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Open-Graded Friction Courses Suitable for Suburban Environments

Final Report

March 2024

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or “t”)
TEMPERATURE				
ºF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	ºC
FORCE, PRESSURE				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

NOTE: volumes greater than 1000 L shall be shown in m^3

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE				
ºC	Celsius	1.8C+32	Fahrenheit	ºF
FORCE, PRESSURE				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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16. Abstract

The Florida Department of Transportation (FDOT) uses a 12.5-mm nominal maximum aggregate size (NMAS) open-graded friction course (OGFC) called FC-5 on multi-lane roads to enhance safety. However, FC-5 is susceptible to premature raveling on high-speed suburban roads due to increased lateral turning, braking and accelerating stresses. To address this issue, the project explored using a finer 9.5-mm NMAS OGFC gradation, a high polymer (HP) modified binder, an alternative friction course (AFC), and a 12.5-mm NMAS stone matrix asphalt (SMA) to improve durability with minimal impact on permeability for its potential use in suburban environments. A literature review was first conducted to review the application of OGFC in the United States and design factors that influence OGFC performance. Subsequently, the study compared 9.5-mm NMAS OGFC, 12.5-mm AFC, and 12.5-mm SMA mixtures with current FC-5 mixtures using two asphalt binder types through comprehensive laboratory testing. Results indicated that the 9.5-mm gradation and HP binder independently impacted OGFC performance in a positive manner and enhanced durability and friction without compromising permeability or rutting resistance. The AFC mixtures demonstrated better durability than FC-5 and 9.5-mm OGFC mixtures while maintaining reasonable drainability and permeability. Therefore, it is recommended that FDOT consider using a 9.5-mm OGFC mixture, AFC mixture, and/or HP binder in suburban areas to improve pavement durability while maintaining safety characteristics. The increased cost of utilizing 9.5-mm OGFC and AFC mixtures is approximately $2 per ton. The study provides mix design procedures and performance requirements for these mixtures. These recommendations aim to facilitate the implementation of 9.5-mm OGFC and AFC mixtures, maintaining construction practices consistent with FC-5 mixtures.

17. Key Words
OGFC Mix Design, FC-5, High Polymer Modified Binder, OGFC Mixture Performance, Durability

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EXECUTIVE SUMMARY

The Florida Department of Transportation (FDOT) currently utilizes an open-graded friction course (OGFC) known as FC-5 on multi-lane roads with a design speed of 50 mph or higher, excluding curb and gutter sections, to enhance safety by reducing hydroplaning and splash/spray during rain events. However, FC-5 layers on high-speed multi-lane suburban roads are prone to premature raveling due to increased lateral stresses from turning movements, rapid acceleration, and braking activities.

The FC-5 mixture is currently designed with a 12.5-mm nominal maximum aggregate size (NMAS) gradation and a polymer-modified PG 76-22 binder. Previous research has identified two strategies with the potential to enhance the durability of the FC-5 mixture: utilizing a 9.5-mm NMAS gradation in place of the 12.5-mm NMAS gradation and/or a high polymer (HP) modified binder, both having minimal impact on permeability.

This project aimed to assess the impact of employing the two previously proposed strategies (i.e., 9.5-mm gradation and HP binder) and two other strategies, including a 12.5-mm stone matrix asphalt (SMA) and an alternative friction course (AFC), to enhance durability with adequate drainage and surface friction for use in suburban environments. Two sets of mix designs were developed in this study, including 9.5-mm NMAS OGFC and 12.5-mm NMAS AFC. These mix designs were compared with the FC-5 mixtures currently used in Florida designed from the same component materials in a comprehensive laboratory experiment, as described below:

- The 9.5-mm OGFC gradations were chosen according to the Georgia Department of Transportation (GDOT) standards. Meanwhile, the AFC gradations were created to fall within the design gradations of the corresponding FC-5 and 12.5-mm SMA mixtures. The design gradations for the four mixture types were established based on the aggregate stockpiles utilized for two selected FC-5 mixtures, including one granite and one Florida limestone.
- After selecting the design gradations for the FC-5, 9.5-mm OGFC, and AFC mixtures, their optimum binder contents (OBCs) were determined based on the Pie Plate Method according to FM 5-558.
- The materials included two aggregate types [i.e., granite (GRN) and FL limestone (LMS)], two polymer-modified binder grades (PG 76-22 and HP), hydrated lime, mineral, and cellulose fibers, representing the materials used in the state.
- Laboratory tests were conducted on gyratory compacted specimens to evaluate the durability (Cantabro Abrasion Test, AASHTO TP 108), permeability (Florida Permeability Method, FM 5-565), cracking resistance (Overlay Test (OT), Tex-248-F), and rutting resistance (Hamburg Wheel Tracking Test (HWTT), AASHTO T324).
- Slab specimens (20 in. x 20 in. x 2.0 in.) were also prepared and polished in the laboratory using the three-wheel polishing device (AASHTO PP 104) and then tested for drainability (Drainability Test, ASTM E2380), surface friction (Dynamic Friction Test, ASTM E1911), and surface texture (Circular Texture Meter, ASTM E2157).
- Two aging conditions were considered: short-term loose mix oven aging for two hours at the compaction temperature (AASHTO R30) and long-term compacted specimen aging using the NCAT Accelerated Weathering System (ASTM D4799).

The comprehensive laboratory experiment showed that using a 9.5-mm NMAS gradation and HP binder in OGFC mixtures independently and jointly has positively affected performance, as summarized below.

- The 9.5-mm gradation has proven to enhance the durability of both GRN and LMS OGFC mixtures, with a significant improvement observed in GRN mixtures utilizing PG 76-22. This is a positive outcome, especially since GRN mixtures are more susceptible to durability issues, as measured by the Cantabro test, compared to LMS mixtures.
- While cracking resistance test results show slight improvement with the 9.5-mm gradation in both GRN and LMS OGFC mixtures, the impact is considered statistically insignificant.
- The permeability of GRN and LMS OGFC mixtures remains largely unaffected by the 9.5-mm gradation, meeting the minimum threshold recommended for OGFC mixtures. Moreover, there is no significant difference in drainability between the 9.5-mm OGFC and FC-5 mixtures for both GRN and LMS aggregates, suggesting that the use of 9.5-mm OGFC mixtures is a viable option that meets permeability requirements compared to FC-5 mixtures.
- Rutting resistance is not adversely affected by the 9.5-mm OGFC gradation.
- The friction properties of 9.5-mm OGFC mixtures are improved compared to FC-5 mixtures.
- The HP binder enhances durability and cracking resistance without compromising other essential properties. Notably, OGFC mixtures with HP binder exhibit better resistance to aging in the NAWS compared to those using PG 76-22.

Furthermore, the comprehensive laboratory experiment showed the promising potential for AFC mixtures, as discussed below:

- Cantabro loss results indicate comparable durability of AFC mixtures to 12.5-mm SMA mixtures. These mixtures showed less impact from NAWS conditioning on Cantabro loss compared to FC-5 and 9.5-mm OGFC, suggesting better durability.
- OT results showed similar cracking resistance in both AFC and 12.5-mm SMA mixtures compared to FC-5 and 9.5-mm OGFC before and after NAWS conditioning.
- The AFC mixtures exhibited higher permeability and drainability than 12.5-mm SMA but lower than FC-5 and 9.5-mm OGFC due to a finer gradation and lower design air voids.
- The AFC mixtures had HWTT rut depths less than the common criterion of 12.5 mm after 20,000 passes, indicating good resistance to moisture damage and rutting.
- The AFC mixtures showed higher DFT40 values than FC-5 mixtures at all polishing cycles, suggesting improved friction in OGFC mixtures. However, the AFC mixtures had lower macrotexture than FC-5 and 9.5-mm OGFC mixtures.

Based on the findings of the study, it is recommended that FDOT consider utilizing a 9.5-mm OGFC, an AFC mixture, and/or HP binder in suburban areas to improve the durability of pavement while maintaining safety characteristics similar to the FC-5 mixture. The cost analysis showed that utilizing 9.5-mm OGFC and AFC mixtures could increase the cost by approximately $2 per ton compared to FC-5 mixtures. The mix design procedures for the 9.5-mm OGFC and AFC mixtures are explained in Section 5.2 to facilitate their implementation. These procedures involve selecting a design gradation and determining an optimum binder content. Additional performance requirements are proposed to ensure the desired performance. For the 9.5-mm OGFC mix design, it is proposed to have a minimum air void content of 15% and a maximum Cantabro loss of 15%. Similarly, for the AFC mixture, it is recommended to have an air void range of 10%-15% and a maximum Cantabro loss of 10%. The proposed requirements for the 9.5-mm OGFC and AFC mixtures can be combined with other requirements already specified for FC-5 mixtures in Section 337 of the FDOT Standard Specifications for Road and Bridge Construction. Additionally, it is worth noting that the construction practices for these mixtures remain the same compared to the FC-5 mixtures.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Cement
AFC	Alternative Friction Course
AMPT	Asphalt Mixture Performance Tester
APA	Asphalt Pavement Analyzer
AR	Asphalt Rubber
ASTM	American Society for Testing and Materials
AWS	Accelerated Weathering System
BHF	Bag House Fine
CPR	Crack Progression Rate
CTM	Circular Track Meter
DFT	Dynamic Friction Test
DGM	Dense-Graded Asphalt
EVA	Ethylene Vinyl Acetate
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FI	Flexibility Index
GDOT	Georgia Department of Transportation
GRN	Granite
HP	High Polymer
HWTT	Hamburg Wheel Tracking Test
IFT	International Friction Index
ITS	Indirect Tensile Strength
LMS	Limestone
LVDT	Linear Variable Differential Transducer
LVE	Linear Viscoelasticity
NAPA	National Asphalt Pavement Association
NAWS	NCAT Accelerated Weathering System
NCAT	National Center for Asphalt Technology
NMAS	Nominal Maximum Aggregate Size
OBC	Optimum Binder Content

OGFC	Open-Graded Friction Course
OT	Overlay Test
SBR	Styrene Butadiene Rubber
SBS	Styrene Butadiene Styrene
SCB	Semicircular Bending
SFE	Surface Free Energy
SIP	Stripping Inflection Point
SMA	Stone Matrix Asphalt
TSR	Tensile Strength Ratio
US	United States
VCA	Voids in Coarse Aggregate
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate

1. INTRODUCTION

1.1 Problem Statement

Open-graded friction courses (OGFCs) are specially designed asphalt mixtures with gap-graded gradations that yield higher air void contents, typically ranging from 15% to 22%, compared to dense-graded asphalt mixtures (DGM) (Alvarez et al., 2006). These unique mix design features help increase permeability and enhance noise absorption.

Inadequate drainage in asphalt pavement can lead to hydroplaning, where water forms a layer between the tire and pavement surface, compromising the driver's control over braking and steering. Additionally, insufficient drainage can generate spray and splash, considerably reducing visibility for drivers. To mitigate these issues, OGFCs, with their high drainage and permeable characteristics, allow water to penetrate the pavement surface and facilitate lateral drainage, thereby reducing hydroplaning, splashing, and spraying under wet conditions (Kandhal, 2002); (Alvarez et al., 2006; Hernandez-Saenz et al., 2016; Dell'Acqua et al., 2011). Moreover, OGFCs can enhance visibility by 2.7 to 3.5 times compared to DGM pavements (Rungruangvirojn and Kanitpong, 2010) and improve pavement friction, particularly under wet conditions (Dell'Acqua et al., 2011; Adam and Shah, 1974). These safety benefits have made OGFCs a favorable option for road safety enhancement, especially in the southern United States (FDOT, 2022; Watson et al., 1998; Chen et al., 2016). Despite their safety benefits, challenges exist related to their application and maintenance, particularly concerning durability.

In Florida, where wet weather is common, the Florida Department of Transportation (FDOT) has adopted a policy requiring the use of OGFC (designated as FC-5) on all multi-lane roadways with design speeds of 50 mph or higher to improve safety. However, this policy restricts OGFC use to roadways without curb and gutter sections, except where a history of wet-weather accidents has been documented (FDOT, 2022). Roadways within curb and gutter sections typically employ dense-graded friction courses, offering good friction but less effective hydroplaning prevention.

With the steady population increase in Florida, many municipalities throughout the state have grown to the extent that developments and commercial centers are now located outside of the traditional curb and gutter areas but still abutting roadways that meet the design criteria for OGFCs. This expansion has led to the use of FC-5 in areas experiencing high lateral stresses, such as those caused by turning, rapid acceleration, and braking, which are not ideal for OGFC applications. As a result, FC-5 layers have shown premature raveling, raising concerns for FDOT. This raveling effect has limited the life expectancy of FC-5 mixtures in Florida to about 14 years, shorter than the approximately 20 years expected for DGM pavements (Tsai et al., 2022).

To address this challenge, FDOT seeks to develop a more durable OGFC for suburban areas, maintaining safety features comparable to FC-5 while offering alternatives for suburban and high-speed pavements in curb and gutter sections. This effort can extend pavement life, reduce maintenance and resurfacing needs, and minimize traffic disruptions. The research presented herein aims to develop such a durable OGFC suitable for suburban applications.

1.2 Research Objectives

FC-5 mixtures are currently used for approximately 50% of the pavement surfaces on Florida’s State Highway System and are designed with a 12.5-mm NMAS and polymer-modified PG 76-22 binder (Moseley, 2019). Because of the frequent OGFC usage, FDOT has sponsored numerous research efforts over the years to improve the durability of FC-5 mixtures. These research efforts include several approaches, from finite element modeling to a better understanding of the mechanisms of OGFC raveling (Arámbula-Mercado et al., 2016) to laboratory and field experiments assessing changes in component materials (Yin et al., 2021; Gu et al., 2021), mix design methods (Mejias de Pernia et al., 2016; Bennert and Cooley, 2014), and construction practices (Tran et al., 2013; Chen et al., 2012; Birgisson et al., 2006). The goal of these research efforts was to extend the OGFC service life. Based on prior FDOT-sponsored research (Bennert and Cooley, 2014; Arámbula-Mercado et al., 2016; Yin et al., 2021), two strategies have shown promise in improving OGFC durability with minimal impact on permeability: using a finer aggregate gradation and a high polymer-modified binder.

In this research, the objective was to evaluate the effect of employing the two previously proposed strategies (i.e., 9.5-mm gradation and HP binder) and two other strategies, including a 12.5-mm stone matrix asphalt (SMA) and an alternative friction course (AFC), to improve the durability of the fraction surface mixture while maintaining adequate drainability, friction and texture properties. These mixtures were compared with the FC-5 mixtures currently used in Florida utilizing the same component materials in a comprehensive laboratory experiment, as described below:

- The materials included two aggregate types (GRN and LMS), two binder grades (PG 76-22 and HP), hydrated lime, mineral, and cellulose fiber, representing the materials used in the state.
- Laboratory tests were conducted on gyratory compacted specimens to evaluate the durability (Cantabro Abrasion Test, AASHTO TP 108), permeability (Florida Permeability Method, FM 5-565), cracking resistance (Overlay Test, Tex-248-F), and rutting resistance (Hamburg Wheel Tracking Test, AASHTO T324).
- Slab specimens were also prepared and polished in the laboratory using the three-wheel polishing device (AASHTO PP 104) and then tested for drainability (Drainability Test, ASTM E2380), surface friction (Dynamic Friction Test, ASTM E1911), and surface texture (Circular Texture Meter, ASTM E2157).
- Two aging conditions were considered: short-term loose mix oven aging (AASHTO R30) and long-term compacted specimen aging using the NCAT Accelerated Weathering System (ASTM D4799).

1.3 Organization of the Report

The report is divided into five chapters. Chapter 1 introduces the challenges of OGFC pavements in Florida and explains the objectives of this study. Chapter 2 presents a comprehensive literature review exploring the application of OGFC in the United States, focusing on Florida. This chapter discusses design factors that influence OGFC performance, such as durability and functionality. It also compares the common OGFC and SMA mix designs in the United States and reviews their performance. Chapter 3 describes the experimental design, including the laboratory testing program, criteria for material selection, and design processes for FC-5, 9.5-mm OGFC, and 12.5-mm SMA. Additionally, it describes the method for designing AFC mixtures and the laboratory tests used in the study. Chapter 4 provides a detailed summary of the mix designs and the laboratory test results and discusses key findings. Lastly, Chapter 5 offers conclusions and recommendations based on the research results.

2. LITERATURE REVIEW

This section presents the findings of the literature review on (1) the history of OGFC application in Florida, (2) the recent OGFC studies in Florida, (3) the existing 9.5-mm/12.5-mm OGFC mix design, (4) OGFC mix design modification, (5) the existing 9.5-mm/12.5-mm SMA mix design, (6) performance tests for OGFC mixtures, and (7) summary of key findings from the literature review. Each topic is discussed in detail in the following sections.

2.1 History of OGFC Usage in Florida

FDOT began investigating the use of friction courses in the late 1960s as a result of the passage of the National Traffic and Motor Vehicle Safety Act of 1966. From this early research, FDOT developed and adopted eight wearing course mixtures in the early 1970s, with four being open-graded. These open-graded mixtures had problems with raveling, rutting, and stripping. In response to these problems and based on guidelines and a design procedure published in 1974 by the Federal Highway Administration (FHWA) (FHWA, 1990), FDOT developed a new OGFC called FC-2 in 1979, which replaced their previous wearing course mixtures. The FC-2 was designed with a modified version of the pie plate method described in the FHWA design procedure (Page et al., 1992).

The FC-2 mixture was required on all high-speed multilane roadways as a mean to reduce the risk of hydroplaning. The mixture was also permitted (as a bid alternate to dense-graded friction courses) for use in urban areas or curbed sections. However, raveling continued to be a recurring problem. The FC-2 mixture had a 3/8-in NMAS, used granite, slag, river gravel, or oolitic limestone aggregate, and used standard viscosity asphalt cement (AC-30) for the binder. In 1994, the binder was changed from AC-30 to an asphalt rubber binder containing 12% ground tire rubber by weight of asphalt cement (ARB-12). The mixture was placed at an approximate layer thickness of 1/2 in. As with previous open-graded mixtures, raveling was the predominant mode of distress, particularly in urban areas with significant turning movements (Page et al. 1992).

In the late 1990s, based on the positive feedback from the Georgia Department of Transportation (GDOT) regarding its D-Modified OGFCs, FDOT developed a similar OGFC called FC-5. The FC-5 mixture has a 1/2-in. NMAS uses only granite or oolitic limestone aggregates and a modified asphalt binder (either a polymer or rubber-modified PG 76-22). The FC-5 is typically placed at a thickness of 3/4 in. When FC-5 was adopted, FDOT also modified a number of pavement design procedures, eliminated the option of using OGFC as a bid alternative to dense-graded friction courses, and restricted the locations where FC-5 mixtures could be used (Cunagin et al., 2014). Due to the sensitivity of the mixture to high lateral stresses, placement restrictions included turn lanes, cross-overs, and shoulders. Furthermore, because of constructability and performance issues, along with feedback from the asphalt pavement industry, the placement of FC-5 was not allowed in curb and gutter sections unless there was a significant safety concern.

2.2 Recent OGFC Studies in Florida

The FC-5 mixture provides several benefits related to water drainage, such as reduced hydroplaning, reduced splash and spray, and improved visibility (Cooley et al., 2000) during wet weather conditions. However, a significant number of pavement sections in Florida surfaced with FC-5 have experienced premature raveling failures. Raveling typically originates from the top downward and may extend completely through the surface layer to the interface of the underlying layer. To better understand the mechanisms of raveling and improve the durability of FC-5, FDOT has sponsored several research projects on OGFC in recent decades. The key findings of these research projects are summarized as follows.

2.2.1 BDS15-977-01: Evaluate the Contribution of the Mixture Components on the Longevity and Performance of FC-5

Bennert and Cooley (2014) investigated the effects of mixture components on the cracking and durability of FDOT FC-5 mixtures. First, the FDOT pavement management system (PMS) database was utilized to collect the field cracking performance and fatigue life of FC-5 pavement sections based on FDOT's pavement cracking rating code. In addition, the material properties and traffic information were collected from the relevant pavement sections, which were correlated with the fatigue life of FC-5 pavement. The correlation analysis results indicated that the effective asphalt content of the mixture had a strong relationship with field cracking performance and pavement fatigue life. In general, the mixture with higher effective asphalt content would yield longer fatigue life, and the FC-5 mixtures with 6% or higher asphalt contents were expected to have excellent fatigue cracking resistance. However, limited correlations were found between the pavement fatigue life with other material properties and traffic parameters.

Based on the field performance survey, Bennert and Cooley (2014) believed that the durability issues associated with FC-5 mixtures in Florida were significantly affected by the mixture's effective asphalt content, which could be addressed by adjusting the optimum asphalt content. To accomplish this goal, they assessed the pie-plate procedure used by FDOT to determine the optimum asphalt content during mix design. Based on the laboratory results, two solutions were proposed to improve the current pie-plate method: 1) conducting the pie-plate test after 2 hours of loose mixture volumetric conditioning; and 2) utilizing appropriate binder types (i.e., PG 76-22 or ARB-12 asphalt binders) rather than using an unmodified binder. In addition, the Draindown and Cantabro Abrasion Loss tests were also suggested as a supplement for the pie-plate method to improve the durability of FC-5 mixtures. Later, the research team further evaluated the effects of aggregate gradation on the durability and fatigue cracking resistance of FC-5 mixtures using the Cantabro Abrasion test and the OT, respectively. The test results indicated that the FC-5 mixture with a fine gradation (9.5-mm NMAS) yielded better durability and fatigue cracking resistance than a coarse gradation (12.5-mm NMAS). However, there are some concerns regarding the stability and rutting potential of 9.5-mm FC-5 mixtures, which might be caused by insufficient stone-on-stone contact.

2.2.2 BDR74-977-04: Understanding Mechanisms of Raveling to Extend OGFC Service Life

Arámbula-Mercado et al. (2016) investigated the mechanisms of raveling in FDOT FC-5 mixtures by conducting finite element (FE) modeling analysis and laboratory mixture performance tests, including permeability, Cantabro, indirect tensile (IDT) strength, and HWTT. In this study, three existing mix designs with known field raveling performance were selected, and another three modified designs with varying mixture components (i.e., gradation, binder type, and aggregate type) were also included. Before the laboratory mixture performance tests, the corresponding aggregate and binder were characterized using typical and advanced techniques to determine their moisture damage resistance. The aggregate morphologic and surface free energy (SFE) test results indicated that the combination of polymer-modified asphalt (PMA) and limestone would yield the least moisture susceptibility, and the granite and asphalt rubber binder (ARB) combination would have the highest moisture susceptibility. In addition, the Glover-Rowe parameter and SFE technique identified that PMA had better moisture damage resistance than ARB, which could be considered suitable tools to select the appropriate materials during mix design.

The mixture performance tests were then conducted to compare the moisture damage resistance among six mix designs. There was no consistent trend regarding the moisture sensitivity ranking among the six mixtures, and some tests showed an opposite trend. For example, the mixture with the best durability based on the IDT test showed the worst moisture resistance in the Cantabro abrasion loss test. Additionally, the HWTT results showed a fair correlation with the IDT results regarding the effects of gradation. Among all the mixture performance tests, the Cantabro test was the best predictor of the durability of OGFC mixtures when compared to observed field performance.

In addition, the modified Lottman method per AASHTO T 283 and the Moisture-Induced Stress Tester (MIST) per ASTM D7870 were used to evaluate the effects of moisture on IDT strength and Cantabro loss. Both methods showed minimal impact on the test results for all six mixtures, which indicated these two conditioning methods could not adequately reflect the effect of moisture intrusion in the field for FC-5 mixtures. Lastly, the two-dimensional FE model was developed with a moving wheel load over a typical FC-5 layer on top of a typical pavement structure, which was used to investigate the mechanisms of raveling initiation and progression in FC-5 mixtures. The influences of climate, traffic, pavement structure, and materials properties on the raveling resistance were evaluated using the FE model. The simulation results indicated that the binder content and air void content of the mixtures affected the raveling resistance the most. Extreme temperatures, high traffic loads, and slow vehicle speeds were also identified as detrimental to the raveling resistance of mixtures, while the pavement's structural capacity underneath the FC-5 layer had the least significant effects on the raveling resistance. In other words, raveling is a problem of material damage rather than structural damage.

2.2.3 BE287: Evaluation of FC-5 with High Polymer (HP) Binder to Reduce Raveling

Arámbula-Mercado et al. (2019) evaluated whether the use of high polymer (HP) binder could produce more durable and cost-effective FC-5 mixtures than those with PG 76-22 PMA using a series of laboratory performance tests, FE mechanical simulation, and life-cycle costs analysis (LCCA). First, dynamic shear rheometer (DSR), Fourier transform infrared spectroscopy (FTIR), and FE techniques were used to investigate the viscoelastic, aging susceptibility, and mechanical properties of two binders at various aging conditions. In general, the DSR results indicated that the HP binder had better mechanical properties in terms of ductility and cracking resistance, which might be attributed to the better aging resistance. In addition, four mastics were prepared using the combinations of two binders and two aggregates (limestone and granite), which were characterized using DSR and SFE. The mastics test results indicated that the mastics with the PMA binder yielded greater modulus than those with HP binder at high reduced frequencies.

Furthermore, the properties of an FC-5 mixture prepared with two binder types were evaluated using the Illinois Flexibility Index (I-FIT), Indirect Tensile Asphalt Cracking Test (IDEAL-CT), Cantabro test, and IDT. The I-FIT and IDEAL-CT results indicated that the mixtures fabricated with HP binder yielded better cracking resistance than those fabricated with PMA regardless of aggregate type. In addition, the Cantabro test results indicated that mixtures with HP binder showed better durability than those with PMA binder, and the durability of FC-5 mixtures were proven to be significantly affected by aging, especially for mixtures using PMA.

To further compare the durability of mixtures using HP and PMA binders, the two-dimensional FE model was used to investigate the mechanical properties of FC-5 mixtures under both short-term and long-term aging conditions. The fracture mechanics mechanism was incorporated in the FE simulation under the long-term aging condition, which was more suitable for evaluating the raveling initiation process. The numerical simulation results indicated that the FC-5 mixtures prepared with the HP binder were less susceptible to raveling. Lastly, LCCA results showed that FC-5 mixtures using HP binder were more cost-effective than those using PMA binder due to increased durability based on Cantabro results.

2.2.4 BE555: Study of Anti-Strip Additives on Granite-Based FC-5 Asphalt Mixtures

Gu et al. (2020) evaluated the effects of liquid anti-strip (LAS) and additional hydrated lime (HL) additives on the durability and moisture susceptibility of FC-5 mixtures fabricated with two granite aggregates. The binder bond strength (BBS) test was first conducted to select the optimum combination of additives (LAS + additional HL) that yielded the best moisture resistance for each aggregate source. Then, the DSR was used to evaluate the effects of the different LAS additives on the performance grade (PG) of modified binders, and the results indicated that the addition of LAS had no significant impact on the binder PG.

For each aggregate source, the FC-5 mixtures were fabricated using two mix designs provided by FDOT. The FC-5 mixtures were conditioned using the Accelerated Weathering System (AWS) to simulate the long-term aging and moisture conditioning in the field, and the Cantabro, tensile strength ratio and HWTT tests were conducted to evaluate their performance. The laboratory test results indicated that the AWS conditioning enhanced the stripping resistance of FC-5 mixtures, which might be explained by the stiffening effects of aging on the binder. In addition, the HWTT test results did not show any benefits of using LAS and additional HL on the moisture resistance of the mixtures, and the Cantabro loss was the only predictor capable of discriminating the influences of anti-strip additives on the durability of FC-5 mixtures. In general, the laboratory mixture test results suggested that the durability of FC-5 mixtures increased by adding 0.5% LAS and an extra 0.5% HL. Lastly, this study conducted a cost-benefit analysis for FC-5 mixtures using different anti-strip additive combinations (LAS + HL). The Cantabro test results were utilized to estimate the life span of each combination, and the results indicated that adding extra additives could extend the service life of FC-5 mixtures with a range of 8 to 20 years. The cost-benefit ratio was then further calculated to assess the cost-effectiveness of FC-5 mixtures with anti-strip additives, and the analysis results showed that adding anti-strip additives could improve the cost-effectiveness of those mixtures.

2.3 Existing 9.5-mm/12.5-mm OGFC Mix Design

According to a national survey on OGFC usage conducted in 2015 by NCAT, OGFC is popular among state DOTs in the non-freeze regions of the U.S. (e.g., southern states) due to its safety and environmental benefits but is seldom used in the freeze regions (e.g., northern states) primarily due to winter maintenance concerns. Although 12.5-mm OGFC mixtures were commonly used among the state highway agencies (SHAs), 9.5-mm OGFC mix designs have attracted more attention recently. As described previously, Bennert and Cooley (2014) investigated the effects of mixture properties on the durability of FC-5 mixtures, and the test results indicated that the FC-5 mixture with a finer gradation (9.5-mm NMAS) yielded better durability and fatigue cracking resistance than the coarse gradation (12.5-mm NMAS). A similar conclusion was also obtained by Watson et al. (2020) and Xie et al. (2019), and their test results showed that 9.5-mm OGFC mixtures had higher tensile strengths after moisture and freeze/thaw conditioning and higher long-term permeability when compared with the state-approved 12.5-mm OGFC. Consequently, some states have recently made changes to their OGFC specifications to allow the use of 9.5-mm OGFC mixtures. For example, the Georgia and South Carolina DOTs have included 9.5-mm OGFC in their specifications, and the Alabama DOT tested a 9.5-mm OGFC mixture on the NCAT Test Track.

Watson et al. (2018) developed a performance-based OGFC mix design procedure that addresses commonly experienced distresses on the roadway, such as raveling and cracking. The mix design procedure includes performance tests and their acceptance thresholds for durability, cracking, and cohesiveness. As air voids were found to be directly related to permeability, a minimum design air void content of 15%, corresponding to a minimum permeability rate of 50 meters/day, was recommended. The Cantabro loss was also a good indicator of mix durability and resistance to raveling with a recommended maximum loss of 20%. The indirect tensile strength test, based on a modified version of AASHTO T 283, and mixture shear test were found to be good indicators of mix cohesiveness. The peak load of the I-FIT was also found to be a good measure of resistance to cracking. In addition, Putman (2012) recommended a maximum percent passing the #4 sieve of 20% to ensure mixture stability.

Tables 1 and 2 provide specific details about the design and gradation requirements for 9.5-mm and 12.5-mm OGFC mixtures in specifications in several states. The aggregate gradation for 9.5-mm and 12.5-mm OGFC mixtures varies from state to state. Furthermore, many states require polymer-modified asphalt binders with a specified binder content range. Some states mandate a minimum binder content based on the combined aggregate bulk specific gravity (Cooley et al., 2009). Air void requirements also vary among states. Some require only the minimum air voids, while others specify a specific air void range. In general, the air voids of OGFC mixtures specified by states are higher than 15%, except for Alabama. Additionally, many states require additional tests during the mixture design or acceptance stages. These include the tensile strength ratio (TSR), draindown, coating retention, and Cantabro tests. A minimum TSR value of 0.8 and a maximum draindown value of 0.3 are commonly required. A maximum Cantabro loss value is also specified, ranging from 15% to 30%. Besides the above-mentioned tests, Louisiana and Texas also require a minimum number of passes at 12.5-mm rut depth using the Hamburg Wheel Tracking Test (HWTT) to ensure good rutting resistance. Furthermore, Texas also utilized the Overlay Test (OT) to characterize the cracking resistance of OGFC mixtures, with a minimum number of OT cycles of 200 required.

