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Evaluation of Enhanced-Friction Asphalt Overlays and Surface Treatments

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Florida Department of Transportation.

SI* (Modern Metric) Conversion Factors

APPROXIMATE CONVERSIONS TO SI UNITS

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

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

(Source: FHWA)

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16. Abstract
Highway agencies are responsible for maintaining pavements with good surface friction performance. High crash locations are often treated with a high friction surface treatment that has very good friction performance but has a high cost. This study examined asphalt surface mixtures with alternative friction aggregates using accelerated laboratory Three-Wheel Polishing Device (TWPD) polishing and Dynamic Friction Tester (DFT) testing as options for High Friction Surface Treatment (HFST). A chip seal with alternative friction aggregate failed to survive conditioning with the TWPD. Standard FDOT 9.5 mm, 4.75 mm, and OGFC mixes with granite and limestone were modified with high and moderate amounts of three alternative friction aggregates (calcined bauxite, quartzite, and slag). Developing equivalent gradation blends required the use of volumetric proportioning to account for differences in aggregate specific gravities. Friction test results showed that some aggregate combinations with slag and calcined bauxite demonstrated improve friction performance. A cost-benefit analysis examined the cost per year of service and the potential crash rate reduction. Studies of crash rate versus pavement friction do not have sufficient friction data beyond conventional asphalt surface mixes, so extrapolated curves were used to estimate the safety impact of HFST. None of the alternative asphalt mixtures demonstrated comparable friction performance to a HFST. However, a number of alternative asphalt friction mixtures showed moderate reductions in crash rate while maintaining a low cost per year of service. Low cost and moderate improvements in safety could make these alternative mixtures a viable option for some crash locations.

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EXECUTIVE SUMMARY

One of the primary responsibilities of the Florida Department of Transportation (FDOT) is to make travel in the state of Florida safer and more efficient. Poor pavement conditions, especially wet pavements, have been identified as one of the major contributing factors in roadway departure crashes. When a pavement surface is wet, the level of pavement friction is reduced, which can lead to skidding or hydroplaning. In spite of the successful use of friction course mixtures, there are still locations on the state highway system in Florida where there is a history of crashes that are related to inadequate pavement friction. These locations are typically identified based on excessive vehicle lane departures and wet-weather crashes. In an effort to address these localized safety issues in 2006, FDOT began using high friction surface treatments (HFST) on locations that had increased incidences of wet-weather crashes.

HFST is a pavement surface treatment consisting of a polymer resin binder that is used to bond a very hard, polish, and abrasion-resistant aggregate, approximately 1–3 mm in size, to the pavement surface (FHWA 2020). HFST provides higher pavement friction values that are generally not achievable with conventional paving aggregates, such as granite and limestone, with the added benefit that they tend to retain this high level of friction over time. While HFST has successfully reduced the number of wet-weather crashes in Florida, there have been a number of issues associated with its use. These issues include premature failures and high costs. As a result of the problems associated with HFST usage, alternative approaches need to be explored to determine if there are feasible options to HFST. The objective of this project was to evaluate alternative asphalt-based solutions to high friction surface treatments. This includes thicker asphalt friction course mixtures and an exploratory thinner asphalt-based surface treatment.

As a method of potentially reducing the cost of an asphalt mixture containing a high friction aggregate, alternatives sources from high friction materials were sought. The NCAT and FDOT research teams selected calcined bauxite from Eufala, AL, steel slag from Frost Proof, FL, and quartzite from Nova Scotia, Canada, for this research project. Ultimately, FDOT elected to use aggregates that were locally available (or in the case of the quartzite, already present in large quantities in Florida).

Cost-benefit analysis of laboratory-produced specimens requires comparing to hypothetical crash risks. Nonetheless, relative comparisons can be conducted between different mix types or treatments. Increasing pavement friction by 15 units from 25 to 40 is estimated to decrease crashes by 30% to 40%.

This project evaluated three asphalt mixture types (FC-9.5, FC-4.75, and FC-5) with two base aggregates (south Florida limestone and Georgia granite), three high friction aggregates (described below), two percentages of friction aggregate, and two test replicates. Blending the HFAs with higher specific gravities, namely the bauxite and slag, required blending by volume instead of by mass. Slabs were produced to evaluate friction using primarily the Three-Wheel Polishing Device and the Dynamic Friction Tester.

All mix designs passed their respective FDOT mix design specification criteria. The granite mixes had higher friction, on average, compared to the limestone mixes. However, the limestone mixes present the greatest opportunity for friction improvement over the control mix. None of

the alternative friction surfaces were within 50% of the friction performance of HFST, however. For most of the limestone mixes, the average DFT increase associated with 10% high friction aggregate in a blend was above 0.04 units. A change in the friction level of 4 units would be expected to result in a crash reduction of over 10%.

This study examined asphalt friction surfaces as an alternative to HFST in terms of cost and performance. This portion of the cost-benefit analysis was strictly based on construction cost and years of service. Every alternative surface mix was significantly cheaper than HFST per square yard. A safety benefit analysis was conducted to evaluate the crash reduction potential of the alternative mixes compared both to an HFST on a hypothetical poor surface and also their respective control mixes. The crash reduction potential of HFST dwarfed the crash reduction potential of the other mixes. However, some of the alternative friction mixes did significantly improve friction over the control sections at similar costs. Specifically, the slag and bauxite modified mixes consistently demonstrated potential to improve friction by 10% to 30%. A standard granite-based asphalt friction mixture may achieve a 10% to 15% further reduction in crashes at a similar cost if the mixture aggregate is modified. A standard limestone-based asphalt friction mixture may achieve a 22% to 27% further reduction in crashes at a similar cost if the mixture is modified.

None of the alternative mixes developed in this project matched the friction capabilities of HFST. Thus, implementing these mixes to replace HFST is not recommended. However, it is recommended that FDOT adopt the TWPD and DFT to develop expectations for friction performance using laboratory produced specimens. This will allow for the development of mixes with enhanced friction beyond what is currently achievable with typical FDOT materials. Applying these mixes to road segments in need in improved friction will help reduce crashes in these locations. Involving safety engineers in decisions regarding potential crash reduction curves for specific projects or locations is crucial. Not every project location will have the same expected crash reduction benefit from improving friction. There may be certain segments that require other friction mitigation methods. Collaborating across disciplines will provide FDOT with better information to make informed decisions.

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1. INTRODUCTION

1.1 Problem Statement

One of the primary responsibilities of the Florida Department of Transportation (FDOT) is to make travel in the state of Florida safer and more efficient. And that responsibility includes building asphalt pavements that are not only smooth and durable, but also with good tire-pavement friction in order to ensure that drivers are able to safely operate their vehicles in all weather conditions. Poor pavement conditions, especially wet pavements, have been identified as one of the major contributing factors in roadway departure crashes. When a pavement surface is wet, the level of pavement friction is reduced, which can lead to skidding or hydroplaning (FHWA 2019). To address this issue, in the 1960s and 1970s, FDOT developed several different types of surface layers called friction courses, which use polish-resistant aggregates, such as oolitic limestone and granite to maintain adequate tire-pavement friction (Page et al. 1993). These friction course mixtures, which have evolved over time and are still in use today, are classified as either dense-graded or open-graded, depending on the gradation of the aggregate in the mixture. Dense-graded mixtures generally have a tighter surface texture and rely primarily on the microtexture of the aggregate to provide friction, while open-graded mixtures have a more open texture and rely not only on the microtexture of the aggregate for friction, but also on the macrotexture of the aggregate particles in the asphalt pavement surface.

In spite of the successful use of friction course mixtures, there are still locations on the state highway system in Florida where there is a history of crashes that are related to inadequate pavement friction. These locations are typically identified based on excessive vehicle lane departures and wet-weather crashes. This includes locations such as tight-radius ramps or horizontal curves, bridge decks, high-volume intersections, and downhill approaches. In an effort to address these localized safety issues, in 2006, FDOT began using high friction surface treatments (HFST) on locations that had increased incidences of wet-weather crashes (TTI 2016).

HFST is a pavement surface treatment consisting of a polymer resin binder that is used to bond a very hard, polish, and abrasion-resistant aggregate, approximately 1–3 mm in size, to the pavement surface (FHWA 2020). HFST provides higher pavement friction values that are generally not achievable with conventional paving aggregates, such as granite and limestone, with the added benefit that they tend to retain this high level of friction over time. The use of HFST in the United States began in the early 1950s as a thin polymer-bonded bridge deck treatment. The industry that promoted this product for many years used a variety of aggregates that they felt performed well. The use of calcined-bauxite as the HFST aggregate was first noted in 1976 (Heitzman, 2017). HFST friction is provided through the microtexture of the aggregate particles along with the high macrotexture of the finished surface (FHWA 2020). The relative ease and speed of construction of HFST, coupled with its ability to dramatically reduce friction-related crashes, makes it a very effective method of improving pavement safety, particularly in areas that would otherwise require costly geometric improvements.

While HFST has successfully reduced the number of wet-weather crashes in Florida, there have been a number of issues associated with its use. These issues include premature failures and high costs. Typical failures that HFST experience include cracking, delamination, and raveling, and in cases where the aggregate ravels severely, the polymer resin binder on the pavement surface is exposed, further reducing pavement friction. The cost of HFST and the availability of high friction aggregates is another issue. The most common aggregate used in HFST is calcined-bauxite, which is an imported product in the United States, significantly increasing its cost. The costly aggregate coupled with the polymer resin binder have led to bid prices ranging from \$26 – \$40/yd^2 in 2011 (TTI 2016), which has limited the overall usage of this treatment. As a comparison, a 1.5 inch layer of a dense-graded friction course (FC-12.5) at \$113/ton equates to \$9.32/yd^2 (FHWA 2020).

As a result of the problems associated with HFST usage, alternative approaches need to be explored to determine if there are feasible options to HFST. This includes the use of more conventional asphalt friction course mixtures (both dense- and open-graded) with varying amounts of high friction aggregate materials, as well as exploring the potential use of other types of surface treatments such as high-friction chip seals.

1.2 Research Objectives

The objective of this project is to evaluate alternative asphalt-based solutions to high friction surface treatments. This includes traditional thicker asphalt friction course mixtures (1.0 to 1.5 inches) and an exploratory thinner asphalt-based surface treatment. The research will determine if these alternatives have the ability to provide similar frictional benefits to HFSTs, but with reduced cost and/or increased durability. Specifically, this project will explore potential high friction aggregate options that could be used in Florida and can be incorporated into asphalt mixtures and/or surface treatments. The project will explore and optimize the type(s) and amount of high friction aggregate(s) needed in existing FDOT friction courses (FC-4.75, FC-9.5, and FC-5) that contain other aggregates commonly used in Florida for surface mixtures (south Florida limestone and Georgia granite) to significantly improve the frictional characteristics of these mixtures.

1.3 Organization of the Report

This report is divided into six chapters. Chapter 1 introduces the challenges of using HFST and the objectives of this study. Chapter 2 presents a literature review summarizing FDOT's experience with HFST, previous usages of alternative aggregates to improve friction in asphalt mixes, and background information for the cost benefit analysis. Chapter 3 details the workplan for this project. Chapter 4 contains the results of the laboratory testing and a summary discussion of the potential friction performance. Chapter 5 describes the cost benefit analysis methodology and presents the results comparing the alternative mixes to HFST and also to the control mixes in the study. Finally, Chapter 6 provides conclusions and recommendations based on the research results.

2. LITERATURE REVIEW

This section presents the findings of a literature review conducted for the Florida Department of Transportation (FDOT) for Project BED59 "Evaluation of Enhanced-Friction Asphalt Overlays and Surface Treatments." The objectives of this project are to evaluate alternative asphalt-based solutions to high friction surface treatments (HFST) and to determine if these alternatives have the ability to provide similar friction benefits to HFST in a more cost-effective manner. This literature review covers the following topics:

1) Previous work sponsored by FDOT relating to the cost-effectiveness of HFST and HFST alternatives
2) A survey of existing literature regarding the usage of alternative friction aggregates in asphalt mixtures
3) High Friction Chip Seal Surface Treatment in New Jersey
4) Potential sources of alternative aggregates to consider for Project BED59
5) Summary of Literature Findings

2.1 FDOT's Experiences with HFST

HFST is a pavement surface treatment consisting of a polymer resin binder that is used to bond a very hard, polish, and abrasion-resistant aggregate, approximately 1 – 3 mm in size, to the pavement surface (FHWA, 2020). HFST provides higher pavement friction values that are generally not achievable with conventional paving aggregates, such as granite and limestone, with the added benefit that they tend to retain this high level of friction over time. The use of HFST in the United States began in the early 1950's as a thin polymer-bonded bridge deck treatment. FDOT has been using HFSTs since 2006 to reduce the number of wet weather crashes (Wilson and Mukhopadhyay, 2016). HFSTs were demonstrated to be highly effective by reducing wet weather crashes by 75% in tight curves. HFST friction is provided through the microtexture of the aggregate particles along with the high macrotexture of the finished surface (FHWA, 2020). The use of calcined-bauxite as the HFST aggregate was first noted in 1976 (Heitzman and Moore, 2017). Calcined-bauxite is a premium aggregate for HFST because it is extremely hard and has very high angularity. It has high abrasion resistance which allows it to maintain angularity even after trafficking.

While HFST has successfully reduced the number of wet-weather crashes in Florida, there have been a number of issues associated with its use. These issues include premature failures and high costs. Typical failures that HFST experience include cracking, delamination, and raveling, and in cases where the aggregate ravels severely, the polymer resin binder on the pavement surface is exposed, further reducing pavement friction (Wilson & Mukhopadhyay, 2016). It should be noted however, that FDOT has made a number of changes to their high friction surface treatment specification (Section 333 of the FDOT Developmental Specifications) which has overall improved its performance. These changes include better surface preparation as well as a requirement for an automated applicator vehicle that uniformly applies both the binder resin and the high friction aggregate.

The cost of HFST and the availability of aggregate is another issue. The most common aggregate used in HFST is calcined-bauxite, which is an imported product in the United States, significantly increasing its cost. Calcined bauxite is a by-product of the production of aluminum and almost all of the U.S. HFST applications use calcined bauxite from China (FDOT 2018). As of 2016, historic bid prices for HFST material with calcined bauxite ranged between \$26/yd^2 and \$34/yd^2 in Florida, but these prices can increase 2-3 times after construction costs are included (FDOT, 2018). As a comparison, a 1.5-inch layer of a dense-graded friction course (FC-12.5) at \$113/ton equates to \$9.32/yd^2, according to the 2020 FDOT Historical Item Averages Cost. It should be noted that other unit bid prices for HFST in 2016 and 2017 were between \$20/yd^2 and \$26/yd^2 (FHWA 2017b). Using published values from a calcined bauxite supplier in China of approximately \$380 - \$440 per ton (SICHENG, 2021*)* and an average spread rate of 12-15 lbs/yd^2 (FDOT, 2018), it is estimated that the cost of the calcined bauxite costs between \$2 and \$4 per square yard in HFST. Although these values are estimates, they demonstrate that the majority of the cost is attributed to the epoxy resin binder and the application process. This has also been reported by FHWA (FHWA, 2017b).

Thus, when calculating the cost-effectiveness of HFST, it is necessary to quantify the cost of allowing an elevated risk for a certain estimation of crashes versus the extremely high cost of HFST compared to other crash mitigation techniques. This calculation results in a benefit-cost (BC) ratio. If the benefits of a project outweigh the costs, the BC will be greater than 1.0, and vice versa. BC calculations on HFSTs have been made by a few state agencies and researchers and have ranged between 18 and 118 on applications in tight curves (Wilson and Mukhopadhyay, 2016). The large spread in BC ratios is due to the differences in the calculation method which require estimates of crash reduction, material prices, crash types, discount rates, as well as location.

2.2 Usage of Alternative Friction Aggregates in Asphalt Pavements

As a result of the high costs and durability issues associated with HFST, FDOT has begun to explore alternative methods to improve friction characteristics of their friction course (FC) mixes. This project is not investigating the replacement of the aggregates in a HFST but is instead looking to asphalt-based solutions to improve friction above what FDOT typically observes on their asphalt surfaces. Many agencies and researchers have conducted similar research in other states in the U.S.

Researchers in Alabama have noted the propensity for limestone aggregates locally available in Alabama have long-term skid resistance issues (Bransford, 1972). In a survey of 22 surface types, both asphalt and concrete, and 800 individual sections, mixes were grouped according to the field skid numbers into three classifications: Dangerous, Caution, and Good. The surfaces were also analyzed according to the dominant aggregate present in the mix or surface treatment. Granite and gravel asphalt mixes were present in the second tier of classifications, “Caution”. These mixes did not produce the highest friction results but had very low rates of friction loss over time. Only one limestone mix was classified in the “Caution” range, and it was estimated that the reason for the increased friction of this particular mix was a higher sand content. Finally, four of the six mixes and surface treatments with slag were classified as “Good”. It is not evident in the paper where the slag source in these pavements was located. However, the most skid resistant asphalt mixes and surface treatments in this study had slag as the predominate coarse aggregate.

The Louisiana Department of Transportation and Development (LaDOTD) uses a friction rating system from I (best) to V (worst) for aggregates based on polished stone value (PSV). An analysis of the aggregates used on Louisiana highways found that sandstone and novaculite (an aggregate type that consisting of silica in the form of chert or flint) from Arkansas yielded the highest SN40 results from a locked-wheel skid trailer (LWST) testing of 294 different pavement sections representing 34 different aggregate sources (Lal Das, 2011). In laboratory testing, mixes with only sandstone as the friction aggregate performed better in laboratory testing than mixes with limestone. However, mixes with a blend of limestone and sandstone did not show any statistical difference with limestone only mixes. Wu et al., (2016) evaluated the LaDOTD aggregate friction rating Table by measuring in situ pavement friction with different friction aggregates and non-friction aggregates blended together. Four mixture types were analyzed: Superpave 12.5 mm and 9.5 mm, Stone Matrix Asphalt (SMA), and Open-Graded Friction Course (OGFC). Testing results showed that the dynamic friction tester (DFT) results were dominated by aggregate type while circular texture meter (CTM) results were dominated by mixture type. This indicated that DFT results were primarily driven by the microtexture of the aggregates while pavement macrotexture was more influenced by mixture type, i.e. gradation. Sandstone and novaculite were the two best friction aggregates, according to LaDOTD's PSV friction rating scale, present in the study.

The Oklahoma DOT (ODOT) sponsored a laboratory evaluation of four regionally available aggregates with perceived good friction performance characteristics (Heitzman and Vrtis, 2015). The four aggregates were mine chat, rhyolite, sandstone, and granite. Using the Three-Wheel Polishing Device (TWPD), Dynamic Friction Tester (DFT), and the Circular Texture Meter (CTM), NCAT identified the sandstone source from Sawyer, Oklahoma as the top performer and recommended it for further evaluation on the NCAT Test Track. The sandstone source was used in an OGFC mix on the 2015 Test Track (West et al., 2019). Long-term monitoring of the in-place sections demonstrated that the sandstone OGFC blend was the best performing of four historical mixtures on the Track using Oklahoma aggregates. Furthermore, the OGFC mixture with sandstone outperformed a HFST with flint aggregate from Oklahoma. The SN40R near the end of trafficking on the Test Track was greater than 50 and showed little change over almost 10 million ESALs.

Researchers from the Texas Department of Transportation (TxDOT) and the University of Texas at El Paso (UTEP) utilized an aggregate friction property measurement system designed by the Maryland State Highway Administration (SHA) to determine the dynamic friction value of coarse aggregate (Dawidczik and Nazarian, 2021; Izzo, 2020). Testing of locally available aggregate sources indicated that sandstone and igneous rock outperformed limestone and dolomite. Gravel sources with high amounts of limestone and calcium carbonate had similar friction performance to limestone while friction values of the gravel sources comprised of siliceous gravel and silica were higher than the limestone (Izzo, 2020).

NCAT and the Mississippi DOT (MDOT) investigated alternative friction aggregates and blending proportions of friction aggregates on 9.5 mm asphalt surface mixtures (Turner and

Heitzman, 2013). They were specifically looking to improve upon the friction performance of a typical gravel-limestone mix. MDOT replaced 50% and 100% of the gravel in the 9.5 mm mix with two alternative friction aggregates, slag and granite. MDOT also investigated substituting crushed gravel for limestone in ultra-thin maintenance mixes. They chose to replace 25% and 50% of the limestone with gravel. Slabs were compacted in the NCAT laboratory and were polished on the three-wheel polishing device. Friction testing was conducted using the DFT at ten different points between 0 and 100,000 polishing cycles. The results of the 9.5 mm mix are shown in Figure 1. Note that the blend percentages in the Figure represent total aggregate replacement instead of friction aggregate replacement. Each slag mixes improved terminal friction after 100,000 cycles versus the granite and the control mix. The mix with 100% of the crushed gravel replaced with granite had improved friction compared to the control mix but the mix with only 50% granite as the friction aggregate performed similar to the control mix.

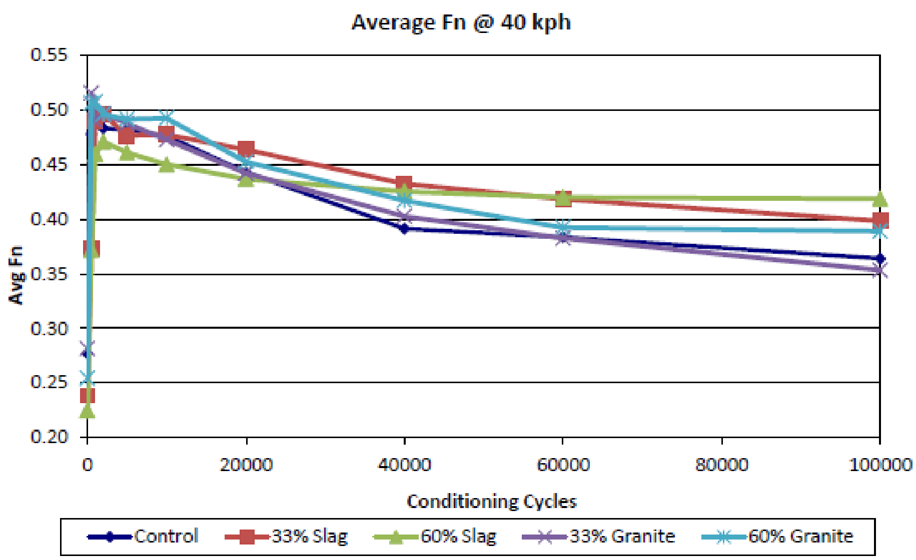

Figure 1: Effects of Slag and Granite as Replacement for Friction Aggregates (Turner and Heitzman 2013)

In the case of the ultra-thin mix, replacing limestone with crushed gravel improved long-term friction. The control mix had 100% limestone aggregate. Two experimental mixes with crushed gravel replacing a portion of the limestone were blended and tested. The crushed gravel replacement for these mixes were 25% and 50%. As expected, the two experimental mixes outperformed the control mix. The improvement from no crushed gravel to 25% crushed gravel was larger than the improvement from 25% to 50% crushed gravel. This is shown in Figure 2. This phenomenon demonstrates the potential to optimize increased friction performance while minimizing additional material costs.

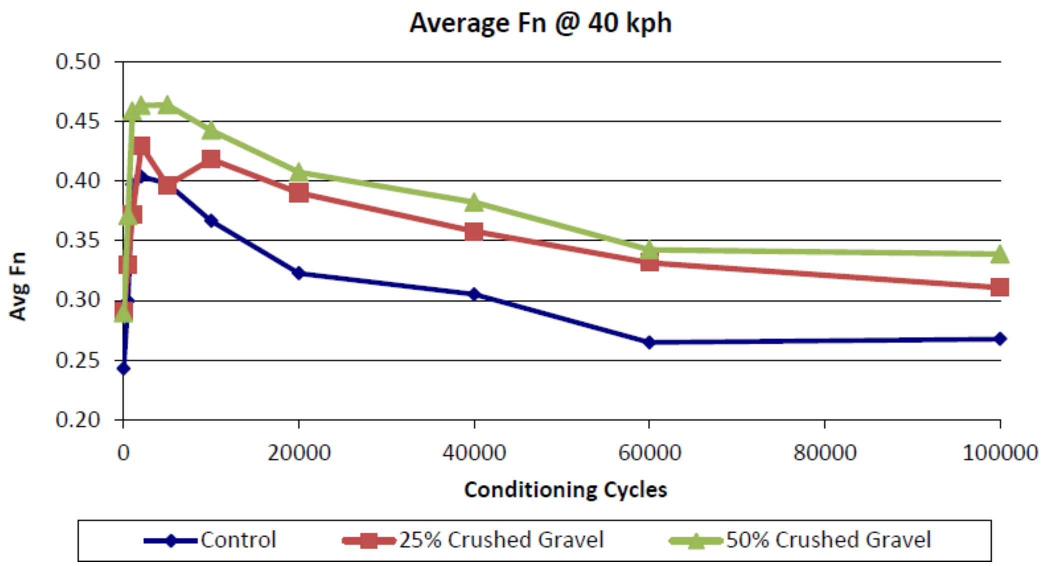

Figure 2: Effects of Crushed Gravel as Friction Aggregates in Ultra-Thin Mix (Turner and Heitzman 2013)

During the 2018-2021 Test Track cycle, the West Virginia Department of Highways (WVDOH) sponsored an NCAT investigation of the friction performance of mixes with varying amounts of dolomite (West et al., 2021) . The WVDOH specifications required that dolomite not exceed 50% of the coarse aggregate in asphalt surfaces where projected traffic was greater than 3.0 million ESALs. In an effort to reduce mixture costs by using more locally available aggregate, WVDOH was interested in reducing that limit and monitoring the friction performance on the Test Track. Two sections were placed in Sections W4 and W5 with coarse aggregate proportions of 70% dolomite and 30% sandstone (70/30) in W4 and 90% dolomite and 10% sandstone (90/10) in W5. The DFT results of the field sections with 70% and 90% dolomite fell dramatically after 1.25 million ESALs, confirming the validity of the WVDOH limit on dolomite. Laboratory slabs were fabricated at 0, 30, 40, 50, 60, 70, and 90% dolomite and were polished using the TWPD and tested with the DFT. The terminal friction coefficient after 100,000 polishing cycles was equal for the slabs with 0% to 50% dolomite. This indicated that there is a critical threshold at which the proportion of aggregate with inferior friction properties must cross before it dominates the superior friction aggregate. In this study, that point was 50%. This is demonstrated in Figure 3. Although the proportion of sandstone was decreasing as dolomite increased from 0% to 50%, the friction performance of the asphalt slabs remained constant. When the mixture was made up of more than 50% dolomite, friction performance deteriorated at a linear pace. This project also demonstrates the potential to optimize material costs and desired friction performance since there is often a non-linear increase in friction from 0 to 100% friction aggregate replacement.

