ALTERNATIVE AGGREGATES AND MATERIALS FOR HIGH FRICTION SURFACE TREATMENTS

by

Bryan Wilson
Associate Research Scientist
Texas A&M Transportation Institute

and

Anol Mukhopadhyay, PhD
Associate Research Scientist
Texas A&M Transportation Institute

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DISCLAIMER

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UNITS CONVERSION PAGE

English to SI (International System of Units) Conversions

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
mils	mils	0.0254	millimeters	mm
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	6.45	square centimeters	cm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
Volume				
gal	gallons	3.785	liters	l
Speed				
mph	miles per hour	1.61	kilometers per hour	km/h
Mass				
lbs	pounds	0.453	kilograms	kg
Force				
lbf	pound-force	4.45	newton	N
Stress				
psi	pounds per square inch	0.00689	megapascals	MPa
Temperature				
°F	degrees Fahrenheit	(°F-32)*0.555	degrees Celsius	°C
Thermal Expansion				
/°F	per degree Fahrenheit	1.8	per degree Celsius	/°C

SI to English Conversions

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
mm	millimeters	39.4	mils	mils
mm	millimeters	0.0393	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
Area				
cm^2	square centimeters	0.155	square inches	in^2
m^2	square meters	10.8	square feet	ft^2
m^2	square meters	1.20	square yards	yd^2
Volume				
l	liters	0.264	gallons	gal
Speed				
km/h	kilometers per hour	0.621	miles per hour	mph
Mass				
kg	kilograms	2.20	pounds	lbs
Force				
N	newton	0.225	pound-force	lbf
Stress				
MPa	megapascals	145	pounds per square inch	psi
Temperature				
°C	degrees Celsius	°C*1.8+32	degrees Fahrenheit	°F
Thermal Expansion				
/°C	per degree Celsius	0.555	per degree Fahrenheit	/°F

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16. Abstract

The State of Florida has used high friction surface treatments (HFSTs) since 2006 to reduce wet weather crashes on tight curves and intersections and to maintain bridge decks; however, the Florida Department of Transportation (FDOT) has reported issues related to premature failure of the treatment. The scope of this project was to: (1) Review the literature and interview industry experts on the state of the practice of HFST; (2) Document all existing HFST projects in Florida and analyze their performance based on distress, skid resistance, and crash reduction; (3) Perform field testing on six projects, evaluating their present performance and conducting forensic analyses as needed; (4) Perform laboratory tests on different aspects of HFST materials and construction practices to improve durability and reduce costs; and (5) Develop a revised HFST specification for Florida and an HFST Guidelines booklet.

The research findings include historic costs, project performance histories, identification of failure mechanisms, crash rate reductions for various applications, benefit-cost analyses, trends between aggregate loss and both resin binder type and mil thickness, thermal compatibility measurements, resin binder gel times under non-ideal situations, an HMA design using calcined bauxite, and comparisons of a few high friction aggregates.

The researchers recommended many ways to improve the design, construction, and quality control of HFST. These are reflected in the proposed specification Section 333. A new user-friendly booklet, titled “High Friction Surface Treatment Guidelines: Project Selection, Materials, and Construction,” was created to assist contractors and FDOT inspectors to implement the new specification.

17. Key Words High friction surface treatment, HFST, horizontal curve, crash reduction, skid resistance, failure mechanism, benefit-cost, calcined bauxite, polymer resin binder, mil thickness, thermal compatibility, coefficient of thermal expansion, gel time, Al_2O_3, specification, guidelines		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia 22312 http://www.ntis.gov	
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EXECUTIVE SUMMARY

The State of Florida has successfully used high friction surface treatments (HFSTs) since 2006 to reduce wet weather crashes on tight curves and intersections and to maintain bridge decks; however, the Florida Department of Transportation (FDOT) has reported issues related to premature failure of the treatment. Various sections of HFST have experienced severe cracking and potholing of the pavement, delamination from the existing surface, and raveling of the aggregate from the resin binder. Another issue with HFST is that the high material costs limit the number of sections that can be treated annually. Consequently, there is a need to research the best materials and practices to eliminate premature HFST failures and reduce overall HFST costs, while maintaining or improving treatment life and friction performance.

The scope of this project was to:

1. Review the literature and conduct industry interviews on the state of the practice of HFST.
2. Document all existing HFST projects in Florida and analyze their performance based on distress, skid resistance, and crash reduction.
3. Perform field testing on six projects and evaluate their present performance and conduct forensic analyses as needed.
4. Perform a range of laboratory tests on different aspects of HFST materials and construction practices to improve durability and reduce costs.
5. Develop a revised HFST specification for Florida and an HFST Guidelines booklet.

Highlighted research findings from project documentation and field testing are:

- The bid unit cost of HFST in Florida was between \$26 and \$40/yd^2, and the total unit cost (including traffic control, repairs, striping, etc.) was between \$36 and \$113/yd^2.
- Crash reduction from HFSTs was most effective on tight curves, where the average reduction in crash rate was 32 and 75 percent for total and wet weather crashes, respectively. Crash rates did not notably change on wide curves/tangent but increased on average for intersections/approach.
- HFST is a cost-effective treatment for tight curves with a history of crashes. The average benefit-cost (BC) ratio on tight curves with a history of crashes was between 18 and 26 (depending on calculation method), with some sections greater than 50 and as high as 118.
- HFST is not cost effective, from a crash reduction perspective, on wide curves/tangents with no history of crashes. The cost effectiveness for bridge deck preservation was not part of this research.
- The cost effectiveness of HFST at intersections/approaches is still inconclusive. Half the observed sections had good BC ratios, while the other half had increased crashes.
- Different distress types were observed in the field (potholing, aggregate loss, surface cracking, substrate tearing, splotchy texture). Through forensic evaluation, several of the failure mechanisms were identified as discussed in the background section.

Highlighted research findings form the laboratory testing include:

- Aggregate loss is a function of binder thickness, where aggregate loss greatly increased for binder thicknesses less than 50 mils.
- A double application of HFST can mitigate issues with aggregate loss.
- Single applications on concrete appear to wear away faster than single applications on HMA; however, this phenomenon has not been proven or disproven yet in the field environment.
- The concrete tested had a coefficient of thermal expansion (COTE) value of 5 x 10^{-6}/°F and asphalt between 7 and 9 x 10^{-6}/°F. In comparison, the COTE of HFST is drastically higher, between 14 and 30 x 10^{-6}/°F. This would imply that stress builds up between HFST and the substrate during thermal cycling.
- The standard gel time test was not drastically responsive to changes in proportioning until a 25 percent change, but it is much more sensitive to temperature.
- A thin HMA overlay mix was successfully design using PG 76-22 binder and a coarse-size calcined bauxite. The design had good rutting resistance. The friction properties, while better than other HMA designs, are inferior to HFST.
- Two calcined bauxite aggregates with similar aluminum-oxide (Al_2O_3) contents both performed well in HFST friction testing. Another aggregate of unknown composition had good friction properties, but was not on par with calcined bauxite. (Of particular concern was the high micro-deval mass loss.)

Based on these and other findings, the researchers recommend the following:

Candidate Projects

The researchers recommend that agencies strongly consider applying HFST on tight crash-prone curves. Agencies should carefully consider if HFST would be effective at reducing crashes at intersection approaches and within intersections (i.e., identify if a significant source of accidents is skid related). When applied on wide curves and tangent sections (i.e., for maintenance of bridge decks), agencies should not expect to see significant economic benefits from crash reduction; however, benefits from pavement preservation may warrant the cost.

As concerns the existing surface type, the researchers do not recommend placing HFST on open-graded friction course (OGFC) pavements. While some projects have successful performance over OGFC, the material often causes more problems like excessive draindown, requirement of double-lift HFST, substrate cracking, and stripping. These surfaces should be milled out and inlaid with dense-graded mix prior to applying HFST.

The department may consider a minimum substrate strength requirement, but stricter requirements on the existing surface type and distress condition should resolve issues with substrate failure. The researchers do not recommend excessively stringent requirements on surface condition as it could unnecessarily drive up the costs of HFST application with marginal benefits to long-term performance.

Materials

The two calcined bauxite sources evaluated in this research are acceptable for HFST. The researchers recommend lowering the minimum required Al_2O_3 content for calcined bauxite to 86 percent. The minimum required content could likely be lowered further with negligible effect to performance; however, the data are not yet available to support this decision. The unknown aggregate type tested in this research may be suited for bridge-deck preservation.

The current specification for polymer resin binders is adequate. In the future, the department may consider a specification with greater flexibility to mitigate problems with thermal incompatibility. This change would need to be balanced with the binder strength and hardness.

An alternative approach to HFST could be incorporating calcined bauxite into HMA design. While a successful design can be created, it is likely an infeasible option considering the economics of producing and constructing such small quantities. It may only be feasible if paving a winding rural road. Even then, the friction performance of this design is inferior to HFST.

Construction

The researchers recommend a contractor requirement to place an HFST test section before full-scale application. This gives the contractor a chance to identify and fix problems, and of equal importance, the FDOT inspector will become familiar with the process and potential issues.

Surface preparation of all projects should include a high-pressure air wash after sweeping to remove remaining dust and debris. Concrete surfaces should require shot blasting to a texture level of concrete surface profile (CSP) 5.

Many problems associated with poor mixing, uneven resin binder thickness, and insufficient aggregate coverage could be solved by using automated application equipment. The researchers recommend FDOT adopt this requirement into their specification. This is expected to increase the cost of HFST early on, especially since very few companies have this capability. With time, as more vendors enter to compete, the costs are expected to decrease.

Neither the gel time test nor the FTIR test are recommended as quality control methods. The tests are not sensitive enough to misproportioning except at extremes, and therefore, the tests are not substitutes for proper maintenance and calibration of the application equipment. Still, the simple gel time test does have a place to ensure against major problems. The required mil thickness in the current HFST specification is adequate and the researchers recommend that contractors and inspectors check the actual mil thickness from time to time with a thin film thickness gauge.

Currently the contractor is required to sweep after the initial cure and do follow-up sweeping after two weeks. The researchers recommend another follow-up sweep between 24 to 48 hours on high-volume roadways.

HFST Specification and Guidelines

After discussing with FDOT and industry leaders, many of these recommendations have been incorporated into a revised FDOT specification for HFST (Section 333). The latest recommended specification is contained in Appendix E

In addition, a user-ready booklet, titled “High Friction Surface Treatment Guidelines: Project Selection, Materials, and Construction,” was developed to mirror the FDOT specification and provide additional insight into many requirements and recommendations. The document can be obtained by contacting the FDOT State Materials Office (Charles Holzschuher. charles.holzschuher@dot.state.fl.us).

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CHAPTER 1
INTRODUCTION

Problem Statement

Crashes on the nation's roadways are a leading cause of fatalities and major injuries in the United States. Roughly 21 percent of fatal crashes occur at intersections and 28 percent at horizontal curves. For horizontal curve crashes, over 80 percent of these involve some form of roadway departure (*1*, *2*, *3*).

In recent years, agencies have learned the effectiveness of high friction surface treatments (HFSTs) to reduce crashes on horizontal curves, especially during wet weather. HFSTs are very thin treatments composed of polish and abrasion-resistant aggregates bonded to the pavement surface using a polymer resin binder (Figure 1.1) (*4*, *5*). When placed on crash-prone curves, HFSTs have reduced crashes by 60, 80, and even 90 percent (*6*, *7*, *8*). This kind of safety performance makes HFSTs very cost effective, and the quick construction and return to traffic are more desirable than time-intensive and costly roadway geometry corrections.

Figure 1.1 – High friction surface treatment

The State of Florida has successfully used HFST since 2006 to reduce wet weather crashes on tight curves and intersections and to maintain bridge decks; however, the Florida Department of Transportation (FDOT) has reported issues related to premature failure of the treatment. Various sections of HFST have experienced severe cracking and potholing of the pavement, delamination from the existing surface, and raveling of the aggregate from the resin binder. Another issue with HFST is that the high material costs limit the number of sections that can be treated annually. Consequently, there is a need to research the best materials and practices to eliminate premature

HFST failures and reduce overall HFST costs, while maintaining or improving treatment life and friction performance.

Research Goals and Scope

The goal of this research was to provide FDOT with an updates HFST specification and accompanying HFST Guidelines, describing the project selection, materials, and construction considerations. These guidelines would help minimize premature HFST failures, thus increasing the HFST service life and reducing long-term costs.

The scope of this project was to:

1. Review the literature and conduct industry interviews on the state of the practice of HFST.
2. Document all existing HFST projects in Florida and analyze their performance based on distress, skid resistance, and crash reduction.
3. Do field testing on six projects and evaluate their present performance and conduct forensic analyses as needed.
4. Perform a range of laboratory tests on different aspects of HFST materials and construction practices to improve durability and reduce costs.
5. Develop a revised HFST specification for Florida and an HFST Guidelines booklet.

Outline

This report contains six chapters:

- Chapter 1 describes the problem, research goals and scope.
- Chapter 2 gives background information for HFST best practices, performance, and failure mechanisms.
- Chapter 3 documents existing HFST projects in Florida.
- Chapter 4 presents field testing procedures and results.
- Chapter 5 details laboratory testing procedures and results.
- Chapter 6 summarizes the research, findings, and offers recommendations.

CHAPTER 2
BACKGROUND

This chapter provides background information about HFSTs, namely:

- Best practices (project selection, materials, and construction),
- Performance and benefit-cost, and
- Failure mechanisms.

HFST Best Practices

The section discusses best practices for project selection, materials, and construction. This information is generalized for the industry and not only based on Florida experience or specifications. Much of this information, (especially what is specific to the FDOT requirements), is also contained in a user-friendly HFST Guidelines booklet. The Guidelines can be obtained by contacting the FDOT State Materials Office.

Project Selection

The primary purpose for installing HFST is to reduce crashes in accident-prone locations. HFST is used to increase skid resistance and even compensate for deficiencies in geometric design. When a particular location may have insufficient super elevation or too small radius, applying HFST can be an economical temporary or permanent solution. Such locations are often loop ramps, tight radius curves, and intersections with high-speed approaches. HFSTs has also been applied in transition lanes, high speed entrance/exit ramps, steep grades, and approaches to rail, schools, trail crossings, and tolling areas. However, the effectiveness of the treatment to reduce crashes in these latter scenarios is questionable since these crashes are more due to driver error and not a friction inadequacy. Typical applications are between 300 and 1,500 ft.

Another use for HFST, common in Florida, is as a bridge deck sealer. The epoxy is used to seal and restore the concrete surface, and the high friction aggregate is then used to ensure adequate skid resistance. In these cases, where crash reduction is not a concern, there is an opportunity for cost-savings by employing more common aggregate like granite or flint.

Whatever location is selected, the existing surface must be in good condition. Cracking on the surface will readily reflect through the HFST. If the strength of surface layer is weak, a problem with certain asphalt pavements, then the high shear forces after HFST construction can accelerate layer failure. Other HMA distresses to look out for include wide spread rutting >0.25 inch deep, raveling, and bleeding. Concrete pavements should likewise be in good condition. Moderate or severe distress and shattered slabs in more than 3 pieces should be removed and replaced. Details on how to address these concerns are discussed in the *Surface Preparation* sub-topic.

Materials

HFST is composed of hard, polish- and abrasion-resistant aggregate bonded to the pavement using a polymer resin binder. This section discusses the most common aggregate and binder types used and gives details on the properties, production, and handling of these materials. A list of manufacturers and suppliers of different aggregate and binder products is provided on the American Traffic Safety Services Association (ATSSA) website for HFST (*9*).

Aggregate

Aggregate specifications require a uniform gradation with a maximum size of 3 to 4 mm and a minimum size just over 1 mm (passing No. 6 sieve, retained on No. 16). The aggregates often have a hardness or durability requirement (LA abrasion or micro-deval). Specifications often require a minimum aluminum oxide content, which relates to the purity of the bauxite. The aggregate should be delivered clean and dry and maintained that way. Friction requirements may be explicitly required in the form of a polished stone value (PSV), texture imaging, or an as-built friction value from a skid trailer or dynamic friction tester (DFT) testing.

Calcined Bauxite

The most common aggregate used for HFST is calcined bauxite (Figure 2.1). Some agencies, like Florida Dev 333, explicitly require this aggregate, while others have strict performance requirements which exclude other options. (*10*)

Figure 2.1 – Calcined bauxite, crushed and graded for HFST

Raw bauxite is an aluminum ore mined in many parts of the world. When heated to a high temperature (1,000 to 1,500 C), the aggregate undergoes calcination, increasing the physical hardness. Compared to other aggregates, this one comes at a higher cost, which can be explained by the following points (*11*, *12*):

- There are no significant reserves of bauxite within the United States. Current leaders in bauxite production are:
  - Australia,
  - China,
  - Brazil,
  - India,
  - Guinea, and
  - Jamaica.
- The use of bauxite for HFST is very small:
  - Of the bauxite mined, more than 95% is converted to alumina.
  - The remaining 5% is used for abrasives, chemicals, proppants, and refractories.
  - HFST uses refractory-grade bauxite, but the refractory industry uses about 24 times more material than the paving industry.

Currently, the calcined bauxite for HFST comes from China. It is being produced at the higher *refractory-grade* temperature (~1,400 C) and has an alumina oxide content of 87% or higher. It is often shipped to the states then crushed to a uniform size between 1 to 4 mm. The aggregate undergoes a rigorous washing and drying before being bagged and shipped to regional businesses like the HFST installer.

In the upcoming years, we expect to see the price of calcined bauxite come down for the following reasons:

- Higher demand for HFST applications,
- Diversification of bauxite suppliers (opening up trade relations with a suppliers in India),
- Potential use of bauxite with lower alumina oxide contents (80%), and
- Potential use of bauxite calcined at the lower *abrasive-grade* temperature (1,100 C).

Alternative Aggregates

Other aggregates such as flint, basalt, granite, quartzite, processed glass, slag, and taconite can be used as alternative aggregate materials. Several of these options have been studied recently by the National Center for Asphalt Technology (*13*). The test results and some of the important observations based on the NCAT study are provided herein. These aggregates can be placed in a similar manner and may perform adequately in a less demanding environment (bridge deck preservation). In critical locations they have not provided the duration of friction service to be classified as an HFST. A brief description of some of these alternative aggregate materials is provided below:

- **Basalt –** A volcanic rock formed by the rapid cooling of lava which is rich in magnesium and calcium oxides and, depending on chemical composition, can be high strength.

- **Emery –** A rock containing corundum (aluminum oxide) and iron oxide that has been used as an abrasive in products such as sandpaper.
- **Granite –** A combination of quartz and potassium feldspar. Its mineral composition and interlocking crystals result in hardness and abrasion resistance, producing polished stone values greater than 62 (*14*).
- **Steel Slag –** An impure by-product of steel production consisting of a complex solution of silicates and oxides. For use in HFSTs, it must first be crushed and screened (*14*).
- **Taconite –** An iron bearing sedimentary rock that contains quartz, chert, or carbonate.

For aggregate selection, resistance to polishing is equally important as high initial friction in HFST applications. Therefore, a test method or parameter which quantifies the polishing resistance of an aggregate will serve as an effective way to qualify alternative aggregate materials in making HFST. An aggressive micro-deval (50 minutes instead of 15 minutes) procedure developed and used by NCAT can be a good test to qualify an aggregate for HFST. (*13*)

Aggregate blending was thought to be an effective way to minimize the aggregate cost and meet the friction demands at the same time. Based on the following field examples (*12*), it seems aggregate blending may not be considered as a cost-effective alternative.

- Vancouver WA used recycled ceramic aggregate blending with bauxite – it didn't perform well because of aggregate polishing out problem
- Wisconsin used basalt and CB blend - didn't perform well
- Issues related to aggregate blending was also reported in UK

Polymer Resin Binder

The role of binder is to hold the high friction aggregate in place. Because of the extreme shear forces inherent to high-speed curves and approaches, the binder must have a high tensile strength and stiffness, much higher than traditional bituminous materials can afford in hot summer months. The most common binder is epoxy-resin. This material, and other types of polymer resins are described below:

- **Epoxy-Resin –** A two-part binder that consists of a resin with a portion of oils that reduce viscosity allowing it to flow (an extender) and an epoxy that contains the curing agent (a hardener) (*14*). Epoxy properties can be adjusted through additives, though some of these additives are non-reactive, meaning they do not contribute to strength or flexibility once the epoxy has cured. This may be susceptible to UV aging. Applications at temperatures below 60°F should be avoided due to excessive curing times. This is the most common resin binder used in Florida.
- **Polyurethane-Resin –** A multi-component binder system consisting of a resin for flow and polyurethane for hardening. This system was designed for faster curing times and can even

be applied at lower temperatures. even at lower temperatures (*14*). This material is also more flexible after curing and is resistant to UV degradation.

- **Polyester-Resin –** Good durability and bond strength. Short to long curing times, depending on the use of an additive. This system may be applied at lower temperatures. It is also resistant to UV aging. It has a good track record, but is less common in Florida.
- **Methyl Methacrylate (MMA) Resin –** Moderate durability and bond strength. It has a faster curing time and may be applied at low temperatures. It is not extensively used, but is allowed under some specifications. When allowed, the specifications have a special provisions for this material since it does not meet the standards for material strength and hardness.
- **Acrylic-Resin –** A two component system in which the aggregate contains the curing agent that was designed to offer a faster curing time than epoxy-resin.
- **Rosin-Ester –** A thermoplastic binder that is pre-applied to the aggregate during a manufacturing process. The aggregate-rosin mix is heated on site for placement on the pavement surface, typically with a handheld box (*14*).

To make the resin-portion (Part B) of these binders workable, a plasticizer is added (*12*). If the plasticizer is non-reactive (does not chemically react with Part A), it acts as filler in the final solidified system. The filler can be UV sensitive and may leave the system over time, making the system more brittle. On the other hand, the use of a reactive plasticizer will not suffer from UV degradation issues and may be a solution to avoid binder degradation over time. The earlier practice was to use cresole as a reactive plasticizer; however, cresole fell out of favor due to environmental concerns. It is still allowed in some states, including Florida, but banned in others.

Polymer resin binders have specified viscosities, gel and cure time, tensile strength, elongation, hardness, compressive strength, water absorption, and adhesive strength. In current practice, binder tests are conducted on new epoxy at room temperature and do not consider performance at elevated temperatures or after environmental exposure. This is one area that could use further study, especially considering that polymer resins properties change with temperature and may change with UV exposure. Other research topics include reducing the effects of thermal incompatibility between HFST and the substrate by increasing the flexibility of the solidified resin systems.

Alternative Systems

The cost of HFST is very high. An alternative high-friction system may be possible at a reduced cost. Two options are:

- Thin gap-graded overlay using calcined bauxite or blend.
- Slurry using calcined-bauxite fines.

However, further research is needed in order to investigate the effectiveness of the above products / approaches.

Based on New Zealand's experience on applying HFST on HMA substrate, some possible control measures as alternative systems or modification of the current practices are listed below:

- Use of harder, stiffer and stronger binder in asphalt substrate
- Use of coarser HMA mix - SMA type mix with polymer modified binder
- Reduction in deflection – increasing the stiffness of the asphalt layer and reducing the stiffness of the HFS layer
- Reduction in striping – use of additives (e.g. adhesion agents) in the HMA binder and the HFS binder or binder modification
- Use of softer / flexible HFS binder – a binder which is tough enough to hold the aggregate (e.g. CB) in place but has very similar properties to conventional HMA so that HFS expands, contracts, bends and breaths with the asphalt.

Construction

Construction of HFST involves surface preparation, mixing and applying the resin binder, then applying aggregate. The treatment can usually be opened to traffic after a few hours of curing. Details for these steps are given in the following subsections.