Table 1. Summary of 9.5-OGFC Design Requirements

Gradation	**FHWA**	**GA**	**LA**	**MS**	**TX**	**NC**	**OK**	**AZ**	**CA**	**UT**	**NV**	**OR**	**NJ**
1/2 inch	100	100	100	100	100	100	100	100	100	100	100	100	100
3/8 inch	95-100	85-100	85-100	90-100	95-100	75-100	90-100	100	90-100	90-100	95-100	90-100	85-100
No. 4	30-50	20-40	25-50	15-30	20-55	25-45	25-45	35-55	29-36	35-45	40-65	22-40	20-40
No. 8	5-15	5-10	5-15	10-20	1-10	5-15	0-10	9-14	7-18	14-20	12-22	5-15	5-10
No. 200	2-5	2-4	2-5	2-5	1-4	1-3	0-5	0-2	0-0	2-4	0-5	1-5	2-4
Design Requirements													
Asphalt Type		76-22	76-22m	76-22	76-XX	76-22							
Asphalt Binder Content (%)		6.0-7.25	≥ 6.5	N/A	6-7	5.5-8.0	≥ 5.1	6-10	5.5-7		6.3-6.8		≥ 6.0
Air Voids (%)	≥ 18		18-24	≥ 15	≥ 22	≥ 18	≥ 18		18-22			16-20	≥ 18
TSR	≥ 0.80			≥ 0.85								≥ 0.80	≥ 0.80
Draindown (%)	≤ 0.30	≤ 0.30	≤ 0.30	≤ 0.30	≤ 0.10	≤ 0.30	≤ 0.20		≤ 0.30				
Cantabro Loss on unaged Samples (%)	≤ 20.0			≤ 30.0	≤ 20.0	≤ 20.0			≤ 15				≤ 30.0
Coating Retention		≥ 0.95		≥ 0.95									
HWTT Criteria (Min passes prior to reaching 12.5-mm rut depth)			5,000		10,000								
Minimum Overlay Test Cycles					200								

Table 2. Summary of 12.5-mm OGFC Design Requirements

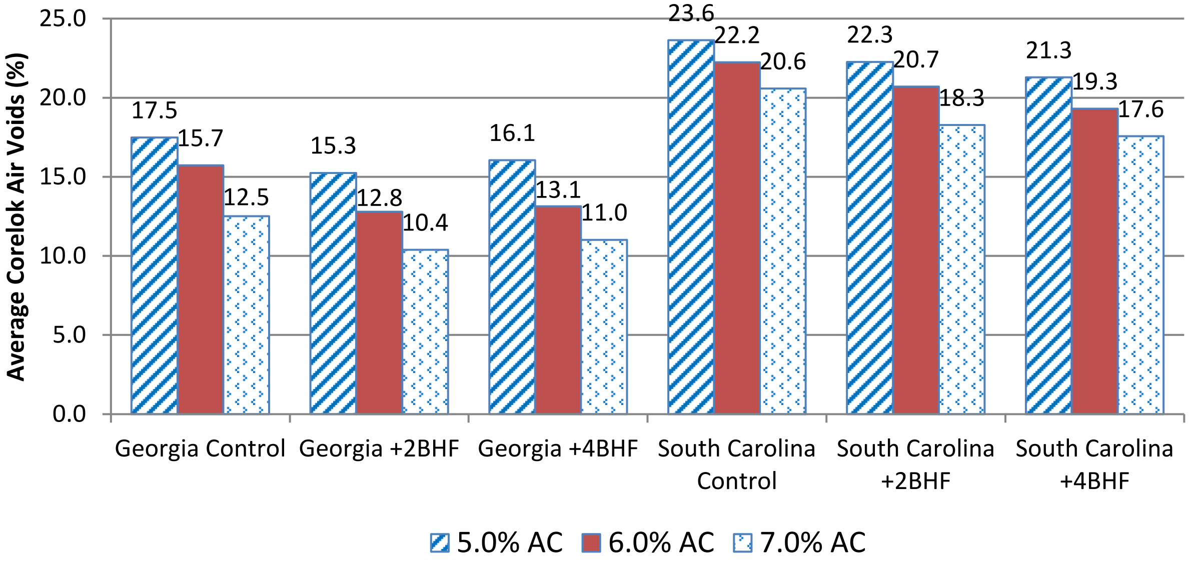
Gradation	**ASTM D 7064**	**AL**	**GA**	**LA**	**MS**	**FL**	**TX**	**SC**	**TN**	**NV**	**OR**	**NJ**	**NE**
3/4 inch	100	100	100	100	100	100	100	100	100	100	100	100	100
1/2 inch	85-100	85-100	85-100	85-100	100	85-100	80-100	85-100	85-100	100	90-98	85-100	95-100
3/8 inch	35-60	55-65	55-75	55-75	80-89	55-75	35-60	55-75	55-75	90-100	--	35-60	40-80
No. 4	10-25	10-25	15-25	10-25	15-30	15-25	1-20	15-25	10-25	35-55	18-2	10-25	15-35
No. 8	5-10	5-10	5-10	5-13	10-20	5-10	1-10	5-10	5-10	5-18	3-15	5-10	5-12
No. 200	2-4	2-4	2-4	2-4	2-5	2-5	1-4	0-4	2-4	0-4	1-5	2-5	0-3
Design Requirements													
Asphalt Type		76-22	76-22	76-22m	76-22	HP/PG 76-22	76-XX	76-22		AC 30			
Asphalt Binder Content (%)		4.7-9.0	5.75-7.25	≥ 6.5	N/A	5.5-8.0	6-7	5.5-7	6-8	6.3-6.8		≥ 5.7	
Air Voids (%)	≥ 18	≥ 12		18-24	≥ 15		≥ 18		≥ 20		16-20	≥ 20	17-19
TSR	≥ 0.80	≥ 0.80			≥ 0.85				≥ 0.80		≥ 0.80	≥ 0.80	
Draindown (%)	≤ 0.30	≤ 0.30	≤ 0.30	≤ 0.30	≤ 0.30		≤ 0.10		≤ 0.30				
Cantabro Loss on unaged Samples (%)	≤ 20.0	N/A			≤ 30.0		≤ 20.0		≤ 20.0			≤ 30.0	
Coating Retention			≥ 0.95		≥ 0.95			≥ 0.95					
HWTT Criteria (Minimum passes prior to reaching 12.5-mm rut depth)				5,000									

2.4 OGFC Mix Design Modification

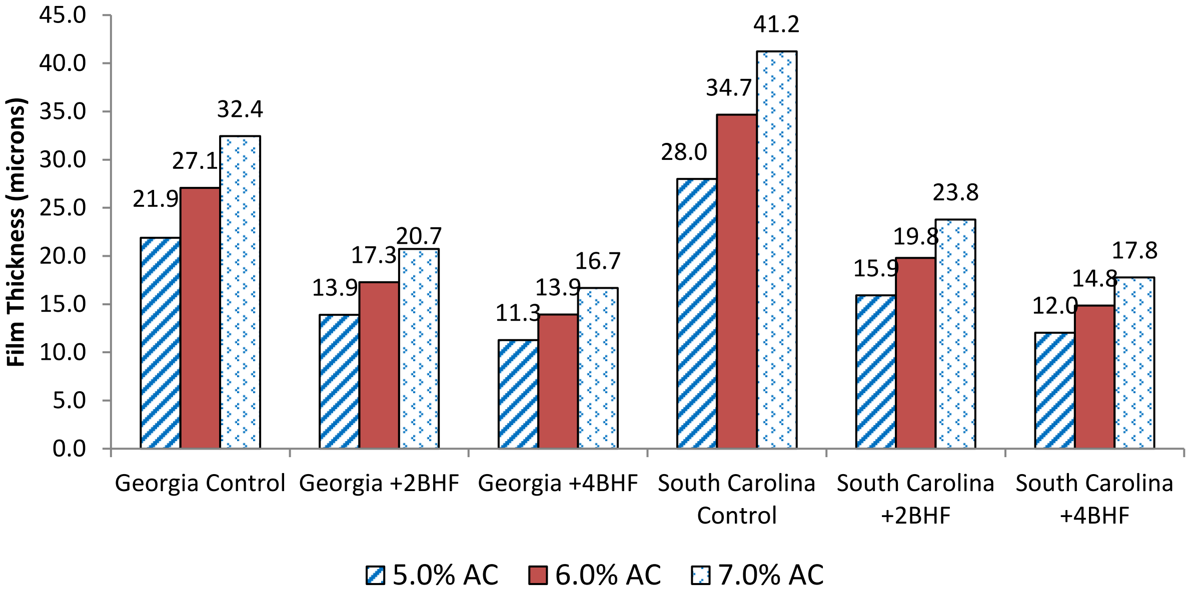
Watson et al. (2018) conducted NCHRP Project 01-55 to develop a performance-based mix design procedure for OGFC that addresses commonly experienced issues like raveling and cracking on the roadway. This project established a balanced mix design approach for designing OGFC mixtures and proposed performance tests and acceptance thresholds for durability, cracking, and cohesiveness. The study modified OGFC designs in Georgia (GA) and South Carolina (SC) by increasing the baghouse fine (BHF) content and binder content, which was expected to provide a more durable OGFC mixture. The effects of these modifications on volumetric properties, durability, permeability, moisture susceptibility, rutting, and cracking resistance were investigated using different laboratory tests.

2.4.1 Effects on Volumetric Properties

The effects of modifications on volumetric properties were investigated using two key parameters of air voids and film thickness, which played a great role in the mixture's permeability and durability, respectively. As mentioned above, the BHF content and binder content were increased for two OGFC mix designs (GA and SC), and the air voids and film thickness results were summarized in Figure 1. As presented in Figure 1 (a), for GA mix design, the air voids generally decreased with the increasing binder content and BHF content, which was expected. However, the air voids did not show any additional decrease between an extra 2% BHF an 4% BHF. For the SC design, the air voids showed an incremental decrease with the increasing binder content and BHF content, which was most likely due to the amount of extra room available in the design from the higher VMA. In addition, the GA design met the air voids requirements at lower binder content, and the air voids of SC design consistently met the minimum 15% criterion even with a higher binder content and BHF content. As shown in Figure 1 (b), for both mix designs, the film thickness significantly decreased with the increasing BFH content, and increased with the increase of binder content, which was expected. This anticipated trend was caused by the great surface area of BHF. The original GA and SC designs met the minimum film thickness requirement of 24.0 microns, but the additional BHF dropped all the modified designs below that point.



(a) Effects on the Air Voids



(b) Effects on the Film Thickness

Figure 1. Effects on the Volumetric Properties (Watson et al., 2018)

2.4.2 Effects on Durability

Arámbula-Mercado et al. (2016) indicated that the Cantabro test was a good predictor of the durability of OGFC mixtures based on the observed field performance. Thus, Watson et al. (2018) utilized the Cantabro test to evaluate the effects of modifications on durability, and the mixtures with lower cantabro loss were expected to yield better durability than those with higher loss values. As shown in Figure 2, for both mix designs, the cantabro loss decreased with the increased binder and BHF content, which was expected. For GA mix design, the mixture with additional 2% and

4% BHF at 5% binder content had comparable cantabro loss with mixture at 6% binder content without extra BHF, which indicated that the increasing BHF content could improve the mixture's durability efficiently. As for the SC mix, the initial 2 % extra BHF showed significant durability improvement, and the test results also showed that increasing the BHF by 2% provided more durability than by increasing the asphalt binder content by 1%.

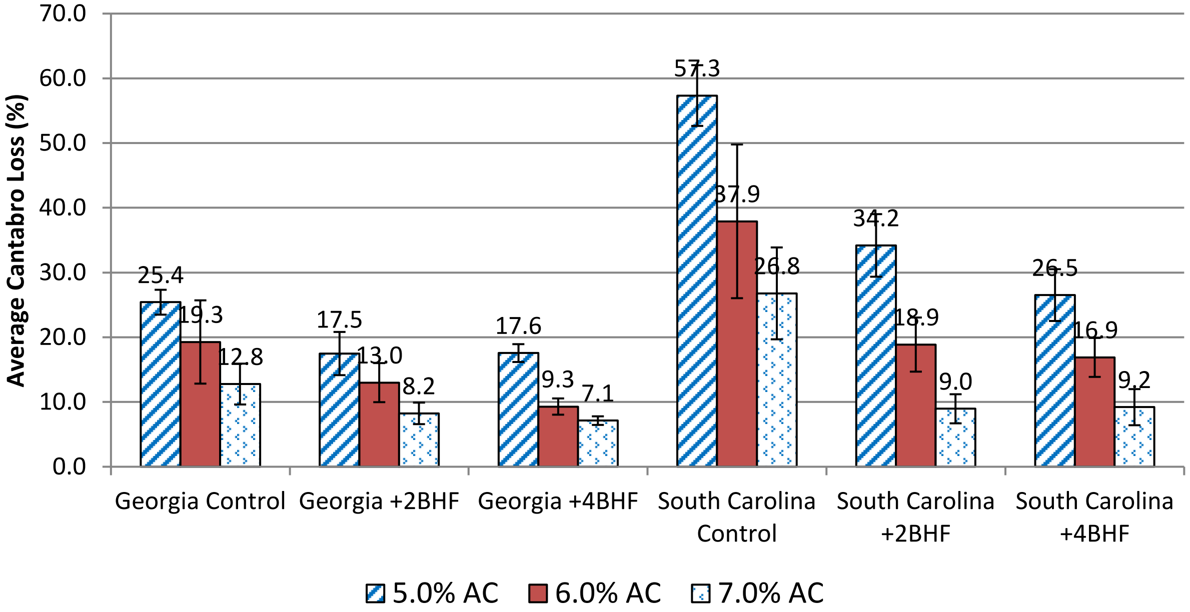


Figure 2. Effects on the Cantabro Loss Results (Watson et al., 2018)

2.4.3 Effects on Permeability

As shown in Figure 3, for GA design, the permeability decreased with the increasing BHF content at 6% binder content, and the permeability values were lower than the recommended criterion of 100 meters/day. For SC design, the permeability showed little decrease with the increasing BHF content, which was most likely due to the high initial air void. To further investigate the effects of binder content on the permeability, the additional binder was added for GA mixtures with extra BHF. As presented in Figure 3, the mixtures using additional 2% BHF and 4% BHF at 5% binder content provide similar permeability to the mixture at 6% binder content without additional BHF. Just as with the Cantabro results shown previously, the mixture with extra 2% BHF is as permeable and resistant to raveling as the mixture with 1% more binder content but without the added BHF. These results indicate that increased BHF adds significant cohesive ability to OGFC mixtures so that permeability and durability can be maintained at a reduced asphalt content.

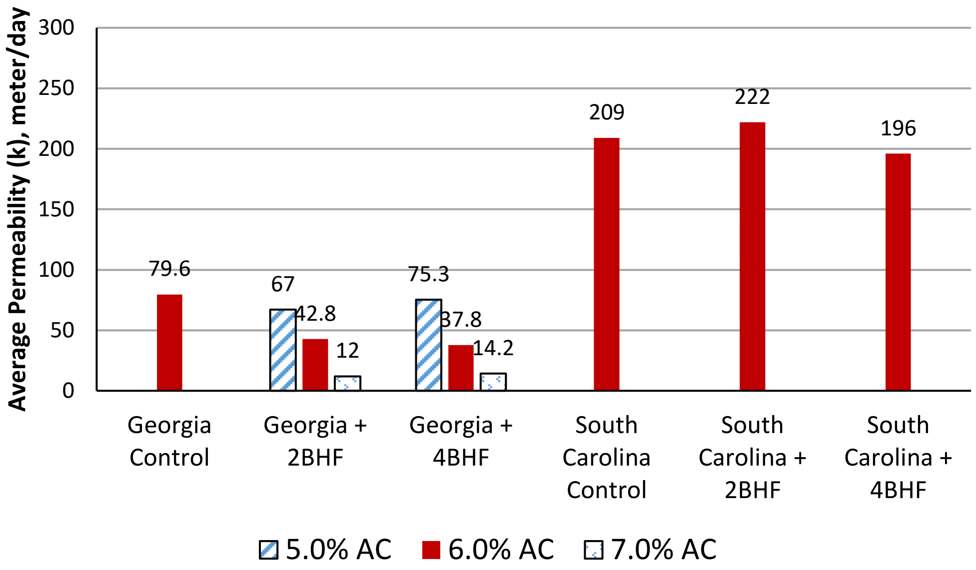
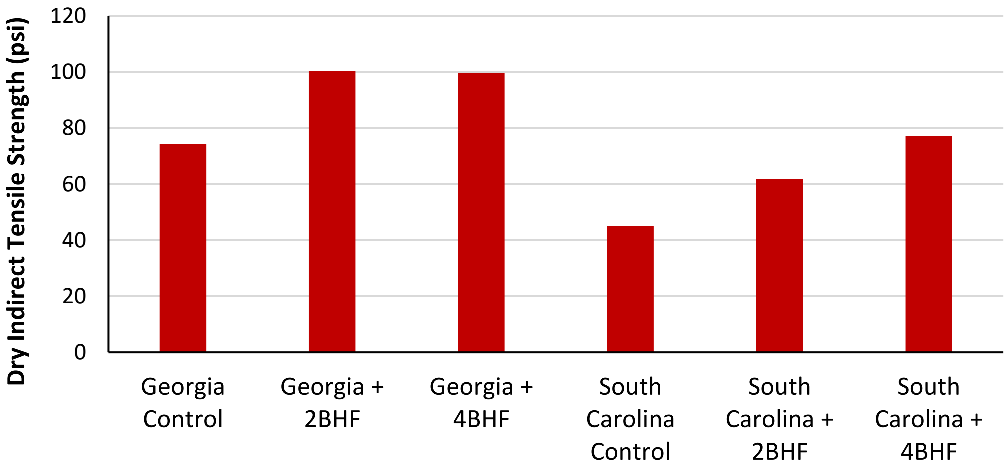


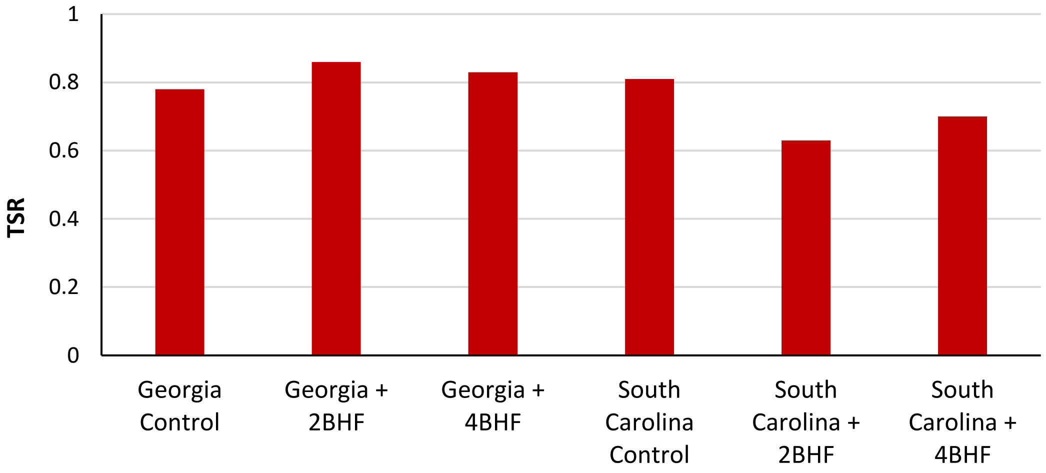
Figure 3. Effects on Permeability (Watson et al., 2018)

2.4.4 Effects on Moisture Susceptibility

The mixture's moisture susceptibility was characterized using TSR test, and the dry indirect tensile strength (ITS) and TSR ratio were measured for each mix design, shown in Figure 4. As presented in Figure 4 (a), for both GA and SC designs, the dry ITS increased with the increase of BHF content. The additional BHF could potentially produce more mastic and consequently a stronger mixture, which resulted in a higher ITS. As shown in Figure 4 (b), the TSR value increased with the GA design but decreased with the SC design. Although the extra BHF could create more mastic, it could also result in less free binder, which was used to coat the coarse materials and provide bonding among aggregates. Thus, for SC design, the decreased trend might be explained by the offset of lower free binder.



(a) Dry Indirect Tensile Strength Results

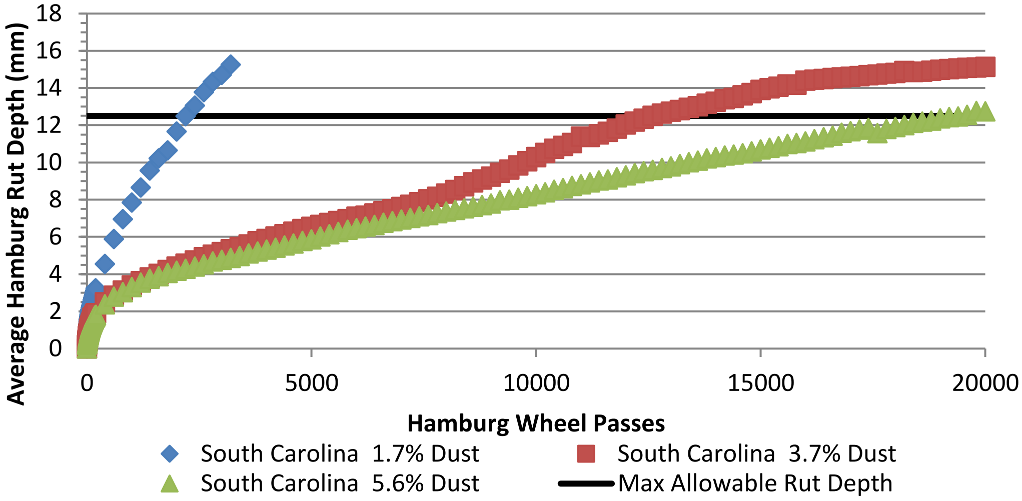


(b) TSR Test Results

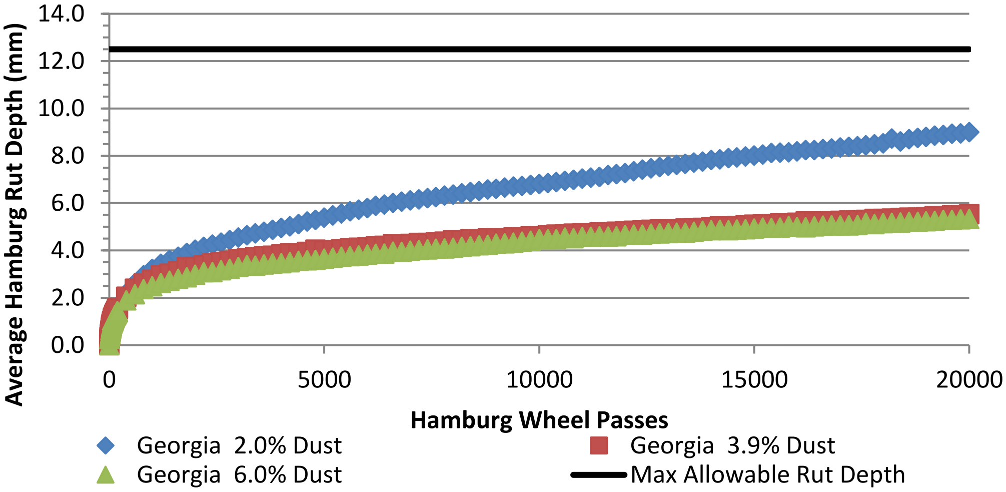
Figure 4. Effects on Moisture Susceptibility (Watson et al., 2018)

2.4.5 Effects on Rutting Resistance

The rutting resistance of OGFC mixtures was evaluated using HWTT, and the evolution curve of rut depth for each mix design was recorded and shown in Figure 5. The black solid line in Figure 5 indicates the rutting criterion of 12.5 mm. As presented in Figure 5 (a), for SC design, the control mixture failed around 2,540 passes, and the mixtures with additional 2% and 4% BHF failed around 15, 194 passes and 19,202 passes, respectively. In general, the additional BHF was able to significantly improve the rutting resistance of SC design. As shown in Figure 5 (b), the GA design showed marked improvement with the addition of 2% BHF but no additional improvement was observed with the 4% BHF specimens based on the HWTT rut depth results.



(a) SC Design

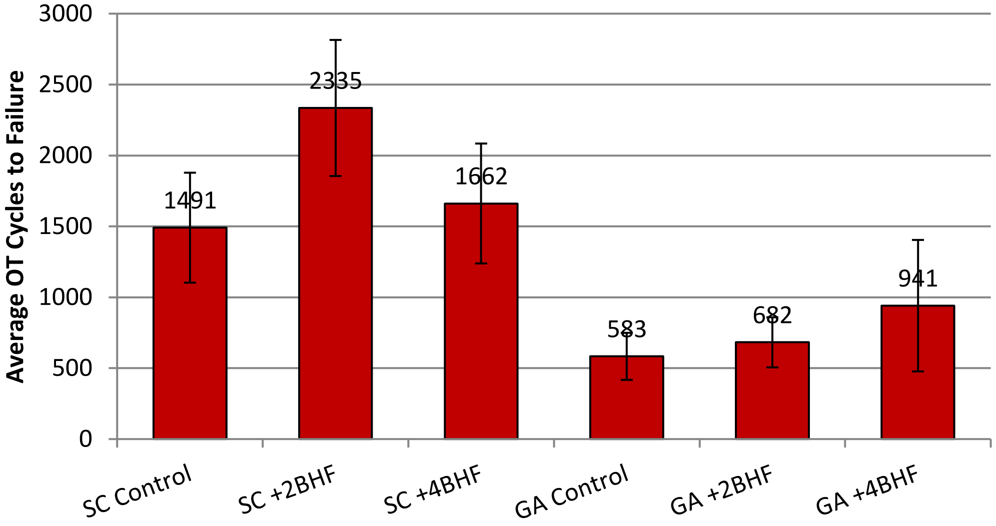


(b) GA Design

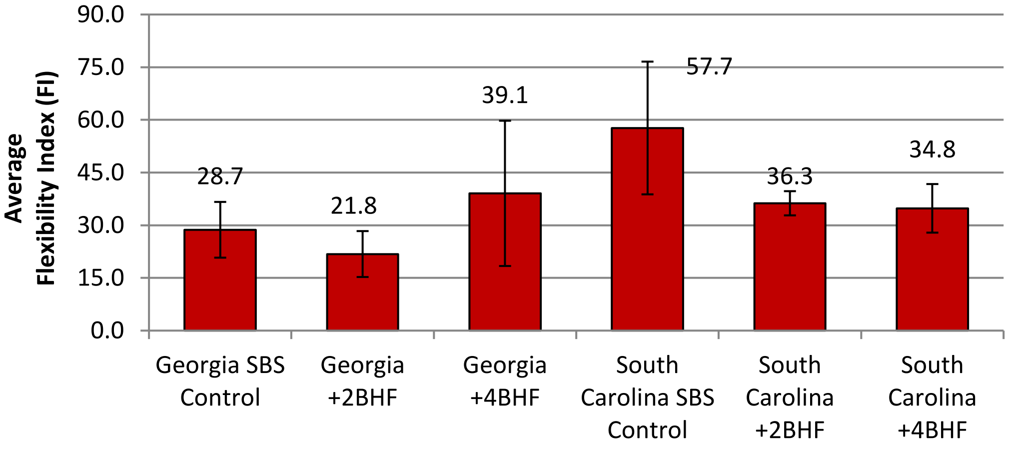
Figure 5. Effects on Rutting Resistance (Watson et al., 2018)

2.4.6 Effects on Cracking Resistance

OT and I-FIT tests were utilized to evaluate the cracking resistance of both mixture designs, and the cracking parameters of OT cycles and flexibility index (FI) were measured and summarized in Figure 6. As shown in Figure 6 (a), for SC design, the OT cycles generally increased with the increase of BHF content. The test results showed a significant improvement with the addition of 2% BHF, but no additional improvement was observed with the extra 4% BHF. In addition, the OT cycles showed an incremental increasing trend with the increasing BHF content for GA design. Based on the OT results, the additional BHF generally increases the cracking resistance of both designs, which might be explained by the extra mortar produced with the additional BHF. As presented in Figure 6 (b), for SC design, the FI of mixture with additional 2% BHF was slightly lower than the FI of control mixture, and the FI of mixture with additional 4% BHF was greater than the other two mixtures. For GA design, the FI decreased with the increasing BHF content, which might be caused by the less free binder discussed above. In general, the OT test showed a different trend from the I-FIT test regarding the effects of additional BHF on the cracking resistance. As indicated by other studies, the FI commonly increases with the increase of air void content (Batioja-Alvarez et al., 2019; Zhou et al., 2017), which contradicts field observations that asphalt pavements with higher in-place air void contents (or lower in-place density) are more susceptible to cracking. The unexpected trend between OT and I-FIT might be attributed to the decreasing air voids with additional BHF, as shown in Figure 1(a).



(a) OT Cycles Results



(b) Flexibility Index Results

Figure 6. Effects on Cracking Resistance (Watson et al., 2018)

2.5 Existing 9.5-mm/12.5-mm SMA Mix Design

SMA is a special type of gap-graded asphalt mixture containing a modified asphalt binder at an elevated binder content, large amounts of high-quality coarse aggregate and mineral filler, and a small amount of cellulous or mineral fibers to inhibit binder drain-down. SMA is typically used as a surface course for high-volume roads due to its superior rutting and cracking resistance (NAPA, 2002). SMA has been widely used for a number of reasons, such as improved rutting resistance, extended service life with improved performance, and improved friction resistance. Although water cannot drain vertically through an SMA layer in the same manner as an OGFC, the surface macro-texture of an SMA is similar to OGFC, which provides improved friction resistance and reduced water splash and spray (NAPA, 2002). The cost of SMA is generally 20-25% higher than conventional dense-graded mixtures, primarily due to the use of modified binders, mineral fillers, and fibers, however, the extra cost may be offset by the extended service life.

In 1997, NCAT developed the first SMA mix design procedure in the United States to provide guidance on the selection of materials, determination of aggregate gradation and optimum binder content, and evaluation of binder draindown potential and moisture susceptibility (Brown et al., 1997). The study recommended a maximum percent passing the No. 4 sieve of 30% to ensure sufficient stone-on-stone contact (Brown et al., 1997). In addition, the use of fiber stabilizers and polymer modified binders were found to be effective in reducing draindown and increasing the rutting resistance of SMA mixtures, respectively. Furthermore, NAPA (2002) proposed several key factors that must be met to produce durable and rut-resistant SMA mixtures, which includes: 1) selecting appropriate gradation to provide stone-on-stone contact; 2) selecting hard, cubical, and durable aggregate; 3) ensuring a minimum binder content of 6% and a design air void content of 4%; 4) requiring a minimum voids in mineral aggregate (VMA) of 17%; and 5) verifying the moisture susceptibility and draindown of the mixtures.