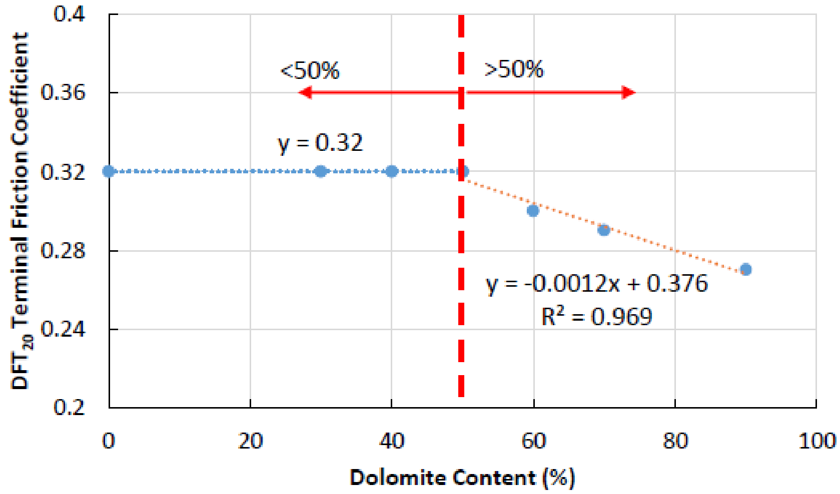

Figure 3: Relationship between Terminal DFT and Dolomite Content (West et al., 2021)

2.3 High Friction Chip Seal Surface Treatment in New Jersey

In the original project proposal, the research team proposed microsurfacing to evaluate the suitability of various alternative aggregates as an asphalt-based surface treatment as an alternative to HFST. Since the project was awarded, the scope was slightly redefined, and this option was no longer considered. However, the research team was asked to include a new surface treatment being used in New Jersey called a High Friction Chip Seal (HFCS) in this literature review.

HFCS is a recently-developed asphalt-based surface treatment alternative to HFST that has been developed in New Jersey and added as an option to the NJDOT specifications as an option for chip seal applications. HFCS is a chip seal utilizing calcined bauxite chips and a fuel-resistant polymer-modified binder (PG 88-22) (NJDOT, 2019). The binder must have adequate high-temperature stiffness to prevent aggregate realignment. If placed in a region susceptible to low-temperature thermal cracking, the binder must also be resistant to this potential distress. The aggregates are precoated with 0.4% to 0.8% fuel-resistant asphalt binder in an asphalt plant before being applied by an aggregate chip spreader to the spray-applied binder (Bennert et al., 2021). A rubber-tire roller is used to seat the aggregates into the hot applied binder. After compaction, the surface is swept and vacuumed.

The calcined bauxite aggregates must have a minimum of 95% passing the No. 6 sieve and a maximum of 5% passing the No. 16 sieve. They must also pass aggregate requirements for polished stone value, resistance to degradation, moisture content, and aluminum oxide (NJDOT, 2019). Hot-applied binder is applied to the pavement surface at an application rate of 0.30 to 0.38 gal/yd^2 and the calcined bauxite is spread at 14 to 18 lb/yd^2. The minimum average SN40R from an HFCS application is 65, and no single measurement below 60 is allowed.

A flint aggregate from Oklahoma and a trap rock source local to New Jersey were used as alternative aggregates in a HFCS to compare against the calcined bauxite. The two alternative aggregates did not meet the gradation band required by NJDOT but they were close to it. The aggregates were polished in a Micro-Deval device at different time intervals and then analyzed using an Aggregate Imaging Measurement Systems (AIMS) device at each interval. Micro-Deval polishing was intended to simulate polishing and wear of the aggregates on the exposed pavement surface. AIMS measured particle size, angularity, and texture of aggregate particles. The Angularity Index (AI), where larger values indicate higher angularity, was highest for the flint aggregate after 30 minutes of polishing and remained the highest angularity at all other polishing time intervals from 30 minutes to 4 hours, as shown in Figure 4. Although initially the Trap Rock had the highest angularity and the calcined bauxite (referred to in Figures 4 and 5 as "Bauxite"), had the lowest, the calcined bauxite and Trap Rock had similar angularity after 30 minutes of polishing to 4 hours. As of July 2022, the sections were performing well and only a portion of the shoulder of the section with flint had begun to ravel. It is expected that this was due to moisture issues (Bennert, personal communication, July 8, 2022). As of May 2024, all HFCS testing in the lab has been done with slabs prepared in the field by cutting them out of the pavement after HFCS application (Bennert, personal communication, May 2, 2024).

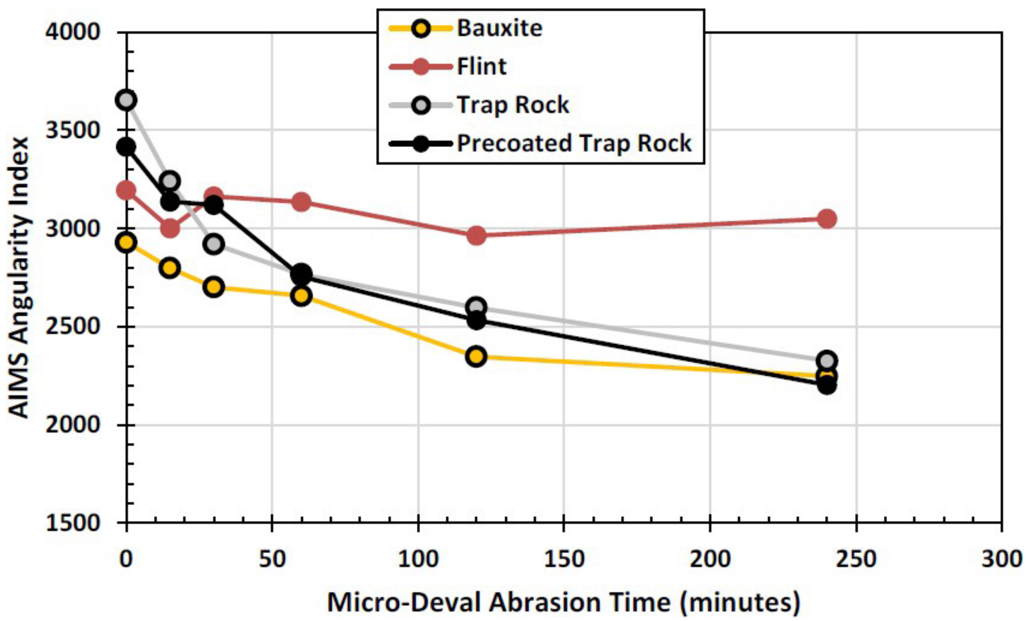

Figure 4: AIMS Angularity Index after Micro-Deval Polishing for Three Aggregates (Bennert et al. 2021)

Other studies on alternative aggregates in HFST have shown that AIMS AI does not always correlate well with surface friction characteristics (Heitzman, et al., 2015) but angularity loss from Micro-Deval testing has demonstrated potential to improve this correlation. Figure 5 shows the percent reduction in AIMS AI for the same aggregates. The flint aggregate outperformed the other two aggregates and demonstrated very little loss in angularity. In field testing (SN40R) of HFCS sections, the flint rock performed very well and even slightly better than the calcined bauxite, as shown in Table 1. These data were collected a few months after the applications (Bennert, personal communication, July 8, 2022). These results agreed with the rankings from the percent reduction in AIMS AI (Bennert et al., 2021).

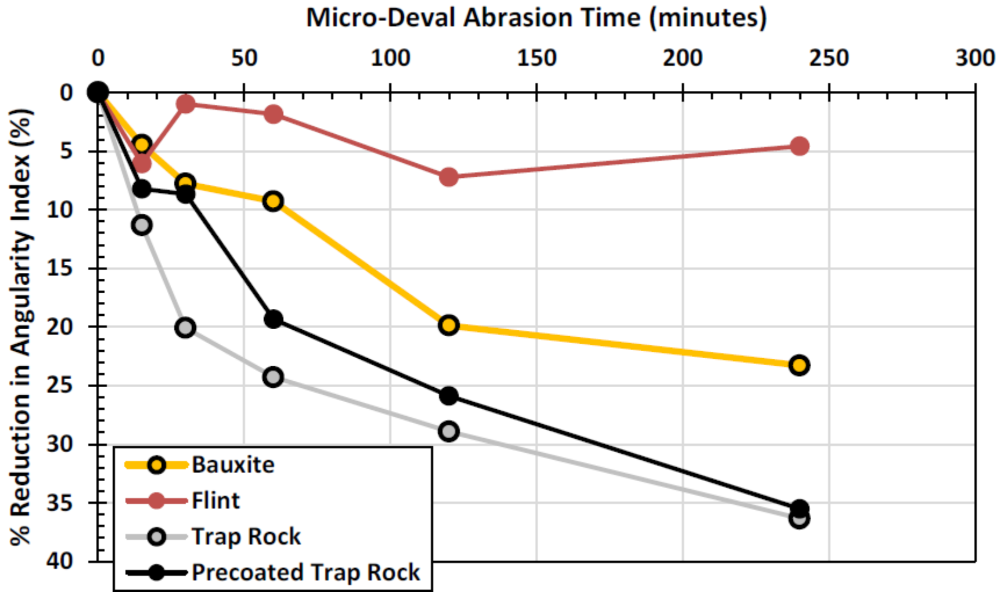

Figure 5: Percent Reduction in AIMS Angularity Index after Micro-Deval Polishing for Three Aggregates (Bennert et al. 2021)

Table 1: SN40R Results from HFCS Sections in New Jersey (after Bennert et al., 2021)

0.1 Mile Section	Trap Rock	Calcined Bauxite	Flint Rock
1	69.0	75.0	75.3
2	63.4	72.7	74.8
3	59.9	69.3	61.9
4	62.0	58.5	70.8
5	66.5	70.4	74.0
6	55.1	71.6	65.2
Average	62.2	69.6	70.3

2.4 Potential Sources of Alternative Aggregates to Consider for Project BED59

One of the objectives of this project was to explore potential high friction aggregate options that could be used in Florida and can be incorporated into asphalt mixtures. Since cost can be a main driving force behind the use of various aggregates, an effort was made to identify potential regional sources which would hopefully minimize transportation costs. Potential regional aggregates are listed in the following section.

2.4.1 Lightweight aggregate from North Carolina

This source of lightweight aggregate is produced by Stalite lightweight aggregate (LWA), and the production facility is located in Gold Hill, North Carolina. It is currently an FDOT approved source (FDOT Facility ID NC563), and the approved products include a No. 67, No. 7, and No. 8 size stone. Friction testing has previously been conducted on this material, both in the NCAT laboratory as well as the Test Track, and performance has been very good. In laboratory testing, Stalite LWA was used as an alternative to calcined bauxite in HFST applications on slabs. Eight total aggregates were used as alternative aggregates and the Stalite LWA had the highest DFT value after 140,000 TWPD cycles of all eight aggregates. Furthermore, the Stalite LWA was used in a chip seal on a Test Track section in 2012 and is still in service, as of 2022 (West et al. 2018). The friction performance of this section has been consistent for the past 8 years and more than 20 million ESALs.

A Stalite representative, Jim Thompson, recalled the product being used in asphalt mixes in Florida approximately twenty-five to thirty years ago. According to Mr. Thompson, Stalite partners with Vulcan Materials and has potential access to rail lines into Florida to reduce shipping costs. The gradations from January 2022 Stalite QC monthly reports were provided by Mr. Thompson and are shown in Table 2. This project would most likely use the 3/8" or the 5/16" products.

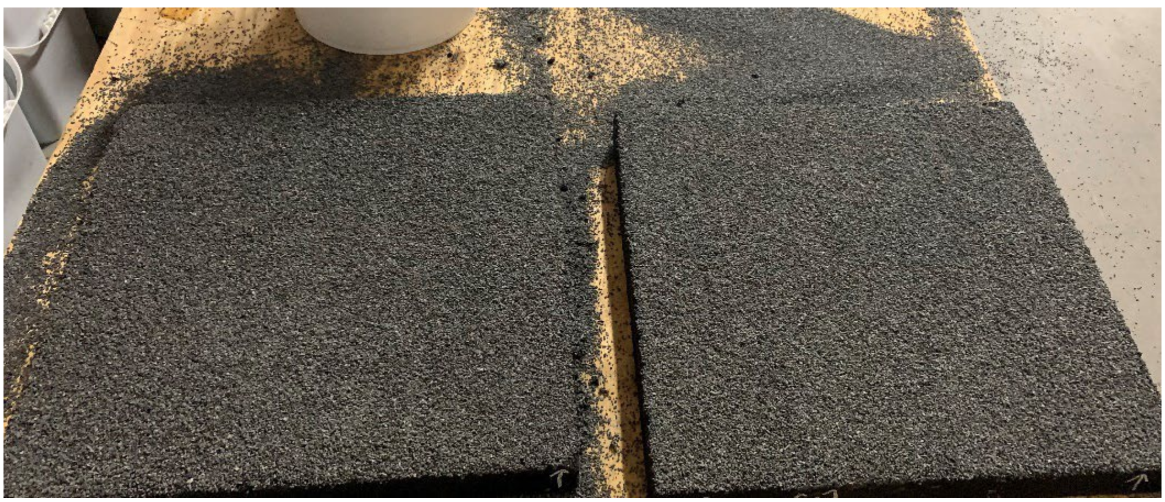

Figure 6: Stalite Lightweight Aggregate as HFST on a Slab (NCAT)

Table 2: Stalite Lightweight Aggregate Product Gradations (Jim Thompson, Stalite)

Sieve Size	3/4"	1/2"	3/8"	5/16" (Unwashed)	5/16" (Washed)
3/4"	94	100	100		
1/2"	57.3	91.2	100		
3/8"	35.4	62.8	97.9	100	100
#4	8.1	10.6	18.6	20.7	29
#8	4.4	4.9	4.3	4.2	4.9
#100			2.4	2.8	2.6
#200			1.9	1.5	0.8

2.4.2 Sandstone from Oklahoma or Alabama

Sandstone from Oklahoma has consistently demonstrated potential for increased friction performance in asphalt mixes (Heitzman and Vrtis, 2015; West et al., 2019). This aggregate source would have entailed significant shipping costs but it has proven friction properties. More locally, sandstone was also present in north Alabama and had been used on the Test Track in combination with slag in an OGFC mix. This mix had excellent friction performance as of June 2022, but it is unclear if this should be attributed to the sandstone or the slag or a combination of both. The United States Geological Survey (USGS) show that a shallow source of sandstone stretches from north Alabama through Pennsylvania, as shown in Figure 7. Sandstone from this region, specifically eastern Kentucky, was used as the primary friction aggregate in a Test Track section in 2021 and performed well in the field. It was uncertain if sandstone from Alabama would have the same friction performance as sandstone from other regions in the U.S.

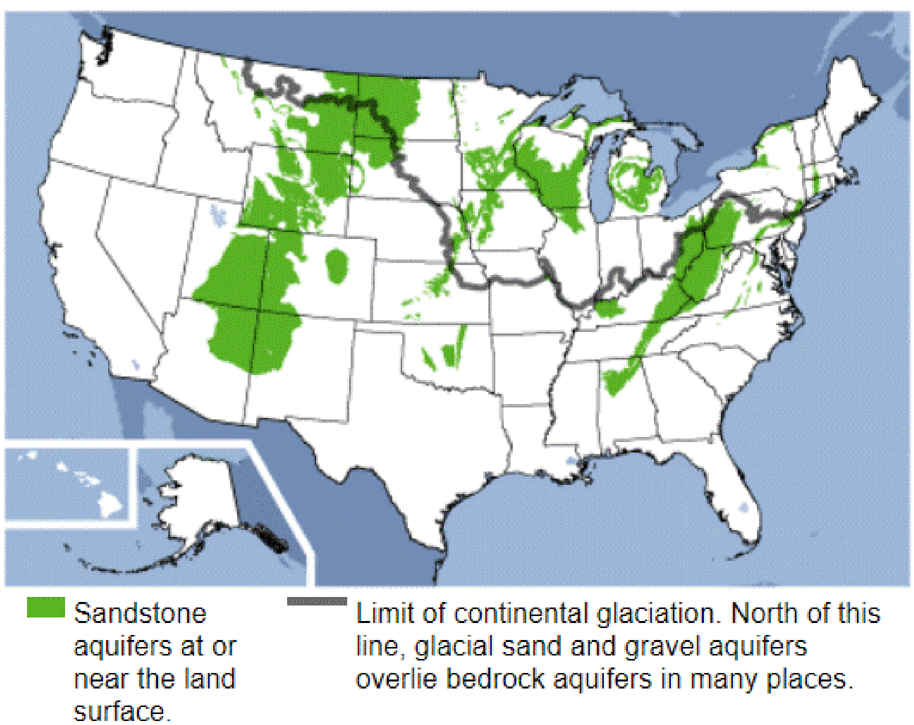

Figure 7: Principal Sandstone Aquifers in the U.S. (USGS, 2021)

2.4.3 Flint from Oklahoma

As previously shown, flint aggregate from Oklahoma has shown potential for good friction performance (Bennert et al., 2021). These specific results, however, were only lab testing results and short-term friction performance. Heitzman and Moore (2017) used flint from Flint Rock Products in Picher, Oklahoma as alternative aggregates for HFST applications with good success in laboratory testing. In another study, NCAT tested flint aggregate from the same source as an alternative aggregate in HFST and maintained SN40R values in the mid-40's after 8 million ESALs (Heitzman, et al., 2015). In this same study calcined bauxite from China and granite from Wisconsin were also used and flint outperformed the granite by less than 5 SN40R unites. The calcined bauxite section had SN40R results of mid 60's after 8 million ESALs. Finally, in the same 2015 study, NCAT used flint, bauxite, slag, and taconite as aggregates in HFST applications on 20" x 20" slabs in the lab. The flint aggregate was the worst performer, although the DFT(40) results after polishing were still above 0.60. The slabs with slag exhibited extremely high DFT(40) values of over 0.80.

The primary concern with using this flint aggregate source in BED59 is that it is at least 800 miles away from Florida. The NCAT researchers prioritized aggregate sources that had potential to reduce shipping costs due to their proximity to Florida or a shipping port.

2.4.4 Steel Slag from Alabama or South Carolina

Steel slag is a by-product of steel production and is produced during the separation of the molten steel from impurities in steel-making furnaces. It has been used successfully as an aggregate in asphalt wearing courses and in surface treatments, both in the United States and internationally. Some of the positive features of steel slag aggregates in asphalt pavements include good frictional properties and stripping resistance, high stability, and resistance to rutting/plastic deformation (FHWA, 2016). The Alabama DOT regularly uses steel slag in their asphalt mixes, including OGFCs. Sources of steel slag that are available regionally include a source in Frost Proof, FL, ten ALDOT approved producers in northern Alabama (typically the Birmingham area or further north) as well as one SCDOT approved producer in South Carolina outside of Charleston.

The potential downside of using steel slag include its propensity to expand or swell if not processed properly (resulting in pavement cracking). In order to address this issue, it is generally recommended that steel slag that is to be used as an aggregate should be stockpiled outdoors for several months to expose the material to moisture from natural precipitation and/or an application of water by spraying. The purpose of this storage (aging) is to allow potentially destructive hydration and its associated expansion to take place prior to use of the material in aggregate applications (FHWA, 2016). SCDOT specifications require that stockpiled slag be tested for expansion testing by the producer in accordance with ASTM D 4792 prior to using in an asphalt mixture. However, ALDOT specifications do not require expansion testing or a minimum stockpiling time. Another potential downside of steel slag is higher bulk specific gravity values (typically 3.2 – 3.6) which creates mixes that cover less volume per ton than typical mixes. It should be noted that FDOT permitted the use of slag materials in friction courses up until the late 1990s.

2.4.5 Calcined Bauxite from Eufala, Alabama

During the preparation of the NCAT proposal for FDOT, calcined bauxite and taconite were identified as two of the three key alternative friction aggregates that should be considered for the study. After the study was awarded to NCAT, suppliers for both aggregates were contacted to obtain more information about the aggregate products they could provide. The taconite product was no longer available as it had begun being processed further for ore and was not available in the necessary sizes. The calcined bauxite supplier located in Alabama, Mineral Manufacturing Inc., manufactures and crushes their calcined bauxite on-site. This source has different sized products with varying amounts of aluminum oxide (Al_2O_3). The aluminum oxide (commonly called alumina) content indicates the grade of calcined bauxite. High friction surface treatments require refractory-grade calcined bauxite with a minimum aluminum oxide content of 87 percent, which can limit the supply. Having a slightly lower grade of calcined bauxite specified might potentially increase supply. This is a specialty product, and Mineral Manufacturing indicated an interest in providing whatever gradation the study needed. A picture of a sample of the product is provided in Figure 8.

Figure 8: Sample of Calcined Bauxite from Eufala, Alabama

2.4.6 Quartzite from Nova Scotia, Canada

The FDOT research team elected to use quartzite from Nova Scotia as a high friction aggregate. By the time this decision was made, the threat of an aggregate shortage had forced FDOT to expand its list of approved sources. The quartzite aggregate was barged down the coast of the U.S. and was available for use in Florida by 2023. The FDOT research team received data from a Canadian agency reporting very high friction values and confirmed this with their own testing. Thus, this aggregate was selected for use in this project.

2.4.7 Selected High Friction Aggregates

The NCAT and FDOT research teams selected calcined bauxite from Eufala, AL, steel slag from Frost Proof, FL, and quartzite from Nova Scotia, CA for this research project. Ultimately, FDOT elected to use aggregates that were locally available (or in the case of the quartzite, already present in large quantities in Florida).

Using specialty aggregate products with mostly uniform gradations, such as calcined bauxite, or material with specific gravities different from typical aggregate, such as slag or bauxite, involve additional mix design challenges such as blending aggregates with a wide range of specific gravity. NCAT has experience with designing dense-graded asphalt mixes with slag (Brown et al., 2002; Turner and Heitzman, 2013). An OGFC mix containing slag and sandstone was designed and constructed at NCAT in 2021. The most appropriate method to resolve the issue is to blend aggregates by volume instead of by weight, using the aggregate gravities to convert from weight to volume. This approach was applicable to both lightweight aggregates and steel slag. Another mix design-related issue that may arise with the usage of alternative aggregates is blending a uniformly graded material, like calcined bauxite, into dense-graded asphalt mix. NCAT had experience with using uniformly graded calcined bauxite in an SMA mix design on the 2015 Test Track to achieve reasonable volumetric results (West et al., 2018). This issue is often resolved by adding a clean sand or by adjusting the proportions of the other stockpiles. The final blends did not match the gradation of the control mixes without the uniformly graded aggregates, but volumetric targets were still achievable.

2.5 Cost-Benefit Analysis of High Friction Surfaces

Conducting a cost-benefit (CB) analysis for friction treatments is typically done considering crash history on particular routes or locations, crash type on a KABCO scale, and actual project costs (Wilson and Mukhopadhyay, 2016; Wilson et al., 2016). Because this project focused on laboratory mixes, this project estimated the cost-benefit of laboratory-created mixes without any field data or actual construction cost. Thus, the CB analysis conducted in this project was a comparison of the costs and potential crash reduction benefits of different high-friction mixes compared to HFST. All mixes that have higher friction than a control mix will have a positive benefit on crash reduction. However, the costs to produce such a mix may outweigh the benefits if either the benefit is not very high compared to the control or the cost is too high. Ultimately, understanding the value of reducing crashes and preventing injury or loss of life must be known by the DOT in order to appropriately apply the results of a laboratory-based study. This study compared asphalt-based high friction products to HFST for comparison. The framework developed more later in this report can be used by FDOT to decide whether to use a higher cost mix type or friction product given the expected crash reduction benefit compared to simply using a HFST with a better known crash reduction benefit.

