of OGFC in rainy days is about

1.409 ($10^{-3}/ (\$/\text{m}^3)$) which is about two times as the ratio of non-OGFC (0.643 ($10^{-3}/ (\$/\text{m}^3)$)). Therefore, the improving driving safety and reducing accident rate function of OGFC is more significant especially in rainy days. It can be concluded that it is cost-effective to use OGFC as a pavement surface treatment in Tennessee highways.



(a) Overall accident reduction relative to cost



(b) Accident reduction in rainy days relative to cost

Figure 6- 4 Cost-benefit analysis: (a) overall accident reduction relative to cost; (b) accident reduction in rainy days relative to cost

6.6 Conclusions

- The unit cost ($\$/\text{m}^3$) of OGFC mixture was about 42% higher than the conventional dense mixture. Considering equivalent structural numbers of OGFC and non-OGFC, the unit cost ($\$/\text{m}^2$) of OGFC was about 59% higher than the dense mixture.

- The five year accident rate reduction analysis indicated that the OGFC mixtures generally reduced the accident rate, especially in rainy days. For some sections, the reduction in rainy days could be as high as 77.8%.
- The cost-benefit analyses based on the ratio of accident rate reduction over cost showed that the cost-benefit ratio of OGFC mixture was about two times as the dense mixture. It also demonstrated that the improving driving safety and reducing accident rate function of OGFC is more significant especially in rainy days and it is cost-benefit to use OGFC on Tennessee highways.

CHAPTER 7 SUMMARY OF DOT SURVEY RESPONSE

A survey was conducted by the University of Tennessee to States Departments of Transportation to collect information on the state of OGFC in the US. This is the response summary.

Table 7- 1 States Response to the Survey

SN	States Responded	Usage of OGFC			No. Responded	Not responded
		Currently	Past	Never		
1	ALABAMA	Y			2	HAWAII
2	ALASKA	N	Y		1	INDIANA
3	ARIZONA	Y			3	IOWA
4	ARKANSAS	N	Y		1	MAINE
5	CALIFORNIA	Y			2	MINNESOTA
6	COLORADO	N	Y		2	MISSISSIPPI
7	CONNECTICUT	N	Y		1	MONTANA
8	DELAWARE	N	Y		4	NEW MEXICO
9	D.OF COLUMBIA*			Y	1	PUERTO RICO*
10	FLORIDA	Y			3	VERMONT
11	GEORGIA	Y			1	WEST VIRGINIA
12	IDAHO	N	Y		1	WYOMING
13	ILLINOIS			Y	1	
14	KANSAS			Y	2	
15	KENTUCKY	N	Y		2	
16	LOUISIANA	Y			2	
17	MARYLAND	Y			1	
18	COMMONWEALTH OF MASSACHUSETTS	Y			4	
19	MICHIGAN	N	Y		2	
20	MISSOURI	Y			1	
21	NEBRASKA	N	Y		1	
22	NEVADA	Y			2	
23	NEW HAMPSHIRE	N/Y	Y		1	
24	NEW JERSEY	N	Y		1	
25	NEW YORK	N	Y		1	
26	NORTH CAROLINA	Y			1	
27	NORTH DAKOTA			Y	1	

28	OHIO	N	Y	2	
29	OKLAHOMA	Y		2	
30	OREGON	N	Y	1	
31	PENNSYLVANIA	N	Y	2	
32	RHODE ISLAND	Y		1	
33	SOUTH CAROLINA	Y		3	
34	SOUTH DAKOTA		Y	1	
35	TENNESSEE	Y		1	
36	TEXAS	N	Y	1	
37	UTAH	Y		1	
38	VIRGINIA	Y		2	
39	WASHINGTON	N	Y	1	
40	WISCONSIN	N	Y	1	
	Totals	18	17	5	64

Questionnaire preamble:

Open graded friction course (OGFC) is a thin layer of permeable asphalt placed on a dense graded asphalt pavement. The use of this layer sometimes is accompanied by increased cost. This questionnaire was prepared by the University of Tennessee, with the aim to find ways to improve the cost effectiveness of OGFC pavements by evaluating the structure underlying the OGFC layer for the state of Tennessee. Your response to this questionnaire will be beneficial to this study and is highly appreciated.

Response to the first two questions:

Q1. Do you currently use OGFC in your state?

Q2. If No, have you used it in the past?

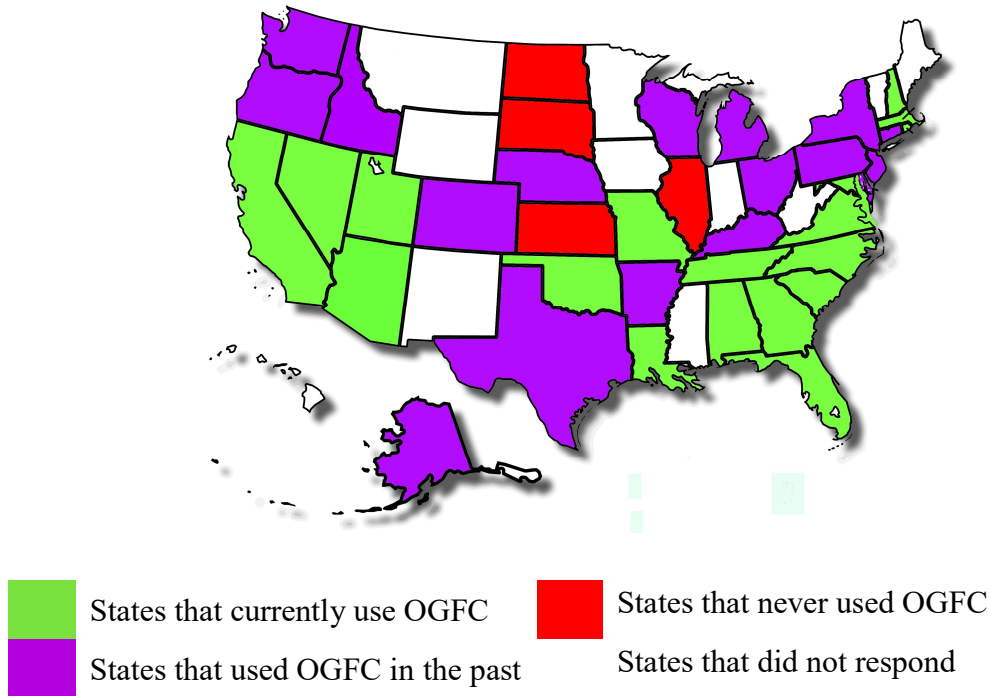


Figure 7- 1 States that responded to the survey

The survey was sent to 52 State DOT's as listed in Table 7- 1 to include District of Columbia and Puerto Rico. 40 states responded to the survey and 12 did not. That means we had a 77% response which is excellent. Figure 7- 1 shows the states that responded to the survey and Figure 7- 2 is one pie chart showing the percent of the responded states. Figure 7- 3 is a summary out of the responded states, of the current use of OGFC among states DOT's. These were responses to the survey questions number 1 and 2.

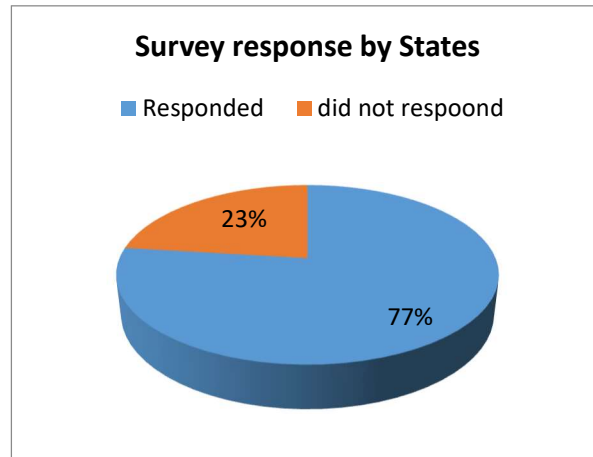


Figure 7- 2 Percent of responded states

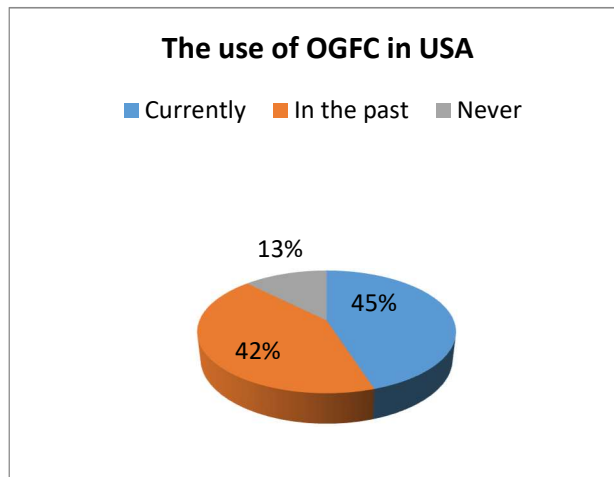


Figure 7- 3 Percent of responded states and the use of OGFC

Q3. Why did your state stop use OGFC?