The specifications of different SHAs were reviewed to collect the gradation and other design requirements for 9.5-mm and 12.5-mm SMA mixtures, as shown in Tables 3 and 4. As presented in Tables 3 and 4, the aggregate gradation of 9.5-mm and 12.5-mm SMA mixtures varied from state to state, and the design air voids were specified typically with a range of 2% to 4.5%. Most of the states required a minimum VMA value of 17%, and a few states also specified the voids filled with asphalt (VFA) range. In addition, polymer modified asphalt binders were typically required by many states to enhance mixture properties of rutting resistance and durability, and the corresponding asphalt content range was also specified by the SHAs. Based on NAPA guidelines, some states also required a minimum binder content based on the combined aggregate bulk specific gravity. In general, a minimum TSR value of 0.8 and a maximum draindown value of 0.3 were required during the mix design or acceptance stages by most of the states. Meanwhile, many states also required a minimum number of passes at a specific rut depth or a maximum rut depth at certain number of wheel passes using the HWTT and APA tests. Furthermore, Texas also used the OT to characterize the cracking resistance of SMA mixtures, and a minimum OT cycle of 200 was required.

Table 3. Summary of 9.5-mm SMA Design Requirements

Gradation	**M 325**	**AL**	**GA**	**MS**	**TX**	**VA**	**UT**	**KY**	**NJ**	**MO**	**WI**	**IL**	**IN**	**PA**
1/2 inch	100	100	100	100	100	90-100	100	100	100	100	100	100	100	100
3/8 inch	70-95	90-100	70-100	90-100	70-100	65-75	90-100	--	70-95	70-95	90-100	90-100	70-95	70-95
No. 4	30-50	26-60	28-50	26-60	30-60	25-32	26-50	30-50	30-50	30-50	35-45	32-69	30-50	30-50
No. 8	20-30	20-28	15-30	20-28	20-40	15-25	20-28	20-30	20-30	20-30	18-28	32-52	20-30	20-30
No. 16	≤ 21	--	--	13-21	6-30	--	13-21	--	≤ 21	≤ 21	--	10-32	≤ 21	--
No. 30	≤ 18	--	--	12-18	6-30	--	13-18	--	≤ 18	≤ 18	≤ 18	4-15	≤ 18	--
No. 50	≤ 15	12-15	10-17	12-15	6-30	--	12-15	--	≤ 15	≤ 15	--	3-10	≤ 15	--
No. 200	8-12	8-10	8-13	8-10	4-12	9-11	8-10	8-12	8-12	8-12	8-12	4-6	8-12	8-13
Design Requirements														
Asphalt Type		76-22	76-22		76-XX	64H /64E		76-22				76-XX		64E
Asphalt Binder Content (%)	≥ 6.0	≥ 6.1	6.0-7.5	5.3-6.6	6-7	≥ 6.3		≥ 6.3	≥ 6	≥ 6	≥ 5.5 (Pbe)			
Design Air Voids (%)	4	3.5-4.0	3.5 ±0.5	4.0	4	2-4	3.5	4	3.5	4	4.5	4	4	3.5-4
VFA			70-90							≥ 75	70-80	75-80		
VMA	≥ 17	≥ 17		≥ 17	≥ 17.5	≥ 17	≥ 17	≥ 17	≥ 17	≥ 17	≥ 17	≥ 17	≥ 17	≥ 18
TSR	≥ 0.8	≥ 0.8	≥ 0.8	≥ 0.8		≥ 0.8		≥ 0.8	≥ 0.8	≥ 0.8	≥ 0.8		≥ 0.7	
Draindown (%)	≤ 0.3		≤ 0.3	≤ 0.3	≤ 0.1	≤ 0.3	≤ 0.3	≤ 0.3	≤ 0.3	≤ 0.3	≤ 0.3			≤ 0.3
Rutting Criteria (maximum rut depth or minimum passes)		4.5 mm APA	20,000 at 12.5-mm rut depth HWTT		12.5mm at 20,000 passes HWTT		10.0mm at 20,000 passes HWTT					20,000 passes at 12.5-mm rut depth HWTT		
Minimum OT cycles					200									

Table 4. Summary of 12.5-SMA Design Requirements

Gradation	**M 325**	**AL**	**GA**	**MS**	**TX**	**VA**	**UT**	**OH**	**NJ**	**MO**	**MN**	**WI**	**IL**	**IN**	**PA**	**OK**
3/4 inch	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1/2 inch	90-100	90-100	85-100	90-100	85-99	83-93	90-100	85-100	90-100	90-100	86-96	90-97	90-99	90-99	90-99	90-100
3/8 inch	50-80	26-78	50-75	26-78	50-75	≤80	45-78	50-75	50-80	50-80	60-85	58-80	50-85	50-80	50-80	65-80
No. 4	20-35	20-28	20-28	20-28	20-32	22-28	20-28	20-28	20-35	20-35	25-35	25-35	20-40	20-35	20-35	22-30
No. 8	16-24	16-24	16-24	16-24	16-28	16-24	16-24	15-24	16-24	16-24	15-25	15-25	16-24	16-24	16-24	16-24
No. 16	--	13-21	--	13-21	8-28	--	13-21	--	--	--	--	--	--	--	--	--
No. 30	--	12-18	--	12-18	8-28	15-20	12-18	--	--	--	--	≤ 18	--	--	--	--
No. 50	--	12-15	10-20	12-15	8-28	--	12-15	10-20	--	--	--	--	--	--	--	--
No. 200	8-11	8-10	8-12	8-10	8-12	9-11	8-10	8-12	8-11	8-11	8-12	8-11	8-11	8-11	8-11	8-12
Design Requirements																
Asphalt Type		76-22	76-22		76-XX	64H/ 64E					58V		76-XX		64E	76-28
Asphalt Binder Content (%)	≥ 6.0	≥5.9	5.8-7.5	5.3-6.6	6 -7	≥ 6.3		5.8-7.5	≥ 6	≥ 6		≥ 5.5 (Pbe)				≥ 6.0
Design Air Voids (%)	4.0	3.5-4.0	3.5 ±0.5	4	4	2-4	3.5	3.5	3.5	4	4	4.5	4	4	3.5-4	4
VFA			70-90							≥ 75	70-80	70-80	75-80			
VMA	≥ 17	≥ 17		≥ 17	≥ 17.5	≥ 17	≥ 17	16-19	≥ 17	≥ 17	≥ 17	≥ 16	≥ 17	≥ 16	≥ 18	≥ 17
TSR	≥ 0.8	≥ 0.8	≥ 0.8	≥ 0.8		≥ 0.8		≥ 0.8	≥ 0.8	≥ 0.8	≥ 0.7	≥ 0.8		≥ 0.7		≥ 0.8
Draindown (%)	≤ 0.3		≤ 0.3	≤ 0.3	≤ 0.1	≤ 0.3	≤ 0.3	≤ 0.3	≤ 0.3	≤ 0.3	≤ 0.3	≤ 0.3			≤ 0.3	≤ 0.2
Rutting Criteria (maximum rut depth or minimum passes)		4.5 mm APA	20,000 passes at 12.5-mm HWTT		12.5 mm at 20,000 passes HWTT		10.0 mm at 20,000 passes HWTT						20,000 passes at 10 mm HWTT			3 mm APA
Minimum OT cycles					200											

2.6 Performance Tests

This section presents a comprehensive review and summary of laboratory performance tests for OGFC and SMA mixtures. These tests can be used to evaluate key properties such as permeability, drainability, friction, macrotexture, rut resistance, and crack resistance. Furthermore, this section provides a summary of previous studies focused on the sensitivity of these tests to changes in the components of these mixtures.

2.6.1 Permeability Test

The permeability of asphalt mixtures can be determined in accordance with FM 5-565. However, permeability criteria for OGFC mixtures differ among agencies, with Mississippi requiring a minimum of 30 meters/day (Putman, 2012). Most of the states surveyed by NCAT responded that they had no permeability requirements.

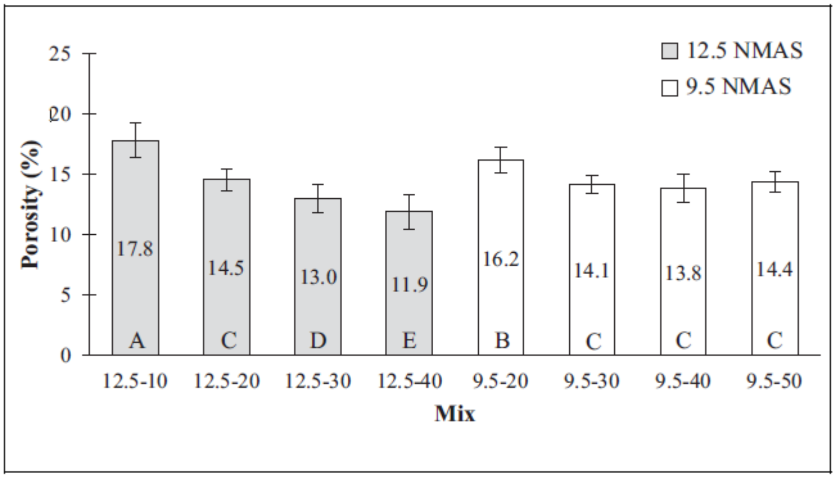
Research conducted by NCAT in 1999 recommended a minimum permeability requirement of 100 meters/day (Kandhal, 1999). Although ASTM D7064 does not require permeability testing for OGFC mixture design, it recommends a permeability rate of 100 meters/day. For OGFC mixtures used to reduce pavement noise, a minimum permeability of 60 meters/day is suggested (Alvarez et al., 2006). The European standard requires a permeability range of 8.6 to 346 meters/day (Ongel, 2007), and NCHRP Project 1-55 recommends a minimum of 50 meters/day.

Numerous studies have focused on identifying the factors that affect the permeability of asphalt mixtures, and several key factors have been identified, including asphalt content, NMAS, aggregate type, aggregate gradation, and air void content (Zube, 1962; Abdullah et al., 1998; Vardanega, 2014). These factors impact the permeability and, consequently, the performance of asphalt pavements throughout their service life.

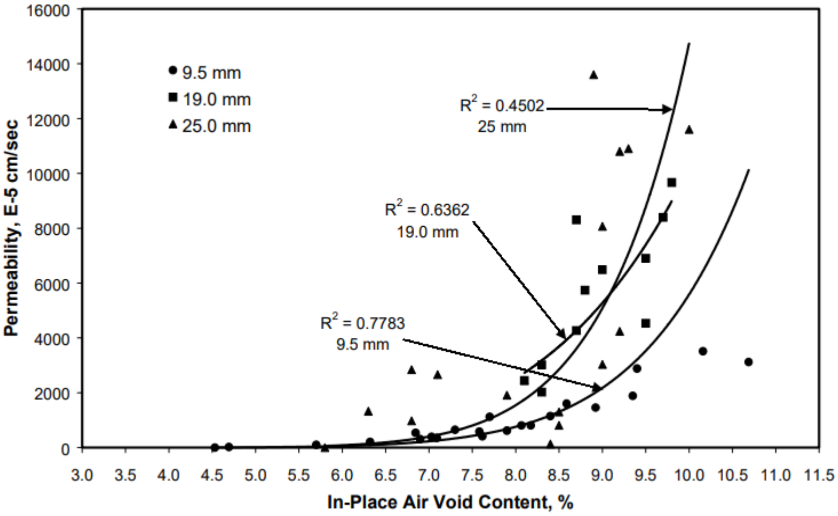
Research by Hasan et al. (2021) demonstrated that the 12.5-mm OGFC mixture provided better permeability compared to the 9.5-mm mixture. However, the larger NMAS mixture exhibited a higher potential for raveling and stripping, as evidenced by Cantabro and Indirect Tensile (IDT) test results. This finding agreed with observations made by Nekkanti et al. (2019) and Cooley et al. (2001).

It was also noted that OGFC mixture porosity decreases as the percentage passing the No. 4 sieve increases, a result of finer materials being added to the mix (Nekkanti et al., 2019). As presented in Figure 7(a) with the x-axis indicating the NMAS and the percent passing of No. 4 sieve, the porosity of 9.5-mm OGFC mixture was less sensitive to changes in the amount of material passing the No. 4 sieve, suggesting that the 9.5-mm OGFC would likely maintain sufficient permeability even with a finer gradation.

In addition, the permeability of SMA mixtures was also found to be influenced by their NMAS (Prowell et al., 2002). As shown in Figure 7 (b), the 9.5-mm SMA mixtures were less permeable than those with larger NMAS at the same air void level, and all SMA mixtures tested (regardless of NMAS) were impermeable at air voids below 6%, suggesting that mixtures with lower permeability are likely to offer enhanced durability by reducing the entrance of water and air, which can lead to moisture damage and oxidation.



(a) OGFC Porosity (Nekkanti et al., 2019)



(b) SMA Permeability (Prowell et al., 2002)

Figure 7. OGFC and SMA Permeability

2.6.2 Drainability Test

The drainability of an asphalt mixture or pavement can be evaluated with ASTM E 2380, Standard Test Method for Measuring Pavement Texture Drainage Using an Outflow Meter. In general, the outflow meter determines the flow rate of water through the surface texture and subsurface voids. In other words, the drainability is affected by the macrotexture and permeability of the asphalt mixture. Technically, asphalt mixtures with coarser macrotexture and better permeability are expected to have better drainability. Wu et al. (2013) evaluated the drainability of several OGFC mixture designs using the outflow meter with a wide range of variables, including asphalt type, layer thickness, and NMAS. As shown in Figure 8, the 9.5-mm OGFC and 12.5-mm OGFC mixtures generally showed a shorter outflow time than three 4.75-mm OGFC mixtures (designated as #4P in Figure 4), which indicated that the drainability of the mixtures was affected by the NMAS. In addition, the three 4.75-mm OGFC mixtures using different binder sources yielded statistically equivalent results, which implied that the binder types had no effect on drainability.

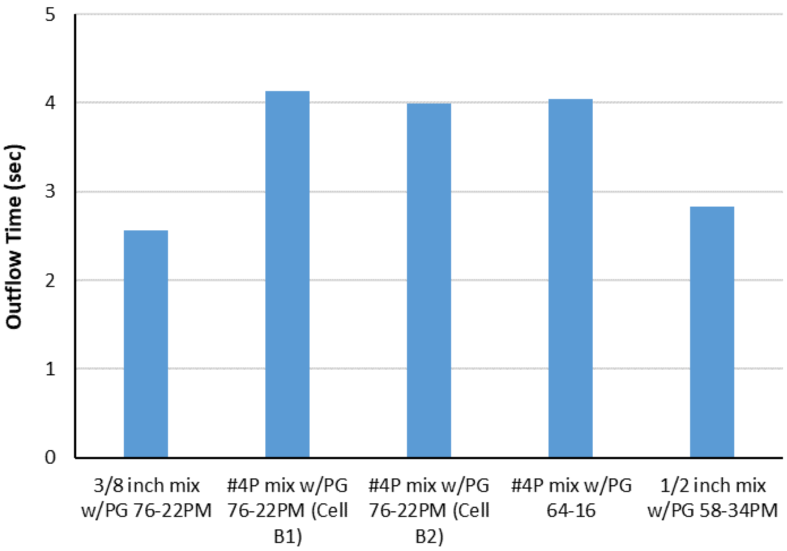


Figure 8. OGFC Drainability (Wu et al., 2013)

2.6.3 Friction and Macrotexture Tests

The dynamic friction tester (DFT) and circular track meter (CTM) are typically used to measure the frictional properties and macrotexture properties of various asphalt, respectively. In addition, the three-wheel polishing device (TWPD) was initially developed at NCAT to simulate the actual traffic abrasion of pavement (Vollor and Hanson, 2006). Later, further studies were conducted to refine the test parameters, which found a reasonable correlation between laboratory results and field results (Erukulla, 2011). The TWPD is designed to polish a 284-mm diameter path on the surface of a test slab, which is operated under wet conditions with specific test parameters of 60 rpm, 50-psi tire pressure, and a 91-lb gross carriage weight. To reduce the test variability, a new set of three TWPD tires is always installed for each test slab prior to polishing. Previous studies indicate that 80,000 to 100,000 TWPD conditioning cycles were needed to reach the terminal surface friction condition (Turner and Heitzman, 2013).

Kowalski et al. (2009) compared the friction performance among OGFC (also known as PFC), SMA and dense-graded asphalt mixtures. The laboratory results, as shown in Figure 9, showed that SMA and OGFC mixtures provided similar wet weather friction. Moreover, their friction numbers were much higher than that of dense-graded mixtures due to their coarser surface texture. McDaniel et al. (2004) investigated the early performance of three field trial projects in Indiana, which included OGFC, SMA, and conventional HMA surfaces. The friction performance of three mixtures was evaluated by the International Friction Index (IFI), which was calculated using DFT and CTM results. The IFI results showed that the OGFC provided the highest friction value, followed by SMA and HMA, and both OGFC and SMA had significantly higher friction values than the conventional HMA. The same conclusions were also obtained by Wasilewska et al. (2016), based on the DFT test results at different test speeds. As shown in Figure 10, Wu et al. (2013) investigated the effects of mixture components (i.e., binder type and NMAS) on friction using several different OGFC mix designs, and the DFT test results showed that the OGFC mixtures with larger NMAS possessed higher friction numbers. In addition, the three 4.75-mm

OGFC mixtures using different binder types showed similar friction results, which indicated that the binder type had no significant effects on the friction property.

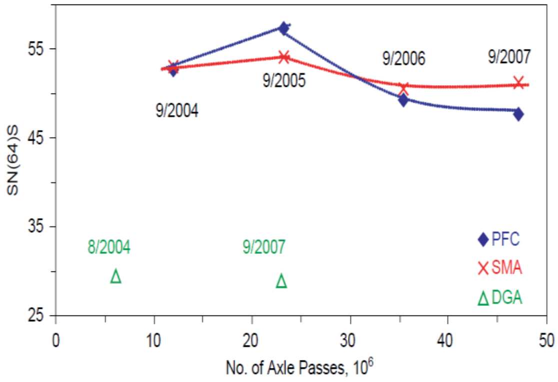


Figure 9. Wet Friction among OGFC, SMA, and DGA (Kowalski et al., 2009)

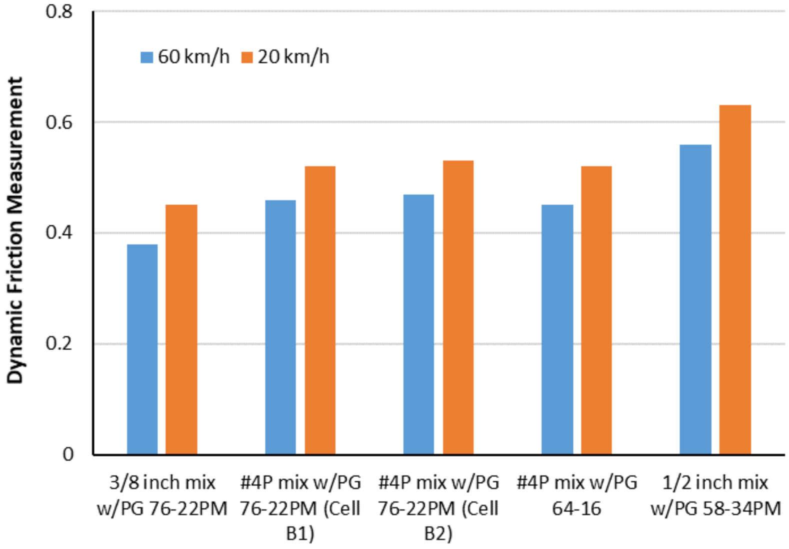


Figure 10. OGFC DFT Results (Wu et al., 2013)

Zelelew et al. (2013) measured the surface macro-texture for 12 pavement wearing surfaces located at Virginia's Smart Road Facility in Blacksburg, which included six conventional Superpave dense-graded asphalt mixtures, two SMA mixtures, two epoxy overlay surfaces, one OGFC, and one concrete surface. As shown in Figure 11, the OGFC mixture showed higher MPD values than the SMA and Superpave mixtures, and the SMA yielded slightly higher MPD results than the Superpave mixtures. In addition, Chen and Huang (2010) compared the surface macrotexture characteristics among OGFC, SMA, and dense-graded mixtures using the CTM, and the test results showed that OGFC possessed the highest MPD value, and both SMA and OGFC had significantly higher MPD values than dense-graded mixtures. Similar conclusions were also obtained by other researchers based on both laboratory and field CTM measurements (Wasilewska et al., 2016; McDaniel et al., 2004; Takahashi et al., 2015). As shown in Figure 12, Wu et al. (2013) also investigated the effects of mixture components (i.e., binder type and NMAS) on the macrotexture property using several different OGFC mix designs. The CTM test results showed that the OGFC mixture with larger NMAS had higher MPD values. As mentioned above, the MPD results generally showed a consistent trend with the friction test results regarding the effects of mixture type and NMAS.

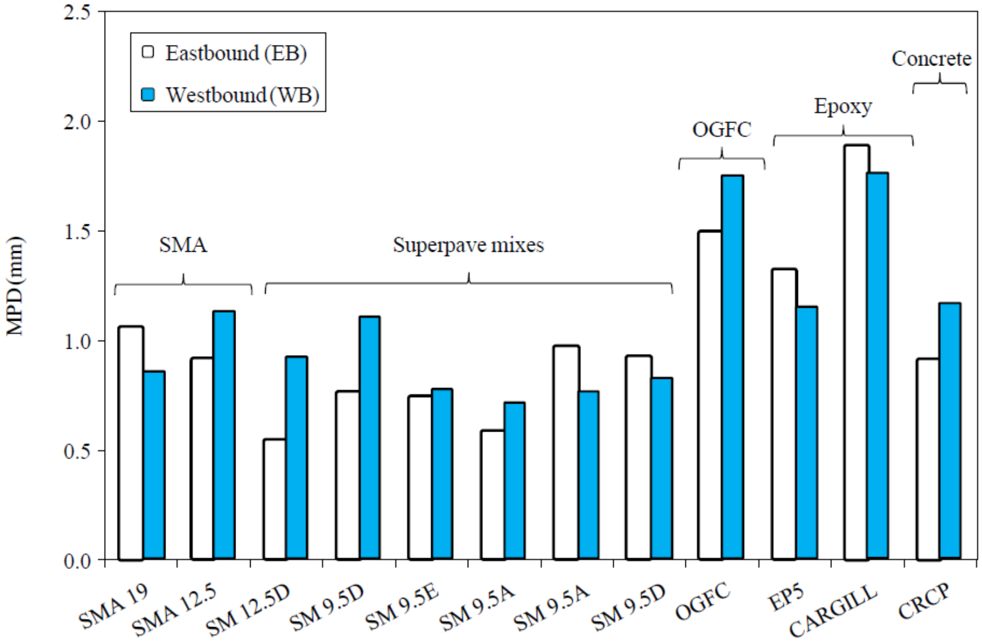


Figure 11. Macrotexture Properties among Different Mixture Types (Zelelew et al., 2013)

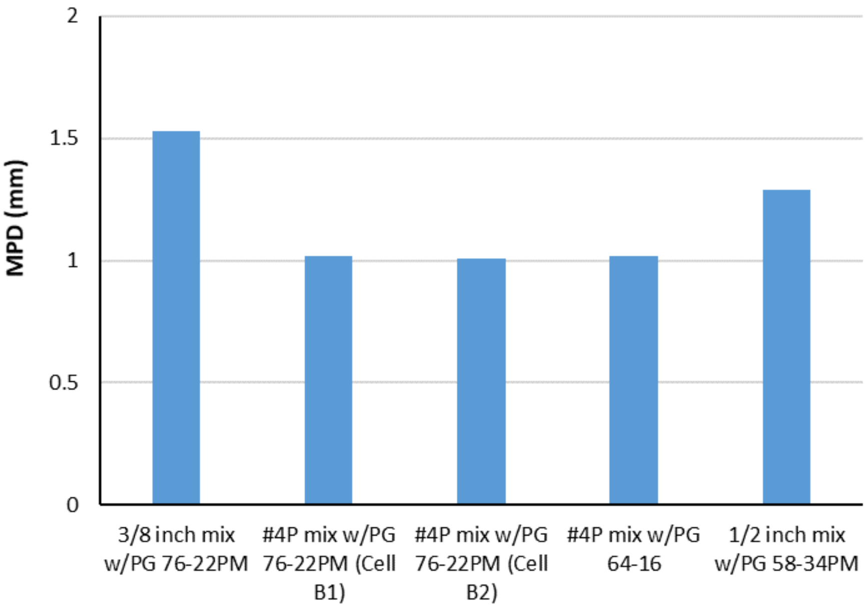
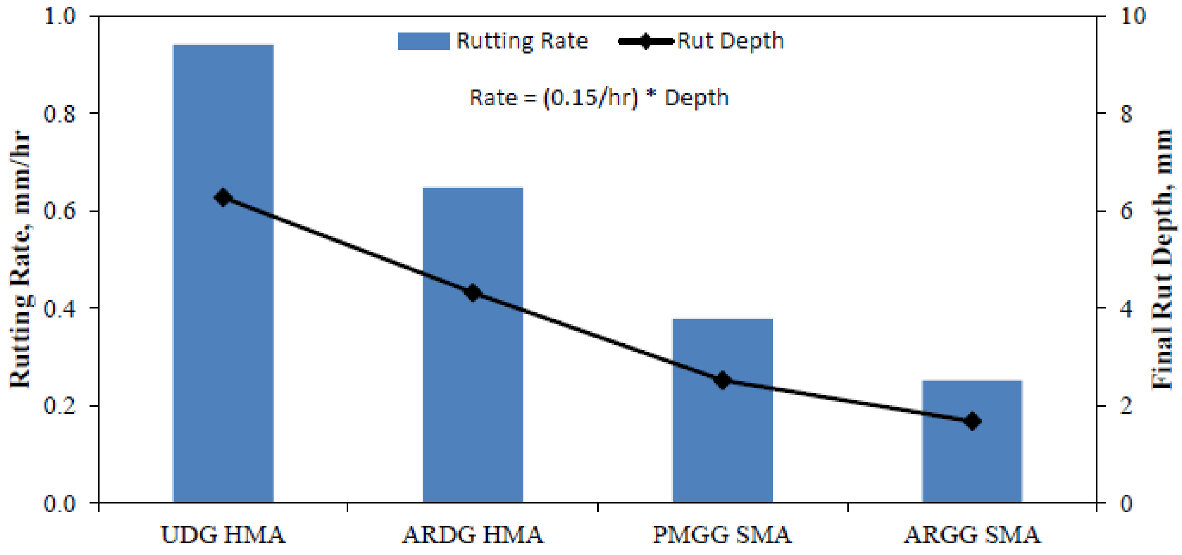


Figure 12. OGFC Macrotexture Result (Wu et al., 2013)

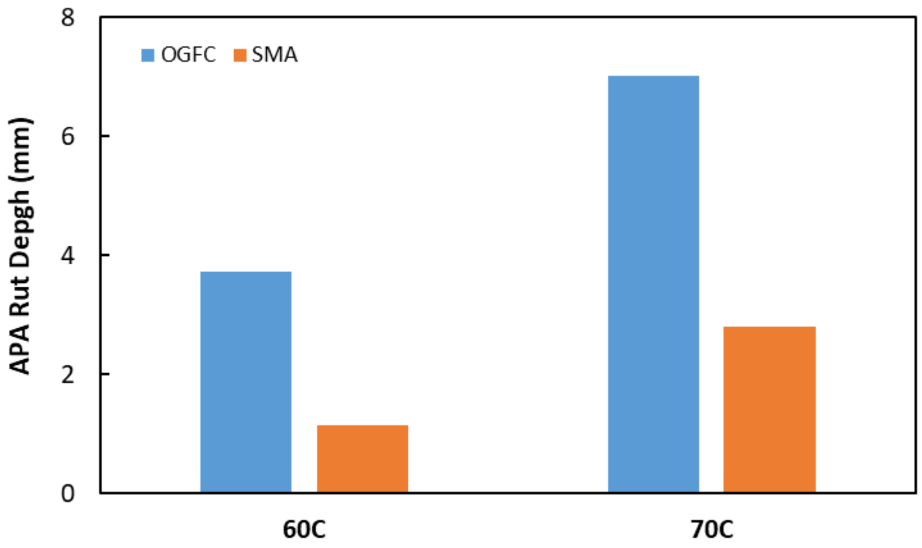
2.6.4 Rutting Tests

The two most common rutting tests are the asphalt pavement analyzer (APA) and the HWTT. The APA test is used to evaluate the rutting susceptibility of an asphalt mixture. The test temperature is set to the critical high temperature of the standard performance-graded (PG) binder identified by the agency for the project for which the HMA is intended. For circumstances where the high-temperature binder grade has been increased, the APA test temperature should remain at the standard PG binder high temperature. The HWTT determines the susceptibility of asphalt mixtures to both stripping and rutting, and the test specimens are submerged and conditioned in a water bath for 30 minutes prior to testing.

SMA is known as a tough, stable, and rut-resistant mixture due to its stone-on-stone contact and rich mortar content, and it generally shows better rutting resistance than conventional dense-graded mixtures (NAPA, 2002). As shown in Figure 13(a), Omer (2014) compared the rutting resistance of SMA and HMA surface mixtures using the HWTT, which included unmodified dense-graded HMA (UDG HMA), asphalt-rubber dense-graded HMA (ARDG HMA), polymer modified gap-graded SMA (PMGG SMA) and asphalt-rubber gap-graded SMA (ARGG SMA). The test results indicated the SMA mixtures had superior rutting resistance than conventional dense-graded mixtures. Similar conclusions were also obtained by Batioja-Alvarez et al. (2020) based on the laboratory HWTT and accelerated pavement testing (APT) devices results. In addition, as shown in Figure 13(b), Wang (2012) compared the rutting resistance of SMA and OGFC mixtures using the APA at different test temperatures, and the test results indicated that the SMA also yielded much better rutting resistance than OGFC mixtures at both temperatures. Gu et al. (2018) observed that OGFC mixtures had less rutting resistance than dense-graded mixtures due to the high air void and binder contents. Although the OGFC showed less rutting resistance due to its high air void content, the use of asphalt binders with high viscosity, appropriate gradation composition, and addition of fiber could improve OGFC’s rutting resistance (Wang, 2012).