This study estimated crash reduction potential of higher friction mixes based on literature. Many studies comparing pavement friction level and crash risk involve more than a single variable. Crash rates depend on numerous factors, such as climate, traffic volume, traffic speed, roadway geometry, condition of tire tread, pavement surface macrotexture, and pavement surface microtexture (friction). Improvements to the pavement surface friction only address a portion of the factors that influence crash rate. In theory, specific data on the potential crash risk at various levels of measured pavement surface friction are needed to examine the relationship between costs (pavement surface cost per year of service) and benefits (level of safety).

The mixes developed in this project were made without regard to which particular segments or crash risk scenario they might be applied to. Thus, this report will detail the estimated crash reduction benefits of improved friction compared with the costs of the mixes associated with the higher friction levels only. These values will be compared to the costs and crash reduction of HFST. Cost information for the aggregates and mix types were gathered from the alternative aggregate suppliers and FDOT.

Crash reduction benefits were generated following two independent research studies. A 2001 literature review by Wallman and Astrom showed data from Sweden that were used to create Figure 9. Note that the results from that dataset only included friction coefficients from 0.15 to 0.40. However, 0.25 to 0.40 is the majority of the typical range of asphalt mixes. Thus, the data range was deemed acceptable for inclusion in this analysis. The data were manipulated to represent crash reduction compared to a baseline friction coefficient of 0.25 (or a friction number of 25). Increasing friction from 25 to 40 resulted in an estimated crash reduction of 40%. The range beyond 40 was also considered because the estimated crash reduction for friction numbers typically associated with HFST (FN ≈ 60-80), resulted in estimated crash reduction generally consistent with the estimates from FHWA (FHWA, 2017b).

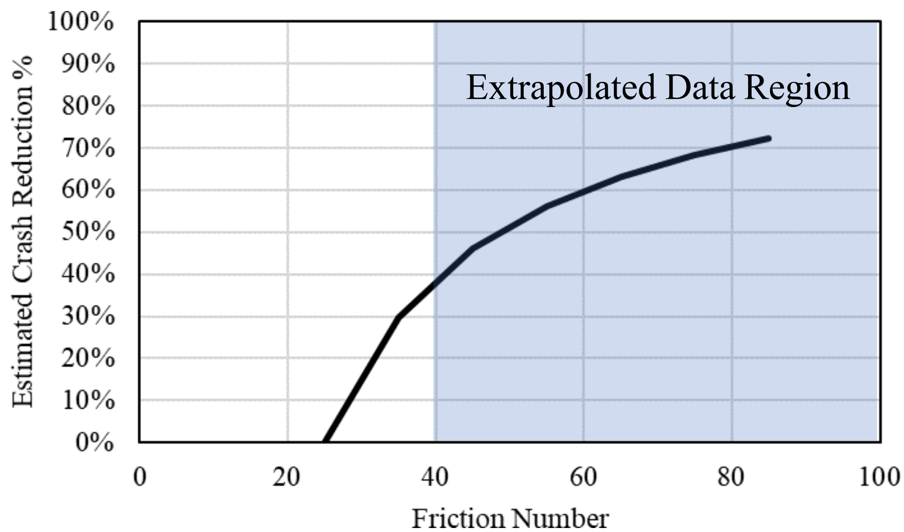

Figure 9: Estimated Relation between Crash Reduction and Friction Number (after Wallman and Astrom, 2001)

Najafi et al. (2017), conducted a study in New Jersey that included friction values as the only regressor variable where the response was crash rate. This analysis was similar to the one in this project because the friction was the only variable available to the research team to compare to potential crash rates. An example of the relationship between crash rate and friction on two routes (one wet and one dry) is shown in Figure 10. Note that the study included an analysis of three route types in both the wet and dry condition. The regression coefficients for all six analyses are shown in Table 3. The minimum and maximum friction values recorded in that study were approximately 20 and 65, respectively.

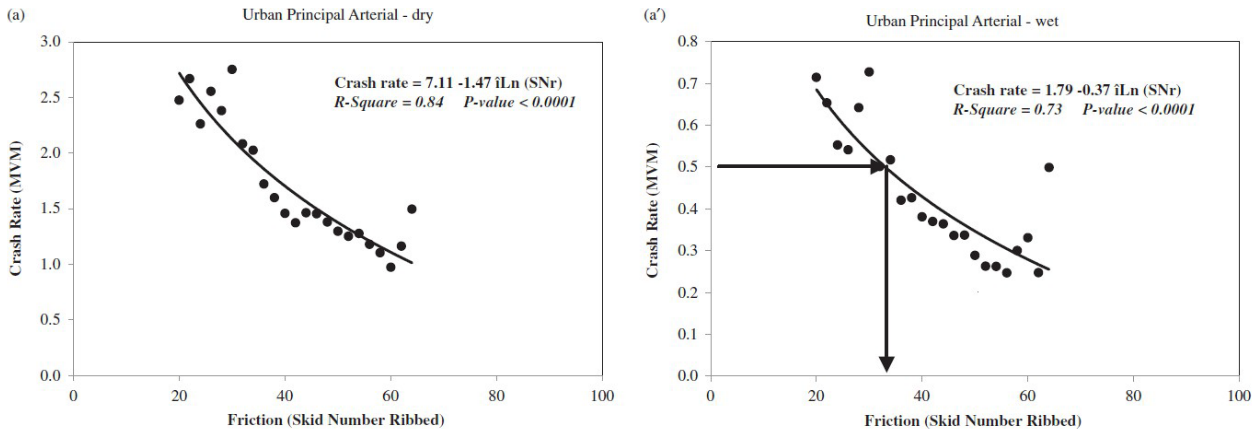

Figure 10: Example of Crash Rate vs. Friction from New Jersey (Najafi et al., 2017)

Table 3: Regression Coefficients for Crash Rates versus Friction for Six Route Types in New Jersey (Najafi et al., 2017)

Route Type	Urban Principal Arterial	Urban Principal Arterial	Urban Interstate	Urban Interstate	Urban Minor Arterial	Urban Minor Arterial
Condition	Dry	Wet	Dry	Wet	Dry	Wet
Intercept	7.11	1.79	2.33	0.96	11.78	3.09
Slope	-1.47	-0.37	-0.47	-0.21	-2.58	-0.69
R^2	0.84	0.73	0.37	0.73	0.65	0.35

The report containing the New Jersey crash data noted that the data associated with the crash rates in the wet condition were suspect. Thus, these data were discarded from this analysis. The crash rate curves from New Jersey were manipulated into crash rate reduction curves with the baseline at a friction level of 25, similar to the previous analysis. The two independent studies reviewed for this project produced reasonably similar results in terms of the estimated crash rate reduction compared to friction. Using the results from the Swedish study and the average of the curves in Figure 11, increasing friction from 25 to 40 is estimated to reduce crashes by 30-40%.

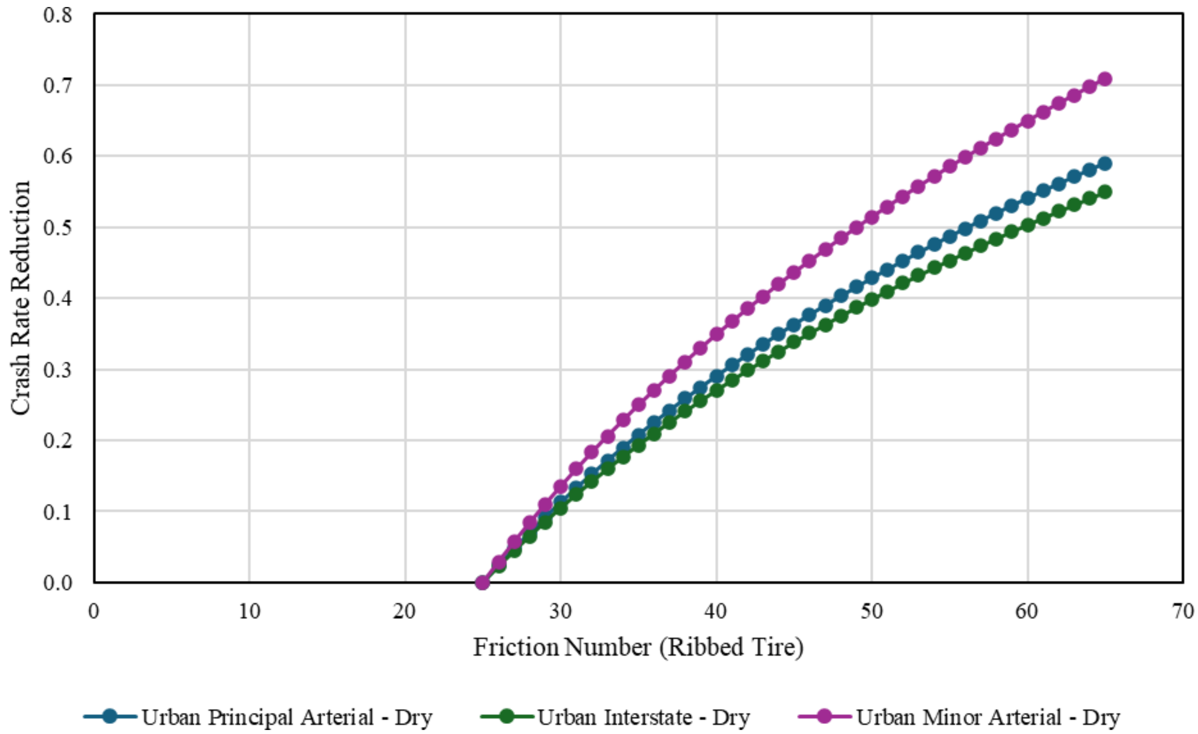

Figure 11: Estimated Crash Rate Reduction for Six Route Types in New Jersey (after Najafi et al., 2017)

These calculated crash rate reductions compared to a baseline friction value of 25 were used in this study to estimate the potential crash reduction of the mixes designed and tested in this project. Again, crash risk is a function of more than simply friction alone. However, studies have shown that friction has one of the highest contributions to crash risks of all potential factors (FHWA, 2017a).

2.6 Summary of Findings

- A high friction surface treatment (HFST) is a pavement surface treatment consisting of a polymer resin binder that is used to bond a very hard, polish, and abrasion-resistant aggregate to the pavement surface. HFST provides higher pavement friction values that are generally not achievable with conventional paving aggregates, such as granite and limestone, with the added benefit that they tend to retain this high level of friction over time.
- FDOT has been using HFSTs since 2006 to reduce the number of wet weather crashes in certain areas. While HFST has successfully reduced wet-weather crashes in Florida, there have been a number of issues associated with its use. These issues include premature failures and high costs. HFST failures typically include cracking, delamination, and raveling. The high costs of HFST is primarily due to the use of calcined bauxite aggregate, which typically originates in China.
- As a result of the high costs and durability issues associated with HFST, FDOT has begun to explore alternative methods to improve friction characteristics of their friction course mixes.

One alternative is to use an alternative high friction aggregate in either a dense- or open-graded friction course mixture.

- Previous studies in Louisiana, Oklahoma, Texas, and Kentucky have shown that sandstone provides good frictional properties. The Oklahoma study showed that sandstone outperformed mine chat, rhyolite, granite, and flint.
- A West Virginia study showed that sandstone as a replacement to dolomite improved friction performance.
- NCAT and the Mississippi DOT (MDOT) investigated alternative friction aggregates and blending proportions of friction aggregates on 9.5 mm asphalt surface mixtures. They were specifically looking to improve upon the friction performance of a typical gravel-limestone mix. MDOT replaced 50% and 100% of the gravel in the 9.5 mm mix with two alternative friction aggregates, slag and granite. The slag mixtures outperformed the granite mixtures.
- The New Jersey DOT recently developed a High Friction Chip Seal (HFCS). HFCS is a chip seal utilizing calcined bauxite chips and a fuel-resistant polymer-modified binder (PG 88-22). They also evaluated a flint aggregate from Oklahoma and a trap rock from the New Jersey area as alternative aggregates to calcined bauxite. Micro-Deval testing and AIMS imaging showed that the flint aggregate had little loss of angularity. In field test sections, the sections with flint had higher friction values than the other materials.
- As a method of potentially reducing the cost of an asphalt mixture containing a high friction aggregate, alternatives sources from high friction materials were sought and evaluated. Potential materials and sources included: lightweight aggregate from North Carolina, Sandstone from Oklahoma or possibly Alabama, Steel slag from Alabama or South Carolina, and calcined bauxite from Eufala, Alabama.
- The NCAT and FDOT research teams selected calcined bauxite from Eufala, AL, steel slag from Frost Proof, FL, and quartzite from Nova Scotia, CA for this research project. Ultimately, FDOT elected to use aggregates that were locally available (or in the case of the quartzite, already present in large quantities in Florida).
- Cost benefit analysis of laboratory-produced specimens requires comparing to hypothetical crash risks. Nonetheless, relative comparisons can be conducted between different mix types or treatments.
- Increasing pavement friction by 15 units from 25 to 40 is estimated to decrease crashes by 30-40%.

3. EXPERIMENTAL PLAN

This chapter presents the experimental workplan of this project. This project evaluated three high friction aggregates (in varying percentages) in conjunction with different FDOT mixtures, as well as with one surface treatment alternative. The full testing program is described below. For each material combination, test slabs were prepared, polished with the three-wheel polishing device (TWPD), and tested with the dynamic friction tester (DFT) and circular texture meter (CTM).

3.1 Experimental Concept

The analysis of the results will focus on comparing the friction performance of the various combinations of materials to the friction performance of a standard HFST. Terminal friction performance is a primary concern and will be used to rank the various friction aggregates. The early peak friction and rate of friction loss will help to distinguish between material combinations with comparable terminal friction ranks. It is anticipated that higher percentages of a friction aggregate will increase the friction performance as illustrated in Figure 12. Friction performance does not correlate linearly with percent friction aggregate, so applying two percentages will provide a general understanding of the influence of friction aggregate exposure on the pavement surface. Further testing with additional intermediate percentages may be needed to have a more complete representation.

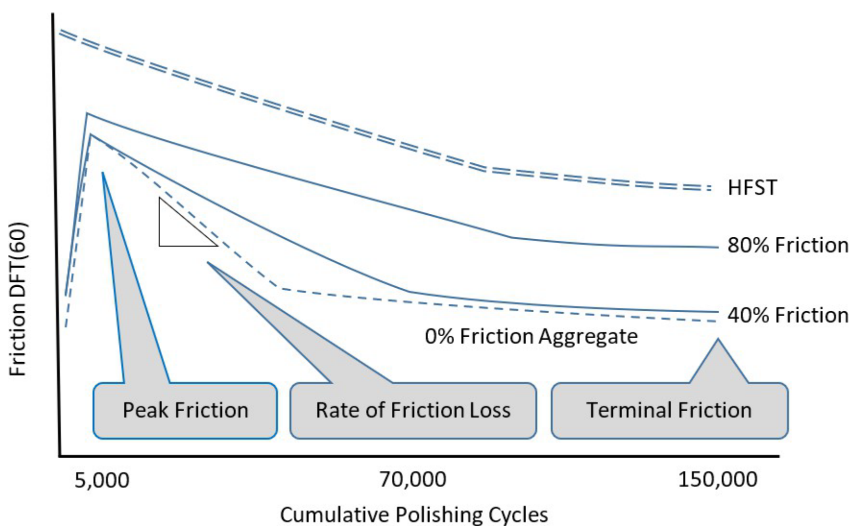

Figure 12: Concept of Percent Friction Aggregate Influence on Friction Performance

Many highway agencies do not report a required minimum acceptable friction value for various reasons, and the research team does not plan to suggest a friction standard for this analysis. Rather, the research team proposes to present the analysis of the various mixture combinations as a ranking of laboratory results. The FDOT can apply the results of this project to examine the level of friction reduction from typical HFST values to determine if sufficient friction improvement is realized to reduce the potential risk for crashes. Figure 13 is an example of how a part of the analysis could be presented. A similar analysis will be applied to the CTM data. The analysis of CTM texture data is expected to focus on the differences between the mixtures types.

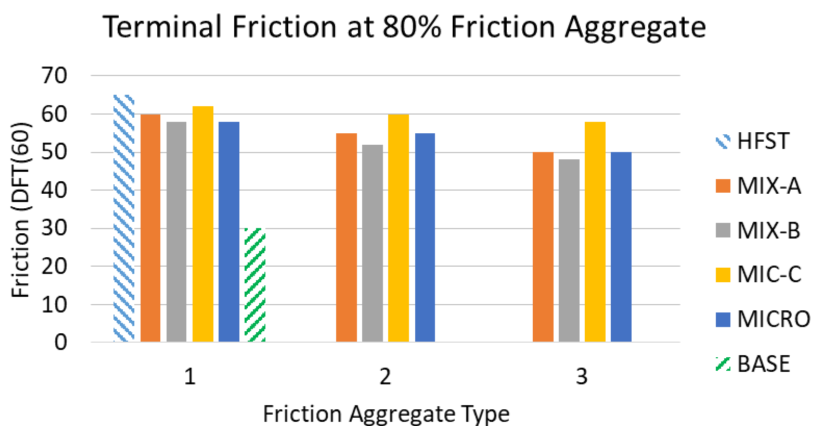

Figure 13: Example Ranking of Friction Aggregate for All Mix Types

3.2 Materials and Mixtures

This project evaluated three asphalt mixture types (FC-9.5, FC-4.75 and FC-5) with two base aggregates (south Florida limestone and Georgia granite), three high friction aggregates (described below), two percentages of friction aggregate, and two test replicates. Each individual blend of materials was specifically designed to meet the FDOT mix design requirements as stated in Sections 334 and 337 of the FDOT Standard Specifications, and Section 334 of the FDOT Developmental Specifications. For the dense-graded mixtures, this includes determining the gradations and specific gravities of the high friction aggregates, establishing the appropriate blend percentages, determining the optimum binder content, and conducting a volumetric analysis based on an N_{design} of 75 gyrations. Other mix design criteria, such as testing of consensus properties and moisture susceptibility testing were waived by the FDOT research team. Table 4 contains the mix design criteria for the three mix types studied in this project. The optimum binder content of the FC-5 mixes were determined using the pie plate method (FM 5-588).

Table 4: FDOT Mix Design Criteria for FC-4.75 and FC-9.5 Mixes

Mix Type	FC-4.75	FC-9.5
Ndes, Gyrations	65	75
Air voids, %	4.0 to 6.0	4.0
VMA	N/A	Min. 15.0
VFA	N/A	73 to 76
D/B Ratio	1.0 to 2.0	0.6 to 1.2
Vbe	12.0 to 15.0	N/A

The limestone aggregate used in the project was from Whiterock Quarry in south Florida, and the granite was from Junction City Mining in west Georgia. The granite designs also included local sand from Georgia. It should be noted that with the addition of the high friction aggregate, the total amount of granite used will likely drop below 60%. In addition, the mixtures did not contain any RAP material, and the binder used in all mixtures was PG 76-22.

As discussed in the literature review, a variety of high-friction aggregates (HFA) were available for this project. The FDOT research team elected to prioritize two local aggregates with high potential for improved friction. These were calcined bauxite from Eufala, AL, and steel slag from Frost Proof, FL. Calcined bauxite was chosen because it was a local source of premium friction aggregate, and slag was selected because it has a well-established history relating to higher friction in asphalt mixes, and it was in the state of Florida. The third source was a quartzite source from Nova Scotia, CA. The quartzite source began shipping FDOT-approved aggregates to FL during the course of this project due to an impending aggregate shortage, and the FDOT team elected to evaluate it as a potential for a friction aggregate. Field friction studies with the locked-wheel friction trailer on pavements in Canada containing the quartzite aggregate yielded high friction values prior to the aggregate being included in this study. A summary of the three aggregates is shown in Table 5. Note that the original slag product had a well-graded gradation and was screened into the sizes shown in Table 5 at NCAT to represent more typical screened aggregate products.

Table 5: High Friction Aggregate Information

High Friction Aggregate	Calcined Bauxite		Slag			Quartzite
Location	Eufala, AL		Frost Proof, FL			Sheet Harbour, Nova Scotia, CA
Photo						
G_{sb}	3.250		3.271			2.682
Sizes Used	3 x 8	3/8" x 8	-1/4"	-1/2"	¾" x #8	ASTM 8s
% Passing						
1"	100	100	100	100	100	100
3/4"	100	100	100	100	100	100
1/2"	100	100	100	100	69	100
3/8"	100	100	100	76	48	92
# 4	83	74	74	33	10	23
# 8	12	10	39	17	1	3
# 16	1	1	29	13	1	2
# 30	1	1	25	10	1	1
# 50	1	1	20	9	1	1
#100	1	0	16	7	1	1
#200	0.7	0.4	10.4	4.6	0.4	0.7

The base designs were FDOT approved granite and limestone mix designs with no HFA in the blend. A maximum HFA percentage was determined according to the limits of the gradation bands. The target maximum was the proportion that caused at least 80% of the coarse material (i.e. material retained on the #4 sieve) to be HFA. This represented the high proportion of the HFA for a particular mix type and blend. Once a mix design was completed, the HFA proportion was approximately halved, and another mix design was completed using this medium amount of HFA. This process was followed for the determination of each mix design. A matrix summarizing the mixtures tested is shown in Table 6.

Table 6: Matrix of Mixtures and Blends

	FC-9.5	FC-4.75	FC-5	Surface Treatment
Base Aggregates	2	2	2	N/A
High Friction Aggregates (HFA) Types	3	2	2	2
% HFA	2	2	2	1
Replicates *(1)*	2	2	2	1

(1) A third replicate may be required for some combinations to maintain reasonable test result repeatability.

Specific descriptions of the various material combinations are as follows:

- FC-9.5: The FC-9.5 mixtures utilized two base aggregates, south Florida limestone (from Whiterock Quarries) and Georgia granite (from Junction City Mining); three high friction aggregate types (calcined bauxite, steel slag, and quartzite), three percentages of friction aggregate (0%; a maximum amount - approximately 80% of the coarse aggregate replacement; and a blend midway in between 0 and the maximum amount).
- FC-4.75: The FC-4.75 mixtures used the same two base aggregates described above (limestone and granite), two high friction aggregate types (calcined bauxite and steel slag), three percentages of friction aggregate (0%; a maximum amount - approximately 80% of the coarse aggregate replacement; and a blend midway in between 0 and the maximum amount).
- FC-5: The FC-5 used two base aggregates (limestone and granite), two high friction aggregate types (calcined bauxite, steel slag), three percentages of friction aggregate (0%, a maximum amount - approximately 80% of the coarse aggregate replacement; and a blend midway in between 0 and the maximum amount). The FC-5 mixtures contained 1% hydrated lime (by weight of total aggregate) for the granite-based mixtures and 0.3% cellulose fibers (by weight of total mix) for all mixtures.
- Surface Treatment: Finally, exploratory work on the suitability of measuring friction performance of high friction chip seals (HFCS) in the laboratory was conducted. FDOT specifically requested that just a single blend of one of the alternative aggregates be used to create a HFCS in the lab. The research team elected to make two sets (one slab with bauxite and another with slag). Slabs were fabricated to match the hot-applied asphalt binder and HFCS aggregate application rates detailed in Section 424.03.03 of the 2022 New Jersey Department of Transportation Road and Bridges Standard Specifications.

Note: In all of the variations described above (except the HFCS), two replicate slabs were fabricated and tested. A third replicate slab was fabricated and tested if the repeatability between the two replicates was outside a reasonable value as discussed later.

3.3 Aggregate Blending

The alternative HFAs were incorporated into the blends by targeting a replacement of a portion of the coarse aggregate. The coarse aggregate was defined as the material comprising the upper

50% of the gradation. Two proportions of HFA were selected: a high proportion (denoted “H”) that targeted replacing approximately 80% of the coarse aggregate in the mix by volume with HFA, and a medium proportion (denoted “M”) that targeted replacing approximately 40% of the coarse aggregate in the mix by volume awith HFA. The gradations of the blends with HFA were unable to match the gradations of the control mixes perfectly because the gradations of the HFAs were not equivalent to the gradations of the limestone or granite products. The FDOT research team elected to have the mixes pass typical volumetric and gradation requirements to prove the feasibility of blending in the real world rather than have a tighter control on the experimental design.