On questions 3, states that stopped using OGFC were asked and responded as shown in Figure 7- 4. 62 % of responses being poor performance, 11 % cost and 27 % had other reasons as summarized below.

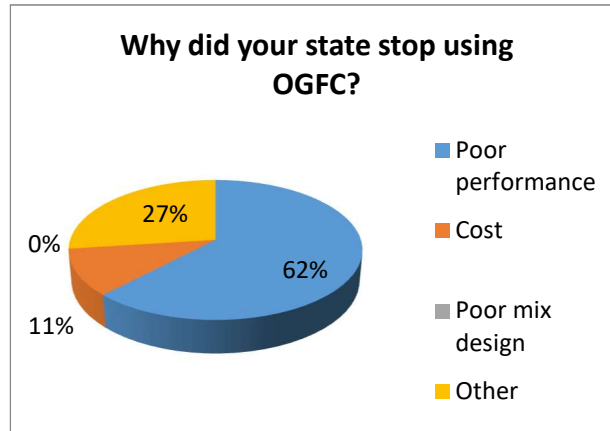


Figure 7- 4 Reasons to why the states are not using OGFC any more

Other reasons were summarized as follows.

1. Stripping of underlying mixes. This state included hydrated lime in their asphaltic concrete mixtures, began using polymer modified AC and fiber in their open-graded mixes and resumed full use.
2. Polymer and crumb rubber modified mixes were used in the past, but clogging and drain down issues during placement resulted into early failure of pavements. The CRM mix performed okay; however, a lower AC layer became unstable requiring it be removed early. It's possible the openness of the OGFC could have hastened the degradation of the lower layer, but it is not believed to have been the root cause
3. At the end of the lifecycle the pavement tends to break off in sheets, particularly at intersections. The pavement overall performed very well, but it got a very bad reputation because of the significant failure at the end of its lifecycle.
4. Tough to remove snow and ice.
5. Raveling was rapid and wide spread.
6. We stopped for about 10 years, but started with a 12.5 mm design based on research from NCAT and GDOT.
7. Aggregate being removed by traffic.

Q 4. What are the reasons that led your state to not use OGFC at all?

This question was targeted to the states that said they never used OGFC at all and for those states those was their last question that needed their response.

1. Cost as compared to benefits.
2. Used it only for parking lots only.
3. Lack of polish resistant aggregates and concerns with icy conditions.

4. We are in the process of working on specs and researching the product to begin using OGFC.
5. Winter weather maintenance (problem with snow and ice control).
6. Additional salt usage during winter snow events led districts to stop specifying OGFC.
7. Due to the use of studded tires during the winter the OGFC will ravel in 1-2 years thus making it uneconomical to use. Wear is 20% more than conventional HMA with studied tires.
8. Accelerates moisture damage of underlying dense HMA concrete.
9. If more structure is needed during repaving, it cannot be overlaid, which becomes a hidden cost of OGFC use.
10. The splash and spray benefit diminish after about 4 to 6 years due to plugging, although a certain amount of benefit can be realized throughout the pavement service life.
11. Stone in the OGFC mix being loosened and propelled into windshields by truck traffic.
12. HMA and WMA are more appealing.

The response can be summarized in Figure 7-5 as a summary of response.

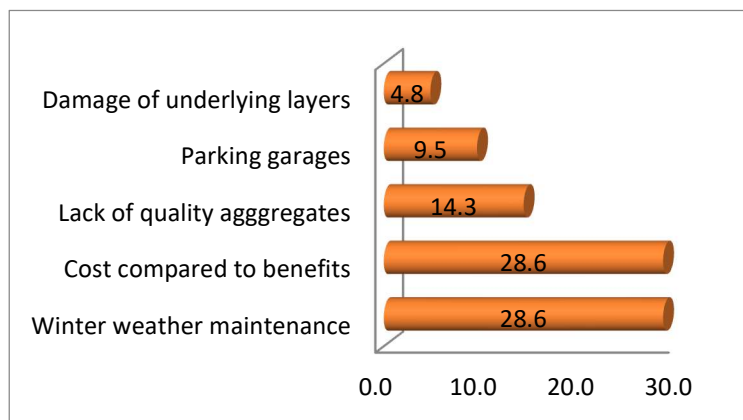


Figure 7- 5 Other reasons that lead to no using OGFC

Q5. About what volume of OGFC (in tons, yd², or miles) is used annually in your state

There were 20 responses on this question, 18 had the answers in tons of OGFC as shown on the distribution shown below and two states had answers in 100 lane miles/year and 165 lane miles/year. A majority of states uses less than 100,000 tons on OGFC per year.

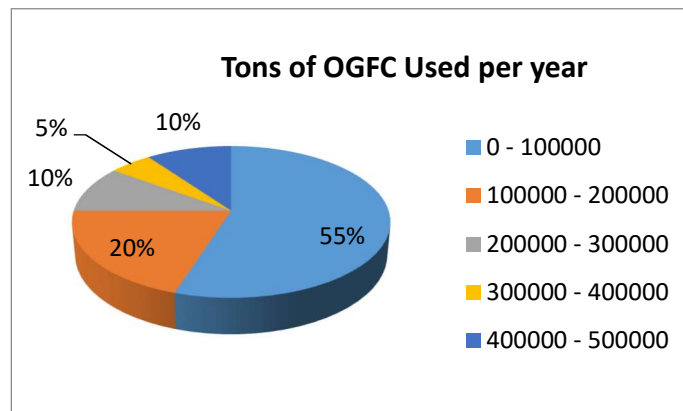


Figure 7- 6 Usage of OGFC in tons per year

Q6. What types of roads is OGFC used in your state?

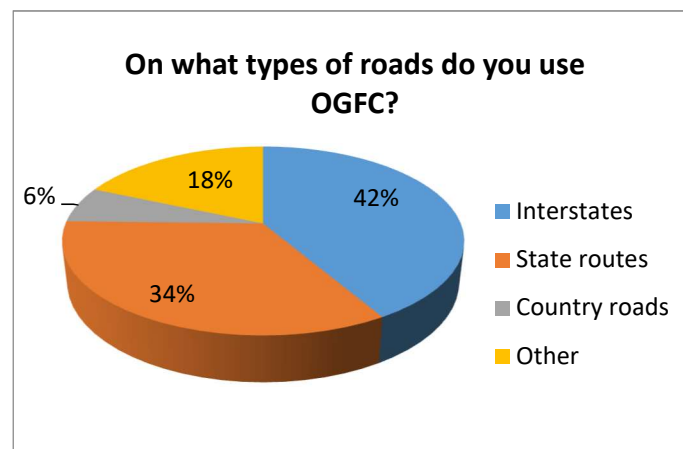


Figure 7- 7 Usage of OGFC on Roads

Other:

- Interstates and divided highways with design speed 50 mph or greater. [12 responses]

- Median shoulders for interstates/turnpikes and parking lots.
- Don't use it as a surface course.
- Parking lots - porous pavements

Q7. Are you aware of any limitations of using OGFC?

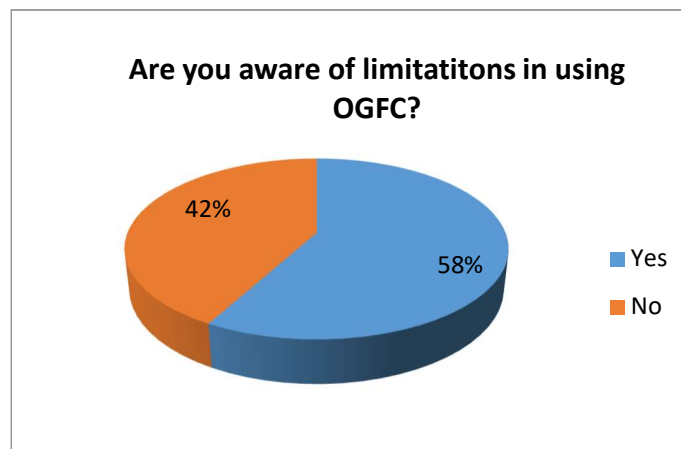


Figure 7- 8 Usage of OGFC in tons per year

Limitations:

- Clogging from sanding material and due to anti-skid application.
- Popping off from water in the OGFC freezing (durability).
- Winter maintenance and black ice (climate related issues).
- Cost.
- Stripping of underlying dense graded pavement.
- Uses OGFC on divided highways with design speed 50mph or greater.
- It shouldn't be used in areas that have extensive turning or stopping movements.
- Increased salt demand.
- OGFC not used as wearing course for roadways. OGFC is only used in porous pavement applications.
- No RAP, curves, curbed sections without special drainage measures, urban environments, upslope of dense mixes.
- Will not resist studded tire wear.