Test Strip

Many agencies require the contractor to place a short test strip before full-scale application. The purpose being to demonstrate to the agency correct surface preparation techniques, performance of the equipment to proportion and mix binder, correct application of rate of materials, and proper curing and sweeping methods. This gives the contractor a chance to fix any problems, and of equal importance, this helps the agency inspector become familiar with the process and potential issues.

Surface preparation

Surface preparation is essential for all successful HFST installations. Prior to the installation of an HFST, the condition of the pavement surface at a site should be examined, particularly for cracks, potholes, and other surface defects. If preexisting conditions are not addressed, the new HFST may delaminate or the existing pavement itself may experience accelerated deterioration.

- Repair pavement defects such as spalls, pot holes, raveling and rutting prior to placing an HFST. Contact the manufacturer's Technical Service Department to review which materials will permit proper adhesion of HFST system. Clean and fill all inadequately sealed joints, including shoulder areas. HFST may be applied over pavements exhibiting minor rutting or heaving; however, the product is not intended as a repair for these conditions and will not level pavements.

- Pavement cracks greater than 1/4 inch in width and depth should be sealed. If sealing with asphalt-based products, do this at least 30 days prior to HFST installation. Otherwise pre-treat joints and cracks with the mixed polymer resin. Once the epoxy in the pre-treated areas has gelled, the HFST binder and aggregate topping installation may proceed.
- Based on the new FDOT specifications, the top layer should be milled and inlaid in the following conditions:
    - Cracking in or outside the wheel path covers 6 percent or more of the surface.
    - Widespread rutting is 0.25 inches or greater.
    - Raveling.
    - Bleeding surface mix.
- It is generally not practical to remove small oil spots, but very large or heavily saturated oil spots may need to be removed by removing and replacing the surface layer.
- Utilities, drainage structures, curbs, joints and any other structure within or adjacent to the treatment location should be protected. Existing pavement markings adjacent to the application should be covered.
- Pavement markings that are not covered or consist of material other than paint should be removed. HFST will not fully adhere to thermoplastic.
- The surface should then be swept clean and have a high-pressure air wash. The air wash uses dry compressed air at a minimum of 180 cfm. The air lance should be maintained perpendicular and within 12 inches of the surface.
- The surface should be abrasively cleaned by shot blasting to remove oils, curing compounds, carbonation, laitance, weak surface mortar, etc. The shot blasting should leave a texture matching the Concrete Surface Profile (CSP) 5 or greater. The texture should not go above 7. CSP reference chips can be purchased online from the International Concrete Repair Institute (ICRI) website.
- The blasted surface should again be swept clean and air-washed.
- There should be no visible moisture present on the surface at the time of the binder application. Compressed air may be used to dry the deck surface. A plastic sheet left taped in place for a minimum of two hours, according to ASTM D 4263, should be used to identify moisture in the deck.
- Joints should be taped to keep aggregate and epoxy out.
- New asphalt surfaces should have a minimum of 30 days traffic before HFST application. This is to close-up the voids in the asphalt surface, to avoid excessive draindown of the resin binder. On low-volume roads, this time should be extended. (*15*)
- New Portland cement concrete should be at least 28 days old before HFST construction.

While there have been many successful applications over open-graded friction course (OGFC), the higher texture, void structure, and lower strength can interfere with construction and decrease the treatment life. Consideration may be given to removing the OGFC and resurfacing with dense-graded asphalt.

Weather Considerations

The temperature, precipitation, and humidity should be considered before applying HFST.

- The surface should be between 60°F - 95°F when using epoxy resins. The curing time of epoxy is excessively long below 60°F, though other types of resin binders will still cure at temperatures near 50°F.
- The resin binder will gel and cure faster at higher temperatures, though the time may be excessively fast if the pavement and ambient temperatures are above 95°F.
- Higher temperatures also decrease the binder viscosity. Initially, this can aid in workability, though excessively low viscosity can cause problems with draindown and aggregate embedment.
- HFST application should be delayed if rain is likely.
- Humidity and wind will affect the cure time and should be considered during application.

HFST Application

HFST application involves four steps:

1. Mixing the binder,
2. Applying and spreading the binder,
3. Placing the aggregate, and
4. Curing and sweeping.

The first three steps can be done using a

- Manual,
- Semi-automated, or
- Fully-automated method.

Each of these methods is described in Table 2.1 and shown in subsequent figures (Figure 2.2 through Figure 2.5).

Table 2.1 – HFST Application Methods

	Binder Mixing	Binder Application	Aggregate Application	Other
Manual	• Combine the components in large plastic container with a power mixer. • Jiffy Mixer attachment should be used (more efficient, no air-entrainment.)	• Pour mixed binder from container. • Binder spread by hand using serrated squeegees • Correct squeegee operation takes training and practice.	• Tossed by hand. OR • Broadcast with a blower.	• Application rate: 200-300 yd^2/hr • Maximum permitted application size, 200yd^2 or where site conditions limit equipment access. • Lower bid price. May work binder into open-graded surfaces better than automated process. • Barriers to entry are too low, permitting underqualified contractors.
Semi-Automated	• Vehicle-mounted mechanical system to meter, mix, monitor, and apply binder • System may be heated to adjust viscosity and accelerate curing	• Pour mixed binder from a hose behind vehicle. • Binder spread by hand using serrated squeegees • Correct squeegee operation takes training and practice.	• Tossed by hand. OR • Broadcast with a blower. OR • Distribution bucket broadcasts agg.	• Application rate: 300 yd^2/hr . • More workability for texture variations such as open-graded surfaces • For manual applications, barriers are high-enough to keep out underqualified contractors, and low-enough to allow healthy competition.
Fully-Automated	• Vehicle-mounted mechanical system to meter, mix, monitor, and apply binder. • System may be heated to adjust viscosity and accelerate curing.	• Applies binder uniformly across paving width. • The binder rate or vehicle speed can be adjusted for different target thicknesses. • No hand working needed.	• Agg. is dropped uniformly onto binder right after automated binder placement. • Process similar to a chip spreader.	• Application rate: 1,500-2,300 yd^2/hr. • Most uniform, Less manual labor • More sensitive to surface texture variation or delayed drain-down into open-textures. • Expensive equipment ($600,000) written into specifications could create excessive barrier to entry.

Binder Mixing

- Proper proportioning and mixing of the binder is critical (*14*).
- Best results achieved using a vehicle-mounted mechanical system to meter, mix, and monitor the binder resin.
- The mixing process should not introduce air or bubbles into the binder.
- Indirectly heating the mixing system and binder components will lower binder viscosity for mixing and spreading. Higher temperatures will also shorten the curing time
- Low viscosity may be a problem on open-graded and new surfaces.
- Quality-control: “Dixie cup” gel time test is often used, but is not very sensitive to off-proportion mixing. A sample of binder is mixed in a small container and the gel time observed. If the binder does not gel within the specified time, there may be problems with binder proportioning or mixing.

Figure 2.2 – Binder mixing methods

Binder Application and Spreading

- Resin binder should be applied and uniformly spread.
- A film thickness between 50 and 65 mils (25 to 32 ft^2/gal) will provide enough binder depth for 50% embedment of the high-friction aggregate. The correct rate can be verified with a wet film thickness gauge.

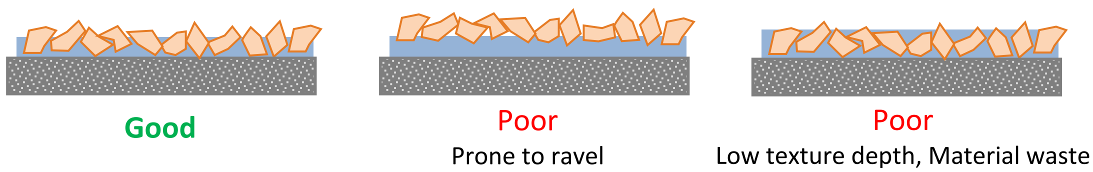


Figure 2.3 – Aggregate embedment depth

- Coarser and open-graded surface textures require higher application rates.
- Two full applications (binder and aggregate) are recommended for open-graded surfaces, where the binder tends to drain down and leave the aggregate with insufficient embedment.
- Personnel manually working the binder should wear spiked shoes to minimize tracking.

Figure 2.4 – Binder spreading

Aggregate Application

- Aggregate should be spread uniformly over the resin binder and
- Aggregate must completely cover binder, NO "wet" spots.
- Uniform in color.

Figure 2.5 – Aggregate spreading

Curing and Sweeping

- Binder takes two to four hours to set, depending on temperature and binder type.
- Before sweeping, aggregate should be very hard to push by hand.
- Only after initial sweeping can road be opened to traffic.
- Clean aggregate may be reused.

Contractor may plan to re-sweep the section after 3-5 days and again after 3-5 weeks

HFST Performance and Benefit-Cost Ratios

HFST performance has been documented in a variety of methods: (1) crash reduction, (2) friction and skid improvements, and (3) service life. This information, as well as benefit-cost approximations are summarized in this section.

Crash Reduction

Many lane-departure and intersection crashes occur when vehicle speed and roadway geometry create a "friction demand" higher than can be achieved from the pavement surface. Rather than invest in costly geometry corrections, an HFST may be applied to increase the "friction capacity." A FHWA technical advisory on pavement friction management stresses that horizontal curves tend to lose friction at a faster rate than other locations and require higher friction (*16*). One of the most cost-effective approaches to addressing high friction demand is the use of HFSTs for critical locations (*17, 18, 19, 20*).

Kentucky placed HFSTs on 26 curves and to date has seen an average reduction from 6.2 to 1.9 crashes per year at those locations. In another study, crashes rates were analyzed on 43 ramp and horizontal curve applications. Yearly wet weather crashes on horizontal curves decreased 86 percent, and total crashes fell 73 percent. On ramps, wet weather crashes and total crashes fell 85 and 66 percent, respectively (*6*). NCHRP report 617 investigated the crash reduction after friction treatments at locations with low friction numbers and a high proportion of wet-road crashes and found reductions of 24 and 57 percent for total and wet weather crashes, respectively (*7*). A 2012 literature review found that friction treatments generally reduce total crashes by 20 to 30 percent, and wet weather crashes by 50 percent (*21*). In a 2008 Wisconsin DOT study, the number of crashes at HFST sites decreased by 93 percent (*8*). Preliminary results from four sites in Michigan saw an overall 60 percent reduction in crashes after one year (*22*).

There are multiple points that should be reviewed when considering the above information about previous HFST applications and findings:

- The crash reduction performance of HFST may be artificially inflated, compared to other pavement treatments. This is because HFST is usually applied to high crash-rate locations while other treatments are placed on a wide range of surfaces. While crash reduction on these problem sections is clearly apparent, other treatments may have also reduced crashes in a comparable scenario.
- Another consideration is that HFST can only be effective where surface friction demand is originally insufficient. The affected crashes are typically wet weather roadway departures around horizontal curves and highway loops. Other types of crashes (distracted/drunk driving, side swipe/head on, etc.) will be largely unaffected by an HFST installation.

- One final note is that many publications discuss HFST crash reductions for a limited set of HFST sections. They highlight the best performers and present a skewed perspective.

Friction and Skid Improvements

Comparisons of skid before and after HFST installations are very common; however, this comparison is not entirely appropriate since HFST skid resistance is independent of the existing surface. A more appropriate discussion is to compare the initial and long-term skid resistance of HFST.

Meggers evaluated the effectiveness of the application of HFST using flint at several locations in Kansas. (*23*) For one project, the initial skid number (SN30R) was 88, and after four years dropped to 58. Another project had an initial SN40R of 70, and after four years, the skid value dropped to 49.

In 2008, the Wisconsin DOT conducted a study to evaluate if the HFST was a cost-effective technique to improve the safety of roadways and found that the average initial friction number was 73, and the value was 59 after five years. (*8*) The Iowa DOT studied the skid resistance of the HFST applied on a highway bridge deck and the results indicated that the initial SN was 67.5, and four years later, the SN was 64.5. (*24*) In another Iowa DOT case study, the average skid number was 74 after application. A case study in Michigan shows that the DFT (at 20kph) was 0.98 after application and 0.94 after one year. (*22*)

Service Life

Like all pavement materials, defining the service like of HFST is very difficult. The rate of deterioration is dependent on many factors such as the existing pavement condition, material selection, construction quality, traffic severity, climate condition, etc. Some of these factors can be controlled by the DOT and contractor while others cannot.

To illustrate the complexity of the issue, consider a comparison of HFST applied in Florida to California. Both states have placed many projects on open-graded mixes, however California is getting much more life out of their applications. This may stem from several issues: (*12*)

- The Florida OGFC has a larger gradation so more material penetrates into the mix.
- Most applications in California were done using a fully-automated system.
- California uses a quality epoxy urethane on almost all projects while Florida has used a variety of resin binders, some of which may be inferior.
- California only uses double-applications over OGFC while Florida has constructed some single-lift applications in the past.
- The climate in Florida is much more severe than California, with higher temperatures, more rain, and more UV exposure.

Some life expectancy values reported in the literatures are summarized below:

- Based on international experience, at least 7-12 years of service can be expected with correctly installed HFSTs. Some of the bridge deck applications in USA indicated a service life of over 15 years.
- Vendors have reported from 5-8 years for 15,000 vehicles per day, and up to 5 years with 50,000 vehicles per day.
- Michigan reports 12-15 years of durability for bridge deck sites, including interstate highways with 48,000-62,000 ADT.
- When incorrectly constructed or applied in the wrong scenario, the service life is drastically reduced (0 to 4 years, depending on the cause of failure.)

What is not stated in the literature, however, are the projects that failed prematurely

Benefit-Cost Ratios

The unit cost of HFST is high compared to typical maintenance projects. Recently, unit costs have ranged from \$25/yd^2 to \$35/yd^2 (*10*). The price, however, has been steadily dropping for larger projects and where small installations have been bundled. For example, a state recently reduced their treatment cost to about \$19/yd^2 by rolling together several locations totaling 77,000 yd^2 into one project. The Kentucky Transportation Cabinet has over 100 HFST projects, mostly on rural two-lane roads. The average unit cost on these small 750 yd^2 projects is between \$19 and \$21/yd^2. The cost of HFST in Florida started between \$34 and \$40/yd^2 and has come down to \$26/yd^2 in 2014 (*10*).

The benefit for safety improvements can be estimated through economic and societal impact savings for the reduced crashes. The National Highway Traffic Safety Administration (NHTSA) routinely provides the societal impact estimations for a variety of crash scenarios. In the method shown in Table 2.2, crash types are divided into the five-category KABCO scale. The scale is used by law enforcement officers to rate injury severity at the scene of the crash as follows:

K − Fatality,
A − Incapacitating injury,
B − Non-incapacitating injury,
C − Possible injury, and
O − Property damage only.

Table 2.2 – Societal Impacts of Motor Vehicle Crashes in 2010 (KABCO scale). (*25*, *26*)

Cost Type	Cost Per Crash By Type (Thousands $)				
	K	A	B	C	O
Lost Quality of Life	$7,750	$919	$252	$108	$31.8
Economic	$1,400	$82.0	$23.7	$19.5	$10.4
Societal Impact (Total Cost)	$9,140	$1,001	$276	$128	$42.3
FDOT Societal Impact (Total Cost)	$10,000	$819	$163	$100	$6.50

The cost for each crash type is the sum of a "Lost Quality of Life" and an "Economic" category. The benefit of a safety improvement would then be the sum of societal impacts that did not occur, most importantly fatal and severe injury crashes, which are several factors more costly than minor crashes. When discussing HFST performance, the total crash reduction is most often the focus, but it is the specific reduction in fatal and severe injury crashes that should be the focus when determining the HFST benefit.

The Florida Department of Transportation (FDOT) also uses the KABCO scale for evaluating the financial impact of crashes. The agency uses a higher cost for fatalities and more conservative costs for injury and property damage. The cost of an average crash (regardless of type or location) is $195,000.

A few benefit-cost ratios for HFST were found in the literature. The Virginia Tech Transportation Institute (VTTI) reported on four projects. The benefit was calculated based on savings to vehicle crashes, injuries, and fatalities, but using numbers much more conservative than those in Table 2.2 (a reduced benefit due to lower assumed crash costs). The project cost was based on the section area and price per SY, rather than the total project cost. The benefit-cost ratios ranged from 0.47 to 8.45, with an average of 3.64, indicating a positive return on investment (*14*). If the values above were considered for the benefit calculation, the saving would be much more pronounced. A CalTrans presentation covered the methodology for calculating benefit-cost from a project planning perspective. One case study had a benefit-cost ratio of 3.03, and example scenarios had much higher ratios (*27*). A recent before and after study from the South Carolina DOT for a series of curve installations indicates benefit-cost ratios of about 24 to 1.

HFST Failure Mechanisms

The service life of HFST is often cited as 7 to 10 years, and even greater in some circumstances. (*14*) But there are many cases where HFST has failed prematurely, resulting in costly repairs and a poor return on investment. The most prominent failure types are aggregate loss, delamination, and cracking. Construction defects can also diminish treatment performance and aesthetic. This section describes the variety of mechanisms that lead to these types of failure.

Aggregate Loss (Raveling)

The most common type of failure is aggregate loss, or raveling. Skid resistance can be significantly compromised depending on how much aggregate is lost. This can occur within the wheel path (Figure 2.6) or across the whole application (Figure 2.7). Aggregate dislodgement under traffic is a result of one of two problems:

1. Insufficient aggregate embedment in the resin binder.
   OR
2. A weak bond between the aggregate and resin binder.

Figure 2.6 – Aggregate loss over uneven texture (Memorial Blvd to I-4)

Figure 2.7 – Aggregate loss over concrete, single HFST application (I-95 to Congress)

Poor aggregate embedment can occur at the time of construction if:

- Binder application rate is too low or non-uniform.
- Binder draindown can occur in open-graded surfaces and new construction. (Figure 2.8)
    - Problem more severe for low viscosity binders and warmer construction temperatures.
    - A second application can mitigate problems embedment problems in the first application.
- Aggregate was applied too late, after binder gel time.

A weak aggregate-binder bond can happen at the time of construction if:

- Aggregate is not clean.
- Aggregate is not dry.
- Aggregate was applied too late, after binder gel time.

Though not necessarily a failure mechanism, insufficient aggregate coverage at construction can also compromise the pavement friction and treatment life.

Figure 2.8 – Aggregate loss over OGFC (FLL Airport)

Delamination

Delamination occurs when the bond between the treatment and existing surface fails. It is recognized by the complete HFST system coming up with little or no substrate attached (Figure 2.9). The root causes of failure are:

- Thermal incompatibility between HFST and the substrate.
- Aged concrete surface not properly prepared with shot blasting.

- Surface contamination during construction – dirt, shot blasting dust, oil spills, etc.
- Surface moisture during construction (including dew).
- Stripping of HFST from trapped or infiltrating moisture.

To avoid this problem, surface preparation practices described in the *Best Practices* section should be followed. If applying over an OGFC, the superelevated curves should be completely treated to prevent water from infiltrating beneath the HFST.

Figure 2.9 – Delamination: Bridge deck and a double layer HFST

Uncured Binder Failure

This is a dramatic failure mode where the binder neither adheres to the surface nor holds the aggregate in place. After construction, the binder never properly cures, but is a sticky viscous gel or a weak plastic. It is a result of:

- Incorrect binder formulation,
- Incorrect proportioning, or
- Poor mixing (most common).

If the binder itself is incorrectly formulated or proportioned, the problem will be wide-spread. If it is a mixing problem, the problem will be manifest as splotchy localized failures.

In the case of two Florida sections (Tampa-I-275 to US 60 and Brandon-US-60 to NB I-75), an inexperienced contractor rented an epoxy mixing truck from the HFST vendor. The equipment malfunctioned and could not completely mix the two epoxy components. After 3 years, the project is covered by localized failures (Figure 2.10). On both projects, the HFST was applied over OGFC. As the aggregate and binder delaminated, moisture collected in the OGFC, stripped the aggregate, and created potholes under traffic. Other examples of uncured binder failure are shown in Figure 2.11and Figure 2.12.

Figure 2.10 – Widespread localized failures due to poor binder mixing (US 90 – I-75 NB)

Figure 2.11 – Soft splotchy areas shortly after construction (I-95 ramp)

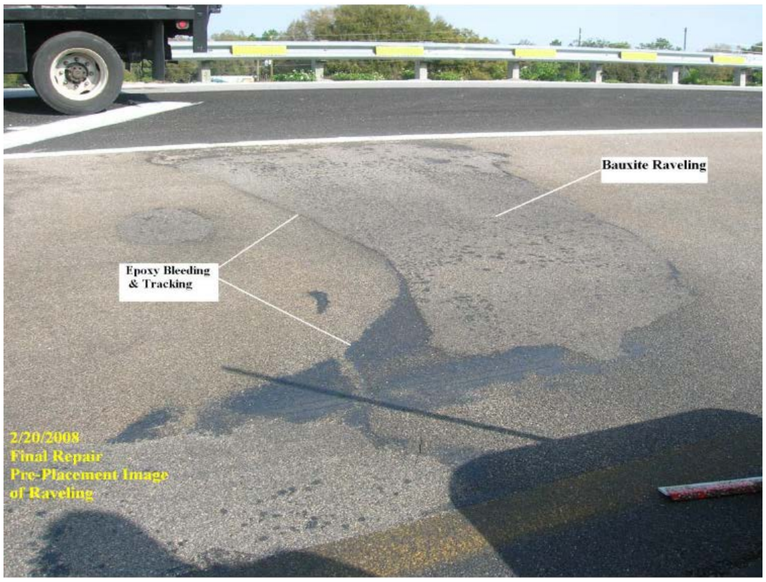


Figure 2.12 – Result of incorrect proportioning: aggregate loss, epoxy bleeding, and epoxy tracking (Polk Co. Parkway to I-4)

Substrate Failure

Some project failures, at face value, appear to be a delamination or cracking problem, but in reality are a failure of the substrate. The cause of substrate failure falls into one of three mechanisms: (1) tearing under higher stress, (2) stripping, and (3) thermal incompatibility. These problems are observed on asphalt pavements and particularly for weaker substrates like OGFC.

Tearing

Substrate tearing is manifest as cracking distress. Figure 2.13 shows both transverse cracking at the approach and random cracking around the curve. The amount and severity of cracking is highest where traffic conditions are most severe. This particular example is an uphill, high-speed off-ramp to a signalized turn. The substrate is an old open-graded mix.

The exact mechanism is not proven but theorized in Figure 2.14. As a vehicle turns, brakes, and accelerates, the tires generate shear forces on the pavement surface. There is also a small amount of slipping that occurs, especially when turning. On an aggressive high-friction surface, the amount of slipping is reduced, and as a consequence, the shear stress between the tire and surface increases. These higher shear stresses can accelerate the deterioration of weak substrates.

Figure 2.13 – Substrate tearing at an approach (transverse) and around curve (random) (Boca Raton-I-95 to Congress)

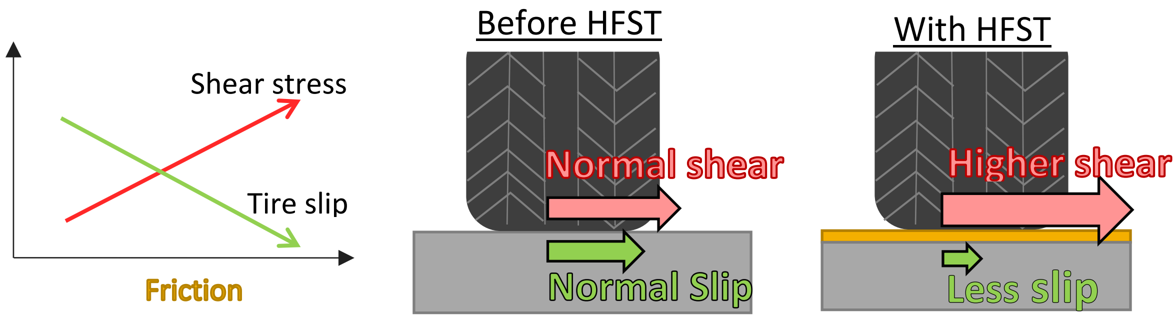


Figure 2.14 – Theoretical mechanism of substrate tearing

Stripping

Stripping may first look like a delamination failure, except that the actual location of failure is in the substrate, and not at the HFST bond interface (Figure 2.15). Moisture at the time of construction, or moisture that later infiltrates, becomes trapped beneath the HFST and can strip the asphalt under traffic and high temperatures. Waters (*28*) investigated HFST failures in New Zealand and found that most cases were a failure within the top 20 mm of the asphalt substrate. This stripping condition is worsened by the previously described mechanism of higher shear stress.