Blending the HFAs with higher specific gravities, namely the bauxite and slag, required blending by volume instead of by mass. This is demonstrated in the example below in Figure 14. This blend is an FC-9.5 blend with 40% limestone and 60% bauxite. The extremely large difference in their gravities (2.450 for limestone vs. 3.250 for bauxite) causes the gradation curves to look differently when plotted by mass versus by volume. In this case, the higher-density aggregate is the dominant component in the blend. Because its density is so much higher than limestone, an individual particle of the bauxite fills the same space as the limestone but weighs 30% more. Therefore, when viewed by mass, the blend appears coarser on the sieves where the bauxite is present because a typical number of particles weighs more for the higher-density HFAs compared to the lower-density limestone. The gradation by volume is more representative of reality in cases like this. Some mixes designed for this project have gradations that fall outside the allowable range when analyzed by mass but pass when calculated by volume. For this reason, gradations were assessed by volume in this project. When there are only small differences in aggregate density, the gradation will look similar when viewed by volume or by mass. For reference, Section 2.1.1.1. of the 2024 TxDOT Standard Specifications for Construction recommends blending by volume when aggregate specific gravities differ by more than 0.300.

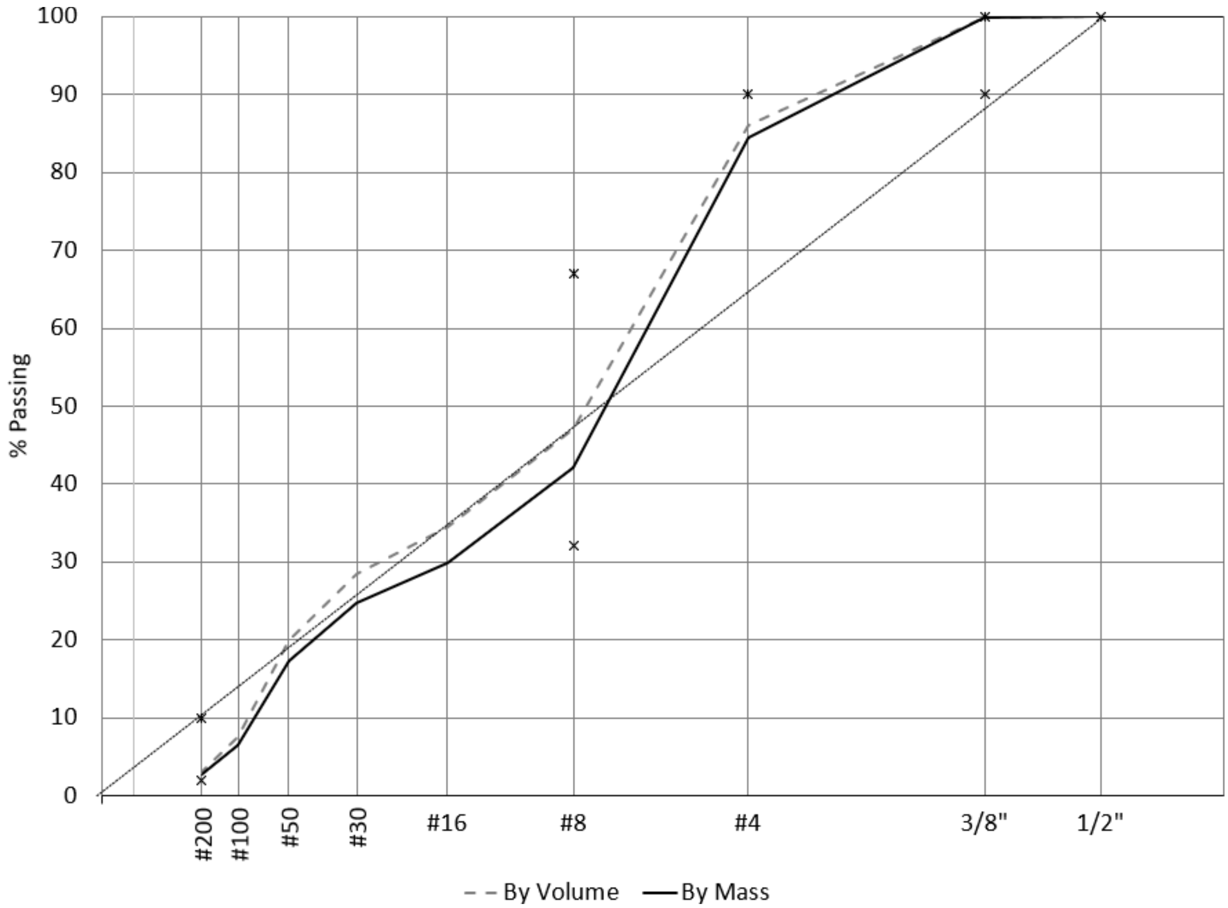

Figure 14: Blending by Volume vs. by Mass Example

3.4 Slab Preparation

Slabs were produced using two different slab compactors in this project. NCAT elected to upgrade the slab compactor while this project was ongoing. While not ideal, it was a necessary decision at the time. Slabs made using the bauxite and slag were compacted using a linear kneading compactor (shown in Figure 15) that measured 20" x 20" at varying thicknesses for CTM and DFT tests. Slabs made with the quartzite aggregate were compacted on an Instrotek Asphalt Rolling Compactor (A.R.C.) as shown in Figure 16, which produced slabs that measured 16" x 19". The FC-4.75 and FC-9.5 slabs were compacted to 1.5 inches thick, and the FC-5 slabs were compacted to 2 inches in thickness. A comparison of the slab sizes between the two compactors is shown in Figure 17.

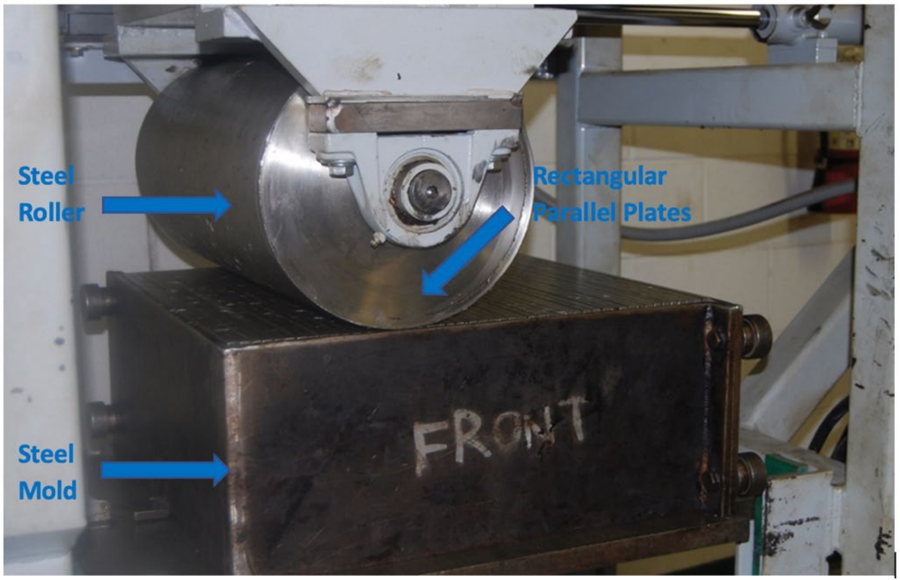

Figure 15: NCAT Linear Kneading Compactor

Figure 16: Instrotek A.R.C. Slab Compactor

Figure 17: Comparison of Slab Sizes between Compactor Types – (Left: A.R.C; Right: NCAT)

Preparation of the test slabs is a key component of the test protocol. The NCAT protocol for fabricating the slabs included preparing four mix batches, avoiding segregation while placing the mix in the heated slab mold, compacting the slab with a linear kneading compactor to a uniform density, and using the flat surface of the bottom of the slab for polishing and testing (the top of the slab was used for the slabs compacted using the A.R.C. compactor). The research team's experience of polishing and testing slabs for friction studies has shown that this test protocol creates repeatable results between two slabs.

3.5 Friction and Texture Testing

Friction was tested using the Dynamic Friction Tester (DFT), and texture was measured using the Circular Texture Meter (CTM). These are shown in Figures 18 and 19, respectively. The DFT was conducted in accordance with ASTM E1911, while the CTM was conducted in accordance with ASTM 2157. The DFT measures the friction coefficient of the asphalt slab by dropping rubber sliders attached to a rotating disk on the surface and measuring the force on the sliders at speeds from 80 km/h to 0. The coefficient is the frictional force divided by the weight of the carriage holding the disk. Friction coefficients from the DFT typically range from 0.20 to 0.50 for asphalt mixes. At least three replicate drops of the DFT wheel were applied for each test. The DFT records data in one km/h increments from 80 km/h to 10 km/hr. by default, the friction coefficients are reported at 20, 40, and 60 km/h. FDOT requested the DFT data at 64 km/hr because it is approximately 40 mph, which is the speed at which field friction testing is conducted in Florida.

DFT is a repeatable test, and NCAT typically assesses variability at the 40 km/h speed because it has been shown to have the best repeatability of the default speeds (Heitzman et al. 2019). The data were checked to ensure that the range of DFT results for each test were within 0.05. If the range was outside this threshold, additional drops were conducted. The results from the two slabs were deemed repeatable if the average results between the two slabs were within 0.05. If this was not the case, an additional slab was compacted and tested. Extra slabs were made for only two mixes during this project.

Regular replacement of the TWPD polishing tires and diligent monitoring of the wear of the DFT rubber pads are critical factors for testing repeatability. The rubber pads on the bottom of the DFT were frequently inspected in accordance with ASTM E1911 and were replaced when they exhibited excessive or uneven wear. The TWPD was developed at NCAT specifically to use the DFT and CTM for measuring the change in the surface after polishing. To obtain repeatable results, a template was built for the DFT and CTM to precisely place the test device over the polished path. Using these templates ensured the DFT and CTM results had the highest probability of being repeatable for numerous increments of polishing.

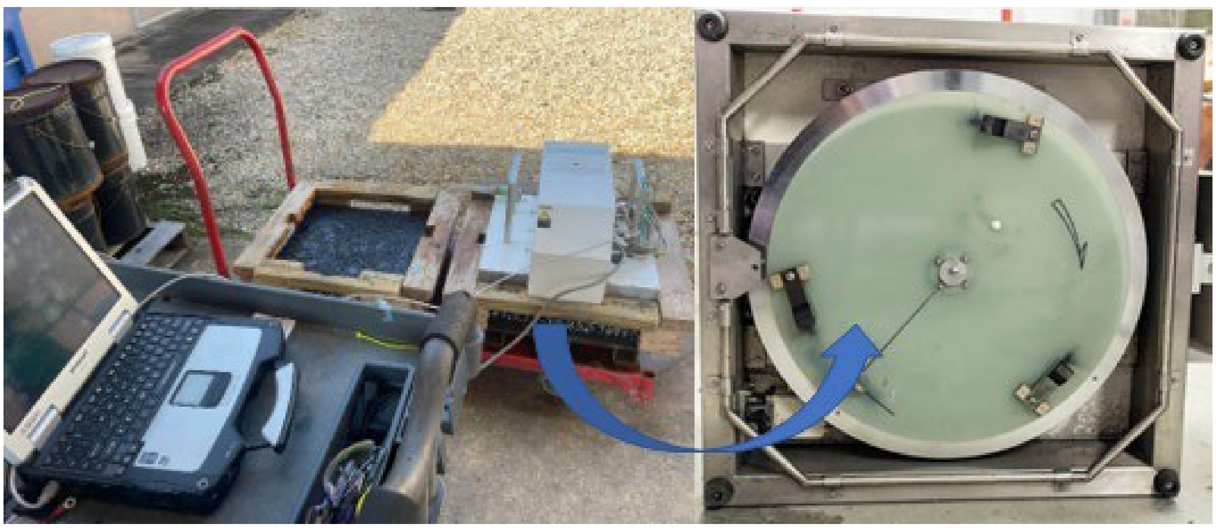

Figure 18: **Dynamic Friction Tester**

Figure 19: Circular Texture Meter

The CTM measured Mean Profile Depth (MPD) by measuring the profile of the testing surface using a laser and calculating the MPD. The circular track is split into eight segments and the MPD is reported for each of the eight segments. The average MPD is also reported for the entire surface.

3.6 Slab Polishing

Slabs were polished using three-wheel polisher devices (TWPD), shown in Figure 20, to remove the film of asphalt from the surface of the aggregates in the TWPD wheelpath and to polish the aggregate particles at the surface. The two TWPDs on the right of Figure 20 were used in this project. The TWPDs had a total weight of 148.5 lbs and rotated at 60 rpm. Water was continuously sprayed onto the surface during polishing to remove debris. DFT and CTM testing was conducted at 0, 5,000, 70,000, and 150,000 TWPD cycles. The wheels were allowed to sit on the slab after polishing for a minimum amount of time to avoid lengthy static loads, typically less than 3 hours. TWPD wheels were replaced when the treads became worn. The wheels were cleaned after every polishing session to remove rubber or asphalt binder from the tire treads. An example of a polished slab is shown in Figure 21.

Figure 20: NCAT Three-Wheel Polishing Devices

Figure 21: Slab after Polishing

DFT results typically increase from 0 to 5,000 cycles because the slick asphalt binder is removed from the service exposing the unpolished aggregate surfaces. From 5,000 cycles to 70,000 cycles the friction decreases due to aggregate polishing. Somewhere between 70,000 cycles and 150,000 cycles friction typically plateaus and at a minimum level and does not drop much further. The purpose of the HFAs was to increase the level of minimum friction. Previous studies at NCAT have demonstrated that the MPD of the slabs does not change much during polishing unless raveling occurs (Heitzman et al., 2019). Some of the limestone slabs in this study did exhibit raveling, and this behavior is clear from the MPD data from CTM testing.

The primary test result for this research project was the friction measured by the DFT. FDOT requested the DFT data at 64 km/hr (DFT(64)) because it is approximately 40 mph, which is the speed at which field friction testing is conducted in Florida. For this project, the DFT(64) measurements will be reported and analyzed. NCAT has successfully used the CTM on the NCAT Test Track to monitor changes in the surface macrotexture but has not observed similar changes in the surface macrotexture of test slabs using the accelerated polishing with the TWPD. The research team primarily used the CTM results to monitor any abnormal changes in the surface, particularly for the surface treatment slabs.

3.7 High Friction Chip Seal Preparation

The two HFCS slabs were produced after the rest of the testing plan was completed. FDOT elected to have the research team prepare two slabs of different aggregates as exploratory testing into the feasibility of creating and evaluating HFCS in the lab. Two HFAs were selected for this exploratory work: slag and calcined bauxite. The HFCS slabs required aggregates that met the HFST gradation band listed in AASHTO MP41-22 and fuel-resistant PG88-22 binder. The bauxite and slag aggregates were processed to meet the required gradation. The recommended aggregate spread rate was 14 to 18 lb/yd^2 and the recommended binder application rate was 0.30 to 0.38 gal/yd^2. Aggregate and binder were weighed to equal 18 lb/yd^2 and 0.38 gal/yd^2 to mimic the applications in New Jersey (Bennert, 2022). The aggregates were preheated and coated with 0.8% binder (Bennert et al., 2021)The asphalt binder was applied to dense-graded slabs quickly to avoid losing the necessary temperature and viscosity to spread the binder evenly. Aggregates were then poured onto the slabs and spread with a spatula. Finally, the aggregates were seated with a wooden board and pressure applied by the engineer. Although some material was in the preparation process, the final rates were within the desired ranges. However, after brooming the surfaces, the bauxite and slag slabs lost 15% and 40% of the aggregate, respectively. It is expected that this was due to the wooden board being a poor seating mechanism in lieu of the rubber wheel rollers used in the field. Nonetheless, this work was exploratory as this was one of the first attempts to produce HFCS in a laboratory setting. Figure 22 shows the steps of this process.

(a) (b) (c)

(d) (e) (f)

(g)

HFCS Lab Preparation Steps:

(a) Weight materials.

(b) Pre-coat aggregates with 0.8% binder.

(c) Apply hot binder as evenly as possible.

(d) Spread binder quickly using wide spatula.

(e) Pour aggregates evenly onto binder.

(f) Spread aggregates with spatula.

(g) Seat aggregates into binder film.

Figure 22: HFCS Lab Preparation Process

A few issues were noted during this process. First, binder application on the bauxite slab was not even due to the binder being poured more slowly than for the slag. The slab and binder film were reheated and spread but the PG88-22 binder did not spread well unless >340°F. Second, a better method of seating the aggregates into the binder is essential. Losing more than 15% of the material, and up to 40%, is not ideal for this treatment. This was confirmed by observing the material loss in the TWPD. Upon completion of polishing, the material in the wheel path of the bauxite was significantly more imbedded than outside the wheel path and there was a high degree of loss in both slabs, especially the slag which had almost all the material in the wheel path removed by the polishing wheels. This is shown below in Figure 23. Any future work involving laboratory preparation of HFCS will need to develop procedures to correct these issues.

Figure 23: Failed HFCS Slab with Slag Aggregate

4. TEST RESULTS AND DISCUSSIONS

This chapter presents a detailed summary of the mix designs and DFT and CTM results. The results of the HFCS slabs are also included. A summary of the best case effects of high friction aggregate on friction is presented at the end.

4.1 Mix Design Results

Three mix designs were provided by FDOT representing control mixes for FC-9.5, FC-4.75, and FC-5 mixes. The gradations and asphalt contents are shown in Table 7. HFAs were added at varying proportions (details shown in Appendix A) to the mixes and the gradations deviated from the control gradations. Instead of matching gradation to eliminate potential differences in texture between mixes, FDOT chose to demonstrate the feasibility of designing mixes to meet volumetric criteria. This required modifications to the gradations to incorporate nearly uniform-graded aggregates in the case of bauxite and well-graded slag.

Table 7: Summary of Control Mix Properties

Property	FC-4.75		FC-9.5		FC-5	
	LMS	GRN	LMS	GRN	LMS	GRN
19 mm (3/4”)	100	100	100	100	100	100
12.5 mm (1/2”)	100	100	100	100	91	97
9.5 mm (3/8”)	100	100	99	99	71	74
4.75 mm (#4)	88	90	78	74	24	24
2.36 mm (#8)	59	69	48	54	10	10
1.18 mm (#16)	44	48	39	42	7	7
0.60 mm (#30)	35	32	32	31	6	5
0.30 mm (#50)	25	20	23	20	4	3
0.15 mm (#100)	11	12	9	9	3	3
0.075 mm (#200)	6.3	7.8	3.2	5.3	2.0	2.4
N_{des}	65	65	75	75	N/A	N/A
AC%	6.8	6.6	6.5	5.7	6.9	6.2
G_{mm}	2.353	2.510	2.350	2.531	N/A	N/A
G_{sb}	2.512	2.708	2.484	2.737	N/A	N/A

A summary of the gradations of the limestone and granite HFA-modified mixes is shown in Tables 8-10. These tables are organized first by the base aggregates used in the design, with the granite designs in the upper half of the Table and the limestone in the lower half. The HFA used for each blend is labeled for each mix type. Except for the control mixes, the mixes are organized by proportion of HFA, with “M” representing the medium amount of HFA and “H” representing the high proportion. Note that the gradation by mass and by volume are shown for each blend. In some cases, the gradation by mass did not meet the specification when the gradation by volume did. The gradation by volume is the more true representation of particle distribution for these mixes. Blending aggregates with different densities by volume solves the problem of misleading gradations. This is an important factor to consider when blending aggregates of vastly different specific gravities. The specific mixture proportions, including the amount of high friction aggregate used, and volumetric properties for these designs are shown in Appendix A.

Table 8: FC-4.75 Mix Design Gradations

FC-4.75	FC-4.75 (Granite)									Specification Criteria	
	Control	Bauxite				Slag					
HF Agg Proportion	N/A	M		H		M		H		Min.	Max.
% Passing	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass		
3/4"	100	100	100	100	100	100	100	100	100		
1/2"	100	100	100	100	100	100	100	100	100	100	
3/8"	100	100	100	100	100	100	100	100	100	95	100
# 4	90	95	94	92	91	92	91	85	84	85	100
# 8	69	64	61	51	48	67	66	59	57		
# 16	48	46	44	37	34	48	47	45	44	30	60
# 30	32	33	32	28	26	34	33	35	33		
# 50	20	21	20	19	17	22	22	24	23		
#100	12	10	10	9	8	12	13	13	13		
#200	7.8	6.3	6.1	6.0	5.6	7.4	7.6	7.9	8.2	6	13
FC-4.75	FC-4.75 (Limestone)									Specification Criteria	
	Control	Bauxite				Slag					
HF Agg Proportion	N/A	M		H		M		H		Min.	Max.
% Passing	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass		
3/4"	100	100	100	100	100	100	100	100	100		
1/2"	100	100	100	100	100	100	100	100	100	100	
3/8"	100	100	100	100	100	100	100	100	100	95	100
# 4	88	91	91	92	91	87	86	85	84	85	100
# 8	59	58	55	56	51	59	58	60	57		
# 16	44	43	41	44	39	44	43	46	43	30	60
# 30	35	35	33	37	33	35	34	37	35		
# 50	25	25	23	27	24	25	24	27	26		
#100	11	11	11	12	10	12	12	14	14		
#200	6.3	6.3	5.9	6.0	5.3	6.2	6.5	7.1	7.6	6	13

Table 9: FC-9.5 Mix Design Gradations

FC-9.5	FC-9.5 (Granite)													Specification Criteria	
	Control	Bauxite				Slag				Quartzite					
HF Agg Proportion	N/A	M		H		M		H		M		H		Min.	Max.
% Passing	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass		
3/4"	100	100	100	100	100	100	100	100	100	100	100	100	100		
1/2"	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
3/8"	99	99	99	100	100	95	94	90	89	98	98	97	97	90	100
# 4	74	77	77	88	86	74	71	71	69	73	73	70	70		90
# 8	54	50	47	51	48	54	51	53	50	54	54	54	54	32	67
# 16	42	40	37	38	35	39	36	38	36	39	39	42	42		
# 30	31	30	29	29	27	27	26	26	25	28	28	31	31		
# 50	20	19	18	19	17	17	16	16	16	17	17	18	18		
#100	9	7	7	8	8	9	9	8	8	8	8	6	6		
#200	5.3	4.5	4.3	5.4	5.1	5.0	5.1	4.8	4.8	4.9	4.9	3.3	3.3	2	10
FC-9.5	FC-9.5 (Limestone)													Specification Criteria	
	Control	Bauxite				Slag				Quartzite					
HF Agg Proportion	N/A	M		H		M		H		M		H		Min.	Max.
% Passing	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass		
3/4"	100	100	100	100	100	100	100	100	100	100	100	100	100		
1/2"	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
3/8"	99	99	99	100	100	95	93	90	88	98	98	96	96	90	100
# 4	78	79	79	86	84	74	72	69	65	70	69	65	64		90
# 8	48	48	46	47	42	53	51	52	48	48	48	49	47	32	67
# 16	39	38	36	34	30	39	38	40	37	37	37	37	36		
# 30	32	32	30	28	25	31	30	31	29	29	29	29	28		
# 50	23	22	21	20	17	21	20	22	21	20	20	20	20		
#100	9	8	8	8	7	9	9	10	9	8	8	8	8		
#200	3.2	3.0	2.8	3.2	2.8	3.8	3.9	4.5	4.5	3.8	3.8	3.9	3.8	2	10

Table 10: FC-5 Mix Design Gradations

FC-5	FC-5 (Granite)									Specification	
	Control	Slag				Quartzite				Criteria	
HF Agg Proportion	N/A	M		H		M		H		Min.	Max.
% Passing	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass		
3/4"	100	100	100	100	100	100	100	100	100	100	
1/2"	97	90	89	85	84	96	96	96	96	85	100
3/8"	74	71	70	69	68	74	74	73	73	55	75
# 4	24	25	24	25	23	24	24	22	22	15	25
# 8	10	10	9	9	8	10	10	9	9	5	10
# 16	7	6	6	5	5	6	6	6	6		
# 30	5	4	4	4	4	4	4	4	4		
# 50	3	3	3	3	3	3	3	3	3		
#100	3	2	2	2	2	3	2	3	2		
#200	2.4	2.0	1.8	2.0	1.7	2.0	1.9	2.0	1.9	2	5
FC-5	FC-5 (Limestone)									Specification	
	Control	Slag				Quartzite				Criteria	
HF Agg Proportion	N/A	M		H		M		H		Min.	Max.
% Passing	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass	Vol.	Mass		
3/4"	100	100	99	100	100	100	100	100	100	100	
1/2"	91	85	83	85	83	91	91	91	92	85	100
3/8"	71	66	63	72	69	72	73	72	73	55	75
# 4	24	25	23	25	23	24	24	20	20	15	25
# 8	10	10	9	10	9	9	9	9	9	5	10
# 16	7	8	6	8	8	7	7	7	7		
# 30	6	7	5	7	6	6	6	6	6		
# 50	4	5	4	5	5	5	5	5	4		
#100	3	3	2	3	3	3	3	3	3		
#200	2.0	2.1	1.0	2.1	1.9	2.2	2.2	2.1	2.0	2	5

4.2 DFT Results

Figures 24 through 29 display the average DFT results for the mixes designed in this study. Note that DFT results were only averaged if the difference between two slabs was 0.05 or less, and if this was not the case, a third slab was prepared and tested. The DFT values are reported at 64 km/hr, per FDOT's request, at 0, 5,000, 70,000, and 150,000 TWPD cycles. For the cycles in which measurements were taken in this study, laboratory polishing and friction testing of slabs produces peak friction values at 5,000 TWPD cycles. The values typically drop from 5,000 cycles to 70,000 cycles rather noticeably. From 70,000 to 150,000 cycles, the friction data typically remain flat or have a very slight decline. It is likely that minimum friction is reached somewhere between 70,000 and 150,000 cycles, on average, but these intermediate points were not tested. For these reasons, the mixes are compared primarily according to their results after 150,000 cycles of polishing. DFT values at 0 cycles are practically meaningless due to the binder film that is on the aggregates before polishing.