(a) SMA and HMA (Omer, 2014)



(b) OGFC and SMA (Wang, 2012)

Figure 13. Rutting Comparison among OGFC, SMA, and HMA

As described above, the APA test only evaluates the rutting resistance of an asphalt mixture, while the HWTT is able to assess the mixture's moisture susceptibility and rutting resistance. In addition, the HWTT is more often used for OGFC and SMA mixtures, as compared to the APA (Arámbula-Mercado et al., 2019; Gu et al., 2020; Batioja-Alvarez et al., 2020). In addition, the commonly used HWTT acceptance threshold is that asphalt mixtures with a high-temperature PG grade of 76 or higher asphalt binder should have no less than 20,000 passes before reaching a 12.5-mm rut depth when tested at 50°C (Watson et al., 2018, West et al., 2018). The APA is typically used as a "go/no go" test to ensure that mixtures susceptible to rutting are not placed on heavily trafficked highways. Based on a correlation between APA results and rutting on the NCAT Test Track, an APA criterion of 5.5 mm was established for heavy traffic pavements

(West et al., 2012). In addition, the current criterion for Federal Aviation Administration (FAA) airport asphalt mixtures is set as a maximum of 10 mm APA rut depth at 4,000 passes, with a hose pressure of 250 psi and a temperature of 64°C (Garg, 2018). Alkuime and Kassem (2020) investigated the correlation between HWTT rut depth at 20,000 passes and APA rut depth at 8,000 passes using 33 asphalt mixtures with a wide range of aggregate NMAS, binder type, binder content, and recycled binder content ratio, which covered plant-produced mixtures, laboratory-prepared mixtures, and field cores. The HWTT and APA rut depth results of 33 mixtures were extracted and plotted against each other, and the linear equation was used to fit the results, as shown in Figure 14. The coefficient of determination (i.e., R^2) is higher than 0.7, which indicates a good linear correlation between HWTT and APA rut depth results although HWTT rut depths are slightly more than twice that of the APA.

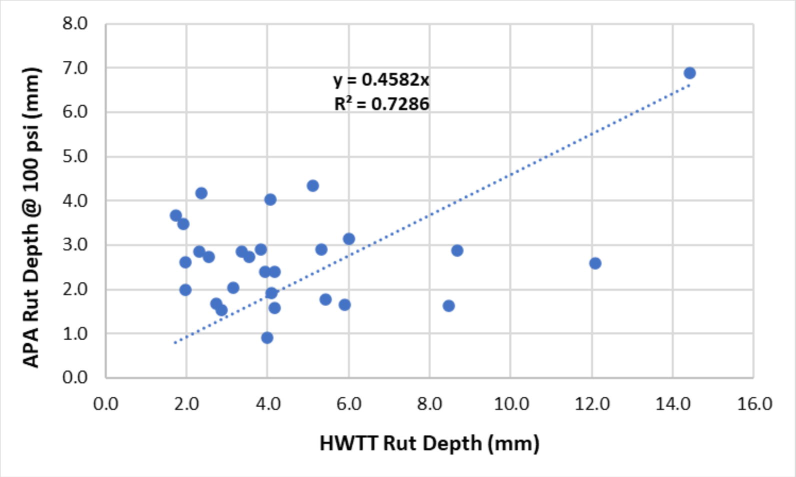
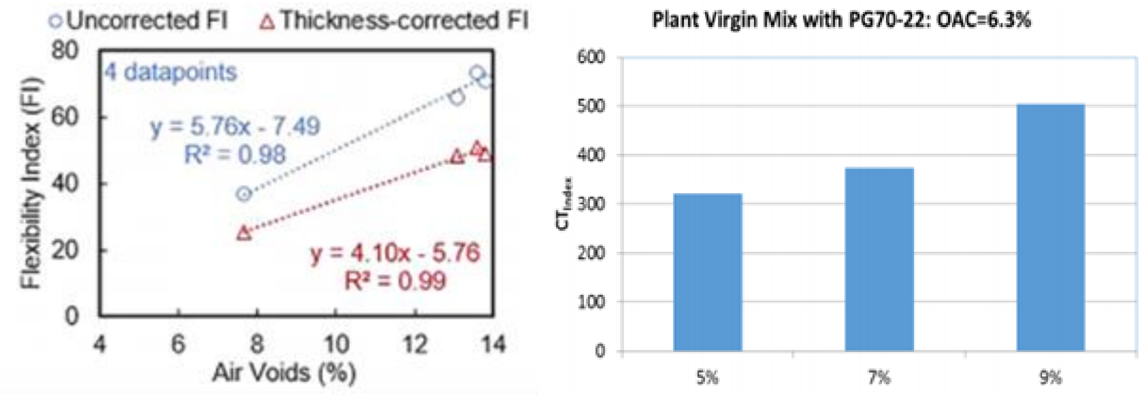


Figure 14. Correlation between HWTT and APA Rut Depth (Alkuime and Kassem, 2020)

2.6.5 Cracking Tests

A number of laboratory cracking tests have been developed to characterize the cracking resistance of asphalt mixtures, and many of them have been evaluated by SHAs for mixture design and acceptance testing. In 2015, NCAT initiated an experiment to validate the laboratory cracking tests using actual NCAT Test Track cracking performance. The NCAT Cracking Group Experiment results has shown that the Illinois Flexibility Index Test (I-FIT), Indirect Tension Asphalt Cracking Test (IDEAL-CT) and Overlay Test (OT) all showed good correlation with field cracking performance at NCAT Test Track (Chen, 2020).

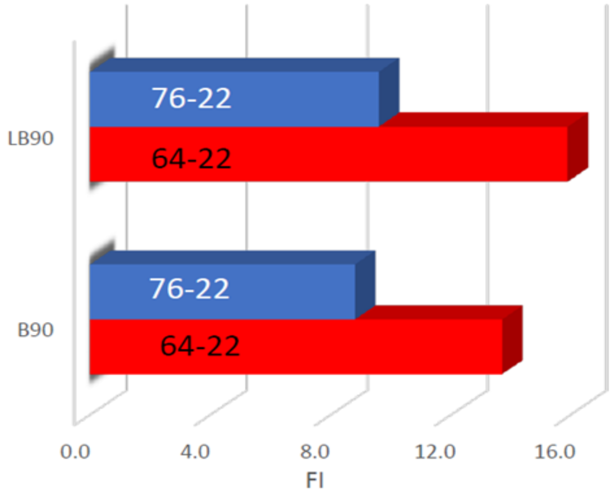
Based on the NCAT Cracking Group Experiment results, the OT parameters (N_f and CPR) had very strong correlations with I-FIT parameter (FI) and IDEAL-CT parameter (CT_{Index}), and all four parameters correlated with the actual field cracking performance well (Chen, 2020). However, the FI and CT_{index} determined from the I-FIT and IDEAL-CT tests show a counterintuitive trend regarding the change in cracking resistance of asphalt mixtures at different air void levels. As shown in Figure 15, for the same mixture type, increasing the target air voids for the test specimens yields higher FI and CT_{index}, indicating that higher air void contents improve the cracking resistance of an asphalt mixture (Batioja-Alvarez et al., 2019; Zhou et al., 2017). This result contradicts field observations that asphalt pavements with higher in-place air void contents (or lower in-place density) are more susceptible to cracking. While research has been conducted to correct the effect of air voids on the FI and CT$_{\text{index}}$ results, no reliable methods have been proposed and adopted.



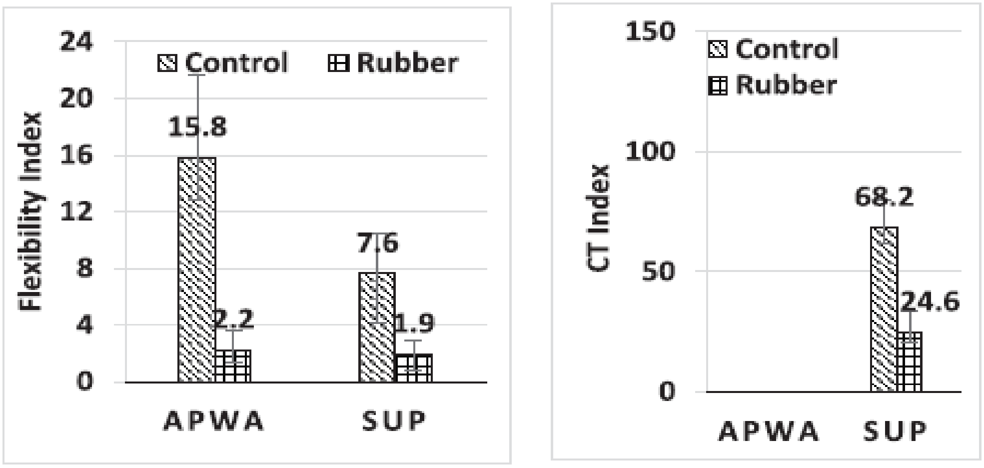
(a) FI vs. Air Voids (Batioja-Alvarez et al., 2019) (b) CT$_{\text{Index}}$ vs. Air Voids (Zhou et al., 2017)

Figure 15. Influence of Air Void Content on FI and CTIndex of Asphalt Mixtures

In addition, I-FIT and IDEAL-CT test results also showed that PMA mixtures did not always show better cracking resistance than unmodified mixtures, which indicated that the additional cost of polymer modification could not provide the expected return on investment. As shown in Figure 16 (a), Fort (2018) evaluated the mixtures from two projects (LB90 and B90) prepared with SBS modified asphalt and unmodified asphalt, and the test results indicated that mixtures prepared with SBS modified asphalt showed lower FI values than the mixtures prepared with unmodified asphalt with the same binder content and aggregate gradation. Hanz (2017) compared the FI results of unmodified asphalt mixtures with three polymer modified asphalt mixtures (SBS and two ElvaloyTM), and similar conclusions were also obtained. As presented in Figure 16 (b), two dense-graded mixtures were designed conform to the American Public Works Administration (APWA) and Superpave (SUP) with rubber modified asphalt and unmodified asphalt. Test results showed that both asphalt mixtures fabricated with rubber modified asphalt showed lower FI and CTIndex values than the control mixtures using unmodified asphalt (Rath et al., 2021). In general, these results contradicted the existing literature and the superior field performance of many existing projects using PMA. Compared with the I-FIT and IDEAL-CT tests, the OT was proved to be able to discriminate the effects of air voids, recycled materials, rejuvenators, modified binders on the cracking resistance of asphalt mixtures (Chen, 2020; Mogawer et al., 2011; Mogawer et al., 2013; Im et al., 2014; Luo et al., 2015; Tran et al., 2016; Xie et al., 2017).



(a) Fort, 2018



(b) Rath et al., 2021

Figure 16. Influence of Polymer Modified Asphalt on FI an CT$_{\text{Index}}$

2.7. Summary

This chapter provided an overview of OGFC in Florida, including its history and the latest studies sponsored by FDOT. It also discussed the existing OGFC and SMA designs used by different SHAs. The NCHRP project 01-55 studied the OGFC mix design modification, and its impact on mixture properties was thoroughly analyzed. Additionally, this section looks at the various laboratory performance tests used for evaluating OGFC and SMA mixtures. The key findings from the literature review are summarized below:

- Based on the results of the FE modeling analysis, raveling is due to material damage rather than structural damage, which is greatly influenced by the binder content and air voids. A review of the field performance of OGFC mixtures in Florida showed that the durability issues associated with OGFC mixtures were significantly affected by the effective asphalt content of the mixture. Finer gradations of OGFC mixtures showed better durability and resistance to cracking than coarser mixtures. Additionally, using high polymer binder and anti-strip additives such as hydrated lime and liquid anti-strip can help improve the durability and cost-effectiveness of OGFC mixtures.

- As per the OGFC specifications of the SHAs, the air voids required were generally greater than 15%. The minimum TSR value was set to 0.8, the maximum drain-down value was 0.3, and the maximum Cantabro loss value was between 15% and 30%.
- NCHRP Project 01-55 evaluated various modifications in OGFC mix design by varying the binder and BHF contents. The test results showed that the air voids decreased with the increase of binder content and BHF content. The film thickness, on the other hand, increased with the increase in binder content and decreased with the decrease in BHF content. Additionally, the OGFC mixtures with higher binder and BHF contents displayed better durability. In general, the use of additional BHF improved the rutting and cracking resistance and had a negligible influence on the moisture susceptibility.
- Based on the SMA specifications from several SHAs, most states require a minimum VMA value of 17%, and a few states specified the VFA range. Moreover, many states require the use of polymer-modified asphalt binders. Generally, most states require a minimum TSR value of 0.8 and a maximum draindown value of 0.3.
- The drainability and permeability of mixtures are influenced by various factors such as asphalt content, aggregate type and NMAS, aggregate gradation, and air void content. The minimum permeability requirements for OGFC mixtures differ by SHAs. NCHRP Project 01-55 recommends a threshold of 50 meters/day. Generally, OGFC and SMA mixtures exhibit greater friction value and higher macrotexture than the conventional dense-graded mixture. Moreover, OGFC and SMA mixtures containing a larger NMAS have better drainability and permeability than those containing a smaller NMAS.
- The parameters of OT (N_f and β), FI, and CT_{Index} have a strong correlation with actual field cracking performance data. However, the test results for I-FIT and IDEAL-CT show unexpected trends concerning how air voids and polymer-modified asphalt binders affect the cracking resistance of asphalt mixtures. These trends contradict the actual field performance.

3. EXPERIMENTAL DESIGN

This chapter presents the experimental design of the project to (1) evaluate the impact of utilizing a finer 9.5-mm NMAS gradation and HP binder to improve the durability of the asphalt mixtures and (2) develop alternative friction courses that are more durable in suburban environments while providing adequate drainability, friction, and texture properties. These mixtures were compared with the FC-5 mixtures currently used in Florida and SMA mixtures designed from the same component materials.

Four different mix designs were evaluated to fulfill the research objectives, including FC-5, 9.5-mm OGFC, 12.5-mm SMA, and one alternative friction mixture. The experiment plan of this project includes four critical steps, as shown in Figure 17.

- Step 1: Select two asphalt binders (PG 76-22 and HP Binder) and two aggregate types, including Granite (GRN) and Limestone (LMS), for the experimental plan.
- Step 2: Develop mix designs and evaluate FC-5, 9.5-mm OGFC, and 12.5-mm SMA mixtures with two asphalt binders to assess the impact of utilizing a finer 9.5-mm NMAS gradation and HP binder and to establish the baseline performance data for the AFC design.
- Step 3: Develop mix designs and conduct performance evaluation for the AFC mixtures.
- Step 4: Conduct performance comparisons and cost analysis.

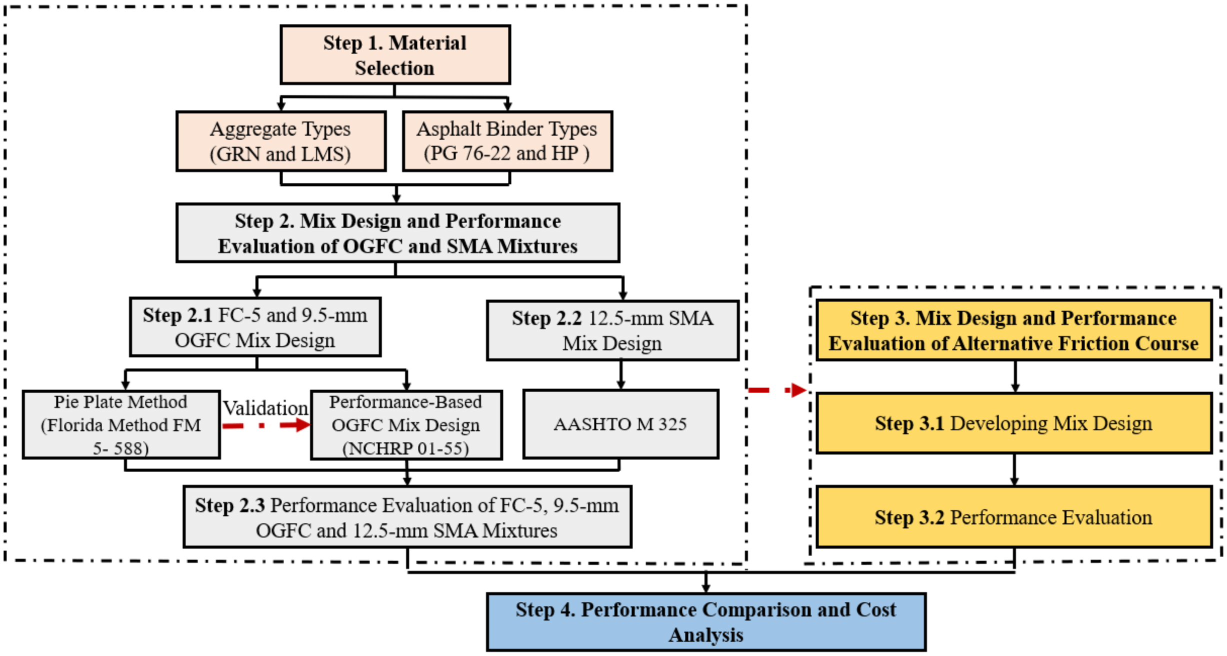


Figure 17. Experiment Plan

3.1 Materials Selection

Two aggregate types (GRN and LMS) and two asphalt binders (PG 76-22 and HP) were selected for this project, which included:

- Asphalt Binder: PG 76-22 from Associated Asphalt in Tampa, Florida, and HP from Gardner Asphalt in Tampa, Florida.

- Aggregates: Georgia GRN from Junction City Mining and Florida LMS from White Rock Quarries in Miami, Florida.

Hydrated lime was incorporated into all the GRN mixtures at a dosage rate of 1.0% by weight of the total aggregate to prevent the mixture from stripping. Additionally, two types of fibers (mineral and cellulose fibers) were used, and both fibers were pre-blended with the aggregate before adding binder during the mixing process. The mineral fiber, at 0.4% by weight of the mixture, was used to determine the OBC for the FC-5 and 9.5-mm OGFC mixtures. The OBC of FC-5 and 9.5-mm OGFCs were chosen based on the binder drainage level. Any binder content that showed excessive drainage evidence was not selected as the OBC. However, when using cellulose fiber, there were no significant differences in drainage levels among different binder contents, even at higher contents. Therefore, cellulose fiber was not used for determining the OBC for FC-5 and 9.5-mm OGFC mixtures. However, it was used with a dosage of 0.3% for specimen fabrication and performance evaluation for all the mixtures, including FC-5, 9.5-mm OGFC, 12.5-mm SMA, and the AFC in this study.

3.2 Mix Design and Performance Evaluation

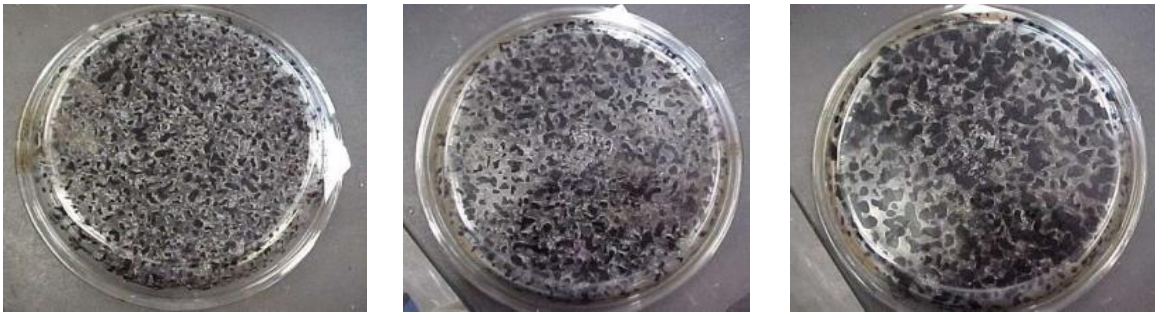
3.2.1 FC-5 and 9.5-mm OGFC Mix Design

The FC-5 and 9.5-mm OGFC mix design were developed in two steps: (1) gradation design and (2) OBC determination. The blend gradation of FC-5 and 9.5-mm OGFC mixtures were determined following Florida and Georgia state specifications, respectively, as shown in Table 5. The 9.5-mm OGFC gradation was determined following the Georgia state specifications because it is not in the Florida specifications and similar aggregate sources used in both states.

Table 5. FC-5 and 9.5-mm OGFC Gradation Requirements

Sieve	FC-5	9.5-mm OGFC
3/4"	100	100
1/2"	85 - 100	100
3/8"	60 - 75	85 - 100
#4	15 - 25	20 - 40
#8	5 - 10	5 - 10
#200	2 - 5	2 - 4

Once the blend gradation was determined, the preliminary OBCs of four mixture designs (2 mix types × 2 aggregate types) were determined using the pie plate method described in Florida Method (FM) 5-588. In this method, at least three 1200-g aggregate batches and PG 67-22 binder were heated for at least two hours in an oven at 320°F ± 5°F. Subsequently, these aggregate batches were mixed with 0.4% mineral fiber and virgin binder at different contents, and the loose mix samples were carefully transferred from the mixing bowl to a pie plate after mixing. The pie plate containing loose mix samples was then conditioned at 320°F ± 5°F for one hour before cooling to room temperature. The OBC was then determined by visually checking the pictures of the pie plate bottom surface with and without loose mixtures. The first approach was to take photos of pie plates with loose mix samples, following FM 5-588, but the quality of the pictures may be impacted by the glare caused by the glassy and black color of asphalt mixtures. Another method was to take photos after removing the loose mix samples by placing the empty pie plate on a white background, enabling the black footprint of the asphalt binder to be distinguished. Subsequently, the binder content of the sample that exhibited sufficient bonding without any evidence of excessive drainage of asphalt binder was selected as the OBC, as shown in Figure 18. Finally, the preliminary OBC was further validated by the performance-based OGFC mixture design procedure developed in NCHRP Project 01-55 with the minimum air voids (vacuum seal method) of 15% and maximum Cantabro mass loss of 20% (Watson et al., 2018; Tran et al., 2021).



(a) 5.3% (b) 5.8% AC (c) 6.3% AC

Figure 18. Reference Pie Plate Pictures of FC-5 Mixtures with PG 67-22 at Different Binder Contents: (a) 5.3% (Insufficient Bonding), (b) 5.8% (Sufficient Bonding), (c) 6.3% (Excessive Drainage) (FM 5-588)

3.2.2 12.5-mm SMA Mix Design

SMA mixture typically has superior durability than OGFC mixtures but is impermeable. This study requires durability and drainability for pavements in suburban environments. Compared to the 9.5 SMA mixture, the 12.5-mm SMA mixture generally has greater macrotexture, which was selected to maximize drainability in this study. Before the mix design, the compaction effort with the Superpave gyratory compactor (SGC), referred to as N_{design}, needed to be determined to match a 50-blow Marshall compaction. For a given blend gradation and binder content, three sets of design pills were prepared for both GRN and LMS using 50 Marshall blows, 35 SGC gyrations, and 50 SGC gyrations. The air voids of the design pills prepared at different compaction levels were then measured. As a result, the specimen prepared with 35 SGC gyrations yielded the closest air voids to those prepared at 50 Marshall blows. Thus, a N_{design} of 35 SGC gyrations was selected for the SMA mix design in this study.

After determining the N_{design}, the 12.5-mm SMA design was developed with two steps: gradation design and OBC determination. The blend gradation of the 12.5-mm SMA design was developed following the Georgia DOT specification, as shown in Table 6. Subsequently, the design pills prepared at multiple binder contents were prepared using the selected N_{design}, and the volumetrics were then measured, including air voids, VMA, and the voids in coarse aggregate (VCA) of the mixture (VCA_{mix}). Based on AASHTO R 46 and M 325, the binder content at 4% air voids was selected as the OBC, which was further validated using the VMA and VCA requirements. The air void, VMA, and VCA requirements for the final gradation and OBC are summarized in Table 6. The minimum VMA was established at 17%, and the VCA of the aggregate blend (VCA_{drc}) was designed to be equal to or higher than VCA_{mix} to ensure stone-on-stone contact. The VCA_{drc} and VCA_{mix} were determined using the following equations:

$$VCA_{drc} = \frac{G_{ca} \times \gamma_w - \gamma_s}{G_{ca} \times \gamma_w} \times 100 \tag{1}$$

where:

G_{ca} = bulk specific gravity of the coarse aggregate
r_w = unit weight of water
r_s = unit weight of coarse aggregate fraction in the dry rodded condition

$$VCA_{mix} = 100 - \frac{G_{mb}}{G_{ca}} \times P_{ca} \tag{2}$$

where:

G_{ca} = bulk specific gravity of the coarse aggregate
G_{mb} = bulk specific gravity of the compacted mix
P_{ca} = percent of coarse aggregate by weight of the mix.

Table 6. Summary of 12.5-mm SMA Mix Design Requirements

Sieve	Control Points
3/4"	100
1/2"	85-100
3/8"	50-75
No. 4	20-28
No. 8	16-24
No. 50	10-20
No. 200	8-12
Design Criterions	**Requirements**
Design Air Voids (%)	4
N_{design} (Gyrations)	35
VMA (%)	≥ 17
Stone on Stone Contact	$VCA_{drc} \geq VCA_{mix}$

3.2.3 Mixture Performance Evaluation

Upon the completion of the mix designs, a comprehensive laboratory characterization was conducted on all the FC-5, 9.5-mm OGFC, and 12.5-mm SMA mixes prepared with two aggregate types (GRN and LMS) and two asphalt binders (PG 76-22 and HP), as shown in Figure 19.

As shown in Figure 19, a series of laboratory tests were performed to evaluate the mixture permeability, rutting resistance, durability, cracking resistance, texture, friction, and drainability. For FC-5 and 9.5-mm OGFC mixtures, all the tests were performed on the design pills (cylinder specimen) with 150 mm diameter prepared at 50 gyrations except for texture, friction, and drainability, which were evaluated using slab specimens. For the 12.5-mm SMA mixtures, all the cylinder and slab specimens were compacted to the target air voids of 5.5 ± 0.5% after trimming.

Additionally, all the loose mix samples were short-term aged (STA) at compaction temperature for two hours per FDOT’s suggestion prior to the specimen preparation for all the tests, and durability and cracking tests were also conducted on the long-term aged (LTA) compacted specimens at two conditions (an additional 1,000- or 2,000-hours specimen aging) in NAWS. Finally, the test results were analyzed to compare the FC-5, 9.5-mm OGFC, and 12.5-mm SMA mixtures. The details of laboratory tests and aging procedures are summarized in Section 3.5.

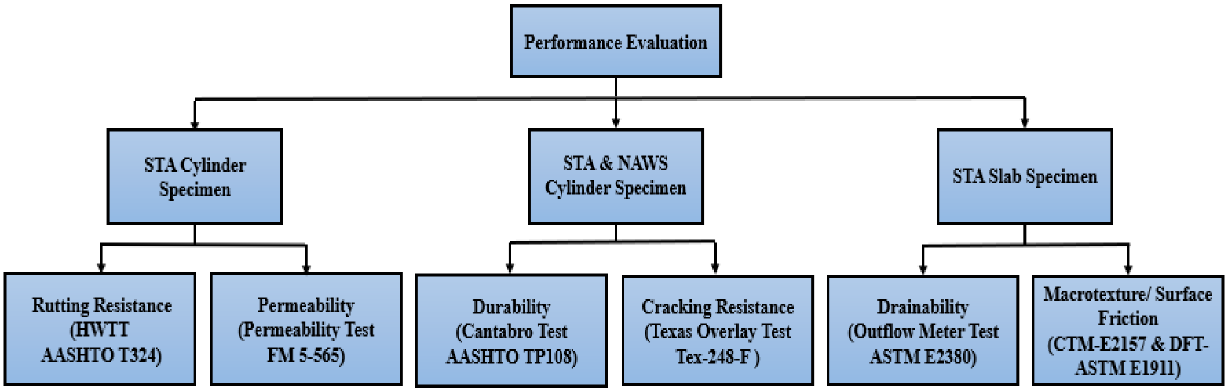


Figure 19. Laboratory Testing Plan

3.3 Mix Design and Performance Evaluation of the Alternative Friction Course

3.3.1 Developing an Alternative Friction Course

In addition to the FC-5, 9.5-mm OGFC, and 12.5-mm SMA mixtures, an AFC was tested for each aggregate type. The AFC was developed based on the FC-5 and 12.5-mm SMA mixtures, which shared the same NMAS and similar coarse aggregate structures.

The AFC mixtures were designed by focusing on balancing permeability and durability performance. The main objective was to create a mixture that would outperform FC-5 in terms of durability while also exceeding the permeability of the 12.5 SMA mixture. To achieve this goal, the maximum Cantabro loss of the alternative friction mixtures was targeted at 10%, significantly lower than the maximum allowable value of 20% for FC-5 mixtures. At the same time, the minimum permeability of the AFC was selected to be higher than that of 12.5-mm SMA mixtures.

Figure 20 shows the FC-5 and 12.5-mm SMA gradations with similar coarse aggregate structures (i.e., percent passing) on 3/4-in, 1/2-in, and 3/8-in sieves. However, the 12.5-mm SMA blend had higher percent passings on the smaller sieves (i.e., #4, #8…), indicating finer gradation. A finer gradation could enhance the durability but reduce the permeability of the asphalt mixture. Therefore, the gradation of the AFC should be designed to be finer than the FC-5 mixture to improve durability and coarser than the 12.5-mm SMA mixture to enhance permeability. In other words, the gradation curve of the AFC mixture should be located between FC-5 and 12.5-mm SMA gradations, as illustrated in Figure 20. In this study, two trial blends were developed to keep the percent passings on the 3/4-in, 1/2-in, and 3/8-in sieves consistent with those of FC-5 while increasing the percent passings of the smaller sieves by changing the stockpile percentage of FC-5 blend.

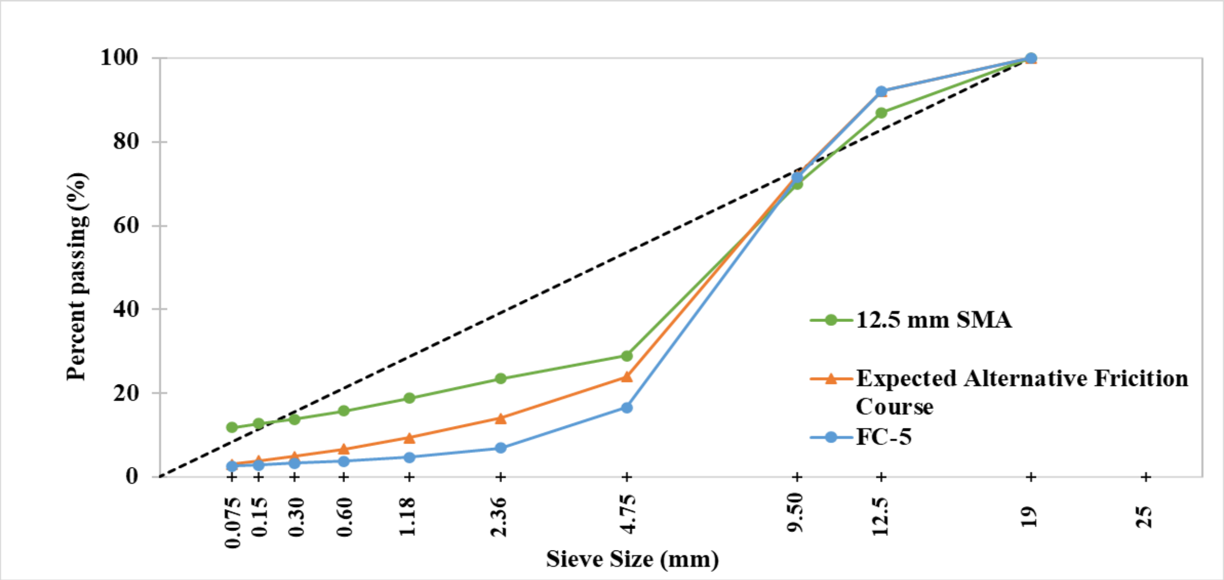


Figure 20. Expected Alternative Friction Course Gradation

Moreover, as for the 9.5-mm gradation and a higher binder content resulted in improved durability but reduced permeability of the OGFC mixtures. Therefore, the binder content of the AFC mixture should be higher than that of the FC-5 mixture to improve durability but should be manageable to ensure the mixture is still porous. For this reason, the binder content was increased by 0.2 to 0.3% compared to the FC-5 mix design. For each trial blend, multiple samples were prepared with different binder contents. These samples were then tested to evaluate their durability and permeability using the Cantabro and permeability tests. The mixture that met the proposed durability and permeability criteria would be selected as the final AFC design for each aggregate type. Note that the PG 76-22 binder was used throughout the design process, considering that HP mixtures typically had better durability and equivalent permeability compared to the corresponding mixtures prepared with the PG 76-22 binder.