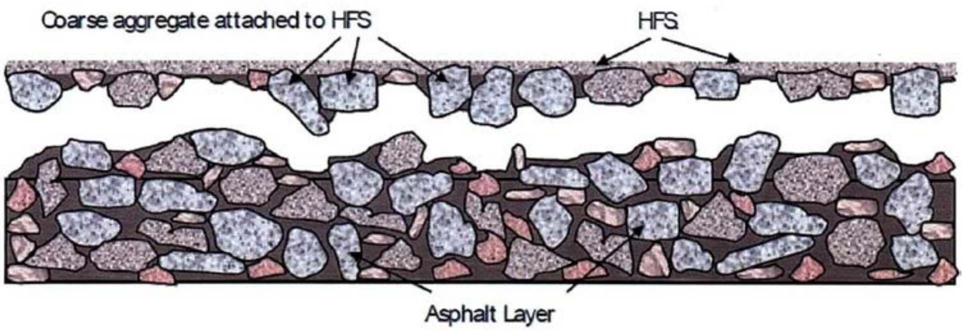


Figure 2.15 – Cohesive failure (*28*)

Thermal Incompatibility

The last substrate-failure mechanism is thermal incompatibility. This type of failure is observed as surface cracking in roughly circular patterns. If the cracked area is removed, the failure in the substrate is in the shape of an inverted cone. (*29*) This is caused by (1) a difference in thermal coefficients, (2) a difference in layer stiffness (resistance to bending) and (3) low tensile strength of the substrate. The thermal coefficient for typical epoxy is 25 to 36 E^{-6} inch/(inch*°F). (*30*). This property for asphalt is unknown, but will be measured in later laboratory testing. With temperature changes, the epoxy layer and asphalt layer expand and contract at different rates, generating thermal stress. If this stress exceeds the substrate strength, then the substrate will fail. One particular epoxy was more susceptible to this problem than other epoxies because it was stiffer and would not flex under these stresses. The project in Figure 2.16 used this epoxy. This product is not in general use anymore.

Figure 2.16 – Random cracking likely from thermal incompatibility (Miami Beach-SR A1A)

Reflective Cracking

Epoxy has some flexibility and generally resists brittle cracking under traffic. Most observed cracking, if not associated with substrate failure, is reflective cracking. Existing cracks will propagate into the HFST under traffic loads or thermal cycling. (Figure 2.17) Two such examples are projects in North Carolina and Colorado. Reflective cracking here was combined with stripping.

Figure 2.17 – Reflective cracking

CHAPTER 3
DOCUMENTATION OF EXISTING PROJECTS

This chapter presents the methods and findings of a comprehensive documentation of all known HFST projects in Florida. The purpose of this effort was to evaluate HFST performance from the following perspectives:

- Treatment durability,
- Skid resistance, and
- Crash rate reduction.

A benefit-cost analysis was performed based on crash reductions.

Procedures

The research involved 1) collecting data for all Florida HFST projects and 2) analyzing the benefit-cost ratios and identifying performance predicting factors. All collected data are summarized in Appendix B.

Data Collection

The researchers identified every known HFST project in Florida through interviews to the DOT Districts. For each project, the researchers attempted to collect the following information:

- Project location,
- Contract and bidding details,
- Roadway geometry,
- Traffic characteristics,
- Construction notes,
- Known distresses,
- Skid data, and
- Crash statistics.

Project location information included the HFST application length, width, and area. The bidding details had the total project cost, and in some cases the unit HFST cost.

Each section was classified by the roadway type: intersections, tight curves, and wide curves/tangents. Tight curves included horizontal curves, curve ramps, loop ramps, and reverse curves, all with radii less than 1,000 ft. Curves with radii greater than 1,000 ft. were grouped with tangent sections. Some projects had multiple section types (e.g. a curved approach) and the researchers decided which section attribute was the most critical from a crash perspective.

Crash data were requested for the 5 years before HFST construction and after construction up to the present. All but two sites had at least one complete year of post-construction crash data. The crash data were limited to crashes within the physical limits of the HFST and excluded crashes occurring within the period of construction activity. The crash data were coded according to the KABCO system and separated based on total and wet weather crashes. Crash rates, in crashes per million vehicles, were calculated using Equation 1.

$$Crash\ Rate/MV\ = \frac{\frac{Crashes}{year}}{AADT * 365} * 1{,}000{,}000 \qquad \text{(Equation 1)}$$

where: MV = Million vehicles

AADT = Average annual daily traffic

Advanced procedures for processing crash data (e.g., normalizing against control sections, identifying and filtering individual crashes based on crash conditions, etc.) were outside the scope of this project. Normalizing against control sections is particularly difficult when many of the sections of concern are outliers. Also, the often-used crash rate metric of crashes per million vehicle miles traveled (MVMT), which normalizes for the section length, was found to misrepresent the data since section lengths were comparatively short.

Data Analysis

The benefit-cost analysis was performed at the level of individual sections of each HFST application, rather than the project level, which would aggregate all sections within a single project. In many cases, a project could have multiple applications on different sections and roadway types.

The HFST benefit was found by comparing the cost of crashes before and after the application. The societal cost of crashes was estimated using three different methods. First, benefit was calculated with the average annual change in total crashes per year for each FDOT-KABCO classification. The crash reductions were multiplied by the corresponding FDOT societal impact values and then summed together. The second approach was done by multiplying the total crashes per year by the average crash cost of $195,000, used within FDOT (*26*). The last approach used the wet weather crashes per year multiplied by $195,000. In each case, the benefit was multiplied by five to represent a minimum 5-year service life.

The HFST cost used in the analysis was the estimated cost of each section. This was calculated as shown in Equation 2. First, the average unit HFST cost was calculated. Rather than using the HFST unit bid unit price, which only considers the materials and labor costs directly associated with the HFST, the comprehensive unit cost considers other costs like traffic control, striping, repairs, etc. Identified outliers were excluded when calculating this average. The comprehensive unit cost was then multiplied by the section area. By using an average unit cost, the researchers could normalize for changing costs over time, remove the effects of high and low bids, and avoid issues when the project costs included other construction work unrelated to the HFST.

$$Cost\ (\$) = Avg.Unit\ HFST\ Cost(\$/yd^2) \times Section\ Area(yd^2) \qquad \text{(Equation 2)}$$

The benefit-cost calculation for each section type is shown in Equation 3. This averages the BC ratio of individual sections. This BC ratio does not normalize for traffic volume as the crash rate calculation does.

$$BC\ ratio = \frac{\sum_i^n [Benefit(\$)_i / Cost(\$)_i]}{n} \qquad \text{(Equation 3)}$$

Results

Project Data

All HFST applications throughout the state are shown in Figure 3.1. There were 23 projects, which comprise 47 unique HFST sections. Of these, complete cost data were only available for 15 projects, and both before and after crash data for 35 sections. There were 16 sections classified as tight curves, 16 and wide curves/tangents, and 6 intersections/intersection approaches.

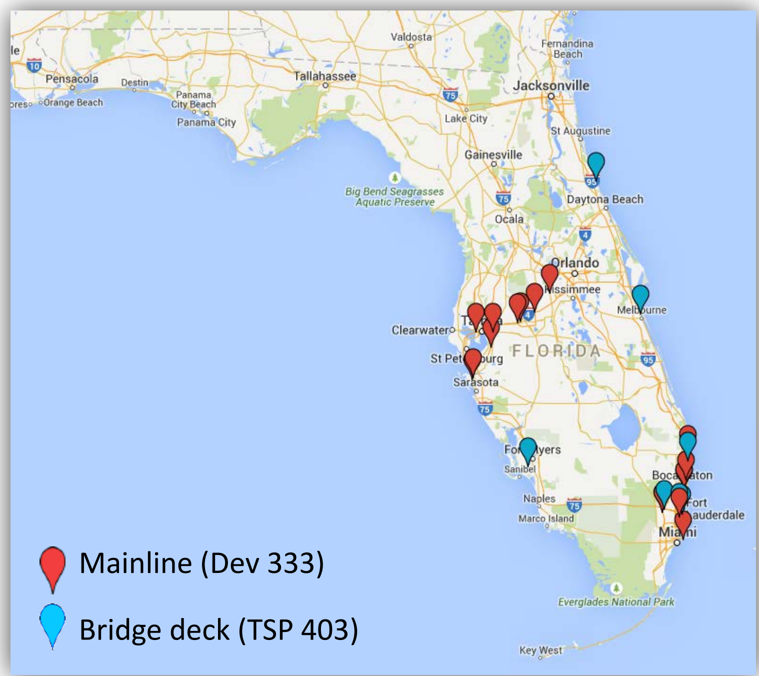
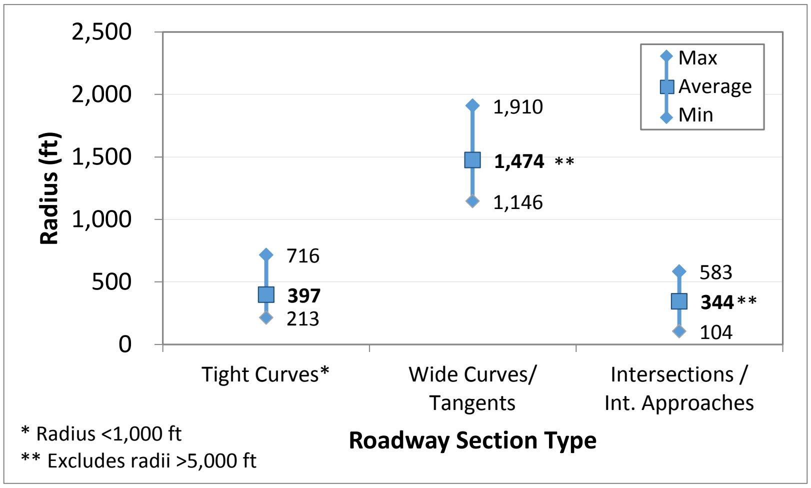


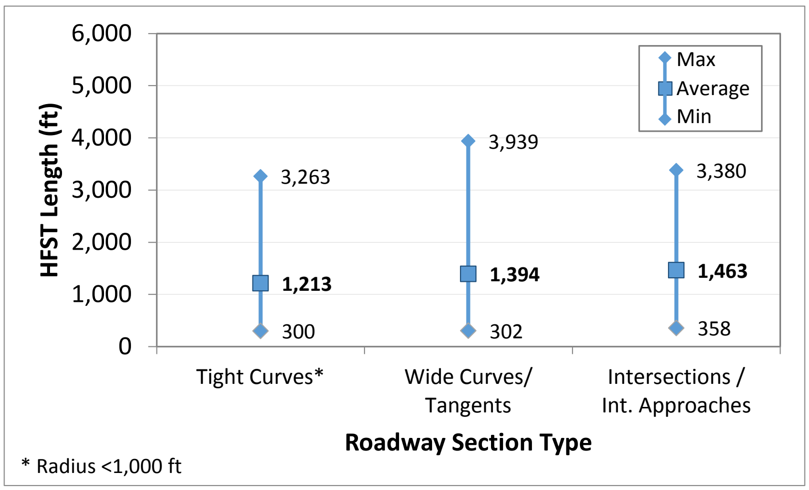
Figure 3.1 – Map of all Florida HFST sections

The range of geometric and traffic properties for each section type is illustrated in Figure 3.2. These graphs show similarities and differences among the section types. For tight curves, the smallest curve radius was 100 ft. and most were less than 750 ft. Wide curve sections had radii ranging from 1,100 ft. to nearly 2,000 ft., and some sections that were not curves. Some of the intersection sections had small radii similar to tight curve sections, though some sections in this group were not on curves. All section types had a similar range in lengths, with wide curve/tangent sections being slightly longer on average. The average traffic volume of the tight curve sections (16,000 AADT) was about half of the other section types (~30,000 AADT). The wide curve/tangent group included a few sections with very high traffic volumes.

Figure 3.3 shows the material properties of each section type. Half of the tight curve sections were constructed on the asphalt mainline. Most of these sections were ramps and loop ramps for the interstate system and had a history of crashes. All of the wide curve/tangent sections were located on concrete bridge decks and were constructed under the bridge division specification TSP 403. Most of these applications were prescribed for maintenance purposes rather than to mitigate crashes. The intersection/approach sections were located on both asphalt and concrete bridge surfaces. Two bridge sections included complex intersection approaches. Most tight curve HFST designs used calcined bauxite while HFST on wide curves/tangents used flint. The intersection/approaches category had sections with bauxite and sections with flint.



(a)



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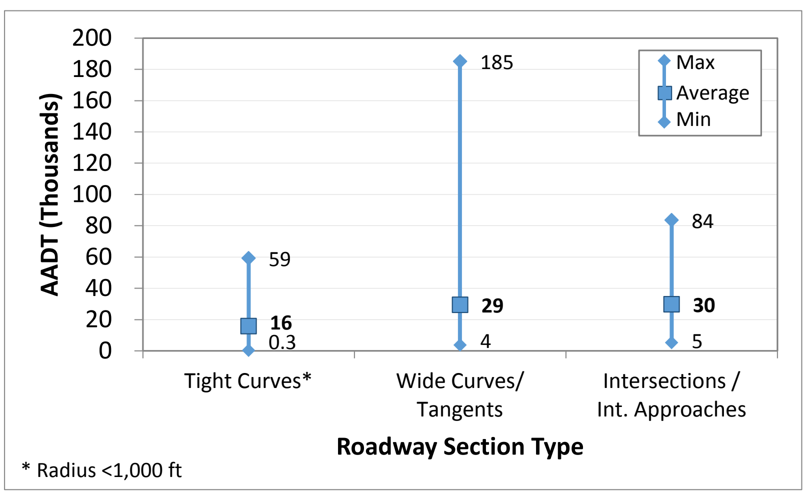
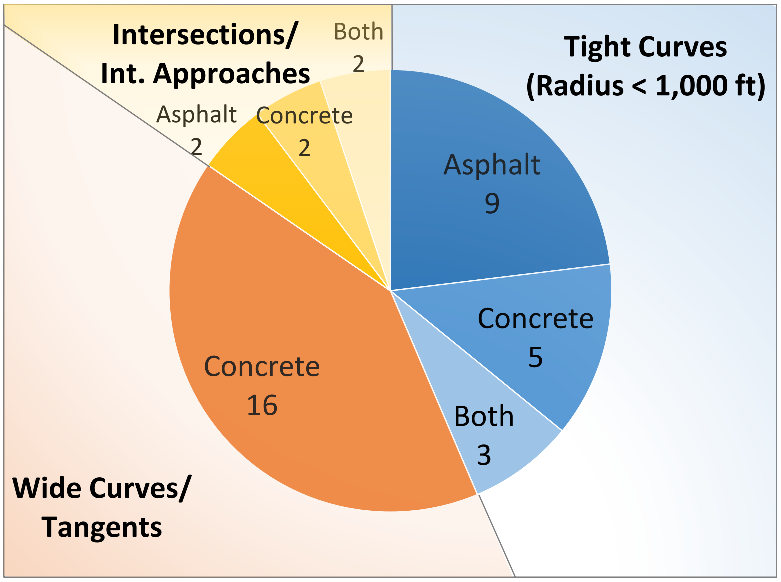
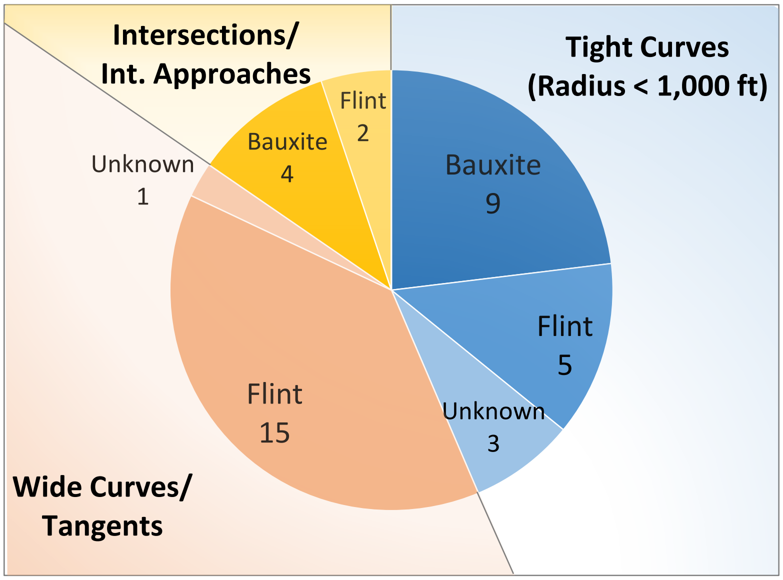


(c)

Figure 3.2 – Geometric and traffic properties of roadway sections: (a) Radius, (b) length, and (c) AADT



(a)



(b)

Figure 3.3 – Material properties of roadway sections: (a) Existing surface type, and (b) HFST aggregate type

The HFST unit costs and estimated section costs (based on total project data) are shown in Figure 3.4. The unit cost of 7 projects could not be determined because they were bid lump-sum, and total project costs were not available for 18 projects. Aside from unusually low and high unit cost bids in 2011, the range of HFST bid unit costs was from \$26 to \$40/yd^2 with an average of \$34/yd^2. The range of comprehensive HFST unit costs (including all related construction costs) was from \$36 to \$113/yd^2, with an average of \$59/yd^2.

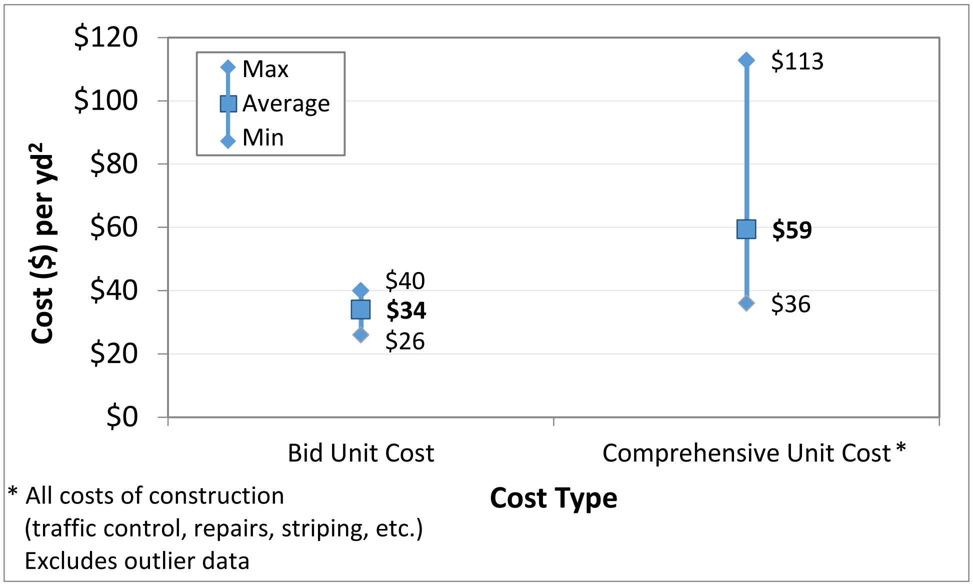
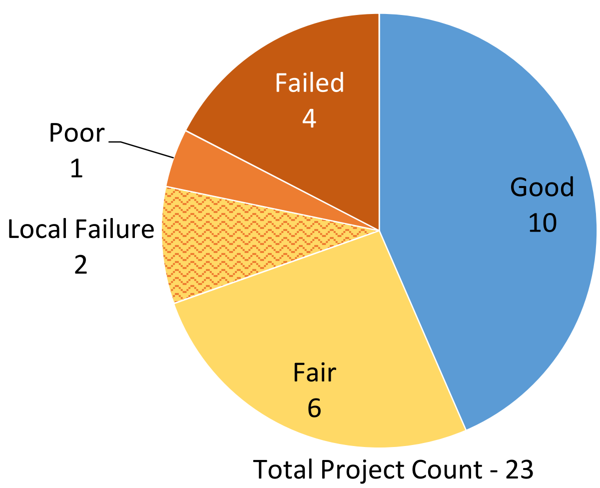


Figure 3.4 – HFST costs

Performance

Distress Condition

The general distress condition of all projects is summarized in Figure 3.5. Ten out of 23 projects (43 percent) are in good condition and 16 projects (nearly 70 percent) are in fair or better condition. Two projects had localized failures but were otherwise in fair or good condition. One project was in poor condition and four projects had severe wide-spread distress. The poor and failed projects constitute 22 percent of all the HFST projects.



Good – No known distress

Fair – Distresses not affecting function

Local Failure – Local distresses affecting function and requiring repair.

Poor – Distresses affecting function but not warranting reconstruction

Failed – Wide-spread distress warranting reconstruction

Figure 3.5 – Distress condition of HFST projects (Subjective rating)

The frequency of specific distresses types is summarized in Figure 3.6. Descriptions and examples of each distress described in the Chapter 2 under HFST Failure Mechanisms. Raveling was the most frequent problem, occurring on 10 projects, and is usually caused by inadequate binder film thickness. The next most frequent problem (four projects) was uncured binder failure, which happens if the binder is improperly mixed, proportioned, or has an incorrect formulation. Delamination occurred on three projects and a potential thermal incompatibility issue on two projects. Substrate tearing, substrate stripping, and reflection cracking occurred on one project each.

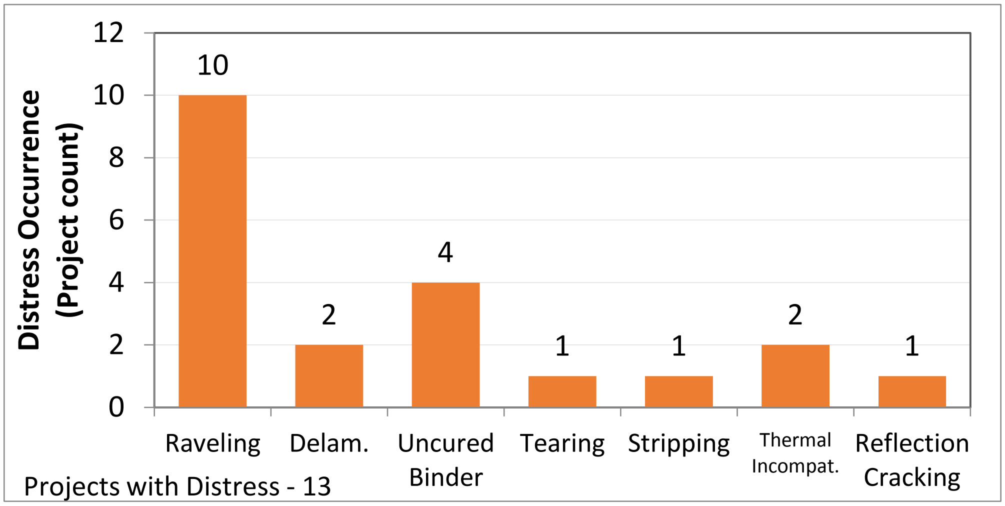


Figure 3.6 – Occurrences of HFST distress

Figure 3.7 shows the distribution of these distresses by surface type. Of the 12 projects with open-graded surfaces, six (or 50 percent) of these had raveling. Five other distress types were noted over OGFC's. Both of the dense-graded asphalt projects had raveling, and had delamination, uncured binder failure, and thermal incompatibility. Of the 12 concrete sections, two had raveling and one had uncured binder failure.

