Open-Graded Friction Courses Suitable for Suburban Environments

by

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ABSTRACT

The Florida Department of Transportation (FDOT) utilizes an open-graded friction course (OGFC), called FC-5, on all multi-lane roadways with a design speed of 50 mph or greater, except for curb and gutter sections, to enhance safety by minimizing hydroplaning. However, FC-5 layers on high-speed multi-lane suburban roadways experience premature raveling due to high lateral stresses caused by turning, rapid acceleration, and braking activities. Currently, the FC-5 mixture is designed with a 12.5-mm nominal maximum aggregate size (NMAS) gradation and a polymer-modified PG 76-22 binder. To improve the durability of the FC-5 mixtures, 9.5 mm NMAS gradation and high polymer modified (HP) binder were evaluated. Besides, an alternative friction course was developed which is more durable in suburban environments and is drainable while maintaining adequate friction and texture properties. The experimental plan included four mix designs (FC-5, 9.5 mm OGFC, 12.5 mm SMA, and an alternative friction course), designed with two aggregate types (granite GRN and limestone LMS), and two binder types (PG 76-22 and HP). The laboratory tests included the Cantabro test, Permeability test, Drainability test, Circular Track Meter (CTM) test, Dynamic Friction Test (DFT), Overlay Test (OT), and Hamburg Wheel Tracking Test (HWTT), which characterized the mixture's durability, permeability, drainability, texture, friction, cracking resistance, and rutting resistance, respectively. Note that the Cantabro and OT specimens were tested both before and after conditioning at the NCAT Accelerated Weathering System (NAWS) to evaluate the aging resistance of the mixtures. The results show that using HP significantly improved the durability and cracking resistance of the asphalt mixture while maintaining permeability, drainability, rutting resistance, macrotexture, and friction resistance. Mixtures with HP showed higher aging resistance compared to those designed with PG 76-22. Using the finer gradation of 9.5 mm NMAS also improved the performance of the FC-5 mixture, but the improvement was generally not significant. The alternative friction course enhanced FC-5 performance, especially with durability. Although the mixture had lower permeability and drainability than that of the OGFC mixture, it was significantly higher than that of 12.5 mm SMA mixtures, indicating its permeable ability. Additionally, the alternative friction courses generally demonstrated higher aging resistance compared to FC-5 and 9.5 mm OGFC mixtures.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Cement
AL	Alabama
AMPT	Asphalt Mixture Performance Tester
APA	Asphalt Pavement Analyzer
AR	Asphalt Rubber
ASTM	American Society for Testing and Materials
AWS	Accelerated Weathering System
AZ	Arizona
BHF	Bag House Fine
CA	California
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
FL	Florida
GA	Georgia
GDOT	Georgia Department of Transportation
GRN	Granite
HP	High Polymer
HWTT	Hamburg Wheel Tracking Test
IFT	International Friction Index
ITS	Indirect Tensile Strength
LA	Louisiana

LMS	Limestone
LVDT	Linear Variable Differential Transducer
LVE	Linear Viscoelasticity
MS	Mississippi
NAPA	National Asphalt Pavement Association
NAWS	NCAT Accelerated Weathering System
NCAT	National Center for Asphalt Technology
NE	Nebraska
NJ	New Jersey
NM	New Mexico
NMAS	Nominal Maximum Aggregate Size
NV	Nevada
NY	New York
OBC	Optimum Binder Content
OGFC	Open-Graded Friction Course
OH	Ohio
OK	Oklahoma
OR	Oregon
OT	Overlay Test
SBR	Styrene Butadiene Rubber
SBS	Styrene Butadiene Styrene
SC	South Carolina
SCB	Semicircular Bending
SFE	Surface Free Energy
SIP	Stripping Inflection Point
SMA	Stone Matrix Asphalt
TN	Tennessee
TSR	Tensile Strength Ratio
TX	Texas
US	United States
UT	Utah

VA	Virginia
VCA	Voids in Coarse Aggregate
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
WA	Washington
WI	Wisconsin
WY	Wyoming

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Open-graded friction courses (OGFCs) are specially designed asphalt mixtures with gap-graded gradations, resulting in higher air void contents (ranging from 15% to 22%) compared to typical dense-graded asphalt mixtures (DGM) [1]. These unique mix design features contribute to increased permeability and enhanced noise absorption.

Asphalt pavement with insufficient drainage ability can cause hydroplaning since water accumulates and builds a layer between the vehicle tire and the pavement surface. This results in the loss of the driver’s ability to control barking and steering. Poor drainage pavement also creates spray and splash clouds, significantly reducing driver visibility. To address these problems, OGFC with high drainage and permeable nature, has been used to penetrate water from the pavement surface and facilitate lateral drainage at the interface with the underlying impermeable layer [2]. Consequently, OGFCs help reduce hydroplaning, splashing, and spraying in wet weather conditions [1, 3, 4] and improve visibility by 2.7- 3.5 times compared to DGM pavements [5]. Besides, the mixture also improves pavement friction, especially in wet conditions [4, 6]. The safety benefits obtained from OGFC mixes make them a preferred choice for enhancing road safety, particularly in the southern states of the United States [7-9]. Despite the safety benefits, challenges exist regarding the application and maintenance of OGFC mixtures, especially concerning their durability, which refers to their resistance to distress and potential failure over time.

In Florida, where wet weather conditions are frequent, FDOT has implemented a friction course policy mandating the use of OGFC (known as FC-5) on all multi-lane roadways with a design speed of 50 mph or higher to enhance safety. However, the policy limits the use of OGFC to roadways without curb and gutter sections, except in areas with a documented history of wet-weather accidents [7]. Roadways within curb and gutter sections typically use dense-graded friction courses, such as FC-9.5 or FC-12.5, which offer good friction characteristics but are less effective in minimizing hydroplaning.

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 has led to the placement of FC-5 in areas subject to high lateral stresses, such as turning movements, rapid acceleration, and braking activities, which are unsuitable for OGFC applications. Consequently, the FC-5 payment layer has experienced premature raveling, which has become a significant concern for FDOT. Under the effect of raveling, the life expectancy of FC-5 in Florida has been limited to nearly 14 years which is typically shorter than about 20 years of DGM pavement [10].

To address this issue and find a more durable solution for suburban areas while maintaining safety characteristics comparable to FC-5, FDOT aims to develop an improved OGFC. This will provide designers with alternative pavement options for suburban areas and high-speed pavements in curb and gutter sections. Most importantly, it will help extend the life of the pavement, minimize maintenance and resurfacing activities, and reduce associated traffic disruptions. This pressing need has motivated the research presented in this paper, which aims to develop a more durable OGFC suitable for suburban applications.

1.2 Research Objects and Scope

FC-5 mixtures are currently designed with a 12.5 mm NMAS and polymer-modified PG 76-22 binder. They constitute approximately 50% of the pavement surfaces on Florida’s State Highway System [11], underscoring the significance of the FC-5 application. Consequently, FDOT has sponsored numerous research efforts over the years to improve the durability of FC-5 mixtures. These research efforts encompassed several approaches, from finite element modeling to understand the mechanisms of OGFC raveling [12] to laboratory and field experiments assessing changes in component materials [13, 14], mix design methods [15, 16] and construction practices [17-19] to extend the OGFC service life. Based on prior FDOT-sponsored research [12, 13, 16] 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 main objective is to (1) evaluate the effect of utilizing a finer 9.5 mm NMAS gradation and high polymer modified (HP) binder to improve the durability of the asphalt mixture and (2) determine alternative friction courses that are more durable in suburban environments and are drainable while maintaining adequate friction and texture properties. The study includes a comprehensive test plan carried out under different aging conditions, as follows:

- 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 (OT, Tex-248-F), and rutting resistance (HWTT, AASHTO T 324).
- 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 (DFT, ASTM E1911), and surface texture (CTM, ASTM 2157).
- Two aging conditions were considered: short-term loose mix oven aging and long-term compacted specimen aging using the NAWS (ASTM D4799).

1.3 Thesis Outline

The thesis is organized into six chapters. Chapter 1 serves as an introduction, addressing the challenges tied to OGFC pavements in Florida and defining the objectives of this study. In Chapter 2, a comprehensive literature review is presented, exploring the application of OGFC in the US with a particular emphasis on Florida. This chapter discusses design factors that influence OGFC performance, particularly durability and functionality. It also discusses the common OGFC and SMA mix designs in the US and provides a comparative analysis of their performance. Chapter 3 describes the research methodology, including the experimental plan, criteria for material selection, and design processes for FC-5, 9.5 mm OGFC, and 12.5 mm SMA. Furthermore, it describes alternative friction mix designs and the laboratory tests employed in the study. Chapter 4 offers a concise overview of the mix designs for the specified mixtures. Chapter 5 reports the laboratory test results and provides an analytical discussion interpreting these findings. Lastly, Chapter 6 draws conclusions based on the research and provides recommendations.

CHAPTER 2 LITERATURE REVIEW

2.1 Use of OGFC Mixtures

2.1.1 Use of OGFC Mixture in the United States

OGFC mixtures were introduced in the 1950s to enhance the friction resistance of asphalt pavement in the United States [20]. The mixture quickly showcased its benefits, especially under wet weather conditions, by improving pavement surface friction and reducing splash and spray. However, it was not until the 1970s that OGFC mixtures were known across the U.S. because of the Federal Highway Administration's (FHWA) program to increase pavement skid resistance. Consequently, many states began to adopt either the mix design method published by FHWA or a recipe mix composition [21].

While OGFC mixtures offered numerous advantages, their usage sharply declined in the 1980s, with many states discontinuing their application [22]. A survey of 47 states in 1988 showed that only 27 states continued using the mixture, while the others stopped using it [23]. By 1998, a survey of 42 states found that 19 states (representing 38%) had stopped using the mixture [20]. A subsequent survey in 2000 showed similar results, with 55% of the 42 responding states halting the use of OGFC mixtures.

The discontinuation was attributed to various factors, but a prevalent concern was the mixture durability. Issues such as raveling and stripping [20, 24], oxidation of the asphalt binder film [23], and inadequate durability [20] were frequently cited. At the time, polymer-modified binders were not available, and fibers were not used in OGFC mixtures. To reduce binder draindown, these mixtures were designed with a relatively low optimum binder content (OBC) [1], which resulted in some of the issues frequently cited. To address these concerns, several improvements have been made to optimize OGFC performance. Various polymers, crumb rubbers, and additives, including warm mix asphalt additives, were explored to improve OGFC durability [25-27]. Using mineral and cellulose fibers reduced binder draindown significantly, allowing for selecting a higher OBC for enhancing cohesion and durability [25, 26]. Several changes were made to the OGFC mix design, emphasizing material selection, gradation design, binder content selection, and moisture evaluation [28]. These changes help optimize aggregate gradations for increased air voids and utilize the Cantabro, draindown, and moisture susceptibility tests for performance assessment [29, 30].

In addition to durability concerns, functional concerns such as clogging and challenges in winter maintenance hindered the widespread adoption of OGFC [31, 32]. Clogging, caused by sediment and dust accumulation, reduces its permeability and effectiveness in noise reduction. Several states reported a significant reduction in OGFC permeability after two to three years [21]. Moreover, in northern US states, maintaining the OGFC integrity during winter proved particularly challenging, further contributing to the diminished use of OGFC [3, 33].

Currently, the utilization of OGFC is largely observed in the Southeastern states [34]. Northern states have reservations due to winter maintenance concerns, but recent improvements in OGFC design and more data on safety benefits may encourage some states to reconsider its use [27]. A survey conducted by Cooley et al. [34] indicates a preference for using OGFC mixtures on higher-speed roadways, with 50% of respondents using it on rural roadways and 75% on urban freeways.

2.1.2 Use of OGFC Mixture 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 1970’s, with four being open-graded. These open-graded mixtures had problems with raveling, rutting, and stripping. In 1979, based on guidelines and a design procedure published in 1974 by the Federal Highway Administration (FHWA) [35], FDOT developed a new OGFC called FC-2, which replaced their existing wearing course mixtures. The FC2 was designed with a modified version of the pie plate method described in the FHWA design procedure [36].

The FC-2 mixture was required on all high-speed multilane roadways to reduce the risk of hydroplaning, but the mixture was also permitted (as a bid alternate to dense-graded friction courses) for use in urban areas or curbed sections. Consequently, 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 which have significant amounts of turning movements [36].

In the late 1990s, based on the positive feedback that the Georgia Department of Transportation (GDOT) had received on its D-Modified OGFCs, FDOT developed a similar OGFC called FC-5. The FC-5 mixture has a 12.5 NMAS that uses only granite or oolitic limestone for the aggregate and uses a modified asphalt binder (either a polymer or rubber-modified PG 76-22). The FC-5 is placed at a thickness of 3/4 in. When FC-5 was first adopted, FDOT also modified a number of pavement design procedures, eliminated the option of using OGFC as a bid alternate to dense-graded friction courses, and restricted the locations where FC-5 mixtures could be used [37]. 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 Critical Factors Affecting OGFC Mixture Performance

OGFC mixture performance is primarily assessed in terms of durability and functionality. Durability is the capability of the asphalt mixture to withstand various forms of distress and failures, such as rutting, reflective cracking, and, most importantly, raveling. Functionality, on the other hand, refers to the ability of the OGFC mixture to retain its characteristics over time, particularly in terms of permeability and noise reduction [3]. It is important to note that surface texture and friction resistance are associated with the mixture's functionality, enhancing skid resistance and preventing hydroplaning [34]. This section reviews prior studies to identify the factors contributing to the durability and functionality of OGFC mixtures. Key findings from these studies emphasize the significance of air voids, binder grade and content, aggregate gradation, bag house fine (BHF) content, and stripping agents. Additionally, factors such as aggregate type and compaction energy have also demonstrated their impacts.

2.2.1 Air Voids

The influence of air voids on the performance of OGFC mixtures was evaluated in terms of permeability and durability. Several studies have consistently demonstrated a clear and direct relationship between air void content and the permeability of OGFC mixtures, indicating that higher air voids result in improved permeability [38, 39]. For instance, Watson et al. [39] conducted a study to establish the relationship between the permeability coefficient and air void content in OGFC mixtures. Their findings showed that increasing air voids from 15.7% to 21.9% raised the permeability coefficient from 80 meters/day to 237 meters/day. Furthermore, a mathematical relationship was formulated to represent the correlation between air void content and permeability, as illustrated in **Equation 1**. This relationship was characterized by a high coefficient of determination (r^2) of 0.94, further underlining the direct relationship between air void content and permeability. Higher air void content not only improves initial permeability but also prevents permeability loss due to particle-related clogging during service life [40].

$$K_{OGFC} = 24.87*AC-324.88 \qquad (1)$$

Where:

K_{OGFC} = Permeability of OGFC mixture (m/day)

AC = Air void content (%)

To ensure desired permeability, a minimum air void threshold is necessary. A minimum design air void content of 18%, determined by the Core Lok method, was recommended to achieve the permeability values of 100 meters/day. However, it was observed that reaching this permeability could pose challenges for certain aggregate types, especially fine gradations [41]. Therefore, an alternative minimum permeability rate of 50 meters/day associated with an air void content of 15% was recommended. The air void can be measured by either the Vacuum method (AASHTO T 331) or the dimensional method, with the recommended air void range being 15-20 percent or 17-22 percent, respectively [39].

In addition to permeability, air voids also play a crucial role in the durability of the OGFC mixtures. James et al. [42] conducted a study to evaluate the effect of air void contents on the durability of the OGFC mixtures. In this study, two mixtures were classified as “good” and “poor” mixtures based on the service life. The “good” mixture exhibited a remarkable service life of 18 years before being replaced due to raveling failure, while the “poor” mixture had a shorter lifespan, being removed after only 8 years due to the same raveling issue. The 'good' mixture reported a Cantabro loss of 19.3% and withstood over 20,000 passes in the HWTT. In contrast, the 'poor' mixture exhibited a higher Cantabro loss of 37.9% and failed after only 2,000 passes in the HWTT. The key difference between the two mixtures was the air void content, with the 'good' mixture designed at 15.4% and the 'poor' mixture with a higher value of 22.2%. These results demonstrated that higher air voids make OGFC mixtures more susceptible to raveling and rutting.

Similarly, in the NCHRP 1-55 project [39], six OGFC mixtures were classified into two groups: three with good and three with poor field performance. The ‘good” mixture group was designed with lower air voids and provided a lower Cantabro loss than the “poor” mixture group. Moreover, although both mixtures met the rut depth requirement after 20,000 passes, the mixture with the highest air void failed after only 3,200 passes. These results indicate the importance of lower air voids in enhancing the durability of OGFC pavement.

In summary, high air void content enhances the permeability and drainability of the OGFC mixture but increases susceptibility to aging, moisture damage, stripping, and particularly raveling [43].

2.2.2 Aggregate Gradation

Gradation plays a vital role in the performance of OGFC mixtures, affecting both their durability and functionality [44-46]. The gradation parameters, including finer gradation, percentage aggregate passing No.4. No.8 sieve, NMAS, and BHF content, have been proven to influence.

2.2.2.1 Finer Gradation

In general, finer gradation has the potential to reduce the permeability of the OGFC mixture as a result of lower air voids [29, 41]. However, it was found that using finer gradation can improve the performance of OGFC mixtures. Bennert and Cooley [16] investigated the effects of mixture properties on the durability of the FC-5 mixtures, finding that the mixture with a finer gradation (9.5 mm NMAS) yielded better durability and fatigue cracking resistance than the coarse gradation (12.5 mm NMAS). Similarly, studies by Watson et al. [30] and Xie et al. [47] demonstrated higher tensile strength, moisture resistance, and long-term permeability in 9.5 mm OGFC mixtures compared to 12.5 mm OGFC mixtures.

2.2.2.2 Percentage of Aggregate Passing No.4 and No.8 Sieve

The percentage of aggregate passing the No. 4 and No. 8 sieves impacts the performance of OGFC mixtures in terms of permeability, surface texture, and durability. Mallick et al. [21] reported that increasing the percentage passing the No.4 sieve resulted in a decrease in permeability. For example, OGFC mixtures designed with 15% passing the No. 4 sieve exhibited the highest permeability at 117 meters/day, whereas mixtures designed with 30% passing the No. 4 sieve had a permeability of 28 meters/day, and those with 40% passing the No. 4 sieve displayed the lowest permeability of 21 meters/day. A survey of nine US highway agencies further supported the conclusion that a higher percentage passing the No. 4 sieve could lead to insufficient permeability, suggesting a recommended range of aggregate passing the No. 4 sieve from 10% to 30% to ensure adequate permeability for OGFC pavement [48].

Similarly, increasing the percentage passing the No. 8 sieve also reduced the permeability of the OGFC mixtures. This was attributed to No. 8 aggregates filling the air voids created by larger aggregates, reducing connected voids but increasing isolated voids. Consequently, this results in fewer porous channels for water drainage [49].

The percent passing the No. 4 sieve also affects the macrotexture of the OGFC surface. Putman et al. [50] measured the macrotexture depth of OGFC mixtures using the sand patch test described in ASTM E965, and the result indicated a strong relationship between macrotexture depth with the percentage of aggregate passing the No.4 sieve with an R^2 value of 0.86. They reported increasing the percentage passing No.4 sieve resulted in decreasing macrotexture value.

In contrast to its impact on permeability and macrotexture, a higher percentage of aggregate passing the No. 4 sieve has shown a positive effect on the durability of OGFC mixtures [21, 48]. Nekkanti et al. [48] conducted a study to evaluate the impact of aggregate passing the No. 4 sieve on the durability of OGFC mixtures. They categorized eight different mixtures into two groups: one with 12.5 NMAS aggregate gradation and percentages passing the No. 4 sieve ranging from 10% to 40%, and the other with 9.5 mm NMAS gradation and percentages passing the No. 4 sieve ranging from 20% to 50%. These mixtures were then evaluated by using Indirect Tensile Strength (ITS) and Cantabro tests. The results indicate that the ITS reached the highest value when the percent passing the No. 4 sieve was 30% for both mixtures. Increasing the percent passing the No.

4 sieve reduced the raveling resistance of the OGFC mixture based on the Cantabro mass loss. Similarly, Mansour and Putman [51] reported that mixtures designed with the percent passing the No. 4 sieve above 20% yielded a Cantabro loss of 4.7 %, while mixtures with less than 20% of the aggregate passing the No. 4 sieve exhibited a higher Cantabro loss of 7.2%. The results highlighted the conclusion that using higher percentages of aggregate passing No.4 could increase the raveling resistance.

In summary, increasing the percentage of aggregate passing the No. 4 sieve in OGFC mixtures decreases their permeability and macrotexture. However, this adjustment can enhance the overall durability of the mixture.

2.2.2.3 Nominal Maximum Aggregate Size (NMAS)

NMAS significantly impacts both the functionality and durability of OGFC mixtures. Higher NMAS enhances the permeability of OGFC mixtures [40, 52]. Momm et al. [53] evaluated the effect of different NMAS sizes on the permeability of the OGFC mixture. Their findings showed that 19 mm NMAS mixtures exhibited the highest permeability performance, followed by 12.5 mm NMAS and then 9.5 mm NMAS mixtures. This conclusion is consistent with Hasan et al. [54] results, which also show a higher permeability of 12.5 mm NMAS mixtures than 9.5 mm NMAS mixtures. Although both mixtures were designed with the same air void content, the presence of more fine particles in 9.5 mm NMAS mixtures clogged the interconnecting voids, consequently reducing permeability.

In addition, Wu et al. [55] evaluated the drainability of several OGFC mixtures with different NMAS sizes using an outflow meter. The result, as shown in **Figure 1**, illustrates that the 9.5 mm OGFC and 12.5 mm OGFC mixtures showed shorter outflow times than the three 4.75 mm OGFC mixtures (designated as #4P), indicating that a higher NMAS size resulted in improved drainability.

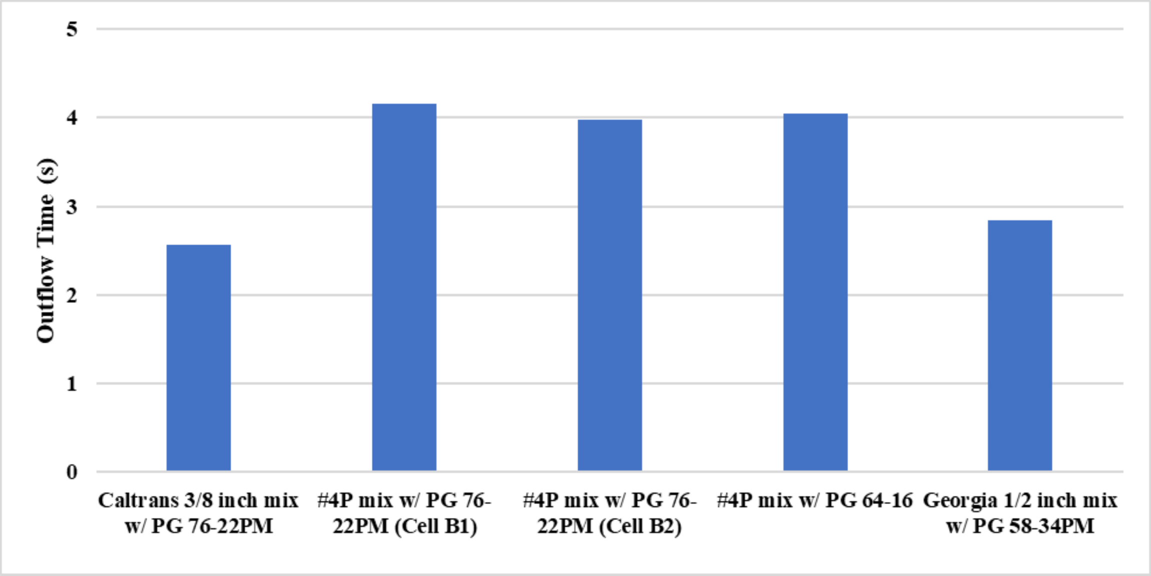


Figure 1. Drainability of Different OGFC Mixtures [55]

The NMAS also shows the influence on the macrotexture of the OGFC mixture. Lu et al. [45] demonstrated a strong relationship between the NMAS and macrotexture with an adjusted $r^2$of 0.76, presented in the formula below:

$$\text{MPD}= 0.7237+0.0554*(\text{NMAS}) \qquad (2)$$

Where:

MPD: Mean Profile Depth

NMAS: Nominal Maximum Aggregate Size

Furthermore, Wu et al. [55] investigated the effect of NMAS sizes on the macrotexture and friction properties of the OGFC mixtures using CTM and DFT tests. The CTM results, as shown in **Figure 2**, indicated that the 9.5 mm OGFC and 12.5 mm OGFC mixtures showed higher MPD values than the three 4.75 mm OGFC mixtures (designated as #4P). The DFT results, as shown in **Figure 3,** exhibited that the 12.5 mm OGFC mixtures provided a higher DFT value than the 9.5 mm OGFC and 4.75 mm OGFC mixtures (designated as #4P). These results demonstrated that the OGFC mixture with a larger NMAS had higher macrotexture and friction resistance.

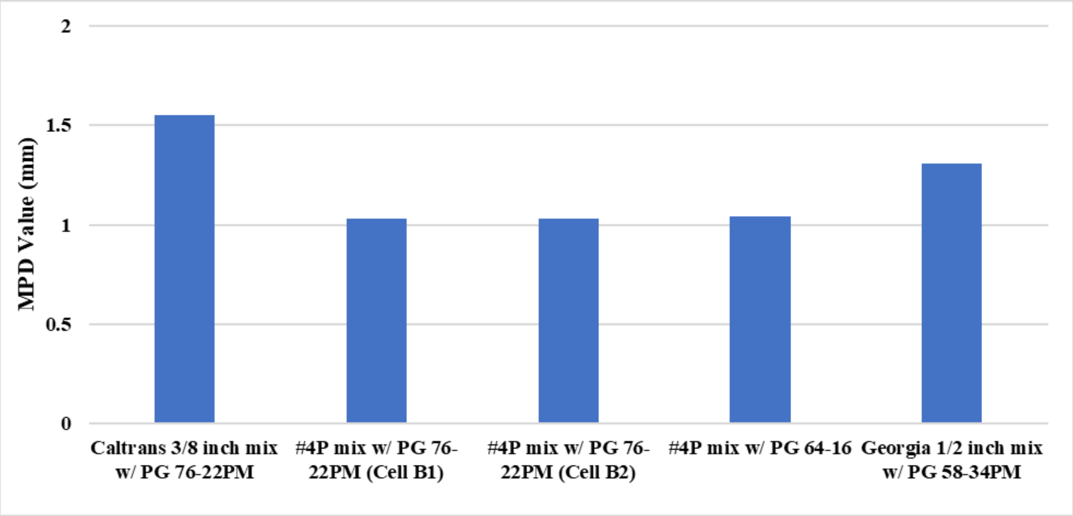


Figure 2. OGFC Macrotexture Result [55]

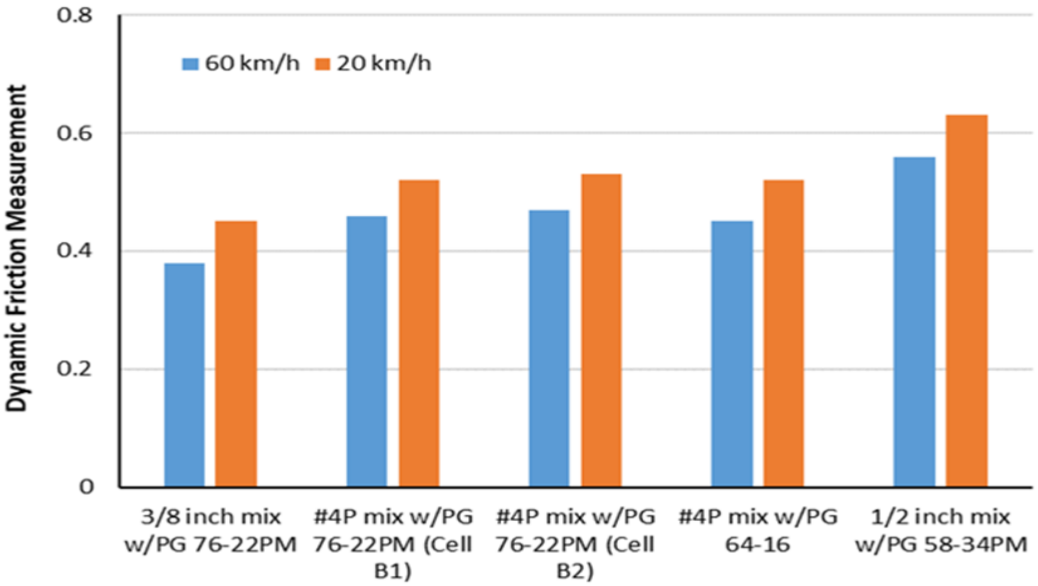


Figure 3. DFT Results of Different OGFC Mixtures [55]

NMAS plays an important role in the durability of OGFC mixtures. OGFC mixtures prepared with smaller NMAS provided better fracture performance and overall durability than those with larger NMAS [54]. Hasan et al. [56] evaluated the influence of the NMAS on OGFC mixtures with three different sizes: 14 mm, 20 mm, and 25 mm, using the ITS and Cantabro tests. The Cantabro test results indicated that larger NMAS sizes resulted in higher Cantabro loss, indicating reduced durability. Meanwhile, in the ITS test, an increase in NMAS substantially decreased the tensile strength of the OGFC mixtures.

In summary, using a higher NMAS in OGFC mixtures enhances permeability, macrotexture, and friction resistance, but it also results in reduced durability.

2.2.2.4 Bag House Fine (BHF)

BHF content is another crucial factor that affects both the permeability and durability of OGFC mixtures. An increase in BHF content typically results in a reduction of air void content, leading to decreased permeability. Watson et al. [39] studied this impact on Georgia and South Carolina OGFC mixtures, as shown in **Figure 4**. In Georgia mixtures with a 6% binder content, those without BHF exhibited the highest permeability at 79.6 meters/day, while the addition of 2% BHF led to a lower permeability of 42.8 meters/day, and 4% BHF resulted in the lowest permeability at 37.8 meters/day. South Carolina mix designs showed a slight reduction in permeability with increased BHF, likely due to high initial air voids.

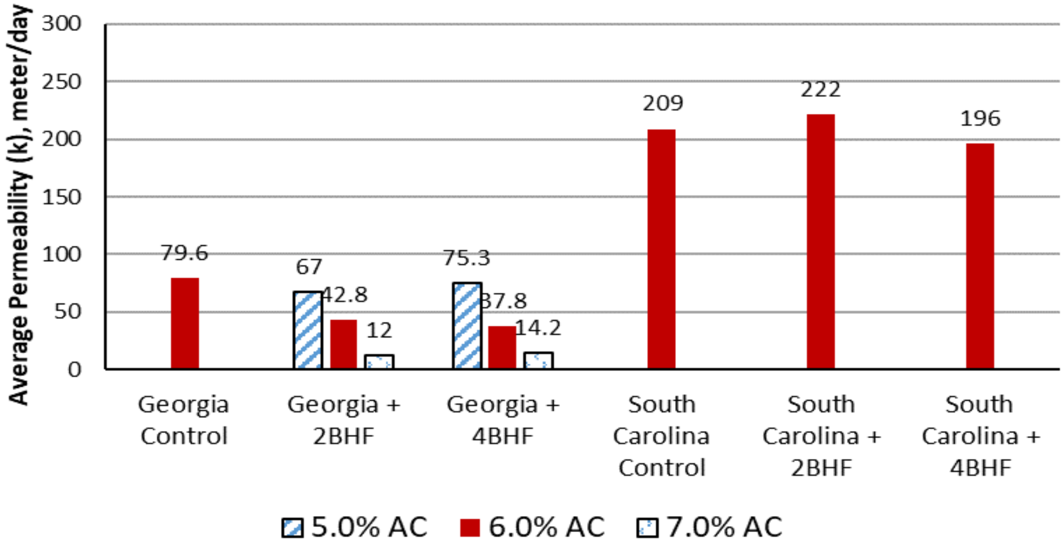


Figure 4. Effects of BHF and Binder Contents on Permeability [39]

BHF content significantly affects the durability of OGFC mixtures. Watson et al. [39] evaluated the influence of BHF on the moisture susceptibility of OGFC mixtures using the ITS test. The dry ITS, and Tensile Strength Ratio (TSR) results are presented in **Figures 5** and **6**. As presented in

Figure 5, the dry ITS increased with the increase of BHF content for both Georgia and South Carolina mix designs, potentially due to increased mastic content, leading to a stronger mixture. In **Figure 6**, the TSR value increased for Georgia but decreased for the South Carolina 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 the South Carolina design, the decreased trend might be explained by the offset of a lower free binder.