- OGFC has limited workability due to the stiff mixture. It also has a short window for compaction. It is the most difficult mix to use but yields the best results when placed properly.
- Next-generation OGFCs, if used, would contain modified asphalt (wet-process rubber or polymer).
- Our specification requires the use of air cooled blast furnace slag which is not available in all areas of the state.
- If poor mix design, failures are spectacular.
- Patching OGFC requires special mix that may not be available.
- Intersections with stopping traffic.
- Lack of suitable aggregates.
- Thickness (I believe it is too thin layer, this was not explained).
- Shorter construction season.
- Very cold, freezing temperatures can lead to raveling of the open-graded mixtures.

Q8. What is the typical pavement structure(s) utilized underneath OGFC layers?

This question had 27 responses with different underlying structures, since this is one of the primary research questions all the responses are given below.

Table 7- 2 Pavement structure and underlying layers

1	2
OGFC 3/4" OGFC	OGFC 1"
Typically around 3" to 5" of structural asphalt beneath it (based on design inputs).	Base 4-10"
Base 8" to 10" limerocks typical, thickness is based on design inputs (ex. Traffic level)	Subbase 6-8"
Subbase when necessary	Subgrade: Stabilized or just compacted? 6-8"
Subgrade - Stabilized. Lime rock Bearing Ratio 40 or greater.	

3	4
3/4" of OGFC 5 inches of dense-graded structural asphalt underneath OGFC. 10" limerock is typical sometimes asphalt base is used in wet areas Subgrade – Not specified	OGFC - Novachip Concrete or Superpave base Densely graded limestone - subbase Compacted only Subgrade
5	6
OGFC Base: Typically HMA or Rubberized HMA gap-graded Subbase: Typically aggregate Subgrade: Stabilized or just compacted, depending on soil type.	OGFC: 1" Modified fiber and polymers or rubber. Base: 8" thick dense graded Asphalt pavement Subbase: Dense Graded Crushed Aggregate Subgrade: Compacted
7	8
OGFC: Dense Graded Surface Courses Base: Dense Graded Crushed Stone Subbase: Gravel Subgrade: Compacted	OGFC: 3/4" OGFC + 4" dense graded HMA Base: 10" limerock Stabilized subgrade 12"
9	10
OGFC 4" OGFC (Porous pavement) Base: 5" Porous media choker course Subbase: 12" min porous media filter course Subgrade: 12" min porous media reservoir Subgrade: Stabilized typically with cement	OGFC: 1 - 12.5 mm Surface Course - 2" Base 1 - 12.5 - 19.0mm Intermediate Course 2-3" Subbase: 25.0mm HMA Base typically 4-8"
11	12
Base asphalt mixes, NMAS typically 25mm (1") - ON TOP of the OGD OGFC: Typically as asphalt stabilized OGD. Subbase: Plain or cement-treated	OGFC 10FX Base 19 mm Binder Base Asphalt or concrete roadway in

aggregate Subgrade: both stabilized or just compacted.	good condition
13 OGFC: Dense HMA Base: Yes Subbase: As needed Subgrade: compacted	14 OGFC: DENSE GRADED ASPHALT CONCRETE Base: GRANULAR BASE Subbase: BORROW MATERIAL Subgrade: Stabilized or just compacted, DEPENDS ON THE SITE CONDITION
15 OGFC 110 psy Base varies (interstates)	16 OGFC: 1.75" Asphalt Intermediate Base: 8-10" Asphalt Base Subbase: 6" Agg. Base Subgrade: Stabilized
17 OGFC 0.75" Base 10"-15" Asphalt Subbase 6" Dense Graded Aggregate Subgrade: Stabilized or Compacted depending on class	18 OGFC: 3" to 6" OGFC Base: 1.5" #8 Subbase: 8" to 32" #2 Subgrade: Uncompacted
19 OGFC 1.25" Base Various mixtures (leveling course, 9.5-mm and 4.75-mm surface mixtures) at depths ranging from 0.7" to 1.25"	20 OGFC: 110 lbs per square yard Base: depends Subbase: depends Subgrade: depends
21 OGFC: 3/4 inches Base: All types Subbase: All types Subgrade: All types	22 OGFC: 2" Base: Pervious aggregate layers. Base: Dense-graded asphalt
23 OGFC varies on each project. I don't	24 OGFC: (SMA or Polymer Modified 12.5

really understand this question
Base 6 HMA

Subbase 6-18 inches
Subgrade Stabilized or just compacted?
Depends

mm Superpave Mix)
Base Graded Aggregate Base or
sometime in south Georgia Cement
Treated Base

25
OGFC: We require the OGFC to always
be placed on top of a wearing layer.

Total bituminous pavement structure
underneath is typically 5" or greater.

26
WE use OGFC as a friction surface over
sma, dense graded HMA and sometimes
over concrete pavements

27
OGFC is used on both Asphaltic
Concrete and Portland Cement Concrete
Pavement

Q9. Does your state have a preferred (most economical or most widely used) pavement structure for structurally supporting OGFCs?

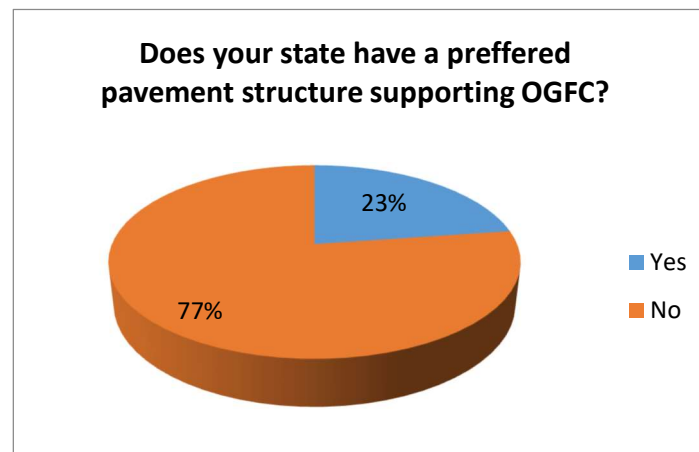


Figure 7- 9 Is the state having a preferred pavement structure?

Q10. If Yes, what is the layer combination (material types and thickness)?

1. 3/4" OGFC, 3" to 5" of SuperPave, dense-graded structural asphalt, and 8"-10" of limerock base
2. HMA Type-A and Rubberized HMA gap-graded are most widely used. Thickness is dependent on the design traffic application.
3. 12.5mm Surface -2"
4. Pavement in good condition to place OGFC
5. 3/4" OGFC + 2" To 12" HMA
6. We typically place open-graded mixtures beneath a 2" lift of SMA, 2" lift of 19 mm Superpave and the layer thickness of 25 mm Superpave is dependent on Average Daily Traffic...truck %.
7. OGFC is always placed on top of a wearing layer as per GFO 6-10.

Q11. Approximately, what is the difference in the cost per lane mile between the traditional dense graded HMA and OGFC?

This question had answers all over the place there are those who responded that OGFC cheaper or expensive than the dense graded HMA and those who responded otherwise. Figure 7- 10 shows the percentages of these responses and details of the responses are given below.

I. OGFC cheaper than dense graded HMA

- About 33% cheaper for OGFC as compared to 1" of dense-graded HMA friction course
- From a study done in 2009, the PFC is \$0.28 per square yard cheaper than a comparable dense-graded mix (\$5.08 versus \$5.36) if both mixes are placed at the normally recommended application rates.
- In 2013, average cost for dense-graded HMA was around \$117/ton. Average cost for OGFC was around \$105.

- OGFC - \$42,000 per lane mile including PG 76-22 @ 110 psy. HMA Surface Type A \$58,000 per lane mile including PG 76-22.