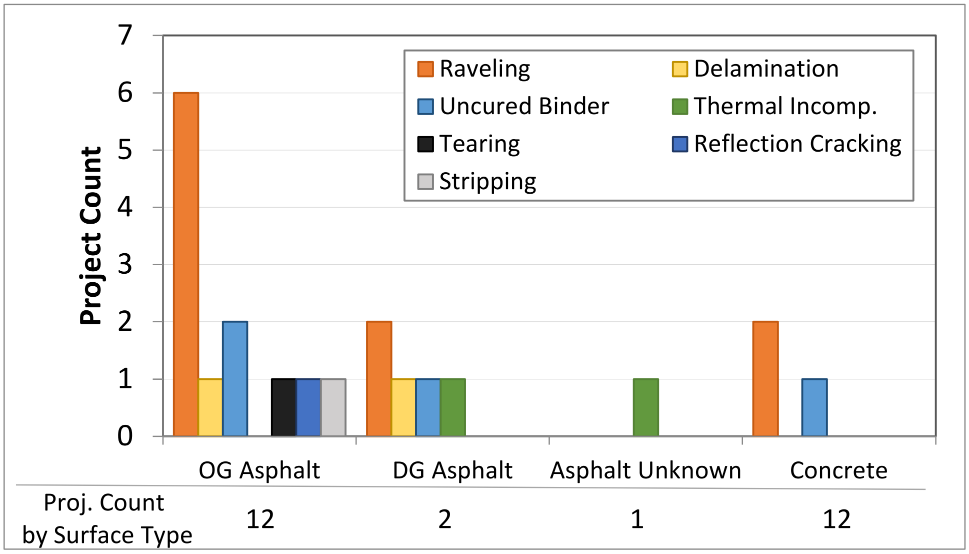


Figure 3.7 – Distribution of HFST distress by surface type

Skid Resistance

The skid resistance data for existing surfaces and HFST are shown in Figure 3.8. The average skid number for HFST (disregarding section age) was 73, well above concrete (51) and asphalt (35) sections. To considering the effect of age, all the HFST skid data are plotted in Figure 3.9 versus time, and the average initial and long-term skid number is shown in Figure 3.10. The data are separated based on aggregate type: calcined bauxite or flint. The aggregate type for five projects was unknown, though expected to be calcined bauxite. The average initial FN for both aggregate types was greater than 70 and for unknown sections greater than 80. Actual long-term FN values, after 6-yrs, were available for three sections and predicted for other sites from best-fit logarithmic regression. The calcined bauxite sections had an average long-term FN of 63 and the unknown sections an FN of 78. If these aggregate types are all the same, the average long-term FN would be 65. Long-term data for flint sections were not available.

Figure 3.11 shows all the associated mean profile depth (MPD) data over time. The initial MPD ranges from 0.038 to 0.074 inches, with an average of 0.048 inches. Over time, the average macrotexture did not seem to change, though it could fall as low as 0.03 inches. Though not shown in these data, from experience, MPD increases when HFST is applied to dense-graded or rigid pavement, and decreases when applied to open-graded pavement.

Crash Reduction

Figure 3.12 illustrates the average crash rate before and after HFST installation. The first figure is for total crashes and the second for wet weather crashes. The data are divided into tight curves (radius <1,000 ft.), wide curves/tangents, and intersections/approaches.

The average total crash rate before HFST was highest for intersections/approaches (2.0 crashes/MV) and then for tight curves (1.0 crash/MV). The initial crash rates for wide curve/tangent sections were significantly lower and essentially negligible (0.1 crashes/MV). (The purpose of applying HFST on these sections was for bridge preservation and not to reduce crashes.) After HFST application, the crash rate decreased for tight curves, and increased for intersections/approaches. The crash rate did not change for wide curve/tangent sections. (No change was expected since there was no history of crashes.)

For wet weather crashes, tight curves had the highest crash rate initially (0.59 crashes/MV). Intersections/approaches had a rate of about 0.3 crashes/MV) and wide curves/tangent sections again had almost no crashes. After HFST applications, the crash rate of tight curves dropped to 0.15 crashes/MV and increased on intersections/approaches to 0.5 crashes/MV, and was still negligible for wide curves/tangents.

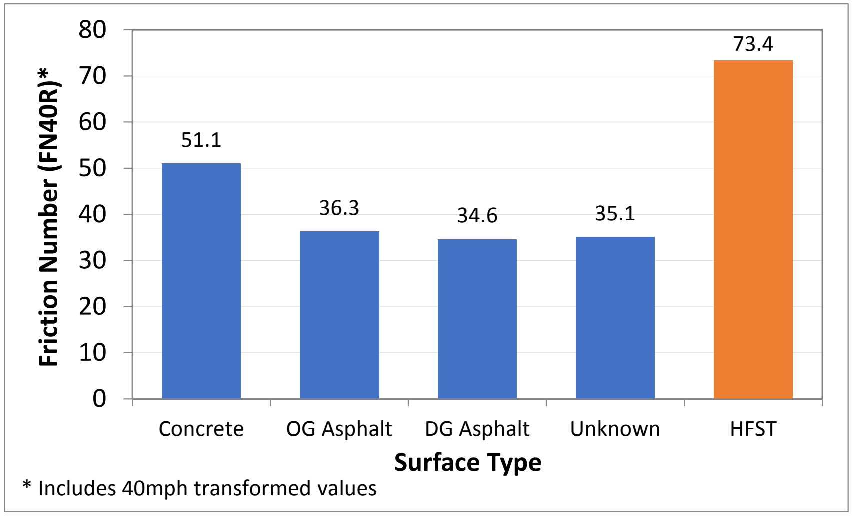


Figure 3.8 – Friction number comparison of existing surface and HFST

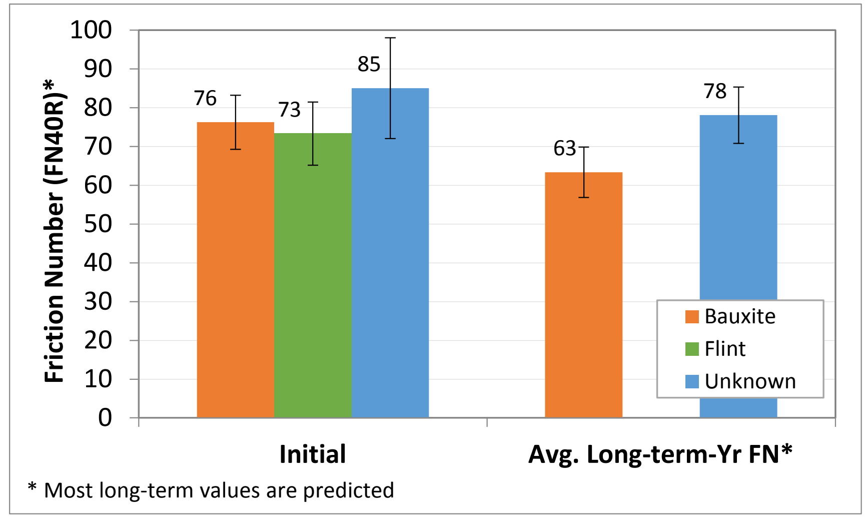


Figure 3.10 – Average short- and long-term skid resistance

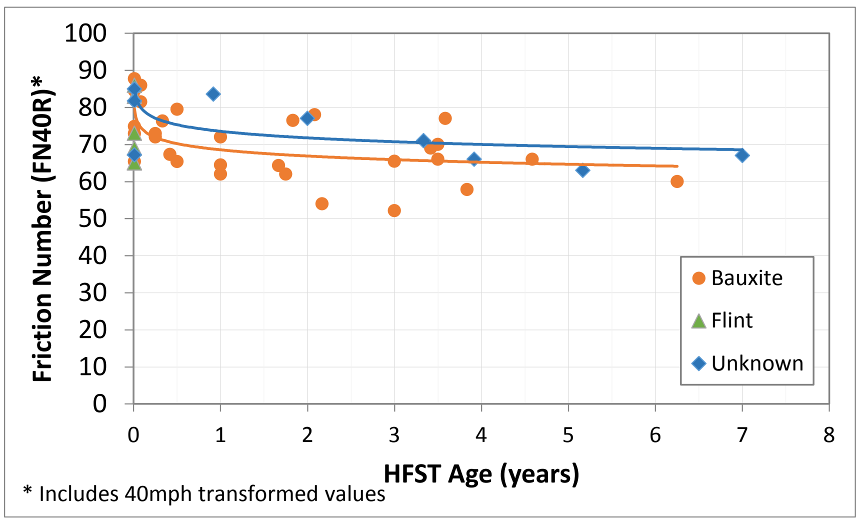


Figure 3.9 – Friction number vs. time

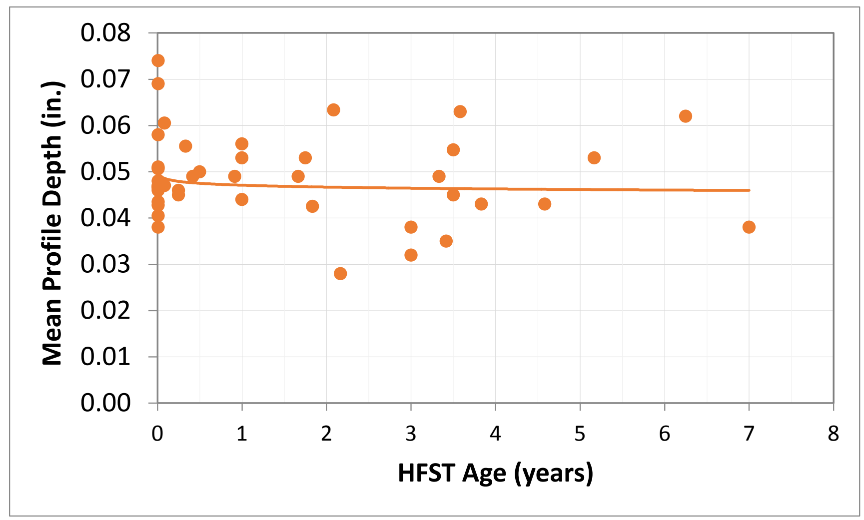
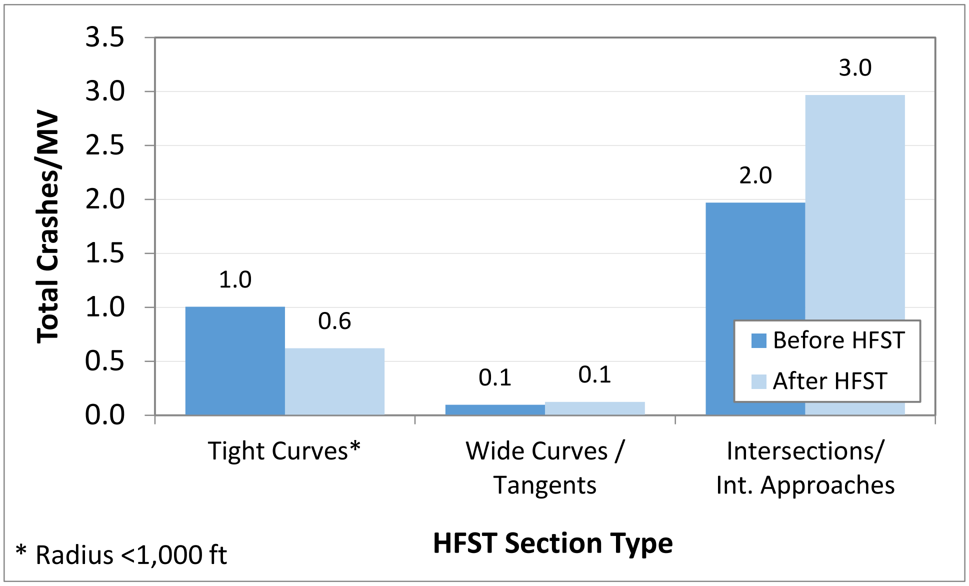
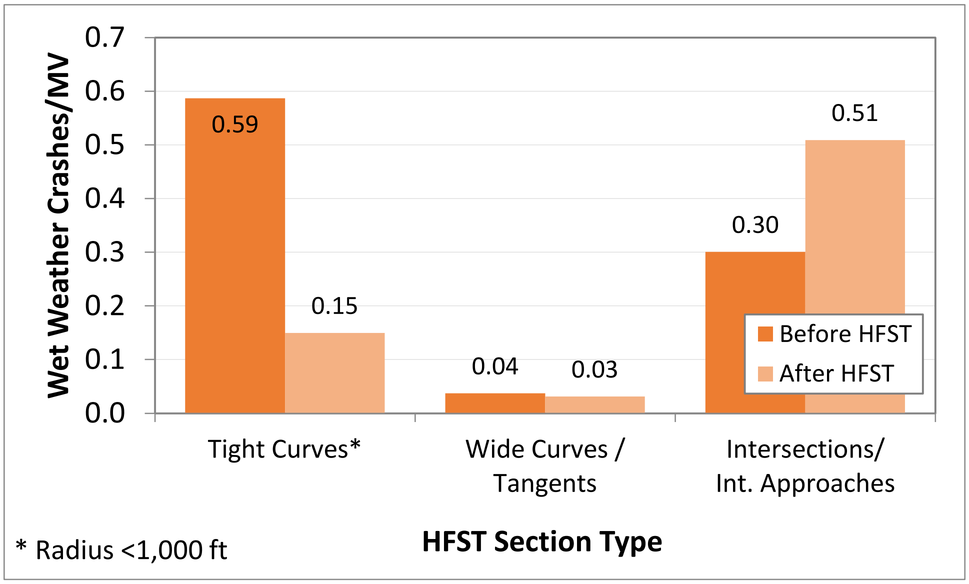


Figure 3.11 – Mean profile depth over time



(a)



(b)

Figure 3.12 – Crashes per million vehicle miles traveled: (a) total crashes and (b) wet weather crashes

These reported values are the overall average change, and in every HFST section type, there are both sections with decreasing and sections with increasing crash rates. This is particularly true for the intersection/approaches category. This point is emphasized again in the BC ratio analysis discussion.

Figure 3.13 shows the average percent change in crash rate by section type for total and wet weather crashes. Negative and positive values indicate a decrease and increase in crash rate, respectively. On average, the rate of total crashes decreased by 32 percent on tight curves, and increased by 51 percent at intersections/approaches, respectively. On average, the rate of wet weather crashes decreased by 75 percent for tight curves, and increased 69 percent for intersections/approaches, respectively. The change in crash rates for wide curves/tangent sections was practically insignificant, given the very low crash rate before HFST. From a statistical perspective, the only significant change in crash rate was for the decrease in wet weather crashes on tight curve sections.

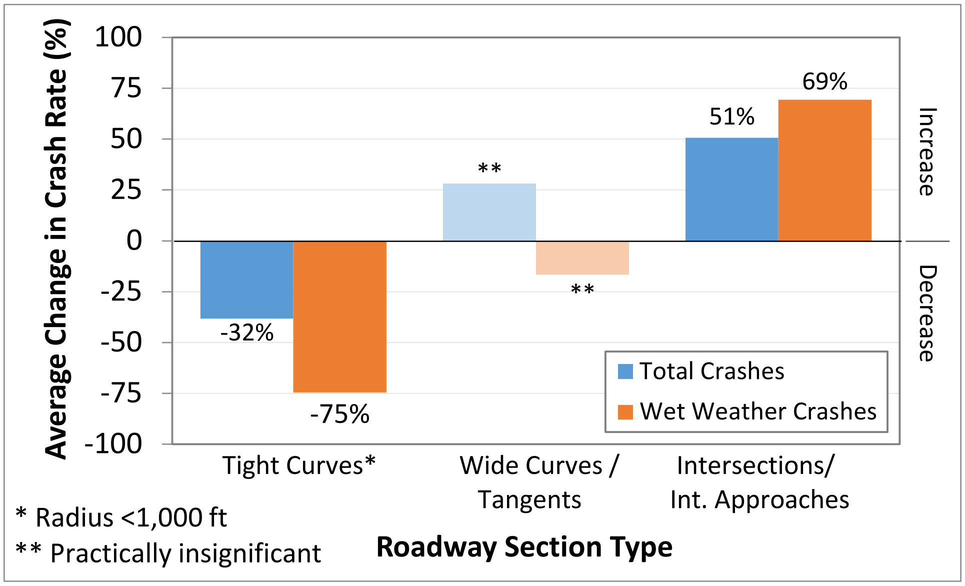


Figure 3.13 – Percent change in crash rate after HFST installation

Benefit-Cost Analysis

The results of the BC ratio analysis are given in Table 3.1 and illustrated in Figure 3.14. The standard deviations of data in this table are very high. The discussion will focus on the average values, but the costs and benefits for each section type have significant variability.

The construction cost on tight curves was the lowest, $171,000 on average. The most expensive applications were on wide curves/tangents, with an average construction cost of $560,000 and with maximum costs over $1.5 million. Over a 5-year period, the benefits were highest for tight curves. The highest benefit estimate was for the Total Crashes-FDOT KABCO method. This method weighs fatalities and high-severity injuries with a higher societal impact cost than low-severity injury or property damage.

On average, only the tight curve sections had positive BC ratios. The average ratio with the Total Crashes-FDOT KABCO method was 24.5. The average ratio was 26.0 for the Total Crashes-Avg. method and 18.0 according to the Wet Weather Crashes-Avg. methods. This suggests that these tight horizontal curves are good candidates for HFST treatments from a BC perspective. Wide curve sections, with their high cost and little-to-no crash history to improve upon, did not have a calculable average BC ratio. This means savings from a crash prevention standpoint is less than the treatment cost. Intersections/approaches also did not have a calculable average BC ratio.

Table 3.1 – Benefit-Cost Analysis Results.

Property		Section Type		
		Tight Curves	Wide Curves/ Tangents	Intersections/ Int. Approaches
Cost	Average	$171,000	$560,000	$476,000
	St. Dev.	$72,000	$673,000	$348,000
Total Crashes-FDOT KABCO Using costs for each FDOT-KABCO category (Table 1)				
5-yr Benefit	Average	$2,522,000	$177,000	-$1,093,000
	St. Dev.	$3,601,000	$1,793,000	$23,034,000
Benefit-Cost	**Average**	**24.5**	—	—
	St. Dev.	37.6	5.2	44.7
Total Crashes-Avg. Using $195,000 average crash cost				
5-yr Benefit	Average	$952,000	$165,000	-$8,529,000
	St. Dev.	$992,000	$1,373,000	$20,279,000
Benefit-Cost	**Average**	**26.0**	—	—
	St. Dev.	37.0	3.7	29.0
Wet Weather Crashes-Avg. Using $190,000 average crash cost				
5-yr Benefit	Average	$596,000	$490,000	-$2,135,000
	St. Dev.	$722,000	$2,399,000	$2,732,000
Benefit-Cost	**Average**	**18.0**	—	—
	St. Dev.	25.7	1.4	5.8

— Ratio was not calculated (benefit is negative)

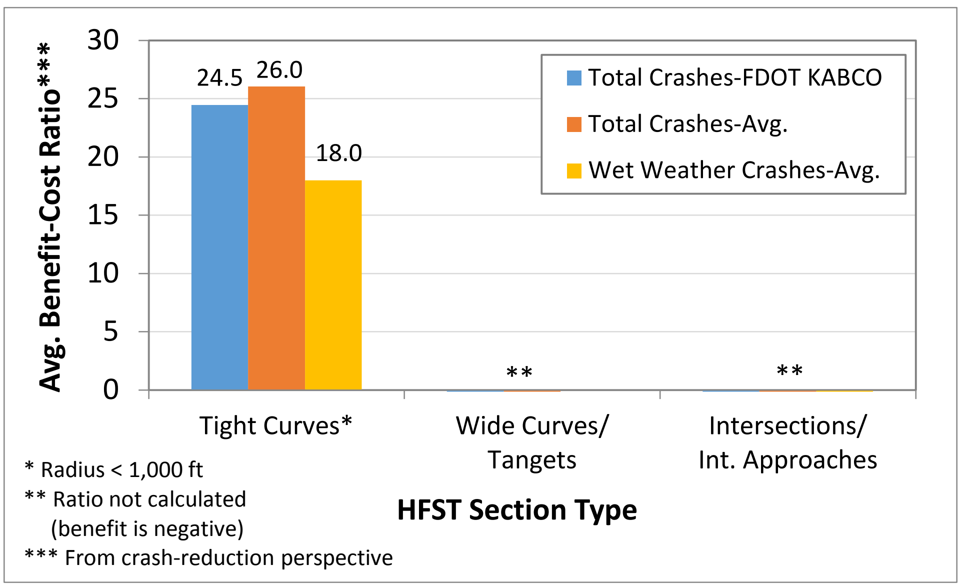


Figure 3.14 – Benefit-cost comparison of HFST on different roadway types

As previously mentioned, the values discussed are averages, and each roadway group had both sections with positive and sections with “negative” BC ratios. Figure 3.15 illustrates the distribution BC ratios for individual HFST sections. The tight curves group still has a strong positive BC ratio trend, with some sections greater than 50, and one as high as 118. The wide curves/tangent group is tightly grouped around zero. The intersection/approaches group, however, shows a wide range of BC ratios. Three projects had negative BC ratios (increased crash rates) and three projects saw strong positive BC ratios. The researchers were unable to determine why crashes increased so dramatically on the three negative sections, but did note that the intersections had unusual geometries.

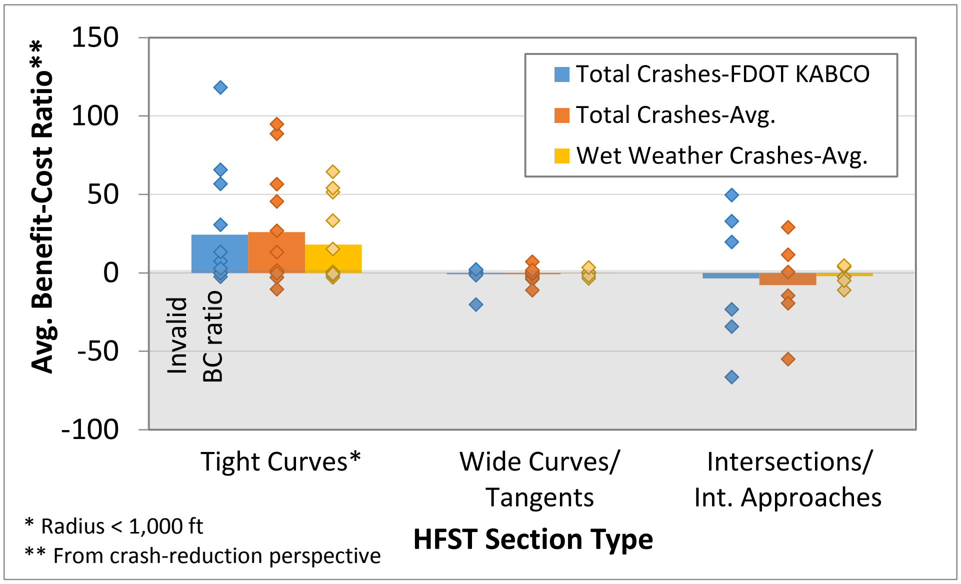


Figure 3.15 - Benefit-cost comparison of individual HFST sections

Summary

The researchers performed a comprehensive documentation of all known HFST projects in Florida. They evaluated the projects for treatment durability, skid resistance, and crash rate reduction. A benefit-cost analysis was performed based on the crash reductions. Key findings are as follows.