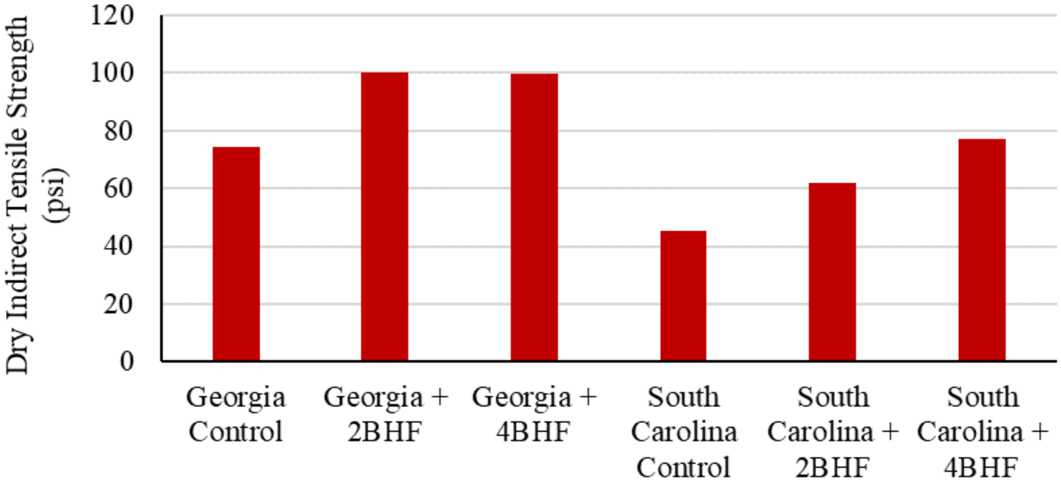


Figure 5. Effect of BHF on Dry Indirect Tensile Strength Results [39]

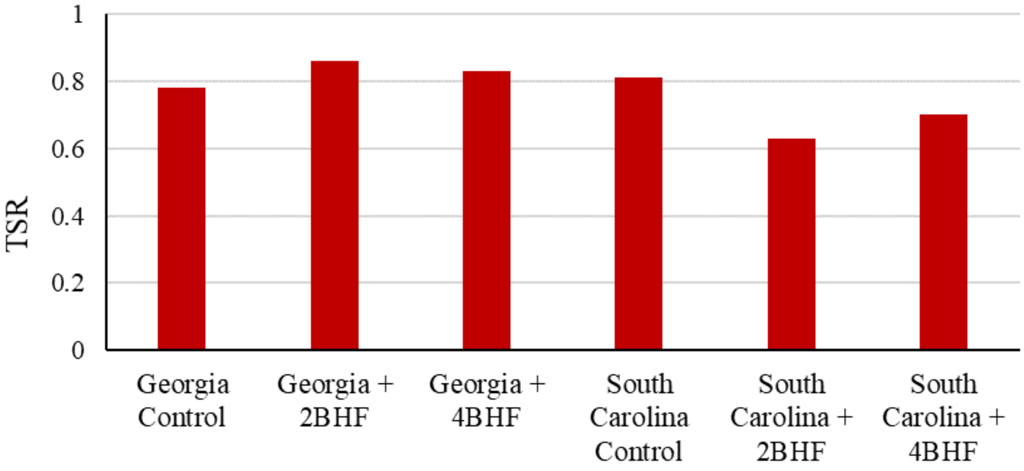


Figure 6. Effect of BHF on TSR Results [39]

Watson et al. [39] also utilized the Cantabro test to evaluate the effects of BHF on the durability of the OGFC mixtures, and the mixtures with lower Cantabro loss were expected to yield better durability than those with higher loss values. As shown in **Figure 7**, for both Georgia and South Carolina designs, the Cantabro loss decreased with the increased BHF content, which was expected. For the Georgia mix design, the mixture with additional 2% and 4% BHF at 5% binder content had comparable Cantabro loss with the 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 South Carolina 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 increasing the asphalt binder content by 1%. Moreover, the addition of BHF improved the rutting and cracking resistance of the OGFC mixtures, as shown by the increasing number of cycles to failure obtained from the HWTT and OT test [39]

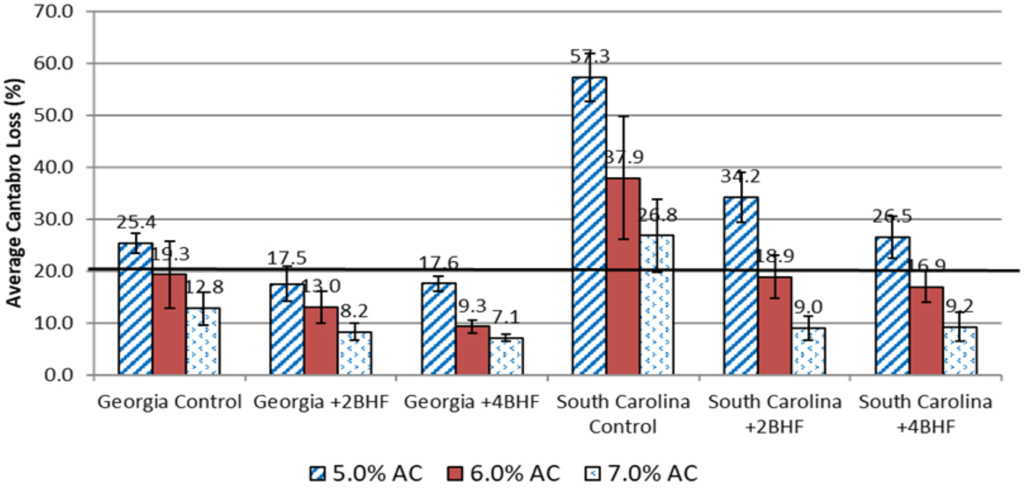


Figure 7. Effects of Binder Content and BHF on Cantabro Loss Results [39]

In summary, the use of BHF in OGFC mixtures has a significant impact on their performance. Increasing BHF content reduces permeability, but it can enhance the overall durability of the mixture.

2.2.3 Asphalt Binder

Asphalt binder, including its type and content, influences the performance of the OGFC mixture. Binder content affects both permeability and durability, while binder types primarily impact durability rather than permeability [54, 57].

2.2.3.1 Binder Content

Multiple research studies have been conducted to establish the relationship between binder contents and the permeability of OGFC mixtures. The results consistently showed that higher binder contents resulted in decreasing air voids and thus reduced permeability [50, 58, 59]. For example, Watson et al. [39] exhibited that increasing binder content from 5% to 7% significantly reduced the permeability of the Georgia design at both 2% and 4% BHF contents, as shown in **Figure 4**. In the mixtures with 2% BHF content, the permeability dropped significantly from 67 meters/day to 12 meters/day. Similarly, for the mixtures using 4% BHF, the permeability decreased from 75.3 meters/day to 14.2 meters/day.

Another study measuring the permeability of three OGFC mix designs at different binder contents showed that increasing binder content from 4.5% to 6% reduced permeability, shifting from higher values (0.5 m^3/day and 0.55 m^3/day) to lower values (0.4 m^3/day and 0.425 m^3/day) [60]. Similarly, Anusha et al. [61] indicated that increasing binder content from 6% to 8% led to a decline in permeability from approximately 125 meters/day to under 100 meters/day [61].

Binder content also plays a role in improving the durability of OGFC mixtures. Generally, increasing binder content resulted in increasing binder film thickness, thus leading to higher raveling resistance [33]. The conclusion was confirmed through the Cantabro loss and binder film thickness shown in **Figures 7** and **8** respectively. For both Georgia and South Carolina mix designs, increasing binder content leads to thicker binder films and lower Cantabro loss, irrespective of BHF contents.

This relationship was further confirmed by many studies, where a higher binder content was associated with a lower Cantabro loss [59-61]. For instance, in the case of OGFC mixtures using asphalt rubber (AR), increasing the binder content from 4.5% to 6% significantly reduced Cantabro loss, from 29.40% to 13.6% [59].

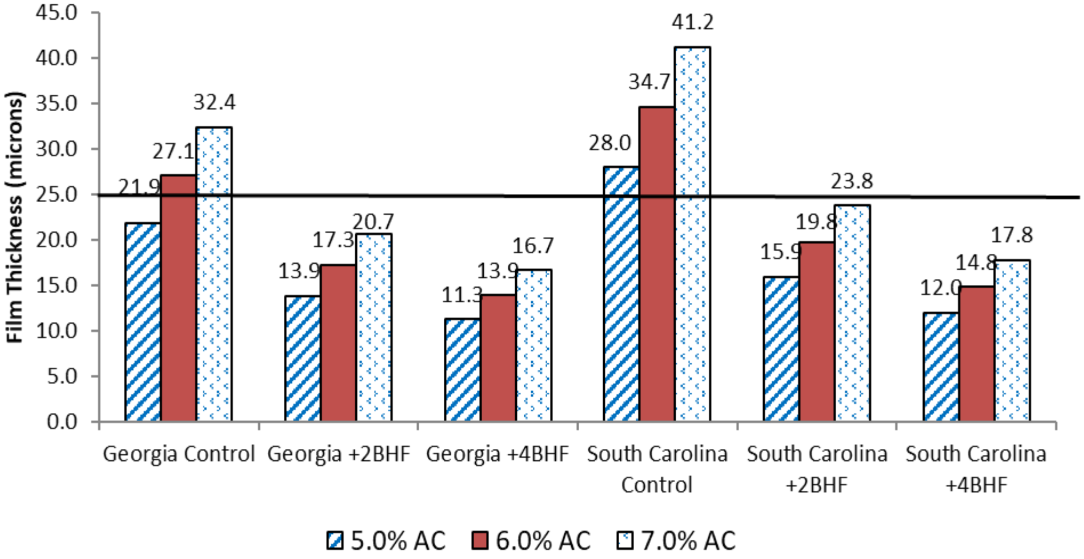


Figure 8. Effects of Binder Content on Film Thickness [39]

In summary, increasing binder content can significantly improve the durability of the OGFC mixtures. However, it's worth noting that increasing binder content beyond a certain threshold can have adverse effects on both permeability and draindown resistance. Conversely, decreasing binder content in an attempt to achieve higher permeability is not recommended, as it can lead to durability issues resulting from insufficient binder content in OGFC mixtures [58, 60, 61].

2.2.3.2 Binder Type

Modified binders, such as asphalt rubber (AR), and polymer-modified binders like styrene butadiene styrene (SBS) [62] are widely adopted by most U.S. state highway agencies (SHAs) due to their benefits in preventing draindown, enhancing resistance to raveling, moisture susceptibility, rutting, cracking, and aging [24, 59, 63-66].

Research by Suresha et al. [67] found that OGFC mixtures with AR binders exhibited higher resistance to Cantabro loss under aged conditions and improved moisture susceptibility than those with unmodified asphalt binders. Lu et al. [64] assessed the impact of modified binders on moisture, rutting, raveling, and reflective cracking resistance of 4.75 mm OGFC mixtures using

ITS, HWTT, Cantabro, and OT. Their results showed that the use of AR binders provided better performance than conventional asphalt binders.

Similarly, Punith et al. [59] proved the better performance of using AR and polymer-modified binders than unmodified binders. The addition of modified binders significantly reduced Cantabro loss and increased the fatigue life of OGFC mixtures by 50% compared to unmodified binders. Additionally, the moisture and rutting resistance, evaluated through ITS and HWTT tests, improved with the implementation of modified binders.

Besides, the presence of rubber or polymer that affected the performance, the dosage of the modification also shows a significant influence. A study sponsored by FDOT evaluated the influence of polymer-modified binders with different SBS contents on the performance of the OGFC mixture [68]. For this purpose, two types of binder were used including conventional PG 76-22 with 2% and 3% of SBS and high polymer modified binder (HP) with 6% to 8% of SBS. Various tests were conducted, including linear viscoelasticity (LVE), surface free energy (SFE), fatigue cracking, creep recovery, IDEAL-CT, semicircular bending (SCB), moisture damage (IDT strength test), and Cantabro test to assess the OGFC mixtures. LVE properties and SFE were determined for mastics with both binders and two aggregate types (GRN and LMS). Mixtures with different binder and aggregate combinations were tested under both aging conditions: unaged and 5 days of aging at 95°C. The results indicated that HP binders improved fatigue cracking and creep recovery, while PG 76-22 exhibited better LVE properties. HP mixtures also demonstrated better resistance to cracking and raveling in both aging conditions. Additionally, numerical simulations revealed lower susceptibility to raveling for HP mixtures, and life cycle cost analysis supported the cost-effectiveness of the FC-5 using HP. In conclusion, using HP was recommended to enhance the raveling resistance of the OGFC pavement in Florida.

Zhang et al. [69] used SBS polymer-modified binders to enhance the durability of OGFC mixtures. PG 64-22 asphalt was modified with different SBS dosages (4.5%, 6.0%, 7.5%, and 9.0%). The study assessed rheological properties using viscosity and frequency sweep tests, and performance was evaluated through Cantabro, TSR, HWTT, and four-point bending tests. Results indicated that increasing SBS content improved elasticity and reduced viscosity sensitivity to temperature changes, resulting in higher complex modulus and reduced phase angle. Higher SBS content increased ITS and stiffness modulus, improving resistance to raveling, moisture susceptibility, fatigue cracking, and rutting, particularly at high temperatures. However, beyond a certain point, the performance enhancement effect diminished, therefore, SBS content of 7.5% was recommended.

In summary, the binder type shows a significant impact on the durability of the OGFC mixtures. This impact may vary depending on the presence of rubber or polymer and the modification dosage.

2.2.4 Fibers and Stripping Agents

OGFC mixtures, susceptible to binder draindown due to a high percentage of coarse aggregate and OBC [41] can be effectively addressed by adding plastic fibers such as cellulose and mineral fiber [3]. Watson et al. [29, 41] confirmed the significant reduction of draindown of OGFC mixtures by adding fiber. Without fibers, the mixture exhibited over 4% draindown, but with fiber, this was reduced to 0.3% by weight of the total mixture. Furthermore, the presence of fibers in OGFC mixtures allows for higher binder contents without draindown concerns, ultimately improving durability. The fibers also enhanced both short-term and long-term resistance to raveling, rutting, and ITS of OGFC mixtures [70-73]. Cooley et al. [74] also confirmed the efficacy of cellulose fibers in improving resistance to reflective cracking.

In addition to fiber, other additives like hydrated lime and anti-stripping agents are commonly employed to ensure mixture performance, particularly in terms of moisture and raveling resistance [64, 75]. FDOT previously employed 1% hydrated lime by weight of aggregate for their OGFC mixture to address the stripping problem. Despite this, premature raveling continued to damage FDOT pavements. Gu et al. [76] investigated the use of liquid agent stripping (LAS), hydrated lime, or their combination to extend the lifespan of FC-5 mixtures in FDOT. They studied two granite-based FC-5 mixtures with varying additive compositions, including 1% hydrated lime by weight of aggregate, 1% hydrated lime plus 0.5% LAS additive by weight of asphalt binder, 1.5% hydrated lime, and 1.5% hydrated lime plus 0.5% LAS additive. Mixture performance was assessed in terms of durability and moisture susceptibility through the Cantabro test, TSR, and HWTT. The testing results showed that the additional LAS, extra hydrated lime, or both enhanced the performance properties of FC-5 mixtures. Finally, a cost-benefit analysis was conducted to assess whether the extended life of FC-5 mixtures would justify the added cost of these additives. The analysis showed that the incorporation of LAS and hydrated lime significantly enhanced the cost-effectiveness of the granite mix design.

2.2.5 Other Factors

Aggregate and compaction energy are additional factors influencing the performance of OGFC mixtures. The aggregate type plays an important role in ensuring the pavement surface microtexture. In 2007, research was conducted by Luce et al. [77] to determine the relationship between friction resistance and aggregate texture, using a locked wheel tester and three different aggregates (siliceous gravel, sandstone, and quartzite) for evaluation. The polishing process was used to evaluate the polishing resistance of each aggregate. Before polishing, quartzite aggregates showed the highest microtexture, followed by sandstone and then siliceous gravel. However, after polishing, quartzite aggregates showed the most significant decrease in microtexture, followed by sandstone and siliceous gravel.

Compaction energy has been shown to impact the permeability of OGFC mixtures. Several studies indicate that increasing compaction energy results in losing permeability performance. Research conducted by Punith et al. [60] assessed the influence of compaction efforts on the permeability of OGFC mixtures. These mixtures were designed with three different binders including a crumb rubber modified binder, 60/70 with fiber, and reclaimed polyethylene, and were compacted with 25 and 50 Marshall blows. The results showed that using 25 blows provided better permeability than using 50 blows. Alvarez et al. [78] evaluated the permeability performance of OGFC mixtures compacted with SGC at three gyration levels: 12, 15, and 50. The results indicate that the permeability of the OGFC mixtures reduced by about 80% when the gyration levels increased from 15 to 50 gyrations. However, the research also recommended not reducing compaction efforts in both laboratory and field to increase air voids and permeability since inadequate compaction can raise concerns about lacking stone-on-stone contact, resulting in losing durability performance [78].

2.2.6 Summary of Factors Affecting OGFC Performance

Table 1 summarizes the factors affecting the performance of OGFC mixtures, as follows.

- Increased permeability can result from higher air voids, larger NMAS, and coarser gradation, while decreases in permeability are associated with a higher percentage passing the No. 4 and No. 8 sieves, and higher compaction energy, binder, and BHF content.

- Enhanced surface texture and friction resistance are associated with a larger NMAS and the use of higher-quality aggregates, whereas reduced surface texture and friction resistance are observed with a higher percentage of aggregates passing through the No. 4 and No. 8 sieves.

- Reduced durability is associated with higher air void content, larger NMAS, and coarser gradation, while improved durability results from a higher percentage of aggregate passing the No. 4 and No. 8 sieve sizes, higher BHF content, higher binder content, the use of a modified binder, and stripping agents, and high-quality aggregates.

Table 1. Summary of Factors Affecting OGFC Performance

Performance Aspects		Gradation				Binder				
	Higher Air Void Content	**Higher Percentage Passing No.4 and No.8**	**Higher NMAS**	**Higher BHF content**	**Coarse Gradation**	**Higher Binder**	**Modified Binder**	**Fibers and Stripping Agent**	**High Quality Aggregate**	**Higher Compaction Energy**
Permeability	Increase	Decrease	Increase	Decrease	Increase	Decrease	NA	NA	NA	Decrease
Surface Texture/ Friction	NA	Decrease	Increase	NA	NA	NA	NA	NA	Increase	NA
Durability	Decrease	Increase	Decrease	Increase	Decrease	Increase	Increase	Increase	Increase	NA

2.3 Design and Performance of OGFC and SMA Mixtures

2.3.1 Design of OGFC Mixtures

The design of OGFC mixtures is similar to that of SMA mixtures as both emphasize stone-on-stone contact and minimal draindown potential. An OGFC mix design can be conducted in five steps, including material selection, selection of trial gradations, selection of design gradation, selection of optimum binder content, and moisture susceptibility evaluation.

For material selection, the requirements for aggregate and asphalt binder chosen for OGFC mixtures are similar to those recommended for SMA mixtures [2, 79]. High-quality aggregates are required for OGFC mixtures to prevent aggregate breakdown and performance degradation. **Table 2** summarizes the aggregate requirements for OGFC mixtures in different states, including abrasion, angularity, particle shape, soundness, absorption, and cleanliness. These aggregate requirements are essential for the performance of the OGFC mixtures [3].

Table 2. Aggregate Requirement for OGFC Mix Design [3, 80, 81]

Characteristic	Test Method	Requirements
Abrasion	ASTM C131, AASHTO T96	Max % Loss at 500 rev.: 30% (OK, OR, TN), 35% (WY), 37% (NV), 40% (VA, AZ, WY, CA, NM, FHWA), 50% (AL, NJ), 45% (FL, NC, WI), 52% (SC) Max % Loss at 100 rev.: 9% (AZ), 10% (CA), 13% (WI)
Angularity	ASTM D5821	Min. with 1 or more fractured faces: 75% (NM), 90% (CA, LA, MS, NV, OR, TX, FHWA) 92% (AZ), 95% (NE, NC, WY, ASTM), 100% (FL, OK, TN, VA, NAPA/NCAT, NC, VT) Min. with 2 or more fractured faces: 75% (CA, OR, FHWA), 85% (AZ), 90% (NE, NC, NV, SC, TN, VA, WY, ASTM, NAPA/NCAT), 95% (OK)
Flat and Elongated	ASTM D4791	Max. flakiness index: 25% (AZ). Max. flat and elongated 5:1 ratio: 5% (VT, WI), 10% (GA, NE, NJ, NC, FL, OK, OR, TX, VA, ASTM), 15% (ID) Max% flat and elongated index in 3:1 ratio: 20% (AL, MS, TN, NAPA/NCAT, VT). 25% (AZ, LA)
Soundness (5 cycles), %	AASHTO T104	15% (GA, VA, SC, NC), 12% (FL, NM, NV, OR, WI), 20% (TX, WY), 9% (TN), 10% (AL, ID)
Absorption	ASTM C127	Max. absorption: 2% (NJ, VA, NAPA/NCAT), Max 2.5% (AZ), Max 4% (NV)
Cleanliness Sand Equivalency	ASTM D2419	Min. sand equivalent: 40% (GA, WI), 45% (NC, OR, LA, WY), 55% (AZ)

The selection of asphalt binders for OGFC mixtures can vary by state specifications. Typically, the binders for OGFC mixtures are modified with polymers and/or crumb rubber to reduce draindown and premature raveling. Common polymers for binder modification are SBS, Styrene Butadiene Rubber (SBR), and Ethylene Vinyl Acetate (EVA) [3]. In addition, stabilizing additives are essential for OGFC mixtures to mitigate asphalt binder draindown during transportation and placement. Common stabilizers are mineral and cellulose fibers, typically added at dosage rates of 0.4% and 0.3% of the total mixture, respectively.

Aggregate gradations for OGFC mixtures can be from 4.75 to 19.0 mm NMAS. The 12.5 mm NMAS gradations are more commonly used. However, the 9.5 mm NMAS gradations have recently gained interest due to their enhanced durability, cracking resistance, and indirect tensile strength compared to the 12.5 mm NMAS [16, 30]. Consequently, some states have updated their OGFC specifications to allow the 9.5 mm OGFC mixtures. For example, the Georgia and South Carolina DOTs have included 9.5 mm NMAS gradations in their OGFC specifications, and the Alabama DOT has tested a 9.5 mm OGFC mixture on the NCAT Test Track.

Three methods have been established to determine the optimum binder content. These methods involve (1) aggregate absorption, (2) visual determination, or (3) compacted specimens [3]. Each method is discussed in the following paragraphs.

The optimum binder content for an OGFC mixture can be determined using the oil absorption of the dominant aggregate fraction, as described in the 1990 FHWA guidelines [82]. This method is adopted by Alabama, Arizona, and Wyoming [50]. The procedure begins by assessing the surface capacity of the dominant aggregate fraction, typically the portion passing the 3/8-inch sieve and retained on the No. 4 sieve. From this fraction, 100 grams of aggregate is separated, dried in an oven, and placed into a funnel equipped with a wire mesh at the bottom, similar to the No. 10 sieve. The funnel, along with the aggregate, is immersed in a specific lubricant oil at room temperature for approximately five minutes and then allowed to drain for an additional two minutes. The funnel and aggregate mixture are then placed in an oven for about 15 minutes at a temperature of 140°F (60°C). The sample is then transferred into a pre-weighed pan for cooling and weighed. The OBC value is subsequently derived from the apparent specific gravity and other pertinent parameters.

Another method for determining the OBC is based on a visual determination of bonding and binder draindown. This method is adopted by Florida, Nevada, and South Carolina. The procedure involves preparing loose mix samples ranging from 1,000 to 1,200 grams with varying binder contents. These mixtures are placed into glass "pie plates." The plates are then placed in an oven for one to two hours at the mixing temperature, typically 320°F (160°C). Afterward, the plates are removed and allowed to cool to room temperature. Each plate with the mixture is then overturned, allowing for a visual inspection of the bond between the mixture and the bottom of the plate and binder draindown. The OBC is chosen based on adequate bonding without evidence of excessive draindown.

The third method for determining the optimum binder content is based on compacted specimens. In this method, three to four samples of OGFC mixtures are prepared at varied binder contents. The mixture is then compacted using the Superpave Gyratory Compactor (SGC) or other devices, depending on the state specifications. After compaction, the volumetric properties of the specimens, such as air voids, Voids Filled with Asphalt (VFA), Voids in Mineral Aggregate (VMA), and Voids in Coarse Aggregate (VCA), are determined. In addition, the performance of the OGFC mixture is evaluated using different tests, such as permeability, draindown, and Cantabro abrasion loss in both unaged and aged conditions, and moisture susceptibility using the TSR test. The binder content that meets the volumetric and performance requirements specified in the state specifications will be selected as the OBC for the OGFC mixture. This method is used by Mississippi, Nebraska, New Mexico, North Carolina, Oklahoma, Oregon, Tennessee, Texas, Virginia, and Louisiana [3].

In a recent study, Watson et al. [39] tried to develop a performance-based OGFC mix design procedure that addresses commonly observed distresses, such as raveling and cracking. The mix design procedure includes performance tests and respective acceptance thresholds for durability, cracking, and cohesiveness. Since air voids were found to be directly correlated with permeability, a minimum design air void content of 15%, corresponding to a minimum permeability rate of 50 meters/day, was recommended. The Cantabro test was also found to be a good indicator of mix durability and resistance to raveling, with a recommended maximum loss set at 20%. The indirect tensile strength test, based on a modified version of AASHTO T 283, and the mixture shear test proved to be good indicators of mixture cohesiveness. A minimum conditioned tensile strength of

50 psi and a TSR value of 0.70 were recommended. The peak load of the I-FIT was identified as a good measure of resistance to cracking, and a minimum Flexibility Index (FI) of 25 was recommended. Finally, HWTT was used as an optional rutting test, with the number of passes to failure at 12.5 mm being selected based on binder grade.

Tables 3 and **4** summarize 9.5 mm OGFC and 12.5 mm OGFC specifications among different SHAs. Polymer-modified asphalt binders are frequently required by states, with the associated range of allowable binder contents. It is worth noting that some states require the minimum binder content based on the combined aggregate bulk specific gravity [83]. Regarding air void requirements, some states only require the minimum air voids, while others have a specific air void range. Generally, the air voids of OGFC mixtures specified by states are higher than 15%, except for Alabama and Oregon. Many states also require TSR, draindown, Cantabro loss, permeability, rutting, coating retention, and VCA during the mixture design and/or acceptance. A minimum TSR value of 0.8 and a maximum draindown value of 0.3 are commonly required by SHAs, and a maximum Cantabro loss value is also specified with a range from 15% to 30%. Some states require checking if the VCA_{drc} of coarse aggregate is less than VCA_{mix} of compacted mixtures to ensure stone and stone contact. In addition to these tests, Louisiana and Texas also require a minimum number of passes at 12.5 mm rut depth using the HWTT to ensure good rutting resistance. Furthermore, Texas also uses the OT to evaluate the cracking resistance of OGFC mixtures, requiring a minimum of 200 OT cycles.