3.3.2 Performance Evaluation of Alternative Friction Course

The performance of the AFC mixture was evaluated using the same testing plan described in section 3.2.3. To assess the performance of the AFC mixtures, the Florida Permeability Test, HWTT, Cantabro Test, Texas OT, CTM, DFT, and Outflow Meter Test were used to evaluate permeability, rutting resistance, durability, cracking resistance, texture, friction, and drainability. The permeability and rutting resistance tests were carried out on unconditioned compacted specimens, while durability and cracking resistance tests were performed on both unconditioned and NAWS-conditioned compacted specimens. The friction and macrotexture tests were conducted on compacted slabs before and after TWPD polishing. All the tests were performed on the cylinder specimen with a 150 mm diameter prepared at 50 gyrations, except for texture, friction, and drainability evaluation, which used slab specimens.

3.4 Performance Comparison and Cost Analysis

After completing the testing plan, the data were analyzed using both graphical value and statistical analyses to determine (1) the impact of using HP on mixture performance and (2) the rankings of the four mixtures, including FC-5, 9.5-mm OGFC, 12.5-mm SMA, and the AFC mix, based on their laboratory test results. The student's *t-test* at a significant level of 0.05 was used for the statistical analysis. In addition, the Games-Howell group analysis at a significant level of 0.05 was used to rank the mixtures in terms of permeability, drainability, raveling, and cracking resistance. Additionally, a cost analysis was conducted to determine the additional cost when replacing the FC-5 mix with the other three mixture types in Florida.

3.5 Laboratory Mixture Conditioning and Testing Methods

3.5.1 NCAT Accelerated Weathering System (NAWS)

Moisture damage and weathering can significantly reduce the durability and cracking resistance of asphalt mixtures. This study used the Accelerated Weathering System (AWS) per ASTM D4799 to evaluate the weathering resistance of the FC-5, 9.5-mm OGFC, 12.5-mm SMA, and AFC mixtures. The AWS chamber has controllable cycles that can simulate various environmental conditions such as rain, relative humidity, sunlight, temperature, and combinations of these factors. It simultaneously simulates the long-term exposure of asphalt pavement materials to moisture, heat, and ultraviolet light, as shown in Figure 21. Previous research has shown that 3,000 hours (four months) in the AWS is equivalent to about 12 years of weathering in the field (Grzybowski, 2013). In another study, Gu et al. (2020) used the AWS to condition OGFC mixtures for different durations and found that increasing conditioning times significantly reduced the durability of the OGFC mixtures for GRN mixtures when hydrated lime was not used. However, when hydrated lime was used, most aging occurred in the first 1,000 hours of NAWS conditioning, with minimum changes between 1,000 and 2,000 hours of NAWS conditioning. Hence, in this study, Cantabro specimens underwent NAWS conditioning for 1,000 and 2,000 hours to verify the impact of both 1,000 and 2,000 hours of NAWS conditioning on the two FC-5 mixtures considered in this study: one with GRN aggregate and hydrated lime and the other with Florida LMS aggregate. After the Cantabro testing was completed, it was confirmed that most of the aging occurred in the first 1,000 hours of NAWS conditioning, so the OT specimens were only conditioned for 1,000 hours in NAWS. The results were then compared to those of specimens without NAWS conditioning to assess the impact of weathering on the durability and cracking resistance.

Figure 21. NCAT Accelerated Weathering System

3.5.2 Cantabro Test

The durability of asphalt mixtures was evaluated using the Cantabro test according to AASHTO TP 108. Three replicate samples were tested for each mixture. The specimens were conditioned in an environmental chamber for at least four hours at 25 ± 1°C (77 ± 2°F) prior to testing. After conditioning, each specimen was placed inside the Los Angeles Abrasion drum without the charge of steel spheres and subjected to 300 revolutions at a speed of 30 to 33 revolutions per minute. Finally, the weight of the specimen was measured after removing the loose mix particles, and the Cantabro loss was calculated as the difference between the initial and final weight divided by the initial weight, as shown in Equation 3. A lower Cantabro loss value indicates better durability and raveling resistance compared to a higher Cantabro loss value.

$$\mathit{Cantabro}\ \text{Loss} = \frac{M_{initial} - M_{final}}{M_{initial}} \times 100 \qquad (3)$$

where:

$M_{initial}$ = the initial mass of the specimen, gram
M_{final} = the final mass of the specimen, g.

3.5.3 Texas Overlay Test

The OT test was performed using the Asphalt Mixture Performance Tester (AMPT) as per Tex-248-F to determine the intermediate temperature cracking resistance of the asphalt mixtures. Each gyratory design pill was trimmed to obtain one OT specimen with dimensions of 150 mm × 76 mm × 38 mm. For each mix, five specimens were tested at one aging condition. The OT specimen obtained was glued to the OT fixture and conditioned in the chamber at 25 ± 1°C (77 ± 2°F) for 2 hours before testing. During the test, one side of the fixture was fixed while the other moved in a displacement-controlled mode, applying a sawtooth waveform once per 10-second cycle (5 seconds of loading, 5 seconds for unloading). The test was performed at 25°C with a maximum displacement of 0.635 mm per cycle. The peak load of each cycle was measured. The test was terminated when the peak load reached 7% of the initial peak load or the number of cycles reached 1,200. The cycle recorded at the test termination was considered the number of cycles to failure (N_f). A power equation was used to fit the peak load versus the number of cycles curve, and the power coefficient (absolute value) of the power equation was determined as the Crack Progression Rate (CPR), as shown in Figure 22. Generally, mixtures with higher N_f and lower CPR values are expected to have better cracking resistance than those with lower N_f and higher CPR values.

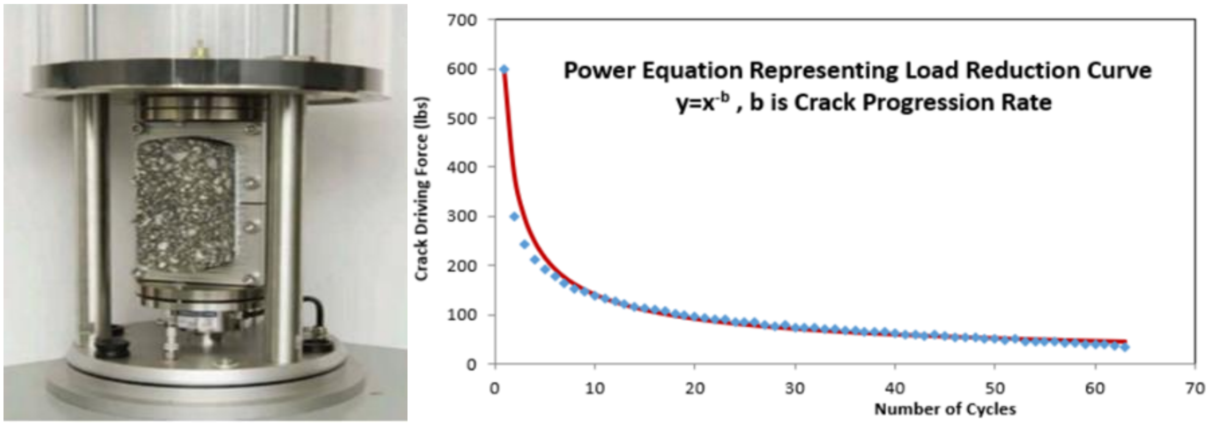


Figure 22. OT Specimen Setup and Illustration of CPR Parameter Calculation (Lee et al., 2019; Zhou et al., 2022)

3.5.4 Permeability Test

The Florida permeability test was conducted per FM 5-565. The test was conducted using a falling head permeability apparatus for 6-inch cylinder specimens, as shown in Figure 23. For each mix design, three replicate specimens were tested. To obtain the test specimen, a 1” thickness is trimmed from the top and bottom faces of the compacted sample. The test specimens are then submerged in a water tank for at least an hour at ambient temperature to reach a saturated state before testing. Then, the specimen is placed on top of the pedestal plate and assembled with the remaining parts, including a graduated cylinder, upper cap, and sealing tube with membrane. The membrane is then inflated to seal the sides of the specimen throughout the entire testing process. Water is added to the graduated cylinder to a level above the upper timing mark and then allowed to flow through the saturated specimen. The time interval taken to reach a known change in the head is recorded. During the testing, the inflated latex membrane seals the sides of the specimen, so the permeability test only determines the vertical flow of water through the specimen.

The coefficient of permeability (k) is calculated based on Darcy's law using the recorded time interval. The Florida permeability test apparatus only determines the vertical flow of water through the specimen since the sides of the specimen are sealed by a latex membrane, preventing any lateral flow. The mixtures with higher k values have better permeability than those with lower values. NCHRP Project 01-55 recommends a minimum k value of 50 meters/day for OGFC mixtures (Tran et al., 2021; Watson et al., 2018).

$$k = \frac{a \times L}{A \times t} \times ln(\frac{h_1}{h_2}) \times t_c \tag{4}$$

where:

k = the coefficient of permeability
a = the area of the testing pipe
L = the length of the specimen
A = the testing area of the specimen
t = the testing duration
h_1 = the initial height of water
h_2 = the final height of water
t_c = the temperature correction for the water

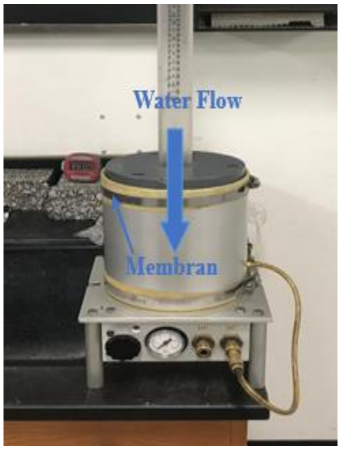


Figure 23. Florida Permeability Test Setup

3.5.5 Drainability Test

To evaluate the drainability of OGFC mixtures, slabs measuring 20” × 20” × 2” thick per ASTM E 2380 were tested with the outflow meter. The outflow meter is a vertical cylinder with an open top and a rubber ring on the bottom to seal against the pavement/specimen surface. The test is conducted by placing the outflow meter on the slab and pouring water into the cylinder to the upper level of the float. The water is then discharged to flow through the surface texture and subsurface voids, and the time taken for the water level to fall from the upper float level to the lower float level is recorded as the outflow time. At least four randomly spaced tests are required for each slab specimen. A shorter outflow time indicates better drainability, which means less hydroplaning potential under wet conditions. Unlike the permeability test, the outflow meter measures the combination of the vertical flow of water through the subsurface voids and the horizontal flow of water through the surface texture, which is affected by the macrotexture and permeability of the asphalt mixture.

Figure 24. Outflow Meter

3.5.6 Hamburg Wheel Tracking Test (HWTT)

The HWTT method, as per AASHTO T 324, was used to assess the rutting resistance and moisture susceptibility of OGFC mixtures. One gyratory specimen was cut in half horizontally, and both halves were further trimmed to obtain one set of HWTT specimens. Two sets of specimens were prepared for each mix and submerged in a 50°C water bath for 45 minutes before testing. After conditioning, a steel wheel with a load of 158±1.0 lb was used to reciprocate over the test specimens at a speed of 52 passes per minute. The test continued until the specimens experienced 20,000 passes or until the maximum impression depth of 12.5 mm was achieved. During the test, the rut depth versus the number of passes was recorded with a linear variable differential transducer (LVDT) device, which was then analyzed to determine the final rut depth and the stripping inflection point (SIP) of the mixture. SIP was determined as the intersection between creep and stripping slopes, as shown in Figure 25. In general, mixtures with a lower rut depth and a higher number of load cycles to reach the SIP indicate better-rutting resistance and lower moisture susceptibility than those with higher rut depth and lower SIP passes.

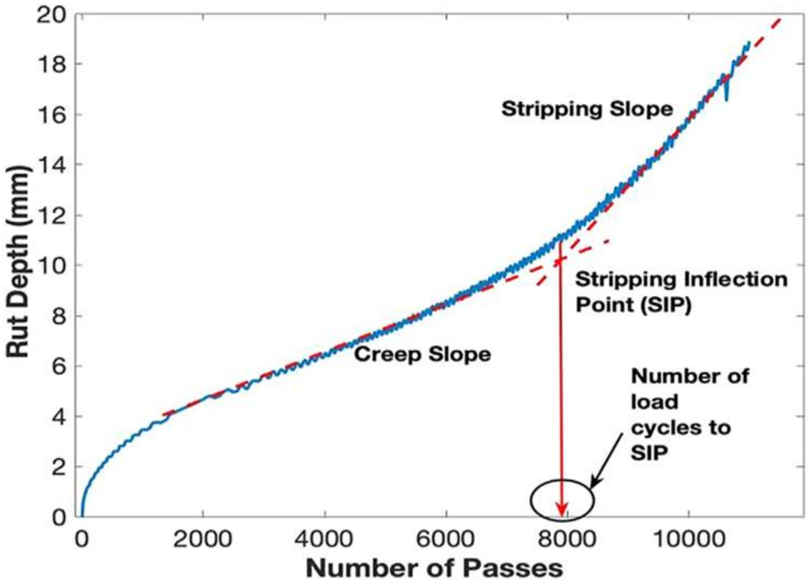


Figure 25. Hamburg Wheel Tracking Test (HWTT) Curve (Giwa et al., 2021)

3.5.7 Linear Kneading Compactor

For the study, a linear kneading compactor was utilized to compact slabs that measured 20" x 20" x 2" thickness for drainability, CTM, and DFT tests. The compactor functioned by applying pressure to a loose mixture sample via a set of rectangular parallel plates to compact the slab. To attain the desired height of the slab, a combination of thick and thin plates was adjusted at the base of the mold. The loose asphalt mixture was then placed within a steel mold with dimensions of 20" x 20" x 8.97". Afterward, the mixture was enclosed by closely fitting steel plates arranged vertically. Finally, the mixture was compacted using a steel roller that moved back and forth along the row of parallel rectangular plates for 5 cycles.

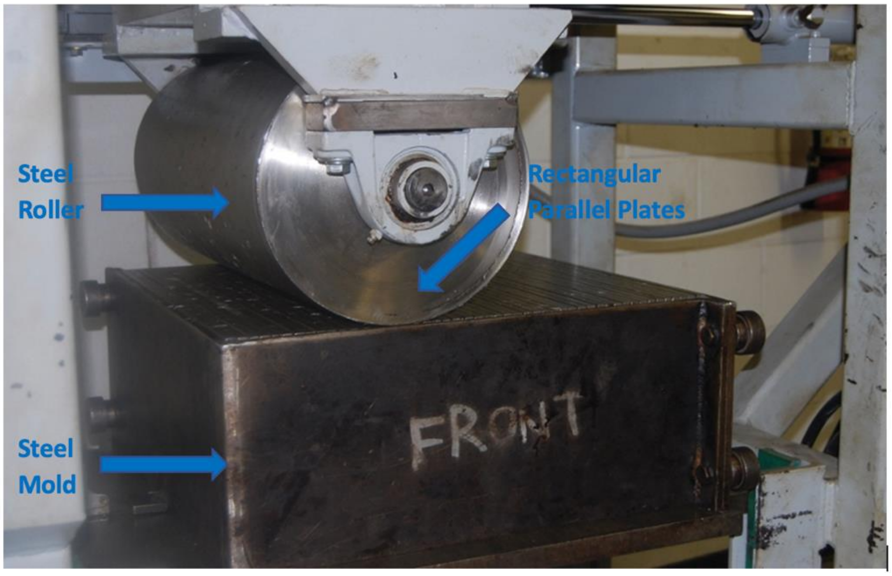


Figure 26. Linear Kneading Compactor (NCAT, 2016)

3.5.8 Three-Wheel Polishing Device (TWPD)

A three-wheel polishing device (TWPD), as specified in AASHTO PP 104, was used to polish slab specimens measuring 20” x 20” x 2” thick. This was done to simulate the traffic polishing of asphalt pavement. The device was operated at a rotational speed of 60 rpm and used three pneumatic tires inflated to 50 psi. During the polishing process, a water spray system was used to remove abraded particles. The carriage weight placed on top of the tires was 90 pounds. The diameter of the polishing path was 11.2 inches, which is the same as that of the DFT and CTM measuring paths. In this study, DFT and CTM were used to evaluate the friction and surface macrotexture of the polished slab specimens after different polishing cycles, including 0 (0k), 5000 (5k), 50000 (50k), and 100000 (100k) cycles.

Figure 27. Three-Wheel Polishing Device

3.5.9 Dynamic Friction Test (DFT)

The friction properties of OGFC mixtures were measured using the DFT as per ASTM E1911. The device used for the test consisted of a horizontal spinning disk with three spring-loaded rubber sliders attached to its lower surface, shown in Figure 28. The test was carried out by spinning the disk on a slab surface while a water spray system simulated wet conditions. The disk rotation speeds ranged from 0 to 90 km/h, allowing the measurement of friction properties at different speeds. During the test, the torque value of the spinning disk was continuously monitored and converted to the force on the sliders by dividing it by the circle radius. The friction measurement was determined by dividing the force by the combined weight of the disk and motor. For each mix, at least four replications were taken at each polishing level, and one slab was required for friction measurement. The rubber sliders were regularly checked and replaced as needed to ensure accuracy and consistency in measurement values. In this study, the friction coefficient of each OGFC slab was recorded at a speed of 40 km/h and labeled as DFT40 since it was repeatable compared to the other speeds. A higher value of the friction coefficient indicates better friction performance.

Figure 28. Dynamic Friction Tester

3.5.10 Circular Track Meter (CTM)

The macrotexture properties of the asphalt mixtures were measured using the CTM following ASTM E2157. This test involves a displacement sensor fixed on a mechanical arm, as illustrated in Figure 29. The mechanical arm rotates clockwise at a fixed height from the slab surface to enable the sensor to measure the vertical macrotexture depth profile. During the test, the computer continuously records the surface profile data, allowing the calculation of the mean profile depth (MPD). To measure MPD for each mix design, at least four replicate measurements were taken at each polishing level on a slab. A higher MPD value indicates better macrotexture properties.

Figure 29. Circular Track Meter

4. TEST RESULTS AND DISCUSSIONS

This chapter presents a detailed summary of the mix designs for FC-5, 9.5-mm OGFC, 12.5-mm SMA, and AFC mixtures, an analysis of the performance test results, and a cost analysis.

4.1. Designs of FC-5 and 9.5-mm OGFC Mixtures

4.1.1 Optimum Binder Contents of FC-5 Mix Designs

The design gradation of FC-5 mixtures was first developed following the FDOT specifications, as shown in Table 5. The pie plate test was then conducted at multiple binder contents to determine the OBC of FC-5 mixtures. The pie plate test was conducted with the FC-5 mixture using granite materials (GRN FC-5) at four binder contents of 5.3%, 5.8%, 6.3%, and 6.8%. Photos of the pie plates with and without loose mix are shown in Figures 30 and 31, respectively.

(a) 5.3% AC (b) 5.8% AC (c) 6.3% AC (d) 6.8% AC

Figure 30. Pie Plate Pictures (with Loose Mixture) of GRN FC-5 Mixtures.

(a) 5.3% AC (b) 5.8% AC (c) 6.3% AC (d) 6.8% AC

Figure 31. Pie Plate Pictures (without Loose Mixture) of GRN FC-5 Mixtures.

Figures 30 and 31 show that as the amount of binder used in the mixture increased, the amount of binder drainage also increased. The mixture with 5.3% binder content had the least binder draindown, while the mixture with 6.8% binder content had excessive draindown. According to FM 5-588, the preliminary OBC for the GRN FC-5 mix design could be chosen from 5.8% to 6.3%. However, when the binder content was set to 6.0%, the corresponding Cantabro loss result was 25.6%, exceeding the maximum allowable value of 20%. To improve the durability, the preliminary OBC was then increased to 6.3%. As a result, the Cantabro loss values of GRN FC-5 mixtures prepared with PG 76-22 and HP binders were 19.5% and 3.1%, respectively, which met the Cantabro loss criterion. Moreover, the design air voids were measured at 19.6% for the mixture using PG 76-22 and 19.4% for the HP mixture, which met the air void minimum requirement of 15%. Therefore, the OBC for the GRN FC-5 mixture was determined to be 6.3%.

FDOT provided the results of the pie plate test for the FC-5 mixture that uses limestone (LMS FC-5). According to the test, a preliminary OBC of 7.0% was designed as shown in Figure 32. The value was then validated by the Cantabro test, which yielded Cantabro loss of 8.1% for PG 76-22 and 3.5% for HP. Both values were well below the maximum allowable value of 20%. Furthermore, the average air voids were measured at 15.1% for PG 76-22 and 15.2% for HP, meeting the minimum air void requirement of 15%. Therefore, 7.0% was confirmed as the OBC for LMS FC-5 mixtures.


(a) 6.5 (b) 7.0 (c) 7.5

Figure 32. Pie Plate Pictures (with Loose Mixture) of LMS FC-5 Mixtures.

4.1.2 Optimum Binder Contents of 9.5-mm OGFC Mix Designs

The OBC for 9.5-mm OGFC using granite materials (GRN) was determined by the pie plate test at four binder contents of 5.3%, 5.8%, 6.0%, and 6.3%. Figures 33 and 34 present the pie plate test results with and without a loose mixture, respectively. As the binder content increased, the binder drainage also increased. The pie plate pictures of mixtures that were prepared with binder contents ranging from 6.0% to 6.3% showed sufficient bonding without excessive binder drainage. Hence, 6.0% was initially selected as the preliminary OBC for GRN 9.5-mm OGFC. However, the Cantabro loss value of 25.6% for the mixture with the PG 76-22 binder did not meet the maximum allowable threshold of 20%. Therefore, the OBC was increased to 6.3% to reduce Cantabro loss. As a result, the Cantabro loss values of GRN 9.5-mm OGFC mixtures prepared with PG 76-22 and HP binders were 11.9% and 2.2%, respectively, which was less than the maximum Cantabro loss criterion of 15%. Additionally, the average air voids of the mixtures at 6.3% binder content were 19.6% for PG 76-22 and 19.8% for HP, which were higher than the minimum requirement of 15%. Therefore, 6.3% was chosen as the OBC for GRN 9.5-mm OGFC mixtures.


(a) 5.3 (b) 5.8 (c) 6.0 (d) 6.3

Figure 33. Pie Plate Pictures (with Loose Mixture) of GRN 9.5-mm OGFC Mixtures.

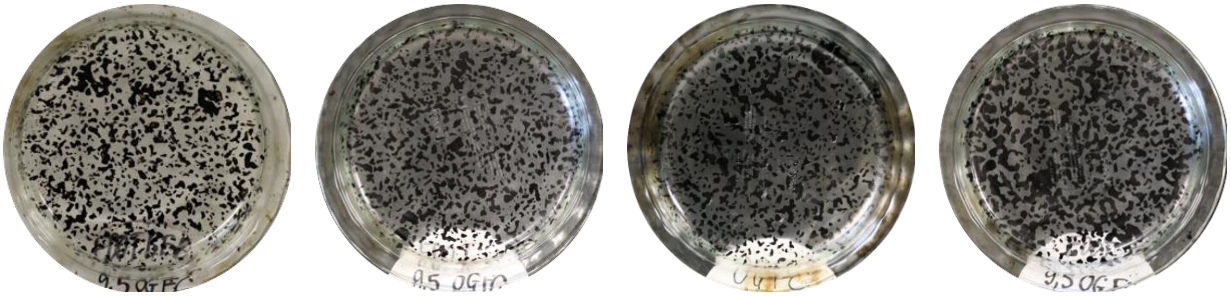

(a) 5.3 (b) 5.8 (c) 6.0 (d) 6.3

Figure 34. Pie Plate Pictures (without Loose Mixture) of GRN 9.5-mm OGFC Mixtures.

The OBC for 9.5-mm OGFC using limestone (LMS 9.5-mm OGFC) was chosen as 7.3% based on the pie plate results provided by FDOT, as shown in Figure 35. The Cantabro test and air voids measurement were then carried out to confirm the selected OBC. The results indicate that the Cantabro loss was 6.1% for the PG 76-22 mixture and 1.7% for the HP mixture, which complies with the maximum allowable criterion of 15%. Additionally, the average air void was recorded at 15.3% for PG 76-22 and 15.9% for the HP mixture, meeting the minimum air void requirement of 15%. As a result, the OBC for the LMS 9.5-mm OGFC mixture was determined to be 7.3%.


(a) 6.5 (b) 7.0 (c) 7.5

Figure 35. Pie Plate Pictures (with Loose Mixture) of LMS 9.5-mm OGFC Mixtures.

4.1.3 Summary of FC-5 and 9.5-mm OGFC Mix Designs

Table 7 shows the gradations and control points for FC-5 and 9.5-mm OGFC mixtures, while Table 8 provides a detailed summary of the FC-5 and 9.5-mm OGFC mixture designs for both aggregate types. The summary includes the OBC, air voids, Cantabro loss, and the criteria. As shown, all FC-5 and 9.5-mm OGFC mixtures met the minimum air void requirement of 15% and the maximum Cantabro losses of 20% for FC-5 and 15% for 9.5-mm OGFC mixtures, respectively.

Table 7. Gradation Summary of FC-5 and 9.5-mm OGFC Mixture

Sieve	FC-5 GRN	FC-5 LMS	FC-5 Control Points	9.5-mm GRN	9.5-mm LMS	9.5-mm Control Points
3/4"	100	100	100	100	100	100
1/2"	92	91	85 - 100	99	100	100
3/8"	72	73	60 - 75	93	93	85 – 100
#4	17	22	15 - 25	33	33	20 – 40
#8	7	9	5 - 10	10	9	5 – 10
#16	5	7		5	7	
#30	4	6		4	5	
#50	3	5		4	5	
#100	3	4		3	4	
#200	2.6	2.9	2 - 5	2.7	3.4	2 - 4

Table 8. Design Summary of FC-5 and 9.5-mm OGFC Mixture

Aggregate	Mixture Type	Binder Type	OBC (%)	Air Void (%)	Cantabro Loss (%)
GRN	FC-5	PG 76-22	6.3	19.6	19.5
GRN	FC-5	HP	6.3	19.4	3.1
GRN	9.5-mm OGFC	PG 76-22	6.3	19.6	11.9
GRN	9.5-mm OGFC	HP	6.3	19.6	2.2
LMS	FC-5	PG 76-22	7.0	15.1	8.1
LMS	FC-5	HP	7.0	15.2	4.8
LMS	9.5-mm OGFC	PG 76-22	7.3	15.3	6.1
LMS	9.5-mm OGFC	HP	7.3	15.9	1.7
Requirement				≥ 15	≤ 20 for FC-5 ≤ 15 for 9.5-mm OGFC

Table 8 shows that the OBC for GRN FC-5 and 9.5-mm OGFC mixtures is 6.3%. However, for LMS mixtures, the OBC for FC-5 and OGFC mixtures is 7.0% and 7.3%, respectively. The difference in OBC between the two aggregate sources is due to LMS having a higher binder absorption compared to GRN. Therefore, higher binder contents are needed for LMS mixtures to meet performance requirements compared to those using GRN. Furthermore, the 9.5-mm OGFC mixture usually yields the same or slightly higher OBC than the corresponding FC-5 mixture, which is expected due to its finer gradation. Mixtures prepared with the same aggregate source also have similar design air voids, which is likely due to the similar blend gradation and binder contents. Moreover, HP mixtures consistently have significantly lower Cantabro loss than the corresponding mixtures prepared with PG 76-22, indicating that HP can significantly improve the durability of OGFC mixtures. Additionally, 9.5-mm OGFC mixtures always have lower Cantabro loss values than the corresponding FC-5 mixtures, especially for the mixtures using PG 76-22, which is likely due to the finer gradation and higher binder content.

4.2 12.5-mm SMA Mix Design

As previously mentioned, the first step in designing the 12.5-mm SMA mix was to determine N_{design}. Figure 36 shows the average air voids for GRN and LMS 12.5-mm SMA mixtures that were compacted at 50 Marshall blows, 35 SGC gyrations, and 50 SGC gyrations. The specimens compacted with 50 gyrations showed the lowest air voids, followed by 35 gyrations and 50 Marshall blows. For the two SMA mixtures tested, the specimens compacted at 35 gyrations showed comparable air voids to those compacted at 50 Marshall blows, with air void differences of around 0.2% for both aggregate types. Because the air void results compacted to 35 SGC gyrations were similar to those compacted to 50 Marshall blows, a N_{design} of 35 SGC gyrations was selected for designing SMA mixtures in this study.

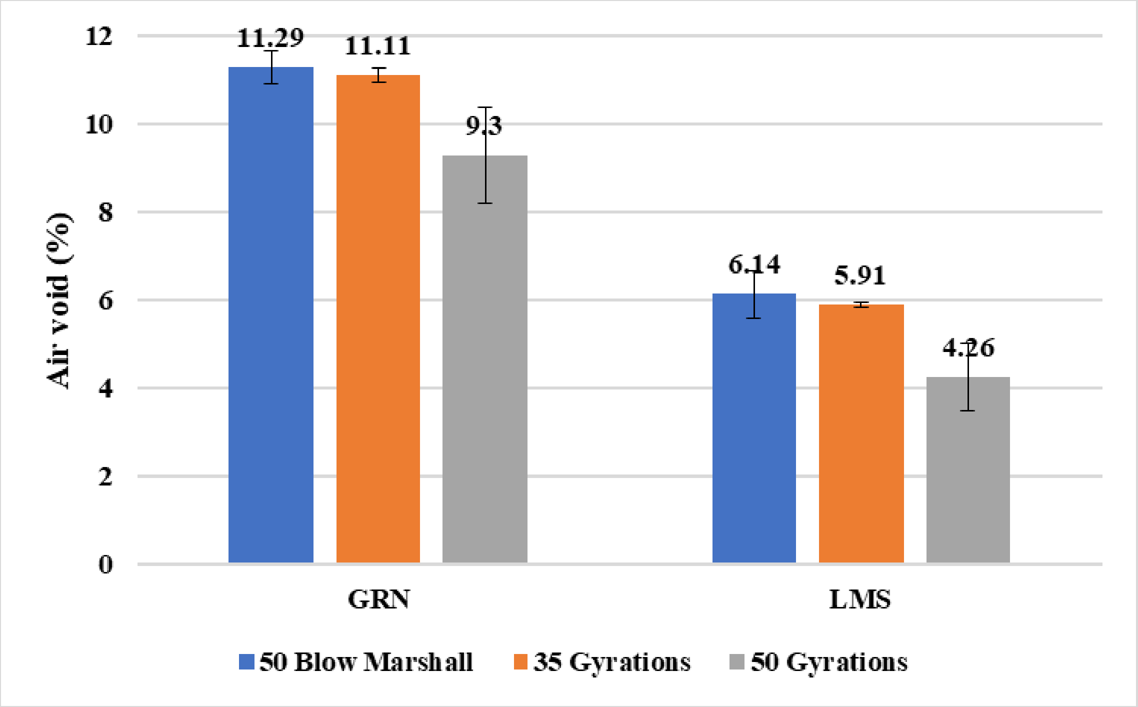


Figure 36. Air Voids of GRN and LMS 12.5-mm SMA at Three Compaction Levels

Once N_{design} was established, the next step was to determine the design gradations and OBCs of the 12.5-mm SMA mixtures for both aggregate types. Table 9 presents the design gradations of two SMA designs and the corresponding control points. As shown, the GRN 12.5-mm SMA gradation was found to be finer than that of LMS 12.5-mm SMA.