- Of the 39 identified HFST sections, 17 were on tight curves, 16 were on wide curves/tangents, and 6 were on intersections/approaches.
- The bid unit cost of HFST in Florida was between \$26 and \$40/yd^2, and the total unit cost (including traffic control, repairs, striping, etc.) was between \$36 and \$113/yd^2. The total cost for a typical tight curve segment was \$171,000.
- Nearly 70 percent of all projects are in good and fair condition. Poor and failed projects constitute 22 percent. Other projects had localized failures.

- The most prominent distress was aggregate loss (raveling), followed by uncured binder failure.
- Raveling occurred on half of all open-graded sections (6 of 12) and all dense-graded sections (2 of 2). Other distresses characteristic of the open-graded surfaces are tearing and stripping.
- The average FN40R of all HFST sections was 73 (compare to 51 for concrete and 35 for asphalt). The initial and long-term FN40R of calcined bauxite HFST was 80 and 63.
- Crashes were most prominent on tight curves and intersections/approaches. Existing crashes on the wide curve/tangent sections were negligible (mostly bridge deck preservation projects).
- Crash reduction from HFSTs was most effective on tight curves, where the average reduction in crash rate was 32 and 75 percent for total and wet weather crashes, respectively. Crash rates increased on average for intersections/approach.
- HFST is a cost-effective treatment for tight curves with a history of crashes. The average BC ratio was between 18 and 26 (depending on calculation method), with some sections as greater than 50 and as high as 118.
- HFST is not cost effective, from a crash reduction perspective, on wide curves/tangents with no history of crashes. The cost effectiveness for bridge deck preservation was not part of this research.
- The cost effectiveness of HFST at intersections/approaches is still inconclusive. Half the observed sections had good BC ratios, and the other sections saw a significant increase in crashes.

CHAPTER 4
FIELD TESTING

This chapter summarizes field testing of existing HFST projects in Florida. The researchers visited six sites to measure current performance and do forensic testing as appropriate. This chapter only presents a summary of our findings. Detailed write-ups for each projects are contained in Appendix C.

Procedures

A variety of projects were chosen with a range of ages, good to failed conditions, and different existing surface types (Table 4.1). The following properties were evaluated:

- Surface distress
- Bond/tensile strength
- Friction

Table 4.1 – HFST Case Studies.

Project	Age (yr)	Condition	Existing Surface
WB US 60 to NB I-75 (Brandon)	3	Failed	FC-5
Mem. Blvd at I-4 Ramp (Lakeland)	3	Good	FC-5 and Concrete
I-95 SB and Ramp (Lake Worth)	< 1	Good w/ local failure	Concrete
I-95 Off Ramp to Congress (Delray Beach)	4	Moderate	FC-5 and FC-9.5
Fort Lauderdale Airport Ramp (Fort Lauderdale)	3	Good and Moderate	Concrete and FC-5
Indian Creek to Collins Ave. (Miami Beach)	3	Moderate	FC-9.5

The general site condition was evaluated noting specific pavement distresses. Cracking severity and extent was noted. On an as-need basis, cores were taken for forensic analysis.

For most projects, cores were taken strategically to represent intact locations, locations near distress, and locations on distress. Tensile-strength "pull-off" testing was done on several of these samples to characterize the HFST bond or the substrate strength (Figure 4.1). Most tests were done on cores in the lab. Some tests were attempted in the field on concrete substrates (I-95 and Ramp, and FLL Ramp) but these tests failed prematurely due to a rain and low temperatures.

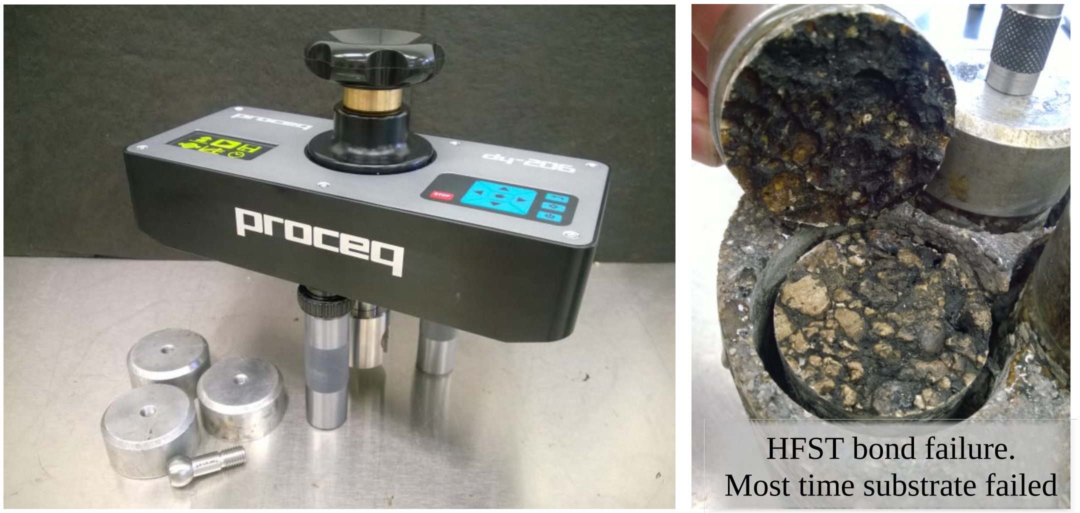


Figure 4.1 – Pull-off test

Friction on each project was tested using a dynamic friction tester (DFT) and circular track meter (CTM) (Figure 4.2). Readings were taken both between and in the wheel paths. When applicable, measurements were also made in distressed/irregular locations where the friction may have been compromised, like over raveling.

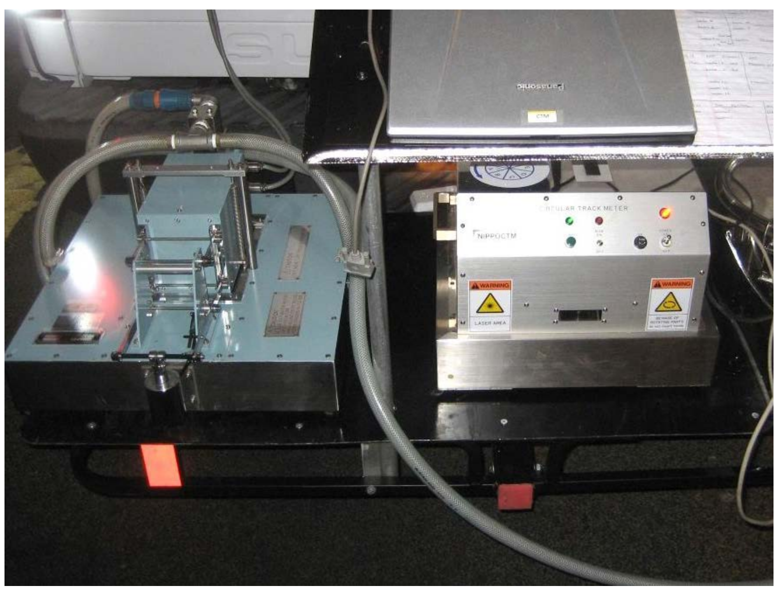


Figure 4.2 – DFT and CTM

Results

The distresses for each project section were carefully evaluated and an attempt was made to identify the cause of failure. The findings are summarized in Table 4.2. Distresses included potholing (from uncured binder failure), raveling, delamination, and cracking. More details are found in Appendix C.

Table 4.2 – Case Study Distresses and Failure Mechanisms.

Project	Distress	Failure Mechanism	Example
US 60 to I-75	Small random potholes	Uncured binder failure (inadequate mixing). Stripping within substrate.	 
Mem. Blvd Ramp	Raveling (limited)	Inadequate film thickness (inconsistent texture on existing surface).	
I-95 and Ramp	None on bridge	-	 
	Splotches and delaminations on ramp	Uncured binder failure (inadequate mixing from equipment malfunction).	

Table 4.2 – Case Study Distresses and Failure Mechanisms. (Continued)

Project	Distress	Failure Mechanism	Example
I-95 to Congress	Transverse and random cracking	Substrate tearing.	 
	Raveling over concrete	Likely no shot blasting. Likely single-lift.	
FLL Ramp	None on bridge	-	 
	Raveling over FC-5	Inadequate film thickness (poor application).	
	Irregular depressions	Unknown. Possible stripping of weak substrate.	
SR A1A	Splotchy texture	Subsequent HFST patches.	 
	Raveling	Inadequate film thickness (poor application).	
	Random cracking	Possible thermal incompatibility.	

Figure 4.3 is a simplified representation of all the pull-off results. The first bar is the average of "higher strength" and intact HFST locations. The second bar generally represents the average at locations with observed distresses. Most sections were over FC-5 with two FC-9.5 sections. Average values for the good locations ranged from 77 to 260 psi. The distressed sections ranged from 37 to 110 psi, including some cores that failed during sample preparation. Most tests failed within the substrate but a few failed at the HFST bond. These were a heavily distressed sample on I-95 to Congress (just after the stop bar), one reading on SR A1A, and one reading on FLL Ramp in the un-distressed area.

Though the field tests on concrete sections were unsuccessful, the researchers noted that the strength when the test failed was between 100 and 250 psi. They also noted that the bond strength over splotchy areas on the I-95 off-ramp at 6th Ave S was very weak and the material was even removable by hand.

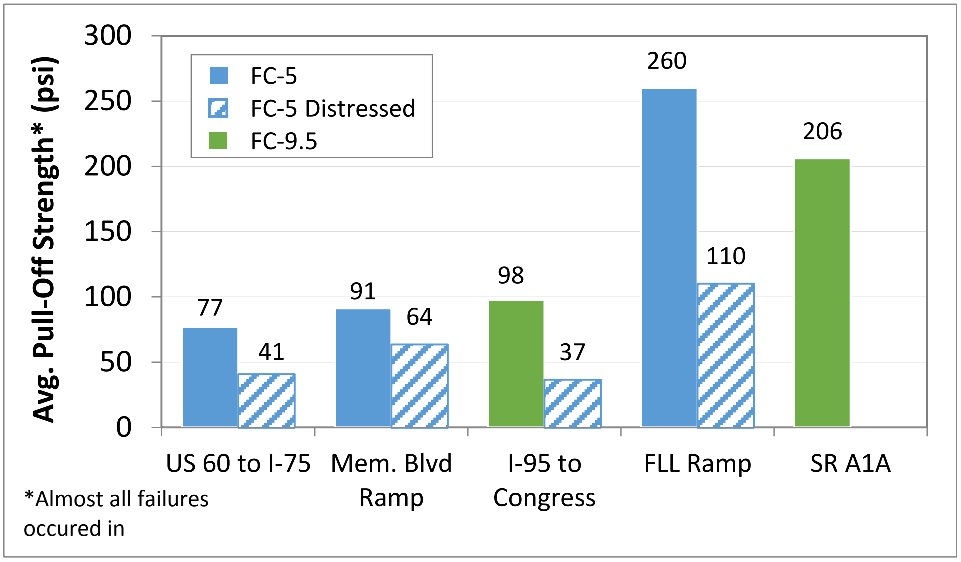
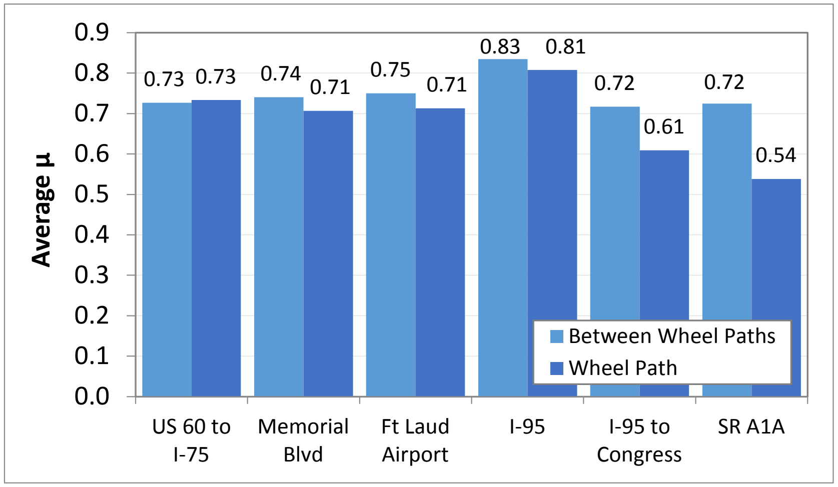
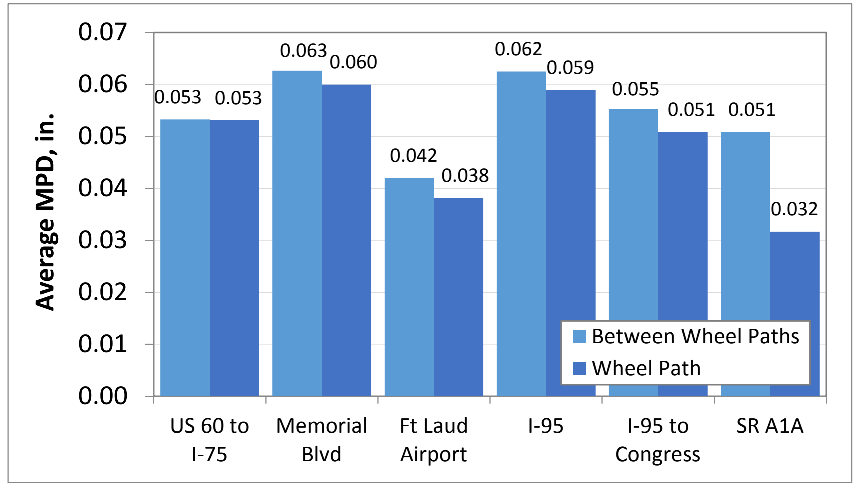


Figure 4.3 – Summary of pull-off test results

The friction results for between and inside the wheel paths are shown in Figure 4.4. Friction consistently decreased in the wheel path under traffic for both the DFT and CTM readings. The average friction coefficient, μ, without traffic was 0.75 and dropped to 0.69 (9 percent decrease) with traffic. For the CTM, the average mean profile depth (MPD) changed from 0.054 to 0.049 inches (11 percent decrease). This is after an average of 3 years.

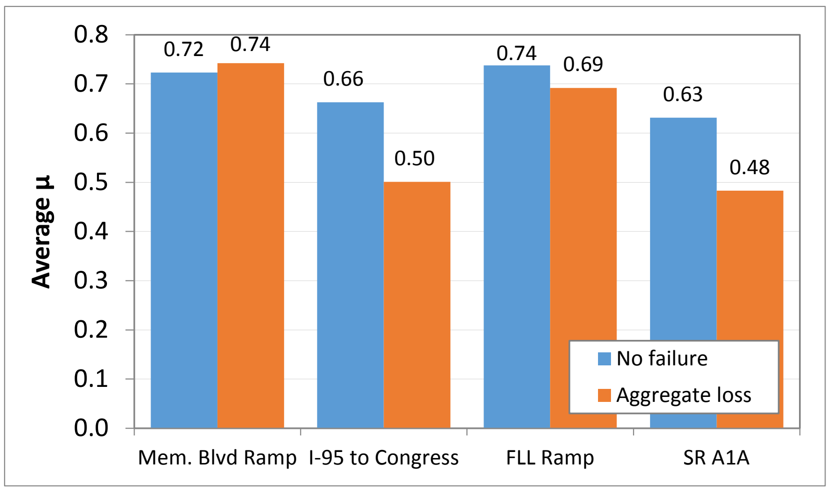
The effect of aggregate loss on friction is illustrated in Figure 4.5. Thought the amount of aggregate loss varied from project to project and considered in this analysis. The average decrease in friction (μ) was 13 percent and for MPD was 21 percent.

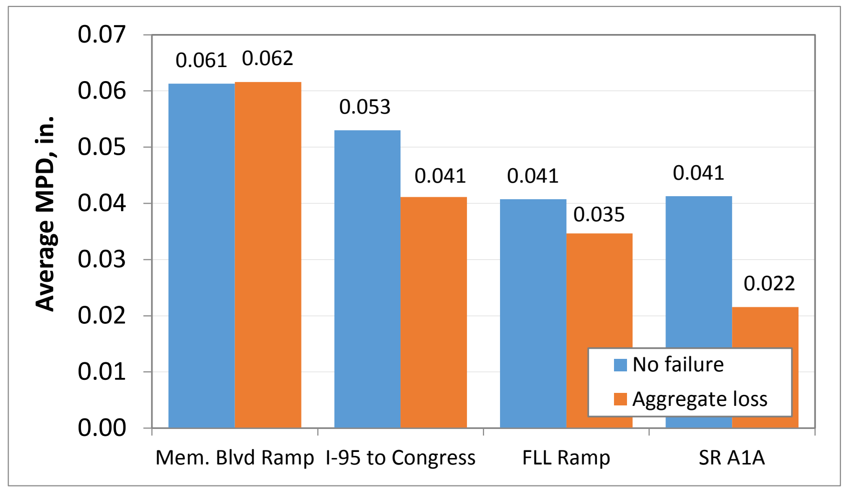




(a) **(b)**

Figure 4.4 – Friction results between and in the wheel paths: (a) DFT and (b) CTM





(a) **(b)**

Figure 4.5 – Friction results in areas with and without raveling: (a) DFT and (b) CTM

Summary

The researchers visited six HFST sites in Florida to measure current performance and conduct forensic testing as appropriate. A variety of projects were chosen with a range of ages, good to failed conditions, and different existing surface types. The following properties were evaluated:

- Surface distress
- Bond/tensile strength
- Friction

The following are key findings:

- Several distress types were observed (potholing, aggregate loss, surface cracking, substrate tearing, splotchy texture). Through forensic evaluation, several of the failure mechanisms were identified as discussed in the background section.
- Average tensile strength values for the good-condition HFST ranged from 77 to 260 psi. Values near distressed HFST ranged from 37 to 110 psi, including some cores that failed during sample preparation. Most tests failed within the substrate.
- The average friction coefficients measured with the DFT in and between the wheel paths were 0.69 and 0.75, respectively.
- The average texture (MPD) values in and between the wheel paths were 0.049 and 0.054 inches, respectively.
- The average decrease in friction and MPD due to aggregate loss was 13 and 21 percent, respectively.

CHAPTER 5
LABORATORY TESTING

This chapter focuses on laboratory testing of factors affecting the performance of HFST, a resin binder quality control test, and alternative HFST materials. The task is divided into a series of smaller experiments as follows:

1. Substrate Strength
2. HFST Aggregate Loss
    2.1. Binder Thickness
    2.2. Binder Type And Temperature
3. Thermal Compatibility
4. Binder Gel Time
5. Alternative Materials
    5.1. HMA With Calcined Bauxite
    5.2. Comparison Of HFST Aggregates

After discussing the materials and sample preparation techniques, the approach, procedures, and results of each experiment are presented as individual sections. Key results are then highlighted.

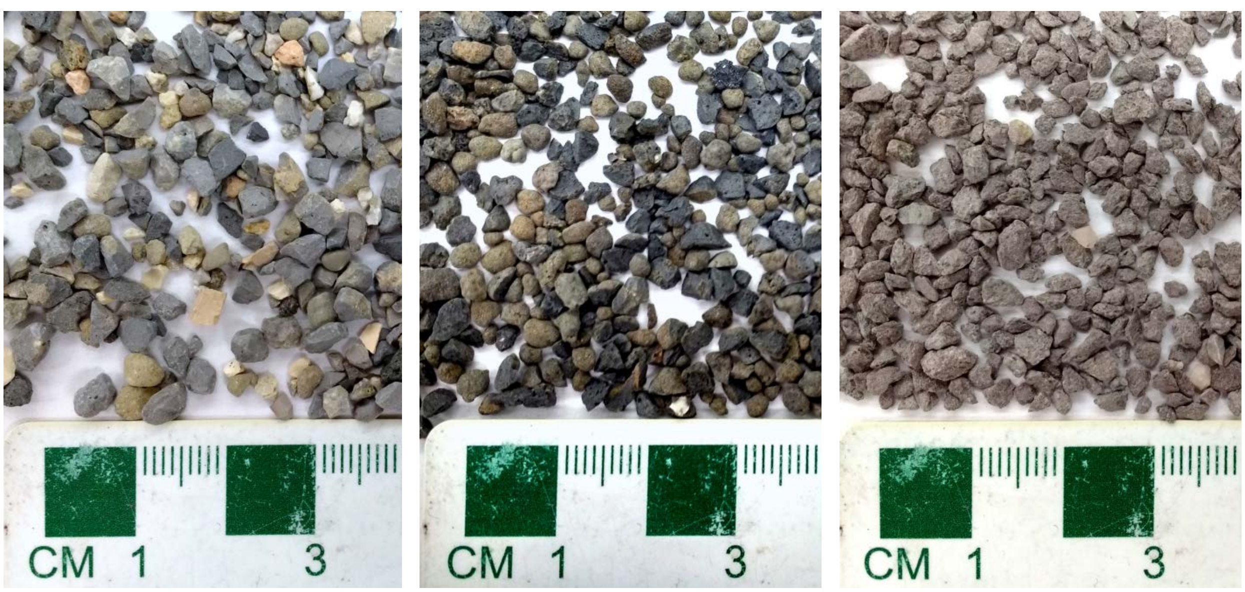
Materials

Materials used in this research are summarized in Table 5.1. These include three substrate types (concrete, FC-5, and FC-9.5), four HFST binders (three epoxy resins and one acrylic polyester resin), three high friction aggregates (two calcined bauxite and one unknown aggregate), and materials for an HMA design incorporating calcined bauxite. The product names for the resin binders and aggregates have been removed. The HFST aggregate is shown in Figure 5.1. The manufacturer of Aggregate B claimed the material had an aluminum-oxide (Al_2O_3) content of 83 percent; however, based on preliminary x-ray spectroscopy tests, the Al_2O_3 content of the aggregate may be closer to 87 percent, similar to Aggregate A. A precise Al_2O_3 content still needs to be verified.

The aggregates were processed by sieving into different sizes, which were then recombined in a controlled manner during sample preparation. Gradations for the HMA substrates and HFST aggregates are shown in Figure 5.2 and Figure 5.3. Detailed substrate mix designs are contained in Appendix D. Gradation for the HMA design aggregates are presented later in Experiment #5.2.

Table 5.1 – Test Materials.