Table 3. Summary of 9.5 and 4.75 mm OGFC Design Requirements [3, 39, 81, 84-88]

Gradation	9.5 mm NMAS																					
	FHWA	AZ 1	AZ 2	CA	FL	GA	ID	LA	MS	NC	NJ 1	NJ 2	NM	NV 1	NV 2	OK	OR	SC	UT	VA	TX	WA
1/2 inch	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	95-100	100	100	100	100
3/8 inch	95-100	100	100	90-100	85-100	85-100	95-100	90-100	90-100	75-100	80-100	85-100	90-100	90-100	95-100	90-100	90-100	80-100	90-100	85-100	95-100	97-100
No. 4	30-50	30-45	31-46	29-36	10-40	20-40	30-50	25-50	15-30	25-45	30-50	20-40	25-55	35-55	40-65	24-45	22-40	20-50	35-45	20-40	20-55	30-50
No. 8	5--15	4-8	5-9	7-18		5-10	5-15	5-15	10-20	5-15	5-15	5-10	0-12			0-10	5-15	5-20	14-20	5-10	1-10	5-15
No. 16					4-12									5-18	12-22							
No. 30													0-8									
No. 50																						
No. 200	2-5	0-2	0-3		2-5	2-4	2-5	2-5	2-5	1-3	2-5	2-4	0-4	0-4	0-5	0-5	1-5	0-4	2-4	2-4	1-4	2-5
Design Requirements																						
Asphalt Type		PG 54-22/ AR-ACFC (20 % ground tire crumb rubber by weight of binder content)	PG 54-22/ AR-ACFC (20 % ground tire crumb rubber by weight of binder content)	58- 34 and rubberized RHMA PG 64-16	76-22, ARB-12, ARB-5	67-22		76-22m	76-22	64-22 76-22	64E-22, 64-22R, 58-28R	64E-22, 64-22R, 58-28R	70-28+ 70-28R+	AC 20 P AC 30		76-22		76-22		70-28	76-XX	58-28
Asphalt Binder Content (%)				5.5-7.0	5.5-7.0 (GRN) 6.5-8.0	6.0-7.25		≥ 6.5		5.0-8.0	≥ 5.5	≥ 6.0	≥ 5.5	6.5%		≥ 5.1		5.5-7.0		5.59-6.01	6-7	4-6
Design Air Voids (%)	≥ 18			18-22		15-18		18-24	15	≥ 18	≥ 15	≥ 18	≥ 18			≥ 18	16-20			≥ 16	22	≥ 15
Min TSR	80					80		80	0.85				80	70	70		80			80		
Max Draindown (%)	0.3			0.3		0.3		0.3	0.3	0.3	Visual Draindown	Visual Draindown	0.3			0.2		0.5		0.3	0.1	0.3
Max Abrasion Loss (%)	20			15					30 (unaged) 40 (aged)		30	30		20	20			15		20	20	
Min Permeability (m/day)									30				92									
Min Overlay test cycles																					200	
HWTT Criteria (Min passes prior to reaching 12.5 mm rut depth								5000													10000	
Min Coating Retention						0.95			0.95													
Stone- Stone Contact (VCAmix)									<VCAdrc				<VCAdrc	<VCAdrc	<VCAdrc					<VCAdrc		

Table 4. Summary of 12.5 mm OGFC Design Requirements [3, 39, 81, 84-88]

Gradation	12.5 mm NMAS																
	ASTM D7064	NCAT	AL	CA	FL	GA 1	GA 2	LA	NC	NE	NJ	OR	SC	VT	TN	TX 1	TX 2
3/4 inch	100	100	100	100	100	100	100	100	100	100	100	99-100	100	100	100	100	100
1/2 inch	85-100	85-100	85-100	95-100	85-100	85-100	80-100	85-100	85-100	95-100	85-100	90-98	85-100	85-100	85-100	80-100	95-100
3/8 inch	35-60	55-75	55-65	78-89	55-75	55-75	35-60	55-75	55-75	40-80	35-60		55-75	55-75	55-75	35-60	50-80
No. 4	10-25	10-25	10-25	28-37	15-25	15-25	10-25	10-25	15-25	15-35	10-25	18-32	15-25	10-25	10-25	1-20	0-8
No. 8	5-10	5-10	5-10	7-18	5-10	5-15	5-10	5-13	5-10	5-12	5-10	3-15	5-10	5-10	5-10	1-10	0-4
No. 16				0-10													
No. 30																	
No. 50																	
No. 200	2-4	2-4	2-4	0-3	2-4	3-5	2-4	2-4	2-4	0-3	2-5	1-5	0-4	2-4	2-4	1-4	0-4
Design Requirements																	
Asphalt Type			76-22	58- 34 and rubberized RHMA PG 64-16	76-22, ARB-12, ARB-5	76-22	76-22	76-22m	76-22		64E-22, 64-22R, 58-28R	PBA-5 PBA-6	76-22	70-28	76-22	76-22	A-R
Asphalt Binder Content (%)			6.0-9.0		5.5-7.0 (GRN) 6.5-8.0 (LMS)	5.75-7.25	5.5-7.0	≥ 6.5	5.0-8.0	5.8–6.8	≥ 5.7		5.5-7.0	6.0-6.5	6-8	5.5-7.0	8-10
Design Air Voids (%)	≥ 18	≥ 18	≥ 12			15-20	18-22	18-24	≥ 18	18 ± 1	≥ 20	13.5– 16		16-21	≥ 18	18-22	18-22
TSR			80			80	80	80			80	80			80		
Max Draindown (%)	0.3	0.3	0.3			0.3	0.3	0.3	0.3	0.3	Visual Draindown	0.7-0.8	0.5	0.3	0.3	0.1	0.1
Maximum Abrasion Loss (%)	20 (unaged) 30 (aged)	20 (unaged) 30 (aged)									30 (aged)		15		20 (unaged) 30 (aged)	20	20
Minimum Permeability (m/day)	100	100													100		
Rutting Criteria (maximum rut depth or minimum passes)								5000									
Min Coating Retention						0.95	0.95						0.95				
Stone- Stone Contact (VCAmix)											<VCAdrc			<VCAdrc			

2.3.2 Existing 9.5 mm and 12.5 mm SMA Mix Design

Stone matrix asphalt (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 cellulose 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 [89]. SMA has been widely used for many 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 [90]. 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 guide the selection of materials, determination of aggregate gradation and optimum binder content, and evaluation of binder draindown potential and moisture susceptibility. The study recommended a maximum percentage passing the No. 4 sieve of 30% to ensure sufficient stone-on-stone contact [91]. In addition, the use of fiber stabilizers and polymer-modified binders was found to be effective in reducing draindown and increasing the rutting resistance of SMA mixtures, respectively. Furthermore, NAPA [90] proposed several key factors that must be met to produce durable and rut-resistant SMA mixtures, which include: 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 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 5** and **6**. The tables show that 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 a 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 5. Summary of 9.5 mm SMA Design Requirements

Gradation	**AASHTO 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		20,000 at 12.5 mm rut depth HWTT		10.0mm at 20,000 passes HWTT					20,000 passes at 12.5 mm rut depth HWTT		
Minimum OT cycles					200									

Table 6. Summary of 12.5 SMA Design Requirements

Gradation	AASHTO 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 rut depth HWTT		20,000 passes at 12.5 mm rut depth HWTT		10.0 mm at 20,000 passes rut						20,000 passes at 10 mm rut depth HWTT			3 mm APA

							depth HWTT									
Minimum OT cycles					200											

2.3.3 Performance Comparison Between OGFC and SMA Mixtures

OGFC and SMA mixtures are designed for different purposes. The OGFC mixtures are primarily designed to enhance safety by facilitating water drainage off the pavement surface. In contrast, SMA mixtures are designed for high durability and resistance to rutting. Although the rough surface texture of an SMA mixture can retain water, enhancing its safety [92], it does not allow water to drain through in the same manner as OGFC mixtures. This distinction is attributed to the high air voids in OGFC mixtures. Pavements become permeable when air voids are higher than 6% [93, 94]. Since the typical design air void of an SMA mixture is 4%, it does not qualify as permeable pavement. As shown in **Figure 9**, all SMA mixtures tested (regardless of NMAS) were impermeable at air voids below 6%. However, an SMA mixture with lower permeability tends to be more durable, as minimal water and air could penetrate the pavement and cause moisture damage and oxidation.

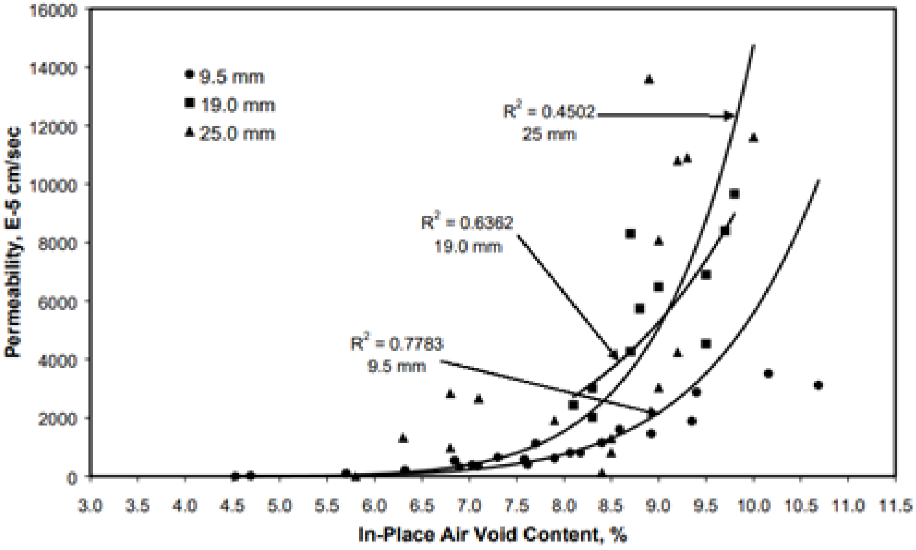


Figure 9. SMA Permeability [95]

Although both SMA and OGFC improve the friction resistance of asphalt pavement due to their high macrotexture surface and a significant proportion of coarse aggregate [90], OGFC mixtures generally show a better friction performance than SMA mixtures [28, 96, 97]. Kowalski et al. [98] compared the friction performance among OGFC (shown as PFC), SMA, and dense-graded asphalt mixtures, and the laboratory results showed that the SMA and OGFC mixtures provided similar wet weather friction, and their friction number is much higher than that of dense-graded mixtures due to their coarser surface texture, as shown in **Figure 10**. McDaniel et al. [99] 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 mixtures had significantly higher friction values than the conventional HMA. The same conclusions were also obtained by Wasilewska et al. [100] based on the DFT test results at different test speeds

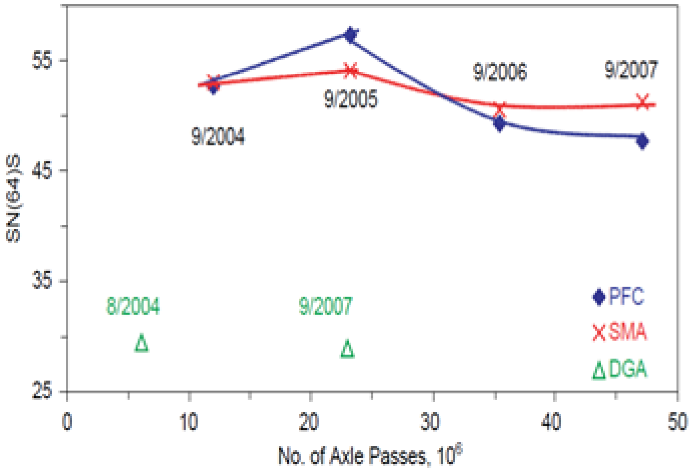


Figure 10. Wet Friction among OGFC, SMA, and DGA [98]

Another research conducted by Wang and Flintsch found that the OGFC surface had the highest macro-texture depth (3.75 mm), followed by the SMA surface (2.25 mm) [101]. Zelelew et al. [102] 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 [103] 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.

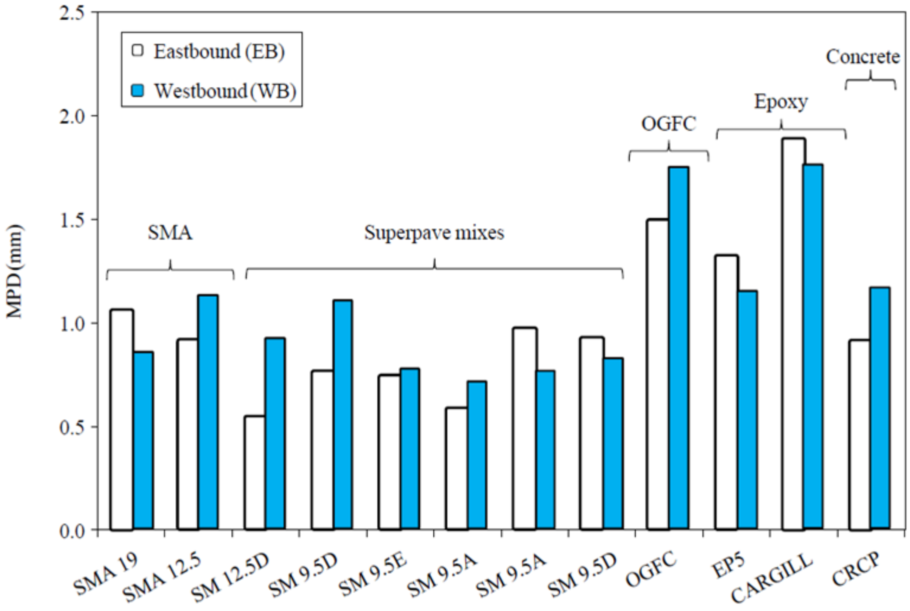


Figure 11. Macrotexture Properties among Different Mixture Types [102]

SMA mixtures are designed with stone-on-stone skeletons to ensure their strength, while their durability mainly results from stabilizing agents such as fibers and modified binders [92]. In general, SMA mixtures show better strength and durability compared to OGFC mixtures. For example, a survey conducted by NCAT to evaluate the performance of 85 SMA projects in the US found no evidence of raveling [104]. In contrast, raveling is a prevalent issue in the OGFC pavements [3, 12]. Furthermore, other forms of distress, such as stripping, cracking, and rutting, are not typically observed in SMA pavements [104]. Sharma [105] compared the performance of SMA and OGFC mixtures using different laboratory tests, including TSR, Dynamic Creep, and HWTT. The TSR results demonstrated better moisture resistance in SMA compared with OGFC. SMA also outperformed OGFC regarding cumulative strain derived from the Dynamic Creep test and rutting resistance evaluated using HWTT.

In addition, as shown in **Figure 12**, 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.

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 the addition of fiber could improve OGFC's rutting resistance [106].

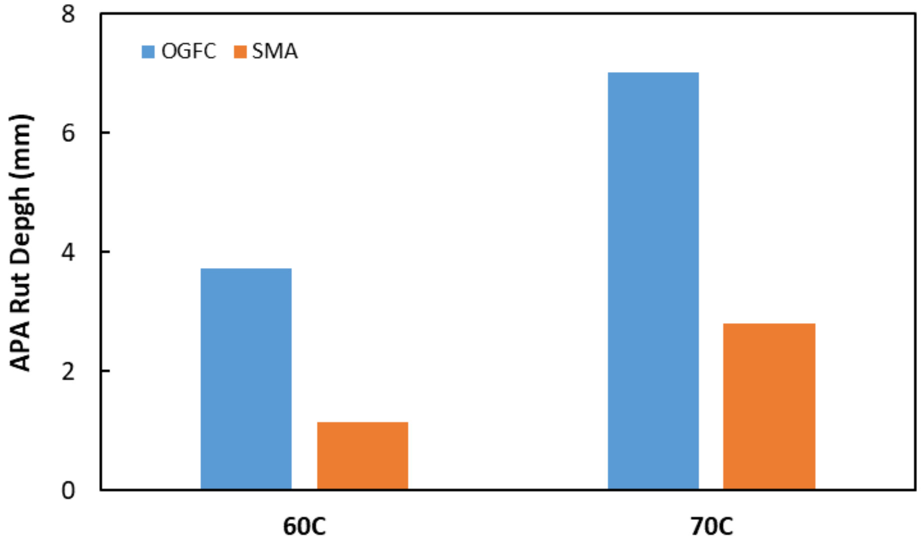


Figure 12. Rutting Comparison among OGFC and SMA Mixture [106]

Additionally, the SMA mixture exhibited superior low-temperature crack resistance and moisture stability under varying aging conditions compared to OGFC mixtures. Moreover, SMA mixtures displayed a longer fatigue life than OGFC mixtures, attributed to their lower air voids and better cohesion within SMA mixtures [107]. Due to its superior performance compared to OGFC, SMA can sustain its service life for an extended period, typically ranging from 20 to 30 years, whereas OGFC pavements tend to experience failures within a shorter span of 10 to 12 years [90, 108]

CHAPTER 3 RESEARCH METHODOLOGY

This chapter describes the experimental plan for the study, which includes 4 steps: 1) selecting materials including aggregate, binders, fibers, and hydrate limes, 2) developing the mix design and conducting performance tests for FC-5, 9.5 mm OGFC and 12.5 mm SMA to establish the performance baseline for the alternative friction course, 3) Using the baseline performance from step 2 to develop mix designs and conduct performance tests for the alternative friction course, and 4) conducting the performance comparisons between FC-5, 9.5 mm OGFC, 12.5 mm SMA, and the alternative friction course. The section describes the laboratory tests used for evaluating the performance of asphalt mixtures including Cantabro test, Overlay test, permeability, drainability, HWTT, DFT, and CTM. The section also provides a summary of the NAWS for conditioning Cantabro and Overlay samples, along with details about the Linear Kneading Compactor and three-wheel polishing devices used for compacting and polishing slabs.

3.1 Experimental Plan

The overall objectives of this project are to (1) evaluate the effect of utilizing a finer 9.5 mm NMAS gradation and HP binder to improve the durability of the asphalt mixtures and (2) develop alternative asphalt friction courses that are more durable in suburban environments and are drainable while providing adequate friction and texture properties. To fulfill the research objectives, four different mix designs including FC-5, 9.5 mm OGFC, 12.5 mm SMA, and one alternative friction mixture will be evaluated, using an experiment plan as illustrated in **Figure 13**. The experiment plan includes four critical steps.

- Step 1: Select two asphalt binders (PG 76-22 and HP Binder) and two aggregate types GRN and LMS for evaluation in this project.
- Step 2: Develop mix designs and conduct performance tests for FC-5, 9.5 mm OGFC, and 12.5 mm SMA mixtures to establish the performance baseline for the alternative friction course design.

- Step 3: Utilize the performance baseline obtained from Step 2 to develop mix designs and conduct performance tests for the alternative friction course mixtures.

- Step 4: Conduct performance comparisons between FC-5, 9.5 mm OGFC, 12.5 mm SMA and the alternative friction courses.

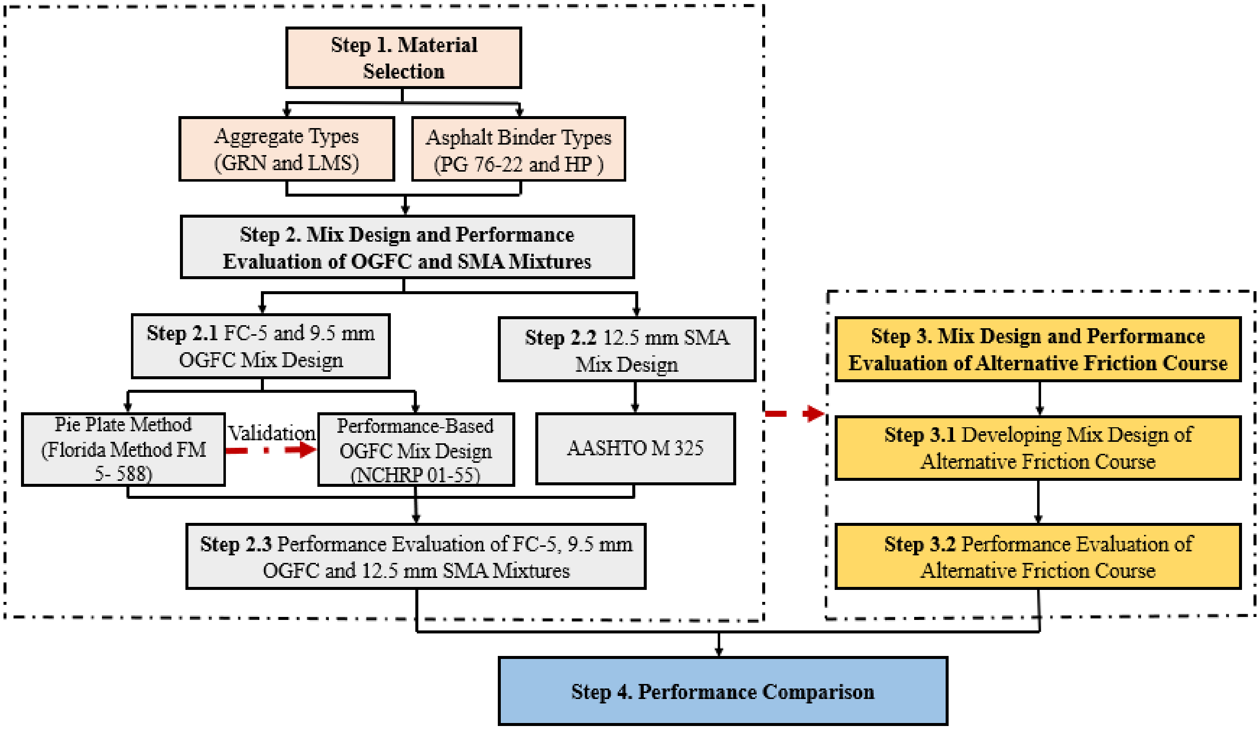


Figure 13. Experiment Plan

The details of the experiment plan are further described in the following sections.

3.1.1 Step 1: Material Selections

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

- Asphalt Binder: PG 76-22 from Mariani 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 fiber) were used in this study for different purposes, and both fibers were pre-blended with the aggregate prior to adding binder during the mixing process.

The mineral fiber at 0.4% by weight of mixtures was solely used to determine OBC for FC-5 and 9.5 mm OGFC mixture. This was because the OBC of FC-5 and 9.5 mm OGFC were determined based on the binder drainage level in which any binder content showing evidence of excessive drainage was not chosen as the OBC. When using cellulose fiber, there were no significant differences in drainage levels among different binder contents, even at higher quantities. Therefore, cellulose was unsuitable for determining the OBC for FC-5 and 9.5 mm OGFC mixtures. On the other hand, cellulose fiber with a dosage of 0.3% was used for specimen fabrication and performance evaluation for all the mixtures including FC-5, 9.5 mm OGFC, 12.5 mm SMA, and the alternative friction course in this study.

3.1.2 Step 2: Mix Design and Performance Evaluation of FC-5, 9.5 mm OGFC and 12.5 mm SMA Mixture

Step 2.1: FC-5 and 9.5mm OGFC Mix Design

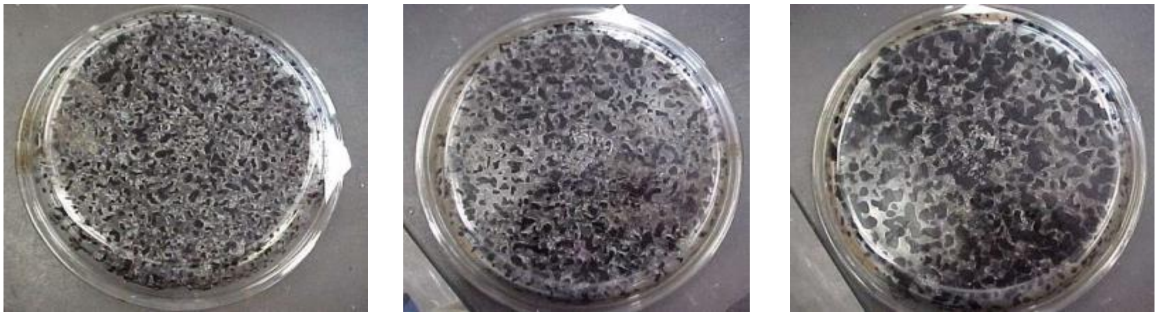
The FC-5 and 9.5 mm OGFC mix design were conducted with two phases: (1) gradation design, and (2) determination of OBC. The blend gradation of FC-5 and 9.5 mm OGFC mixtures were determined following Florida and Georgia state specifications, respectively. 9.5 mm OGFC was designed using the Georgia specification because there is no 9.5 mm OGFC design in Florida specifications and similar aggregate materials are typically used in both states. **Table 7** summarizes the gradation requirements for both FC-5 and 9.5 mm OGFC.

Table 7. FC-5 and 9.5 mm OGFC Gradation Requirements

Sieve	**Control Points**	
	FC-5	**9.5 mm OGFC**
3/4‘’	100	100
1/2"	85 - 100	100

3/8"	55 - 75	85 - 100
#4	15 - 25	20 - 40
#8	5 - 10	5 - 10
#200	2 - 4	2 - 5

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 the method, at least three 1200g aggregate batches and PG 67-22 binder were heated for a minimum of two hours in an oven at 320 ± 5°F. Subsequently, these aggregate batches were mixed with 0.4% mineral fiber and virgin binder at different contents, and the loose mixtures were carefully transferred from the mixing bowl to a pie plate after mixing. The pie plate was then conditioned in the oven for one hour at 320 ± 5°F before cooling to room temperature. The mixtures were evaluated based on pictures taken from the bottom surface of the pie plate in two different ways. The first way was the pie plate with loose mixtures, following FM 5-588. However, the quality of the pictures may be impacted by the glare caused by glassy and black color asphalt mixtures. Therefore, the second way was recommended to take the pictures of pie plate without loose mixtures. In this way, after cooling the samples to room temperature, the pie plates were reheated in the oven until the loose mixtures could be easily removed when overturning the plate without sliding and causing any smudge. Finally, the pictures were captured by placing the empty pie plate on a white background, enabling to distinguish the black footprint of the asphalt binder. Based on the observation from these pictures, the OBC was chosen on the sample that exhibited sufficient bonding without any evidence of excessive drainage of asphalt binder, as shown in **Figure 14**. 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% [39, 63]



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

Figure 14. Reference Pie Plate Pictures of FC-5 Mixtures with PG 67-22 at Different Binder Contents: (a) 5.3% (Insufficient Bonding/Drainage), (b) 5.8% (Sufficient Bonding/Drainage), (c) 6.3% (Excessive Bonding/Drainage) (FM 5-588)

Step 2.2: 12.5 mm SMA Mix Design

In this study, SMA and OGFC mixtures were evaluated to establish a performance baseline for the alternative friction course. As mentioned previously, both durability and drainability are important characteristics of OGFC pavement in suburban environments. Although SMA mixtures offer superior durability than OGFC, they are typically much less permeable than OGFC mixtures. Thus, to make it drainable, the selected SMA mixture for use in suburban environments should have greater surface macrotexture that allows water to flow through the surface voids. In addition, 12.5 mm SMA in general has greater macrotexture than 9.5 mm SMA mixtures. Therefore, 12.5 mm SMA was selected to maximize drainability in this study.

The first step of designing 12.5 mm SMA involved determining a compaction effort with the Superpave gyratory compactor (SGC), referred to as N_{design}, that would match with a 50-blow Marshall compaction. Three SMA mix designs were prepared for each GRN and LMS using a 50-blow Marshall compaction, 35 and 50 SGC gyrations. The air voids at different compaction levels were then measured using the Core Lok method. As a result, N_{design} of the 12.5 mm SMA mixture was selected as it yielded an average air void content closest matched that of the 50-blow Marshall.

After determining the N_{design}, the design gradation and OBC of the mixture were determined following AASHTO R 46, Standard Practice for Designing Stone Matrix Asphalt, AASHTO M

325, Standard Specification for Stone Matrix Asphalt, and specifications from the Georgia DOTs. The gradation limit was obtained from the Georgia DOT specification for the SMA mixture. The mixture was compact at the N_{design} determined from the previous step. The air void, VMA, and VCA requirements for the final gradation and OBC are summarized in **Table 8**. Particularly, the design air void was set at 4% and the minimum VMA was established at 17%. Finally, the 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:

$$VCA_{drc} = \frac{G_{ca} \cdot \gamma_w - \gamma_s}{G_{ca} \cdot \gamma_w} \cdot 100 \qquad (1)$$

Where:

G_{ca} = bulk specific gravity of the coarse aggregate, AASHTO T85
γ_w = unit weight of water, 1000 kg/m3(62.4 lb/ft3)
γ_s = unit weight of coarse aggregate fraction in the dry rodded condition (AASHTO T19)

$$VCA_{mix} = 100 - \frac{G_{mb}}{G_{ca}} \cdot P_{ca} \qquad (2)$$

Where:

G_{ca} = bulk specific gravity of the coarse aggregate, AASHTO T85
G_{mb} = bulk specific gravity of the compacted mix
P_{ca} = percent coarse aggregate by weight of the mix

Table 8. 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	$VCA_{drc} \geq VCA_{mix}$

Step 2.3: Performance Evaluation of FC-5, 9.5 mm OGFC, and 12.5 mm SMA Mixtures

Upon the completion of the mix design, 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 15.**

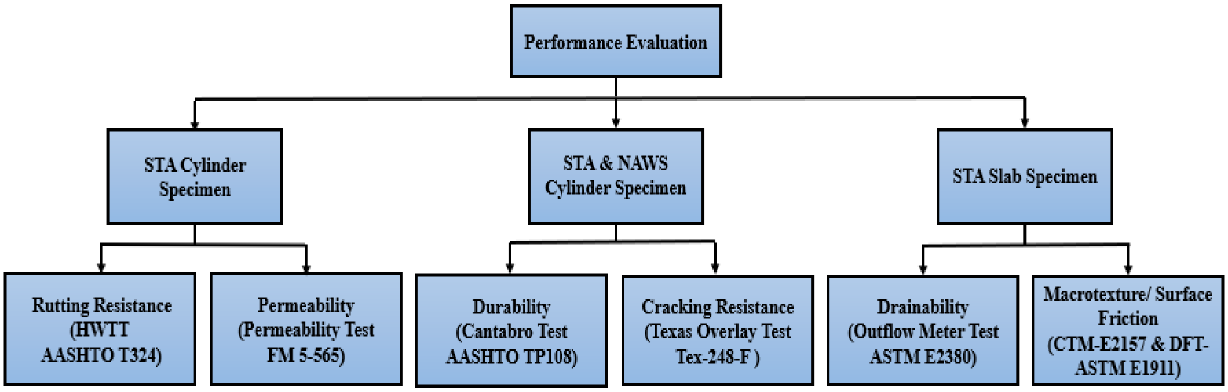


Figure 15. Laboratory Testing Plan

As shown in **Figure 15**, a series of laboratory tests were performed to evaluate the mixture permeability, rutting resistance, durability, cracking resistance, texture, friction, and drainability, which includes the Florida Permeability Test, HWTT, Cantabro Test, OT, CTM, DFT and Outflow Meter Test. For FC-5 and 9.5 mm OGF mixtures, all the tests were performed on the design pills (cylinder specimen) with 150 mm diameter prepared at 50 gyrations except that texture, friction, and drainability evaluation used slab specimens. For 12 mm SMA mixtures, all the cylinder and slab specimens were compacted to the target air voids of 5.5 ± 0.5% after trimming. Additionally, the loose mixtures 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 evaluate and compare the mixture performance of the FC-5, 9.5 mm OGFC, and 12.5 mm SMA mixtures. The details of laboratory tests and aging procedures will be presented in section 3.2.

3.1.3 Step 3: Mix Design and Performance Evaluation of an Alternative Friction Course

Step 3.1: Developing an Alternative Friction Course

The first step was determining the performance baseline for the alternative friction course. Based on the performance evaluation of the FC-5, 9.5 mm OGFC, and 12.5 mm SMA mixtures completed in Step 2.3, FC-5 and 12.5 mm SMA were selected as the performance baseline to develop the alternative friction course in Step 3. The decision to use FC-5 instead of 9.5 mm OGFC was driven by the FDOT's greater expertise with the FC-5 mixture. Moreover, the fact that FC-5 and 12.5 mm SMA shared the same NMAS allowed to use their gradation as the control points for designing the alternative friction course's gradation.

The design approach for the alternative friction mixtures was based on the concept of balancing performance between permeability and durability. The objective was to create a mixture that surpassed FC-5 in durability while exceeding the permeability of the 12.5 SMA mixture. To accomplish this, the maximum Cantabro loss of the alternative friction mixtures was targeted at 10% which was significantly lower than the maximum allowable value of 20% for OGFC mixtures. At the same time, the minimum permeability of the alternative friction course was selected to be higher than 12.5 mm SMA mixtures.

Secondly, after establishing the performance baseline, the gradation and OBC of the alternative friction courses were determined following the performance requirements. The gradation for the alternative friction mixture could be developed based on either FC-5 or 12.5 mm SMA gradation. Considering FDOT has more experience with FC-5 than the 12.5 mm SMA mixture, the gradation of the alternative friction mixture was adjusted based on FC-5 gradation. Moreover, as mentioned previously, a finer gradation could enhance the durability, but reduce the permeability of the

OGFC mixture. Therefore, the gradation of the alternative friction course was designed to be finer than the FC-5 mixture to improve durability and coarser than the 12.5 mm SMA mixture to ensure permeability performance. Two gradation trials were prepared for each aggregate type. In these trials, the percentages of aggregate passing ¾, ½, and 3/8 inches remained consistent with those of FC-5 while adjustments were made to the percentages passing through smaller sieves (No.4, No.8…). These adjustments aimed to position the alternative friction mixture gradation between FC-5 and 12.5 SMA gradation, ensuring that it would be finer than FC-5 and coarse than 12.5 mm SMA gradation, as shown in **Figure 16**.

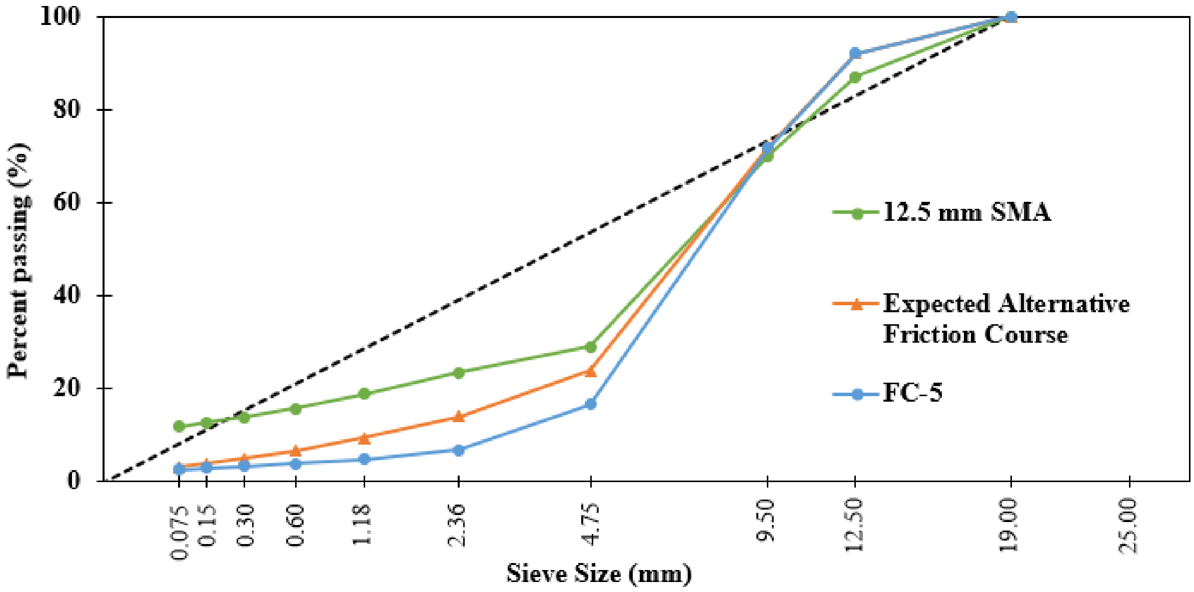


Figure 16. Expected Alternative Friction Course Gradation

Moreover, similar to finer gradation, higher binder content resulted in improved durability, but reduced the permeability of the OGFC mixtures. Therefore, the binder content of the alternative friction mixture should be higher than that of the FC-5 mixture to improve durability, but should not be too high to ensure permeability. It was recommended to be increased by 0.2 to 0.3% compared to the FC-5 mix design. These trial mixtures were then compared with each other in terms of durability and permeability using the Cantabro and Permeability test. The mixture that had better durability and still maintained permeability would be selected as the alternative friction course mixture for each aggregate. 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 PG 76-22 binder.