II. OGFC expensive than dense graded HMA

- At an equivalent thickness of 1" Dense Graded HMA \$90,000 per lane mile OGFC \$120,000 per lane mile.
- Typically, the OGFC is costing \$5-10 per mix ton more for the Dense grade HMA due to the amount of coarse aggregate required and the more strict aggregate requirements (lower LA) plus the added cost of the PG 76-22 vs. PG 64-22.
- This depends, but OGFC today has estimated price of \$120/ton and HMA is \$80/ton. OGFC has 18% voids, HMA has 7% voids.
- Surface mixes cost \$35 per Ton, OGFC mixes cost \$45 per Ton.
- 5-10% higher for OGFC compared with dense HMAC.
- The cost depends on the thickness. OGFC costs 30% more per ton.
- About 1.5 times more.
- Approximately \$25K extra.
- I think you should have asked for cost by the ton. We usually place OGSC 1 inch thick and HMA 3.5 inches thick. OGSC this last year ran about \$73.50 per ton or \$3.70 per square yard. HMA was about \$68 per ton.
- OGFCs are typically \$30 to \$40 per ton higher than wearing layers [2 responses].

III. Other

- Minimal
- Initial cost is approximately 15%
- Difference is about \$22,000
- \$31,000

- First installation was 2010 for a park and ride lot. Will monitor and see what the life cycle costs are.
- Unknown
- No data [2 responses]
- They (1-1/4" OGFC vs 1-1/4" 411D) are approximately equivalent (<\$0.50 difference per yd²) before considering interlayers such as leveling courses or milling/ cold planning.
- N/A [6 responses]
- We use the OGFC as a wearing course. The cost is approximately \$87,000 per lane mile.
- Negligible
- . The difference between PEM (Porous European Mix which is open-graded) and polymer modified 12.5 mm Superpave is approximately \$9,100 per lane mile. However, the PEM is placed at 1-1/4" while the 12.5 mm SP mix is placed at 1-1/2".
- Don't know.

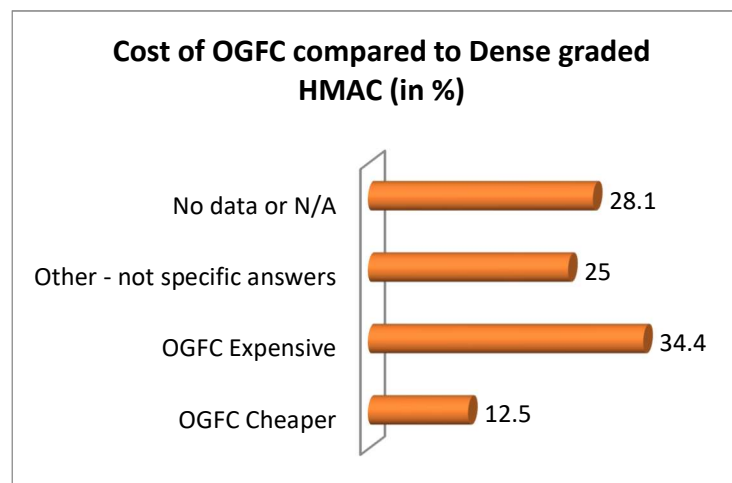


Figure 7- 10 Cost Difference between OGFC and dense graded HMAC (in%)

Q12. What material(s) do you typically use as an interlayer for open-graded mixtures?

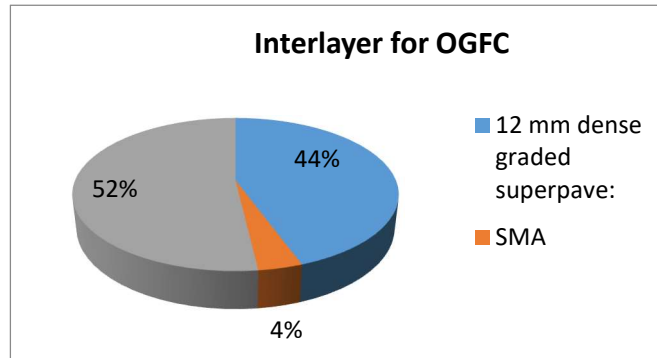


Figure 7- 11 Materials used as the interlayer for OGFC

Other:

- Either 9.5mm or 12.5mm dense-graded Superpave mix is used beneath OGFC.
- When installed as a functional wearing layer, it's not typical to place an interlayer. Specification requirements for surface preparation and sufficient tack coat are all that's required.
- OGFC is generally used as a surface layer build directly on the existing HMA.
- 9.5mm Superpave Surface Course.
- Full depth OGFC.
- We do not restrict the material that we place OGFC on. Except we do not allow OGFC on another OGFC, we require that the old OGFC be milled first.
- Not sure what's meant by "interlayer" here. Typically, our designs will involve SMA surface, some combination of intermediate & base asphalts, the OGD, then agg/CTA base, and subgrade.
- Dense graded mixes with underseal.
- OGFC is used to overlay pavements in areas of wet weather issues.
- We did not place more than one layer of OGFC. Our existing OGFC pavements overlay CRCP or dense HMA.
- 12.5mm or 19mm dense graded HMA.

- 4.75-mm high asphalt content leveling courses, 4.75-mm lower asphalt content leveling courses, 9.5-mm and 4.75-mm standard surface courses.
- 1/2-inch HMA or 3/4-inch HMA, we do not place OGSC on top of SMA.
- Please clarify this question.

Q13. How would you rate the field performance of open-graded pavements placed over these interlayers?

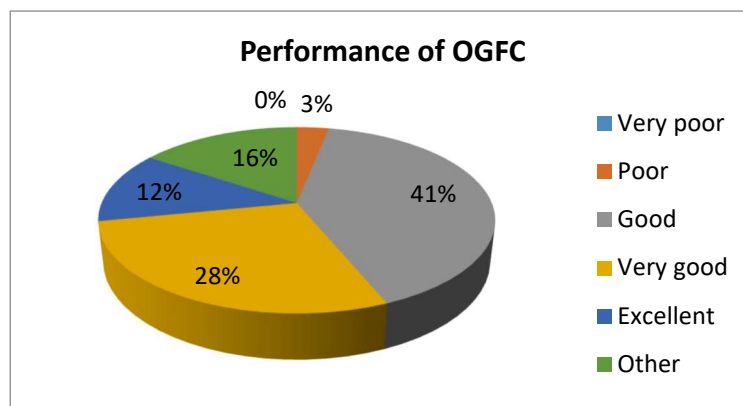


Figure 7- 12 Performance of OGFC, very poor being 0%

Other:

- Concerned about the behavior of OGFC during winter months, and the potential for safety concerns due to “black icing”.
- One state had the oldest placed section that is 9-years old and still in acceptable performance.
- One state primarily uses PFC in lieu of OGFC the past few years.

Q14. If you selected “poor”, what caused the poor performance?

- Construction practice: temperature, compaction
- Difficulty of snow and ice removal.

Q15. Do you use stabilizing agents or additives?

88% percent of respondents use additives on OGFC mixes to increase performance. Figure 7-13 shows the percent response to questions and Figure 7-14 shows the types of additives used.

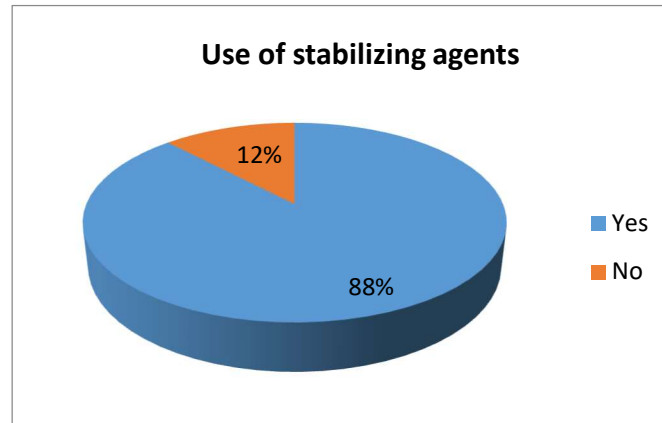


Figure 7- 13 Percent of states using stabilizing agent

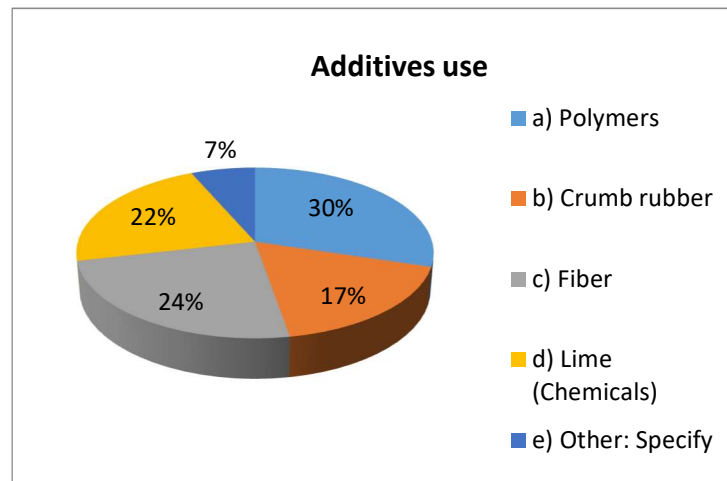


Figure 7- 14 Types of additives used

Other:

- WMA - Chemical process to lower temp and eliminate the fibers completely.