Figure 24 and Figure 25 show the average DFT results for the FC-4.75 mixes. The control mix for the granite mixes was as good or better than the bauxite-modified mixes and the slag-modified mix at a medium proportion. Only the high proportion of slag-modified granite mix outperformed the control mix. This was unexpected and indicated that the control mix may have better friction properties than previously expected. The granite-bauxite mixes were the first mixes developed in this study. The results puzzled the research team, and much time was spent attempting to better understand why adding a known HFA as bauxite could reduce the friction values. Ultimately, since the study did not aim to examine the effects of different materials on friction mix design, this question remained unanswered. The research team was unable to determine why the bauxite did not improve the friction of this mix. One potential explanation is that there was not enough differential polishing between the two aggregate types on the surface of the mix.. Aggregates have been shown to have improved friction when they have a composition of hard and soft minerals, compared to aggregates with minerals of the same hardness (Dahir and Mullen, 1971). It is hypothesized that this phenomenon may be occurring on a larger scale on the mix surface. However, it must be noted that these aggregates were not tested and assigned a hardness value. Further research is necessary to better understand the effects of aggregate material properties on mix friction performance.

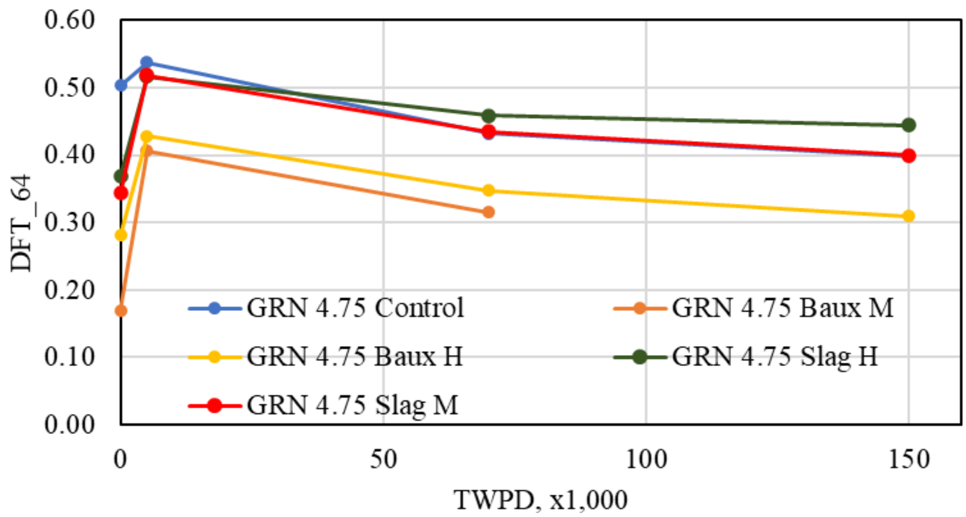

Figure 24: DFT Results – GRN FC-4.75 Mixes

The HFAs had a tremendous impact on the DFT results of the limestone slabs. Both slag and bauxite increased the friction by at least 10 points, with the bauxite being the largest increase of approximately 15 points. These results seem to agree with the hypothesis regarding blending materials of different hardness.

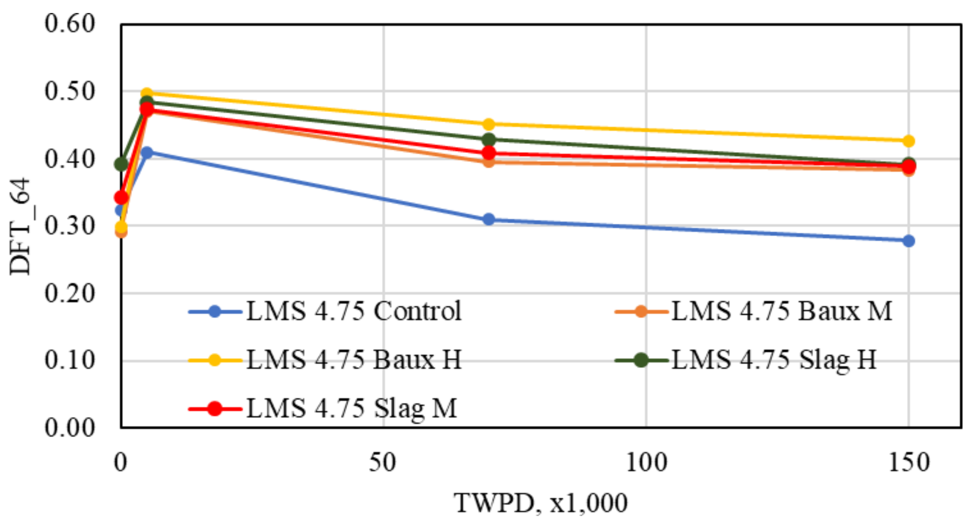

Figure 25: DFT Results – LMS FC-4.75 Mixes

Figure 26 shows the results of the granite FC-9.5 mixes. Similar to the FC-4.75 mixes, the control mix was not the worst performer. However, in this case the slag HFA improved friction while the bauxite HFA had a minimal effect. Adding quartzite to the mix only worsened the results. These results were unexpected but confirmed through testing replicate slabs.

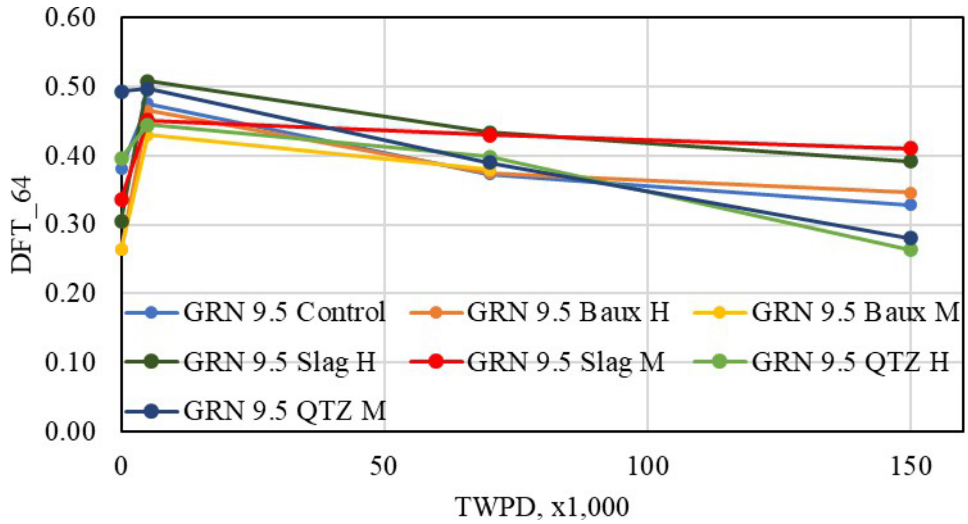

Figure 26: DFT Results – GRN FC-9.5 Mixes

The results of the limestone mixes are shown below in Figure 27. The control mix and the quartzite mixes were the bottom three performers, with DFT results similar to one another. The mix with the high proportion of bauxite demonstrated almost a 50% increase in friction compared to the limestone control. The medium bauxite mix and high slag mix had similar improvements compared to the control mix, and the medium-slag mix exhibited a 12% improvement in friction results.

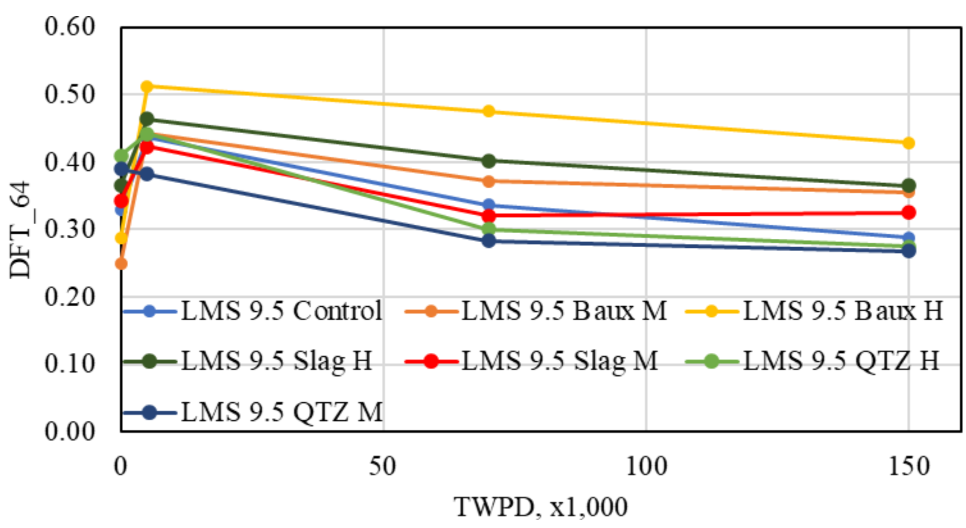

Figure 27: DFT Results – LMS FC-9.5 Mixes

Slag and quartzite were selected for usage in the FC-5 mixes. The bauxite was not included in the FC-5 mixes due to its gradation not fitting within the required gradation for FC-5 mixes. Figure 28 shows the slag-modified granite mixes, which exhibited almost equal improvement over the control mix of approximately 15%. The quartzite aggregate (also shown in Figure 28) did not have a large effect on the friction compared to the control mix after 150,000 cycles, despite having the highest results at 70,000 cycles.

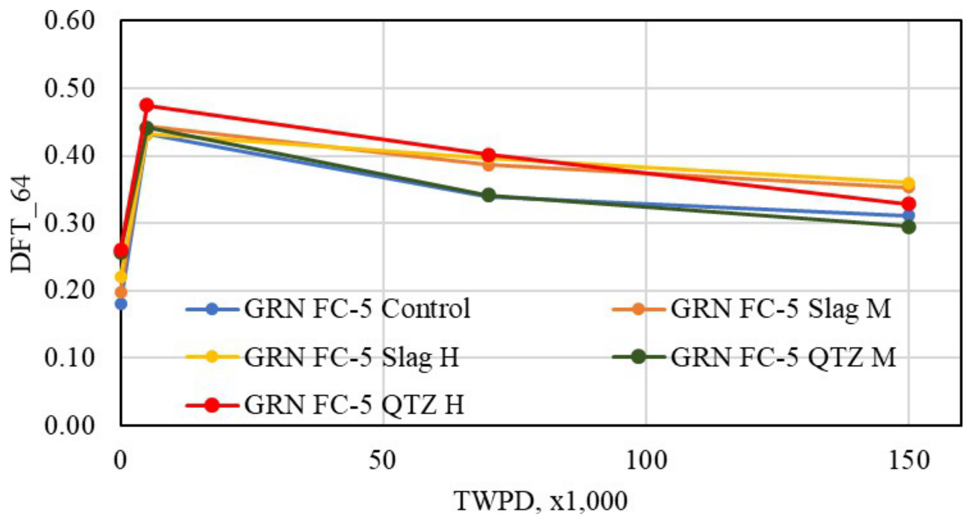

Figure 28: DFT Results – GRN FC-5 Mixes

Figure 29 shows the results of the limestone FC-5 mixes. Both quartzite mixes significantly underperformed compared to the control, and the results between the two quartzite slab replicates were consistent. The research team could not identify a specific reason for the poor performance of the quartzite aggregate. However, the slag mixes yielded large improvements of 23% and 36% for the medium- and high-proportion slag mixes, respectively.

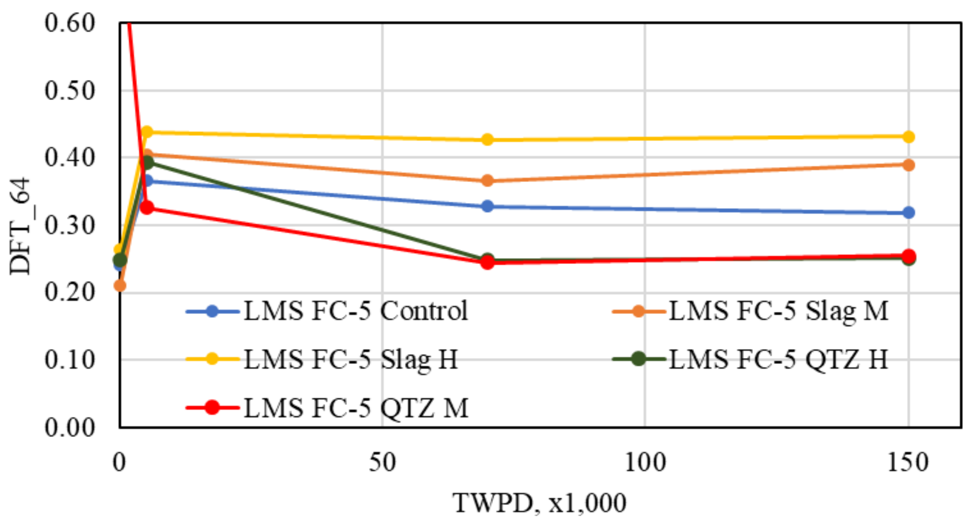

Figure 29: DFT Results – LMS FC-5 Mixes

Complete tables containing the summarized DFT results at each TWPD cycle for each mix are shown in Table 11 (Granite) and Table 12 (Limestone). No data were recorded for the Granite-FC-9.5-Bauxite-Medium mix because the research team decided to stop investigating the cause of the low DFT results when blending bauxite and granite after over a month of testing.

Table 11: All DFT_64 Results for Granite Mixes

Mix Size	Alternative Aggregate	HF Volume	TWPD Cycles (x 1,000)			
			0	5K	70K	150K
4.75	Control	None	0.50	0.54	0.43	0.40
	Bauxite	Medium	0.17	0.41	0.32	0.38
		High	0.28	0.43	0.35	0.31
	Slag	Medium	0.34	0.52	0.44	0.40
		High	0.37	0.52	0.46	0.45
9.5	Control	None	0.38	0.48	0.37	0.33
	Bauxite	Medium	0.26	0.43	0.38	N/A
		High	0.26	0.47	0.38	0.35
	Slag	Medium	0.34	0.45	0.43	0.41
		High	0.31	0.51	0.43	0.39
	Quartzite	Medium	0.49	0.50	0.39	0.28
		High	0.40	0.45	0.40	0.26
FC-5	Control	None	0.18	0.43	0.34	0.31
	Slag	Medium	0.20	0.44	0.39	0.35
		High	0.22	0.43	0.40	0.36
	Quartzite	Medium	0.26	0.44	0.34	0.30
		High	0.26	0.48	0.40	0.33

Table 12: All DFT_64 Results for Limestone Mixes

Mix Size	Alternative Aggregate	HF Volume	TWPD Cycles (x 1,000)			
			0	5K	70K	150K
4.75	Control	None	0.32	0.41	0.31	0.28
	Bauxite	High	0.30	0.50	0.45	0.43
		Medium	0.29	0.47	0.40	0.38
	Slag	High	0.39	0.48	0.43	0.39
		Medium	0.34	0.47	0.41	0.39
9.5	Control	None	0.33	0.44	0.34	0.29
	Bauxite	High	0.29	0.51	0.48	0.43
		Medium	0.25	0.44	0.37	0.36
	Slag	High	0.37	0.46	0.40	0.37
		Medium	0.34	0.42	0.32	0.33
	Quartzite	High	0.41	0.44	0.30	0.28
		Medium	0.39	0.38	0.28	0.27
FC-5	Control	None	0.24	0.37	0.33	0.32
	Slag	High	0.26	0.44	0.43	0.43
		Medium	0.21	0.41	0.37	0.39
	Quartzite	High	0.25	0.39	0.25	0.25
		Medium	0.74	0.33	0.25	0.26

Figures 30, 31, and 32 show the impact on the DFT results from a 10% increase in HFA (by volume) from zero. The quartzite results are not shown and neither are the granite results because the HFA did not positively affect the mix friction. With the limited results shown in this study, it appears that a small addition of some HFAs in the limestone mixes with no other alternative aggregates results in improved friction. This represents the potential to improve the friction of typical FDOT mixes. As calculated from the slope of the lines in the figures below, the degree of improvement from adding the first 10% HFA to the mixes varied between a minimum of 0.017 DFT units for the LMS FC-9.5 mix with limestone and slag and a maximum of 0.045 DFT units for the FC-4.75 limestone mix with bauxite. Adding HFA beyond 25% had varying effects. For example, the rate of friction improvement disappeared after adding more than 25% slag to the LMS 4.75 mix. It is possible that at approximately 25% HFA, the influence of the slag HFA was maximized. These figures demonstrate the feasibility of improving the friction in the limestone mixes. Note that with the exception of the slag in the FC-9.5 limestone mix, the average DFT increase for the first 10% HFA (by volume) is 0.03 to 0.04 units. Referring back to Figure 9 and Figure 11, a change in the friction level of 4 units would be expected to result in a crash reduction of over 10%. Thus, every 1% HFA by volume is estimated to reduce crashes by approximately 1% without considering other pavement factors.

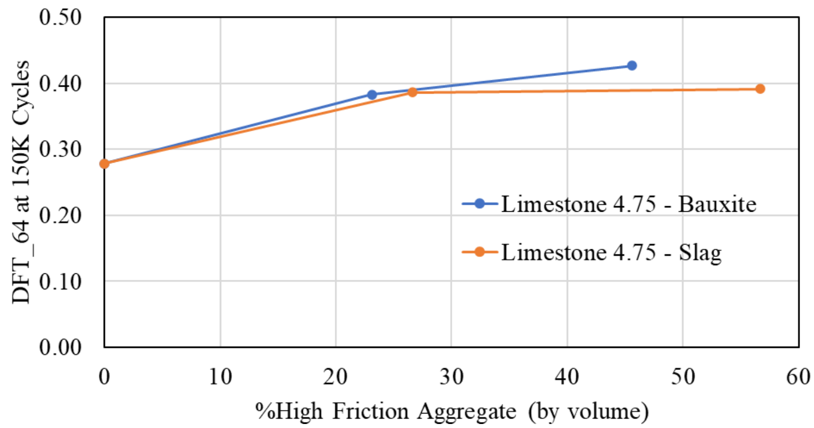

Figure 30: DFT_64 vs. %HFA (Limestone FC-4.75 Only)

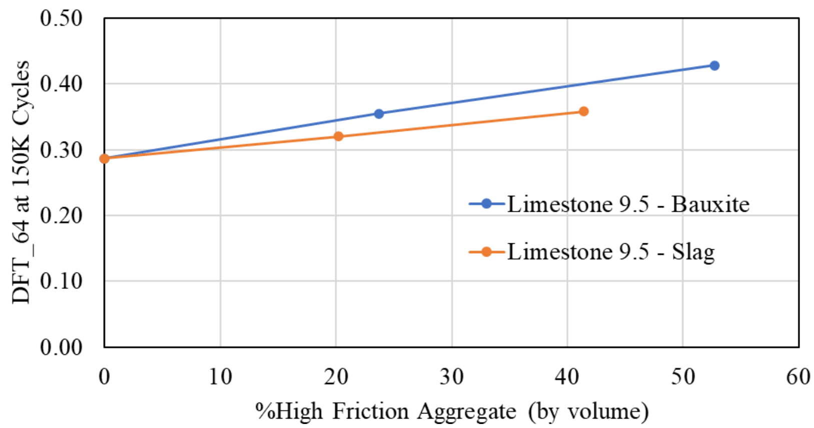

Figure 31: DFT_64 vs. %HFA (Limestone FC-9.5 Only)

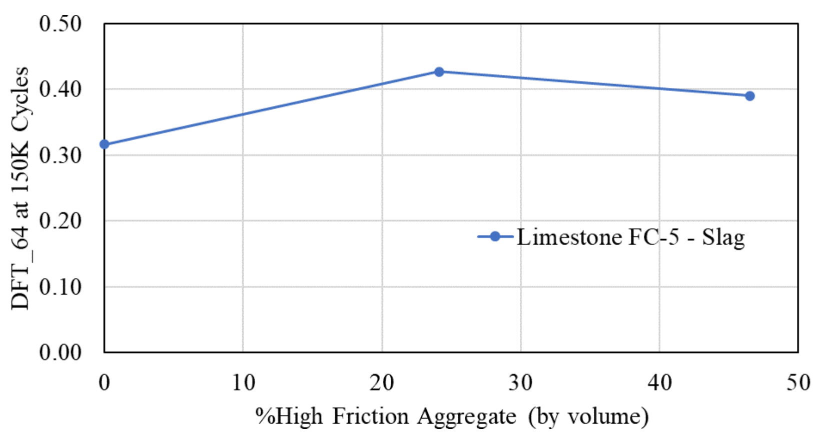

Figure 32: DFT_64 vs. %HFA (Limestone FC-5 Only)

4.3 CTM Results

This section contains the mean profile depth (MPD) results from CTM testing of the slabs after each polishing cycle. It has been demonstrated that the TWPD can simulate the mechanism of aggregate polishing and changing friction. However, it does not appear that the TWPD can simulate the mechanisms that create texture change in the field. MPD does not typically change with polishing in the TWPD due to the lack of the impacts from long-term environmental aging. When MPD changes do occur, it is typically due to raveling of the slabs. This happened on a few of the limestone mixes in this project, and examples are provided in this section. Finally, other than ranking the mix types appropriately and to verify raveling, the MPD was not used to assess the quality of the mixes in this study.

Figure 33 and Figure 34 show the mean profile depth of the granite and limestone FC-4.75 mixes, respectively. For the granite mixes the MPD results were all under 0.5 mm for the entire duration of polishing. No major profile changes were noted except for in the GRN 4.75 Bauxite High mixture. However, the profile results all remained reasonably in the expected range given the fine gradation.

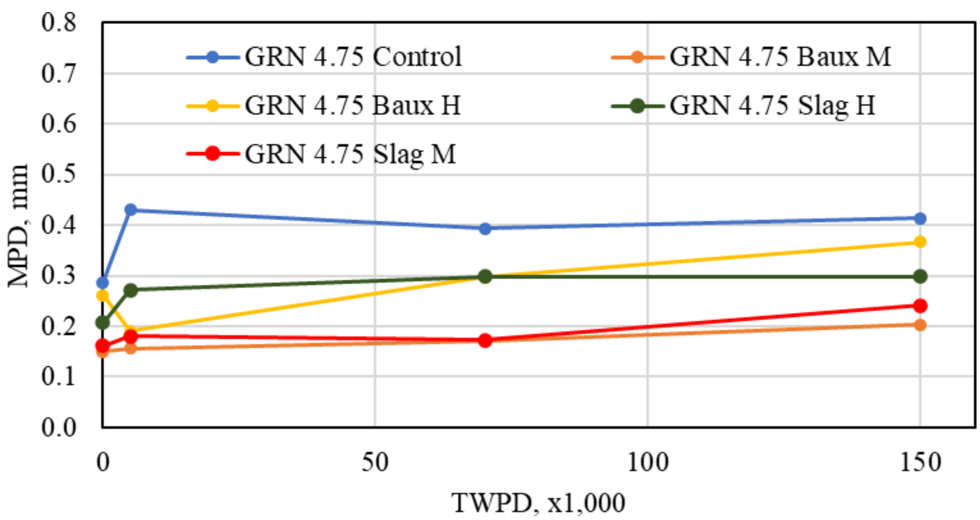

Figure 33: CTM Results – GRN FC-4.75 Mixes

Figure 34 shows the results of the FC-4.75 limestone mixes. Note the sharp increase in MPD from zero cycles to 5,000 cycles. This is an indicator of raveling. A photo of a raveled slab of the limestone FC-4.75 control mix after 5,000 cycles is shown in Figure 35. Note that removal of the fine aggregate from the polished wheelpath. This caused the profile depths to increase in the polished area. It is assumed that the limestone mixes were too dry or had too much binder absorption and these may have been the reason for the early raveling under the TWPD wheels.