Step 3.2 Performance Evaluation of Alternative Friction Course

The same performance test described in Step 2.3 was used to evaluate the performance of the alternative friction course. Similar to OGFC and 12.5 mm SMA mixture, the alternative friction mixtures were evaluated the permeability, rutting resistance, durability, cracking resistance, texture, friction, and drainability, using the Florida Permeability Test, HWTT, Cantabro Test, Texas OT, CTM, DFT and Outflow Meter Test. The permeability and rutting resistance were conducted on unconditioned compacted specimens; the durability and cracking resistance on unconditioned and NAWS conditioned compacted specimens; and friction and macrotexture on compacted slabs before and after TWPD polishing. Note that all the tests were performed on the cylinder specimen with 150 mm diameter prepared at 50 gyrations except that texture, friction, and drainability evaluation used slab specimens.

3.1.4 Step 4: Performance Comparison among FC-5, 9.5 mm OGFC, 12.5 mm SMA, and Alternative Friction Course

Upon the completion of the above testing plan, Step 4 focused on comparing the performance characteristics of FC-5, 9.5 mm OGFC, 12.5 mm SMA, and the alternative friction course, focusing on permeability/drainability, rutting resistance, durability (raveling), cracking resistance, friction and surface macrotexture.

Firstly, the *p-value* obtained from the student's *t-test* at a significant level of 0.05 was used to evaluate the influence of HP on the performance of the mixtures compared to PG 76-22. The analysis was conducted with the null hypothesis indicating no observed significant difference between the two sets of samples and the alternative hypothesis which exhibits a significant difference. The two samples were assumed to have unequal variance. If the p-value is less than 0.05, it is enough evidence to reject the null hypothesis which means that using HP can significantly improve the performance of the OGFC mixtures.

Subsequently, Games-Howell post-hoc group analysis at a significant level of 0.05 was conducted to statistically rank the mixture types in terms of permeability, drainability, raveling, and cracking resistance. Mixtures shared in the same group proved no significant difference between them. The mean value analysis was used to compare the mixtures in terms of rutting, surface texture, and friction resistance. As a result, the analysis will help determine if using a finer gradation of 9.5 mm NMAS can significantly improve the performance of the FC-5 mixture. It also determines mixture type shows the best overall performance and if the alternative friction course is suitable for suburban environments.

The effect of aging on the raveling and cracking resistance of the asphalt mixtures was evaluated using Games-Howell post-hoc group analysis at a significant level of 0.05 and slope analysis. Having the same group and a lower slope between aging conditions indicates better aging resistance.

3.2 Laboratory Mixture Tests

3.2.1 NCAT Accelerated Weathering System (NAWS)

Moisture damage and weather aging can significantly reduce the durability and cracking resistance of asphalt mixtures. In this study, the Accelerated Weathering System (AWS) per ASTM D4799 was employed to assess the weathering resistance of FC-5, 9.5 mm OGFC, 12.5 mm SMA, and the alternative friction mixtures. The AWS chamber has controllable cycles to simulate various environmental conditions, including rain, relative humidity, sunlight, temperature, and a combination of the above; thus, it can simulate the long-term exposure of asphalt pavement materials to moisture, heat, and ultraviolet light simultaneously, as shown in **Figure 17**. Grzybowski showed that 3,000 hours (four months) in the AWS was equivalent to approximately 12 years of weathering in the field [109]. Gu et al. [76] utilized the AWS to condition OGFC mixtures at different durations, and the Cantabro loss results indicated that increasing conditioning times substantially reduced the mixture's durability. In this study, the Cantabro specimens underwent NAWS conditioning for 1,000 and 2,000 hours, while the OT specimens were exposed to 1,000 hours of NAWS conditioning. The obtained results were compared to the test results of specimens without NAWS conditioning to assess the impact of weathering on the durability and cracking resistance of the mixture.

Figure 17. NCAT Accelerated Weathering System

3.2.2 Cantabro Test

The Cantabro test was performed per AASHTO TP 108-14 to evaluate the durability of the asphalt mixtures. Three replicate samples were tested for each mixture, and the specimens were conditioned in an environmental chamber for at least 4 hours at 25 ± 1°C (77 ± 2°F) prior to testing. Subsequently, 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. In the end, the specimen weight 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**. Technically, a mixture with a lower Cantabro loss value was expected to have better durability and raveling resistance than that with a higher Cantabro loss value.

$$Cantabro\ Loss = \frac{M_{initial} - M_{final}}{M_{initial}} \cdot 100 \tag{3}$$

Where:

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

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

3.2.3 Texas Overlay Test

The OT was conducted using the Asphalt Mixture Performance Tester (AMPT) per Tex-248-F to evaluate 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. Five specimens were tested for each mix at one aging condition. The trimmed OT specimen was first glued to the OT fixture and conditioned in the chamber at 25 ± 1°C (77 ± 2°F) for 2 hours prior to testing. During the test, one side of the fixture was fixed while the other side moved in a displacement-controlled mode applying a sawtooth waveform once per 10-second cycle (5 seconds of loading, 5 seconds for unloading). Testing is performed at 25°C with a maximum displacement of 0.635 mm per cycle. The peak load of each cycle was measured, and the test is considered to have reached failure when the peak load reached 7% of the initial peak load and the number of cycles to failure (Nf) was recorded. In addition, the test was also terminated when the cycle number reached 1,200. At last, 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 18**. Generally, mixtures with higher Nf and lower CPR values are expected to have better-cracking resistance than those with lower N_f and higher CPR values.

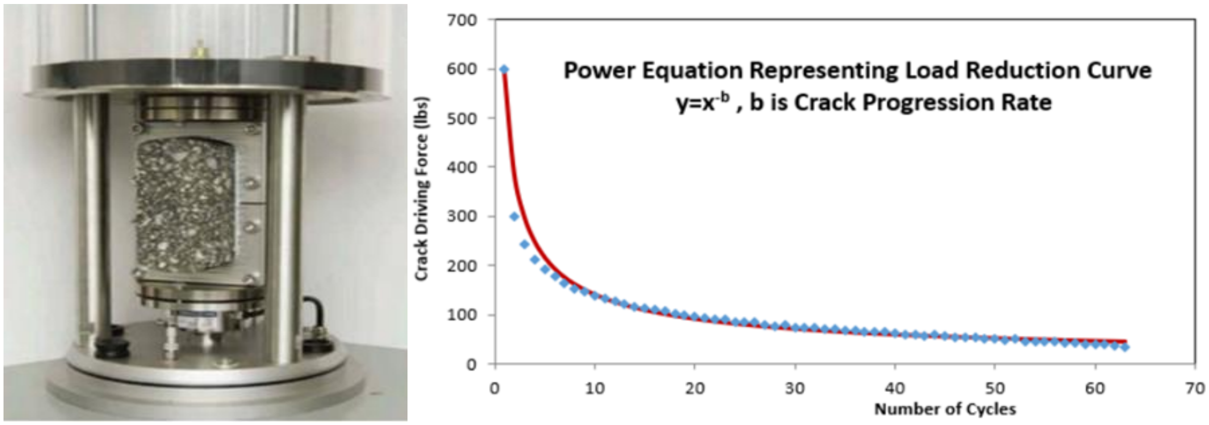


Figure 18. OT Specimen Setup and Illustration of CPR Parameter Calculation [110, 111]

3.2.4 Permeability Test

The Florida permeability test was conducted per FM 5-565 to assess the permeability of OGFC mixtures with the use of the falling head permeability apparatus for 6-inch cylinder specimens, as shown in **Figure 19**. Three replicate specimens were tested for each mix design, and the test specimen was obtained by trimming 1-inch thickness from the top and bottom faces of the compacted sample. Then the test specimens were submerged into a water tank for a minimum of 1 hour at ambient temperature to reach a saturated state prior to testing. Subsequently, the specimen was placed on top of the pedestal plate and assembled with the remaining part including a graduated cylinder, upper cap, and sealing tube with membrane. The membrane was then inflated to seal the sides of the specimen throughout the whole test process. Next, water was added into the graduated cylinder to a level above the upper timing mark, and then allowed to flow through the saturated specimen, and the interval of time taken to reach a known change in the head was recorded. During the testing, the inflated latex membrane sealed the sides of the specimen, so the permeability test only determined the vertical flow of water through the specimen. The recorded time interval was used to calculate the coefficient of permeability (k) based on Darcy’s law, as shown in Equation 4. The mixtures with higher k values had better permeability than those with lower values, and a minimum k value of 50 meters/day was recommended for OGFC mixtures by NCHRP 01-55 [39, 63]

$$k = \frac{aL}{At} \cdot ln\frac{h_1}{h_2} \cdot t_c \qquad (4)$$

Where, k = coefficient of permeability, cm/s; a = inside cross-sectional area of the buret, cm2; L = average thickness of the test specimen, cm; A = average cross-sectional area of the test specimen, cm2; t = elapsed time between and, s; = initial head across the test specimen, cm; = final head across the test specimen, cm; = temperature correction for viscosity of water. A temperature of 20°C (68°F) is used as the standard.

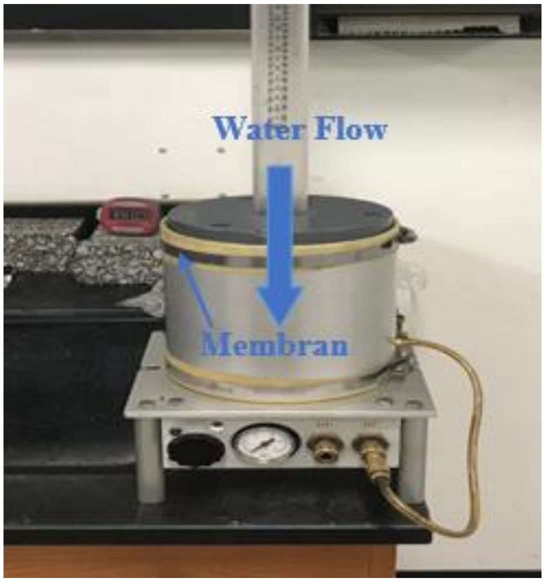


Figure 19. Florida Permeability Test Setup

3.2.5 Drainability Test

The drainability of OGFC mixtures was evaluated by conducting the outflow meter test on slab specimens with dimensions of 20-inch × 20-inch × 2-inch per ASTM E 2380. As shown in **Figure 20**, the outflow meter is a vertical cylinder containing water, which has an open top and a rubber ring on the bottom to seal against the pavement/specimen surface. The outflow meter was first placed on the slab specimen, then water was poured into the cylinder to the upper level of float. Then the water was discharged to flow through the surface texture and subsurface voids, and the time required for the water level to fall from the upper float level to the lower float level is recorded as the outflow time. A minimum of four randomly spaced tests are required for each slab specimen. Generally, a shorter outflow time indicates better drainability, which is also an indication of less hydroplaning potential under wet conditions. Compared to the permeability test, the outflow meter measured the combination of the vertical flow of water through the subsurface voids and the horizontal flow of water through the surface texture, which was affected by the macrotexture and permeability of the asphalt mixture.

Figure 20. Outflow Meter

3.2.6 Hamburg Wheel Tracking Test (HWTT)

The HWTT per AASHTO T 324 was used to determine the rutting resistance and moisture susceptibility of OGFC mixtures. One gyratory sample was cut in half horizontally and both pieces were further trimmed to obtain one set of HWTT specimens. For each mix, two sets of specimens were prepared and submerged in a 50°C water bath for 45 minutes prior to 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 testing 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 21**. 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.

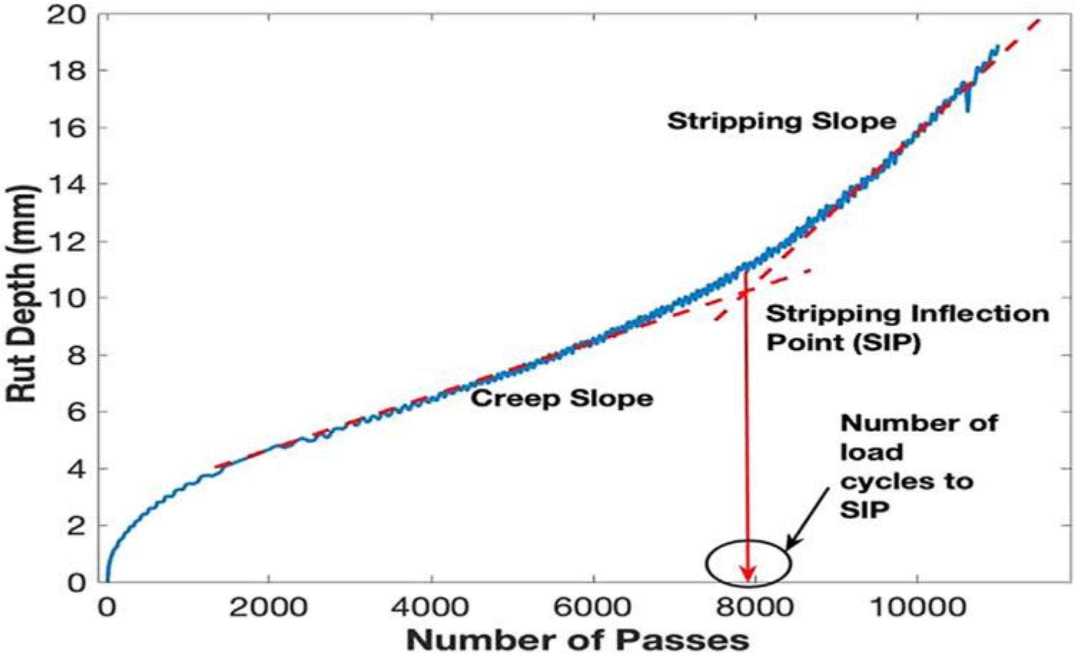


Figure 21. Hamburg Wheel Tracking Test (HWTT) Curve [112]

3.2.7 Linear Kneading Compactor

In the study, the linear kneading compactor was used to compact slabs with dimensions of 20-inch × 20-inch × 2-inch for drainability, CTM and DFT tests, as shown in **Figure 22.**

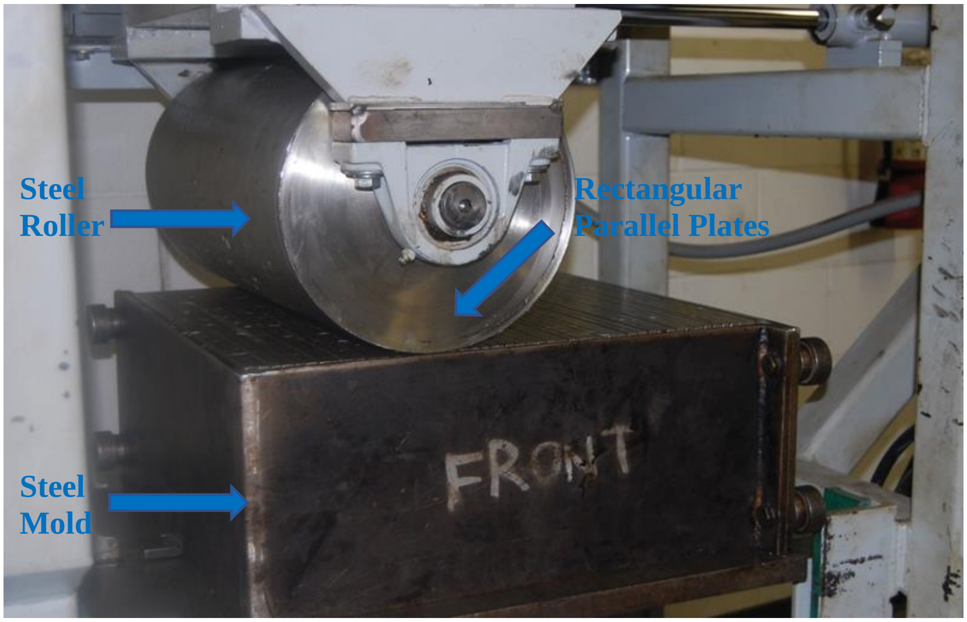


Figure 22. Linear Kneading Compactor [113]

With this compactor, a slab was compacted by applying pressure to a loose mixture through a set of rectangular parallel plates. First, to attain the designed slab height, a combination of thick and thin plates was adjusted at the base of the mold. After that, the loose asphalt mixture was placed within a steel mold with the dimensions of 20” × 20” × 8.97”. The mixture was then 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 in 5 cycles.

3.2.8 Three-Wheel Polishing Device (TWPD)

A three-wheel polishing device (TWPD) per AASHTO PP 104 was used to polish slab specimens with dimensions of 20” × 20” × 2” to simulate the field traffic polishing of asphalt pavement, as shown in **Figure 23**. During the laboratory polishing process, the TWPD was operated at a rotational speed of 60 rpm using three pneumatic tires with an inflation pressure of 50 psi, and a water spray system was used to wash away abraded particles. The carriage weight on top of the tires is 90 lbs. The diameter of the polishing path is 11.2 inches, which is identical to that of the DFT and CTM measuring paths. In this study, the DFT and CTM were conducted on slab specimens polished after different cycles to monitor the evolution of friction and surface macrotexture including 0 (0k), 5000 (5k), 50000 (50k), and 100000 (100k) cycles.

Figure 23. Three-Wheel Polishing Device

3.2.9 Dynamic Friction Test (DFT)

The DFT following ASTM E 1911 was used to measure the friction properties of OGFC mixtures. The device includes a horizontal spinning disk with three spring-loaded rubber sliders fixed on its lower surface, as shown in **Figure 24**. The test was performed by spinning the disk on a slab surface while a water spray system was working to simulate a wet condition. The disk rotation speeds ranged from 0 and 90 km/h, enabling the measurement of the friction properties at various speeds. During the test, the torque value of the spinning disk was continuously monitored, which was 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.

Each mix required one slab for friction measurement with at least four replications at each polishing level. Additionally, the rubber sliders were regularly checked and replaced as needed to ensure accurate and consistent 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 because the DFT value at 40 km/h was repeatable compared to other speeds. A higher value of the friction coefficient indicates better friction performance.

Figure 24. Dynamic Friction Tester (DFT)

3.2.10 Circular Track Meter (CTM)

The CTM, following ASTM E 2157, was employed to measure the macrotexture properties of the asphalt mixtures. The test consists of a displacement sensor fixed on a mechanical arm, as shown in **Figure 25**. The mechanical arm rotates clockwise at a fixed height from the slab surface allowing the sensor to measure the vertical macrotexture depth profile. During the test process, the computer continuously recorded the surface profile data, enabling the calculation of mean profile depth (MPD). Each mix design required a slab for measuring MPD with at least four replicate measurements at each polishing level. A higher MPD value indicates a better macrotexture property.

Figure 25. Circular Track Meter (CTM)

CHAPTER 4 MIX DESIGN AND SUMMARY

This chapter describes the final mix designs of FC-5, 9.5 mm OGFC, alternative friction course, and 12.5 mm SMA for both GRN and LMS, focusing on the OBC, gradation, and design requirements.

4.1 FC-5 and 9.5 mm OGFC Mix Design and Summary

4.1.1 FC-5 Mix Design

To determine OBC for FC-5 mixture using granite (GRN FC-5), the pie plate test was first conducted at 4 binder contents: 5.3, 5.8, 6.3%, and 6.8%. **Figures 26** and **27** present the pie plate pictures with and without loose mixtures, respectively.

(a) 5.3 **(b) 5.8** **(c) 6.3** **(d) 6.8**

Figure 26. Pie Plate Pictures (with Loose Mixture) of GRN FC-5 Mixtures: (a) 5.3%, (b) 5.8 %), (c) 6.3%, (d) 6.8%.

(a) 5.3 **(b) 5.8** **(c) 6.3** **(d) 6.8**

Figure 27. Pie Plate Pictures (without Loose Mixture) of GRN FC-5 Mixtures: (a) 5.3%, (b) 5.8 %), (c) 6.3%, (d) 6.8%.

Figures 26 and **27** illustrate a consistent trend where the asphalt drainage and bonding with the pie plates increased with the increase of binder contents. The mixture designed with 5.3% asphalt content showed the least asphalt drain down and bonding with the bottom of the plate, followed by 5.8%, and then 6.3%. 6.8% of asphalt content exhibited excessive asphalt draindown and bonding. Compared with the reference pictures from FM 5-588, as shown in **Figure 14**, it was evident that the preliminary OBC for GRN FC-5 mix design could be selected from 5.8% to 6.3%. It was decided to process at 6.0% as the preliminary OBC for the GRN FC-5 mixture. However, the average Cantabro loss result of GRN FC-5 mixture with 6.0% PG 76-22 binder was 25.6%, which exceeded the maximum allowable value of 20%. Therefore, the OBC was increased to 6.3% to reduce the Cantabro loss. 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 fell within the maximum Cantabro loss of 20%. 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, an OBC of 6.3% was used for the GRN FC-5 mixture.

Regarding the FC-5 mixture using limestone (LMS FC-5), FDOT provided the pie plate test results, designing 7.0% as the preliminary OBC, as shown in **Figure 28.** The value was then validated by the Cantabro test, yielding the Cantabro loss of 8.1% for PG 76-22 and 3.5% for HP. Both values were lower than the maximum allowable value of 20%. In addition, the average air voids were measured at 15.1% for PG 76-22 and 15.2 % for HP, satisfying the minimum air void requirement of 15%. Consequently, 7.0% was confirmed as the OBC for LMS FC-5 mixtures.

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

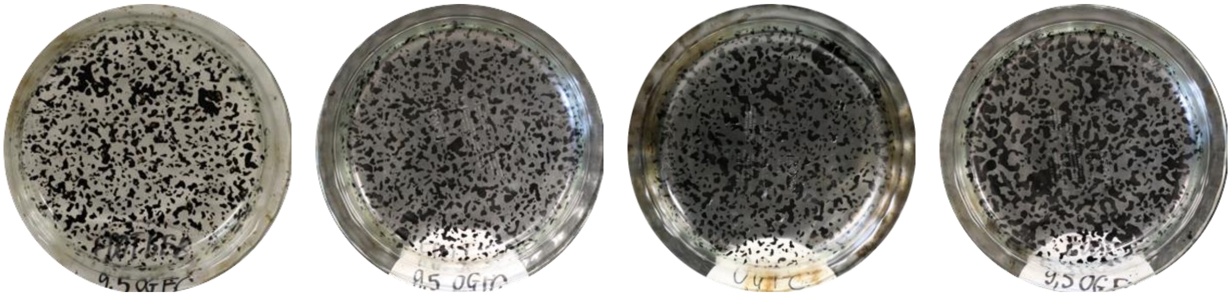
Figure 28. Pie Plate Pictures (with Loose Mixture) of LMS FC-5 Mixtures (a) 6.5 %, (b) 7.0 %, (c) 7.5 %.

4.1.2 9.5 mm OGFC Mix Design

To determine the OBC for 9.5 mm OGFC using granite (GRN 9.5 mm OGFC), the pie plate test was conducted across four different binder contents: 5.3, 5.8, 6.0, and 6.3%. **Figures 29 and 30** present the pie plate test results with and without a loose mixture, respectively. Based on the visual observation, the pie plate pictures of 6.0% and 6.3% showed sufficient draindown and bonding, which closely resembled the reference picture in FM 5-588. Then, 6.0% was selected as the preliminary OBC for GRN 9.5 mm OGFC, but the corresponding Cantabro loss value of the mixture with PG 76-22 binder was recorded at 25.6% at this binder content, which was higher than the maximum allowable threshold of 20%. To address this issue, 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 met the maximum Cantabro loss criterion of 20%. 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 mixture, which were higher than the minimum requirement of 15%. Therefore, 6.3% was selected as the OBC of GRN 9.5 mm OGFC mixtures.

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

Figure 29. Pie Plate Pictures (with Loose Mixture) of GRN 9.5 mm OGFC Mixtures (a) 5.3 %, (b) 5.8 %), (c) 6.0 and (d) 6.3 %.



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

Figure 30. Pie Plate Pictures (without Loose Mixture) of GRN 9.5 mm OGFC Mixtures (a) 5.3 %, (b) 5.8 %), (c) 6.0 and (d) 6.3 %.

Regarding 9.5 mm OGFC using limestone (LMS 9.5 mm OGFC), 7.3% was selected as the preliminary OBC based on the pie plate results provided by FDOT, shown in **Figure 31**. The Cantabro test and air voids measurement were then performed to validate the selected OBC. The results show that the Cantabro loss was 6.1% for the PG 76-22 mixture and 1.7% for the HP mixture, demonstrating compliance with the maximum allowable criteria of 20%. Moreover, the average air void was reported at 15.3% for PG 76-22 and 15.9% for the HP mixture, which met the minimum air void requirement of 15%. Therefore, the OBC for the LMS 9.5 mm OGFC mixture was determined as 7.3%.

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

Figure 31. Pie Plate Pictures (with Loose Mixture) of LMS 9.5 mm OGFC Mixtures (a) 6.5%, (b) 7.0 %), (c) 7.5%.

4.1.3 Design Summary for FC-5 and 9.5 mm OGFC Mixture

Table 9 presents the summary of the gradation for both FC-5 and 9.5 mm OGFC mixture. Each mixture type includes the gradation for GRN and LMS as well as the associated control points.

Table 9. Gradation Summary of FC-5 and 9.5 mm OGFC Mixture

Sieve	Design Gradation of FC-5			Design Gradation of 9.5mm OGFC		
	GRN	LMS	Control Points	GRN	LMS	Control Points
3/4‘’	100	100	100	100	100	100
1/2"	92	91	85 - 100	99	100	100
3/8"	72	73	55 - 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 - 4	2.7	3.4	2 - 5

Figures 32 and **33** present the gradation charts for FC-5 and 9.5 mm OGFC for both aggregate types, respectively. As shown in the below figures, the gradations of two aggregates for each mix type were very similar.

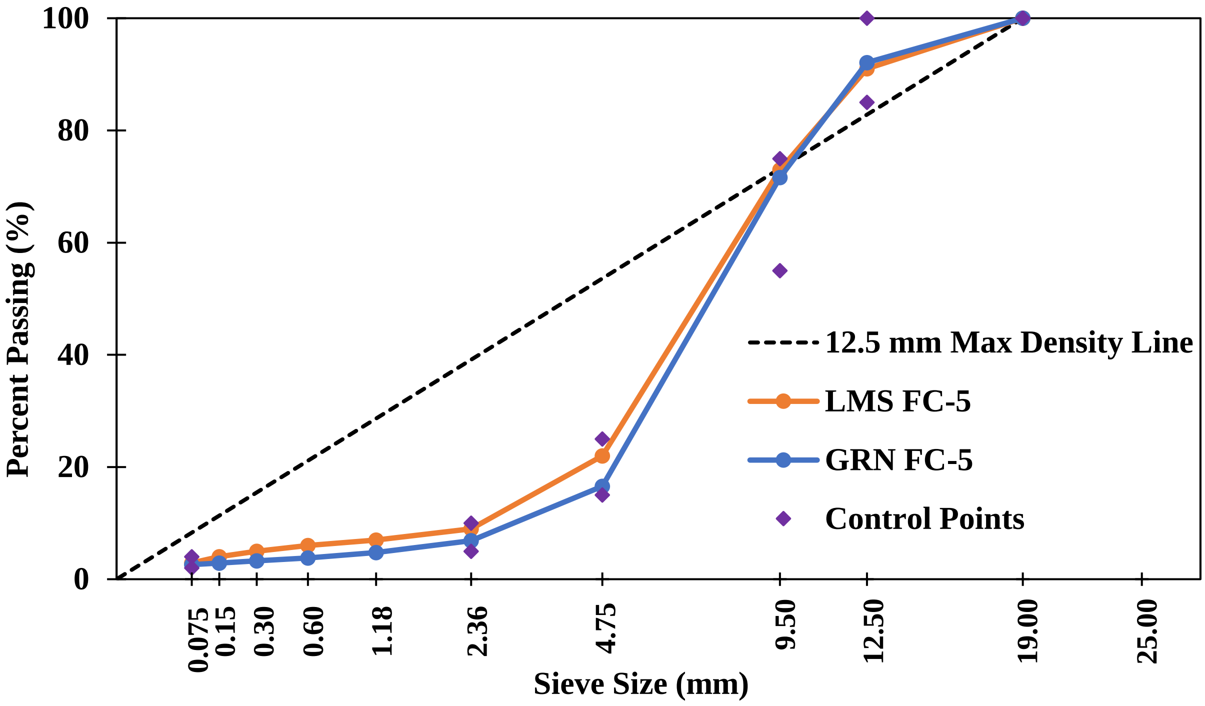


Figure 32. GRN and LMS FC-5 Gradation Curves

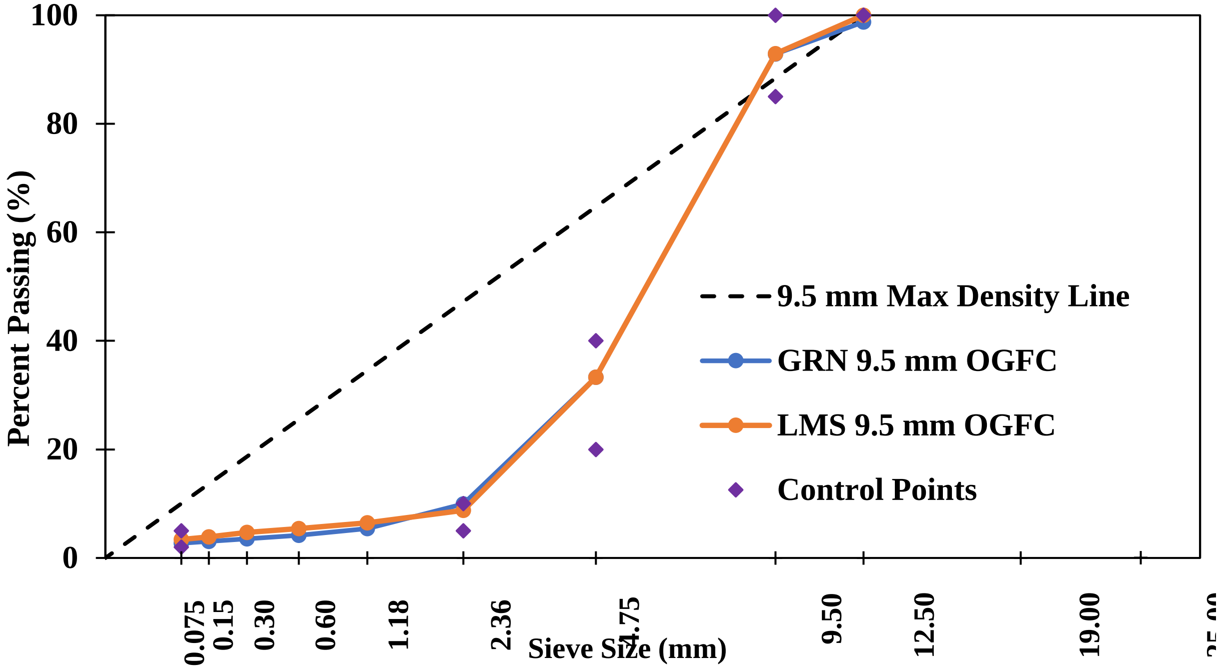


Figure 33. GRN and LMS 9.5 mm OGFC Gradation Curves

Table 10 presents the design summary for the FC-5 and 9.5 mm OGFC mixture. The OBC of GRN FC-5 and 9.5 mm OGFC mixtures was the same at 6.3%. For LMS mixtures, the OBC of FC-5 and OGFC mixtures were 7.0% and 7.3%, respectively. The OBC difference between the two aggregate sources might be attributed to the higher binder absorption of LMS compared to GRN. Therefore, higher binder contents were required for LMS mixtures to meet the performance requirement than those using GRN. Moreover, the 9.5 mm OGFC mixture typically yielded the same or slightly higher OBC than the corresponding FC-5 mixture, which was expected due to the finer gradation. Note that all the air void and Cantabro loss values satisfied the minimum air void requirement of 15% and maximum Cantabro loss of 20%.