- Starting to use warm mix with additives to replace fibers with good results

Q16. How is the performance of OGFC with above mentioned additives?

It seems as if the performance of OGFC is not very improved with additive as compared to the increase in cost. Figure 7-15 summarizes responses on this question.

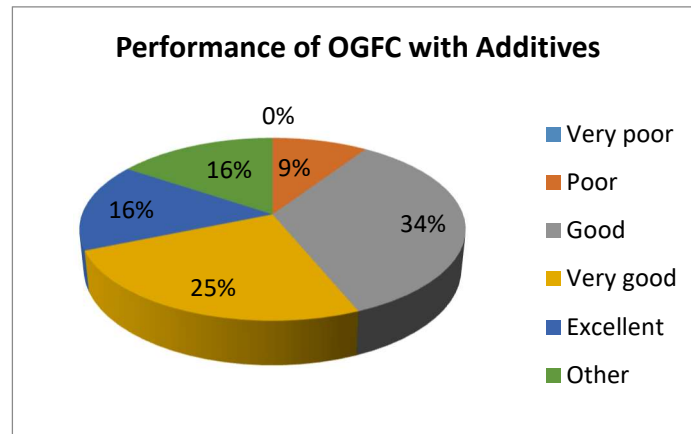


Figure 7- 15 Performance of OGFC with additives

Other:

- Concerned about the behavior of OGFC's during winter months, and the potential for safety concerns due to "black icing".
- Not sure. Too early to tell.
- Could be improved, WMA seems to help with constructability.
- Too new to tell.
- The CRM binders seemed to work okay.
- Too soon to tell, but we have high hopes.

Q17. About how long (in years) do open-graded pavements last in your state?

Table 7- 3 Number of years OGFC in operation

Length in years	response
-----------------	----------

0 - 5	2	
5 - 10	15	
10 - 12	7	
12 – 15	5	
> 15	5	Could be clogged but no other issues
N/A	5	
Unknown	2	

- Seven to 15 years, depending on the existing pavement condition and traffic.
- 14 years average. 10 years minimum, 22 years maximum.
- 8 years in heavy traffic, 20 years in light traffic
- The few we did a long time ago had catastrophic failures early in the pavement life
- Range was 8-18 years (stopped in 1994) - AC20 was used as the binder
- With the polymers, 20+ years

Figure 7-16 indicates that most pavements with OGFC (54%) (last 5 to 12 years).

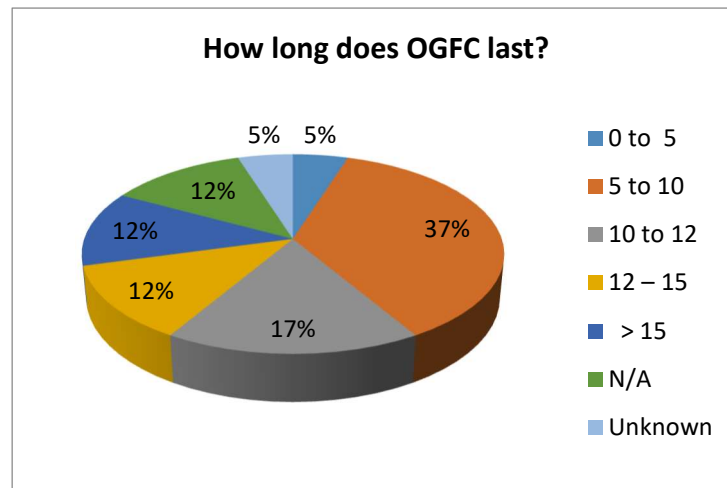


Figure 7- 16 Performance of OGFC with additives

Q18. What are the potential concerns for using open-graded pavements in your state?

Main Table 7-4 lists concern from the respondents, the main concerns are winter weather maintenance, clogging and raveling which accounts for 62% of all the concerns.

Table 7- 4 Potential concerns of using OGFC

Concern	Responses	Remarks
Raveling	13	
Clogging	10	
Winter mtnc problems	19	Increases accidents rate
Stripping of underlying layers	3	
Long term durability issues	4	Short pavement life
Construction and mtnc. of thin layers	3	
Studded tires	2	
Cost	4	
Flushing at intersections	1	
Catastrophic failures	3	Esp. without polymers
Increased salt usage	1	
Early polishing	1	
De-bonding	2	
Aggr. polishing and traction	2	
None	1	

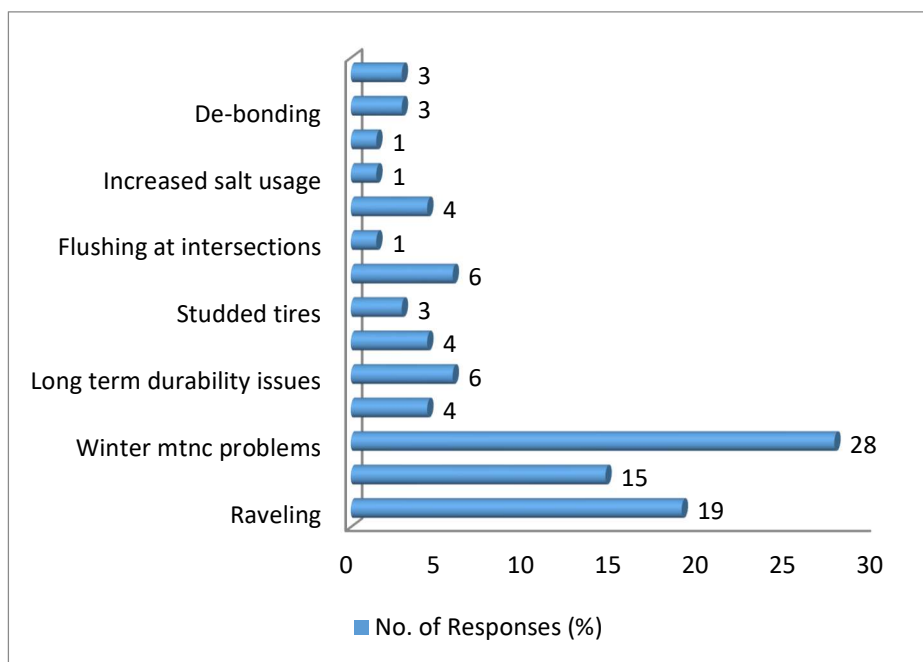


Figure 7- 17 Potential concerns for using OGFC

Q19. Are open-graded pavements in your state either flushed or cleaned?

94% of OGFC pavement are not cleaned or flushed as shown in Figure 7-18.

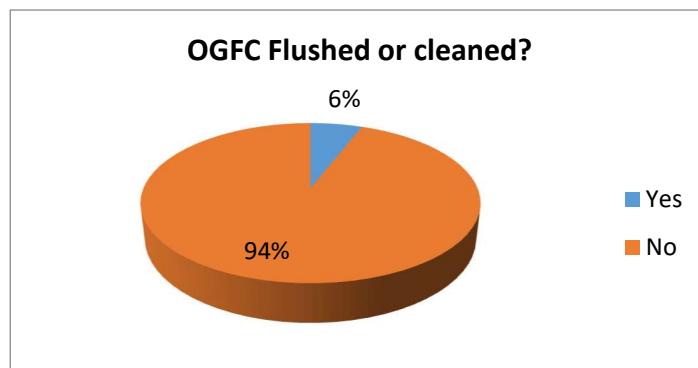


Figure 7- 18 OGFC pavements flushed or cleaned

Q20. If yes, by what method cleaning is performed?

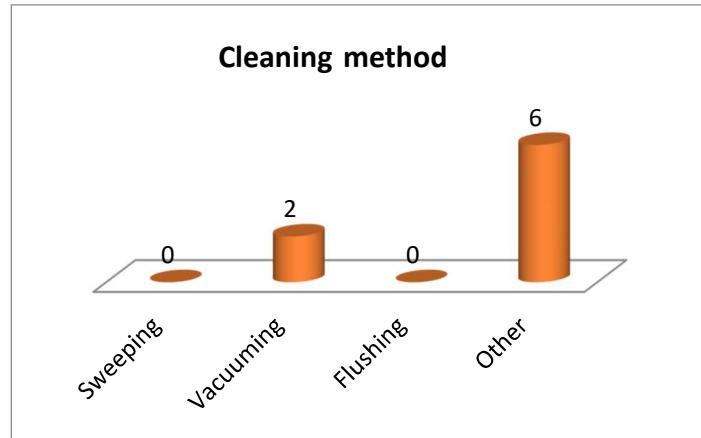


Figure 7- 19 OGFC pavement cleaning methods

Other:

- Not many are old enough to require cleaning.
- Considered light shot-abrasion.
- Surface abrasion techniques to clean out the fines in clogged OGFC by blasting with steel balls and vacuuming them up.
- State considered it, but wanted to see how they performed without flushing/cleaning.
- N/A [5 responses].