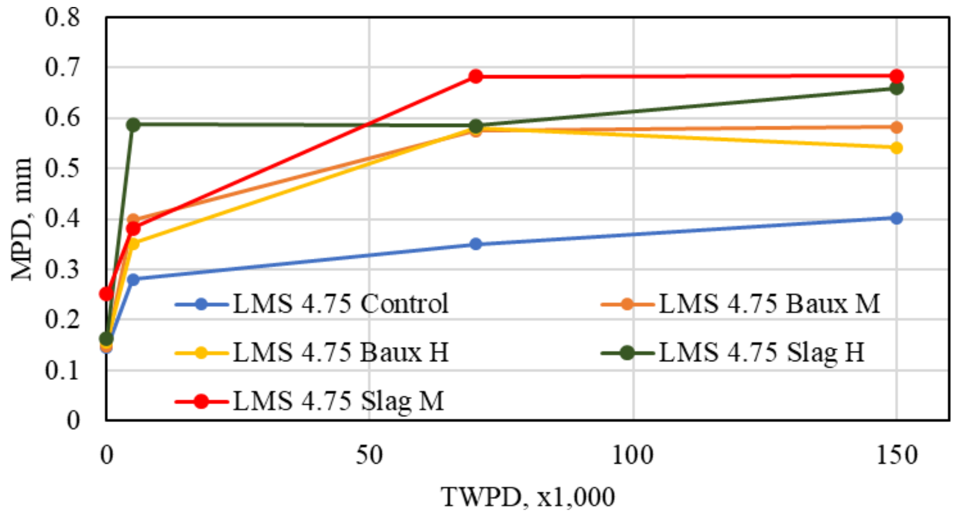

Figure 34: CTM Results – LMS FC-4.75 Mixes

Figure 35: Initial Raveling of LMS FC-4.75 Slab at 5,000 TWPD Cycles

Figure 36 and Figure 37 show the results of the granite FC-9.5 designs and the limestone FC-9.5 designs, respectively. The granite FC-9.5 designs had lower profile measurements than the FC-4.75 mixes, which is not common. Both sets of mix types were designed to be fine-graded, which contributes to lower texture and MPD. However, it was not expected that the FC-9.5 would have lower MPD results than the FC-4.75 mixes. Almost all of the limestone FC-9.5 mixes demonstrated early raveling from 0 to 5,000 CWPD cycles. However, the degree of raveling was not uniform across all slabs. The limestone FC-9.5 bauxite-high slab experienced a dramatic increase in MPD from 5,000 to 70,000 cycles and is shown after 70,000 cycles in Figure 38. In general, the FC-9.5 MPD values for both base aggregates were lower than expected. However, since the DFT is relatively insensitive to MPD, these values were not expected to impact the friction results drastically.

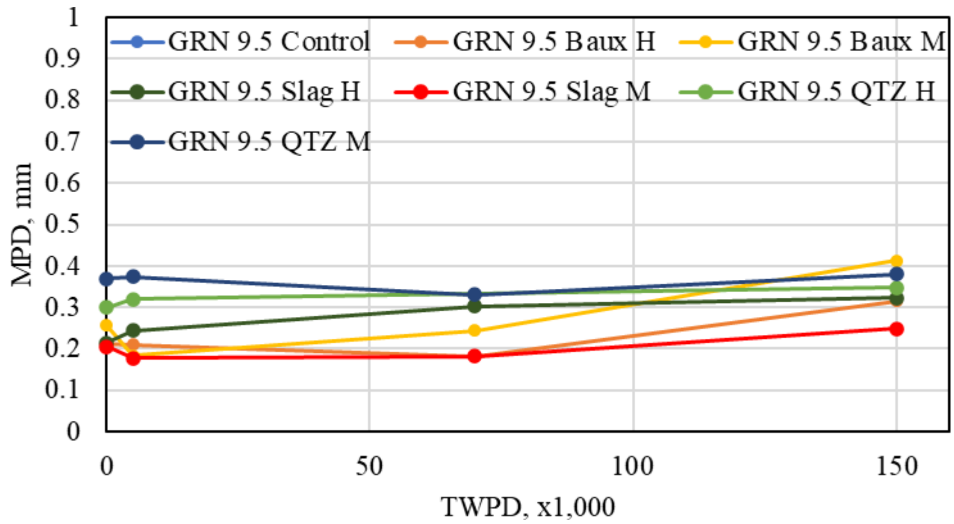

Figure 36: CTM Results – GRN FC-9.5 Mixes

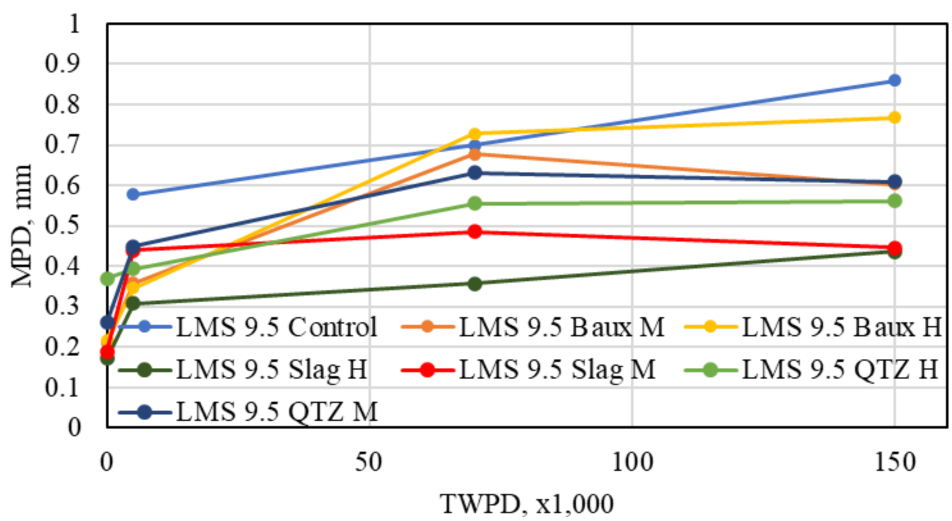

Figure 37: CTM Results – LMS FC-9.5 Mixes

Figure 38: Raveling of LMS FC-9.5 Bauxite (High) Slab

Finally, the FC-5 results for the granite and limestone mixes are shown in Figure 39 and Figure 40, respectively. Note the significantly higher MPD of the open-graded mixes compared to the smaller NMAS and finer dense-graded mixes. The MPD of the FC-5 mixes was generally consistent throughout the TWPD cycles for both aggregate types. It is assumed that the MPD decreased from 0 to 5,000 cycles on some of the FC-5 mixes because either surface binder was pushed into the open voids or the wheelpath was further densified under TWPD traffic. Finally, the average results for the MPD of each blend are summarized in Table 13 for the granite mixes and Table 14 for the limestone. Note that there were a few data recording errors that preventing the MPD from accurately being reported. These instances are denoted with an "N/A" in the Tables below.

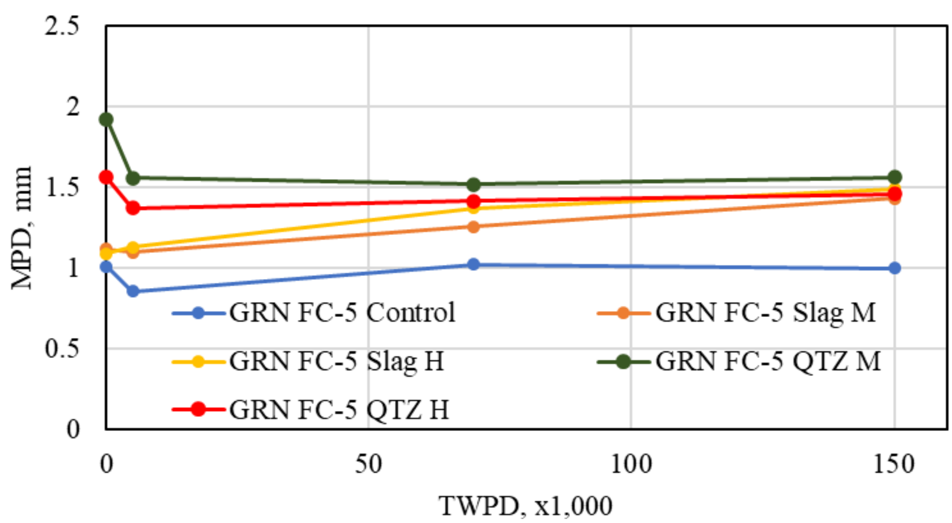

Figure 39: CTM Results – GRN FC-5 Mixes

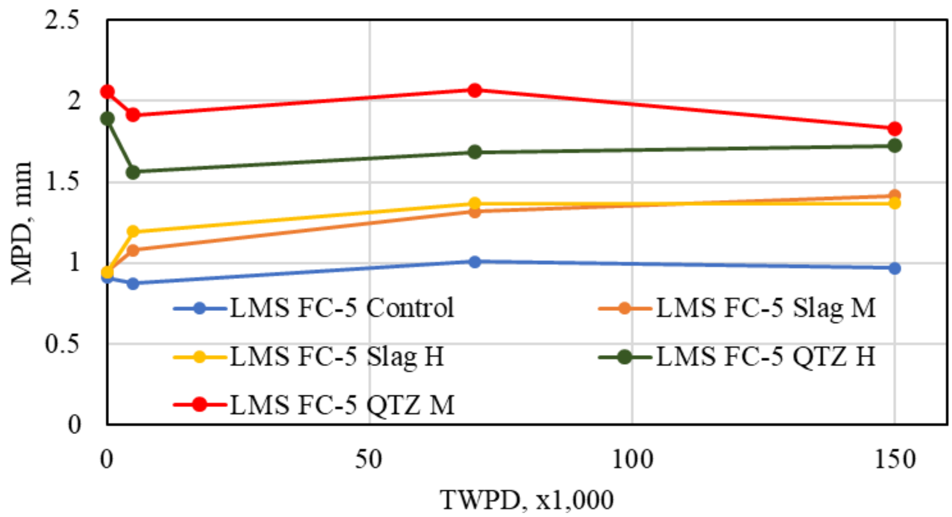

Figure 40: CTM Results – LMS FC-5 Mixes

Table 13: Summary of Granite MPD Results

Mix Size	Alternative Aggregate	HF Volume	TWPD Cycles (x 1,000)			
			0	**5K**	**70K**	**150K**
4.75	**Control**	None	0.29	0.43	0.39	0.41
	Bauxite	Medium	0.26	0.19	0.30	0.37
		High	0.15	0.16	0.17	0.20
	Slag	Medium	0.21	0.27	0.30	0.30
		High	0.16	0.18	0.17	0.24
9.5	**Control**	None	N/A	0.18	0.19	N/A
	Bauxite	Medium	0.21	0.21	0.18	0.32
		High	0.26	0.18	0.24	0.41
	Slag	Medium	0.22	0.24	0.30	0.32
		High	0.21	0.18	0.18	0.25
	Quartzite	Medium	0.30	0.32	N/A	0.35
		High	0.37	0.37	0.33	0.38
FC-5	**Control**	None	1.01	0.86	1.02	1.00
	Slag	Medium	1.09	1.13	1.37	1.49
		High	1.12	1.10	1.26	1.43
	Quartzite	Medium	1.56	1.37	1.41	1.46
		High	1.92	1.56	1.52	1.56

Table 14: Summary of Limestone MPD Results

Mix Size	Alternative Aggregate	HF Volume	TWPD Cycles (x 1,000)			
			0	5K	70K	150K
4.75	Control	None	0.15	0.28	0.35	0.40
	Bauxite	High	0.16	0.35	0.58	0.54
		Medium	0.15	0.40	0.58	0.58
	Slag	High	0.16	0.59	0.59	0.66
		Medium	0.25	0.38	0.68	0.68
9.5	Control	None	N/A	0.58	0.70	0.86
	Bauxite	High	0.22	0.35	0.73	0.77
		Medium	0.21	0.36	0.68	0.60
	Slag	High	0.17	0.31	0.36	0.44
		Medium	0.19	0.44	0.49	0.45
	Quartzite	High	0.37	0.39	0.56	0.56
		Medium	0.26	0.45	0.63	0.61
FC-5	Control	None	0.91	0.87	1.01	0.97
	Slag	High	0.94	1.19	1.37	1.37
		Medium	0.95	1.08	1.32	1.42
	Quartzite	High	1.89	1.56	1.69	1.73
		Medium	2.06	1.92	2.07	1.83

4.4 High Friction Chip Seal Results

The testing plan for the HFCS slabs was the same for the other slabs in this study. However, the research team was uncertain if the chip seal would remain intact during polishing. Testing at 0 cycles for both slabs yielded expecte results. The slag HFCS slab had an MPD of 2.25 mm and a DFT_64 of 0.80, while the bauxite HFCS had an MPD of 2.38 mm and a DFT_64 of 0.70. However, after only 5,000 cycles in the polisher almost all the aggregate had been removed from the slag slab and by 70,000 cycles the elevation difference between the wheelpath and outside the wheelpath was so great (shown in Figure 41) that the DFT pads could not make contact with the wheelpath and recorded a DFT value of 0.02. Polishing was ceased on the slag slab at this point.

The bauxite slab also had significant material loss but not as bad as the slag. Ultimately, the bauxite aggregate was seated better than the slag aggregate during sample preparation. However, because the binder was not applied as evenly for the bauxite, the surface was rougher than the slag slab. This is shown in Figure 42. Due to this roughness, the polishing was terminated at 130,000 cycles because the TWPD began to rock back and forth. To prevent damage, the TWPD should not be used to polish uneven surfaces.

Figure 41: Loss of Aggregate in Wheelpath of Slag HFCS


Figure 42: Roughness of the Bauxite HFCS Slab

A summary of the reliable portion of the data that was collected for the HFCSs is provided in Table 15 and the MPD data are shown in Figure 43. These data should not be used for any application except to demonstrate the failure of this particular attempt at producing HFCS in a lab. The experience and results were shared with Tom Bennert, who first proposed the HFCS, and he commented that future applications should use a rubber mat over the top of the chip seal and roll it with a landscape roller (Bennert, personal communication, May 2, 2024).

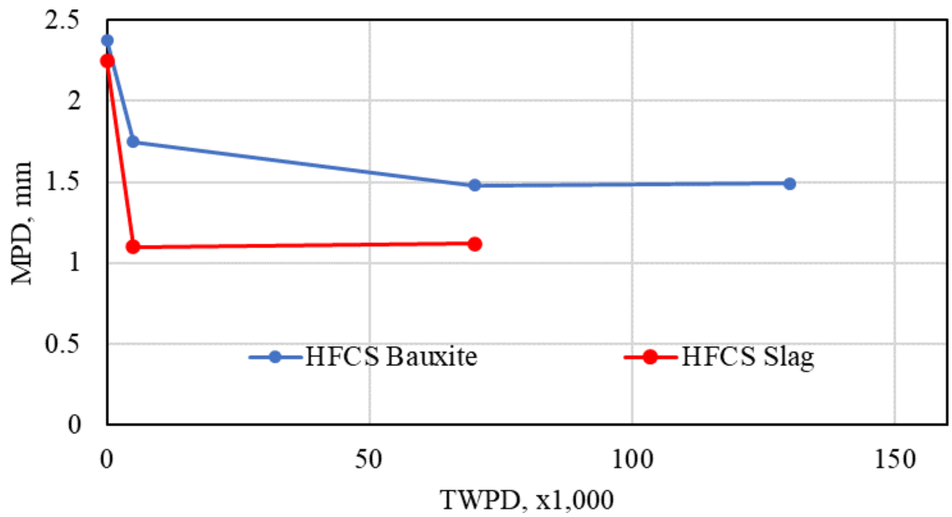

Figure 43: HFCS MPD Results

Table 15: HFCS DFT and CTM Results

TWPD Cycle	Bauxite		Slag	
	DFT	CTM	DFT	CTM
0	0.70	2.38	0.80	2.25
5,000	N/A	1.75	N/A	1.10
70,000	N/A	1.48	N/A	1.12
130,000	N/A	N/A	N/A	N/A

5. COST-BENEFIT ANALYSIS

This section includes the results of the cost-benefit (CB) analysis conducted using the results from the previous section. Unit cost values include materials, production, and placement of each study surface as well as related cost associated with preparing the existing asphalt surface, such as milling. These values were provided by FDOT and are representative of recent individual projects in Florida and statewide annual data. The unit cost is adjusted to better reflect small construction projects (typical for projects addressing high crash locations). The unit cost does not include other related construction costs (such as mobilization and traffic control). Expected crash rate reductions relative to different friction levels also are included in this section to estimate the relative value of these cheaper alternative friction mixtures compared to HFST.

5.1 Basic Parameters for Asphalt Mixes

Material costs were a part of the awarded bid unit cost provided by the agency. Mix production and placement were also part of that unit cost and this analysis assumes mix production and placement is reasonably the same for all asphalt mixes, therefore the primary change in awarded bid unit cost is associated with material cost. For purposes of the CB analysis, the material cost is assumed to be 50% of the awarded bid unit cost and the production and placement costs were assumed to also be 50% of the bid unit cost. The production and placement costs were not affected by the alternative aggregate usage. The cost of the alternative asphalt friction mixes were adjusted to account for the cost of the selected friction aggregate products (calcined bauxite at $700/ton, quartzite at $50/ton and slag at $25/ton). The material costs were adjusted to account for amount of friction aggregate and then combined with the production and placement to establish an estimated awarded bid unit cost. For example, a standard asphalt friction unit cost of $200/ton in-place is estimated to be $100/ton for the asphalt mixture material and $100/ton for the production and placement. The adjusted material cost for 50% calcined bauxite ($700/ton) in the mixture is $400/ton (50% of $100 + 50% of $700). The total bid unit cost is $500/ton ($400/ton for material plus $100/ton for production and placement). This is a general approximation of the adjusted unit cost and does not breakout the cost of the asphalt binder in the mixture. By treating the cost estimates in this manner, the rankings of the products are not expected to change if the cost of the materials were to be a different proportion of the bid unit cost.

Additional data was obtained from FDOT to determine the impact of small projects on the awarded bid unit costs. The posted unit cost commonly used is the annual weighted average awarded unit cost that takes into account the size of the project. This value is heavily biased towards the projects with higher quantity. A comparison of the actual awarded bid unit costs of large quantity projects versus small quantity projects noted that there was an increase in awarded bid unit cost for projects with very small quantity.

For this study, a small quantity project is defined as 1.0 lane-mile of paving to represent the length of a short safety project where HFST might be applied. The milling quantity is based on square yards and there are different bid items for each depth of milling. The asphalt paving bid item is based on tons of asphalt mixture placed and the quantity for a small project is determined using the typical paving thickness for the identified asphalt mixture and a constant of 0.055 tons per square yard for 1-inch thickness. The small quantity unit cost is taken from a regression equation applied to approximately one year of awarded bid prices for each bid item. In general, the small quantity project bid price is 50% higher than the annual weighted average awarded unit cost. Table 16 is a summary of this analysis and the impact on unit cost for items such as milling, Superpave asphalt mix, and open-graded FC-5 mix.

Table 16: Impact of Small Project Quantity on Unit Cost

SMALL QUANTITY PROJECT (1.0 lane-miles)	Overlay Thickness	Quantity	Units	Weighted Avg. Unit Cost	Small Quantity Unit Cost	Percent Increase
Milling (1.5-in)		7000	yd^2	$ 3.75	$ 6.25	69%
Milling (1.0-in)		7000	yd^2	$2.88	$ 4.87	67%
Milling (0.75-in)		7000	yd^2	$ 3.80	$ 4.54	19%
SP Concr., Traf C	1.5-in	577.5	TN	$ 150.69	$ 221.16	47%
SP Concr, Traf C, PG 76	1.5-in	577.5	TN	$ 161.00	$ 257.92	60%
AC Friction, FC-5, PG 76	0.75-in	288.75	TN	$218.43	$ 335.28	53%
AC Friction, FC-9.5, PG 76	1.0-in	385	TN	$ 200.98	$ 284.39	42%
AC Friction, FC-12.5, PG 76	1.5-in	577.5	TN	$178.69	$ 260.24	46%

Table 17 lists the unit cost for each friction surface. The mixes are designated using abbreviated names. For example, the (G)ranite FC-(9.5) (B)auxite (H)igh proportion mix is denoted as G9.5BH. The slag mixes are marked with an “S” and the quartzite mixes use a “Q”. Mixes marked as “C” denote the three control mixes used as a baseline for the study. The small quantity costs for the asphalt friction surfaces shown below represent the bid price per ton adjusted for the cost of the HFA material and for a small 1.0 lane-mile quantity. Both the granite and limestone friction mixes use the same bid items for each mix type. The unit cost of a FC-4.75 was projected from the FC-9.5 unit cost with a higher asphalt binder. The project unit cost combines the cost of surface milling and the asphalt friction surface converted to square yards. The milling cost is specific for the required depth of milling (shown in Table 16) and is directly related to the asphalt overly thickness. All asphalt mixtures were computed to a square yards basis by applying a constant of 0.055 tons of mixture per square yard for 1-inch compacted thickness. This equates to an average density of 147 pcf. The project unit cost for HFST includes milling and an asphalt surface under the HFST.

Finally, for this study, the expected in-service life for all asphalt mixes is 15 years. The in-service life does not account for inadequate design, non-complying materials, or poor construction practices.

Table 17: Project Paving Unit Cost Converted to Square Yards

Item	Description	Sm.Quant Unit Cost	Unit	Depth	Unit Cost	Unit
HFST	High Friction Surface Treatment (HFST)	$53.00	yd^2	n/a	$80.50	yd^2
Standard asphalt friction surfaces *(2)*						
	ASPH CONC FC, TRAF C, FC-9.5, PG76-22	$284.39	TON	1.0-in	$20.51	yd^2
	ASPH CONC FC, TRAF C, FC-4.75, PG76-22	$307.74	TON	0.75-in	$17.23	yd^2
	ASPH CONC FC, INC BIT, FC-5, PG76-22	$335.23	TON	0.75-in	$18.36	yd^2
Alternative asphalt friction surfaces *(2)*						
G95BH	Granite 9.5, high bauxite	$711.02	TON	1.0-in	$43.98	yd^2
G95BM	Granite 9.5, medium bauxite	$525.79	TON	1.0-in	$33.79	yd^2
G475BH	Granite 4.75, high bauxite	$743.71	TON	0.75-in	$35.21	yd^2
G475BM	Granite 4.75, medium bauxite	$551.88	TON	0.75-in	$27.30	yd^2
G475QH	Granite 9.5, high quartzite	$257.47	TON	1.0-in	$19.03	yd^2
G95QM	Granite 9.5, medium quartzite	$275.26	TON	1.0-in	$20.01	yd^2
GFC5QH	Granite FC-5, high quartzite	$301.89	TON	0.75-in	$16.99	yd^2
GFC5QM	Granite FC-5, medium quartzite	$311.97	TON	0.75-in	$17.40	yd^2
G95SH	Granite 9.5, high slag	$237.97	TON	1.0-in	$17.96	yd^2
G95SM	Granite 9.5, medium slag	$262.88	TON	1.0-in	$19.33	yd^2
G475SH	Granite 4.75, high slag	$237.40	TON	0.75-in	$14.33	yd^2
G475SM	Granite 4.75, medium slag	$270.23	TON	0.75-in	$15.68	yd^2
GFC5SH	Granite FC-5, high slag	$274.31	TON	0.75-in	$15.85	yd^2
GFC5SM	Granite FC-5, medium slag	$305.51	TON	0.75-in	$17.14	yd^2
L95BH	Limestone 9.5, high bauxite	$786.80	TON	1.0-in	$48.15	yd^2
L95BM	Limestone 9.5, medium bauxite	$534.21	TON	1.0-in	$34.25	yd^2
L475BH	Limestone 4.75, high bauxite	$761.14	TON	0.75-in	$35.93	yd^2
L475BM	Limestone 4.75, medium bauxite	$551.88	TON	0.75-in	$27.30	yd^2
L95QH	Limestone 9.5, quartzite high	$253.47	TON	1.0-in	$18.81	yd^2
L95QM	Limestone 9.5, quartzite medium	$270.59	TON	1.0-in	$19.75	yd^2
LFC5QH	Limestone FC-5, quartzite high	$286.32	TON	0.75-in	$16.35	yd^2
LFC5QM	Limestone FC-5, quartzite medium	$311.05	TON	0.75-in	$17.37	yd^2
L95SH	Limestone 9.5, slag high	$235.71	TON	1.0-in	$17.84	yd^2
L95SM	Limestone 9.5, slag medium	$261.75	TON	1.0-in	$19.27	yd^2
L475SH	Limestone 4.75, slag high	$240.92	TON	0.75-in	$14.47	yd^2
L475SM	Limestone 4.75, slag medium	$270.23	TON	0.75-in	$15.68	yd^2
LFC5SH	Limestone FC-5, slag high	$266.52	TON	0.75-in	$15.53	yd^2
LFC5SM	Limestone FC-5, slag medium	$297.71	TON	0.75-in	$16.82	yd^2

(1) HFST cost includes the cost of the milling and AC layer required for the new HFST

(2) All standard and alternative friction surfaces include the cost of milling

5.2 Basic Parameters for HFST

The unit cost for HFST is different than AC mixes. An HFST is a thin layer of calcined bauxite aggregate placed in a polymer resin applied to the pavement surface. The cost of calcined bauxite and the polymer resin can vary significantly. The study did not determine the unit cost of each material as it related to the contract bid price used in the CB analysis. The project unit cost for HFST includes milling, placement of an asphalt surface, and placement of the HFST, which is typical for FDOT. Table 17, above, included the unit cost for HFST based on two projects provided for the study.

In-service life (durability) is projected to be 10 years and is relative to HFST durability and the loss of friction. The loss of friction is a result of friction aggregate debonding due to aging of the polymer resin binder, not due to aggregate polishing. In-service life does not account for poor design, materials, or construction, which results in early debonding between the HFST and the asphalt mixture layer.