Table 10. Design Summary of FC-5 and 9.5 mm OGFC Mixture

Aggregate	Mixture Type	Binder Type	OBC (%)	Air Void (Vacuum seal method) (%)	Air Void Requirement (Vacuum seal method) (%)	Cantabro Loss (%)	Cantabro Loss Requirement (%)

GRN	FC-5	PG 76-22	6.3	19.6	≥15	19.5	≤ 20
		HP		19.4		3.1	
	9.5mm OGFC	PG 76-22	6.3	19.6		11.9	
		HP		19.6		2.2	
LMS	FC-5	PG 76-22	7	15.1		8.1	
		HP		15.2		4.8	
	9.5mm OGFC	PG 76-22	7.3	15.3		6.1	
		HP		15.9		1.7	

4.2 12.5 mm SMA Mix Design and Summary

As mentioned previously, the first step of the 12.5 mm SMA mix design was to determine N_{design}. **Figure 34** presents the average air voids for GRN and LMS 12.5 mm SMA mixtures compacted at 50 Marshall blows, 35 and 50 SGC gyrations. As shown, the specimen compacted with 50 gyrations showed the lowest air voids, followed by 35 gyrations and 50 Marshall blows. In general, the specimens compacted at 35 gyrations showed comparable air voids with the specimens compacted at 50 Marshall blow, and the air voids differences were around 0.2% for both aggregate types. The air voids results indicated that 35 SGC gyrations yielded comparable compaction efforts with 50 Marshall blows. Therefore, the N_{design} for SMA mix design was determined as 35 gyrations in this study.

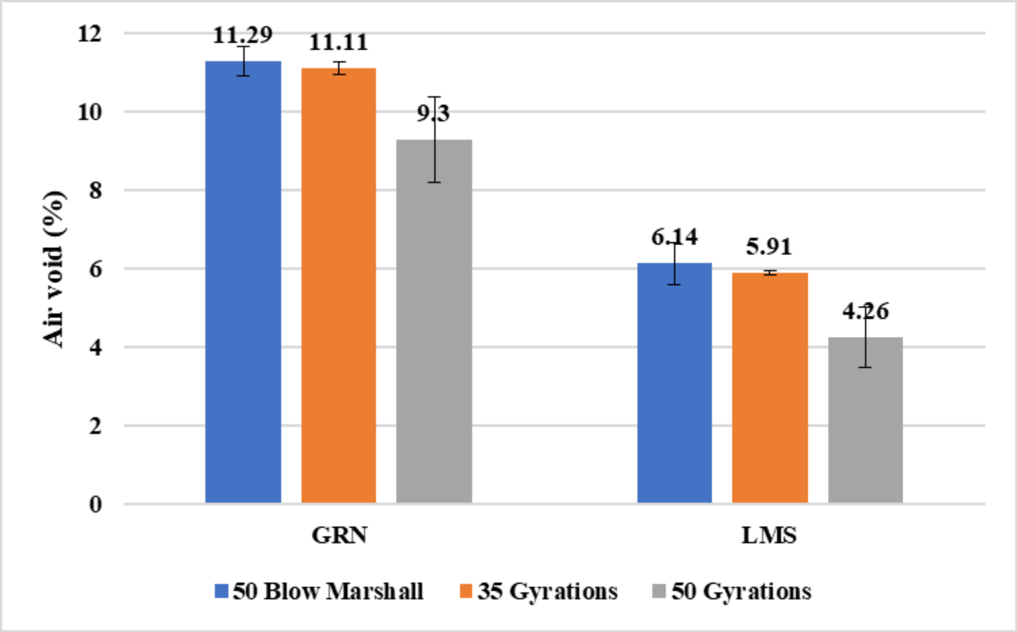


Figure 34. Air Voids Summary of GRN and LMS 12.5 mm SMA at Different Compaction Levels

After establishing N_{design}, the next step was to determine the OBC for the mixture. **Table 11** presents the gradation summary for the 12.5 mm SMA mixture, which includes the gradation for each aggregate and the associated control points.

Table 11. Gradation Summary for 12.5 mm SMA Mixture

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

Figure 35 presents the gradation curves for both GRN and LMS 12.5 mm SMA mixtures, and GRN 12.5 mm SMA gradation was finer than that of LMS 12.5 mm SMA.

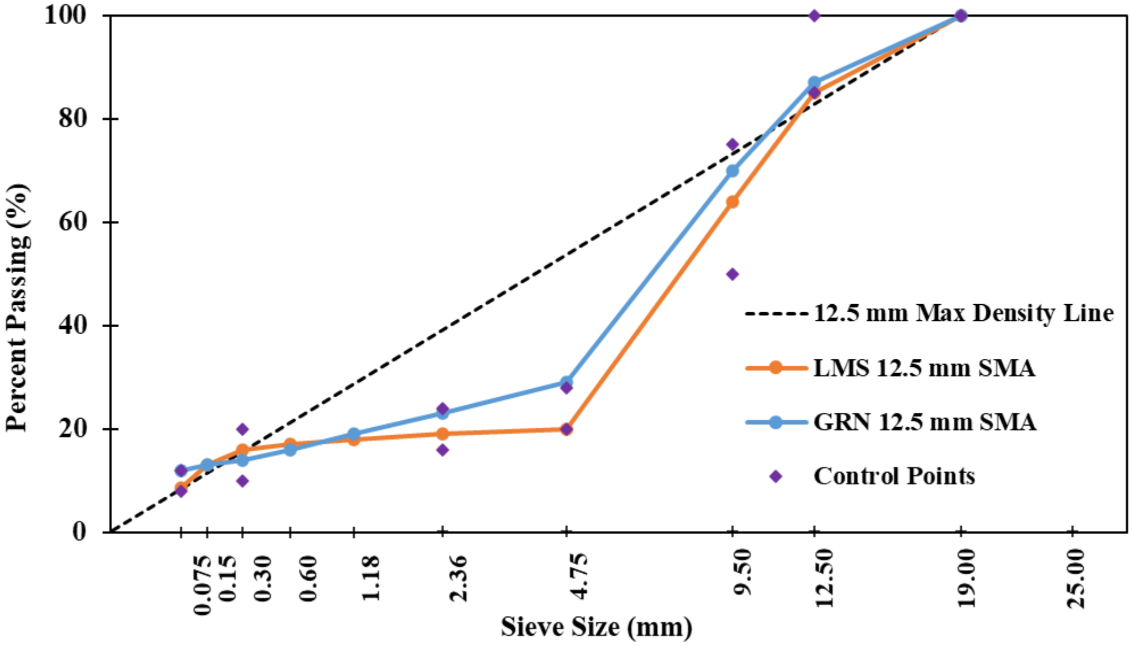


Figure 35. GRN and LMS 12.5 mm SMA Gradations

Table 12 presents the design summary of 12.5 mm SMA mixtures for both aggregate types including OBC, VMA, VCA_{drc}, VCA_{mix}, and the associated criteria. The volumetrics of SMA samples prepared with different binder contents were measured after compaction, and the OBC was determined when the air voids were 4.0%. The OBC of the GRN SMA mixture was lower than the OBC of LMS SMA, which was consistent with the FC-5 mix designs. Note that the SMA mixtures at the OBC also met the VMA and VCA requirements.

Table 12. Design Summary of 12.5 mm SMA Mixture

Aggregate	OBC (%)	V_a (%)	Va Requirement (%)	VMA (%)	VMA Requirement (%)	VCA_{drc}	VCA_{Mix}	VCA Requirement

GRN	6.5	4.0	4.0	18.2	≥ 17%	42.3	42.3	$VCA_{Mix} \leq VCA_{drc}$
LMS	7.5	4.0		17.0		40.6	40.3	

4.3 Alternative Friction Course Design and Summary

4.3.1 Alternative Friction Course Design for GRN

Following the procedures described in Step 3.1 of the experiment plan, two gradation options for the GRN alternative friction mix were proposed, as shown in **Figure 36**. Both options were designed to fall within the gradation of FC-5 and 12.5 mm SMA and Option #1 was designed to be finer than Option #2 by increasing the percentage passing of sieves smaller than 3/8 inch. The asphalt contents for both gradation options were fixed at 6.5%. Subsequently, the Cantabro and permeability tests were conducted to evaluate the durability and permeability of these two mixtures, and the test results were summarized in **Figure 37.**

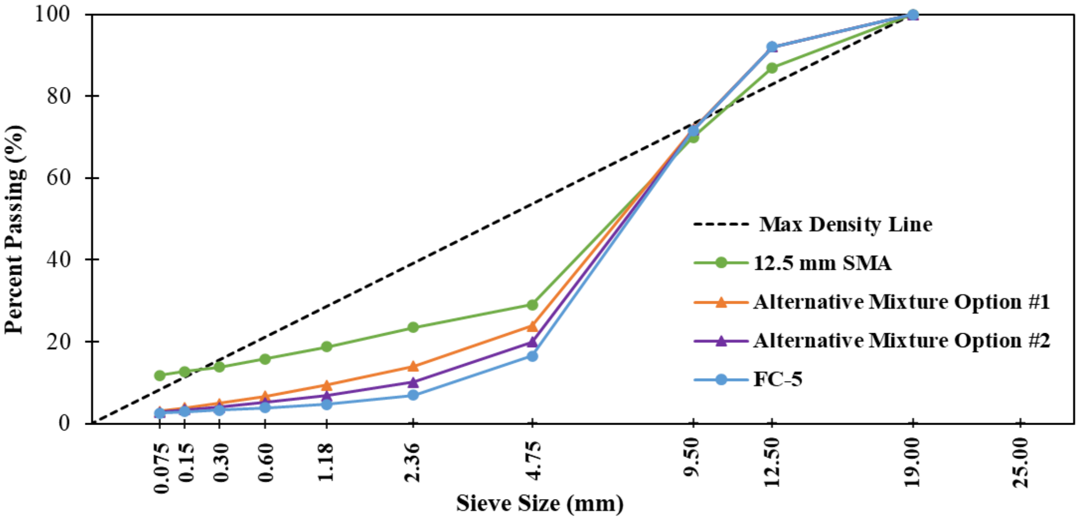


Figure 36. Alternative Friction Course Gradation Options for GRN

As presented, the FC-5 mixture generally showed the highest Cantabro loss and permeability, followed by alternative friction course option #2, alternative friction course option #1, and 12.5 mm SMA mixtures. As expected, the durability and permeability of two alternative friction mixtures generally fell between those of FC-5 and 12.5 mm SMA mixtures except that the

Cantabro loss of alternative friction course Option #1 was less than 12.5 mm SMA mixture. Option #1 was more durable and less permeable than Option #2, which was mainly caused by the finer gradation of Option #1 at the same binder content level. Both options met the performance criteria mentioned above with the maximum Cantabro of 20% and minimum permeability of 20 m/day. Based on the test results, Option #1 was selected as the final alternative friction course design considering its superior durability while ensuring the permeability

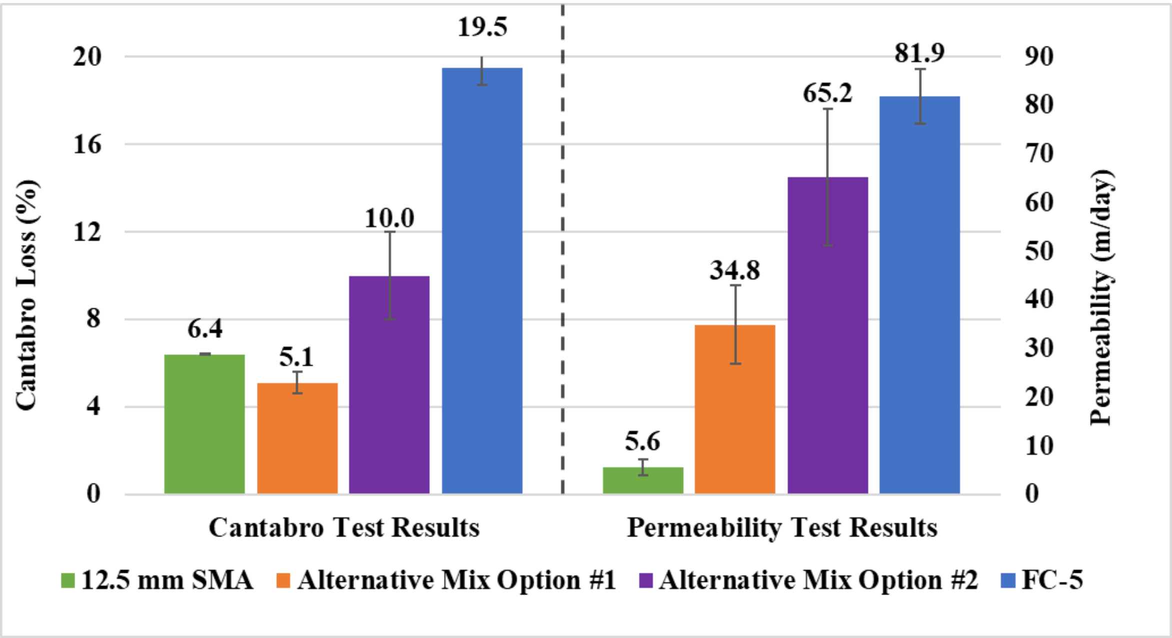


Figure 37. Performance Evaluation for GRN Alternative Friction Course Options

4.3.2 Alternative Friction Course Design for LMS

Similar to GRN, two gradation options were designed for the LMS alternative friction course, as shown in **Figure 38**. Although both gradations had a similar percentage passing ¾, ½, and 3/8 inches and No.200 sieves, Option #2 was designed to be finer than Option #1 by increasing the percentage passing of smaller sieves from the No.4 sieve. Option 1 was designed with 7.3% of asphalt content, while option 2 was designed with a lower content of 7.0%. Both mixtures were then evaluated in terms of durability and permeability using the Cantabro test and Permeability test respectively. The testing results are presented in **Figure 39**.

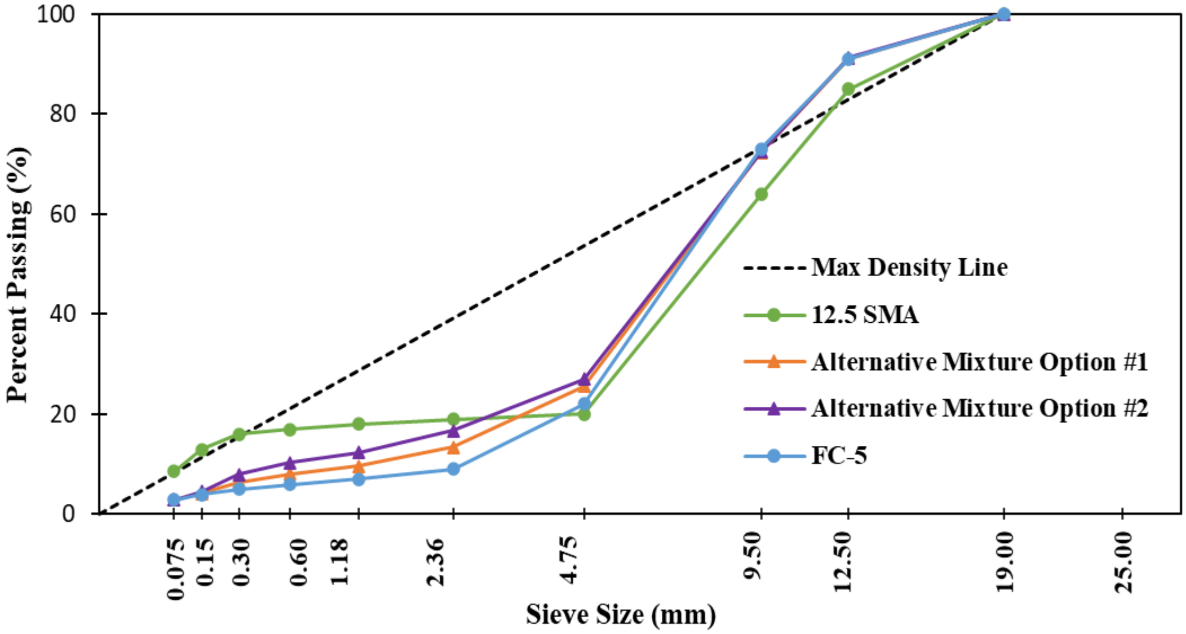


Figure 38. Alternative Friction Course Gradation Options for LMS

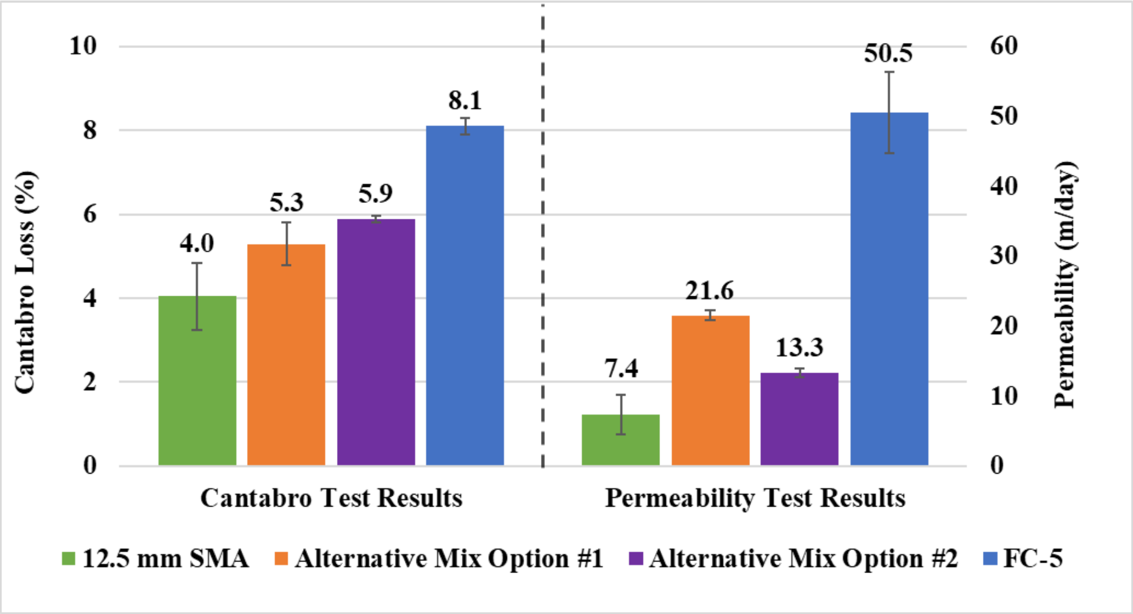


Figure 39. Performance Evaluation for LMS Alternative Friction Course Options

In terms of durability, a similar trend with GRN was observed for LMS in which both options had a lower Cantabro loss than the FC-5 mixture, but a higher value than 12.5mm SMA, as shown in

Figure 39. This proves the efficacy of using finer gradation and higher binder content to enhance the durability of the FC-5 mixture. Despite the coarse gradation of Option #1 relative to Option #2, using higher AC allowed Option #1 to have a comparable Cantabro loss of 5.3% with Option #2 of 5.9%.

In terms of permeability, both options showed permeability values lower than those of FC-5, which was expected given the finer gradation and higher binder content of these options. However, they were still higher than the permeability of 12.5 mm SMA. In addition, Option #1 with 21.6 m/day in permeability was higher than the 13.3 m/day of Option #2.

Based on the Cantabro and permeability test results, Option #1, which demonstrated similar durability and better permeability performance than Option #2, was selected as an alternative friction course for LMS OGFC in Florida.

4.3.3 Alternative Friction Course Design Summary

Table 13 summarizes the final alternative friction course design information for two aggregates including N_{design}, OBC, air voids, gradation, and associated FC-5 control points. As shown, both alternative friction course gradations fell into the FC-5 gradation band at all sieves except #4 and #8 sieves, and the passing percentages of No.4 and No.8 sieves were greater than the maximum allowable values in FC-5. Thus, the FC-5 gradation band could be modified to get the alternative friction course gradation band by increasing the passing percentages of No.4 and No.8 sieves while keeping the passing percentages of other sieves unchanged. In addition, the OBC of the GRN mixture was lower than the OBC of the LMS mixture, which was attributed to the higher binder absorption of LMS compared to GRN. **Figure 40** presents the gradation curves of two alternative friction course designs, which were almost identical between the two aggregate types.

Table 13. Gradation and Design Summary for Alternative Friction Course

Alternative Friction Course			
Sieve	**GRN**	**LMS**	**FC-5 Control Points**
3/4‘’	100	100	100

1/2"	92	91	85 - 100
3/8"	72	72	55 - 75
#4	24	26	15 - 25
#8	14	13	5 - 10
#16	9	10	
#30	7	8	
#50	5	6	
#100	4	4	
#200	3.0	2.9	2 - 4
N_{design} (Gyration)	50.0		
OBC (%)	6.5	7.3	
Va (%)	13.5	11.0	

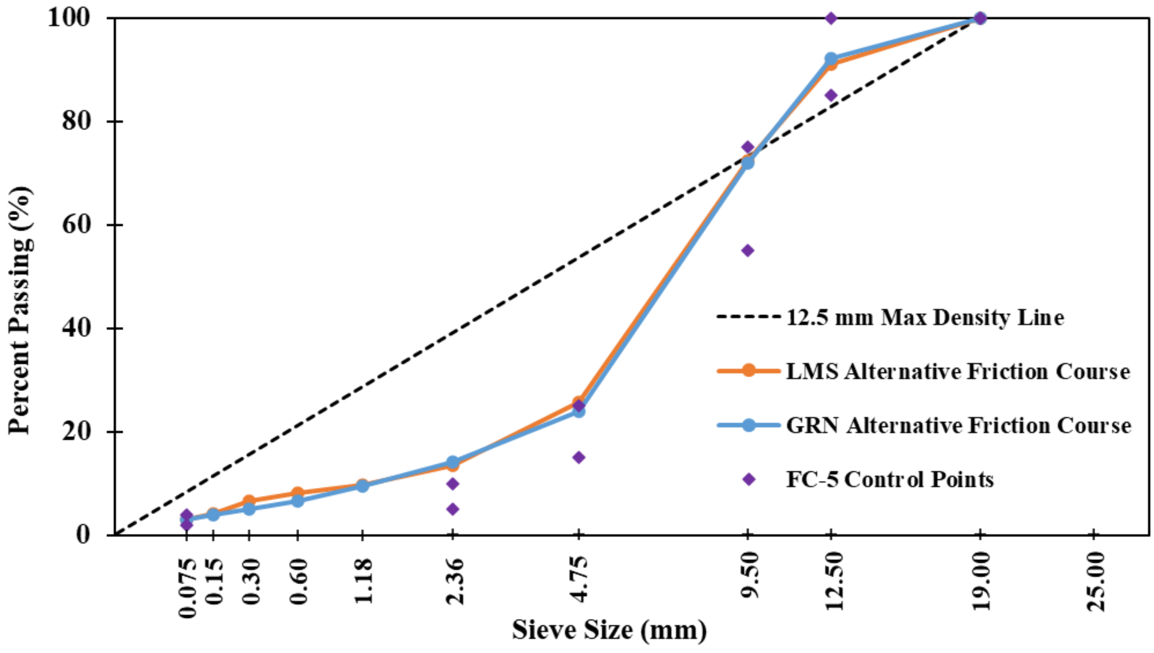


Figure 40. GRN and LMS Alternative Friction Course Gradations

CHAPTER 5 TEST RESULTS AND DISCUSSION

This chapter presents the test results for the FC-5, 9.5 mm OGFC, 12.5 mm SMA, and alternative friction course prepared with two aggregates (GRN and LMS) and two binder types (PG 76-22 and HP). The results were analyzed to (1) evaluate the effect of using finer gradation 9.5 mm NMAS and HP on the performance of the asphalt mixtures and (2) compare the performance of the alternative friction mixture with the other mixtures.

In this chapter, the average Cantabro, OT, permeability, and drainability test results are presented using column charts, and the error bars represent one plus and minus standard deviation. For data analysis, both mean value and group statistical analyses were used. The Games-Howell post-hoc group analysis at a significant level of 0.05 was first conducted to rank the performance of four mixtures prepared with the same binder type and aging condition. Then, the student's *t-test* was conducted to compare the performance of mixtures prepared with PG 76-22 binder and the corresponding HP mixtures at the same aging condition. The HWTT results are also presented using column charts, but only mean value analysis was conducted.

In addition, the evolution of Cantabro loss and OT CPR results in different aging conditions are presented using line graphs. Meanwhile, the Games-Howell post-hoc group analysis at a significant level of 0.05 was also performed for each mixture type to evaluate the effect of NAWS conditioning on durability and cracking resistance for both binder types. Moreover, the slopes of line graphs were used to evaluate the rate of performance change due to the influence of different aging conditions. The greater the magnitude of the slope indicates, the steeper the line and the greater the rate of durability change. Combining both group analysis and slope allows to rank the mixture in terms of aging susceptibility.

The MPD and DFT results were plotted against the TWPD polishing cycles to monitor the evolution of macrotexture and friction resistance throughout different polishing processes, and only mean value analysis was used to rank four mixture types and evaluate the effects of various influence factors (binder type and gradation).

The capital letters shown above the columns and line graphs represent the group analysis results, where mixtures sharing the same letter had no statistically significant difference among their test results. With the student t-test, if the *p-value* was less than a significant value of 0.05, the performance difference between HP and PG 76-22 mixtures was considered to be statistically different.

5.1 Cantabro Test Results

5.1.1 Cantabro Test Results of GRN Mixtures

Figures 41, 42, and 43 present the Cantabro loss results of GRN mixtures prepared with two binders at 0, 1000, and 2000 hours of conditioning in the NAWS room, respectively.

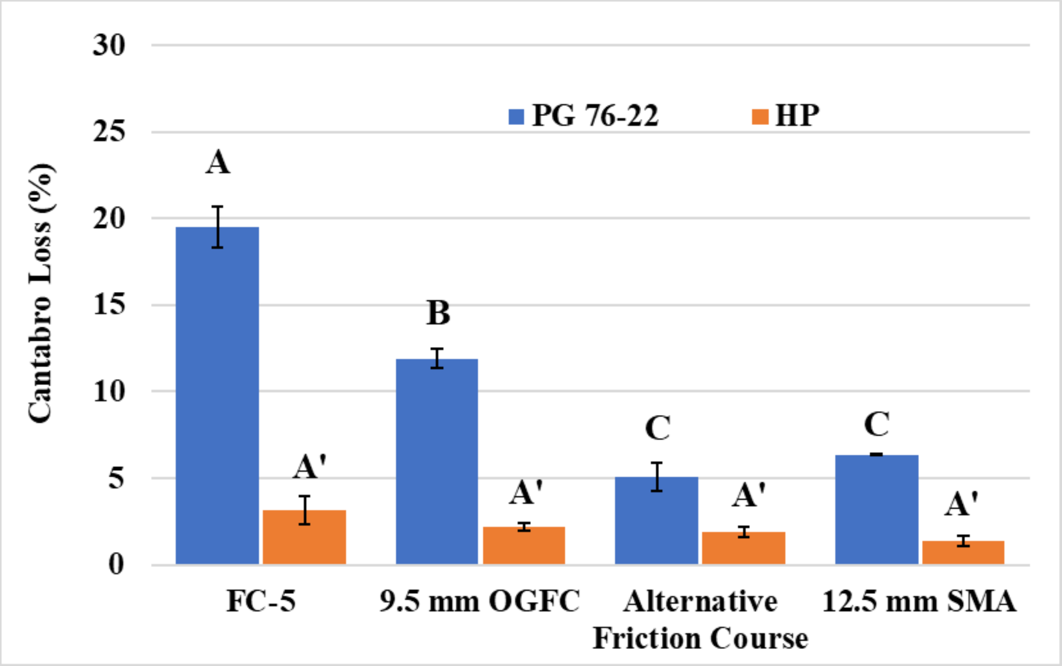


Figure 41. Cantabro Loss GRN Mixtures at 0 Hour in NAWS

Figure 41 presents the Cantabro loss results of GRN mixtures before conditioning in the NAWS room. In terms of mixtures designed with PG 76-22, the FC-5 mixture exhibited the highest average Cantabro loss, followed by the 9.5 mm OGFC mixture, 12.5 mm SMA mixture, and the alternative friction mixture with the lowest value. The group analysis results indicated that the alternative friction mixture provided statistically equivalent raveling resistance compared to the 12.5 mm SMA mixtures and showed significantly better durability than FC-5 and 9.5 mm OGFC mixtures. In addition, the 9.5 mm OGFC mixture showed statistically lower Cantabro loss results than the FC-5 mixture, which implied that finer gradation could significantly improve the raveling resistance of the OGFC mixture. For HP mixtures, the 12.5 mm SMA mixture obtained the lowest average Cantabro loss results, followed by the alternative friction mixture, 9.5 mm OGFC mixture, and FC-5 mixture. However, the group analysis results showed that no significant difference existed among the four mixture types, which indicated that the effect of HP on mixture durability was dominant regardless of the mixture types.