Table 9. Gradation Summary for 12.5-mm SMA Mixtures

Sieve	GRN	LMS	Control Points
3/4"	100	100	100
1/2"	87	85	85-100
3/8"	70	64	50-75
#4	29	20	20-28
#8	23	19	16-24
#16	19	18	
#30	16	17	
#50	14	16	10-20
#100	13	13	
#200	11.8	8.6	8-12

Table 10 shows the mix designs for 12.5-mm SMA mixtures, including OBC, VMA, VCA_{drc}, VCA_{mix}, and the respective criteria for both aggregate types. After compaction, the volumetrics of SMA mixtures with varying binder contents were measured, and the OBC was determined at 4.0% design air voids. It was observed that the OBC of the LMS SMA mixture was higher than that of the GRN SMA mixture, which was consistent with the FC-5 mix designs. It is worth noting that all the SMA mixtures met the VMA and VCA requirements at the OBC.

Table 10. Design Summary of 12.5-mm SMA Mixtures

Aggregate	OBC (%)	VMA (%)	VMA Criterion (%)	VCA_{drc}	VCA_{Mix}	VCA Criterion
GRN	6.5	18.2	≥ 17%	42.3	42.3	$VCA_{Mix} \leq VCA_{drc}$
LMS	7.5	17.0	≥ 17%	40.6	40.3	$VCA_{Mix} \leq VCA_{drc}$

4.3 Alternative Friction Course Design

4.3.1 GRN Alternative Friction Course Design

Two options for the GRN alternative friction mix were developed following the procedure described in Section 3.3. This was done by adjusting the stockpile percentages of the GRN FC-5 mixture. These options are shown in Figure 37, and they are located between 12.5-mm SMA and FC-5 design gradations. The blend named Option #1 is designed to be finer than Option #2, especially for sieves finer than 3/8 inch. Both blends have an asphalt content of 6.5%.

After that, the Cantabro and permeability tests were conducted to evaluate the durability and permeability of these two mixtures. The test results are summarized in Figure 38. Based on the test results, it was found that the FC-5 mixture had the highest Cantabro loss and permeability, followed by AFC Option #2, AFC Option #1, and 12.5-mm SMA. The durability and permeability of the two alternative friction mixtures generally fell between those of FC-5 and 12.5-mm SMA mixtures. However, the Cantabro loss of AFC Option #1 was less than that of the 12.5-mm SMA mixture. Both options of alternative friction mixture met the performance criteria with the maximum Cantabro loss of 10% and more permeable than the 12.5-mm SMA mixture. It was observed that Option #1 was more durable and less permeable than Option #2, mainly due to its finer gradation. Therefore, based on the test results, Option #1 was selected as the final AFC design. This decision was taken considering its superior durability while ensuring permeability, which met the desired performance criteria.

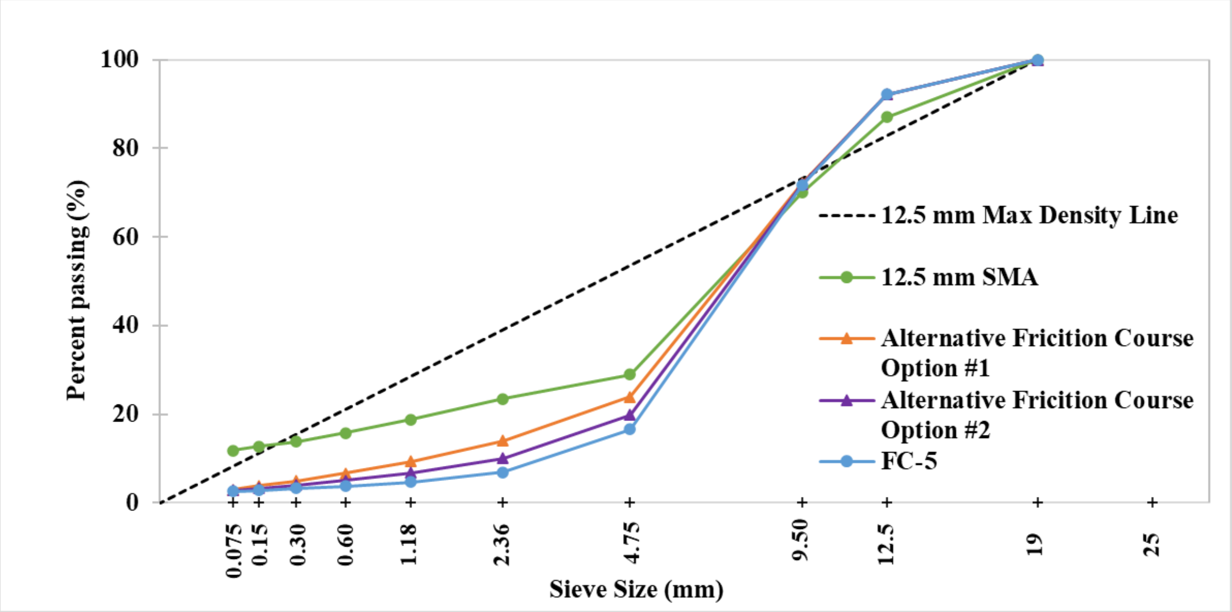


Figure 37. Alternative Friction Course Gradation Options for GRN

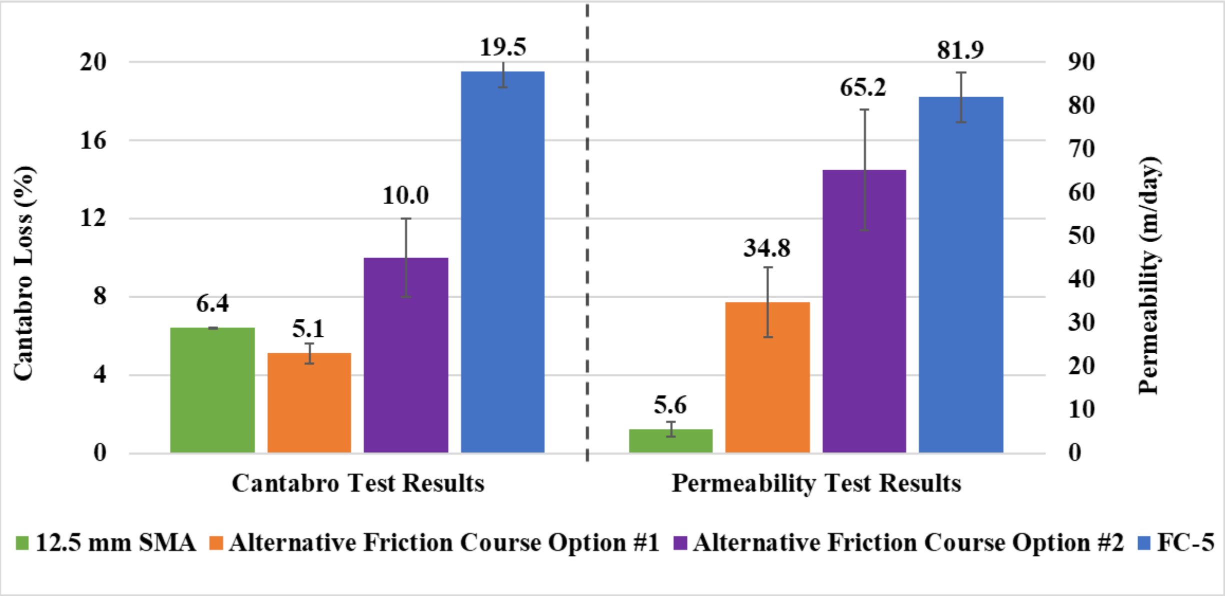


Figure 38. Performance Evaluation for GRN Alternative Friction Course Options

4.3.2 LMS Alternative Friction Course Design

Two gradation options were also developed for the LMS alternative friction course, similar to the GRN alternative friction course. These options, shown in Figure 39, fell between the design gradations of the FC-5 and 12.5-mm SMA, for the No.4 sieve. Option #2 was designed to be finer than Option #1. The preliminary OBC of Option #1 and Option #2 gradations were selected to be 7.3% and 7.0%, respectively, which was about the same or slightly higher than the FC-5 mixture. Both mixtures were prepared and then evaluated in terms of durability and permeability through the Cantabro test and Permeability test, respectively. The testing results are presented in Figure 40.

Similar to the GRN mix designs, the FC-5 mixture showed the highest Cantabro loss and permeability, followed by AFC Option #2, AFC Option #1, and 12.5-mm SMA. The durability and permeability of the two alternative friction mixtures generally fell between those of FC-5 and 12.5-mm SMA mixtures. However, the permeability of AFC Option #2 was less than that of AFC Option #1. Both options met the performance criteria with the maximum Cantabro loss of 10% and more permeable than the 12.5-mm SMA mixture. Therefore, Option #1 was selected due to its similar durability, but improved permeability compared to Option #2.

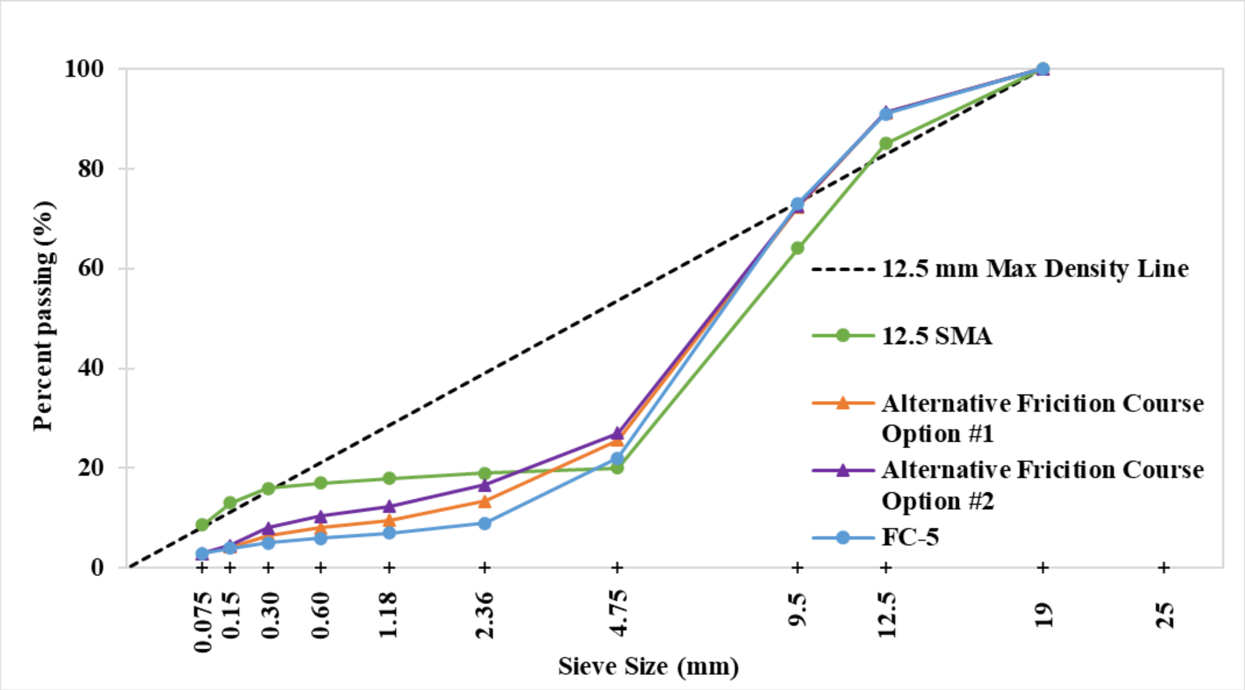


Figure 39. Alternative Friction Course Gradation Options for LMS

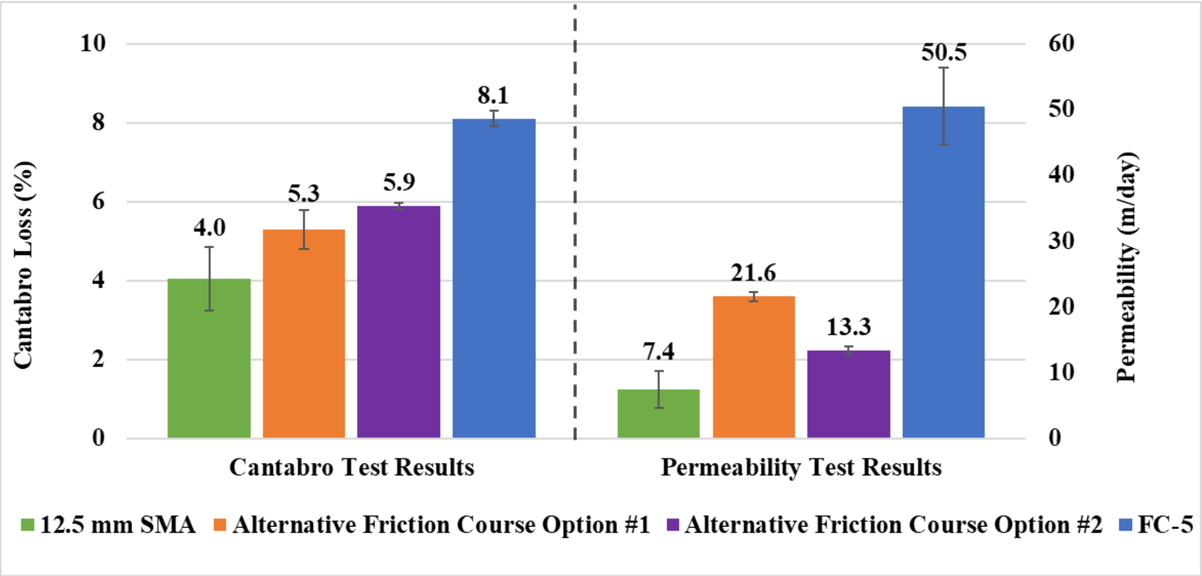


Figure 40. Performance Evaluation for LMS Alternative Friction Course Options

4.3.3 Summary of Alternative Friction Course Mix Designs

Table 11 provides a summary of the design gradations of alternative friction courses for two types of aggregates and the FC-5 control points. The design gradation of the alternative friction courses mixtures for both aggregate types was almost identical. The design gradations for both aggregate types fell into the FC-5 gradation band for all sieve sizes except for the No. 4 and No. 8 sieves. The percent passings for No.4 and No.8 sieves were greater than the maximum allowable values for FC-5, and the percent passing for the 3/8-in sieve was very close to the high limit of FC-5. Therefore, the FC-5 gradation requirements need to be modified for the AFC gradation by increasing the limits for the No. 4 and No. 8 sieves while keeping the limits of other sieves unchanged. A preliminary gradation band for the AFC mixture was proposed based on the limited volumetric and performance results for both aggregate types, which could be achieved using the current stockpiles for FC-5.

Table 11. Gradation Summary for Alternative Friction Course

Sieve	GRN	LMS	FC-5 Mix Control Points	Preliminary Control Points for Alternative Friction Course Mixture
3/4"	100	100	100	100
1/2"	92	91	85 - 100	85 - 100
3/8"	72	72	60 - 75	60 - 75
#4	25	26	15 - 25	25 - 35
#8	14	13	5 - 10	10 - 15
#16	9	10		
#30	7	8		
#50	5	6		
#100	4	4		
#200	3.0	2.9	2 - 5	2 - 5

Table 12 summarizes the design information, performance results, and the criteria and testing standards associated with the AFC mixture designs for both aggregate types. The N_{design} was set at 50 gyrations for the AFC design, which was the same for the FC-5 design. The OBC of the GRN mixture was lower than that of the LMS mixture, which was likely due to the higher binder absorption of LMS compared to GRN. Additionally, preliminary criteria for air voids and performance were proposed for the AFC design based on limited test results from the laboratory experiment conducted in this study.

Table 12. Mixture Design and Performance Summary for Alternative Friction Course

Description	GRN	LMS	Preliminary Criterion	Test Standard
N_{design}	50	50	50	N/A
OBC (%)	6.5	7.3	N/A	N/A
Air Voids (%)	13.5	11.0	10 – 15	AASHTO T331
Cantabro Loss (%)	5.1	5.3	≤ 10	AASHTO T401

4.4 Mixture Durability Evaluation

4.4.1 Cantabro Test Results for GRN Mixtures

Figures 41, 42, and 43 present the Cantabro loss results for GRN mixtures that were conditioned for 0, 1,000, and 2,000 hours in NAWS, respectively. Each mixture was tested with two binders. Each chart shows the average test results. The error bars represent plus and minus one standard deviation. The letters above the columns show the results of statistical grouping analysis. Mixtures with the same letter had no significant difference in test results. The letters A and A' represent the statistical grouping analysis results of mixtures prepared with PG 76-22 and HP binders, respectively. Additionally, a student's *t-test* was conducted to determine if HP significantly improved mixture performance compared to PG 76-22 with a significance level of 0.05.

Figure 41 shows the Cantabro loss test results for GRN mixtures without NAWS conditioning. Among the mixtures with the PG 76-22 binder, the FC-5 mixture showed the highest average Cantabro loss, followed by the 9.5-mm OGFC mixture, the 12.5-mm SMA mixture, and the AFC mixture. Based on the statistical grouping analysis, the AFC mixture had statistically equivalent raveling resistance to the 12.5-mm SMA mixtures, which had significantly better durability than FC-5 and 9.5-mm OGFC mixtures. Moreover, the 9.5-mm OGFC mixture had a statistically lower Cantabro loss than the FC-5 mixture, meaning a finer gradation can improve the raveling resistance of the OGFC mixture. Among the mixtures with the HP binder, the 12.5-mm SMA mixture had the lowest average Cantabro loss results, followed by the AFC mixture, 9.5-mm OGFC mixture, and FC-5 mixture. However, the statistical grouping analysis results showed that there was no significant difference among the four mixture types. This indicates that the effect of HP on mixture durability was dominant, regardless of the mixture types.

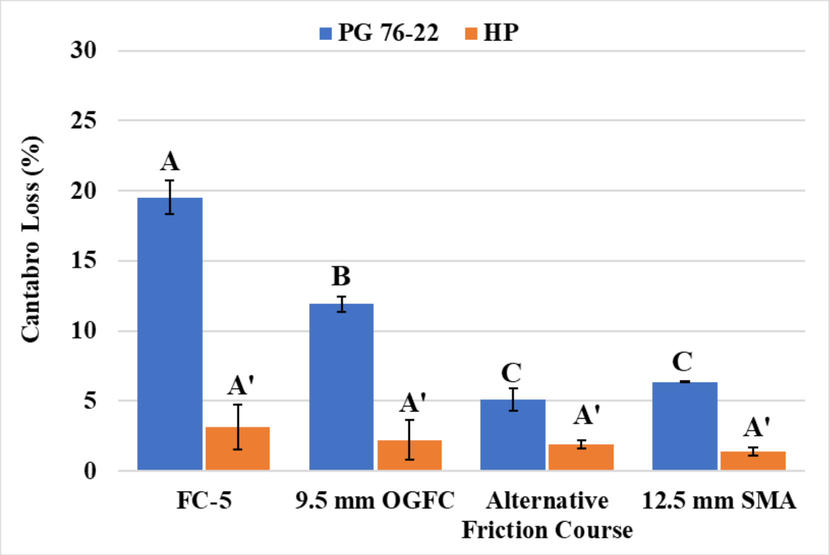


Figure 41. Cantabro Loss of GRN Mixtures without NAWS Conditioning

Figure 42 presents the Cantabro loss results of all the GRN mixtures after 1000 hours of NAWS conditioning. For PG 76-22 mixtures, the average Cantabro loss of the FC-5 mixture was the highest, followed by the 9.5-mm OGFC mixture, the AFC mixture, and the 12.5-mm SMA mixture. A statistical analysis showed no significant difference between the 9.5-mm OGFC and FC-5 mixture. In addition, the AFC mixture provided statistically equivalent raveling resistance with the 12.5-mm SMA mixture, and both mixtures had significantly higher raveling resistance than the FC-5 mixture. For HP mixtures, the FC-5 mixture yielded the highest average Cantabro loss, followed by the 9.5-mm OGFC mixture, 12.5-mm SMA mixture, and the AFC mixture. However, a statistical analysis showed that there were no significant differences between 9.5-mm OGFC and FC-5 mixtures or between the AFC and 12.5-mm SMA mixtures. Additionally, both 12.5-mm SMA and AFC mixtures had significantly better durability than 9.5-mm OGFC and FC-5 mixtures.

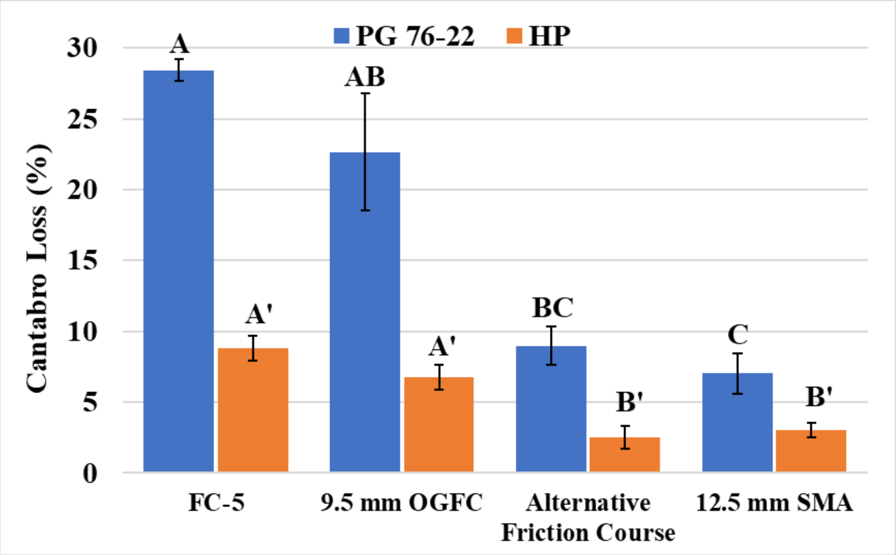


Figure 42. Cantabro Loss of GRN Mixtures after 1000 Hours of NAWS Conditioning

Figure 43 presents the Cantabro loss results for all mixtures after 2000 hours of NAWS conditioning. Among the mixtures with PG 76-22, the AFC and 12.5-mm SMA mixtures exhibited lower average Cantabro loss compared to the FC-5 and 9.5-mm OGFC mixtures. A statistical analysis showed no significant difference existed between the AFC and 12.5-mm SMA mixtures. This agrees with the observations from the other two aging conditions that the AFC and 9.5-mm OGFC mixtures could significantly improve the raveling resistance of the FC-5 mixture with PG 76-22. For HP mixtures, the 12.5-mm SMA and AFC showed lower average Cantabro loss values than the 9.5-mm OGFC mixtures. However, no significant difference in Cantabro loss was observed among the three mixture types. Moreover, the Cantabro loss difference between 9.5-mm OGFC mixture and FC-5 mixtures was not significant. This suggests that the effect of HP on mixture durability generally remained dominant regardless of the mixture types, even after 2000 hours of NAWS conditioning.

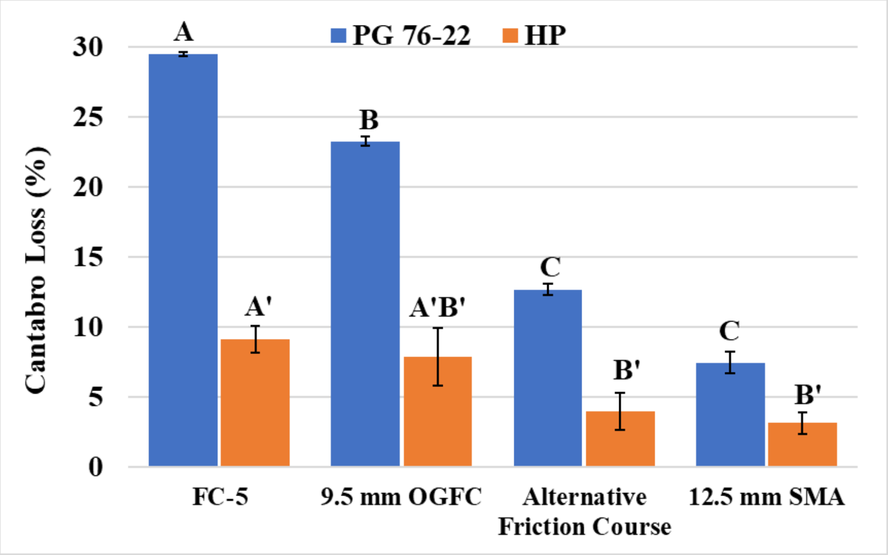


Figure 43. Cantabro Loss of GRN Mixtures after 2000 Hours of NAWS Conditioning

Figures 41-43 demonstrate that the use of HP results in lower average Cantabro loss values than PG 76-22, regardless of the type of mixture or aging condition. To further assess the impact of HP on the durability of asphalt mixtures, a student's *t-test* was performed at a significant level of 0.05. The test was done for the GRN mixtures at the three aging conditions. The corresponding *p-values* are summarized in Table 13 where all *p-values* are less than 0.05. This indicated that HP mixtures had significantly better durability than the PG 76-22 mixtures. In other words, HP binder could significantly improve the durability of the mixture, regardless of its type.

Table 13. *p-values* for Comparing Binder Types based on Cantabro Loss of GRN Mixtures

Mix Design	0 Hours NAWS	1000 Hours NAWS	2000 Hours NAWS
FC-5	0.001	0.000	0.034
9.5-mm OGFC	0.003	0.018	0.005
Alternative Friction Course	0.040	0.004	0.008
12.5-mm SMA	0.001	0.048	0.003

In summary, there were consistent trends in the raveling resistance of the four GRN mixtures across all three aging conditions. When considering mixtures prepared with PG 76-22, the AFC mixture exhibited statistically equivalent raveling resistance to the 12.5-mm SMA mixture. Both of these mixtures demonstrated statistically similar or better raveling resistance compared to the 9.5-mm OGFC and FC-5 mixtures. In addition, the 9.5-mm OGFC mixture showed significantly higher raveling resistance than the FC-5 mixture, except for the 1000-hour NAWS conditioning. The enhanced durability of the AFC mixture likely stemmed from their finer gradation relative to the two OGFC mixtures. For HP mixtures, no significant difference was observed among the four mixtures across three aging conditions, except that the AFC and 12.5-mm SMA mixtures exhibited statistically better raveling resistance than the two OGFC mixtures after 1000 hours of NAWS conditioning. These results underscore the impact of HP binder on mixture durability, regardless of the mixture type.

4.4.2 Cantabro Test Results for LMS Mixtures

Figures 44, 45, and 46 present the Cantabro loss of LMS mixtures after 0, 1000, and 2000 hours of NAWS conditioning, respectively. As shown in Figure 44, the 12.5-mm SMA, alternative friction course, and 9.5-mm OGFC mixtures showed lower average Cantabro loss values than the FC-5 OGFC. However, a statistical analysis showed that there were no statistical differences among the four mixture types for both binders.

Similar trends were observed for the Cantabro test results of LMS mixtures after 1000 hours and 2000 hours of NAWS conditioning, shown in Figures 45 and 46. The only exception was that the AFC mixture showed statistically lower Cantabro loss than the two OGFC mixtures after 2000 hours of NAWS aging. In general, the LMS mixtures showed comparable durability regardless of mixture type when using the same binder type. In other words, the Cantabro loss results of four LMS mixtures were less discriminative than GRN mixtures, which may be attributed to the higher binder contents and lower air voids of LMS mixtures.

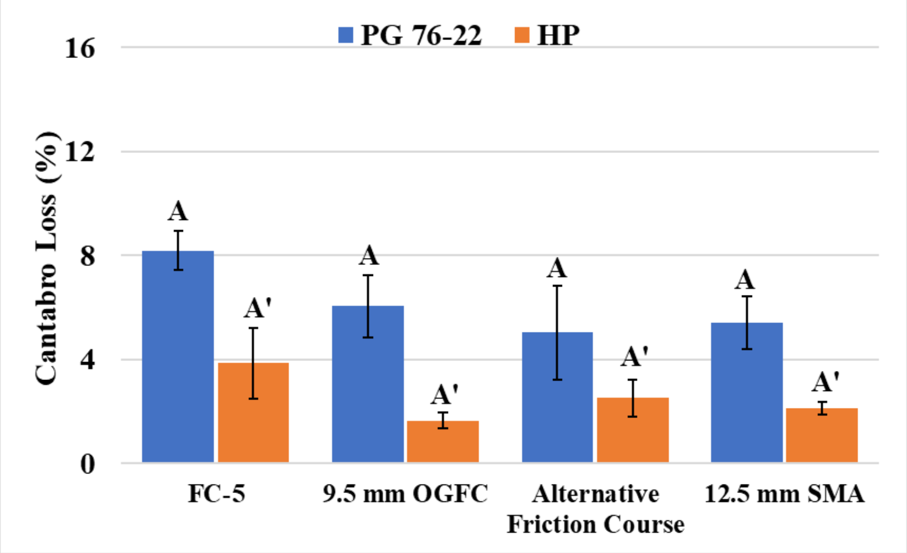


Figure 44. Cantabro Loss of LMS Mixtures without NAWS Conditioning

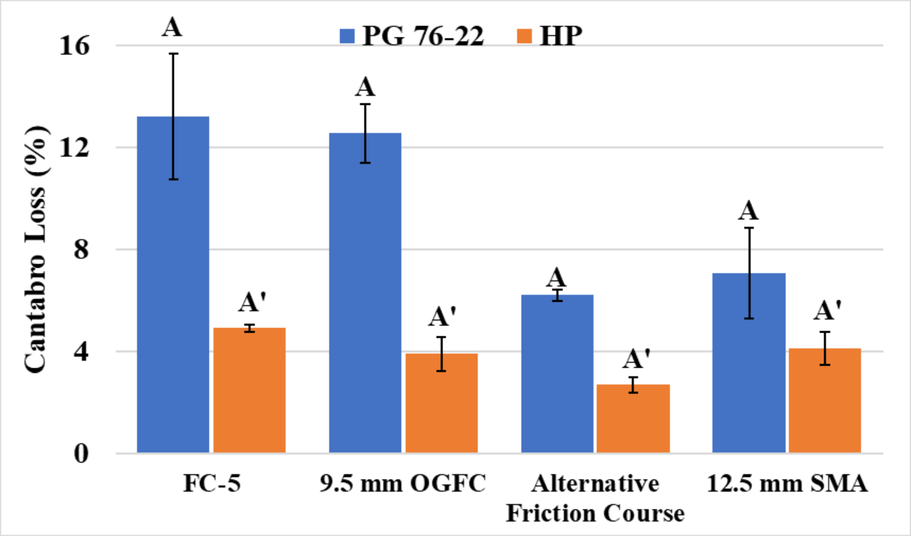


Figure 45. Cantabro Loss of LMS Mixtures after 1000 Hours of NAWS Conditioning

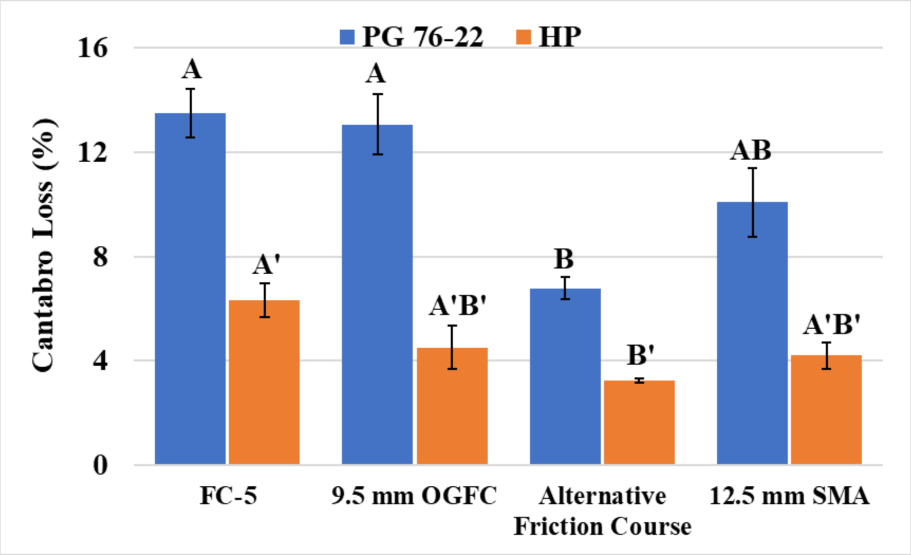


Figure 46. Cantabro Loss of LMS Mixtures after 2000 Hours of NAWS Conditioning

As for the GRN mixtures, the LMS mixtures with the HP binder showed lower Cantabro loss (i.e., better durability) than those with the PG 76-22 binder. In addition, the student's *t-test* was conducted to examine if there was a significant difference between mixtures prepared with two binder types under all three aging conditions. As presented in Table 14, all the *p-values* were lower than 0.05 for all LMS mixtures at all three aging conditions, except for the AFC mixture without NAWS aging and 12.5-mm SMA mixture after 1000 hours of NAWS aging (see yellow highlight). Therefore, the HP binder could significantly improve the durability of the four mixtures in all aging conditions, which is consistent with the findings from the GRN mixtures.