5.3 Basic Parameters for Crash Rates

Crash risk data specific to Florida conditions (driver, vehicle, roadway, climate, etc.) were not available for this study, so two other studies which examined crash risk as a function of surface friction were reviewed and scrutinized with consideration to Florida conditions. Figure 44 combines the New Jersey dry condition roadway categories data into a single crash rate with the Swedish crash rate curve versus pavement friction curve. The extrapolated regions of the curves were used to extrapolate the curve into pavement friction values typically associated with HFST. The New Jersey curve and Swedish curve exhibit slightly different predictions for crash rates on high friction pavements. It must be noted that neither study may reflect Florida conditions. Statewide average crash rates may not be representative of high crash locations. High crash rate locations will vary based on the parameters at each location. This study used the results of both studies to examine the impact of pavement friction on crash risk.

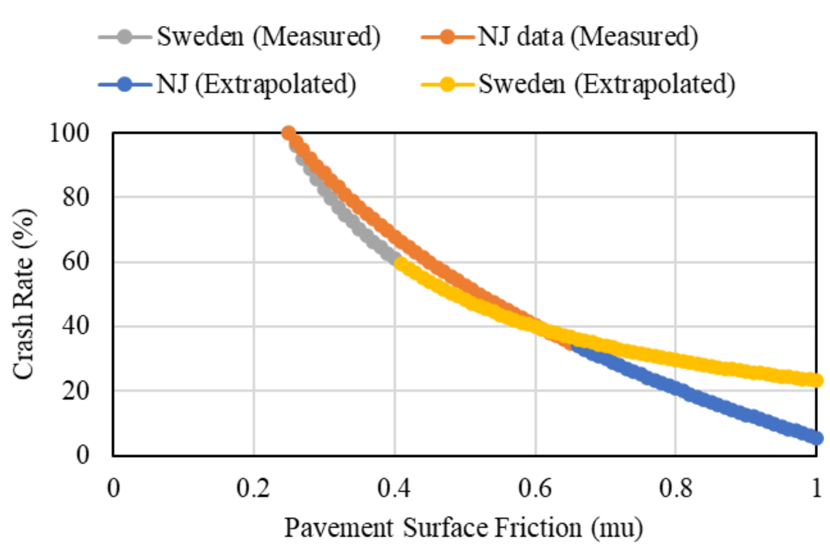

Figure 44: Estimated Crash Rate Response to Pavement Friction

The results of NCAT accelerated laboratory friction testing are reasonably equivalent to field friction. Measured lab friction results give an equivalent ranking of surface mixes to measured friction tests on the NCAT Test Track, but the values are not the same as field friction. All the friction data for this analysis is from NCAT accelerated laboratory friction testing, so the crash rate response to pavement surface friction can be compared for all the pavement surfaces in this study.

NCAT accelerated lab pavement friction studies commonly use 150K TWPD cycles to simulate friction decay to a minimum friction value over the life of a pavement. Thus, it can be assumed to be reasonably equivalent to 15+ years of in-service pavement surface polishing. For analysis purposes, crash rates are converted from percent crash reduction to crashes per 10K TWPD cycles. This is reasonably equivalent to crashes per year of pavement surface life.

This study ignored friction measured between 0-5K cycles. The 0K and 5K measured values do not reflect the actual change in friction from initial placement to peak friction. Initial friction (0K, prior to traffic) measures a surface completely covered with asphalt binder film. Peak friction occurs when the asphalt film is removed from the surface and the aggregate is exposed. The time for the asphalt pavement surface to transition from low initial friction to peak friction involves testing that was not a part of this study.

5.4 Cost Benefit by Project Paving Costs

This cost benefit analysis compares the cost of the friction surfaces based on the completed pavement surface installation cost and based on the cost per year of service. As noted above, the project paving cost values will be used for this analysis as the installed surface cost that includes milling, asphalt paving, and HFST. The FDOT HFST project cost includes milling, an asphalt overlay, and the placement of the HFST. All the asphalt friction projects are milling and asphalt paving which vary in cost based on the thickness of the overlay. The analysis does not include other typical project costs, such as mobilization and traffic control.

The project paving cost does account for the size of the project and the data shows that small quantity projects of 1.0 lane-mile of paving (typical of a project to address a high crash rate location) have 40 to 60% higher awarded unit item prices compared to the standard annual weighted average unit cost. The unit cost for HFST was not adjusted since the quantity already represents a high crash location small quantity.

The analysis based on cost per year of service accounts for the incremental cost of a paving project for each year the pavement provides good performance. The cost per year of service is based on commonly accepted pavement surface life expectancy assuming good performance. For an asphalt concrete surface the life expectancy of 15 years is used and for a HFST the life expectancy of 10 years is used. The study did not examine years of pavement performance data to better refine these values since this is a general statewide analysis not specific to route types. The cost benefit analysis does not apply present worth economic theory since public agencies do not invest funds “present worth” to cover the cost of future projects. To make a one-to-one comparison between friction surfaces, asphalt unit costs typically bid as tons of mixture in-place were converted to cost per yd^2 to place all unit costs in the same units. The asphalt unit cost per square yard must account for the layer thickness placed.

This study examines asphalt friction surfaces as an alternative to HFST. This portion of the cost benefit analysis is strictly based on construction cost and years of service. Table 18 presents the relative change in cost of an asphalt-based alternative surface in comparison to the cost and service of a HFST. Note that every alternative surface mix is significantly cheaper than HFST per square yard. When including the expected years in service, the alternative surfaces appear even cheaper compared to HFST. This result is not surprising given the high cost of HFST. The next section of the cost benefit will consider the safety provided by the surface friction.

Table 18: Cost Benefit of Project Paving Unit Cost Using Years of Service Benefit

SURFACE TYPE	SM. QNT. PROJ. UNIT COST ($/yd^2)	PERCENT OF HFST UNIT COST (%)	UNIT COST PER YEAR ($/yd^2-YR)	PERCENT OF HFST SERVICE COST (%)
HFST	$80.50		$8.05	
FC-9.5 Control	$20.51	25%	$1.37	17%
FC-4.75 Control	$17.23	21%	$1.15	14%
FC-5 Control	$18.36	23%	$1.22	15%
G95BH	$43.98	55%	$2.93	36%
G95BM	$33.79	42%	$2.25	28%
G475BH	$35.21	44%	$2.35	29%
G475BM	$27.30	34%	$1.82	23%
G475QH	$19.03	24%	$1.27	16%
G95QM	$20.01	25%	$1.33	17%
GFC5QH	$16.99	21%	$1.13	14%
GFC5QM	$17.40	22%	$1.16	14%
G95SH	$17.96	22%	$1.20	15%
G95SM	$19.33	24%	$1.29	16%
G475SH	$14.33	18%	$0.96	12%
G475SM	$15.68	19%	$1.05	13%
GFC5SH	$15.85	20%	$1.06	13%
GFC5SM	$17.14	21%	$1.14	14%
L95BH	$48.15	60%	$3.21	40%
L95BM	$34.25	43%	$2.28	28%
L475BH	$35.93	45%	$2.40	30%
L475BM	$27.30	34%	$1.82	23%
L95QH	$18.81	23%	$1.25	16%
L95QM	$19.75	25%	$1.32	16%
LFC5QH	$16.35	20%	$1.09	14%
LFC5QM	$17.37	22%	$1.16	14%
L95SH	$17.84	22%	$1.19	15%
L95SM	$19.27	24%	$1.28	16%
L475SH	$14.47	18%	$0.96	12%
L475SM	$15.68	19%	$1.05	13%
LFC5SH	$15.53	19%	$1.04	13%
LFC5SM	$16.82	21%	$1.12	14%

5.5 Cost Benefit of Safety Risk

This safety benefit analysis examines the relationship between crash rate and pavement surface friction. Often a theoretical cost-benefit analysis that includes safety becomes one-sided because the cost of safety supersedes all other factors. Pavement surface friction varies over time, so the predicted crash rate varies as the friction varies, thus a safety analysis must examine the accumulated crashes and not only the change in crash rate. This analysis method compares cumulative crashes over the analysis period. The process used in this analysis could be applied to more regionally appropriate crash data to obtain more site-specific results.

The analysis period uses lab friction performance divided over the TWPD cumulative polishing cycles into 15 equal 10K cycle increments. This analysis is based on friction data measured from the accelerated lab polishing protocol. Past studies have confirmed that the results of accelerated lab polishing and testing are similar to long term field polishing on the NCAT Test Track and the correlation is strong enough to establish a general comparison to years of field friction performance between polished surfaces. This approach isolates the friction performance of the pavement surface from other field variables, such as curve geometry, traffic volume, sight distance, etc. that are not accommodated in accelerated lab polishing. The accelerated lab friction curves often show the minimum friction well before 150K cycles. By using the lab friction performance curves, this analysis accounts for the differences in the time when minimum friction is reached. By dividing the 150K cycles into 10K increments the analysis would be similar to 1-year increments of field performance.

The accelerated lab study limited the number of friction measurements during the 150K cycles of polishing to 0K, 5K, 70K and 150K. These points in the 150K polishing protocol are sufficient to establish an approximate peak friction (5K), initial estimates of final friction (70K), and final friction (150K). In many cases the measured friction at 70K and 150K are similar, which confirms that the polished surface did reach a plateau condition. The authors acknowledge that more testing over the course of the 150K polishing would establish a more definitive friction performance curve but would have increased the cost of the study. The actual shape of the performance curve between 5K and 70K is the least accurate. Friction could have dropped to a reduced condition at 20K, 30K, 40K, etc. If there is a need to have a more definitive friction performance curve, another study would be needed. For this analysis, the assumption is made that the friction performance is a linear change from 5K to 70K.

5.5.1 Steps of the Safety Benefit Analysis.

1. Examine all the friction performance curves and inquire if any results are questionable. For example, in the case of this analysis, the friction performance of the baseline granite 4.75 mix is notably higher than other mixes. This exception was adjusted through the analysis by manually reducing the crash response for the granite 4.75 control mix to be similar to the crash response for the granite 9.5 control mix.

2. Compute the friction values at each 10K polishing increment for each friction surface using linear interpolation, as shown in Figure 45. Since these are accelerated test results and there are multiple 10K increments between measured friction values, the accuracy of the computed 10K values is not significant to the analysis. The friction value used for the first 10K increment does

not apply to the initial friction value. The 10K friction value represents the measured 5K friction value adjusted for the slope of the friction performance curve between 5K and 70K.

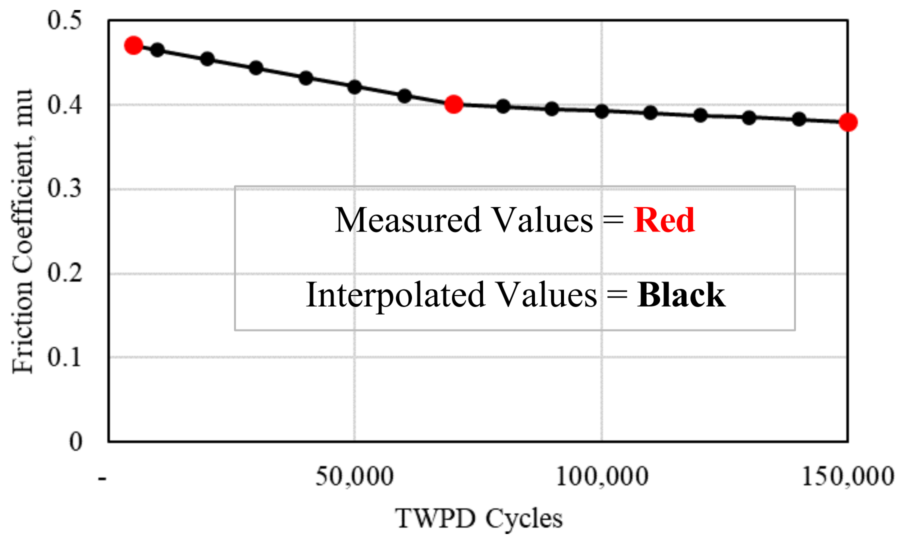

Figure 45: Example Laboratory Friction Curve for Safety Analysis

3. Select the appropriate friction versus crash rate curve. There are numerous factors that influence this curve and the curve for each segment of roadway is unique. In particular, the friction versus crash rate curve for high crash rate locations would be expected to be different from the curve representing a state-wide trend of all roadway segments. For this analysis, the study selected curves that were developed for other studies because there was no indication that FDOT had this type of data after some inquiry. For this example, the curve from the New Jersey dataset is selected in Figure 46.

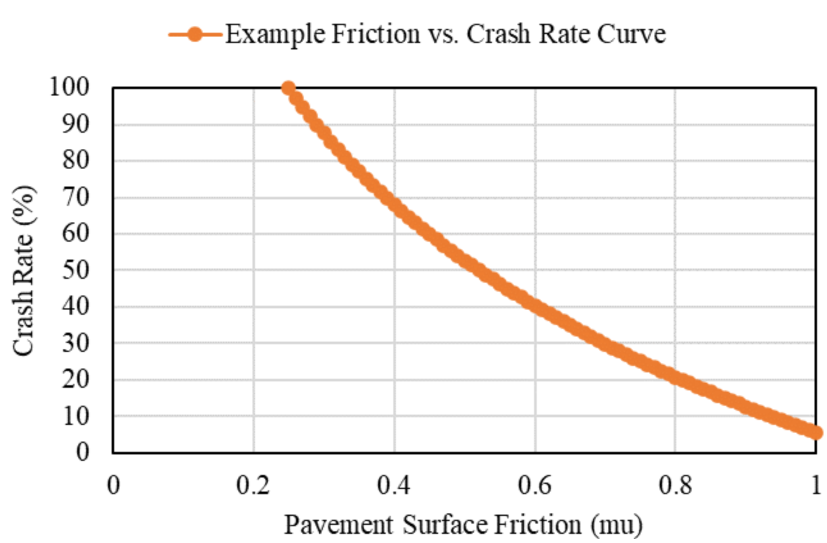

Figure 46: Example Friction vs. Crash Rate Curve for Safety Analysis Example

4. Using the desired friction curve, create a Table reflecting the crash rate for each 0.01 mu increment of friction from the minimum value to the highest value necessary, as shown in Table 19. Similar to computing the friction value for each polishing increment, the values of crash rate for each 0.01 mu only need to be marginally accurate.

Table 19: Example Crash Rate Table from Friction Curve

Friction, mu	Crash Rate Relative to mu = 0.25, %
0.25	100.0
0.26	97.3
0.27	94.8
0.28	92.3
0.29	89.9
0.3	87.6
…	…
0.42	64.7
0.43	63.1
0.44	61.5
0.45	60.0
….	….
1.00	16.3

5. Build a table of crash rates for each 10K polish increment referencing the computed friction for each 10K increment. For example, for each 10K increment select the crash rate that corresponds to the friction value in the range. For this analysis a simple look-up feature of Excel was applied to select the closest crash rate reduction value. This is demonstrated in Figure 47.

Friction, mu	Crash Rate, %
…	…
0.36	75.2
0.37	73.3
0.38	71.5
0.39	69.7
0.40	68.0
0.41	66.3
0.42	64.7
0.43	63.1
0.44	61.5
0.45	60.0
0.46	58.5

TWPD Cycle	DFT (mu)	Crash Rate, %
5K	0.46	58.5
10K	0.45	60.0
20K	0.44	61.5
30K	0.43	64.7
…	…	
130K	0.38	71.5
140K	0.38	71.5
150K	0.38	71.5

Figure 47: Example of Crash Rate Reduction Value Selection Process

6. For each friction surface, including the control surfaces, determine the crash rates for each of the 10K friction performance increments over the 150K polishing period. Divide this value by the number of increments in the analysis to determine the average crash rate for the life of the pavement compared to a surface with a friction level of 0.25 for the same timeframe. The baseline for this analysis is the expected number of crashes if the poor friction surface were left in place for the entire lifespan. In other words, this is the 100% crash rate value. This is demonstrated in Table 20. In the example below, Surface A has a higher average crash rate, which would be expected to result in approximately 15.5% more crashes than Surface B. This method allows for an equal relative comparison of safety performance for a Safety Benefit analysis but is improved by comparing the friction surfaces to a control surface.

Table 20: Cumulative and Average Crash Rate Calculation Example

TWPD Cycle Segment	Crash Rate (CR)						Avg. Crash Rate, %
	10K	20K	30K	…	140K	150K	
Surface A	63.1	66.3	68.0	…	87.6	87.6	78.0
Surface B	52.8	54.2	57.0	…	68.0	69.7	62.5

7. Subtract the average crash rate from 100 to determine the average crash reduction over the life of the friction surface. This analysis provides a head-to-head comparison of all friction treatments, including HFST, compared to the same baseline of 100% crashes if the surface were to remain at a poor friction level.

8. Because it is highly unlikely that any alternative friction surface will provide similar results to the HFST, further analysis can be conducted to compare the alternative friction surfaces to the control mixes. Divide the average crash rate, not crash reduction, of the alternative friction surfaces by the crash rate of the corresponding control mix surface. Positive values indicate a surface that has improved safety over the control mix. The comparison to a control surface (assumed to represent typical pavement friction) is made with the intention of assessing the safety improvement of alternative friction surfaces over standard friction surfaces (granite or limestone) when both are placed new. It considers the good surface friction performance of the baseline mix early in its life.

Table 21 and Table 22 contain the results of Step 7 and Step 8, respectively, of this analysis process for the data collected in this project. The bottom of each table has data for a HFST not previously discussed. Data from a lab-fabricated HFST from a former NCAT study was included to represent HFST in the lab. The DFT_60 values are shown in Table 23. Note that the crash reduction comparisons do not yield the same results between the two crash curves. This occurs because the crash rate versus friction coefficient curves between the two studies are not exactly similar. In both cases the HFST represents extrapolated data, but the New Jersey results are measured data up to a friction coefficient of 0.60. The New Jersey data, however, do unrealistically imply that an extrapolated friction coefficient of 1.0 can reduce crashes by 95%. Nonetheless, the data were the best available for this analysis.

Table 21: Crash Reduction Comparison for Granite Mixtures

Granite Mixtures				
	Swedish Crash Curve		New Jersey Crash Curve	
	Average Crash Reduction Compared to Poor Friction Surface	Crash Reduction Compared to Control Surface	Average Crash Reduction Compared to Poor Friction Surface	Crash Reduction Compared to Control Surface
G95C	35.2%	baseline	28.2%	baseline
G475C	35.7%	baseline	35.7%	baseline
GFC5C	28.1%	baseline	22.3%	baseline
G95BH	36.4%	2%	29.0%	1%
G95BM	40.6%	8%	32.6%	6%
G475BH	28.7%	-11%	22.7%	-20%
G475BM	28.3%	-12%	22.2%	-21%
G475QH	32.5%	-5%	26.2%	-15%
G95QM	34.0%	-2%	27.9%	0%
GFC5QH	38.1%	14%	30.8%	11%
GFC5QM	27.6%	-1%	22.0%	0%
G95SH	45.0%	15%	37.5%	13%
G95SM	44.3%	14%	36.1%	11%
G475SH	48.6%	20%	42.0%	10%
G475SM	45.8%	16%	38.4%	4%
GFC5SH	38.0%	14%	30.2%	10%
GFC5SM	37.3%	13%	29.6%	9%
HFST	75.9%	N/A	83.9%	N/A

Table 22: Crash Reduction Comparison for Limestone Mixtures

Limestone Mixes				
	Swedish Crash Curve		New Jersey Crash Curve	
	Average Crash Reduction Compared to Poor Friction Surface	Crash Reduction Compared to Control Surface	Average Crash Reduction Compared to Poor Friction Surface	Crash Reduction Compared to Control Surface
L95C	26.4%	baseline	21.0%	baseline
L475C	20.7%	baseline	16.7%	baseline
LFC5C	23.9%	baseline	18.8%	baseline
L95BH	49.0%	31%	42.5%	27%
L95BM	35.6%	13%	28.1%	9%
L475BH	47.1%	33%	40.0%	28%
L475BM	40.2%	25%	32.6%	19%
L95QH	20.4%	-8%	16.5%	-6%
L95QM	14.0%	-17%	11.4%	-12%
LFC5QH	9.0%	-20%	7.2%	-14%
LFC5QM	4.5%	-26%	3.7%	-19%
L95SH	39.8%	18%	32.1%	14%
L95SM	26.4%	0%	21.0%	0%
L475SH	44.0%	29%	36.4%	24%
L475SM	41.7%	26%	33.9%	21%
LFC5SH	44.5%	27%	36.1%	21%
LFC5SM	35.3%	15%	27.8%	11%
HFST	75.9%	N/A	83.9%	N/A

Table 23: DFT_60 Results from Lab-Fabricated HFST on Slabs

TWPD	0	5K	70K	150K
Lab HFST	0.99	0.95	0.86	0.78

The crash reduction results compared to the baseline of a poor friction surface (Step 7 above) in Table 21 and Table 22 are presented graphically in Figure 48 and Figure 49, respectively. Note that HFST is obviously the safest surface in terms of crash reduction compared to a control mix. The granite mixes had a higher crash reduction potential than the limestone because the overall friction is higher in granite mixes and the denominator represents a poor friction surface with essentially no crash reduction potential. From this analysis, no alternative surfaces come close to the performance of HFST.

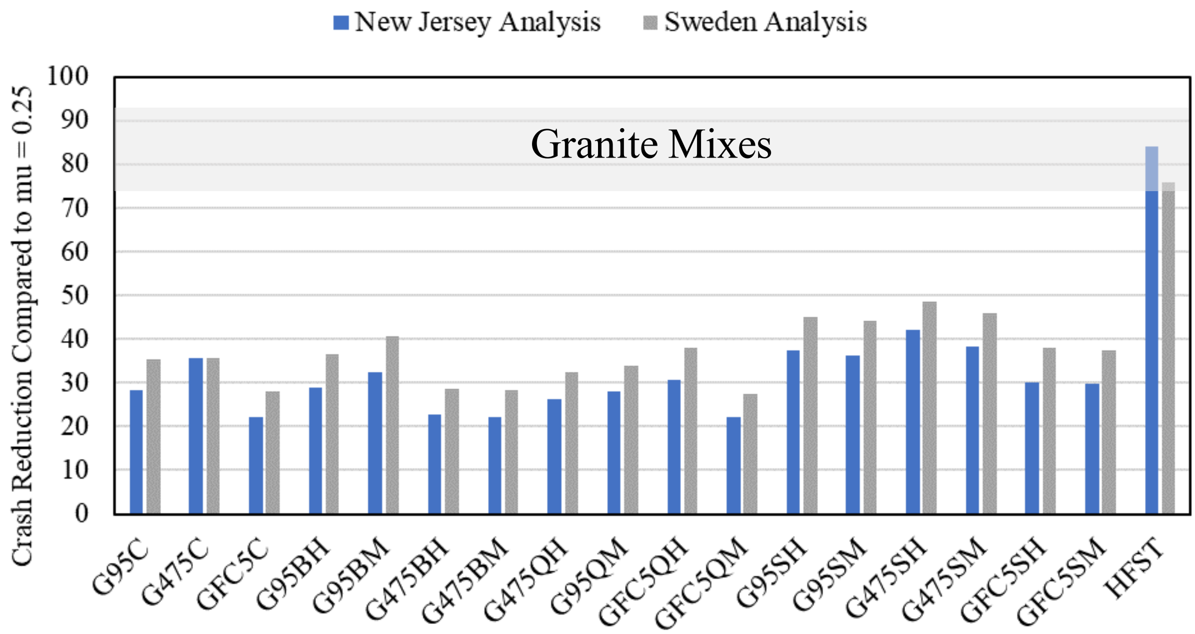

Figure 48: Comparison of Alternative Friction Surfaces to Crash Reduction of HFST – Granite Mixes

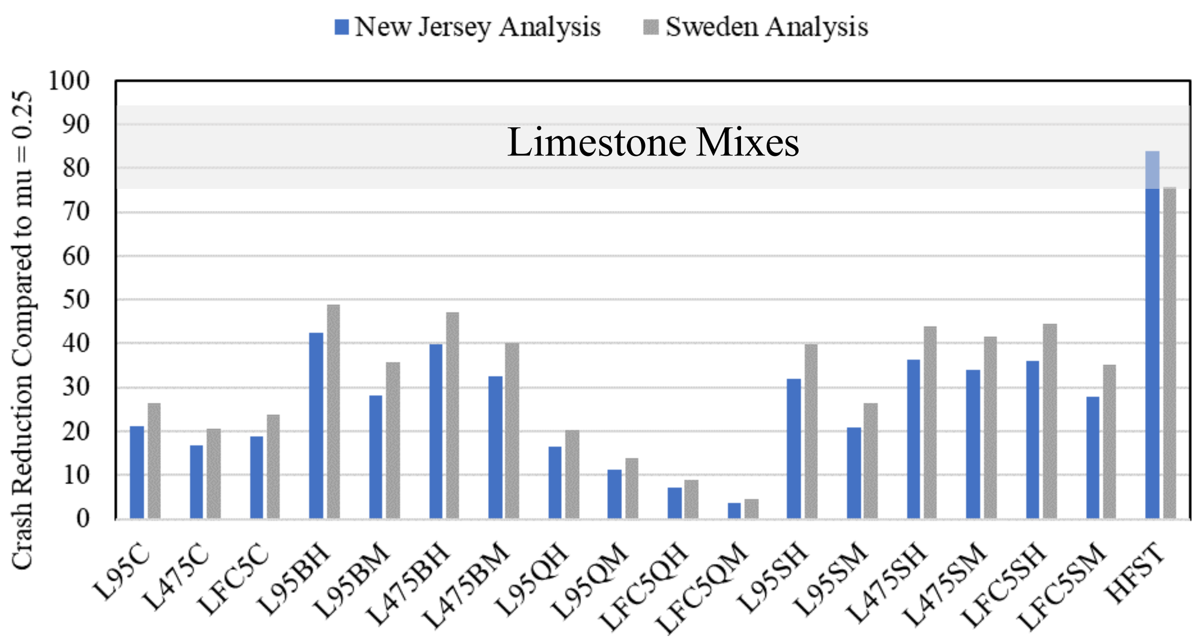

Figure 49: Comparison of Alternative Friction Surface to Crash Reduction of HFST – Limestone Mixes

Because HFST is very expensive and has been shown to sometimes have negative cost benefit ratios associated with in for certain route types or locations, it is useful to remove it from the analysis and compare the friction of the alternative treatments to the friction of the control sections. This analysis provides FDOT with a better understanding of the potential to increase friction in asphalt mixes for applications where higher friction is needed but not to the degree that HFST provides. As was previously shown, the costs of every alternative friction mix was significantly less, sometimes as much as 8x less, than the cost of HFST. A comparison of the alternative granite friction mixes is presented in Figure 50 and the comparison for the limestone mixes is shown in Figure 51. The magnitude of the change in the granite mixes compared to the control mix approaches half of the magnitude of the change in the limestone mixes. This is due to the higher friction levels of the granite control mixes in the denominator of that calculation. The limestone mixes represent the largest opportunity for friction improvement. Specifically, the slag and bauxite modified mixes consistently demonstrate potential to improve friction by 10 to 30%. The next section will compare the costs of these alternative friction surfaces to their respective performance compared against the typical costs of HFST and control mixes.