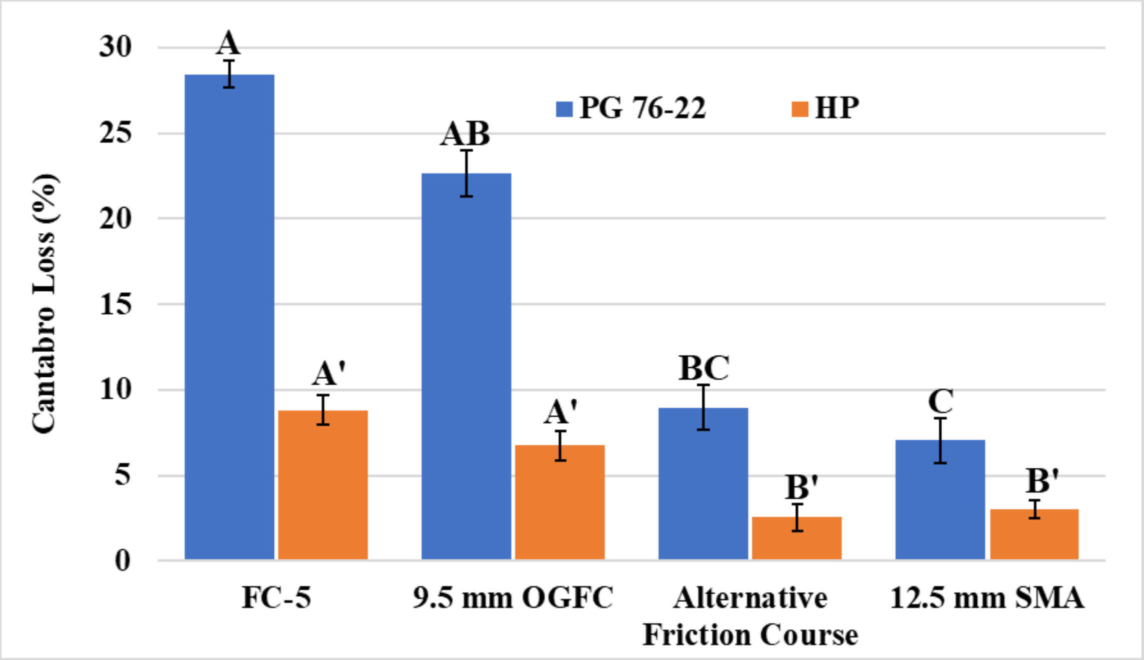


Figure 42. Cantabro Loss of GRN Mixtures after 1000 Hours in NAWS

Figure 42 presents the Cantabro loss results of all the GRN mixtures after 1000 hours of conditioning in the NAWS room. In terms of mixtures using PG 76-22, the average Cantabro loss was highest for the FC-5 mixture, followed by the 9.5 mm OGFC mixture and then the alternative friction mixture. The 12.5 mm SMA mixture showed the lowest Cantabro loss. This result indicated that using the finer gradation of 9.5 mm NMAS and the alternative friction course could improve the raveling resistance of the FC-5 mixture. However, the group analysis shows no significant difference between the 9.5 mm OGFC and FC-5 mixture. The alternative friction course 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 the mixtures using HP, **Figure 42** shows that the Cantabro loss of the FC-5 mixture maintained the highest rank, followed by the 9.5 mm OGFC mixture. However, the group analysis displayed no significant difference between these two mixtures. Following them in the rank were the 12.5 mm SMA mixture and then the alternative friction mixture. However, these two mixtures showed no significant difference from each other, and both were significantly lower than the FC-5 and 9.5 mm OGFC mixture. The results confirmed the better raveling resistance of the alternative friction mixture compared with the FC-5 mixture.

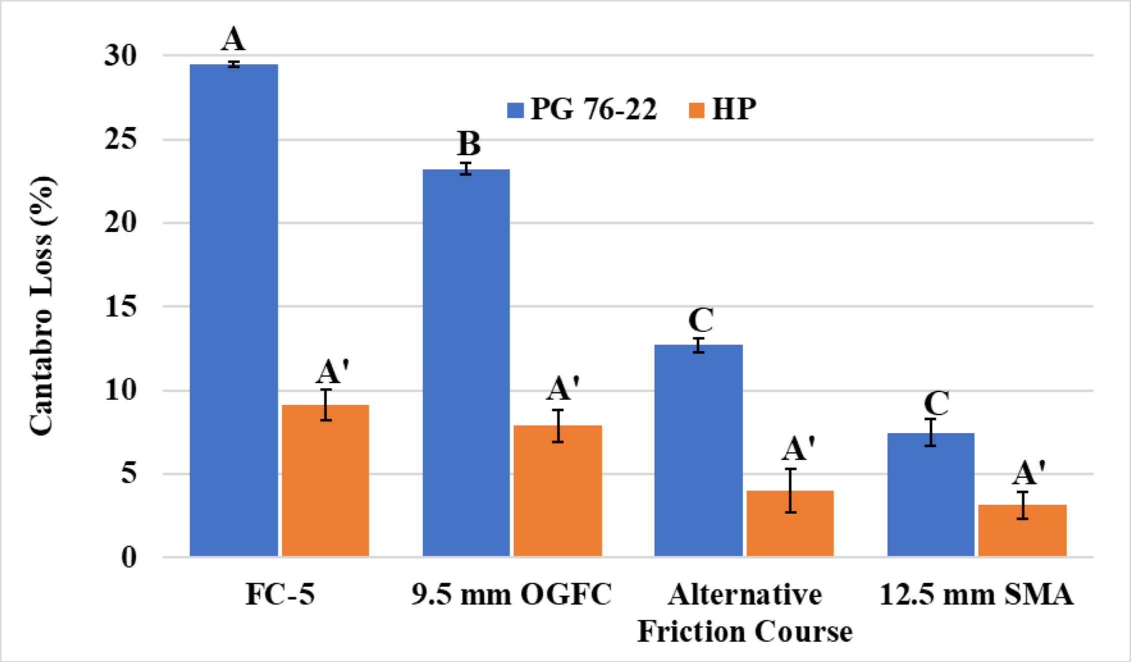


Figure 43. Cantabro Loss of GRN Mixtures after 2000 Hours in NAWS

Figure 43 exhibits the Cantabro loss from all mixtures after 2000 hours of conditioning in the NAWS room. Among the mixtures designed with PG 76-22, both the alternative friction and 12.5 mm SMA mixture maintained lower Cantabro loss than the FC-5 and the 9.5 mm OGFC mixture. The group analysis showed no significant difference between the alternative friction and 12.5 mm SMA mixture, but both showed a significantly lower than the FC-5 and 9.5 mm OGFC mixture. This analysis highlighted the conclusion drawn from the two previous conditioning stages that with PG 76-22, the alternative friction and 9.5 mm OGFC mixture generally significantly improved the raveling resistance of the FC-5 mixture.

In terms of mixtures using HP, **Figure 43** shows a similar trend with PG 76-22 mixtures, with the FC-5 mixture displaying the highest Cantabro loss, followed by the 9.5 mm OGFC and then the alternative friction mixture, while the 12.5 mm SMA mixture had the lowest value. However, in contrast to the PG 76-22 mixtures, there was no significant difference in Cantabro loss between the HP mixtures, as confirmed by the group analysis. This result indicates that when using HP, the alternative friction and 9.5 mm OGFC mixture could improve the raveling resistance of the FC-5 mixture, but not significantly.

In sum, the group analysis results generally showed a consistent trend regarding the performance comparison among four mixture types for all three aging conditions. For mixtures prepared with PG 76-22, the alternative friction mixture showed statistically equivalent raveling resistance with the 12.5 mm SMA mixture, and both mixtures showed statistically generally better raveling resistance than the 9.5 mm OGFC and FC-5 mixtures. In addition, the 9.5 mm OGFC mixture consistently showed significantly higher raveling resistance than the FC-5 mixture except at 1000 hours of NAWS conditioning. Moreover, the better durability of alternative friction and 12.5 mm SMA mixtures was most likely attributed to their higher binder content and finer gradation compared to the OGFC mixtures. For HP mixtures, no significant difference was observed among four mixtures except at 1000 hours of conditioning, the alternative friction mixture and 12.5 mm SMA mixtures showed statistically better raveling resistance than the two OGFC mixtures.

Analyzing the effect of using HP on durability, **Figures 41**, **42,** and **43** consistently showed a lower Cantabro loss for mixtures using HP compared to those using PG 76-22 at all three aging conditions. To assess whether using HP can statistically improve the durability of the asphalt mixture, *p-values* were computed for each mixture type at each aging condition. The corresponding *p-values* for GRN mixtures at three aging conditions are detailed in **Table 14.** As presented, *p-values* were less than 0.05 for all GRN mixtures at all aging conditions, which indicated that HP mixtures yielded significantly better durability than those prepared with PG 76-22 mixtures.

Table 14. P-Values of GRN Mixtures using PG 76-22 and HP at Three Aging Conditions

Mix Designs	P- Values		
	0 Hrs NAWS	1000 Hrs NAWS	2000 Hrs 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

5.1.2 Cantabro Test Results of LMS Mixtures

Figures 44, 45, and **46** present the Cantabro loss of LMS mixtures at 0, 1000, and 2000 hours of conditioning in the NAWS room, respectively.

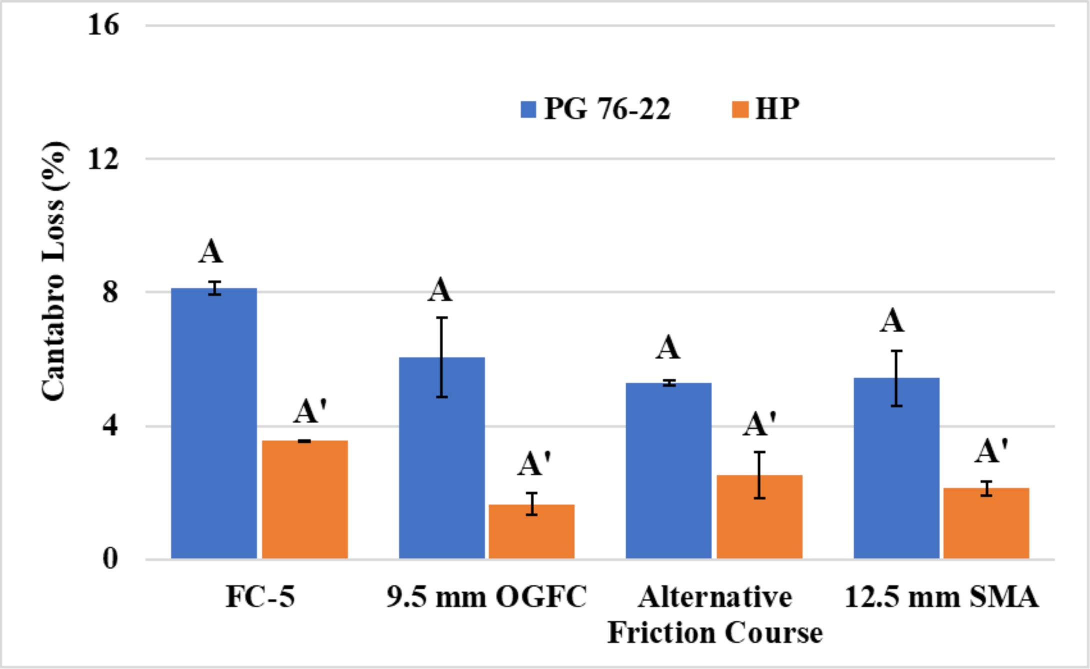


Figure 44. Cantabro Loss of LMS Mixtures at 0 Hour in NAWS

Figure 44 presents the Cantabro loss of LMS mixtures at 0 hour in the NWAS room. In terms of mixtures using PG 76-22, FC-5 showed the highest Cantabro loss, followed by the 9.5 mm OGFC, indicating that using the finer gradation can improve the raveling resistance of LMS FC-5 mixtures. While the 12.5 mm SMA and the alternative friction mixture showed the lowest value, indicating their improvement in raveling resistance. However, the group analysis showed no significant difference between these mixtures.

In terms of mixtures using HP, the FC-5 mixture reported the highest Cantabro loss, followed by 12.5 mm SMA and then the alternative friction mixtures. Notably, the 9.5 mm OGFC mixture provided the lowest value of Cantabro loss. However, similar to PG 76-22 mixtures, no significant difference was identified among the LMS mixtures designed with HP.

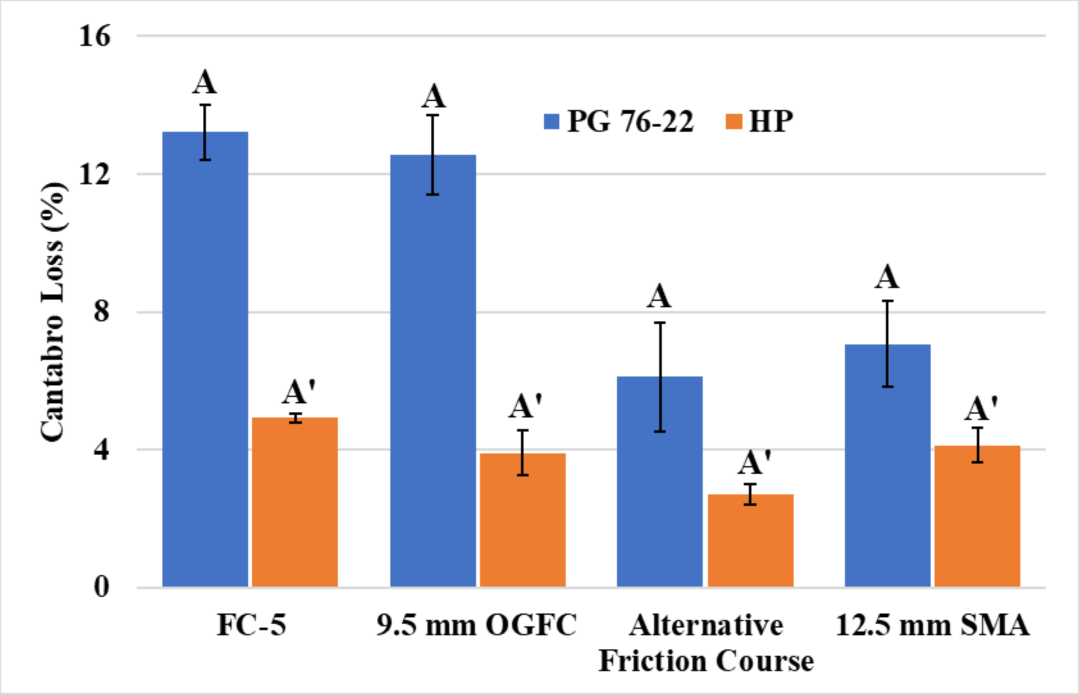


Figure 45. Cantabro Loss of LMS Mixtures after 1000 Hours in NAWS

Figure 45 presented the Cantabro loss of the LMS asphalt mixture after the first 1000 hours of conditioning. For both binders, FC-5 showed the highest Cantabro loss, followed by the 9.5 mm OGFC and then 12.5 mm SMA mixtures. The alternative friction mixture had the lowest Cantabro loss. However, the group analysis showed no significant difference between these mixtures. This indicated that the alternative friction mixture and 9.5 mm OGFC mixture enhanced the raveling resistance of the FC-5 mixture, but the enhancement was not significant.

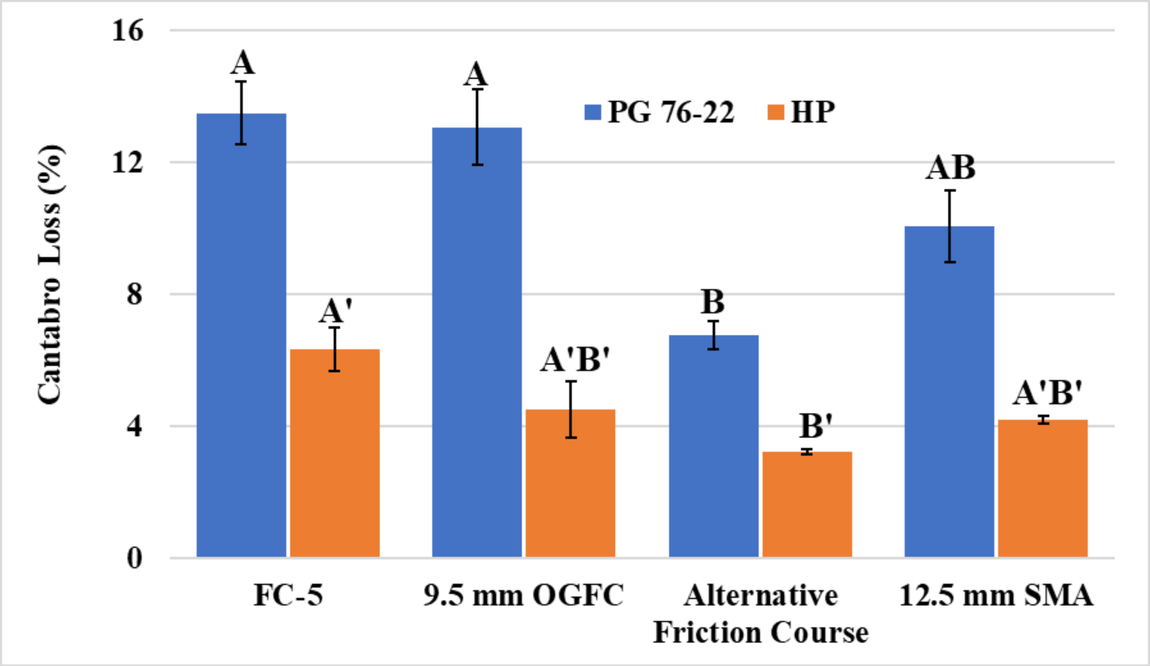


Figure 46. Cantabro Loss of LMS Mixtures after 2000 Hours in NAWS

Figure 46 continues the evaluation, presenting the Cantabro loss of all LMS mixtures measured after 2000 hours of aging in the NWAS room. A similar trend with the mixtures after 1000 hours of conditioning was observed. For mixtures using PG 76-22, the Cantabro loss of the FC-5 mixture remained the highest, followed by the 9.5 mm OGFC and then the 12.5 mm SMA mixtures, while the alternative friction mixture had the lowest value. The group analysis showed that the alternative friction mixture had statistically equivalent raveling resistance to the 12.5 SMA mixture and significantly enhanced performance compared to the FC-5 and 9.5 mm OGFC mixtures. Moreover, the difference between the FC-5 and 9.5 mm OGFC mixture was not significant.

For mixtures using HP, similar to PG 76-22 mixtures, the FC-5 showed the highest Cantabro loss, followed by the 9.5 mm OGFC, which indicated the better raveling resistance of using finer gradation. This was followed by the 12.5 mm SMA and then the alternative friction mixture. However, the group analysis indicated no significant difference between the FC-5 and 9.5 mm OGFC mixture. Moreover, the alternative friction course provided a statistical equivalent with the 9.5 mm OGFC and 12.5 mm SMA mixture but was significantly lower than that of the FC-5 mixture. The analysis confirmed that using the alternative friction mixture significantly enhanced the raveling resistance of the LMS FC-5 mixture.

Based on the analysis of Cantabro loss of LMS mixtures during three aging conditions, it was evident that the 12.5 mm SMA and alternative friction mixture generally provided better durability than the FC-5 and 9.5 mm OGFC mixtures. However, no significant difference in durability between these mixtures was observed for both binders, with one exception: after 2000 hours of conditioning, the alternative friction mixture showed a significant difference with the FC-5 mixtures at both binder types. This result indicated that using the alternative friction mixture and HP could enhance the durability of the FC-5 mixture and the benefit became significant after long-term aging in the NAWS room.

Regarding the effect of using HP on durability, **Figures 44, 45,** and **46** demonstrated the better durability performance of HP mixtures compared to PG 76-22 mixtures across all aging conditions. *p-values* from the *t-test* at a significance level of 0.05 confirmed the significant improvement since the *p-values,* as shown in **Table 15**, were less than 0.05 for all LMS mixture, except for the alternative friction mixture at 0 hours and 12.5 mm SMA after the first 1000 hours of conditioning.

Table 15. P-values of LMS Mixtures using PG 76-22 and HP at Three Aging Conditions

Mix Designs	**P- Values**		
	0 Hrs NAWS	**1000 Hrs NAWS**	**2000 Hrs 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

5.1.3 Effect of Aging on Mixture Durability

This section presents the effect of aging on the mixture resistance to raveling for all four mixtures prepared with both binder types. The aging susceptibility of each mixture type was characterized using the group analysis at three conditioning stages and the slope of Cantabro loss only before and after 1000 hours of NAWS conditioning, considering that no significant difference was observed between 1000 hours and 2000 hours. Technically, the mixtures with greater slopes and different groups between conditioning were expected to be more susceptible to aging than those with lower slopes and same groups.

5.1.3.1 Effects of Aging on GRN Mixture Durability

Figure 47 presents the evolution of Cantabro test results of GRN mixtures prepared with two binders at three conditioning stages. As shown, the Cantabro loss of all mixtures consistently increased following each aging condition, indicating the progressive reduction in raveling resistance due to the effect of the weathering condition. However, the group analysis indicated that each mixture experienced a different level of reduction throughout the conditioning process. The Cantabro loss of FC-5 and 9.5 mm OGFC mixtures prepared with both binders significantly increased after the first 1000 hours of NAWS conditioning, but no statistical difference was observed between 1000 hours and 2000 hours of conditioning. The results implied that the raveling resistance of OGFC mixtures reduced significantly from 0 hour to 1000 hours of NAWS conditioning, but the effects of weather aging reached a plateau after 1,000 hours of NAWS aging. The Cantabro loss results of the alternative friction and 12.5 mm SMA mixtures prepared with both binders were statistically equivalent at three aging conditions except for the alternative friction mixture using PG 76-22 significantly increased after 2000 hours of NAWS conditioning. This result implied that two OGFC mixtures were more susceptible to NAWS conditioning than the alternative friction and 12.5 mm SMA mixtures.

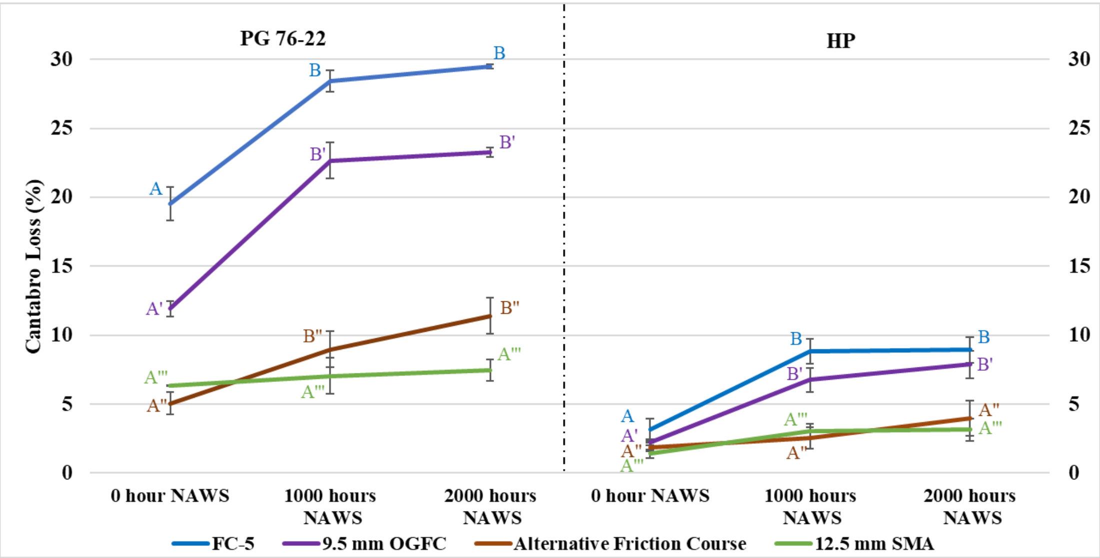


Figure 47. Cantabro Loss of GRN Mixtures at Three Aging Conditions

Table 16 summarizes the slopes of Cantabro loss for the mixtures before and after 1000 hours of conditioning. As presented, the HP mixtures consistently yielded lower slope values than the mixtures using PG 76-22 for all four mixture types, which demonstrated that the HP binder provided better-aging resistance than the PG 76-22 binder. In addition, the slope values of the alternative friction mixture and 12.5 mm SMA mixtures were consistently lower than the two OGFC mixtures, indicating better-aging resistance. This finding was consistent with the group analysis results.

Table 16. Graph Slope of GRN Cantabro Loss from 0 to 1000 hours in NAWS

Mix Designs	**Graph Slope (0-> 1000 hours)**	
	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

5.1.3.2 Effects of Aging on LMS Mixture Durability

Figure 48 exhibits the evolution of Cantabro test results of LMS mixtures, prepared with two binders at three aging conditions. As shown, Cantabro loss for all LMS mixtures after 1000 and 2000 hours of conditioning in the NAWS room was increased, indicating reduced raveling resistance due to the combined effects of aging and moisture damage.

As shown in **Figure 48**, the Cantabro loss of the 9.5 mm OGFC mixture significantly increased after 1000 hours of conditioning for both binders, following an insignificant increase. This trend was also observed for the FC-5 and 12.5 mm SMA mixtures designed with PG 76-22. However, when designed with HP, both mixtures showed no significant increase for all three aging conditions. Similarly, the alternative friction mixture exhibited no significant Cantabro loss increase for both binders at all three aging conditions. These results indicate that the alternative friction mixture displayed the lowest aging susceptibility, while the 9.5 mm OGFC mixtures showed the highest aging susceptibility.

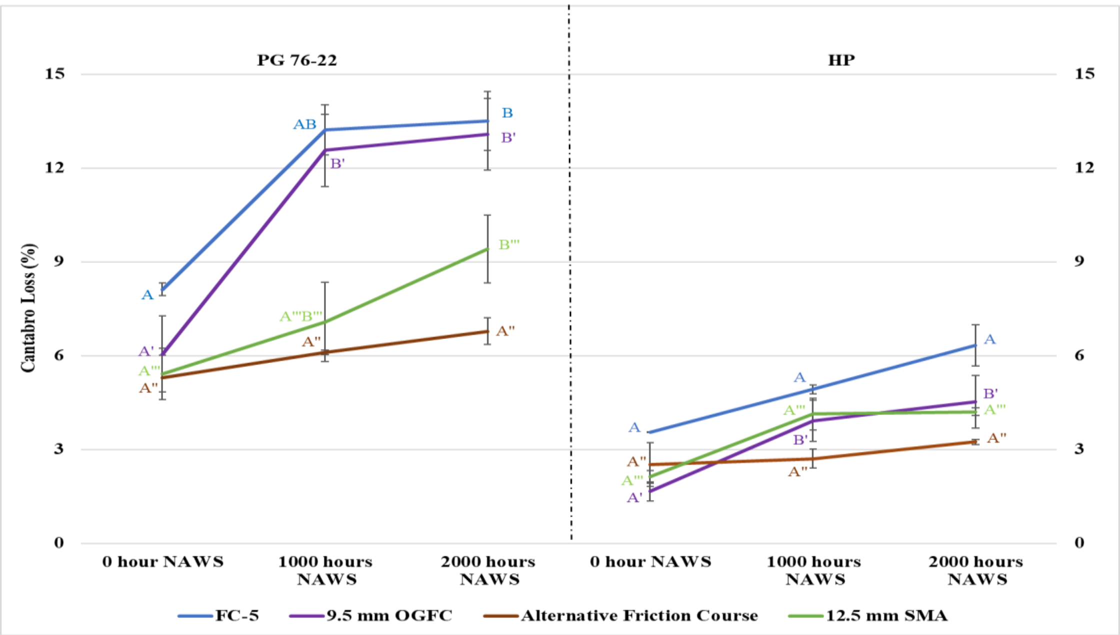


Figure 48. Cantabro Loss of LMS at Three Aging Conditions

Table 17 displays Cantabro loss slopes for GRN mixtures before and after the initial 1000 hours of conditioning. Overall, HP mixtures exhibited lower slopes than PG 76-22 mixtures, indicating better aging resistance for HP compared to PG 76-22. Additionally, the alternative friction mixture had the lowest slope, indicating the highest aging resistance, while the 9.5 mm OGFC had the highest slope, indicating the lowest aging resistance. This conclusion aligns with the group analysis results.

Table 17. Graph Slope of LMS Cantabro Loss from 0 to 1000 hours in NAWS

Mix Designs	Graph Slope (0-> 1000 hours)	
	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

5.2 Overlay Test Results

5.2.1 Overlay Test Results of GRN Mixtures

Figures 49 and **50** present the OT CPR results of GRN mixtures before and after 1000 hours of conditioning in the NAWS room, respectively.

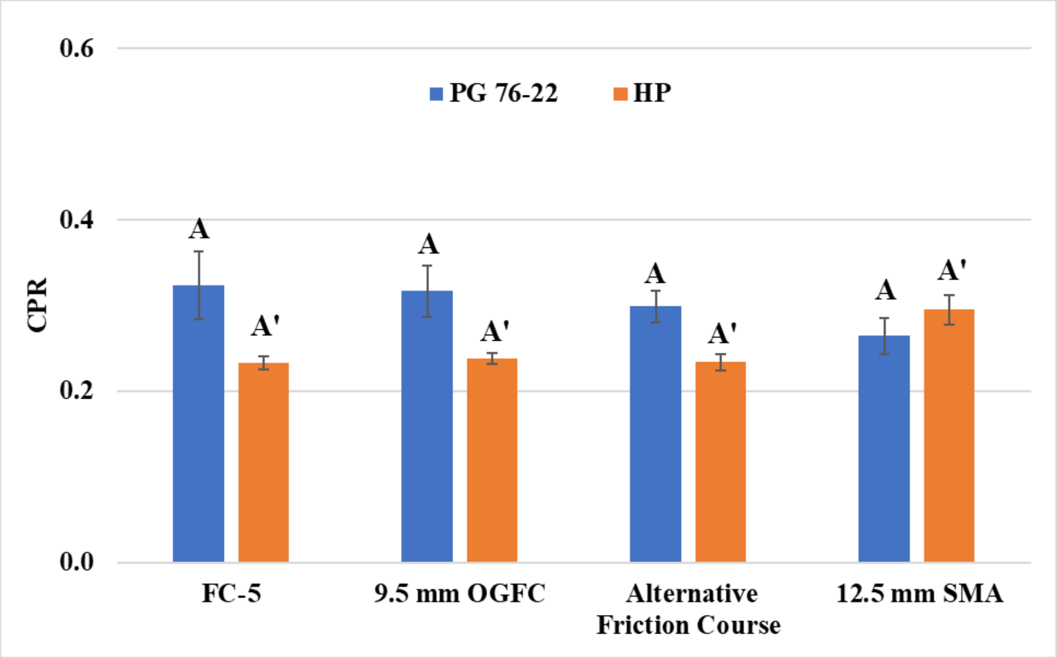


Figure 49. OT CPR Results of GRN Mixtures at 0 Hour in NAWS

As presented in **Figure 49**, before conditioning in the NAWS room, the PG 76-22 mixtures ranked in CPR value from highest to lowest: FC-5, 9.5 mm OGFC, alternative friction mixture, and 12.5 mm SMA. However, statistical analysis revealed no significant differences between these mixtures. For HP-designed mixtures, the 12.5 mm SMA mixture had the highest CPR, while the FC-5, 9.5 mm OGFC, and the alternative friction mixture showed similar CPR values. Similar to mixtures designed with PG 76-22, group analysis indicated no significant difference between HP mixtures. Therefore, using the alternative friction mixture and finer gradation of 9.5 mm OGFC did not significantly improve the cracking resistance of the GRN FC-5 mixture at 0 hours of NWAS conditioning.