Material Name	Description
Substrates	
Concrete	Concrete (Lab mix)
FC-5	Open-graded HMA (Plant mix)
FC-9.5	Dense-graded HMA (Plant mix)
HFST	
Resin Binders	
A	Epoxy resin
B	Epoxy urethane resin
C	Cresole modified epoxy resin
D	Acrylic polyester resin
Aggregates	
A	Calcined bauxite from China (Refractory grade, ~87% Al_2O_3)
B	Calcined bauxite from India (Refractory grade, ~87% Al_2O_3)
C	Unknown aggregate type from UK (~60% SiO_2, ~20% Al_2O_3)
HMA Design	
Bauxite	Calcined bauxite, coarse aggregate (Refractory grade, ~87% Al_2O_3)
Limestone	Various coarse and fine aggregates
76-22 PMA	Polymer modified asphalt (PG 76-22)



(a) (b) (c)

Figure 5.1 – HFST Aggregates: (a) calcined bauxite (China), (b) calcined bauxite (India) and (c) unknown aggregate type (UK)

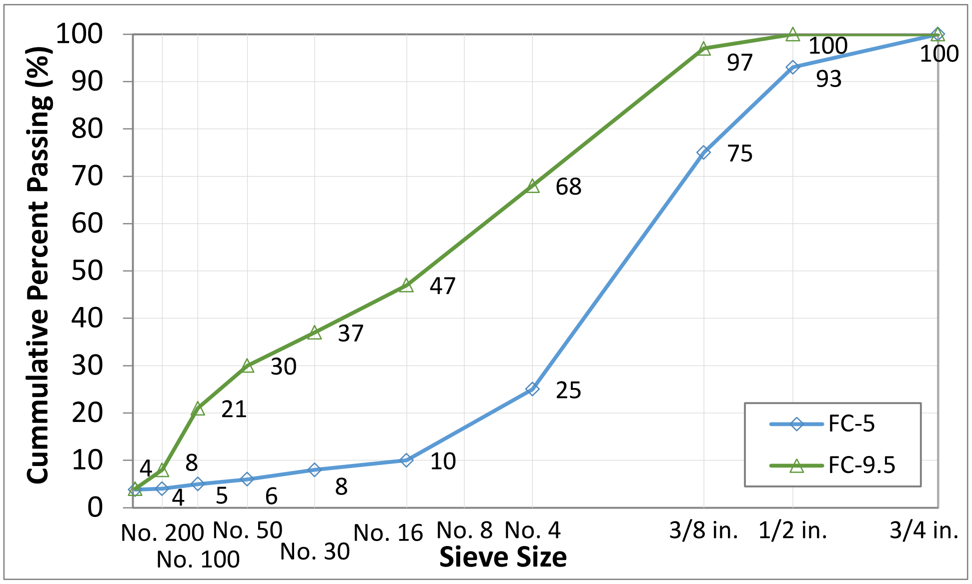


Figure 5.2 – Substrate gradations

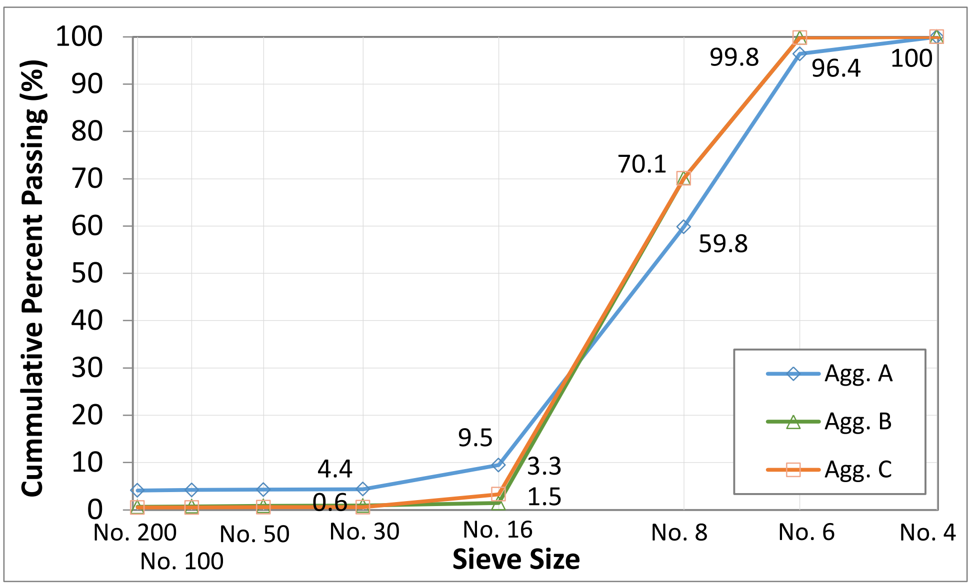


Figure 5.3 – HFST Aggregate gradations

Sample Preparation

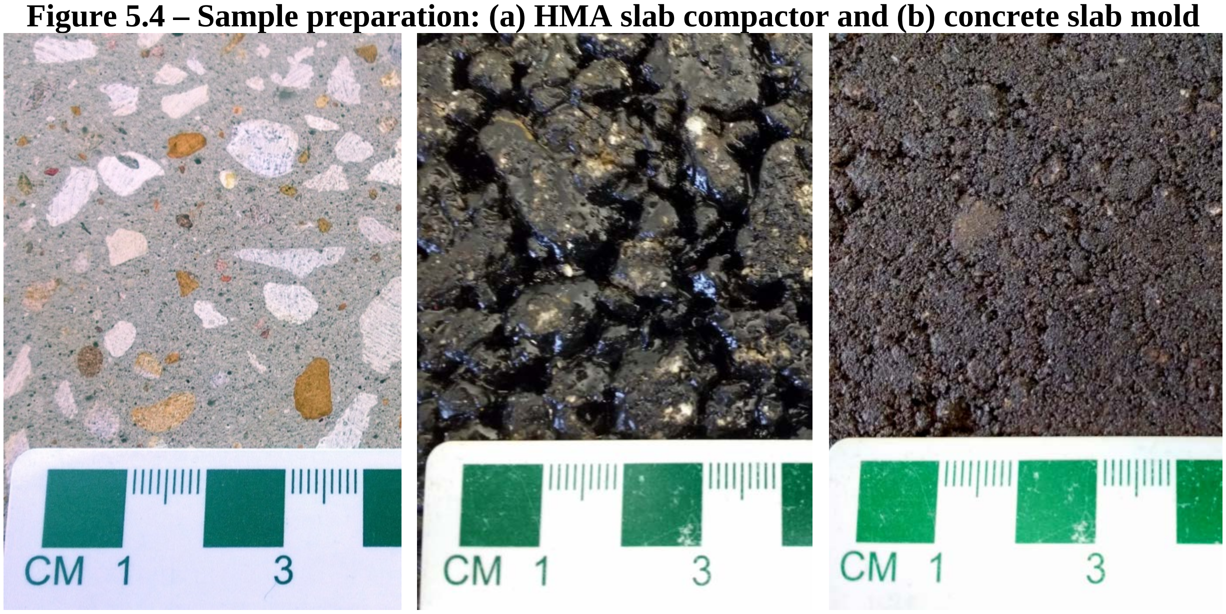
Similar sample preparation techniques were used in many of the experiments. These general techniques are described in this section, and variations are discussed in the individual experiments.

HMA substrates were molded using a Superpave gyratory compacter for cylindrical samples and a PMW linear kneading compactor for slabs (Figure 5.4). The target air voids for FC-5 and FC-9.5, representing in-service pavements, was 19 and 5 percent, respectively. Concrete samples were cast in cylindrical molds and shallow square molds. The slabs were 20 by 20-inch square and 1.5 inches thick.

Figure 5.5 illustrates the surface texture of each substrate type. Concrete samples were treated with an angle grinder equipped with a ridged diamond wheel to simulate a shot-blasted surface in the field. The resulting macrotexture was much lower than a shot blasted surface, but the microtexture was still aggressive, which is most critical in creating a strong bond. The researchers confirmed the surface would yield a high bond strength greater than 250 psi.

(a) (b)

Figure 5.4 – Sample preparation: (a) HMA slab compactor and (b) concrete slab mold



(a) (b) (c)

Figure 5.5 – Substrate surfaces: (a) concrete after grinding, (b) FC-5, and (c) FC-9.5

Unless specified in the testing plan, HFST was placed on the substrate according to FDOT guidelines in Dev 333. Binder was proportioned according to the manufacturer's recommendations and mixed for 3 minutes, either by hand or with a jiffy mixer depending on the sample size. Binder was spread with a 3/16-inch notched neoprene squeegee (Figure 5.6). The target thickness was 50 mils, though 40-45 mils was most commonly achieved as measured with a thin film thickness gauge. Aggregate was added until rejection (approx. 12 lb/yd^2). Concrete and FC-5 samples had two layers of HFST and FC-9.5 samples had one. Due to the aggressive texture of HFST, the amount of binder needed to achieve 50 mils in the second application was considerably higher than the first.

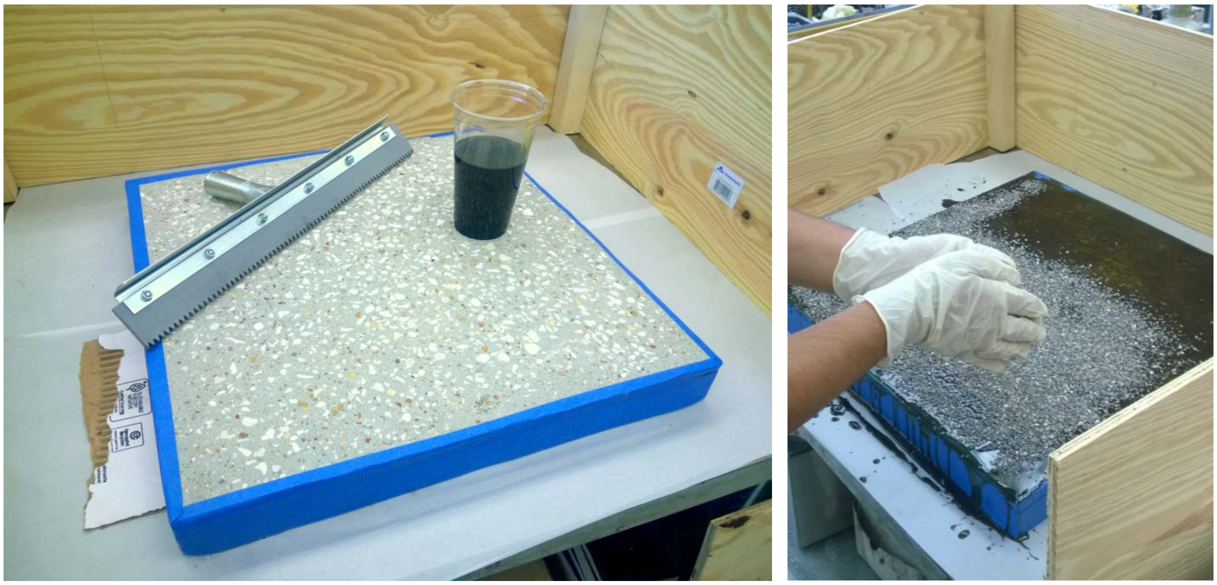


Figure 5.6 – HFST application

Experiment 1 – Substrate Strength

Overview

Some HFST projects in Florida showed signs of substrate failure (Figure 2.13). This happens when additional stress is introduced to the pavement following the HFST application, causing it to fail. These stresses include shearing under breaking/turning traffic and thermal cycling stress. The purpose of this experiment is to investigate a test method to test the substrate strength to verify whether the material might fail after HFST placement.

Procedures

In this experiment, the strength of three substrate types was evaluated with a pull-off tensile strength test and a cyclic shearing test. HMA substrates will be molded and conditioned to achieve a range of target strengths. The testing plan is shown in Table 5.2.

Table 5.2 – Testing Plan for Substrate Strength

Substrate Material	Target Layer Strength	Preparation Method		Test
		% Voids	Moisture weakening	
FC-5	Very Low	19	Y	ASTM C1583 (Tensile Strength) AND Cyclic shearing
	Low	14	Y	
	Moderate	14	N	
FC-9.5	Moderate	8	Y	
	Mod-High	5	Y	
	High	5	N	
Concrete	Very High	NA	N	

Pull-Off Tensile Strength Test

The pull-off tensile strength test is a common test for concrete and can be used to verify the bond strength of HFST. In this experiment, it was used to measure the strength of the substrate.

Cylindrical substrate samples were prepared to the specified air voids and HFST applied. Epoxy Resin Binder A and Aggregate A were used for all samples. According to the test plan, samples were subjected to moisture weakening in the moisture-induced stress tester (MIST), using 1000 cycles at 40 psi and 60°C. Samples were cored with a 2-inch barrel through the HFST and about 1.5 inches into the substrate (Figure 5.7). Steel pulls stubs were glued to the top surface and loaded in tension with a Proceq DY 206, at a rate of 5 psi/second, until failure. Three measurements were made on a single sample.

Figure 5.7 – Pull-off tensile strength test

Cyclic Shearing Test

The cyclic shearing test was performed using a modified Texas Overlay Test method. The traditional method replicates the scenario of bottom-up cracking in an overlay. A gyratory HMA sample is cut and glued to two plate halves. One plate is fixed while the other is cycled in and out at a predetermined strain. This causes a crack in the middle of the specimen that propagates upward until failure, which is defined when the measured load is less than 93 percent of the initial maximum load. Sample performance is based on the number of cycles until failure.

The modified cyclic shearing test represents a different scenario of top-down cracking caused by shearing forces from braking and turning vehicles. The samples were cut to 3 inches wide, 1.5 inches thick, and 6-inches long. The samples were inverted and the top was glued to the two overlay test plate halves. The bottom of the sample, facing up, was glued to a solid plate to provide the confinement an overlay would have in the field. The samples were tested at an elevated temperature, 100°F, with a displacement of 0.025 inches and a complete cycle time of 10 seconds. The test was terminated when load had dropped 93 percent of the initial maximum load or after 1,000 cycles. Triplicate samples were tested.

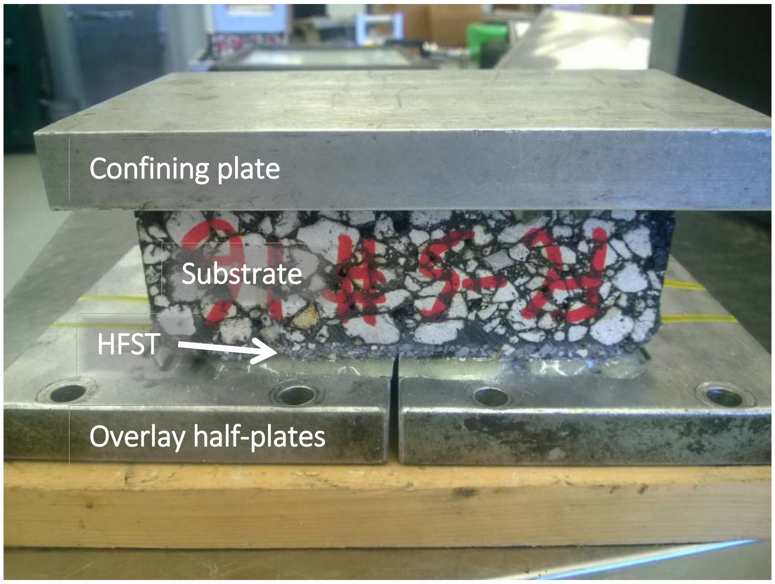


Figure 5.8 – Prepared cyclic shear sample

Results

The pull-off test results are shown in Figure 5.9. The moisture conditioned samples had tensile strengths ranging between 9 and 65 psi. The un-conditioned HMA samples had tensile strengths of 121 and 176 psi, and concrete of 217 psi. These effect of moisture conditioning is very clear. FC-9.5 had a lower strength than FC-5, which is due to the lower-grade asphalt binder in the mix. This trend of FC-9.5 being weaker than FC-5 is evident in many of the experiments. The

FC-5 sample with 14 percent voids and no moisture conditioning was mistakenly tested several months after being molded.

Based on this graph and results from previous field tests, the researchers may consider a minimum substrate tensile strength criteria. A specific minimum value cannot be determined based on these results, but it would be somewhere between 75 and 120 psi.

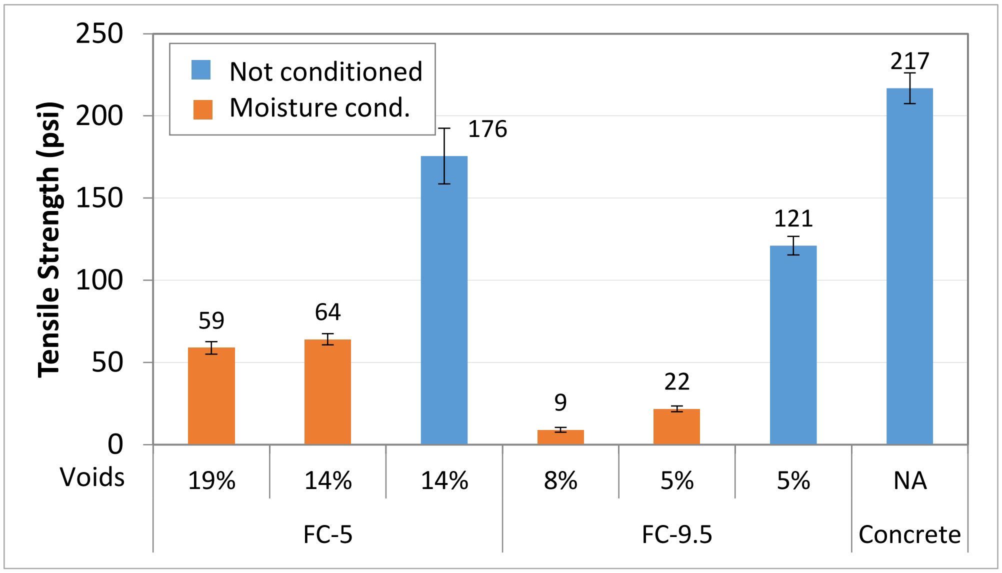
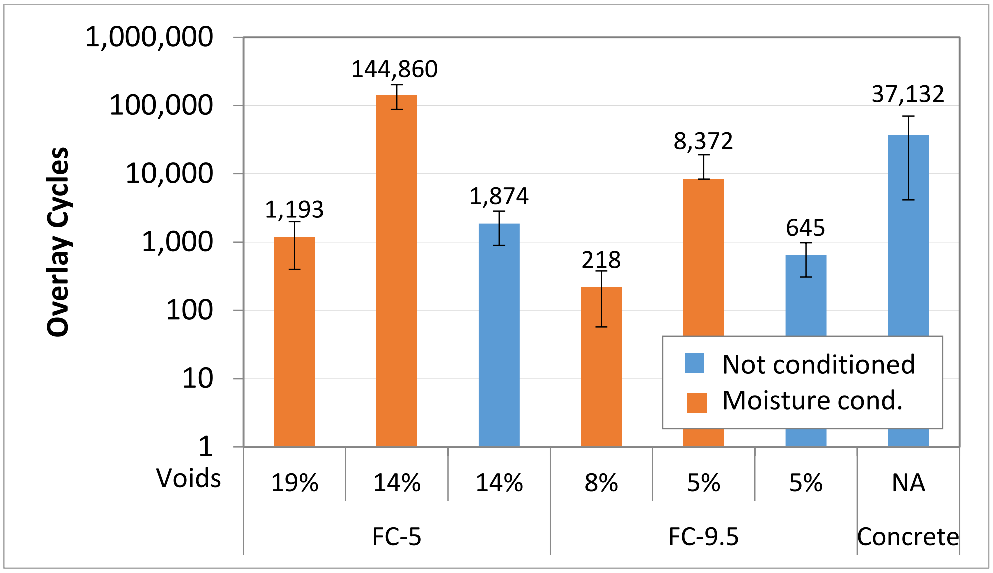
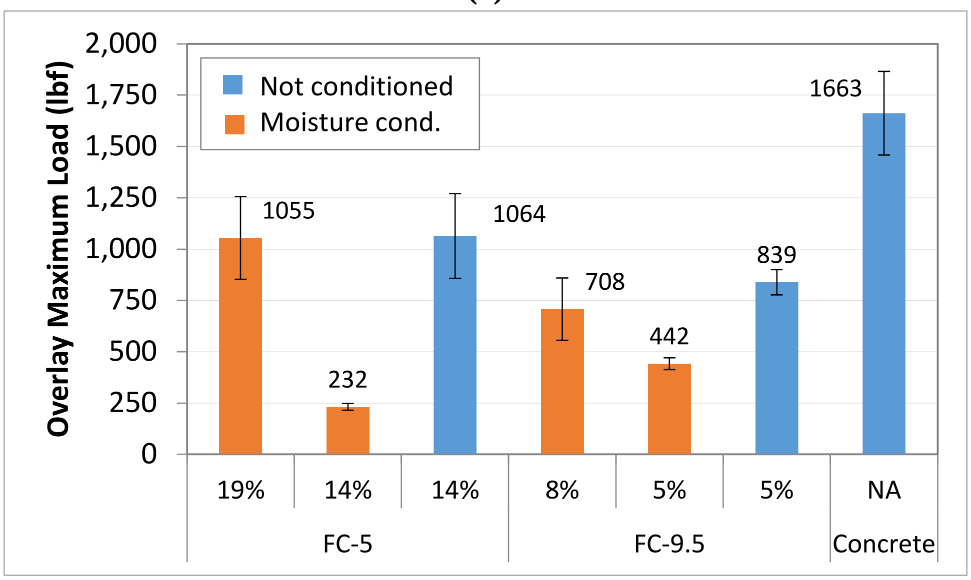


Figure 5.9 – Pull-off test results

The cycling shear test results (overlay cycles and maximum load) are shown in Figure 5.10. FC-5 had the most cycles to failure. This is because the mix is inherently more flexible with a high void content and higher-grade asphalt. Concrete had the highest strength which was also expected. Other trends with mix type, void content, and moisture conditioning are not clearly evident. Overall, the researchers found this test to be inconsistent and a poor predictor of field performance. The sample preparation and test procedures require further refinement to improve the accuracy and repeatability of the test.



(a)



(b)

Figure 5.10 – Cyclic shear test results: (a) cycles to failure and (b) maximum load

Experiment #2.1 – Aggregate Loss (Binder Thickness)

Overview

The most common distress in HFST is aggregate loss (Figure 2.6). This is caused by inadequate binder thickness. In Florida, this has been a particular problem for HFST constructed over open-graded HMA, where the first application of binder drains into the pavement and does not contribute to holding the HFST aggregate. This concept is illustrated in Figure 5.11, where the binder film thickness over FC-5 (OGFC) and FC-9.5 (dense-graded) decreases over time, especially when the binder is at an elevated temperature. The decrease in thickness is most dramatic in the FC-5, arriving at less than 10 mils after just 5 minutes.

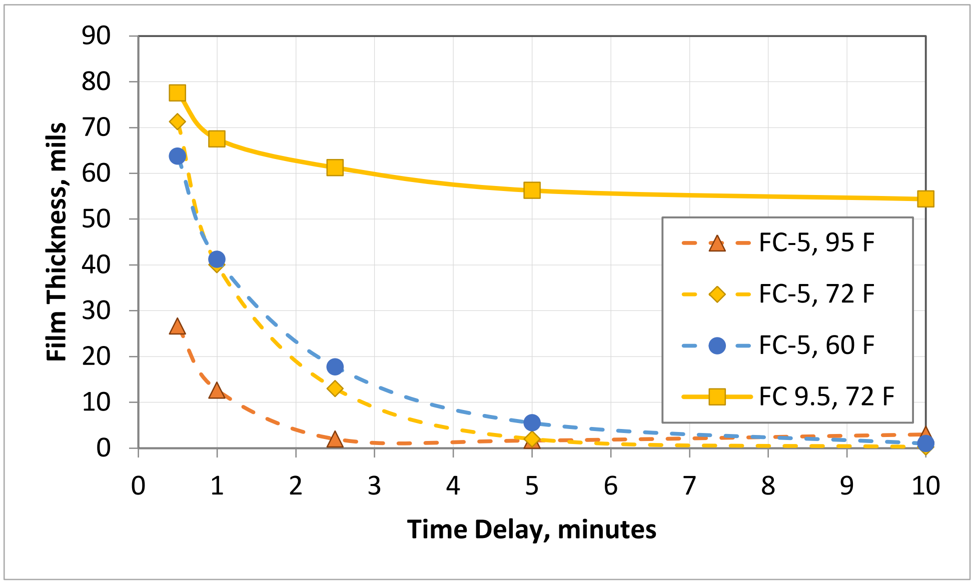


Figure 5.11 – HFST binder drain down vs. time and temperature (laboratory)

The purpose of this experiment was to evaluate aggregate loss from HFST when constructed with various binder thicknesses, single and double applications, and over different substrate types.

Procedures

The test matrix is presented in Table 5.3. The two FC-5 samples were both double layer applications with one layer having a significant delay in the application of aggregate. This would allow the binder more time to drain down. Samples with FC-9.5 and concrete had single applications with binder thicknesses between 20 and 70 miles and one sample with a double HFST application.