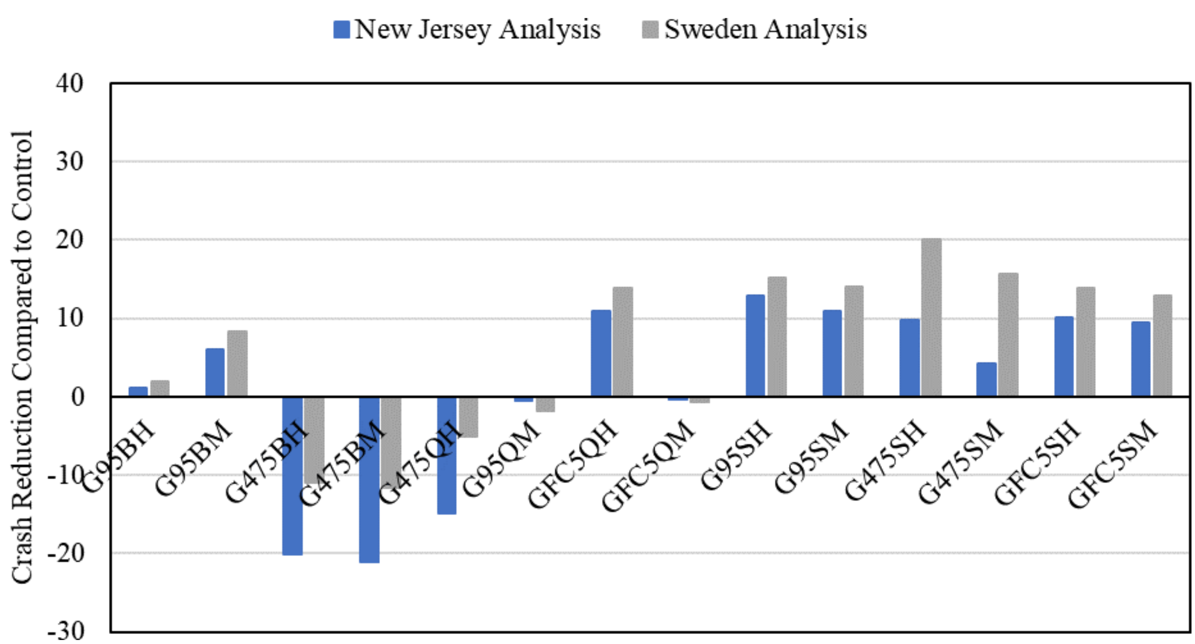

Figure 50: Crash Reduction Potential Compared to Control – Granite

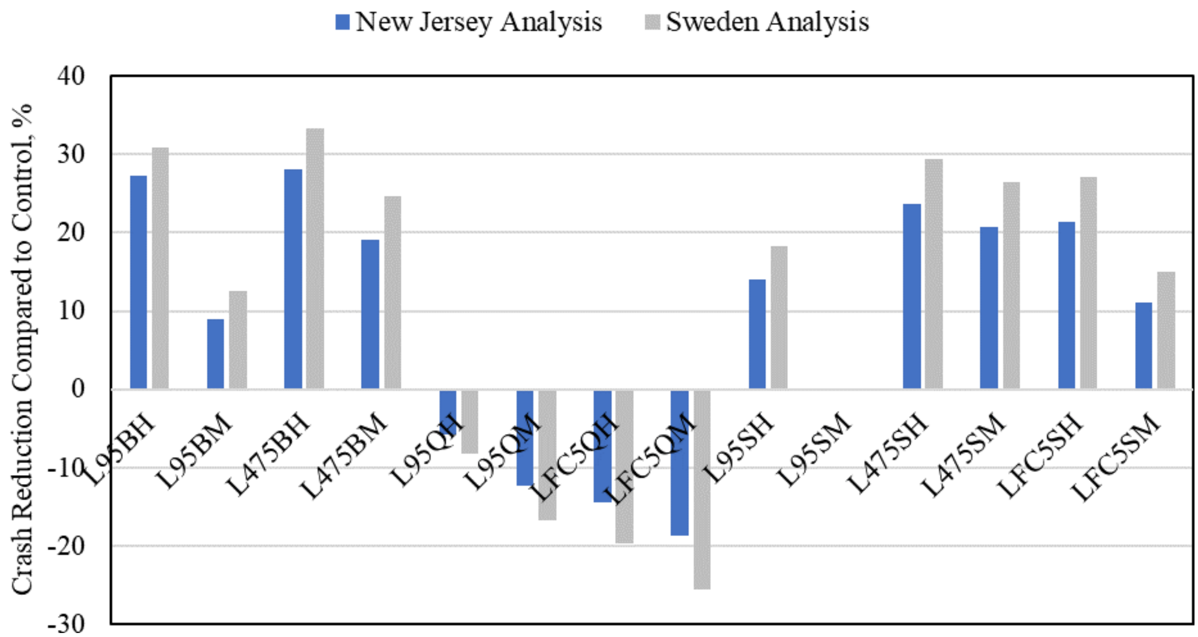

Figure 51: Crash Reduction Potential Compared to Control – Limestone

5.6 Cost Benefit Summary

The cost benefit associated with each of the friction surfaces are a combination of individual contract bid items needed to represent the construction tasks to develop the intended surface. The bid item price for each alternative asphalt mix was adjusted for the amount (and unit price) of friction aggregate substituted into the mixture. Each bid item price was adjusted to take into consideration the expected higher price for a small project bid quantity which would be typical for correcting the surface of a high crash rate location. All asphalt mixture unit prices (per ton) were converted to prices per square yard for the design layer thickness. The adjusted price items were combined as the project paving cost. The HFST project cost included milling, asphalt layer, and placement of the HFST. The asphalt friction surface project cost included milling and the asphalt layer, which were matched for the design thickness. A HFST surface was demonstrated to be two to eight times more expensive than the alternative surfaces. The final step for establishing the cost benefit of each friction surface project computed the cost per year of service.

It is clear that the HFST provided the highest crash reduction compared to every alternative friction course, in terms of long-term crash rate when applied to a poor friction (friction level = 0.25) surface. While every mix showed reduced crashes compared to leaving a poor friction surface in place for the entire analysis period, HFST produced at least twice as much crash prevention compared to the alternative surfaces. However, as discussed previously, the HFST was the most expensive option.

The analysis using the control friction surface baseline has value for considering if one or more of the alternative asphalt surface mixtures included in the study would increase safety in a pavement segment where the friction demand does not necessarily warrant HFST but may still require enhanced friction. Alternative asphalt friction mixtures which significantly improve friction compared to the control without significantly increasing cost may be considered for routine use as an asphalt friction surface. Ultimately, FDOT personnel would need to conduct a similar analysis for a specific project location to determine the value of improving friction by a specific amount. If the cost of an alternative friction mix is below this amount, it should be considered for use.

Figure 52 displays the results of using the high crash baseline and the average of the two crash rate curves used in this analysis. This summary figure provides a visual comparison of three sets of data (HFST, standard friction surfaces, and alternative friction surfaces). The values for the HFST clearly show that this surface is the premier surface for crash reduction benefit and also the highest cost. The two sets of results for the standard friction surfaces (granite and limestone) meet the expectation that the crash reduction potential for the granite mixes is better. Note that this study did not have data to differentiate the cost of granite and limestone friction mixes. The results of the granite and limestone alternative asphalt friction surfaces vary and some of those mixes could improve safety (higher crash reduction) without a cost increase.

The high crash baseline analysis favors the granite aggregate because the values are being compared to a poor friction surface. Because granite has higher friction than the limestone, it is intuitive that the crash reduction versus a surface with poor friction would be higher for granite.

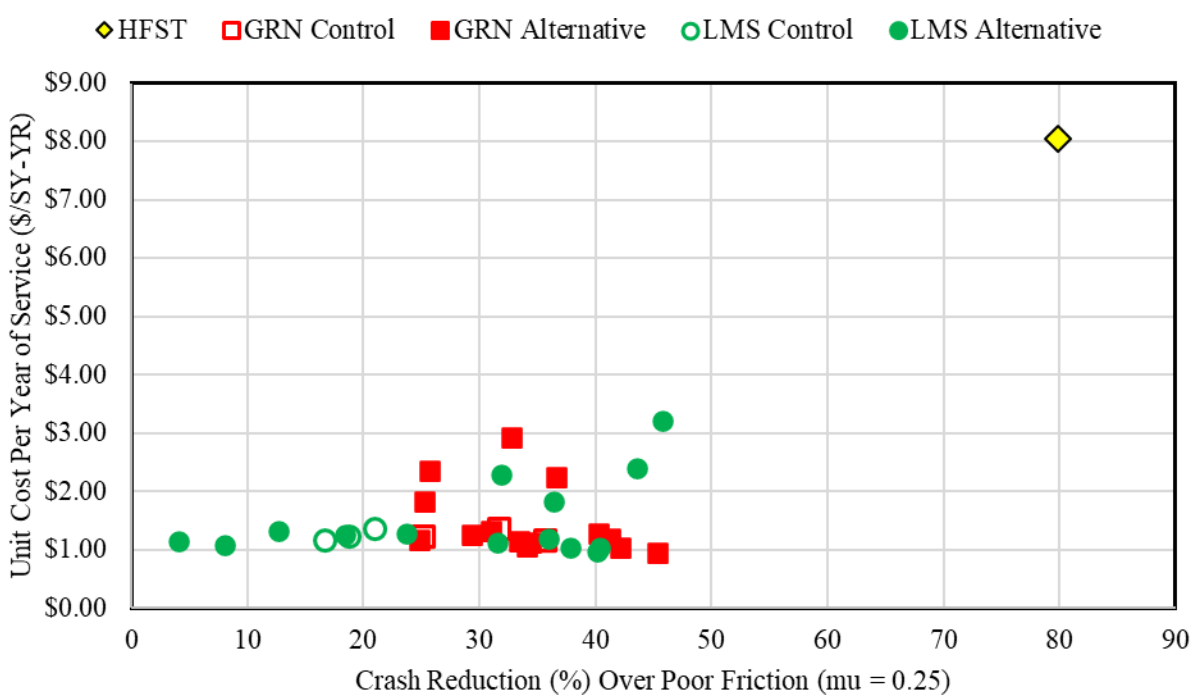

Figure 52: Cost and Crash Reduction Comparison of All Friction Surfaces

Figure 53 displays the results of using the control asphalt friction surfaces baseline and the average of the two crash rate curves used in this analysis. This summary figure provides a visual comparison of how the alternative asphalt friction surfaces compare to the average baseline asphalt friction surface for the purpose of determining if an improvement in the standard asphalt friction surface mixture is warranted. Alternative asphalt friction surfaces that improve safety (reduce crashes) at minimal increase in cost are viable candidates. The standard asphalt friction surface cost is $1.15 to $1.37 per square yard for each year of service, per Table 18. A standard granite-based asphalt friction mixture may achieve a 10-15% further reduction in crashes at a similar cost if the mixture aggregate is modified. A standard limestone-based asphalt friction mixture may achieve a 22-27% further reduction in crashes at a similar cost if the mixture is modified.

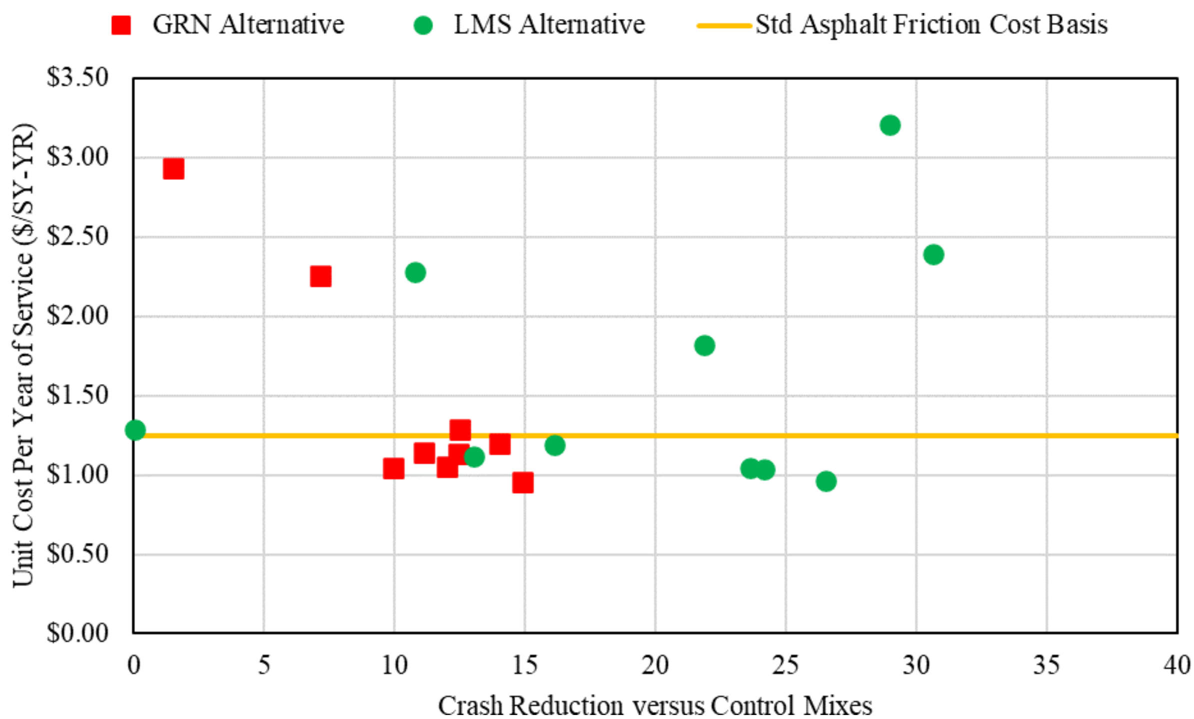

Figure 53: Cost and Crash Reduction Comparison of Alternative Surfaces Compared to Controls

It is probable that the cost of slag would change if demand for the products was created by these types of mixes. Thus, it is important to even consider mixes that are slightly more expensive than the control mixes if they provide significantly higher friction. It is likely that on certain routes with limestone mixes an increase in friction of 25% would be considered a cost-effective option. Therefore, this analysis method should be considered as a tool to acquire price and crash reduction potential information so that pavement, materials, and safety engineers can make effective decisions.

It is important to note that this study does not address the impact of pavement surface macro-texture as a factor in crash reduction. Macro-texture is an important pavement surface feature for reducing wet weather crash potential. The macro-texture of a HFST is very high compared to the macro-texture of a 4.75mm NMAS asphalt mixture. The consideration of any alternative asphalt friction surface should include the surface macro-texture in the decision.

6. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

This section contains a summary of the findings from the lab testing and cost benefit analysis. Also included are final conclusions and recommendations for implementation and future research.

6.1 Findings and Conclusions

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

6.1.1 Summary of Mix Design Results

- Achieving volumetrics with alternative aggregates is feasible. However, many high friction aggregates (slag, bauxite, lightweight aggregate) will inherently have high absorption. This will require more asphalt binder to be supplied to mixes modified with these types of aggregates which will drive up cost.
- When blending aggregates with different specific gravities (approx. 0.300 difference), it is critical that the gradation is determined and approved by volume and not by mass. Considering the volume will prevent overly heavy or light aggregate particles from influencing the gradation and will give an accurate representation of particle distribution regardless of aggregate densities.

6.1.2 Summary of DFT Results

- The DFT was generally sensitive to aggregate changes in the blends, especially to the type and amount of high friction aggregate. However, this was more so with the limestone mixes than the granite mixes.
- The granite aggregate had better friction properties than expected. The limestone aggregate behaved as the research team expected by demonstrating lower resistance to polishing.
- The bauxite aggregates significantly improved the friction performance of the limestone mixes but either harmed or had no effect on the granite mixes. It is probable that the granite aggregates already had adequate friction and attempts to improve it inadvertently decreased it. It is not considered that the bauxite material in the granite slabs had low friction properties. There is little knowledge available about incorporating friction into mix design, so it is possible that interactions of some fundamental material properties are influencing these results in an unknown manner.
- The slag aggregate resulted in an improvement in friction in almost every blend it was used. This product was selected due to its local availability in Florida.
- The quartzite aggregate failed to positively influence the blends in a meaningful way. This result was surprising to the research team. The aggregate was selected because it had documented instances of usage in higher friction applications.
- Including 10% slag or bauxite by volume into the coarse fraction of the the limestone mixes is estimated to increase the friction by approximately 4 points.

6.1.3 Summary of CTM Results

- The CTM ranked mixes appropriately according to their size. However, the FC-9.5 and FC-4.75 had MPD values that were more similar than expected.
- Most MPD changes during polishing were due to raveling of the mix, and this only happened in some of the limestone dense-graded mixes.
- MPD plays a role in the safety of a pavement by indicating macrotexture. However, the TWPD does not simulate the environmental effects in the lab well that typically cause texture to increase nor does it simulate the densification or tightening the mat that also often occurs, especially early in the life of a pavement.

6.1.4 Summary of Cost Benefit Analysis

- There are frequently multiple factors influencing the crash rate of a particular pavement. Road geometry, speed limit, traffic volume, etc. also play a role. However, the effect of friction on crash reduction can be estimated and used to make decisions regarding friction treatments and allowable mixture types in certain applications.
- HFST is much more expensive than the other options presented in this report. However, despite the cost, it has unmatched friction performance.
- Cost estimates of enhanced friction mixes must consider the added costs of small quantities. Furthermore, they must include the costs of the premium aggregates in the blend too. Cost must be considered along with performance and should not be the only reason a product is selected for use in a friction-related application.
- The HFST yielded the highest expected crash reduction. Unsurprisingly, it had almost three times as much crash reduction benefit as other experimental surfaces in this study.
- The largest benefit cost ratios are likely to be found with limestone mixes. This is due to the lower inherent friction in the limestone aggregates. There was less benefit in adding the HFAs to the granite mixes because the granite friction results were already higher than expected.
- Calculating a benefit cost ratio using laboratory results requires many assumptions. The framework developed here, which considers cost alongside expected crash reduction from lab testing, can be used to compare different options such as a traditional mix in an overlay versus a higher friction mix, or to compare a high friction mix to a HFST for friction enhancement. This provides engineers with a valuable tool to consider more cost-effective options for implementing enhanced friction surfaces at specific locations.

6.2 Recommendations for Implementation and Future Research

The following recommendations are made regarding potential implementation:

- None of the alternative mixes should be implemented to replace HFST with the expectation of matching or exceeding friction performance of HFST.
- Consider using the TWPD and DFT to develop expectations for friction performance using laboratory produced specimens. This project demonstrated the feasibility of

improving pavement friction by adding high friction aggregates. Consider utilizing calcined bauxite and local steel slag as potential high friction aggregates. Texture is also an important characteristic of pavements safety, but assessing potential changes over time in texture is difficult in the lab.

- Require mix designers to submit blends by volume when designing mixes where there is a difference in gravities larger than 0.300.
- Involve safety engineers in decisions regarding potential crash reduction curves for specific projects or locations. Not every project location will have the same expected crash reduction benefit from improving friction. There may be certain segments that require other friction mitigation methods. Collaborating across disciplines will provide FDOT with better information to make informed decisions.
- Future investigation into texture thresholds could help FDOT establish guidelines for texture during mix design or project planning to be to prevent inadvertently designing mixes with higher microtexture but lower macrotexture.

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APPENDIX A - MIX DESIGNS

Table 24: Granite Mix Designs – By Mass

	FC-4.75					FC-9.5							FC-5				
	Control	Bauxite		Slag		Control	Bauxite		Slag		Quartzite		Control	Slag		Quartzite	
	N/A	M	H	M	H	N/A	M	H	M	H	M	H	N/A	M	H	M	H
GRN 7s													27		11	41	40
GRN 78s													25	39			
GRN 89s	12					37	22		18		16		38	28	33	22	
GRN M10s	38	30	33	14	6	28	25	30	15	5	21	10					
GRN W10s	38	24		43	19	13			31	38	28	26	9	8	7	9	8
Sand	12	18	17	11	15	22	25	20	12	11	16	26					
Lime													1	1	1	1	1
3 x 8 Bauxite		28	50														
3/8 x 8 Bauxite							28	50									
-1/4" Slag				32	60												
-1/2" Slag									24	46							
3/4" x 8 Slag														24	48		
Quartzite #8											19	38				27	51
AC%	6.6	6.5	6.4	6.5	6.3	5.7	5.9	5.9	5.7	6	5.9	5.9	6.2	6	6.3	6.5	6.3
Va, %	4	4.3	4	5	4	4	4	4	4	4	4	4					
VMA, %	18.1	18	18.3	19.4	17.9	16.3	16.1	16.2	16.3	17	16.6	17.4					
VFA, %	78	76.1	78	74	78	75	75	75	75	76	76	76					
D/B Ratio	1.3	1.1	1.0	1.3	1.5	1.0	0.9	1.1	1.0	0.9	0.9	0.6					
Vbe, %	14.1	13.7	14.3	14.4	13.9	12.3	12.1	12.2	12.3	13	12.6	13.4					
Gmm	2.510	2.621	2.692	2.643	2.757	2.531	2.643	2.747	2.643	2.726	2.517	2.480					

Table 25: Limestone Mix Designs – By Mass

	FC-4.75					FC-9.5							FC-5				
	Control	Bauxite		Slag		Control	Bauxite		Slag		Quartzite		Control	Slag		Quartzite	
	N/A	M	H	M	H	N/A	M	H	M	H	M	H	N/A	M	H	M	H
LMS C41													44	32		41	39
LMS C51						26.5	26		22	6	22		27	22	6	17	
LMS C53													22	9	33		
LMC C54	38	15		18.5		26											
LMS F20	27	22		25	15				28	21	24	25					
LMS F22	31	31	44	23	22	46	43.5	38	24	24	27	26	7	6	6	5	5
BHF	4	4	4	1.5		1.5	1.5	2	1	1	2	2		1	1	1	1
3 x 8 Bauxite		28	52														
3/8 x 8 Bauxite							29	60									
-1/4" Slag				32	63												
-1/2" Slag									25	48							
3/4" x 8 Slag														30	54		
Quartzite #8											25	47				28	55
AC%	6.8	7	6.9	6.9	6.5	6.8	7.0	6.4	7.0	6.3	6.6	6.1	6.9	6.1	6.1	6.4	6.3
Va, %	4.5	4.5	4.4	4.1	4.5	4	4	4	4	4	4	4					
VMA, %	16.7	16.6	16.4	16.6	17.1	15.3	15.7	16.8	15.7	15.1	16.5	16.6					
VFA, %	73	73	73	75	74	74	74	76	74	74	76	76					
D/B Ratio	1.1	1.1	1.1	1.2	1.5	0.6	0.6	0.5	0.8	1.0	0.7	0.7					
Vbe, %	12.2	12.1	12	12.5	12.6	11.3	11.7	12.8	11.7	11.1	12.5	12.6					
Gmm	2.353	2.521	2.677	2.533	2.736	2.350	2.516	2.692	2.492	2.652	2.399	2.445					