Q20. On open-graded paving projects, is the full shoulder-width typically paved with open-graded mix, or is only a portion of the shoulder width paved with open-graded mix?

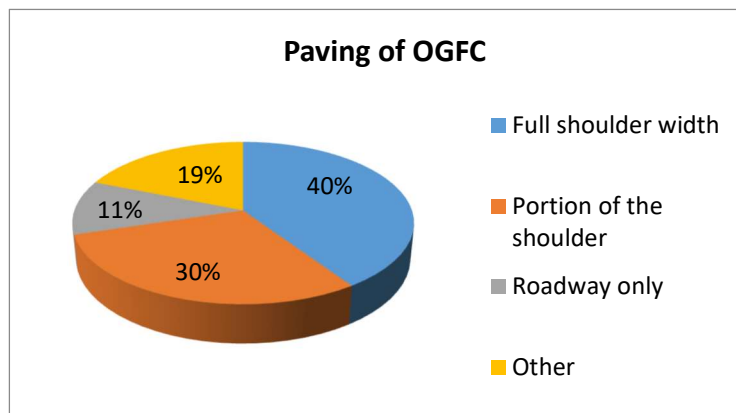


Figure 7- 20 Width of OGFC layer

Other:

- Shoulders 5ft and less typically paved with OGFC (full shoulder width). All other areas have 8" overlap onto shoulder (portion of shoulder paved).
- It is chip sealed or slurry sealed.
- Site specific decision.
- Usually Full Shoulder width when project location is 5,000' above Mean Sea Level, Roadway only when project site is below 5,000' MSL.
- Median shoulder applications are full width.
- 4'
- All of the above, depends on design application. District design has authority to choose any. I often recommend 2 ft. wider than the stripe as this allows for water to collect into this area and run onto the shoulder.
- Both - project dependent.
- The outside shoulder is paved 4 feet.
- Porous pavements only.
- We do both, selecting project-by-project.
- Usually roadway only, but not always.
- OGFC typically laps onto shoulder by 1'

Q21. If only a portion of the shoulder width is paved, how much

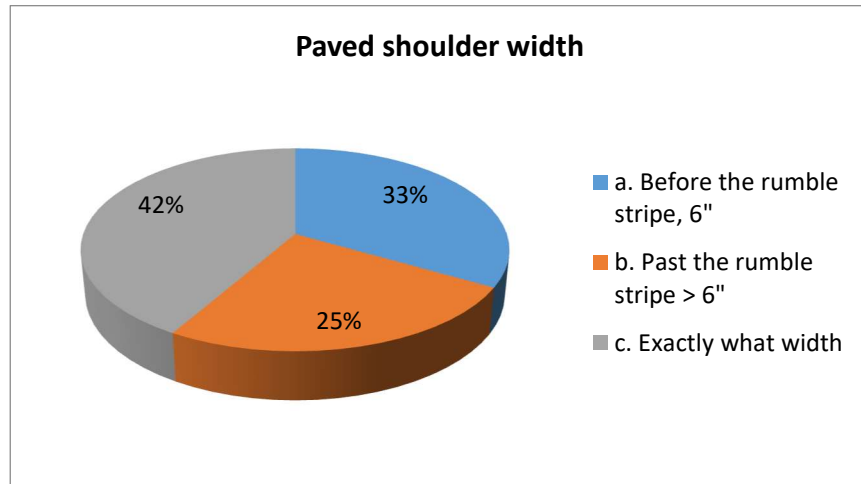


Figure 7- 21 Paved shoulder width

Other:

- Just to the rumble strips or 2-foot into the shoulder
- 4 feet on the outside, past rumble strip on the inside.
- Typically, 12" on inside shoulder and 18" on outside shoulder
- The OGFC laps onto shoulder by 1 foot.

APPENDIX

Survey Questions:

The University of Tennessee

Optimize Application of Open Graded Friction Course (OGFC) in Tennessee

Open graded friction course (OGFC) is a thin layer of permeable asphalt placed on a dense graded asphalt pavement. The use of this layer sometimes is accompanied by increased cost. This questionnaire is prepared by the University of Tennessee, with the aim to find ways to improve the cost effectiveness of OGFC pavements by evaluating the structure underlying the OGFC layer for the state of Tennessee. Your response to this questionnaire will be beneficial to this study and is highly appreciated.

1. Do you currently use OGFC in your state?

- a. Yes b. No
2. If No, have you used in in the Past?
a. Yes b. No
3. If the answer to Q2 is Yes, why did you stop using OGFC?

4. If the answer to Q2 is No, what are the reasons that led to your state not using OGFC at all?
5. About what volume of OGFC (tons, yd², or miles) is used annually in your state?

6. On what road types (classes) do you use OGFC?
7. Are you aware of any limitations in using OGFC?
8. What is the typical pavement structure(s) utilized underneath OGFC layers?
9. Do you have a preferred (most economical or most widely used) pavement structure for structurally supporting OGFCs?
a. Yes b. No
10. If Yes, what is the layer combination (material types and thickness) you prefer?
11. Approximately, what is the difference in the cost per lane mile between the traditional dense graded HMA and OGFC?
12. What material(s) do you typically use as an interlayer for open-graded mixtures (i.e. 12-mm dense grade Superpave, SMA, etc.)?
13. Do you use stabilizing agents or additives? YES_____ NO_____
14. If yes what additives:
Polymers
Crumb rubber
Fiber
Lime (chemicals)
Other Specify _____

15. How would you rate the field performance of open-graded pavements placed over these interlayers? Poor, Good Very good or Excellent?
16. If you selected “poor”, what caused the poor performance?
17. About how long do open-graded pavements last in your state?
-
18. What are the potential concerns for using open-graded pavements in your state?
19. Are open-graded pavements in your state either flushed or cleaned? If so, by what process is this performed?
20. On open-graded paving projects, is the full shoulder-width typically paved with open-graded mix, or is only a portion of the shoulder width paved with open-graded mix?
21. If only a portion of the shoulder width is paved, how much (i.e. before the rumble stripe, 6” past the rumble stripe, etc.)

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

The project focused on the study of optimize application of open graded friction course (OGFC) in Tennessee. Two types of OGFC (limestone and gravel), eight underlying layer material (TLD1, TLD2, BM, BM2, D, SMA, CS64-22 and CS76-22) and two kinds of tack coats (anionic asphalt emulsion and ultrafuse tack coat) were selected. Property of OGFC and the bonding property of the composite structure combined by OGFC and underlying layer were explored.

- Cantabro loss test and permeability test of OGFC were conducted first. OGFC with limestone aggregate (OGFC1) showed larger Cantabro loss and permeability.
- In the strength test, the shear strength and the direct shear stiffness were recorded.

Test results were as the table below.

	Shear strength ranking	Shear stiffness ranking
OGFC1-Anionic	SMA>TLD>BM2>CS76-22 >BM>D>CS64-22	BM2>SMA>BM>TLD> CS64-22>CS76-22>D
OGFC2-Anionic	SMA>BM2>TLD>CS76-22>CS64- 22>BM>D	BM2>SMA>BM>CS76- 22>CS64-22>D>TLD
OGFC1-Ultrafuse	BM2>SMA>BM>CS76-22>CS64- 22>D>TLD	BM2>TLD>CS64-22>CS76- 22>BM>SMA>D
OGFC2- Ultrafuse	SMA>BM2>BM>TLD>CS76- 22>CS64-22>D	SMA>BM>BM2>CS76- 22>CS64-22>TLD>D

- In the study of the influencing factors on the shear property, temperature, underlying layer and tack coat application rate all significantly contributed to the shear strength between OGFC and underlying layers with temperature as the most significant factor followed by surface texture depth of underlying layer. At low to intermediate temperatures (0 °C to 25 °C), tack coat rate played a significant role in shear strength. However, at high temperature (50 °C), tack coat application rate did not cause significant change in shear strength. The optimal tack coat was not

only affected by temperature, but also underlying layer. At intermediate to high temperatures, surface texture depth of underlying layer played a significant role in shear strength, indicating that selection of appropriate underlying layer with adequate roughness with OGFC is important to the bonding properties between OGFC and underlying layer. The effect of surface texture depth of underlying layer on shear strength was influenced by tack coat application rate, and vice versa. At low texture depth or low tack coat rate, the other factor became insignificant. The surface texture depth of underlying layer was found to be indicative of the interface roughness which correlated well with shear strength. Usually, the higher the surface texture depth, the higher the shear strength between OGFC and underlying layer.