20-inch by 20-inch slab substrates were used in this experiment. Epoxy Resin A and Aggregate A were used for all samples. When applying the HFST, the binder thickness was carefully monitored with a thin-film thickness gauge. For FC-5 samples, the original binder application rate was estimated to be 50 mils thick, and by the time the aggregate was actually applied, the thickness was 30 mils for the no-delay sample and between 8 and 10 mils for the 5-minute delay sample. All other samples had between 45 and 50 mils of binder when aggregate was applied. After 24 hours of curing, loose aggregate was removed with a wire-bristle brush, and the untested sample was weighed and the initial texture (mean-profile depth) was measured with a circular-track meter (CTM).

Table 5.3 – Testing Plan for Aggregate Loss vs. Binder Thickness

Substrate Material	HFST		Test
	Application Type	Binder Thickness (mils)	
FC-5	Double	50	Traffic in 3-Wheel Polisher Raveling and texture
	Double (w/ 5-minute delay)	50	
FC-9.5	Single	30	
	Single	70	
	Double	50	
Concrete	Single	20	
	Single	30	
	Single	50	
	Single	70	
	Double	50	

The samples were subjected to 20,000 cycles of simulated turning traffic in the three-wheel polishing device. To increase the test severity, the samples were tested at elevated temperatures by heating the polisher water-bath (Figure 5.12). FC-5 and concrete samples were heated to a temperature of 140°F. This temperature was chosen to simulate the summer pavement surface temperature. The researchers found that 140°F was too severe for the FC-9.5 substrate, so these samples were tested at only 100°F. Subsequently, this temperature was too low (negligible material loss), so the same samples were tested again at 130°F.

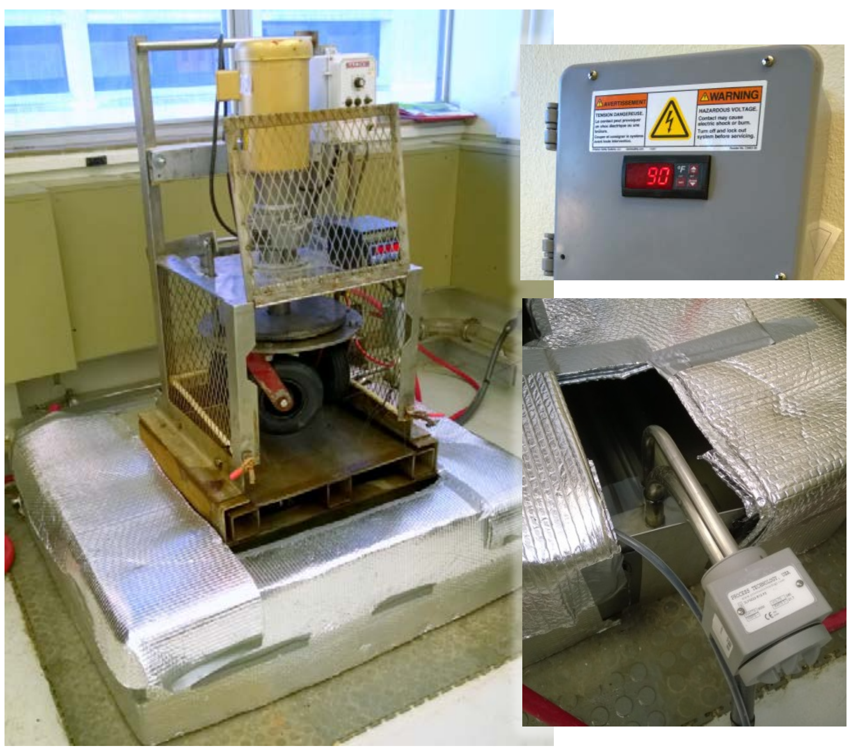


Figure 5.12 – Three-wheel polisher with heated water-bath

After polishing, the samples were dried for 36 hours at 140°F and were reweighed, and the final texture was measured. The change in mass and texture was calculated. Due to extensive material and time requirements for this test, only one sample of each type was tested.

Results

The mass loss of the samples is shown in Figure 5.13. In a few instances, the researchers noted problems with making reliable mass-loss readings due to damage of the HMA substrates during handling. Mass loss was noted most extensively on the concrete slabs at 20, 30, and 50 mils where the polisher had begun to wear through to the concrete. The wearing away was top-down and, therefore, not indicative of a bond failure between the HFST and the concrete. FC-9.5 samples had minimal wear, though these were tested at a lower temperature. The double-lift FC-5 samples also had very good performance, even the sample with the delayed aggregate application. The delay sample had a binder thickness of ~10 mils for the first layer, which had virtually no effect once it was covered by another layer. In all cases, double layer HFST samples had very good performance.

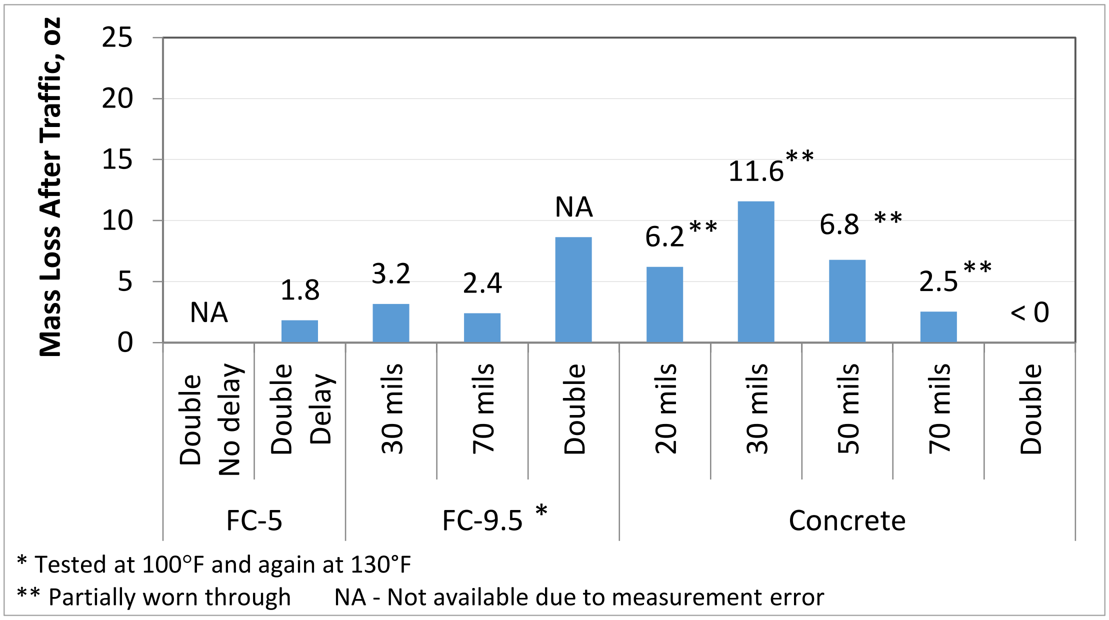


Figure 5.13 – Mass loss of HFST (different substrates and binder thicknesses)

The change in texture is illustrated in Figure 5.14. These measurements were more reliable than the mass loss measurements. Texture loss was most noted on the single-layer concrete samples. Texture losses on the FC-5 and FC-9.5 samples were essentially identical. The texture loss here was less related to aggregate loss and more to the softening of the HMA and epoxy and subsequent embedment of the aggregate.

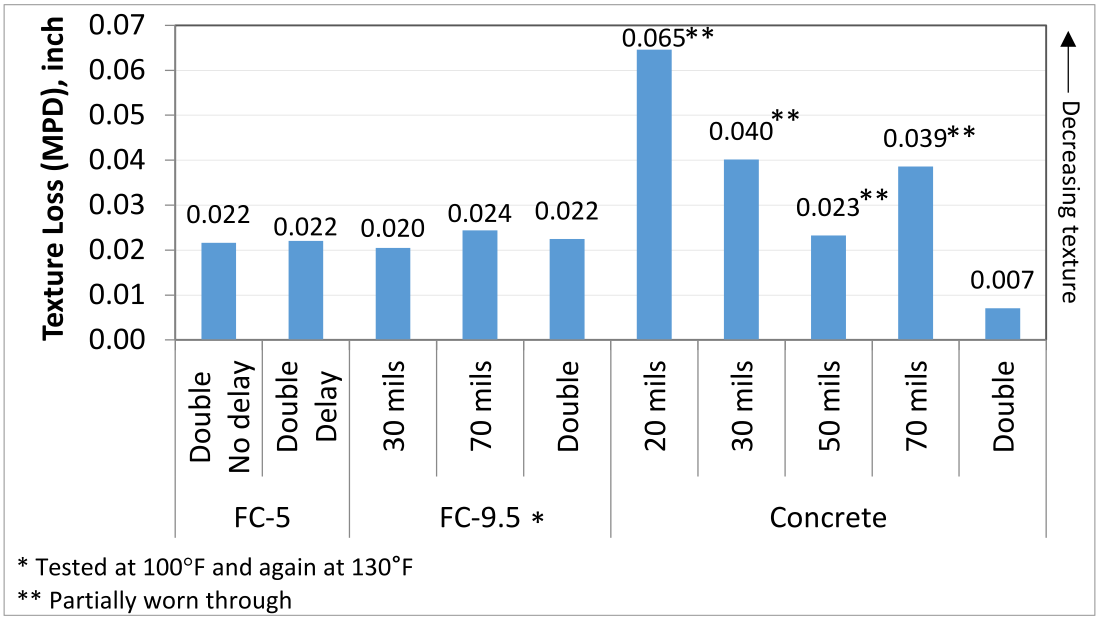


Figure 5.14 – Texture loss of HFST (different substrates and binder thicknesses)

One theory for why the HFST on concrete wears faster is that because the slab is stiffer, the shearing forces under the tire are absorbed directly by the HFST aggregate and resin binder. The stiff substrate enables a more effective abrading action. Asphalt substrates, however, help to absorb the stress and even deform under traffic. For this reason, a double-lift HFST may be better suited for concrete surfaces when severe turning and breaking and accelerating traffic are present. On the other hand, the lab conditions are not a perfect representation of field conditions and there is little evidence in the field for or against using a single-lift HFST on concrete. Due to cost, the single-lift is the recommended method at this time.

Experiment #2.2 – Aggregate Loss (Resin Binder Type and Temperature)

Overview

Continuing the investigation of aggregate loss, this experiment focused on the effect of resin binder type and temperature.

Procedures

The testing plan is shown in Table 5.4. The test used only concrete slabs, which were molded in the same method as Experiment #2.1. Four HFST designs were tested, each using a different binder type. The HFST was a double application with a target 50 mils of binder on each lift and Aggregate A. The samples were tested in the three wheel polisher at either 75°F or 140°F for 50,000 cycles. A longer testing time was used than in the previous experiment because the double layer HFST was more resistant to wear. Sample weights and texture measurements were made before polishing and after polishing with 36 hours of drying. Again, only one sample of each type was tested due to material and time limitations.

Table 5.4 – Testing Plan for Aggregate Loss vs. Binder Type and Temperature

Substrate Material	Resin Binder	Test Temp (F)	Test
Concrete	A	75	Traffic in 3-Wheel Polisher Raveling and texture
		140	
	B	75	
		140	
	C	75	
		140	
	D	75	
		140	

Results

The mass loss results are shown in Figure 5.15. Mass loss was negligible (less than 4 oz) at 75°F for all binder types, except Binder D, at 75°F. Mass loss of Binder D was slightly above 5 oz, but the researchers expect this is an error in the measurement method. When raising the temperature to 140°F, the sample mass loss increased and for Binder C, and the polishing wheels wore completely through to the concrete (Figure 5.16). The high temperature was above the glass transition point for this particular epoxy. This result, however, is not a direct indication of poor performance in the field, especially since Binder C has good performance at the lower temperature. This is still a point to consider for the high summer temperatures observed in Florida.

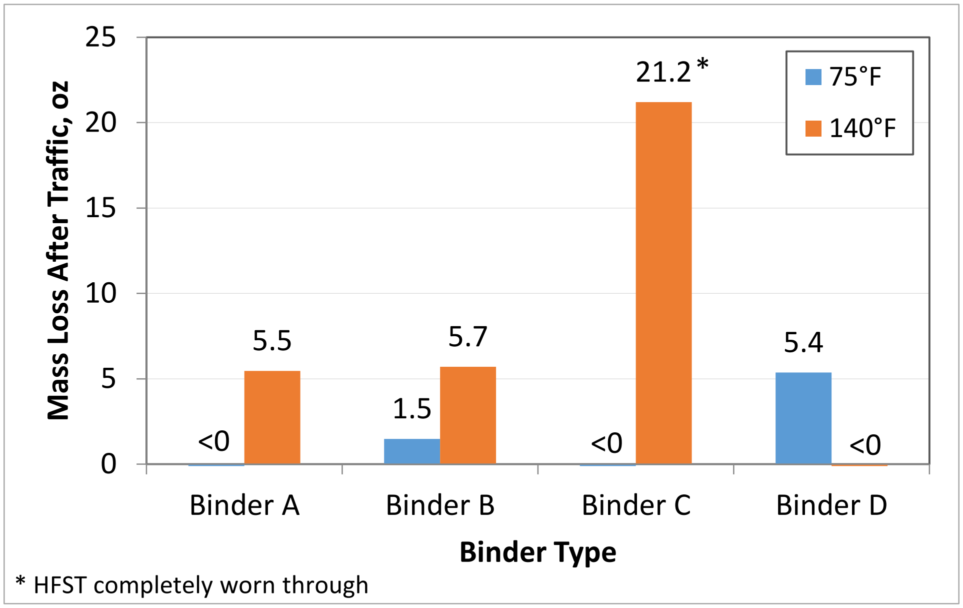


Figure 5.15 – Mass loss of HFST (four binder types and two temperatures)

Figure 5.16 – Failure of Binder C sample at 140°F

The surface texture (mean profile depth) for HFST, before trafficking, was 0.078 inches for all samples, and ranged between 0.075 and 0.082 inches, respectively. The change in surface texture after trafficking is shown in Figure 5.17. In every case, texture loss increased at the higher temperature. Texture loss at 75°F was 0.011 inches on average, and at 140°F was 0.024 inches on average for resin Binders A, B, and D. The HFST was completely worn through for Binder C and had a resulting texture loss of 0.053 inches. The average texture after trafficking for all samples (excluding the failed Binder C sample), was just above 0.05 inches, which is still considered high macrotexture.

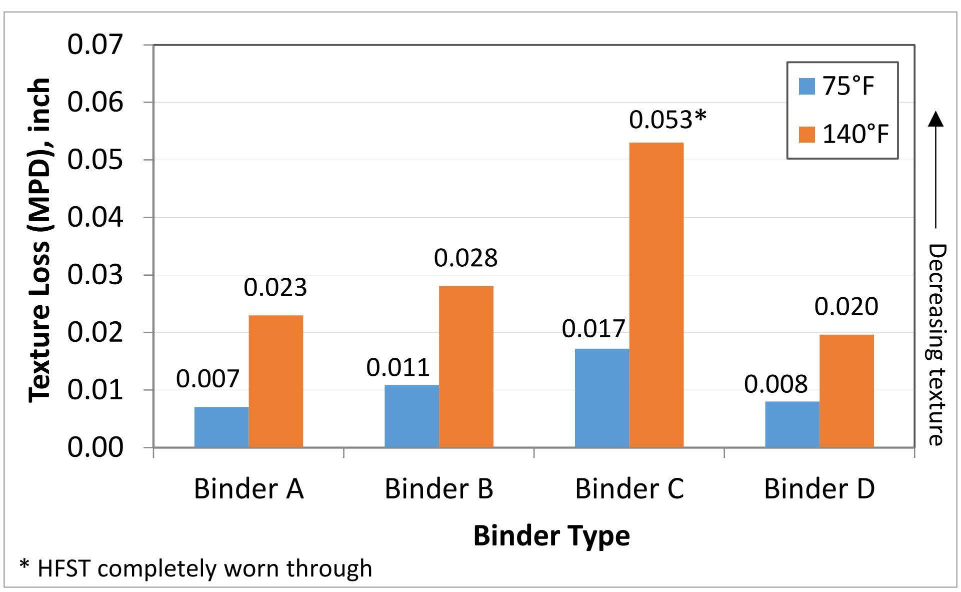


Figure 5.17 – Texture loss of HFST (four binder types and two temperatures)

Experiment #3 – Thermal Compatibility

Overview

Some HFST failures are related to thermal incompatibility between the HFST and the substrate. As the pavement temperature cycles, the HFST and substrate try to expand and contract at different rates which creates a build-up of stress at the bond. If the bond is insufficient, this could lead to delamination (Figure 2.9), and if the substrate is weak, this could cause cracking (Figure 2.16) and even pop-out-like failures of the substrate.

Procedures

The test plan for this experiment is shown in Table 5.5. The researchers measured the coefficient of thermal expansion (COTE) for three substrate materials and four HFST designs using AASHTO T336 (Coefficient of thermal expansion of Hydraulic Cement Concrete). The researchers also measured the linear COTE of the four HFST designs using ASTM C531 (Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes).

Table 5.5 – Testing Plan for Thermal Compatibility

Material	Test Temperature (°F)		Test
	Minimum	Maximum	
Concrete	50	140	Modified AASHTO T336
FC-5	50	77	
FC-9.5	50	86	
HFST-Binder A	50	113	
HFST-Binder B	50	113	
HFST-Binder C	50	113	
HFST-Binder D	50	113	
HFST-Binder A	50	113	ASTM C531
HFST-Binder B	50	113	
HFST-Binder C	50	104	
HFST-Binder D	50	113	

Concrete samples were molded in 4-inch diameter cylinders and cut to a height of 6.8 inches after curing. Asphalt samples were molded in a Superpave gyratory compactor in a 6-inch diameter mold and then cored down to a 4-inch diameter and a height of 6.8 inches. HFST samples were prepared by mixing binder and aggregate and layering the mixture into 4-inch diameter cylinders and 10-inch-long prismatic molds. The HFST design was 41 percent aggregate and 59 percent aggregate by volume. This design replicates the lower half of HFST which is stone-on-stone contact with no air voids (Figure 5.18). The HFST was mixed an applied in shallow lifts to avoid excessive-heating and shrinking during exothermic curing.

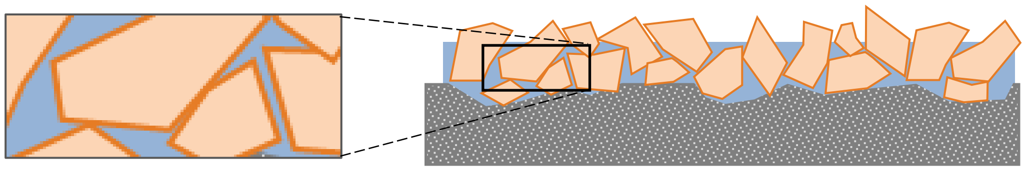
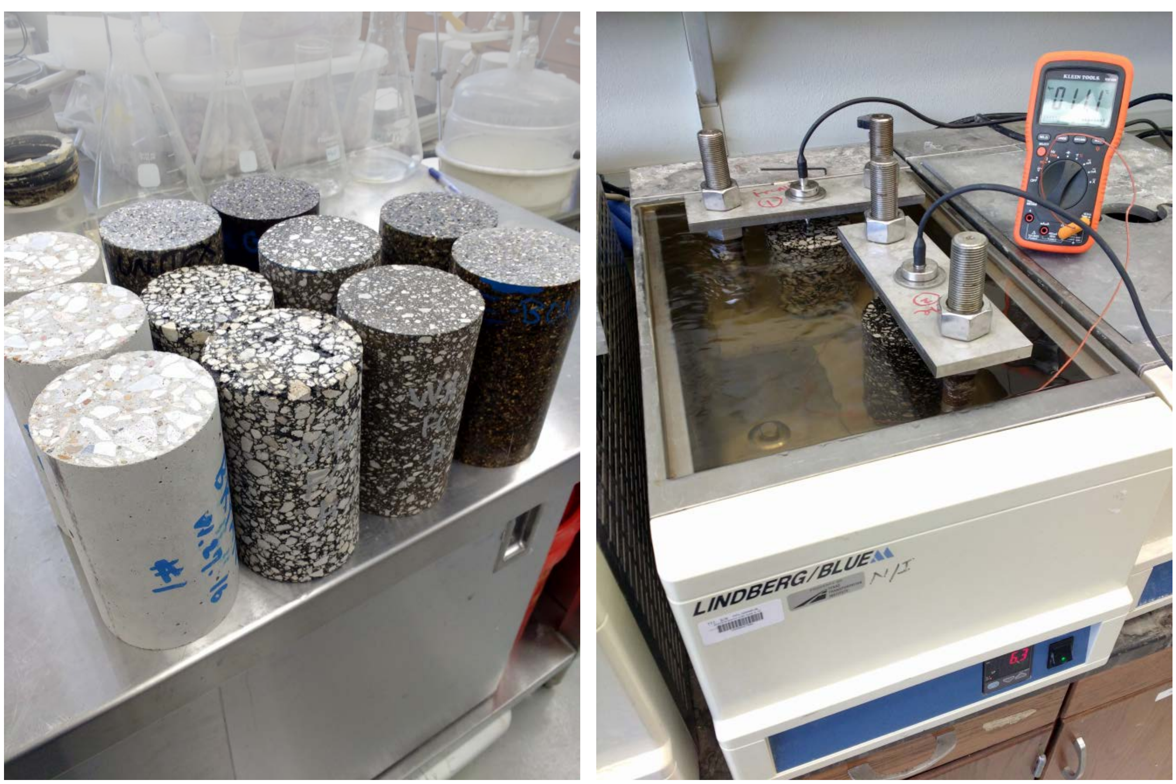


Figure 5.18 – High-density HFST material replicated in COTE samples

The samples and test set up for AASHTO T336 are shown in Figure 5.19. The test is specified for concrete samples but was modified for testing HMA and HFST. A cylinder is submerged in a water bath and an LVDT is lowered to touch the sample and secured in place. The bath and sample is brought to a low temperature, 50°F, and a reading is made from the LVDT. By the AASHTO method, the temperature is then raised to 140°F. This temperature, however, is too high for the HMA and HFST samples and causes them to soften and deform. Therefore, the FC-5, FC-9.5, and HFST samples were raised to 77, 86, and 113°F, respectively. After a high-temperature LVDT reading was made, the temperature was returned to 50°F and a final measurement taken. In some cases, the samples showed signs of shrinkage during the test, in which case the heating and cooling cycles were repeated until no further shrinkage was observed.



(a) **(b)**

Figure 5.19 – AASHTO T336: (a) cylinder samples and (b) water bath and LVDT set-up

The samples and test set up for ASTM C531 are shown in Figure 5.20. The test is specified for mortars, grouts, surfacings, and polymer concretes. A prism sample is measured in a length comparator at a high and low temperature. A low temperature of 50°F and a high temperature of 113°F (104°F for Binder C), were chosen to correspond with the AASHTO T336 test and avoid glass transition stages. Repeated measurements and temperature cycling was done until no shrinkage was observed.

(a) **(b)**

Figure 5.20 – ASTM C531: (a) HFST prism samples and (b) length comparator

Results

The test results for the substrates and average of all HFST samples is shown in Figure 5.21. Concrete had the lowest COTE of 5 x 10^{-6}/°F. Dense- and open-graded HMA had similar COTE values of 7 and 9 x 10^{-6}/°F. The HFST had considerably higher average COTE values of 20 and 24 x 10^{-6}/°F, depending on the test method. Because of the drastically different COTE values, HFST bonded to these substrates will induce stress with thermal cycling.

Figure 5.22 shows the COTE results for each HFST type. The AASHTO test yielded lower COTE values on average, ranging from 15 (Binder D) to 23 x 10^{-6}/°F (Binder B). The ASTM procedure, on the other hand, had a range between 14 (Binder D) to 30 x 10^{-6}/°F (Binder A). Binder D is a polyester acrylic resin while other binders are epoxy type resins. The researchers are unsure why the COTE rankings are different for the two test types, but it is most likely due to differences in the sample densities or errors with material proportions. Still, it is clear that HFST has a considerably higher COTE than substrate materials and that the COTE for HFST binder types are not the same.