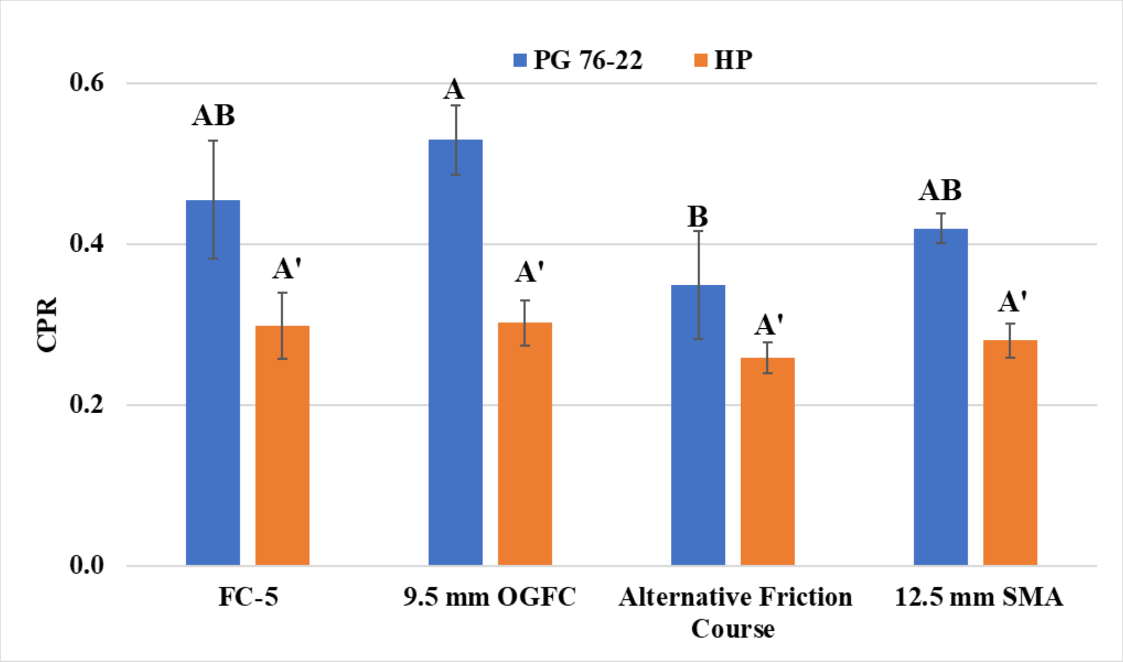


Figure 50. OT CPR Results of GRN Mixtures after 1000 Hours in NAWS

Figure 50 displays CPR values for GRN mixtures after 1000 hours of conditioning. When designed with PG 76-22, the alternative friction mixture showed the highest cracking resistance, followed by the 12.5 mm SMA, FC-5, and then the 9.5 mm OGFC mixture. However, group analysis found no significant differences in CPR between these mixtures, except for the alternative friction mixture, significantly lower than the 9.5 mm OGFC mixture. For HP-designed mixtures, the alternative friction mixture had the highest cracking resistance, followed by the 12.5 mm SMA, and FC-5 and 9.5 mm OGFC mixture, which had similar values. Group analysis revealed no significant differences between these mixtures using HP. Therefore, it is concluded that the alternative friction mixture and 9.5 mm OGFC did not significantly improve cracking resistance for GRN FC-5 after 1000 hours of aging. In summary, at both aging conditions, the alternative friction mixture and 9.5 mm OGFC showed statistically equivalent cracking resistance compared to the FC-5 mixture.

In terms of the effect of HP on the performance of the asphalt mixture, **Figures 49** and **50** demonstrate that, except for the 12.5 mm SMA mixtures at 0 hours of aging, GRN mixtures using HP consistently exhibited lower CPR values than those using PG 76-22 at both aging conditions. This suggests that HP can enhance the cracking resistance of the asphalt mixtures. Moreover, the *t-test* results in **Table 18**, with all *p-values* below 0.05 except for the 12.5 mm SMA mixture at 0 hour of conditioning, further support this conclusion. In summary, using HP binder significantly improves cracking resistance, particularly for the FC-5, 9.5 mm OGFC, and alternative friction mixtures

Table 18. Value of GRN Mixtures Using PG 76-22 and HP at Two Aging Conditions

Mix Designs	**P- Values**	
	0 Hrs NAWS	**1000 Hrs 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

5.2.2 Overlay Test Results of LMS Mixtures

Figures 51 and **52** present the OT CPR results of LMS mixtures before and after 1000 hours of conditioning in the NAWS room, respectively.

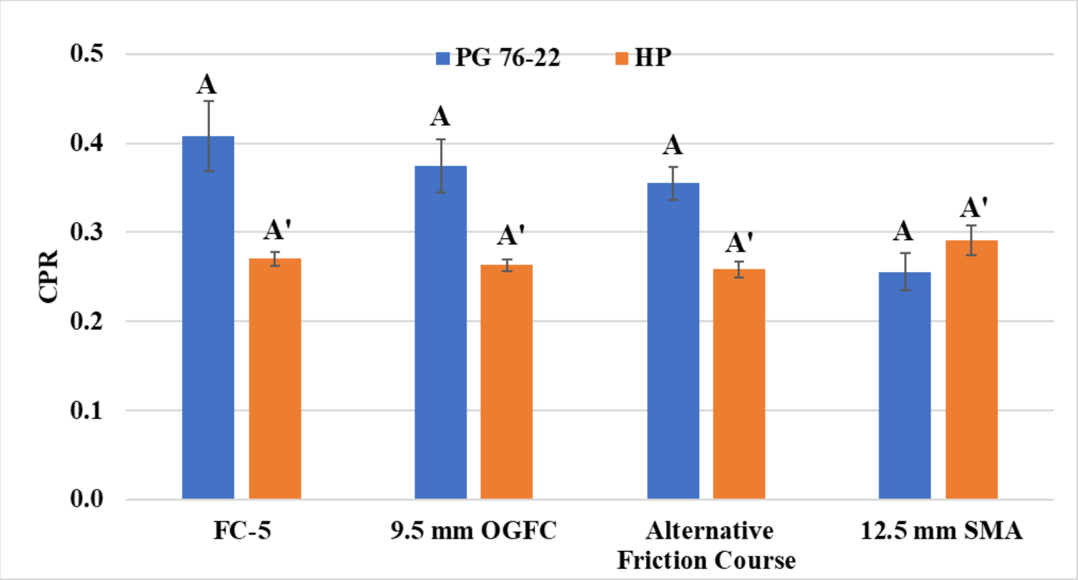


Figure 51. OT CPR results of LMS Mixtures at 0 Hour of NAWS

In **Figure 51**, with PG 76-22, the 12.5 mm SMA mixture had the lowest CPR, followed by the alternative friction and 9.5 mm OGFC mixture, while the FC-5 showed the highest values. However, the group analysis revealed no significant differences in CPR values between these mixtures. For LMS mixtures using HP, the 12.5 mm SMA mixture had the highest CPR, followed by the FC-5, 9.5 mm OGFC, and the alternative friction mixture with similar CPR values. Similar to PG 76-22 mixtures, no statistically significant differences among these HP mixtures were observed. Therefore, using alternative friction mixtures and 9.5 mm OGFC did not significantly change the cracking resistance of the LMS FC-5 mixture at both binders.

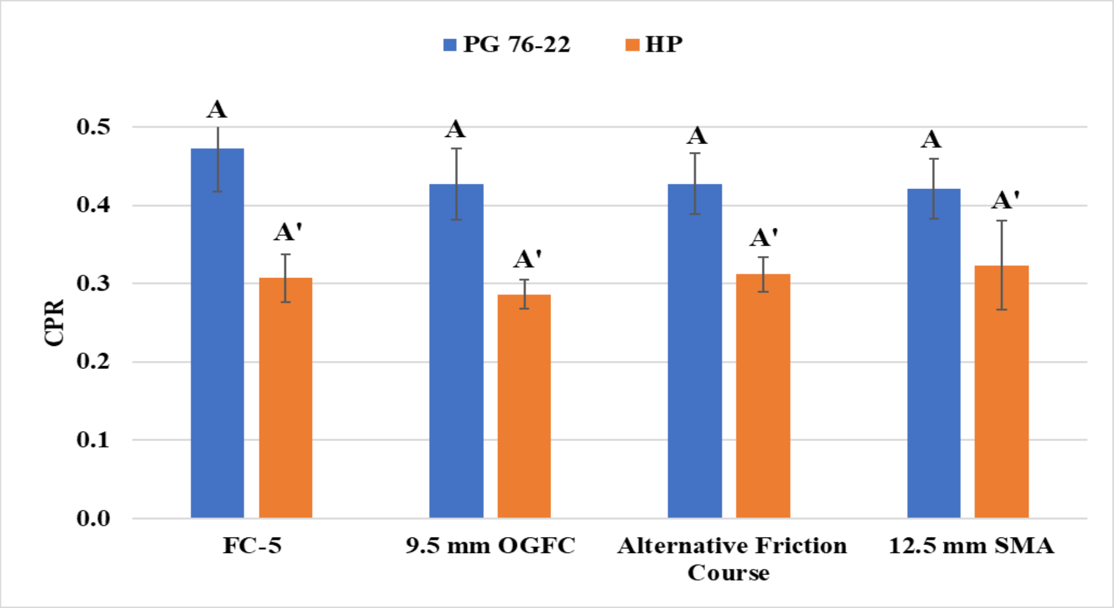


Figure 52. OT CPR results of LMS Mixtures after 1000 Hours in NAWS

In **Figure 52**, after 1000 hours in the NAWS room, PG 76-22 mixtures showed 12.5 mm SMA with the lowest CPR value, indicating the best cracking resistance, followed by the alternative friction mixture and 9.5 mm OGFC mixture had similar CPR values. The FC-5 mixtures had the highest value, demonstrating the lowest cracking resistance. However, the group analysis found no significant differences between the PG 76-22 mixtures. In HP mixtures, the 12.5 mm SMA mixture had the highest CPR, followed by the alternative friction mixture and FC-5 with the same CPR, while the 9.5 mm OGFC had the lowest CPR. Similar to PG 76-22 mixtures, group analysis showed no significant differences in CPR values between HP mixtures.

Analyzing LMS mixtures at both aging conditions, it is evident that the alternative friction and 9.5 mm OGFC mixtures had lower average CPR values than the FC-5 mixtures, suggesting potential for improved cracking resistance. However, this improvement was not significant, as confirmed by group analysis results.

Regarding the impact of using HP on cracking resistance, LMS mixtures consistently displayed lower CPR values than those using PG 76-22 at both aging conditions, excluding the LMS 12.5 mm SMA mixture at 0 hour of NAWS. This suggests that HP has the potential to enhance the cracking resistance of LMS asphalt mixtures. *P-values* from the *t-test*, as shown in **Table 19,** support this conclusion, with all LMS mixtures having *p-values* below 0.05, except for the 12.5 mm SMA mixture. This analysis indicates that using HP significantly improves the cracking resistance of all LMS asphalt mixtures, particularly for the FC-5, 9.5 mm OGFC, and alternative friction mixtures.

Table 19. P-Values of LMS Mixtures Using PG 76-22 and HP at Two Aging Conditions

Mix Designs	**P- Values**	
	0 Hrs NAWS	**1000 Hrs 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	0.067	0.345

5.2.3 Effect of Aging on Mixture Cracking Resistance

5.2.3.1 Effect of Aging on GRN Mixture Cracking Resistance

Figure 53 displays the evolution of OT-CRP results for GRN mixtures after 1000 hours of conditioning. All GRN mixtures, except 12.5 mm SMA with HP, showed increased CPR values, indicating reduced cracking resistance due to aging and moisture damage. Group analysis revealed that CPR values significantly increased for FC-5, 9.5 mm OGFC, and 12.5 mm SMA with PG 76-22, while the alternative friction mixtures showed no significant difference. Therefore, it is concluded that the alternative friction mixture exhibited the best aging resistance among PG 76-

22 mixtures. Moreover, all HP mixtures, significantly increased in CPR after conditioning, except for 12.5 mm SMA, indicating lower aging susceptibility for the 12.5 mm SMA mixture.

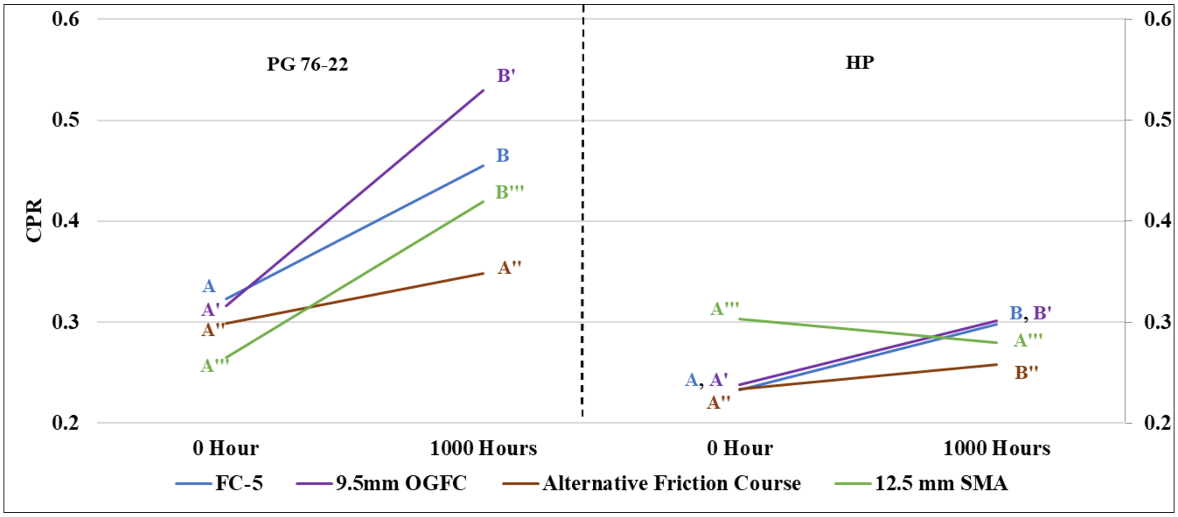


Figure 53. Figure 53 OT- CPR Results of GRN at Two Aging Conditions

Table 20 summarizes the slope of each mixture, showing that HP mixtures had a lower slope than PG 76-22, indicating better-aging resistance. The slopes of the alternative friction and 12.5 mm SMA mixtures were generally lower than the FC-5 and 9.5 mm OGFC mixtures, suggesting better-aging resistance.

In conclusion, both group and slope analysis indicate that for GRN mixtures, the alternative friction mixtures better maintain cracking resistance after aging compared to the FC-5 and 9.5 mm OGFC mixtures. Moreover, HP showed better aging resistance than PG 76-22.

Table 20. Slope Summary for OT CPR Results of GRN Mixtures

Mix Designs	**Graph Slopes (0-> 1000 hours)**	
	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

5.2.3.2 Effect of Aging on LMS Mixture Cracking Resistance

Figure 54 presents the OT- CRP results of GRN mixtures prepared at two aging conditions. For LMS mixtures, there is a consistent increase in CPR values from 0 to 1000 hours in the NAWS room, indicating decreased cracking resistance due to aging and moisture. With PG 76-22, the FC-5 and 9.5 mm OGFC mixture showed no significant difference in CPR between the two aging conditions. However, the alternative friction and 12.5 mm SMA mixtures exhibited a significant increase, highlighting their higher aging susceptibility compared to FC-5 and 9.5 mm OGFC. With HP, there was no significant increase in CPR values for the FC-5, 9.5 mm OGFC, and 12.5 mm SMA between the two aging conditions. The alternative friction mixture, however, showed a significant increase in CPR after 1000 hours of aging, indicating a higher aging susceptibility.

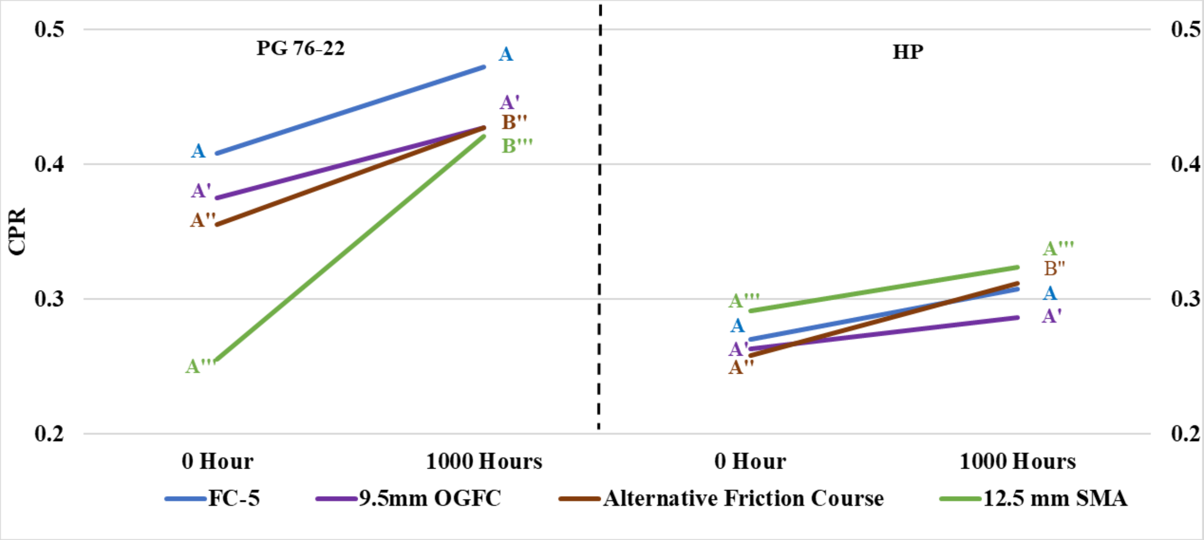


Figure 54. OT- CPR Results of LMS at Two Aging Conditions

Table 21 summarizes the slope of each LMS mixture from 0 to 1000 hours in NAWS. The alternative friction mixture showed the highest slope for both binders, indicating the highest susceptibility to aging, consistent with group analysis. Additionally, all HP mixtures had a lower slope than PG 76-22 mixtures, suggesting a better aging resistance.

In summary, based on both group and slope analysis, with LMS mixtures, the alternative friction mixture was more aging susceptible than the FC-5 and 9.5 mm OGFC mixtures. Moreover, HP can improve the aging resistance of the asphalt mixtures.

Table 21. Slope Summary for OT CPR Results of LMS Mixtures

Mix Designs	Graph Slopes (0-> 1000 hours)	
	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

5.3 Permeability Test Results

5.3.1 Permeability Test Results of GRN Mixutes

Figure 55 presents the permeability coefficient (k) results of GRN mixtures at both binder types PG 76-22 and HP.

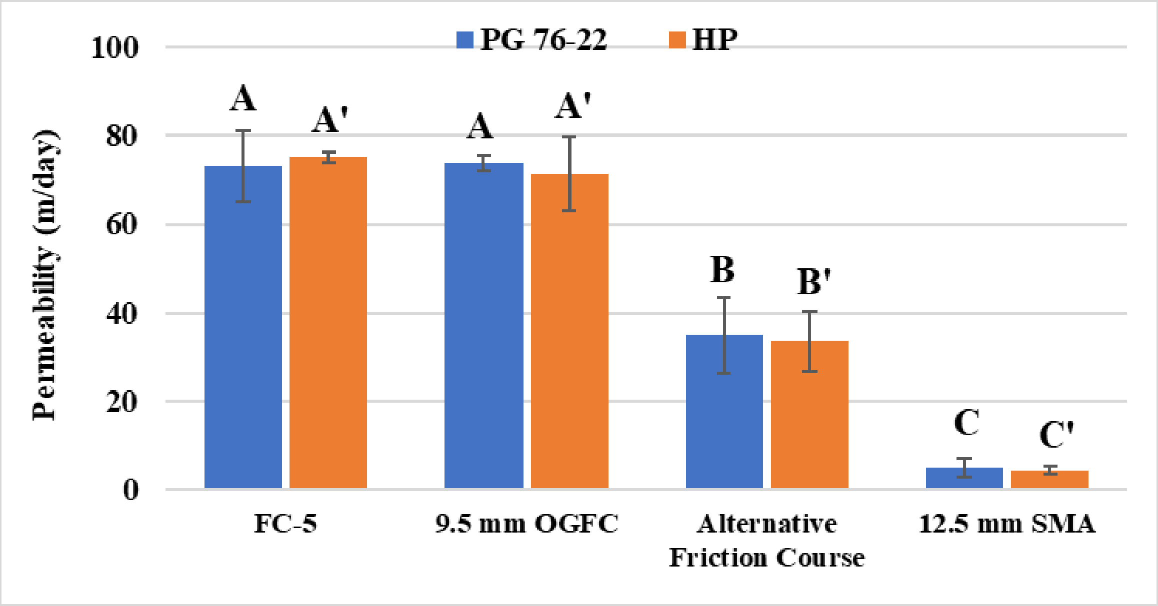


Figure 55. Permeability Test Results of GRN Mixtures

As presented in **Figure 55**, for GRN mixtures, the FC-5 and 9.5 mm OGFC mixture had the highest permeability coefficients at both binders, followed by the alternative friction mixtures and the 12.5 mm SMA mixture with the lowest value. The results were consistent with the air voids of the mixtures, as higher air voids yielded better permeability. Group analysis showed that the FC-5 and 9.5 mm OGFC mixture had statistically equivalent permeability, suggesting that using finer gradation did not negatively impact the permeability of the FC-5 mixtures. Both FC-5 and 9.5 mm OGFC mixtures had permeability coefficient values greater than the minimum threshold of 50 m/day recommended for the OGFC mixtures [39]. This further confirmed that using 9.5 mm OGFC mixtures could maintain the permeability requirement of OGFC pavement. The permeability of the alternative friction mixtures falls between that of FC-5/9.5 mm OGFC and 12.5 mm SMA mixture. The group analysis showed that the alternative friction course provided a significantly higher permeability than 12.5 mm SMA for both binders, however, significantly lower than the FC-5/ 9.5 mm OGFC mixture.

Regarding the impact of using HP on permeability compared with PG 76-22, it was generally observed that mixtures using PG 76-22 provided slightly better permeability, except for the FC-5 mixture. Statistical evaluation using *p-values* from the *t-test* at a significance level of 0.05, as shown in **Table 22**, showed that all *p-values* were higher than 0.05, indicating no statistical difference in permeability between HP and PG 76-22 mixtures. This suggests that using HP would not significantly affect the permeability performance of the GRN asphalt mixture.

Table 22. P-Values from Permeability Test of Mixtures Using PG 76-22 and HP

Mix Designs	**P- Value**	
	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

5.3.2 Permeability Test Results of LMS Mixtures

Figure 56 presents the permeability coefficient (k) results of all LMS mixtures at both binder type PG 76-22 and HP.

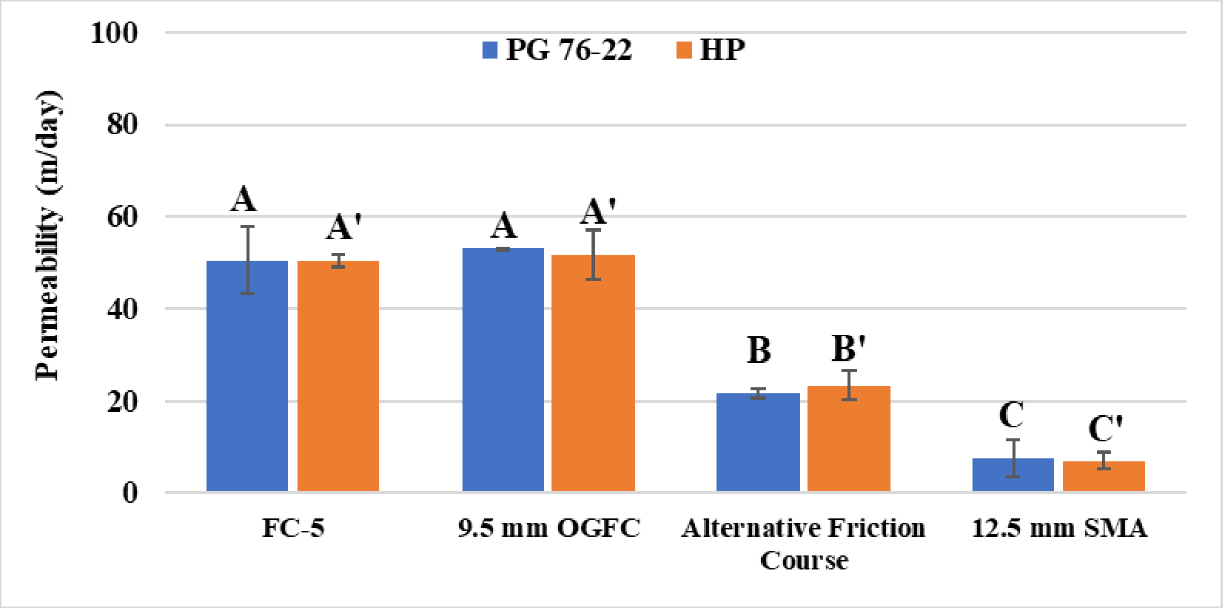


Figure 56. Permeability Test Results of LMS Mixtures

As shown in **Figure 56**, similar to GRN, the permeability coefficient for LMS FC-5 and 9.5 mm OGFC mixtures was the highest, followed by the alternative friction mixture and then the 12.5 mm SMA mixture. This aligns with the expected relationship between air void values and permeability, where higher air voids indicate better permeability. Group analysis found no significant difference between the FC-5 and 9.5 mm OGFC mixtures, suggesting that finer gradation did not significantly impact the permeability of the FC-5 mixtures. Both mixtures had permeability values exceeding the minimum threshold recommended for OGFC mixtures (50 meters/day) [39]. Additionally, the alternative friction mixture had significantly higher permeability than the 12.5 mm SMA mixture, indicating its better permeability. However, the alternative friction mixtures had significantly lower permeability compared to FC-5 and 9.5 mm OGFC mixtures for both binders.

Regarding the effect of using HP on LMS asphalt mixture permeability, no consistent trend was observed between the two binders. Statistical evaluation using *p-values*, as shown in **Table 22** revealed that all *p-values* were higher than 0.05, indicating no significant difference in permeability between HP and PG 76-22 mixtures. Therefore, it can be concluded that mixtures prepared with HP would not exhibit a significant difference in permeability performance compared to corresponding mixtures prepared with PG 76-22.

5.4 Drainability Test Results

5.4.1 Drainability Test Results of GRN Mixutes

Figure 57 presents the drainability of GRN mixtures, respectively. **Table 23** summarizes *p-values* from the *t-test* conducted for the drainability test.

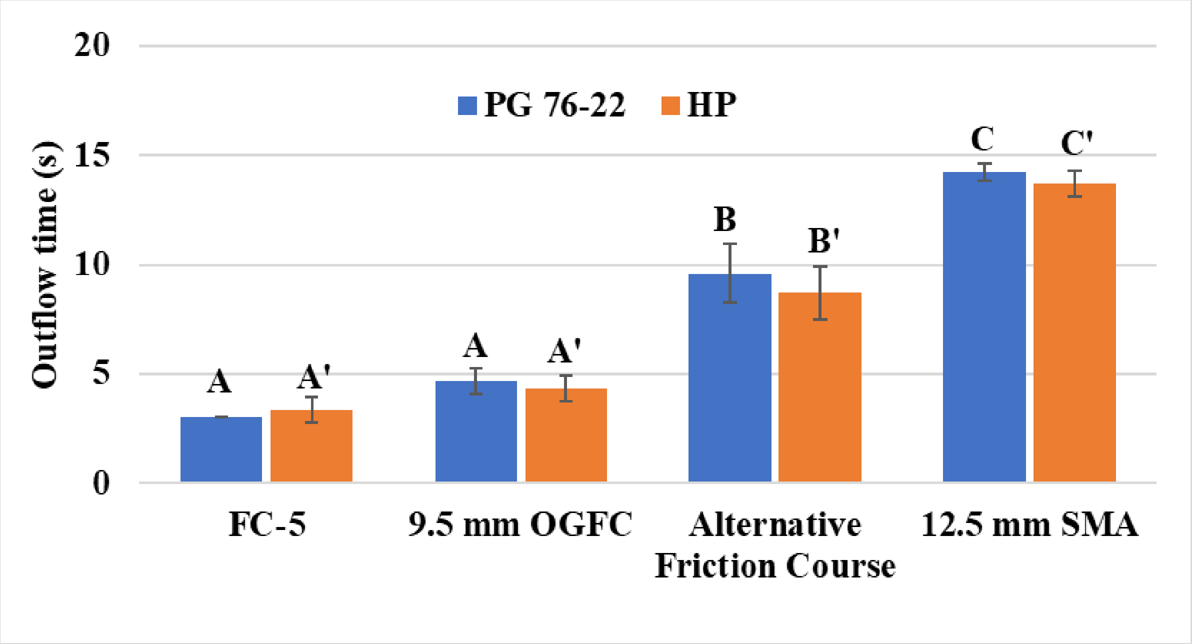


Figure 57. Drainabillity Test Results of GRN Mixtures

As shown in **Figure 57**, for GRN mixtures, the FC-5 mixture exhibited the shortest outflow time, indicating the highest drainability, followed by the 9.5 mm OGFC and alternative friction mixtures. In contrast, the 12.5 mm SMA mixtures had the longest outflow time, indicating the lowest drainability. The findings align with the expected relationship where mixtures designed with coarse gradation and higher air voids tend to have better drainability. Group analysis found no significant difference between 9.5 mm OGFC and FC-5 for both binders, suggesting that finer gradation (9.5 mm NMAS) does not significantly affect the drainability of the FC-5 mixtures. The alternative friction mixtures had significantly shorter outflow times than the 12.5 mm SMA mixture, demonstrating significantly better drainability. However, the alternative friction mixtures had significantly lower drainability than the FC-5 and 9.5 mm OGFC for both binders.

Table 23. P-Values from Drainability Test of Mixtures Using PG 76-22 and HP

Mix Designs	P- Value	
	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

Regarding the effect of using HP on GRN asphalt mixture drainability, while GRN mixtures using PG 76-22 generally showed slightly longer outflow times than those using HP, statistical analysis, as shown in **Table 23**, showed that *p-values* were higher than 0.05, indicating no significant difference. Therefore, it can be concluded that using HP does not significantly influence the drainability of GRN asphalt mixtures.

5.4.2 Drainability Test Results of LMS Mixutes

Figure 58 presents the outflow number of LMS mixtures at both binder types.

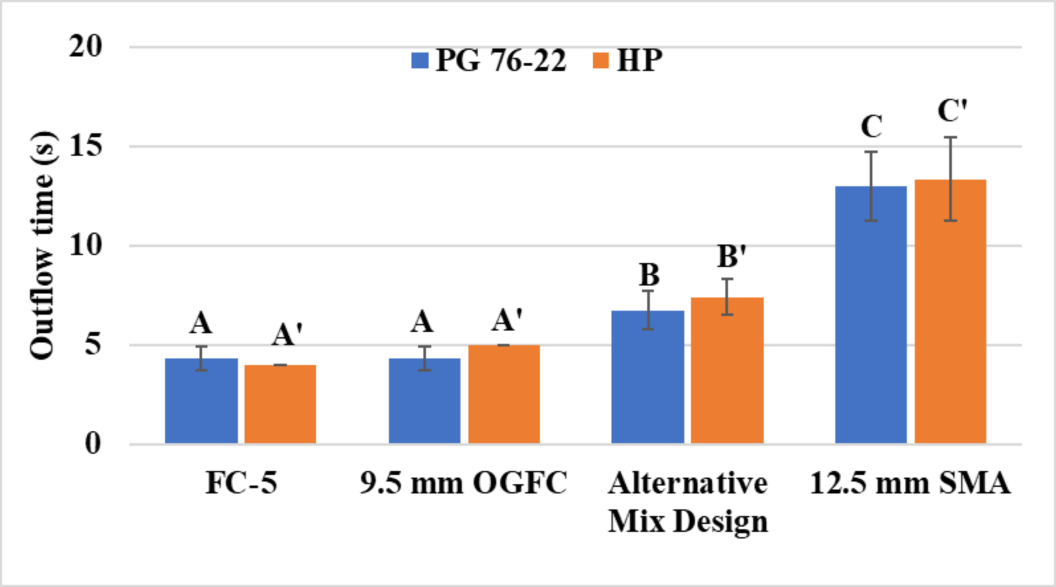


Figure 58. Drainabillity Test Results of LMS Mixtures

As shown in **Figure 58**, similar to GRN mixtures, LMS FC-5 mixtures had the shortest outflow times, indicating the best drainability for both PG 76-22 and HP. This was followed by the 9.5 mm OGFC and then alternative friction mixtures, while the 12.5 mm SMA mixture had the longest outflow times. The findings are consistent with the expected relationship where mixtures designed with coarse gradation and higher air voids tend to have better drainability. Group analysis found no significant difference in drainability between FC-5 and 9.5 mm OGFC, suggesting that using finer gradation (9.5 mm NMAS) does not significantly impact FC-5 mixtures' drainability. The alternative friction mixture had significantly higher drainability than the 12.5 mm SMA mixture. However, the drainability of the alternative friction mixture was significantly lower than that of the FC-5 and 9.5 mm OGFC mixtures.