- In the fatigue test, fatigue life, cumulative dissipated energy, and RDEC were used to analyze the fatigue behavior of the composite specimens. The contact area between OGFC and its underlying layer were tested and correlated to the fatigue performance. The fatigue life of OGFC-TLD was longer than that of OGFC-BM. With the increase in tack coat dosage, the number of loading cycle to failure decreased, which may be attributed to the lubricating effect of tack coat. The plateau value (PV) of OGFC-TLD was lower than that of OGFC-BM under the same loading condition, leading to a better fatigue performance of OGFC-TLD. In addition, with the increase in tack coat dosage, PV increased for both OGFC-TLD and OGFC-BM, implying a degraded fatigue performance because more dissipated energy was turned to fatigue damage. Power law relationship was found to exist between PV and fatigue life, which was independent of the underlying layer type and tack coat dosage rate. The total dissipated energy of OGFC-TLD was larger than that of OGFC-BM at same stress and same tack coat dosage. As tack coat dosage increased, total dissipated energy decreased. There existed a power law relationship between cumulative dissipated energy and fatigue life, which was independent of tack coat application rate, but dependent on underlying layer

material. The OGFC-TLD interface contact area was larger than that of OGFC-BM, leading to a better fatigue performance of OGFC-TLD. The plateau value failure criterion appeared effective for evaluating the shear fatigue performance of multilayer structures.

- In the study of the effect of interface characteristics on the bonding performance, Shear strength and shear stiffness were employed to characterize the shear bonding properties. Texture depth was tested to evaluate the surface roughness of underlying layers. Adhesive failure, cohesive failure, and non-contact area at the failed interfaces were identified and correlated to the shear strength and shear stiffness. Results showed that there were no significant differences in adhesive failure area between OGFC-TLD and OGFC-BM. The cohesive failure area of OGFC-TLD was larger than that of OGFC-BM. The non-contact area between OGFC and BM was larger in contrast with the area between OGFC and TLD at the same tack coat application rate. With the increase in tack coat application rate, the adhesive failure area and non-contact area decreased and the cohesive failure area increased. The shear force to overcome the adhesive bonding between OGFC and BM was larger than that of OGFC and TLD at the same tack coat application rate because of the larger interface roughness caused by BM's coarser aggregate gradation. At the optimal tack coat application rates for OGFC-TLD and OGFC-BM, the difference in the shear force to overcome the cohesive bonding between OGFC-BM and OGFC-TLD was very slight. It was the shear force to overcome the adhesive bonding that made the shear strength and the shear stiffness of OGFC-BM larger than those of OGFC-TLD.
- The unit cost (\$/m³) of OGFC mixture was about 42% higher than the conventional dense mixture. Considering equivalent structural numbers of OGFC and non-OGFC, the unit cost (\$/m²) of OGFC was about 59% higher than the dense mixture.

- The five year accident rate reduction analysis indicated that the OGFC mixtures generally reduced the accident rate, especially in rainy days. For some sections, the reduction in rainy days could be as high as 77.8%.
- The cost-benefit analyses based on the ratio of accident rate reduction over cost showed that the cost-benefit ratio of OGFC mixture was about two times as the dense mixture. It also demonstrated that the improving driving safety and reducing accident rate function of OGFC is more significant especially in rainy days and it is cost-benefit to use OGFC on Tennessee highways.
- A survey was conducted by the University of Tennessee to State Departments of Transportation to collect information on the state of OGFC in the US.

REFERENCE

- Alvarez, A. E., Martin, A. E., Estakhri, C. K., Button, J. W., Glover, C. J., and Jung, S. H. (2006). "Synthesis of current practice on the design, construction, and maintenance of porous friction courses."
- Alvarez, A. E., Martin, A. E., and Estakhri, C. (2009). "Drainability of permeable friction course mixtures." *Journal of Materials in Civil Engineering*, 22(6), 556-564.
- Alvarez, A. E., Martin, A. E., Estakhri, C., and Izzo, R. (2009). "Determination of volumetric properties for permeable friction course mixtures." *Journal of Testing and Evaluation*, 37(1), 1.
- Anderson, K., Uhlmeier, J., Sexton, T., Russell, M., and Weston, J. (2012). "Evaluation of Long-Term Pavement Performance and Noise Characteristics of Open-Graded Friction Courses – Project 2: Final Report." Washington State Department of Transportation.
- Anderson, K., Uhlmeier, J., Sexton, T., Russell, M., and Weston, J. (2012). "Evaluation of Long-Term Performance and Noise Characteristics of Open-Graded Friction Courses – Project 1: Final Report." Washington State Department of Transportation.
- Anderson, K., Uhlmeier, J., Sexton, T., Russell, M., and Weston, J. (2012). "Summary Report on the Performance of Open-Graded Friction Course Quieter Pavements: I-5 Lynnwood, SR-520 Medina, I-405 Bellevue." Washington State Department of Transportation.
- Anderson, K. W., Uhlmeier, J. S., Sexton, T., Russell, M., and Weston, J. (2013). "Summary Report on the Performance of Open Graded Friction Course Quieter Pavements: I-5 Lynnwood, SR-520 Medina, I-405 Bellevue."
- Becker, R. (1998). "Effects of strain localization on surface roughening during sheet forming." *Acta Materialia*, 46(4), 1385-1401.
- Biligiri, K. P. (2013). "Effect of pavement materials' damping properties on tyre/road noise characteristics." *Construction and Building Materials*, 49, 223-232.
- Boudabbous, M., Millien, A., Petit, C., and Neji, J. (2013). "Energy approach for the fatigue of thermoviscoelastic materials: Application to asphalt materials in pavement surface layers." *International Journal of Fatigue*, 47, 308-318.
- Carpenter, S. H., and Jansen, M. "Fatigue behavior under new aircraft loading conditions." *Proc., Aircraft/Pavement Technology In The Midst Of Change*.
- Chen, J.-S., and 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, Y., Lopp, G., and Roque, R. (2012). "Test Method to Evaluate the Effect of Interface Bond Conditions on Top-Down and Reflective Cracking." *Engineering Journal*, 16(4), 91-98.
- Chen, Y., Lopp, G., and Roque, R. (2013). "Effects of an asphalt rubber membrane interlayer on pavement reflective cracking performance." *Journal of Materials in Civil Engineering*, 25(12), 1936-1940.
- Collop, A., Sutanto, M., Airey, G., and Elliott, R. (2009). "Shear bond strength between asphalt layers for laboratory prepared samples and field cores." *Construction and Building Materials*, 23(6), 2251-

2258.

- Collop, A., Sutanto, M., Airey, G., and Elliott, R. C. (2011). "Development of an automatic torque test to measure the shear bond strength between asphalt." *Construction and Building Materials*, 25(2), 623-629.
- Cooley, L., Brumfield, J., Mallick, R., Mogawer, W., Partl, M., Poulikakos, L., and Hicks, G. (2009). "Construction and Maintenance Practices for Permeable Friction Courses. NCHRP REPORT 640, TRB." ISBN 978-0-309-11796-8.
- Deysarkar, I. (2004). "Test set-up to determine quality of tack coat."
- Diakhaté, M., Millien, A., Petit, C., Phelipot-Mardelé, A., and Pouteau, B. (2011). "Experimental investigation of tack coat fatigue performance: Towards an improved lifetime assessment of pavement structure interfaces." *Construction and Building Materials*, 25(2), 1123-1133.
- FHWA, F. H. A. (1990). "Open Graded Friction Courses." Federal Highway Administration (T 5040.31), Washington, DC.
- Gong, H. (2013). "Research on Stress Analysis and Compaction of Double Layered Asphalt Pavement." Chongqing Jiaotong University.
- Hassan, H., and Taha, R. "Use of open-graded friction course (OGFC) mixtures in Oman." *Proc., Performance of Bituminous and Hydraulic Materials in Pavements: Proceedings of the Fourth European Symposium, Bitmat4, Nottingham, UK, 11-12 April 2002*, CRC Press, 65.
- Hicks, R., Finn, F., Monismith, C., and Leahy, R. (1993). "VALIDATION OF SHRP BINDER SPECIFICATION THROUGH MIX TESTING (WITH DISCUSSION)." *Journal of the Association of Asphalt Paving Technologists*, 62.
- Huang, B., Mohammad, L. N., and Chris Abadie, P. (1999) "Fundamentals of Permeability in Asphalt Mixtures." *Proc., The Annual Meeting of the Association of Asphalt Paving Technologist*.
- Huber, G. (2000). *Performance survey on open-graded friction course mixes*, Transportation Research Board.
- Hwee, L. B., and Guwe, V. "Performance-related evaluation of porous asphalt mix design." *Proc., Malaysian Road Conference, 6th, 2004, Kuala Lumpur, Malaysia*.
- International, A. (2010). "ASTM D7064/D7064M-08: Standard practice for open-graded friction course (OGFC) mix design." ASTM International, West Conshohocken, PA.
- Jimenez, F., and Perez, M. "Analysis and evaluation of the performance of porous asphalt: the Spanish experience." *Proc., Surface Characteristics of Roadways, International Research and Technologies: Symposium on Surface Characteristics, 1st, 1988, State College, Pennsylvania, USA*.
- Kandhal, P. S., and Mallick, R. B. (1998). *Open graded friction course: state of the practice*, Transportation Research Board, National Research Council.
- Kandhal, P. S., and Association, N. A. P. (2002). *Design, construction, and maintenance of open-graded asphalt friction courses*, National Asphalt Pavement Association.
- King Jr, W., Kabir, S., Cooper Jr, S. B., and Abadie, C. (2013). "Evaluation of open graded friction course (OGFC) mixtures."
- Kowalski, K., McDaniel, R., Shah, A., and Olek, J. (2009). "Long-Term Monitoring of Noise and Frictional Properties of Three Pavements: Dense-Graded Asphalt, Stone Matrix Asphalt, and Porous Friction Course." *Transportation Research Record: Journal of the Transportation Research Board*(2127), 12-19.