Table 14. *p-values* for Comparing Binder Types based on Cantabro Loss of LMS Mixtures

Mix Design	0 Hour NAWS	1000 Hour NAWS	2000 Hour NAWS
FC-5	0.021	0.028	0.001
9.5-mm OGFC	0.032	0.001	0.001
Alternative Friction Course	0.185	0.029	0.001
12.5-mm SMA	0.024	0.114	0.016

4.4.3 Effect of NAWS Conditioning on Mixture Durability

This section presents additional analysis that sheds light on the impact of NAWS conditioning on mixture durability. Scatter plots are used to compare the average Cantabro loss results before and after 1,000 hours and 2,000 hours of NAWS conditioning, with error bars indicating plus or minus one standard deviation. The plots use capital letters to denote the Games-Howell post-hoc grouping analysis results at a significance level of 0.05. Different letters represent statistically different Cantabro loss results. Additionally, steeper slopes between two aging conditions indicate more significant changes in the Cantabro loss results between these aging conditions.

Effects of Weathering on GRN Mixture Durability: Figure 47 shows the Cantabro loss results for GRN mixtures with two binders before (i.e., 0 hours) and after 1,000 and 2,000 hours of NAWS conditioning. The FC-5 and 9.5-mm OGFC mixtures were more sensitive to the 1,000-hour NAWS conditioning than the AFC and 12.5-mm SMA mixtures.

In addition, there was a statistically significant increase in the Cantabro loss results for the FC-5 and 9.5-mm OGFC mixtures, as well as the AFC mixture with the PG 76-22 binder, after undergoing 1,000 hours of NAWS conditioning. However, there was no significant increase in Cantabro loss results for these mixtures after being conditioned from 1,000 to 2,000 hours. Moreover, the Cantabro loss results for the 12.5-mm SMA mixtures with both binders were not statistically affected by the NAWS conditioning.

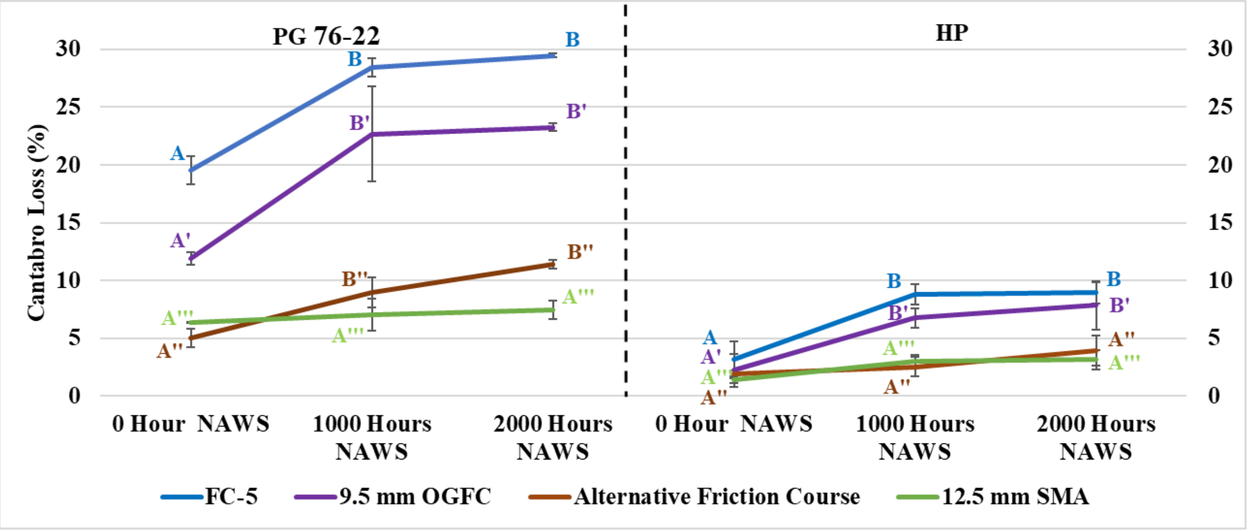


Figure 47. Cantabro Loss of GRN Mixtures at Three Aging Conditions

Table 15 summarizes the slopes of Cantabro loss results obtained before and after 1,000 hours of NAWS conditioning. The slopes of the AFC and 12.5-mm SMA mixtures were consistently lower than those of the two OGFC mixtures, indicating better resistance to aging. Furthermore, the HP mixtures consistently showed lower slopes than the PG 76-22 mixtures in three of the four mix types, which indicates that the HP binder had better resistance to aging than the PG 76-22 binder.

Table 15. Cantabro Loss Graph Slopes (0 to 1000 Hours of NAWS) for GRN Mixtures

Mix Design	PG 76-22	HP
FC-5	8.89	5.69
9.5-mm OGFC	10.75	4.53
Alternative Friction Course	3.90	0.66
12.5-mm SMA	0.69	1.60

Effects of Weather Conditioning on LMS Mixture Durability: Figure 48 shows the Cantabro loss results for LMS mixtures before (i.e., 0 hours) and after 1,000 and 2,000 hours of NAWS conditioning. The FC-5 and 9.5-mm OGFC mixtures were generally more sensitive to the 1,000-hour NAWS conditioning than the AFC and 12.5-mm SMA mixtures.

In addition, a statistically significant increase in the Cantabro loss results existed for only 9.5-mm OGFC mixtures. There was no significant increase in Cantabro loss results for the other mixtures. Compared to GRN mixtures, the enhanced durability of LMS mixtures can be attributed to higher binder contents, lower air voids, and other factors. Softer LMS aggregate can better absorb impacts in the rotating drum, and the network of asphalt binder holds the aggregate together through bonding on the surface and through absorbed binder in the pores of the LMS aggregate.

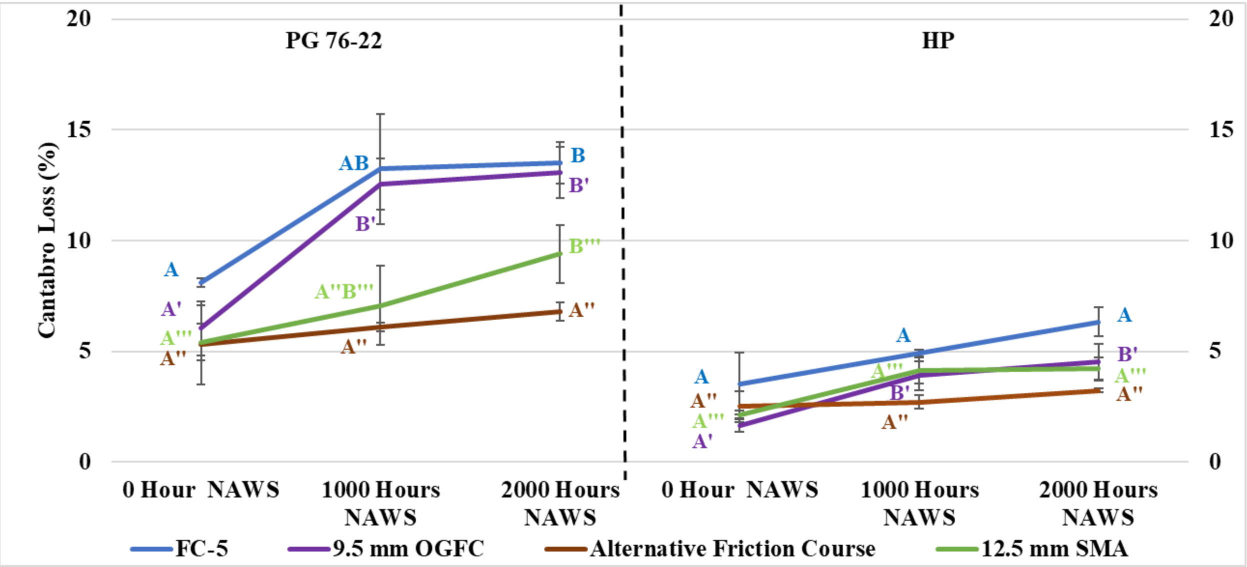


Figure 48. Cantabro Loss of LMS Mixtures at Three Aging Conditions

Table 16 shows the slopes of Cantabro loss results obtained before (i.e., 0 hours) and after 1,000 hours of NAWS conditioning. The AFC mixture had the lowest slope, indicating better resistance to aging, while the 9.5-mm OGFC had the highest slope, indicating lower resistance to aging. Moreover, the HP mixtures had lower slopes than PG 76-22 mixtures in three of the four mix types, indicating better resistance to aging for the HP binder.

Table 16. Cantabro Loss Graph Slopes (0 to 1000 Hours of NAWS) for LMS Mixtures

Mix Design	PG 76-22	HP
FC-5	5.11	1.38
9.5-mm OGFC	6.51	2.25
Alternative Friction Course	0.81	-0.31
12.5-mm SMA	1.65	2.00

4.5 Mixture Cracking Resistance Evaluation

4.5.1 Overlay Test Results for GRN Mixtures

Figures 49 and 50 show the OT CPR results of GRN mixtures. As shown, the AFC and 12.5-mm SMA mixtures displayed lower CPR values compared to the FC-5 and 9.5-mm OGFC mixtures, indicating better cracking resistance. This was generally true, except for the HP mixtures before NAWS conditioning (Figure 49). In addition, there was no statistical difference among the four mixtures prepared with both binders, except for the AFC mixture showing notably better cracking resistance than the 9.5-mm OGFC mixture after 1000 hours of NAWS conditioning.

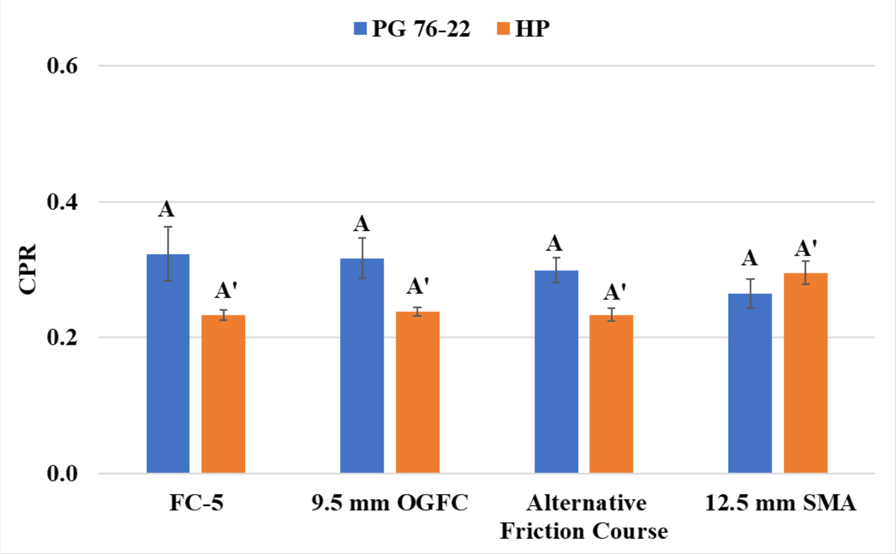


Figure 49. OT CPR Results of GRN Mixtures without NAWS Conditioning

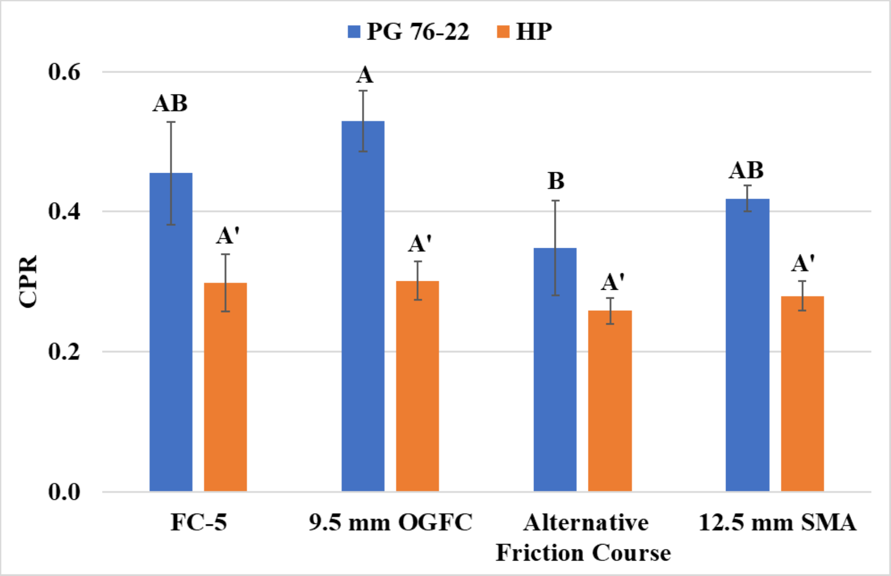


Figure 50. OT CPR Results of GRN Mixtures after 1000 Hours of NAWS Conditioning

Figures 49 and 50 also show that the HP mixtures consistently exhibited lower average CPR values compared to the mixtures with the PG 76-22 binder, both before and after NAWS conditioning. Furthermore, a student's *t-test* was conducted at a significance level of 0.05 to compare mixtures prepared with the two binders, as summarized in Table 17. All *p-values* were below 0.05, except for the 12.5-mm SMA mixture before NAWS conditioning (see yellow highlight). These results suggest that the HP binder effectively enhances mixture cracking resistance compared to the PG 76-22 binder for both aging conditions.

Table 17. *p-values* for Comparing Binder Types Based on OT CPR of GRN Mixtures

Mix Design	0 Hour NAWS	1000 Hour NAWS
FC-5	0.006	0.005
9.5-mm OGFC	0.001	0.004
Alternative Friction Course	0.003	0.033
12.5-mm SMA	0.096	0.036

4.5.2 Overlay Test Results for LMS Mixtures

Figures 51 and 52 present the OT CPR results of LMS mixtures before and after 1000 hours of NAWS conditioning, respectively. For mixtures prepared with the PG 76-22 binder, the AFC and 12.5-mm SMA mixtures generally had lower average CPR values than the FC-5 and 9.5-mm OGFC mixtures both before NAWS conditioning and after 1000 hours of NAWS conditioning, indicating better resistance to cracking. However, an opposite trend was observed for the HP mixtures, where the AFC and 12.5-mm SMA mixtures generally had similar or greater average CPR values than the FC-5 and 9.5-mm OGFC mixtures both before and after NAWS conditioning. However, the results of the statistical analysis showed that no significant difference existed among the four mixtures prepared with both binders before and after NAWS conditioning, which agrees with the observations from the GRN mixture test results.

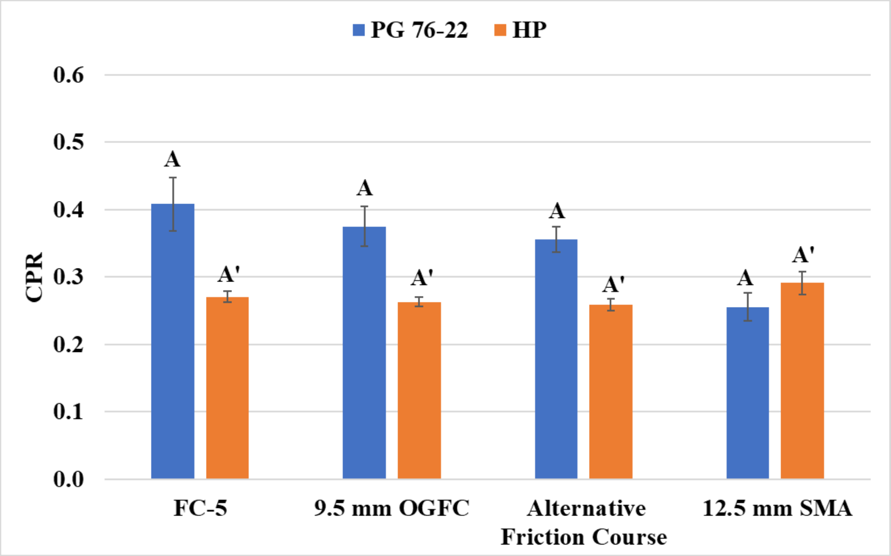


Figure 51. OT CPR Results of LMS Mixtures without NAWS Conditioning

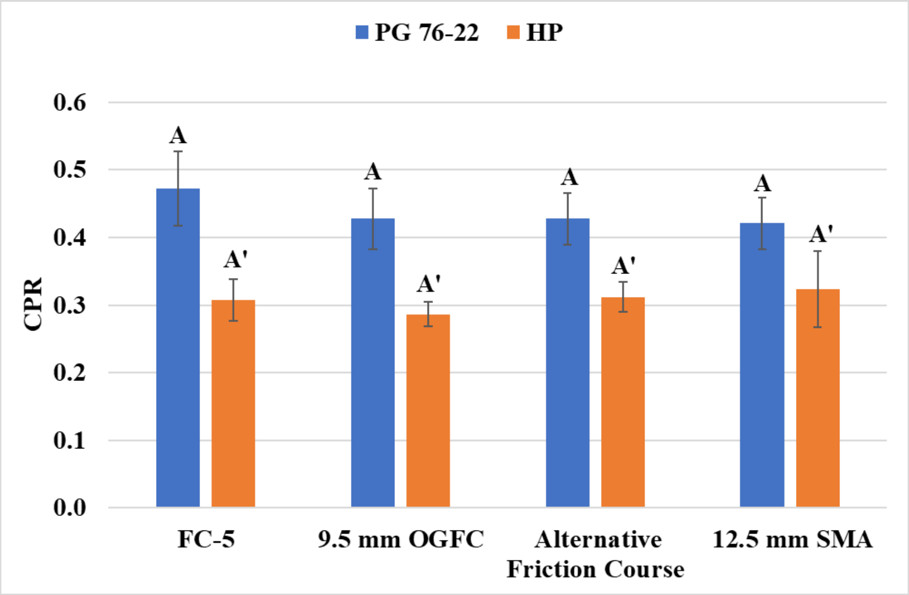


Figure 52. OT CPR Results of LMS Mixtures after 1000 Hours NAWS Conditioning

Figures 51 and 52 also show that the average CPR values of the HP mixtures were consistently lower than those of mixtures with the PG 76-22 binder in seven of the eight comparisons. Furthermore, the *student's t-test* results (i.e., *p-values*) presented in Table 18 confirmed that the HP binder significantly enhances mixture cracking resistance across all mixture types, with the exception of the 12.5-mm SMA mixture.

Table 18. *p-values* for Comparing Binder Types Based on OT CPR of LMS Mixtures

Mix Designs	0 Hour NAWS	1000 Hour NAWS
FC-5	0.001	0.001
9.5-mm OGFC	0.002	0.001
Alternative Friction Course	0.008	0.004
12.5-mm SMA	0.345	0.067

In summary, the OT results showed that the AFC and 12.5-mm SMA mixtures generally exhibited better resistance to cracking compared to the FC-5 and 9.5-mm OGFC mixtures. However, the statistical analysis indicated that the difference was not statistically significant for mixtures using the same aggregate and binder under the same aging condition. Moreover, the OT results suggest that the HP binder significantly enhances mixture cracking resistance compared to the PG 76-22 binder.

4.5.3 Effect of NAWS Conditioning on Mixture Cracking Resistance

Effect of Weather Conditioning on GRN Mixture Cracking Resistance: Figure 53 shows the OT CRP data and corresponding statistical grouping results for GRN mixtures before NAWS conditioning and after 1,000 hours of NAWS conditioning. The results indicated that the CPR of most mixtures increased after 1,000 hours of NAWS conditioning, suggesting a reduction in mixture cracking resistance, except for the 12.5-mm SMA mixture prepared with the HP binder. Additionally, the decrease in cracking resistance was deemed statistically significant for most mixtures after 1,000 hours of NAWS conditioning, except for the AFC mixture with the PG 76-22 binder and the 12.5-mm SMA mixture with the HP binder.

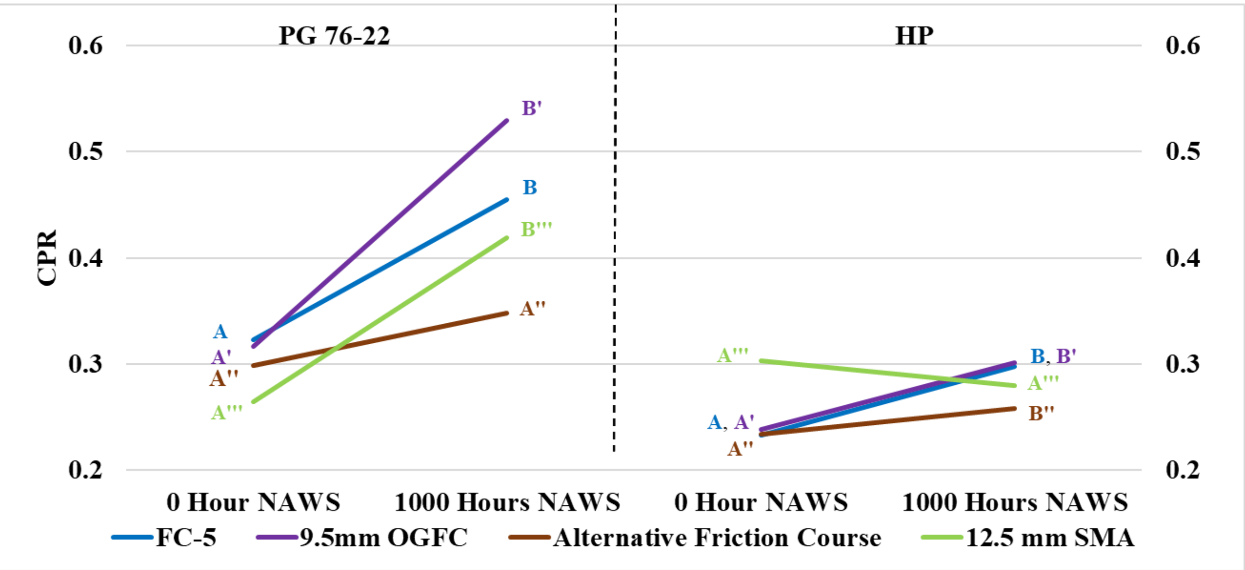


Figure 53. OT CPR Results of GRN Mixtures before and after NAWS Conditioning

Table 19 summarizes the slopes of the OT CPR results for GRN mixtures before and after 1000 hours of NAWS conditioning. The results show that the HP mixtures had smaller slopes than the corresponding ones that used PG 76-22 binder for all mixture types. This indicates that HP mixtures had better resistance to aging than those using PG 76-22.

Table 19. OT CPR Graph Slopes for GRN Mixtures

Mix Designs	PG 76-22	HP
FC-5	0.132	0.065
9.5-mm OGFC	0.213	0.064
Alternative Friction Course	0.049	0.025
12.5-mm SMA	0.155	-0.023

Effect of Weather Conditioning on LMS Mixture Cracking Resistance: Figure 54 presents the OT CPR data and corresponding statistical grouping results for LMS mixtures. Following 1,000 hours of NAWS conditioning, the CPR values of all mixtures increased, indicating a decrease in mixture cracking resistance.

Moreover, the CPR results for FC-5 and 9.5-mm OGFC mixtures using PG 76-22 remained statistically equivalent before and after NAWS conditioning, while the CPR values of the other two mixtures exhibited a statistical increase post-NAWS conditioning. In the case of HP mixtures, most CPR values showed no statistical difference before and after NAWS conditioning, except for the AFC mixture.

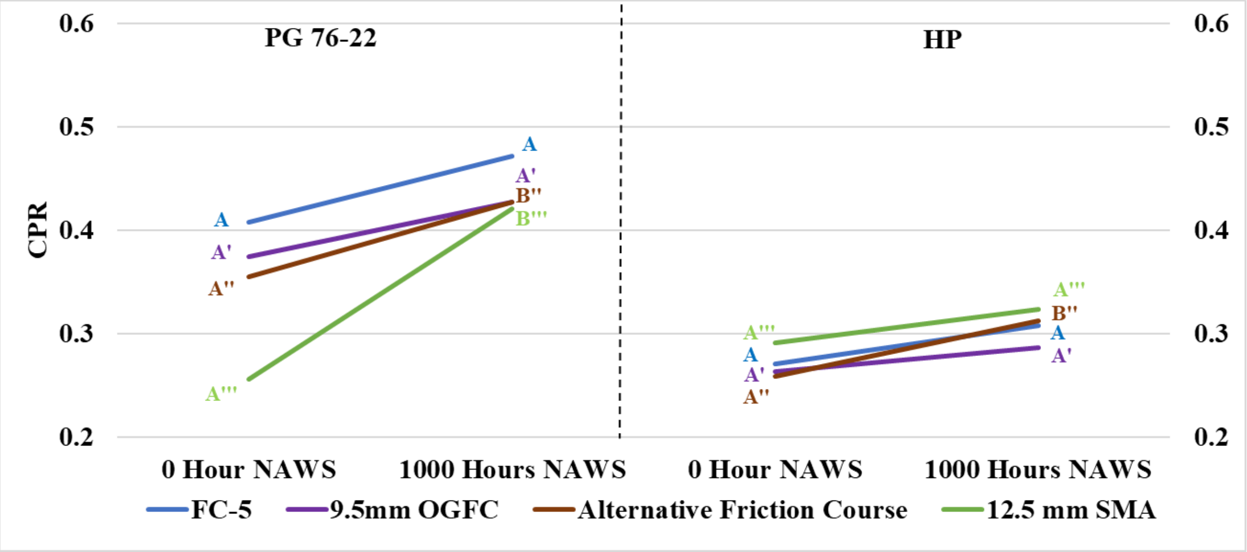


Figure 54. OT CPR Results of LMS Mixtures before and after NAWS Conditioning

Table 20 summarizes the slopes of the OT CPR results for LMS mixtures before and after 1000 hours of NAWS conditioning. The data indicates that the HP mixtures exhibited smaller slopes than those utilizing the PG 76-22 binder, highlighting better resistance to aging in HP mixtures.

Table 20. OT CPR Graph Slopes for LMS Mixtures

Mix Designs	PG 76-22	HP
FC-5	0.064	0.037
9.5-mm OGFC	0.053	0.024
Alternative Friction Course	0.072	0.053
12.5-mm SMA	0.166	0.033

4.6 Mixture Permeability Evaluation

The results of the permeability tests for GRN and LMS mixtures are presented in Figures 55 and 56, respectively. Two types of binders, PG 76-22 and HP, were tested. The data indicate that the FC-5 and 9.5-mm OGFC mixtures had the highest average permeability, followed by the AFC mixtures and the 12.5-mm SMA mixtures with the lowest permeability value. As expected, the mixtures with higher air voids had better permeability.

Statistical analysis showed that the FC-5 and 9.5-mm OGFC mixtures had statistically equivalent permeability, indicating that using a finer gradation did not negatively affect the permeability of the 9.5-mm OGFC mixtures. Furthermore, both mixtures exceeded the minimum threshold of 50 m/day recommended for OGFC mixtures (Watson et al., 2018), indicating that 9.5-mm OGFC mixtures could maintain the permeability requirement. In addition, the AFC mixtures showed significantly higher permeability than the 12.5-mm SMA mixtures but significantly lower permeability than the FC-5 and 9.5-mm OGFC mixtures, regardless of aggregate and binder type.