Regarding the effect of using HP on LMS asphalt mixture drainability, while LMS mixtures using HP generally showed slightly higher outflow times than those using PG 76-22, all *p-values* in **Table 23** were higher than 0.05. Therefore, it can be concluded that no significant difference was observed in outflow times between mixtures using PG 76-22 and HP, indicating that using HP showed no significant change in the drainability of LMS mixtures.

5.5 Hamburg Wheel Tracking Test (HWTT) Results

5.5.1 HWTT Results of GRN Mixtures

Figure 59 presents the HWTT rut depth versus loading passes curve for GRN mixtures.

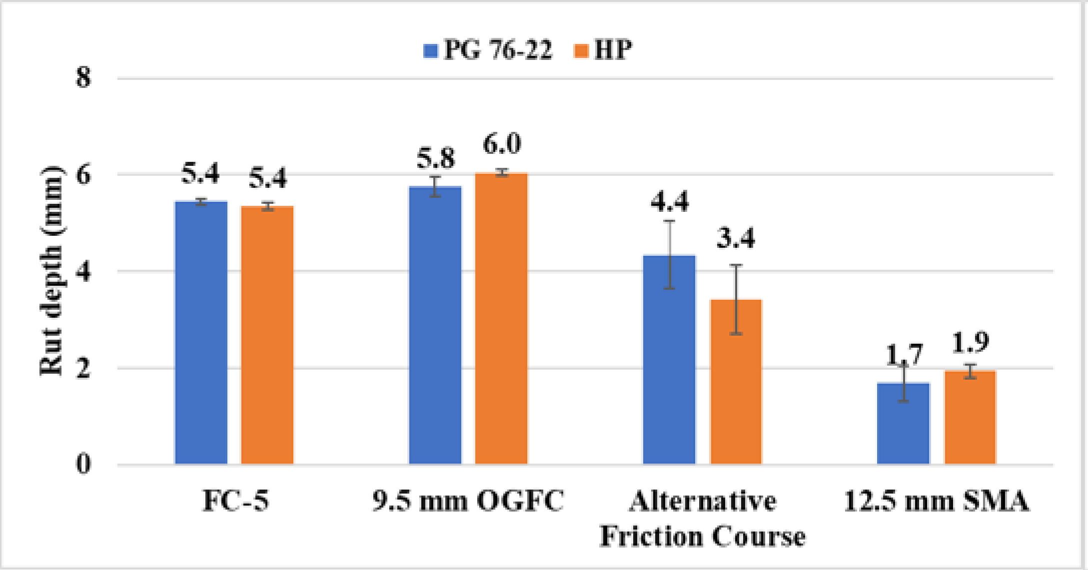


Figure 59. HWTT Rut Depth Results of GRN Mixtures

As shown in **Figure 59**, All GRN mixtures showed good rutting resistance, with rut depths less than 12.5 mm after 20,000 passes, and no evidence of stripping. This indicates that these mixtures provided good rutting and moisture resistance. The 12.5 mm SMA mixtures exhibited the lowest rut depth for both binders, consistent with the superior rutting resistance of SMA mixtures. The ranking was followed by the alternative friction mixtures and then the FC-5 mixtures. The 9.5 mm OGFC mixtures had the highest rut depth, but the differences with FC-5 were not considered practically significant for HWTT, 0.4 mm for PG 76-22, and 0.6 mm for HP mixtures.

The difference in rut depth between alternative friction and FC-5 was around 1.0 mm for PG 76-22 and 2.0 mm for HP, suggesting relative improvement in rutting resistance with the alternative friction mixture. Compared to the 12.5 mm SMA mixture, the differences were 2.7 mm for PG 76-22 and 1.5 mm for HP, indicating that alternative friction mixtures had relatively higher rut depths than 12.5 mm SMA.

Regarding the effect of using HP on rutting resistance, the difference between HP and PG 76-22 mixtures was less than 1.0 mm for all mixtures, not considered practically significant for HWTT. Therefore, it can be concluded that using HP does not affect the rutting resistance of GRN mixtures.

5.5.2 HWTT Results of LMS Mixtures

Figure 60 presents the HWTT rut depth versus loading passes curve for LMS mixtures.

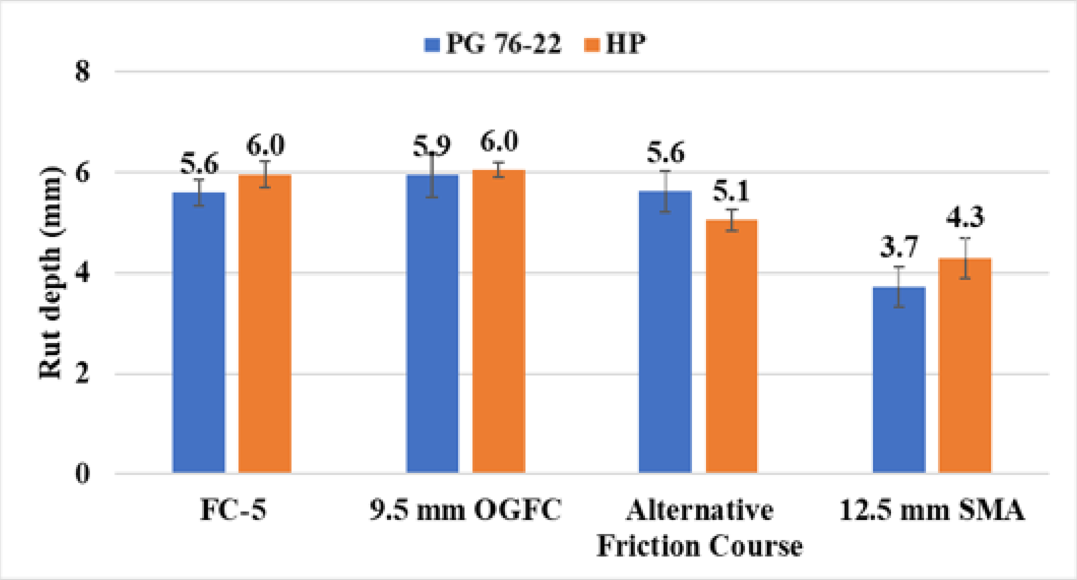


Figure 60. HWTT Rut Depth Results of LMS Mixtures

As shown in **Figure 60**, all LMS mixtures exhibited rut depths below 12.5 mm after 20,000 passes with no evidence of stripping, indicating good rutting and moisture resistance. Similar to GRN mixtures, LMS 12.5 mm SMA mixtures had the smallest rut depths, followed by alternative friction mixtures. The FC-5 and 9.5 mm OGFC mixture had slightly higher rut depths, but the difference between them was minimal, indicating that finer gradation did not significantly impact the rutting resistance of the FC-5 mixture.

While alternative friction mixtures had lower rut depths than FC-5 and 9.5 mm OGFC for both binders, the differences were less than 1.0 mm, considered not statistically significant in HWTT. Therefore, for LMS aggregate, using alternative friction mixtures did not practically influence rutting resistance compared to FC-5 and 9.5 mm OGFC mixtures. Compared to 12.5 mm SMA, the difference with the alternative friction mixture was about 1.9 mm for PG 76-22 and 0.8 mm for HP. Thus, the alternative friction mixture designed with PG 76-22 showed slightly lower rutting resistance than the 12.5 mm SMA mixture.

Regarding the effect of using HP on rutting resistance, the difference in rut depths between HP and PG 76-22 mixtures was less than 1.0 mm, not practically significant for HWTT. Therefore, using HP did not impact the rutting resistance of FC-5 mixtures compared with PG 76-22.

5.6 Dynamic Friction Test (DFT) Results

5.6.1 DFT Results of GRN Mixtures

Figure 61 represents the DFT40 data of GRN mixtures and their corresponding evolution curves with different polishing cycles at 0k, 5k, 50k, and 100k. **Table 24** summarizes the percentage differences in DFT40 data between the two consecutive polishing stages. This expressed the percentage increase or loss of DFT40 after different polishing cycles.

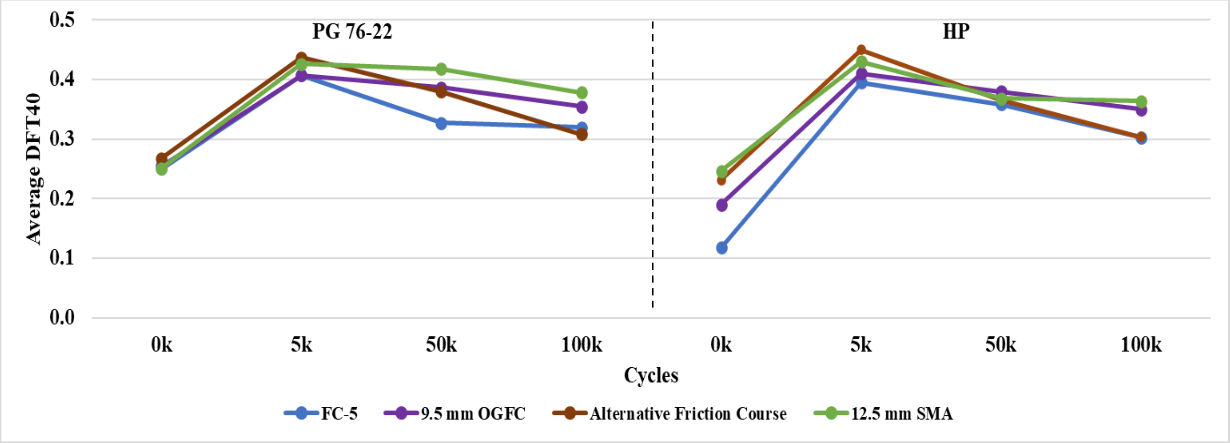


Figure 61. DFT40 Results of GRN Mixtures

Table 24. Percentage Changes of DFT40 of GRN Mixtures between Polishing Stages

Percentage Changes of DFT40 of GRN Mixtures				
Mixture Type	**Binder**	**0k to 5k**	**5k to 50k**	**50k to 100k**
FC-5	PG 76-22	61	-20	-3
	HP	236	-9	-16

9.5 mm OGFC	PG 76-22	60	-5	-8
	HP	112	-6	-9
Alternative Friction Course	PG 76-22	63	-13	-19
	HP	94	-19	-17
12.5 mm SMA	PG 76-22	69	-2	-9
	HP	74	-14	-1

In **Figure 61**, before polishing, DFT40 values for GRN mixtures using PG 76-22 were similar, but HP mixtures showed differences, with the 12.5 mm SMA and alternative friction mixtures having higher DFT40 values. After 5,000 polishing cycles, all mixtures saw a significant increase in DFT40 values, especially for FC-5 and 9.5 mm OGFC with HP, experiencing a significant rise of 236% and 112%, respectively, as shown in **Table 24**. The increase in the DFT40 values could be attributed to the removal of surface asphalt film under the effect of 5,000 cycles of polishing, exposing more surface texture to the test. After 50,000 and 100,000 polishing cycles, DFT40 values consistently decreased for all GRN mixtures as a result of aggregate wearing off under the effect of polishing. The friction losses ranged from 2% to 20%, suggesting that GRN mixtures generally reached terminal friction after 100,000 cycles

The DFT40 value of the alternative friction and 9.5 mm OGFC mixture was generally higher than that of FC-5 mixtures for both binders at all polishing conditions, indicating that using these mixtures could improve the friction resistance of FC-5 mixtures. However, the improvement was not significantly practical. Regarding the influence of HP on friction resistance, significant differences in DFT40 values with PG 76-22 mixtures were observed before polishing, but these distinctions became minimal during different polishing cycles. The maximum difference observed at different polishing cycles was 0.01 after 5,000 cycles, 0.05 after 50,000 cycles, and 0.02 after 100,000 cycles. This suggests that using HP does not practically influence the friction resistance of asphalt mixtures.

5.6.2 DFT Results of LMS Mixtures

Figure 62 displays the DFT40 data and their corresponding evolution curves with different polishing cycles (0K, 5K, 50K, and 100K) for LMS mixtures. **Table 25** summarizes the percentage differences in DFT40 data between the two consecutive polishing stages, representing the percentage increase or loss of DFT40 from the effect of different polishing cycles.

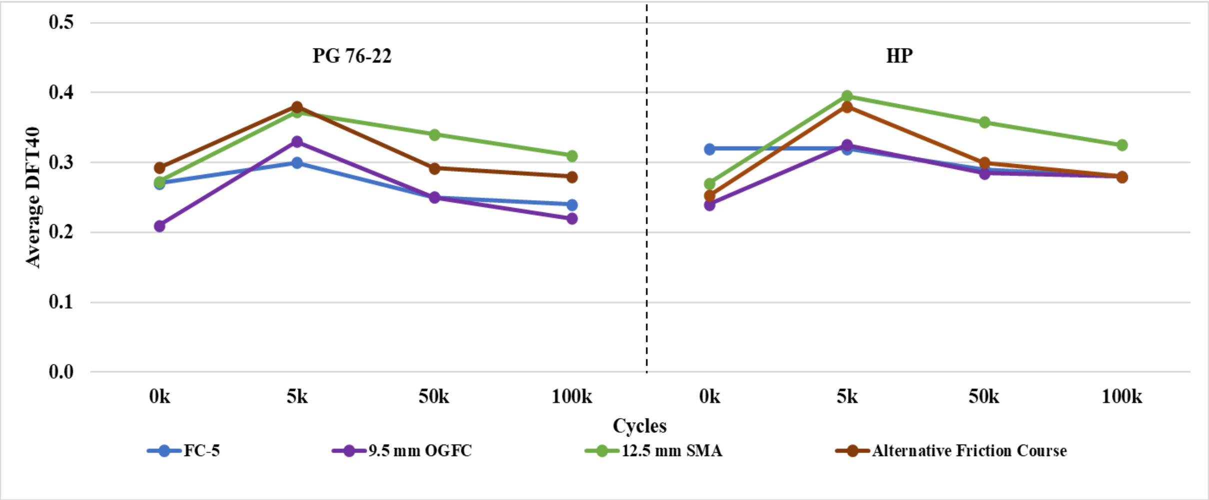


Figure 62. DFT40 Results for LMS Mixtures

Table 25. Percentage Changes of DFT40 of LMS mixtures between Polishing Stages

Percentage Changes of DFT40 of GRN Mixtures				
Mixture Types	**Binder**	**0k to 5k**	**5k to 50k**	**50k to 100k**
FC-5	PG 76-22	13	-18	-3
	HP	4	-10	-5
9.5mm OGFC	PG 76-22	53	-25	-10
	HP	35	-12	-2
Alternative Friction Course	PG 76-22	30	-23	-4
	HP	50	-21	-7
12.5 mm SMA	PG 76-22	37	-9	-9
	HP	46	-9	-9

As presented in **Figure 62**, before polishing, the 9.5 mm OGFC mixture had the lowest DFT40 value for both binders, while trends for other mixtures were inconsistent between binder types. After the first polishing stage of 5,000 cycles, DFT40 values generally increased significantly for all LMS mixtures, except for FC-5, which increased by only 13% for PG 76-22 and 4% for HP, as shown in **Table 25**. After 50,000 cycles, DFT40 values decreased due to aggregate wear, resulting in friction losses ranging from 9% to 25%. The decreasing trend continued after 100,000 cycles, with friction losses ranging from 2% to 10%. This suggests that all LMS mixtures reached terminal friction after 100,000 cycles.

The 12.5 mm SMA and alternative friction mixtures consistently provided higher DFT40 values than FC-5 and 9.5 mm OGFC mixtures for both binders at all polishing stages, indicating that using alternative friction could improve FC-5 mixture friction. However, improvement became minimal after 100,000 cycles. The difference in DFT40 value between 9.5 mm OGFC and FC-5 mixtures was generally not significant under all polishing cycles, indicating that using finer gradation did not negatively impact LMS FC-5 mixture friction.

Regarding the influence of using HP on friction resistance, after polishing, the difference in DFT40 value between mixtures designed with PG 76-22 and HP was minimal. Therefore, using HP showed no practical influence on the friction resistance of the mixtures.

5.7 Circular Track Meter (CTM) Test Results

5.7.1 MPD Results of GRN Mixutes

Figure 63 represents the MPD results and their associated evolution curves with different polishing cycles at 0K, 5K, 50K, and 100K for GRN mixtures. **Table 26** summarizes the percentage differences in MPD values between the two polishing stages. This exhibits the percentage increase or loss of MPD under the effect of different polishing cycles.

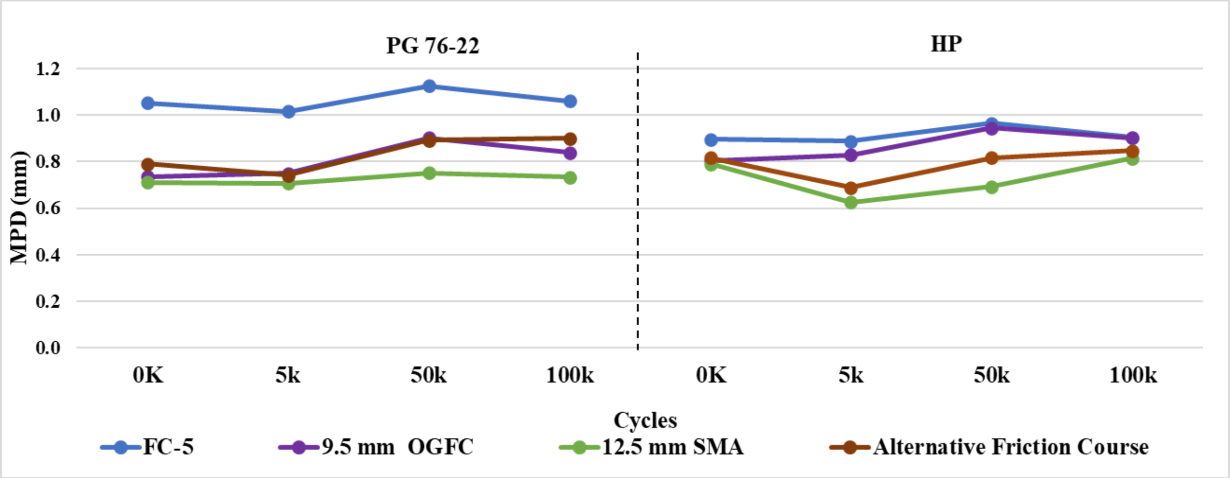


Figure 63. MPD Results of GRN Mixtures

Table 26. Percentage Changes of MPD between Polishing Stages of GRN Mixtures

Percentage Changes of MPD of GRN Mixtures				
Mixture Types	**Binder**	**0k to 5k**	**5k to 50k**	**50k to 100k**
FC-5	PG 76-22	-3	11	-6
	HP	-1	9	-6
9.5mm OGFC	PG 76-22	2	20	-7
	HP	3	14	-4
Alternative Friction Course	PG 76-22	-6	20	1
	HP	-16	19	4
12.5 mm SMA	PG 76-22	-1	6	-2
	HP	-21	11	18

Figure 63 shows that before polishing, GRN FC-5 mixtures had the highest MPD values, indicating the highest macrotexture, followed by the alternative friction, 9.5 mm OGFC, and 12.5 mm SMA mixtures with the same value. After 5,000 cycles, MPD values generally decreased for all mixtures, except 9.5 mm OGFC, which slightly increased, about 2% for PG 76-22, and 3% for HP, as shown in **Table 26**. After 50,000 cycles, MPD values increased for all mixtures. After 100,000 cycles, the values were not significantly changed compared with the previous polishing

stage, ranging from 1 to 7%, except for an 18% increase in the 12.5 mm SMA mixture using HP, as shown in **Table 26**.

During different polishing conditions, the FC-5 mixtures consistently had the highest macrotexture, followed by the 9.5 mm OGFC and alternative friction mixtures, with the 12.5 mm SMA exhibiting the lowest macrotexture. Using alternative friction mixtures provided less macrotexture than the FC-5 mixtures, aligning with expectations and drainability performance in **Figure 57**. Moreover, at all polishing cycles, coarser FC-5 mixture had greater macrotexture than finer 9.5 mm OGFC mixtures when designed with PG 76-22. However, with HP, the difference in MPD values was minimal. This suggests that finer gradation of 9.5 mm NMAS could reduce macrotexture in GRN FC-5, especially when designed with PG 76-22.

In terms of the effect of using HP on macrotexture, no consistent trend was observed between mixtures using HP and PG 76-22 during different polishing cycles. Therefore, it could be concluded that HP had no impact on the macrotexture of the asphalt mixture.

5.7.2 MPD Results of LMS Mixutes

Figure 64 represents the MPD results and their corresponding evolution curves with different polishing cycles at 0K, 5K, 50K, and 100K for LMS mixtures. **Table 27** summarizes the percentage differences in MPD values between the two successive polishing stages, exhibiting the percentage increase or loss of MPD values under the effect of different polishing cycles.

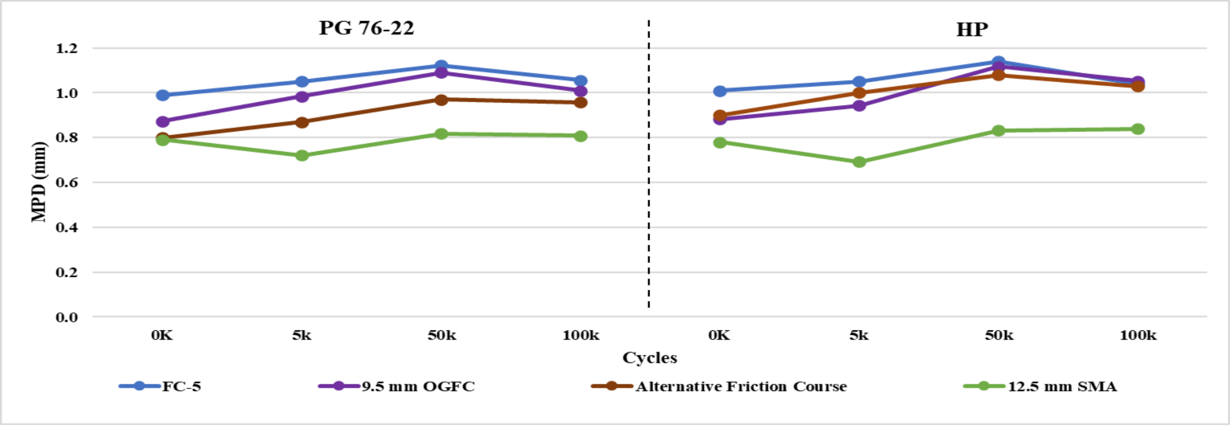


Figure 64. Results of LMS Mixtures

Table 27. Percentage Changes of MPD between Polishing Stages of LMS Mixtures

Percentage Changes of MPD of LMS Mixtures				
Mixture Types	**Binder**	**0k to 5k**	**5k to 50k**	**50k to 100k**
FC-5	PG 76-22	6.1	6.9	-5.9
	HP	4.0	8.6	-8.8
9.5mm OGFC	PG 76-22	12.8	10.7	-7.3
	HP	6.8	18.6	-5.7
Alternative Friction Course	PG 76-22	14.7	8.7	-4.1
	HP	11.1	8.0	-4.6
12.5 mm SMA	PG 76-22	-9.8	14.6	-1.2
	HP	-11.4	20.3	1.0

Figure 64 shows that before polishing, the MPD values of the FC-5 mixtures at both binder types were the highest, followed by the alternative friction and 9.5 mm OGFC mixtures. The 12.5 mm SMA mixtures were the lowest. After 5,000 cycles of polishing, most LMS mixtures experienced increased MPD values ranging from about 4% to 15%, except for the 12.5 mm SMA, which decreased by about 10% for PG 76-22 and 11% for HP, as shown in **Table 27**. After 50,000 cycles of polishing, there was an increase in MPD values for all the LMS mixtures, ranging from 7% to 20%, as shown in **Table 27**. In contrast, after 100,000 cycles, most of the LMS mixtures experienced a decreasing trend, except for the 12.5 mm SMA mixture designed with HP which experienced a slight increase. However, the percentage change between the two polishing stages was minimal, ranging from 1 to 9%.

FC-5 mixtures generally provided the highest macrotexture at both binder types for all polishing cycles. This was followed by the 9.5 mm OGFC and alternative friction mixtures. The 12.5 mm consistently exhibited the lowest macrotexture. This indicated the macrotexture of finer gradation 9.5 mm OGFC and alternative friction course was lower than that of the FC-5 mixture. However, after 50,000 and 100,000 cycles, the MPD values of FC-5, 9.5 mm OGFC, and alternative friction mixtures converged. Moreover, the ranking between these mixtures was consistent with the drainability performance of LMS mixtures shown in **Figure 58,** where mixtures with a higher MPD value yield faster drainage channels, leading to an increase the drainability.

Regarding the influence of using HP on macrotexture, although HP mixtures generally provided better macrotexture than PG 76-22 mixtures, the difference was minimal. Therefore, it could be concluded that using HP had no significant impact on the macrotexture of the LMS mixtures.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This thesis aimed to achieve two main goals: (1) assess the impact of using a finer gradation of 9.5 mm NMAS and HP on the asphalt mixture performance, and (2) develop a durable and drainable alternative friction course for suburban areas while preserving friction and surface texture. The literature review focused on OGFC mixture performance, considering durability and functionality. The study involved four mix designs: FC-5, 9.5 mm OGFC, 12.5 mm SMA, and an alternative friction mixture. The research followed a four-step plan, including binder and aggregate selection, mix design and performance evaluation of OGFC and SMA mixtures, alternative friction course design and performance evaluation, and performance comparison between the asphalt mixtures. A comprehensive set of laboratory tests was conducted to assess various aspects of the mixtures, including permeability, rutting resistance, durability, cracking resistance, texture, friction, and drainability, using the Florida Permeability Test, HWTT, Cantabro Test, OT, CTM, DFT, and Outflow Meter Test. Testing involved 150 mm diameter specimens (50 gyrations for OGFC and the alternative friction mixtures, 35 gyrations for SMA specimens) and slab specimens for drainability, texture, and friction assessments. Before testing, loose mixtures underwent short-term aging, and durability and cracking resistance were further evaluated after long-term aging up to 2,000 hours using the NAWS system. Key conclusions are outlined below.

In terms of the mix design process:

- OBC of mixtures designed with LMS was higher than that of GRN.
- OGFC mixtures were designed with the highest air voids, followed by the alternative friction course and 12.5 mm SMA with the lowest value.
- In the case of OGFC mix design, relying solely on the pie plate method to determine OBC did not consistently yield the desired performance for the mixture. Introducing additional criteria, such as minimum air voids and maximum Cantabro loss, demonstrated potential in addressing this issue.
- For 12.5 mm SMA mixtures, mixtures designed with 35 gyrations provided a similar air void with those using 50-blow Marshall.
- For the alternative friction course, the gradation was designed to fall between FC-5 and 12.5 mm SMA. It was modified based on the FC-5 gradation, using a similar percentage aggregate

passing ½”, 3/8” sieve, but the percentage passing in smaller sieves (No.4 and No.8…) was higher. The OBC of the alternative friction course was higher than that of FC-5 mixtures, increasing by 0.2% for GRN mixtures and 0.3% for LMS mixtures.

In terms of the influence of finer gradation 9.5 mm NMAS and HP:

- Using finer gradation improves the durability of both GRN and LMS FC-5 mixture, especially with GRN mixtures using PG 76-22 with a significant improvement.
- Using finer gradation improves the cracking resistance of both GRN and LMS FC-5 mixture,but not significant.
- The utilization of a finer gradation did not result in a statistical difference in the permeability with both GRN and LMS FC-5 mixtures. Notably, both FC-5 and 9.5 mm mixtures exhibited permeability coefficient values that exceeded the minimum threshold of 50 meters/day, as recommended for OGFC mixtures [38]. This highlighted that using the 9.5 mm OGFC mixtures can meet the required permeability standards for both GRN and LMS OGFC pavement. The drainability results show no significant difference between the 9.5 mm OGFC and FC-5 mixtures for both GRN and LMS.
- The difference in rut depths between the 9.5 mm OGFC and FC-5 mixture was less than 1.0 mm, which was not practically different in the HWTT test. Therefore, the 9.5 mm OGFC mixture did not have a negative influence on the rutting resistance of the FC-5 mixture.
- GRN 9.5 mm OGFC mixtures provided a higher DFT value than the FC-5 mixture at all polishing cycles, demonstrating the improvement in friction of the 9.5 mm OGFC mixture. While for LMS mixtures, the finer gradation would not impact the friction of the FC-5 mixture. Regarding MPD values, coarser FC-5 mixtures exhibit greater macrotexture than the finer mixtures of the 9.5 mm OGFC mixture for both GRN and LMS.
- Using HP significantly improves the durability, and cracking resistance of the asphalt mixtures, without compromising the permeability, drainability, texture, rutting, and friction resistance of the GRN and LMS asphalt mixture. Mixtures using HP exhibited better-aging resistance than those designed with PG 76-22.

In terms of the performance of the alternative friction course:

- The alternative friction mixture exhibits statistically equivalent durability to the 12.5 mm SMA mixture and has the potential to enhance the durability of FC-5 mixtures for both GRN and LMS. Notably, the improvement is significant for GRN mixtures designed with PG 76-22, whereas, for LMS mixtures, the enhancement becomes significant after 2000 hours of conditioning in the NAWS room. Both the 12.5 mm SMA and alternative friction mixtures display better-aging resistance compared to FC-5 and 9.5 mm OGFC mixtures.
- Both the alternative friction and 12.5 mm SMA mixtures demonstrate better cracking resistance compared to the FC-5 and 9.5 mm OGFC mixture for both GRN and LMS. However, the group analysis revealed no significant difference among these mixtures, suggesting that the alternative friction mixture does not significantly enhance the crack resistance of the FC-5 mixture. Moreover, in GRN mixtures, the alternative friction and 12.5 mm SMA showed better-aging resistance than FC-5 and 9.5 mm OGFC. Conversely, in LMS mixtures, the alternative friction and 12.5 mm SMA exhibit lower aging resistance than FC-5 and 9.5 mm OGFC mixtures.
- The alternative friction mixture had significantly higher permeability and durability than the 12.5 mm SMA mixture for both GRN and LMS. However, the mixture also significantly reduced the permeability and durability compared to the FC-5 and 9.5 mm OGFC mixtures.
- All GRN and LMS mixtures had an average rut depth of less than 12.5 mm after 20,000 passes and showed no evidence of stripping. This demonstrated that the mixtures could provide good rutting resistance and moisture resistance. The 12.5 mm SMA mixture provided the lowest rut depth, followed by the alternative friction mixture. The FC-5 and 9.5 mm OGFC had the highest rut depth.
- The DFT40 value of the alternative friction mixture consistently exceeded that of FC-5 mixtures for both binder and aggregate types at all polishing cycles, suggesting that the use of the alternative friction mixture had the potential to enhance the friction resistance of FC-5 mixtures
- The FC-5 mixtures consistently displayed the greatest macrotexture at both binder and aggregate types across all polishing cycles, with the 9.5 mm OGFC and alternative friction mixtures following behind. The 12.5 mm mixture consistently exhibited the lowest macrotexture. Consequently, using the alternative friction mixtures resulted in a reduction in macrotexture compared to the FC-5 mixtures.

6.2 Recommendations

Future research and implementation activities based on the findings of the thesis are provided as follows:

- Establish the mix design threshold for the alternative friction mixture including volumetric criteria (minimum air voids, VMA...) and performance requirements in terms of durability and permeability.
- Perform life cycle cost analysis to compare the cost-effectiveness of the friction courses designed with PG 76-22 and HP.
- Construct a field project for evaluating the long-term field performance of the OGFC mixture designed with HP and the alternative friction mixtures designed with HP and PG 76-22. This field evaluation will provide valuable insights into the field performance of these mixtures, helping to validate the laboratory findings. The potential challenges associated with producing and constructing the mixtures with HP need to be identified.
- Evaluate the feasibility and benefits of incorporating RAP into the OGFC mixtures. Investigate the potential environmental and economic advantages of using RAP while considering the possible challenges associated with using RAP with the mix design and construction process.

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