- Li, H., Jiang, Z., Wei, D., Han, J., and Tieu, A. (2011). "Study on surface asperity flattening during uniaxial planar compression." *Wear*, 271(9), 1778-1784.
- Li, H., Jiang, Z., Wei, D., and Zhang, X. (2013). "Microtexture based analysis of surface asperity flattening behavior of annealed aluminum alloy in uniaxial planar compression." *Tribology International*, 66, 282-288.
- Li, H., and Yu, B. (2013). "Fatigue Performance and Prediction Model of Multilayer Deck Pavement with Different Tack Coat Materials." *Journal of Materials in Civil Engineering*, 26(5), 872-877.
- Li, S., Liu, X., and Liu, Z. (2014). "Interlaminar shear fatigue and damage characteristics of asphalt layer for asphalt overlay on rigid pavement." *Construction and Building Materials*, 68, 341-347.
- Litzka, J. H., Pass, F., and Zirkler, E. (1994). "Experiences with thin bituminous layers in Austria." *Transportation Research Record*(1454).
- Liu, K.-W., Alvarez, A. E., Martin, A. E., Dossey, T., Smit, A., and Estakhri, C. K. (2010). "Synthesis of Current Research on Permeable Friction Courses: Performance, Design, Construction, and Maintenance."
- Mallick, R. B., Kandhal, P., Cooley, L. A., and Watson, D. (2000). "Design, construction, and performance of new-generation open-graded friction courses." *Asphalt Paving Technology*, 69, 391-423.
- MENT, B. B. O. A. (1998). "Guideline Document for the Assessment and Certification of Thin Surfacing Systems for Highways." *British Board of Agrément, Watford*, 19-22.
- Miró, R., Martínez, A., and Pérez, F. "Evaluation Of The Effect Of Heat-Adhesive Emulsions For Tack Coats With Shear Test From The Road Research Laboratory Of Barcelona." *Proc., 2006 Annual Meeting of the Transportation Research Board*.
- Miró, R., Pérez-Jiménez, F., Martínez, A., Reyes-Ortiz, O., Paje, S., and Bueno, M. (2009). "Effect of crumb rubber bituminous mixes on functional characteristics of road pavements." *Transportation Research Record: Journal of the Transportation Research Board*(2126), 83-90.
- Mohammad, L., Raqib, M., and Huang, B. (2002). "Influence of asphalt tack coat materials on interface shear strength." *Transportation Research Record: Journal of the Transportation Research Board*(1789), 56-65.
- Mohammad, L., Bae, A., Elseifi, M., Button, J., and Scherocman, J. (2009). "Evaluation of bond strength of tack coat materials in field: Development of pull-off test device and methodology." *Transportation Research Record: Journal of the Transportation Research Board*(2126), 1-11.
- Nielsen, C. B. (2006). *Durability of porous asphalt: International experience*.
- Ogundipe, O. M., Thom, N., and Collop, A. (2013). "Investigation of crack resistance potential of stress absorbing membrane interlayers (SAMIs) under traffic loading." *Construction and building materials*, 38, 658-666.
- Poulikakos, L., and Partl, M. (2009). "Evaluation of moisture susceptibility of porous asphalt concrete using water submersion fatigue tests." *Construction and Building materials*, 23(12), 3475-3484.
- 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*.
- Raab, C., El Halim, A. A., and Partl, M. N. (2012). "Interlayer bond testing using a model material." *Construction and Building Materials*, 26(1), 190-199.
- Raposeiras, A. C., Vega-Zamanillo, Á., Calzada-Pérez, M. Á., and Castro-Fresno, D. (2012). "Influence of

- surface macro-texture and binder dosage on the adhesion between bituminous pavement layers." *Construction and Building Materials*, 28(1), 187-192.
- Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D.-Y., and Kennedy, T. W. (1996). "Hot mix asphalt materials, mixture design and construction."
- Ruiz, A., Alberola, R., Perez, F., and Sanchez, B. (1990). "Porous asphalt mixtures in Spain." *Transportation Research Record*(1265).
- Sabita (1995). "The design and use of porous asphalt mixes." Southern African Bitumen Association, Roggebaai, South Africa.
- Shen, S., and Carpenter, S. H. (2006). "Dissipated energy concepts for HMA performance: Fatigue and healing."
- Smit, A., and Waller, B. "Evaluation of OBSI for measuring tire-pavement noise." *Proc., Noise Conference*.
- Suresha, S., Varghese, G., and Shankar, A. R. (2009). "A comparative study on properties of porous friction course mixes with neat bitumen and modified binders." *Construction and Building Materials*, 23(3), 1211-1217.
- Tashman, L., Nam, K., Papagiannakis, T., Willoughby, K., Pierce, L., and Baker, T. (2008). "Evaluation of construction practices that influence the bond strength at the interface between pavement layers." *Journal of Performance of Constructed Facilities*, 22(3), 154-161.
- Trevino, M., and Dossey, T. (2006). "A research plan for measuring noise levels in highway pavements in Texas."
- Tschegg, E. K., Kroyer, G., Tan, D.-M., Stanzl-Tschegg, S. E., and Litzka, J. (1995). "Investigation of bonding between asphalt layers on road construction." *Journal of Transportation Engineering*, 121(4), 309-316.
- Van Dijk, W., Moreaud, H., Quede ville, A., and Uge, P. "The fatigue of bitumen and bituminous mixes." *Proc., Presented at the Third International Conference on the Structural Design of Asphalt Pavements, Grosvenor House, Park Lane, London, England, Sept. 11-15, 1972*.
- Watson, D., Moore, K., Williams, K., and Cooley, L. (2003). "Refinement of new-generation open-graded friction course mix design." *Transportation Research Record: Journal of the Transportation Research Board*(1832), 78-85.
- Watson, D., Cooley Jr, L., Moore, K., and Williams, K. (2004). "Laboratory performance testing of open-graded friction course mixtures." *Transportation Research Record: Journal of the Transportation Research Board*(1891), 40-47.
- West, R. C., Zhang, J., and Moore, J. (2005). "Evaluation of bond strength between pavement layers." *NCAT report*, 05-08.
- Williams, D. A. (1998). *Microdamage healing in asphalt concretes: relating binder composition and surface energy to healing rate*.
- Wu, H., Huang, B., and Shu, X. (2013). "Characterizing fatigue behavior of asphalt mixtures utilizing loaded wheel tester." *Journal of Materials in Civil Engineering*.
- Xie, H., Jiang, Z., and Yuen, W. (2011). "Analysis of friction and surface roughness effects on edge crack evolution of thin strip during cold rolling." *Tribology International*, 44(9), 971-979.
- Zhou, F., and Scullion, T. (2005). *Overlay tester: a rapid performance related crack resistance test*, Citeseer.
- Zhou, F., and Scullion, T. "Overlay tester: A simple and rapid screening test for characterizing crack resistance

of HMA mixes." *Proc., 10TH INTERNATIONAL CONFERENCE ON ASPHALT PAVEMENTS-
AUGUST 12 TO 17, 2006, QUEBEC CITY, CANADA.*