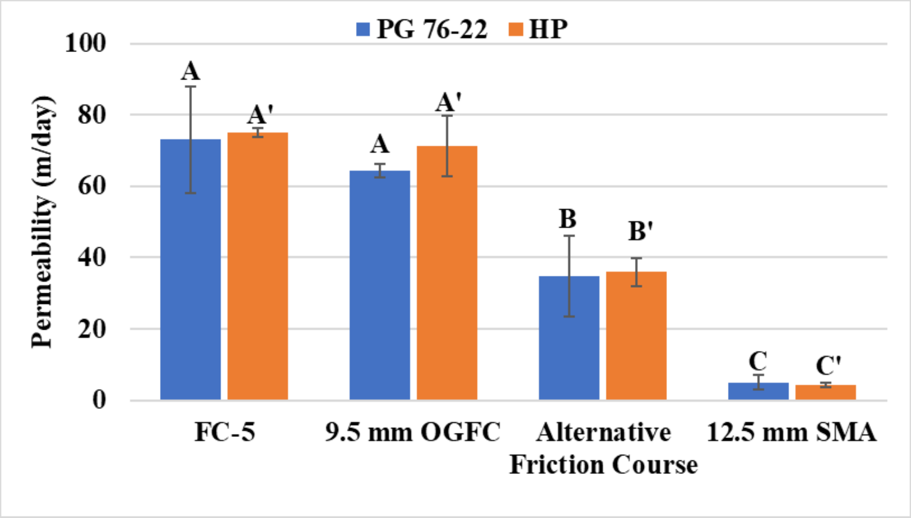


Figure 55. Permeability Test Results of GRN Mixtures

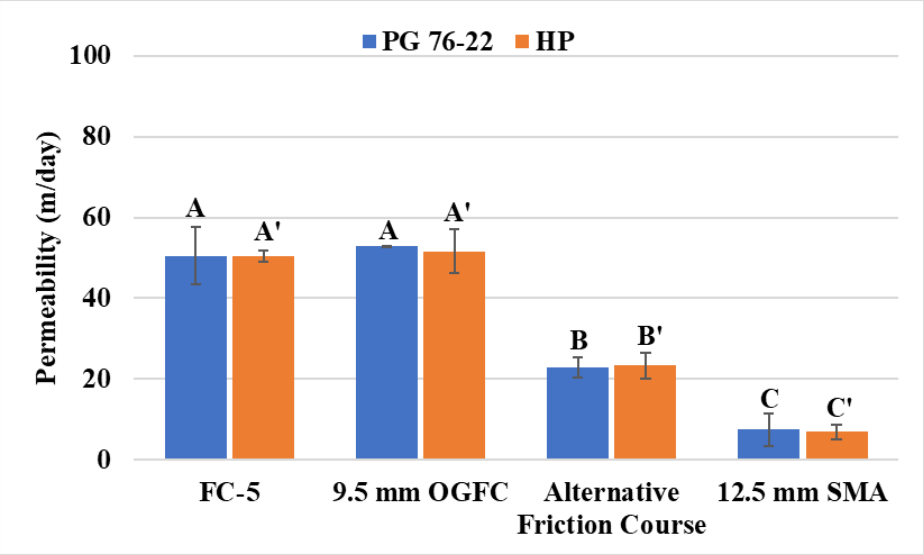


Figure 56. Permeability Test Results of LMS Mixtures

Figures 55 and 56 also show that the mixtures made with PG 76-22 and HP binders had comparable average permeability results for both aggregate types. A student's *t-test* was performed at a significance level of 0.05 to compare mixtures prepared with PG 76-22 and HP binders for both aggregate types, and all the *p-values* were greater than 0.05, indicating that the binder type did not significantly impact permeability.

Table 21. *p-values* for Comparing Binder Types Based on Permeability Test Results

Mix Design	GRN	LMS
FC-5	0.87	0.97
9.5-mm OGFC	0.80	0.36
Alternative Friction Course	0.84	0.51
12.5-mm SMA	0.65	0.82

4.7 Mixture Drainability Evaluation

The results for the outflow time of GRN and LMS mixtures are provided in Figures 57 and 58, respectively. The FC-5 mixtures demonstrated the highest drainability with the shortest average outflow time across all aggregate and binder types. This was followed by the 9.5-mm OGFC mixtures, AFC mixtures, and 12.5-mm SMA mixtures. Coarser gradations and higher air voids generally lead to better drainability. However, a statistical analysis showed that there was no significant difference between FC-5 and 9.5-mm OGFC mixtures for GRN and LMS aggregates with both binders.

Moreover, the AFC mixtures had a significantly shorter outflow time than the 12.5-mm SMA mixture but significantly longer outflow time than two OGFC mixtures. These findings suggest that air voids have a greater impact on drainability than gradation or mix type.

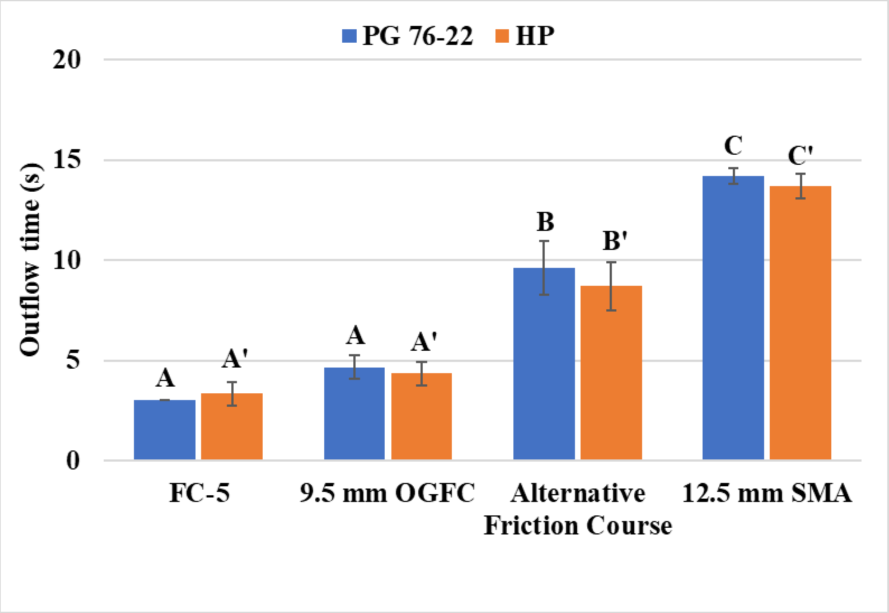


Figure 57. Drainability Test Results of GRN Mixtures

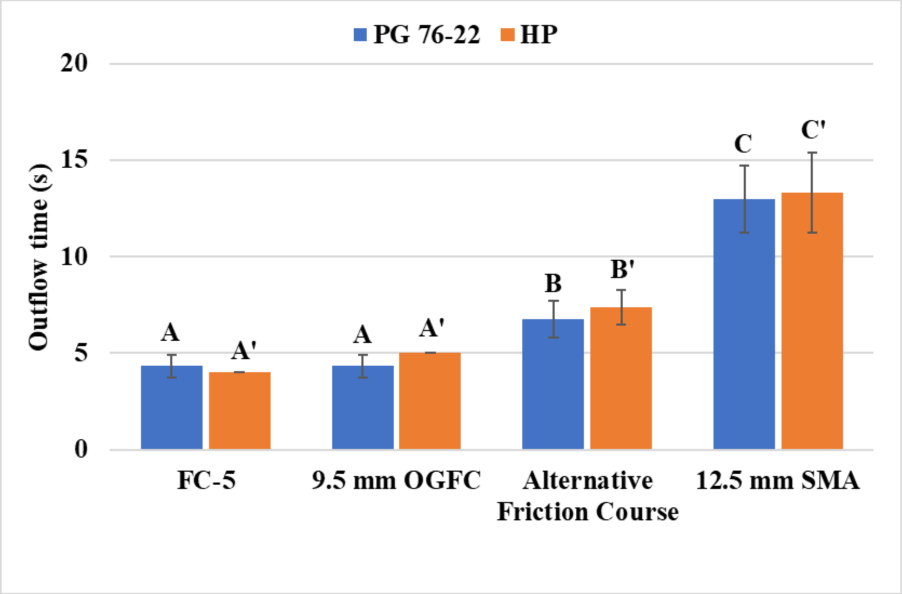


Figure 58. Drainability Test Results of LMS Mixtures

Figures 57-58 also show that mixtures prepared with PG 76-22 and HP binders had comparable average outflow time for both aggregate types, which was consistent with permeability results. Additionally, p-value results in Table 22 indicate that the binder type did not significantly affect the drainability performance.

Table 22. *p-values* for Comparing Binder Types Based on Drainability Test Results

Mix Design	GRN	LMS
FC-5	0.42	0.42
9.5-mm OGFC	0.52	0.17
Alternative Friction Course	0.35	0.34
12.5-mm SMA	0.21	0.84

4.8 Mixture Rutting Resistance Evaluation

Figures 59 and 60 show the HWTT rut depth results for GRN and LMS mixtures. Testing was conducted using both binders. All mixtures were found to have rut depths below the commonly accepted criterion of 12.5 mm after 20,000 passes. Additionally, no stripping was observed in any mixtures, indicating good resistance to moisture damage and rutting.

Among all the mixtures tested, the 12.5-mm SMA mixtures showed the best rutting resistance, followed by AFC mixtures and two OGFC mixtures. The rutting resistance of AFC mixtures was generally between two OGFC mixtures and SMA mixtures, which is consistent with other performance test results discussed earlier.

The maximum rut depth difference between FC-5 and 9.5-mm OGFC mixtures was 0.6 mm, which is practically insignificant. This result demonstrates that finer gradation did not significantly impact the rutting resistance of OGFC mixtures. The rut depth difference between mixtures prepared with HP and PG 76-22 binders ranged from 0.0 to 1.0 mm, which is not considered practically different. Therefore, it was concluded that using the HP binder did not significantly improve the rutting resistance of these mixtures compared to the PG 76-22 binder.

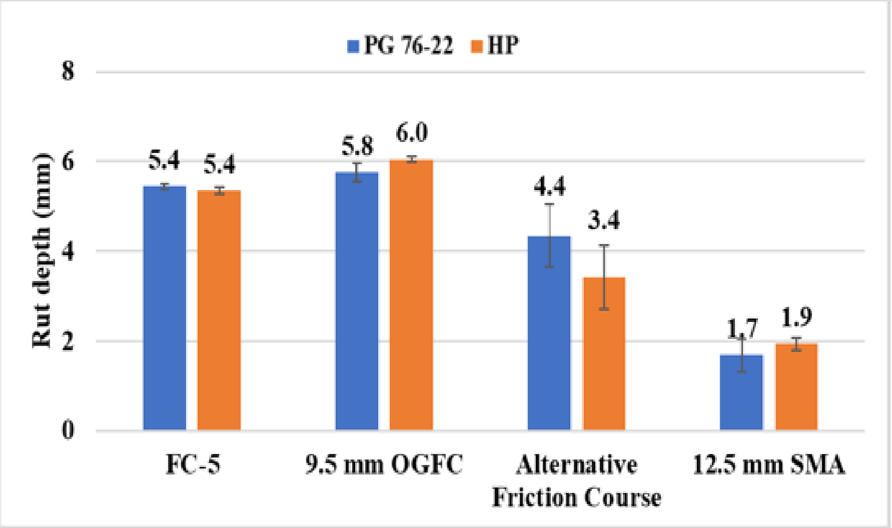


Figure 59. HWTT Rut Depth Results of GRN Mixtures

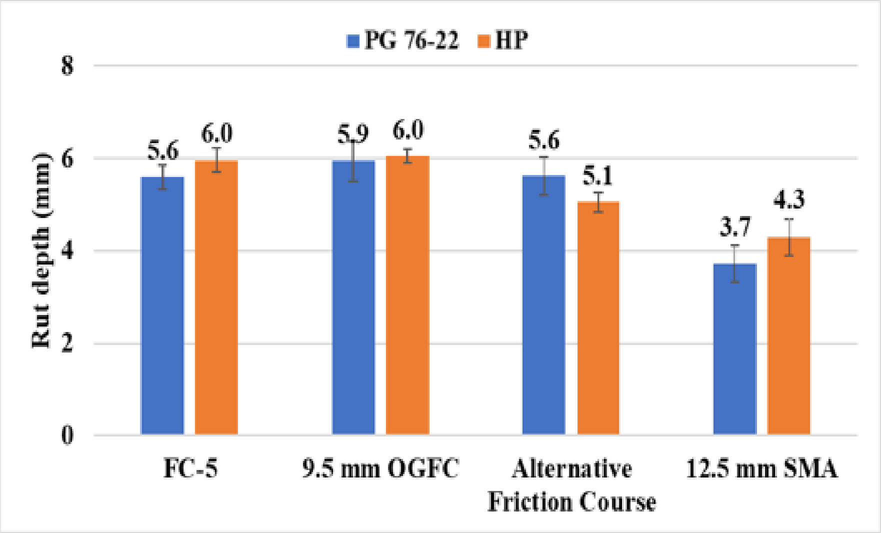


Figure 60. HWTT Rut Depth Results of LMS Mixtures

4.9 Surface Friction Evaluation

The graphs in Figures 61 and 62 show the evolution of DFT40 for the GRN and LMS mixtures, respectively, before and after three TWPD polishing cycles of 5,000, 50,000, and 100,000 cycles cumulatively. Both binders were utilized in testing these mixtures. In the initial stages of polishing (0 to 5,000 cycles), the DFT40 increased due to the removal of asphalt film from the surface for all mixtures. However, it subsequently decreased due to aggregate polishing.

The mixtures containing GRN aggregates (as shown in Figure 61) demonstrated higher DFT40 values than those containing LMS aggregates (as shown in Figure 62) after three TWPD polishing cycles. This can be attributed to the fact that GRN aggregates are known to be harder and have more angular edges and rougher textures to start with than LMS aggregates.

When comparing the same aggregate type, the 12.5-mm SMA exhibited slightly better friction than the other OGFC mixtures. There was no clear trend among the three OGFC mixtures. However, both the 9.5-mm OGFC and AFC mixtures exhibited comparable or slightly better friction than the FC-5 mixtures.

Moreover, the HP mixtures generally displayed comparable friction performance to the corresponding mixtures prepared with the PG 76-22 binder, regardless of the mixture and aggregate type. This suggests that the friction performance was not impacted by the binder type.

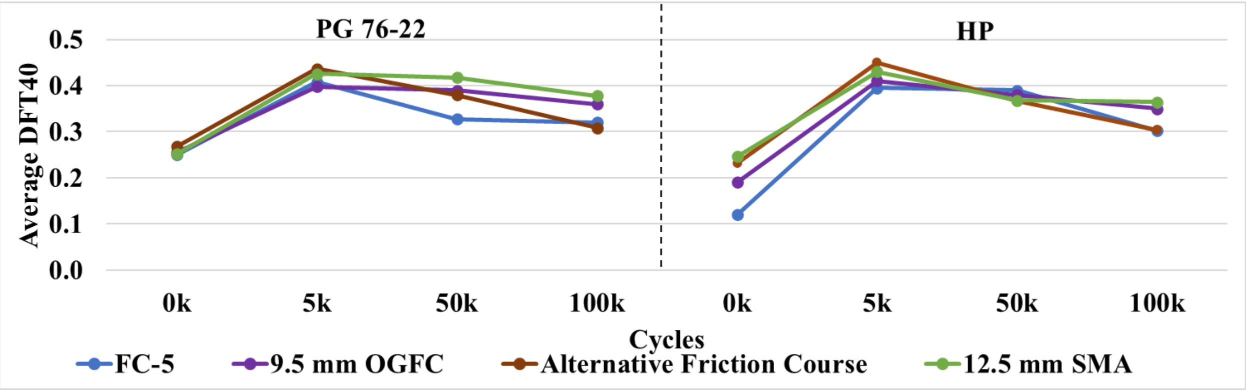


Figure 61. DFT40 Results of GRN Mixtures

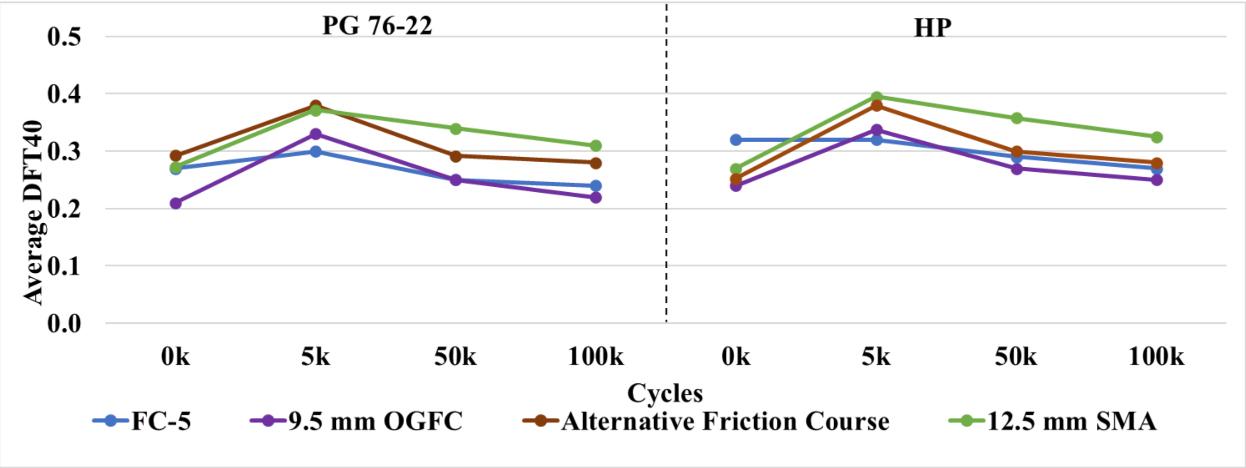


Figure 62. DFT40 Results for LMS Mixtures

4.10 Surface Macrotexture Evaluation

Figures 63 and 64 show the changes in MPD before and after three rounds of polishing (5,000, 50,000, and 100,000 cycles cumulatively) for GRN and LMS mixtures, respectively. For each aggregate type, the FC-5 mixtures had the highest MPD, while the 12.5-mm SMA mixtures showed the lowest MPD. Additionally, the 9.5-mm OGFC mixtures exhibited a higher MPD than the AFC mixtures, with their MPDs falling between the FC-5 and SMA mixes. The MPD results aligned with the drainability test results previously discussed, indicating that a coarser gradation and higher air voids in the mixtures typically lead to better drainability and macrotexture. Furthermore, no consistent trend was identified in comparing the MPD results between mixes that employed different binders, as macrotexture heavily depends on the aggregate properties.

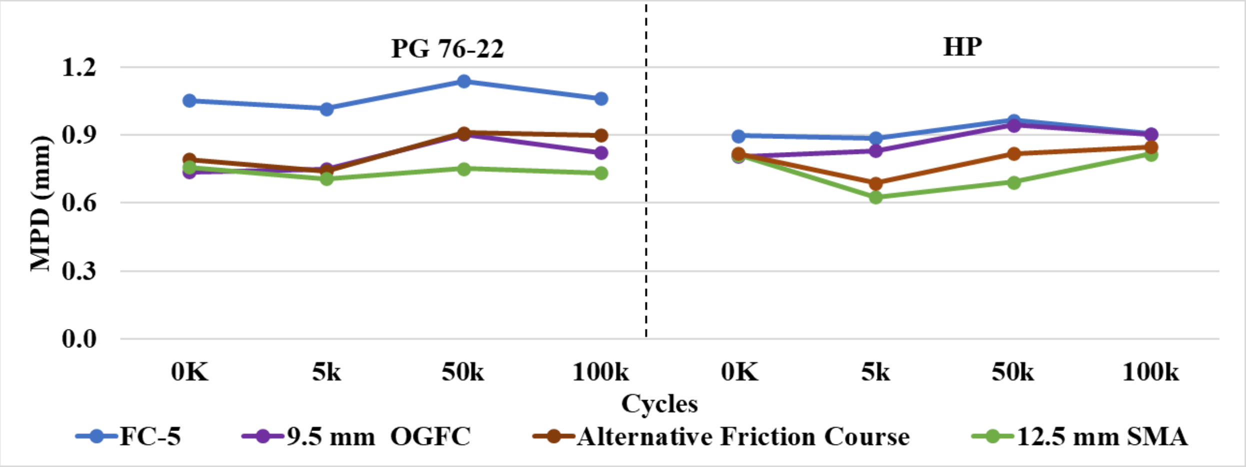


Figure 63. MPD Results of GRN Mixtures

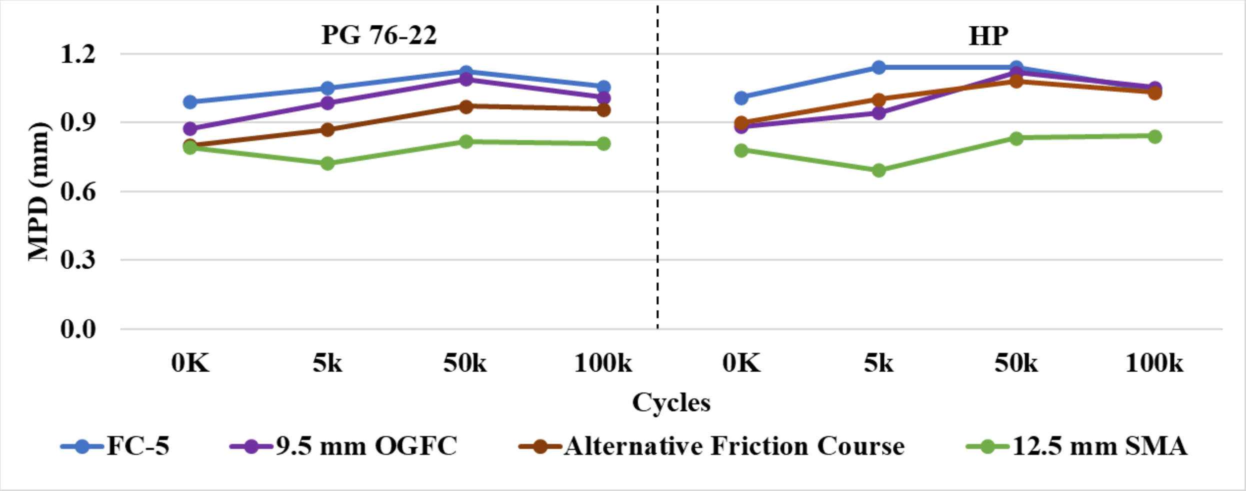


Figure 64. MPD Results of LMS Mixtures

4.11 Cost Analysis

Based on the laboratory test results, 9.5-mm OGFC, AFC mixtures, and/or HP binders could be utilized in suburban areas to increase pavement surface durability while maintaining permeability requirements for safety. The component materials of the 9.5-mm OGFC and AFC mixtures are almost the same as those of the FC-5 mixture, except for a slightly higher asphalt binder content of 0.2 to 0.3%. The production and construction protocols for these mixtures are identical to those for the FC-5 mixture. The extra cost of using 9.5-mm OGFC and AFC mixtures is around $2 per ton, which is to account for the additional 0.2 to 0.3% binder content. This price is based on the latest FDOT Asphalt Price Index for modified binder (PG 76 & Higher) of $743 per ton.

5. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Findings and Conclusions

The major findings and conclusions of the project are summarized below:

Regarding the mix design process:

- The FC-5, 9.5-mm OGFC, 12.5-mm SMA mixtures, and the AFC were designed to have varying air voids, with the highest in the FC-5 and 9.5-mm OGFC mixtures and the lowest in the 12.5-mm SMA mixtures.
- Using only the pie plate method to determine the optimum binder content for OGFC mixtures may not always achieve the desired performance. Therefore, incorporating other requirements, such as minimum air voids and/or maximum Cantabro loss, showed promise in addressing this challenge.
- For designing 12.5-mm SMA mixtures with the aggregate types tested in this study, an N_{design} of 35 gyrations can produce similar air voids to 50 Marshall blows.
- The gradation for the AFC was designed to be between the design gradations of the FC-5 and 12.5-mm SMA mixtures. It was modified based on the FC-5 gradation, with similar percent passings on the 1/2'' and 3/8" sieves, but with higher percent passings for smaller sieve sizes (i.e., No.4 and finer). The optimum binder content of the AFC was higher than that of FC-5 mixtures, increasing by 0.2% for GRN mixtures and 0.3% for LMS mixtures.

Regarding the effect of 9.5-mm NMAS gradation and HP binder on performance:

- Using a 9.5-mm gradation improves the durability of both GRN and LMS OGFC mixtures. This is especially true for GRN mixtures using PG 76-22, which shows a significant improvement.
- A 9.5-mm gradation has a statistically insignificant effect on cracking resistance of both GRN and LMS mixtures.
- Using a 9.5-mm gradation did not significantly affect the permeability of GRN and LMS OGFC mixtures. Both FC-5 and 9.5-mm OGFC mixtures can meet the minimum permeability threshold of 50 meters/day recommended for OGFC mixtures. In addition, there was no significant difference in drainability between the 9.5-mm OGFC and FC-5 mixtures for both GRN and LMS aggregates. This suggests that using 9.5-mm OGFC mixtures is a viable option that can meet the permeability requirements for OGFC mixtures, as compared to FC-5 mixtures.
- The difference in HWTT rut depths between the 9.5-mm OGFC and FC-5 mixtures was less than 1.0 mm, which is considered insignificant. Therefore, it can be concluded that using the 9.5-mm OGFC gradation did not have a negative impact on the rutting resistance of OGFC mixtures.
- The 9.5-mm OGFC mixtures presented higher DFT values than the corresponding FC-5 mixtures at all polishing cycles for GRN aggregate, suggesting that the friction of 9.5-mm OGFC mixtures is better than that of FC-5 mixtures. However, the 9.5-mm gradation does not affect the friction of LMS OGFC mixtures. Moreover, coarser FC-5 mixtures exhibit

greater macrotexture than finer 9.5-mm OGFC mixtures for both GRN and LMS aggregates.

- The use of HP binder in OGFC mixtures has been found to greatly enhance their durability and resistance to cracking. Moreover, the permeability, drainability, texture, rutting, and friction resistance of the GRN and LMS OGFC mixtures remain unaffected using HP binder. Compared to OGFC mixtures using PG 76-22, those with HP binder demonstrated better resistance to aging in the NAWS.

With respect to the potential performance of the AFC mixtures:

- Based on the Cantabro loss results for the GRN mixtures with PG 76-22 binder, the durability of the AFC mixtures is statistically comparable to that of the 12.5-mm SMA mixtures, which is statistically more durable than the FC-5 and 9.5-mm OGFC mixtures. However, the durability improvement of the AFC and 12.5-mm SMA mixtures with HP binder is statistically insignificant after STA but becomes significant after NAWS conditioning as compared to the FC-5 and 9.5-mm OGFC mixtures with HP binder. In addition, for the LMS mixtures with both binder types, the durability of the AFC mixtures is also statistically comparable to that of the 12.5-mm SMA mixtures in all aging conditions, but they are not statistically more durable than the FC-5 and 9.5-mm OGFC mixtures until after 2,000 hours of NAWS conditioning. This suggests the AFC mixture can be more durable than FC-5 and 9.5-mm OGFC mixtures in the field.
- Based on the OT results, the cracking resistance of the AFC and 12.5-mm SMA mixtures are statistically comparable to the FC-5 and 9.5-mm OGFC mixture for both aggregate types. Moreover, both the AFC and 12.5-mm SMA mixtures show similar or less impact of NAWS conditioning on their OT CRP results compared to FC-5 and 9.5-mm OGFC mixtures. This suggests that the AFC mixture can have similar or better cracking resistance than FC-5 and 9.5-mm OGFC mixtures.
- The AFC mixtures have higher permeability and drainability than 12.5-mm SMA mixtures but are lower than FC-5 and 9.5-mm OGFC mixtures. This is mainly because the AFC mixtures have lower design air voids due to the slightly finer gradation than the OGFC mixtures.
- All the mixtures had average HWTT rut depths below the commonly used criterion of 12.5 mm after 20,000 passes, and there was no indication of stripping. The rut depths in the AFC mixtures were higher than those in the 12.5-mm SMA mixtures but lower than those in the FC-5 and 9.5-mm OGFC mixtures. This indicates that the AFC mixtures can provide good resistance to moisture damage and rutting.
- The DFT40 value of AFC mixtures was higher than that of FC-5 mixtures for both binder and aggregate types at all polishing cycles. This indicates that the use of AFC mixtures has the potential to improve friction resistance in comparison to OGFC mixtures.
- The AFC mixtures showed higher macrotexture than the 12.5-mm SMA mixture but lower than the FC-5 and 9.5-mm OGFC mixtures. Hence, using the AFC mixtures can reduce macrotexture compared to the FC-5 mixtures. A surface with a higher macrotexture would enable water to drain more quickly.

According to the results of the mixture tests for a given binder type, it is suggested to use 9.5-mm OGFC and AFC mixtures instead of FC-5 mixtures in suburban areas. This can improve pavement durability while also meeting the safety permeability requirements. This change would increase the cost by approximately $2 per ton compared to FC-5 mixtures. In addition, HP binder can be used to further enhance the durability of 9.5-mm OGFC and AFC mixtures, as well as FC-5 mixtures in suburban areas. The use of HP binder in place of PG 76-22 binder does not affect the permeability, drainability, friction and macrotexture of the respective mixture.

5.2 Recommendations for Implementation and Future Research

This study showed that using a 9.5-mm OGFC gradation or HP binder resulted in better durability, cracking resistance, and surface friction than FC-5 mixtures. These improvements were achieved without compromising on rutting resistance, permeability, and drainability. Furthermore, AFC mixtures could further enhance the durability and resistance to cracking, moisture damage, and rutting to a similar level to 12.5-mm SMA mixtures. Although their permeability and drainability were significantly reduced, the AFC mixtures were still reasonably permeable. Therefore, it is recommended that FDOT consider utilizing a 9.5-mm OGFC mixture, AFC mixture and/or HP binder in suburban areas to enhance pavement durability while upholding safety characteristics similar to the FC-5 mixture.

Design procedures for the two mixtures are discussed in this section to support their implementation. The procedures involve selecting a design gradation and determining an optimum binder content (OBC). The gradation requirements for both 9.5-mm OGFC and AFC mixtures are provided in Table 23. The gradation requirements for 9.5-mm OGFC mixtures are based on the Georgia Department of Transportation (GDOT) specifications. The gradation requirements for AFC mixtures were established during this study. The requirements for both gradations can be developed based on the aggregate stockpiles currently used for FC-5 mixtures. Once the design gradation is selected, the OBC can be determined based on the Pie Plate Method per FM 5-558.

To ensure that the design gradation and the selected OBC yield the desired performance, additional performance requirements are outlined in Table 23. For the 9.5-mm OGFC mix design, it is proposed to have minimum air voids of 15% and a maximum Cantabro loss of 15%. Similarly, for the AFC mixture, it is suggested to have an air void range of 10%-15% and a maximum Cantabro loss of 10%.

The air void requirements are determined based on the bulk specific gravity of compacted asphalt specimens determined using the vacuum sealing method as per AASHTO T331. Additionally, the asphalt specimens used for air void determination and Cantabro loss testing are compacted to N_{design} of 50 gyrations with a target gyratory sample height of 115 mm. Before compaction, the loose mix samples are short-term oven-conditioned for two hours at the compaction temperature.

The requirements listed in Table 23 can be combined with other material requirements already mentioned for FC-5 mixtures in Section 337 of the FDOT Standard Specifications for Road and Bridge Construction. It is also noted that the construction practices for these mixtures remain the same compared to the FC-5 mixtures, including the in-place thickness.

Table 23. Preliminary Design Requirements of 9.5-mm OGFC and Alternative Friction Course Mixtures

Sieve Size	**FC-5**	**9.5-mm OGFC**	**Alternative Friction Course**
3/4"	100	100	100
1/2"	85 - 100	100	85 - 100
3/8"	60 - 75	85 - 100	60 - 75
#4	15 - 25	20 - 40	25 - 35
#8	5 - 10	5 - 10	10 - 15
#200	2 - 5	2 - 4	2 - 5
Mix Property	**Test Standard**	**9.5-mm OGFC**	**Alternative Friction Course**
N_{design}	N/A	50	50
Air Voids (%)	AASHTO T 331	≥ 15	10 -15
Cantabro Loss (%)	AASHTO T 401	≤ 15	≤ 10

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