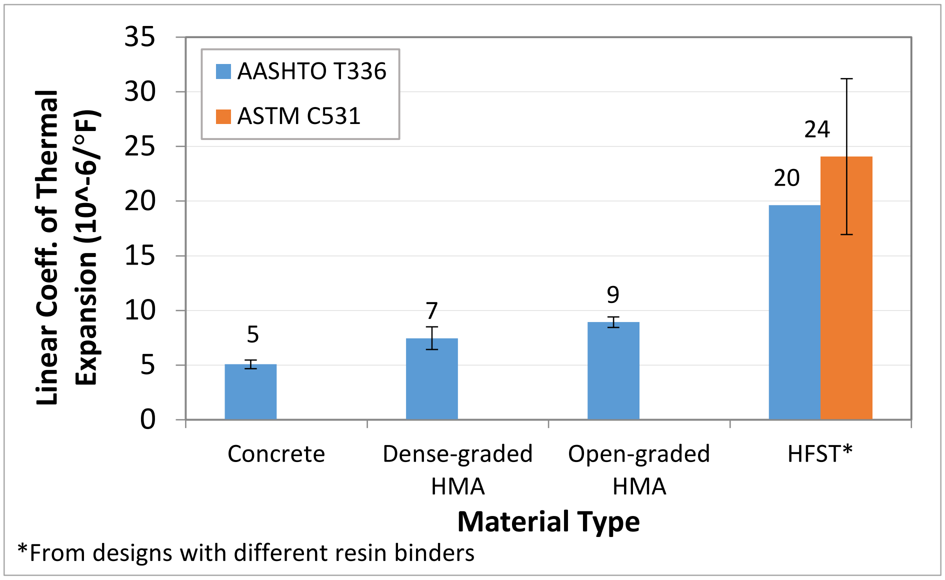


Figure 5.21 – Coefficient of thermal expansion results for different materials

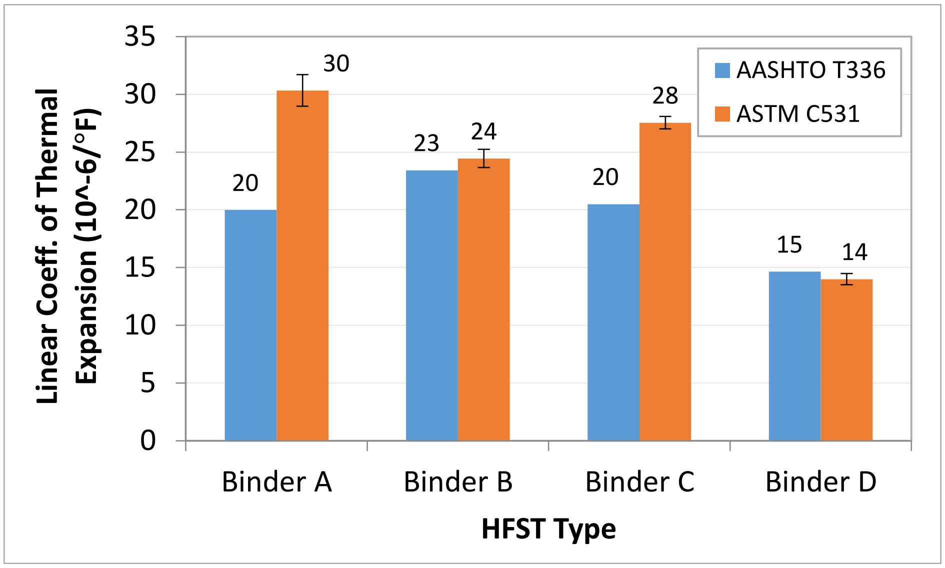


Figure 5.22 – Coefficient of thermal expansion results for HFST types

Experiment #4 – Binder Gel Time

Overview

A critical part of HFST construction is ensuring the binder components are thoroughly mixed. If mixing is inadequate, the resin binder will not cure, leading to aggregate loss, delamination, and potential substrate failure (Figure 2.10). The DOT wanted suggestions on a quality control method that might mitigate this type of problem. This experiment, therefore, focused on methods to measure inadequate binder proportioning, primarily through the gel time test.

Procedures

The test plan is shown in Table 5.6. The gel time of the four binder types were measured according to ASTM C881 (Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete). The researchers investigated the effect of binder proportioning and temperature.

Table 5.6 – Testing Plan for Binder Gel Time

<table>
<tr><th>Binder Type</th><th>Proportion of Part B</th><th>Temperature (F)</th><th>Test</th></tr>
<tr><td rowspan="13">A
B
C
D</td><td>+25%</td><td rowspan="7">72</td><td rowspan="13">ASTM C881 (gel time)</td></tr>
<tr><td>+15%</td></tr>
<tr><td>+10%</td></tr>
<tr><td>Recommended</td></tr>
<tr><td>-10%</td></tr>
<tr><td>-15%</td></tr>
<tr><td>-25%</td></tr>
<tr><td rowspan="6">Recommended</td><td>50</td></tr>
<tr><td>60</td></tr>
<tr><td>72</td></tr>
<tr><td>80</td></tr>
<tr><td>90</td></tr>
<tr><td>100</td></tr>
</table>

In ASTM C881, a 2 oz. (60 g) sample is thoroughly mixed in a paper cup and allowed to cure. During the cure, the sample is checked to see if it has started to gel, noted by a gelatinous ball forming in the cup (Figure 5.23). The time this occurs is the gel time. In most cases, the proportioning calculations were done by volume. For example, if the volume of Part B was increased by 25 percent, Part A was reduced by 25 percent. In the case of Binder B, the same method was done, but by weight. In the case of Binder D, the acrylic polyester resin has a mixing ratio of roughly 98 percent Part A and 2 percent Part B. In this case, the Part B volume was increased up to 3 percent by volume, and decreased down to 1 percent by volume, essentially increasing and decreasing the amount of Part B by 50 percent.

For testing at the different temperatures, the binder parts were first stabilized at the target temperature and after mixing the materials were returned to cure at that same temperature.

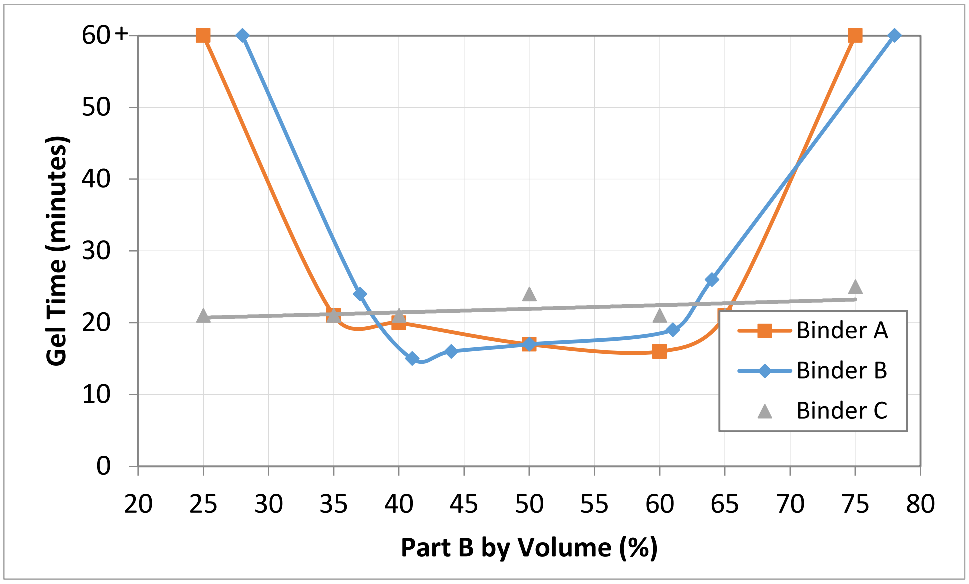
To a small extent, the researchers also considered whether Fourier transform infrared spectroscopy (FTIR) could be used to detect differences in binder proportioning. The base binder parts were measured with FTIR separately and then measured with FTIR again after mixing but before the gel time. This was only done with Binder B.

Figure 5.23 – Gel time test

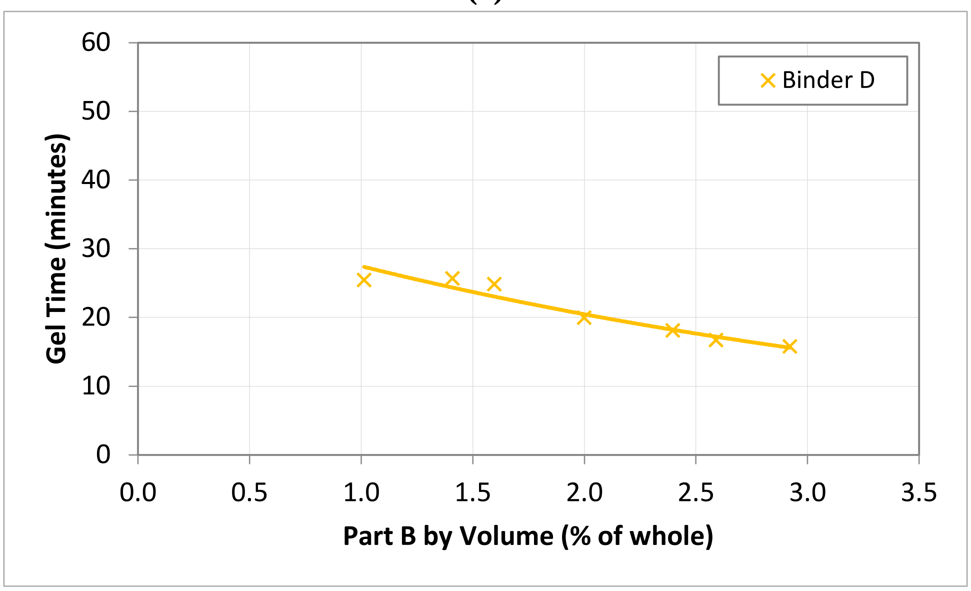
Results

The effects of binder proportioning on gel time is shown in Figure 5.24. Both Binders A and B had a gel time of 18 minutes at the recommended design. When altering the proportions +/- 15 percent, gel time was still relatively stable, ranging between 15 and 25 minutes. When moving beyond this to +/- 25 percent, the sample did not gel even after 60 minutes. Binder C, on the other hand, had a gel time of just over 20 minutes at the recommended design, and the gel time remained consistently between 20 and 25 minutes, even at the extremes. Binder D had a gel time of 20 minutes at the recommended design. As Part B increased from 2 to 3 percent, the gel time decreased to about 15 minutes, Reducing Part B to 1 percent increased the gel time to 25 minutes. If the test were done at greater extremes, eventually both Binder C and Binder D would reach a no reaction condition where the binder never gels.

While the gel time test is a simple “quick check” test method, these results suggest that it will only identify extremes in poor proportioning and mixing. For Binder C, the binder could be improperly mixed at a ratio of 3:1, and it would still gel in a comparable time. Binder D did have a good linear gel time vs. proportioning trend, but the differences in gel times are still within minutes of each other and could easily be confounded with other factors like temperature. To further complicate the issue, trying to identify errors during production would prove very difficult. In most cases, poor binder mixing and proportioning happens randomly and in small localized spots. The chances of first detecting the problem are low, and then trying to correct the problem in a timely manner is likely not possible.



(a)



(b)

Figure 5.24 – Gel time vs. proportioning: (a) epoxies and (b) polyester urethane

The results of the gel time vs. temperature tests are shown in Figure 5.25. The three epoxy type resins, Binders A, B, and C, had similar curing trends where the gel time increased to over 30 minutes at 60°F and did not gel at 50°F. At higher temperatures, the gel time dropped to 10 minutes at 90°F and less than 8 minutes at 100°F. Binder D, an acrylic polyester resin, is designed to cure at a wide range of temperatures and the gel time can be controlled with an additive. This additive was adjusted according to the manufacturer’s recommendation. The gel time stayed between 10 and 20 minutes and longer or shorter curing times can be achieved by increasing or decreasing the additive.

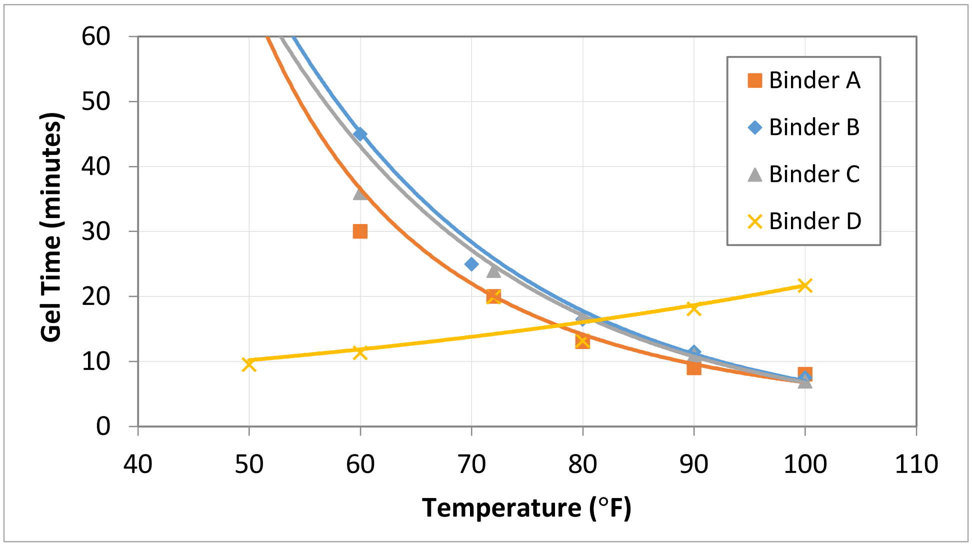
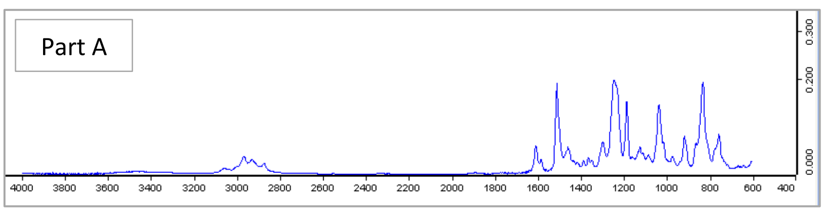
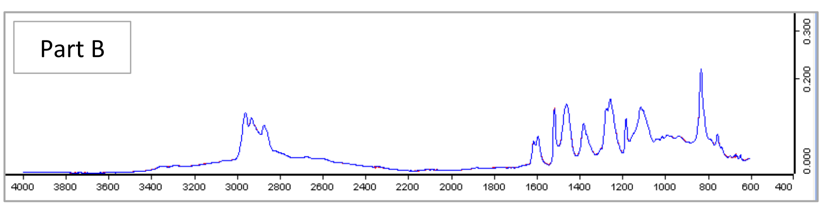


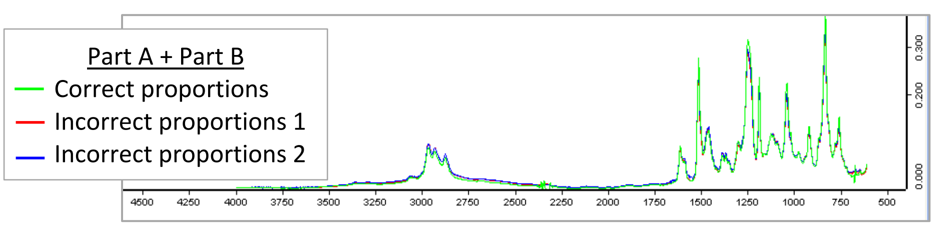
Figure 5.25 – Gel time vs. temperature

The FTIR results for Binder B are shown in Figure 5.26. First the individual Parts A and B are shown followed by a graph of both parts mixed correctly and incorrectly. The results of the correct and incorrect proportions overlay each other almost perfectly, making it impossible for an operator to tell which result is which. The researchers felt that the FTIR was not a promising tool to detect correct mixing and proportioning, so no further testing was done on this topic.



(a)





(c)

Figure 5.26 – FTIR analysis of Binder B: (a) Part A, (b) Part B, and (c) mixed

Experiment #5.1 – Alternative Materials (HMA with Bauxite)

Overview

HFST is a premium road surfacing material using quality high-cost components. On average, the bid unit HFST price in Florida was $34/yd^2, which is significantly higher than traditional paving materials (~$5 to $7/yd^2 per inch for HMA) and even less for seal coat. In addition, in many cases before installing HFST, the contractor needs to mill out the existing HMA layer, place new HMA, and then surface with HFST. The purpose of this experiment was to find if a high-skid HMA design could be made utilizing calcined bauxite. This could possibly eliminate the need for HFST altogether.

Procedures

The researchers attempted to find a mix design incorporating calcined bauxite that would be suitable for a high performance thin HMA overlay. The starting point for this process was the Texas Item 347, Thin Surface Mixtures, which specifies two fine-graded thin overlay mixes (TOMs). The first mix, TOM-C, has a nominal maximum aggregate size (NMAS) of 0.375 inches. The second mix, TOM-F, has a NMAS of 0.187 inches (No. 4 sieve). The TOM-C can be constructed between 0.75 and 1.25 inches thick, and the TOM-F between 0.5 and 1.0 inches thick. The minimum asphalt contents of the TOM-C and TOM-F are 6.0 and 6.5 percent, respectively. The mixtures have a gap-graded structure, using a skeleton of high-quality coarse aggregate for strength, and filled with binder and fines to reduce the voids. These mixtures have unique design and construction challenges, but when successfully done, perform very well.

A TOM-C and TOM-F design were both attempted using a coarser gradation of calcined bauxite and limestone aggregates from Florida. The different aggregates used are listed below (Table 5.7). The binders used were a PG 76-22 polymer-modified asphalt, a PG-76-22 rubber modified asphalt, and a PG 80-22. The optimum asphalt content was defined at 4 percent voids with between 50 and 100 gyrations in the SGC.

Once a successful design was achieved, performance samples were molded and tested in the Hamburg Wheel Tracking Test (rutting susceptibility) and the Texas Overlay Test (cracking susceptibility). A slab was also molded and tested for friction with the DFT and CTM. The slab was conditioned in the 3-wheel polisher up to 100,000 cycles, and friction measurements were made after 2,000, 30,000, and 100,000 cycles.

Results

A successful TOM-C design was achieved with the mixture properties in Table 5.8 and the gradation in Figure 5.27. The mix successfully passed the Hamburg test with 0.12 inches rutting after 20,000 cycles at 122°F. Due to operator errors and material shortages, reliable results for the overlay test are not available. The results that were available suggest the mix may require more asphalt (6.5 percent) to achieve satisfactory cracking resistance performance.

Table 5.7 – Mix Design Materials.

Agg. Type		C. Bauxite	C. Bauxite	C. Bauxite	Limestone	Granite	Lime
Name		3x4	4x8	4x20	F-22	Filler	
Description		Passing – No. 3 Retained – No. 4	Passing – No. 4 Retained – No. 8	Passing –No. 4 Retained – No. 20	Screenings	Fines	
Cum. Percent Passing (%)	3/4 in.	100	100	100	100	100	100
	1/2 in.	100	100	100	100	100	100
	3/8 in.	100	100	100	100	100	100
	No. 4	27.6	99.9	100	100	100	100
	No. 8	0.1	4.9	44.8	89.4	100	100
	No. 16	0.1	1.4	10.5	70.1	100	100
	No. 30	0.1	0.2	0.2	54.4	100	100
	No. 50	0.1	0.1	0.2	30.7	99.9	100
	No. 200	0.1	0.1	0.2	2.2	81.1	100

Table 5.8 – TOM-C Mix Design Properties

Percent by Weight (%)				Asphalt		G_{mm} (Rice)
C. Bauxite	Limestone	Granite	Lime	Type	%	
3x4	F-22	Filler				
Passing – No. 3 Retained – No. 4	Screenings	Fines				
71	20	8	1	PG 76-22, PMA	6.0	2.769

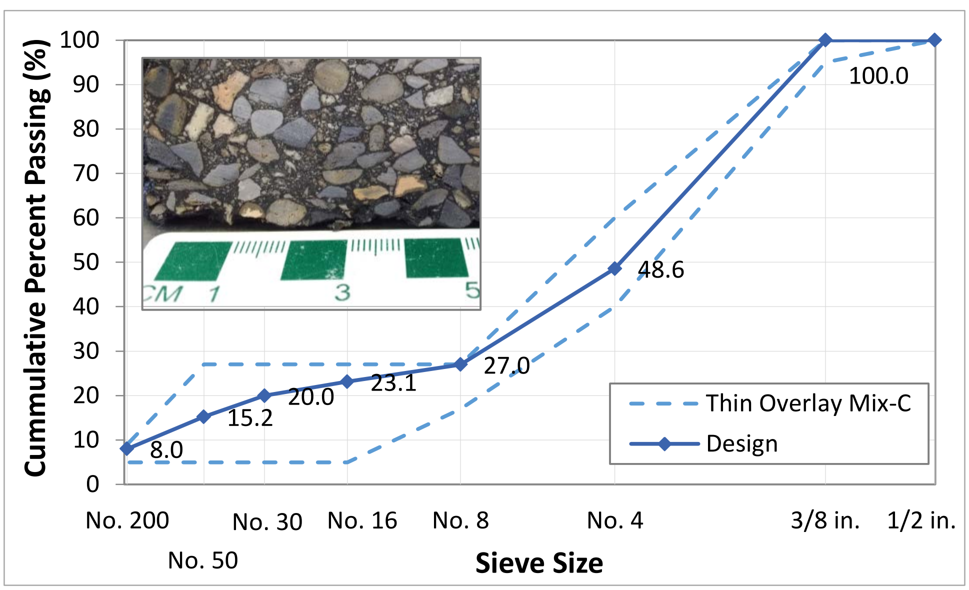
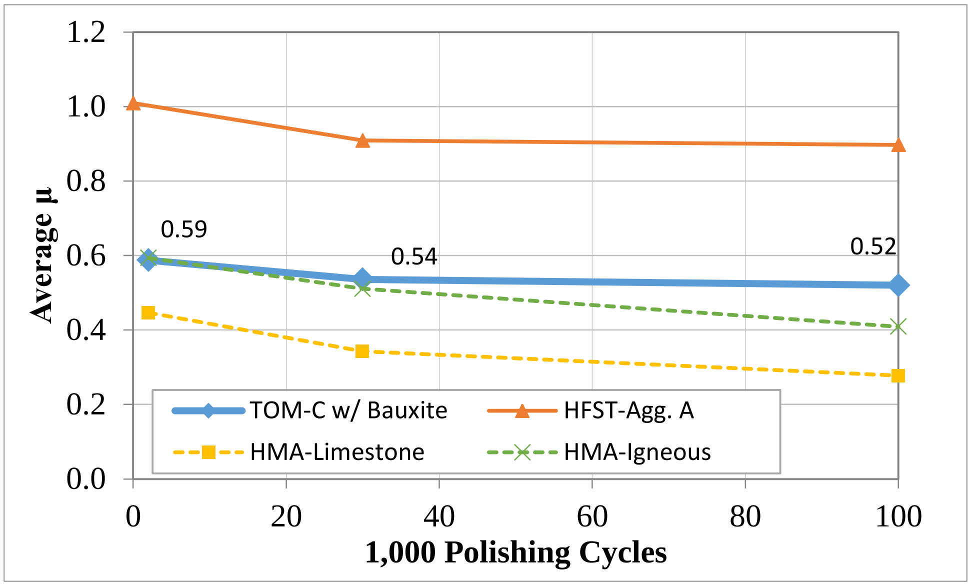
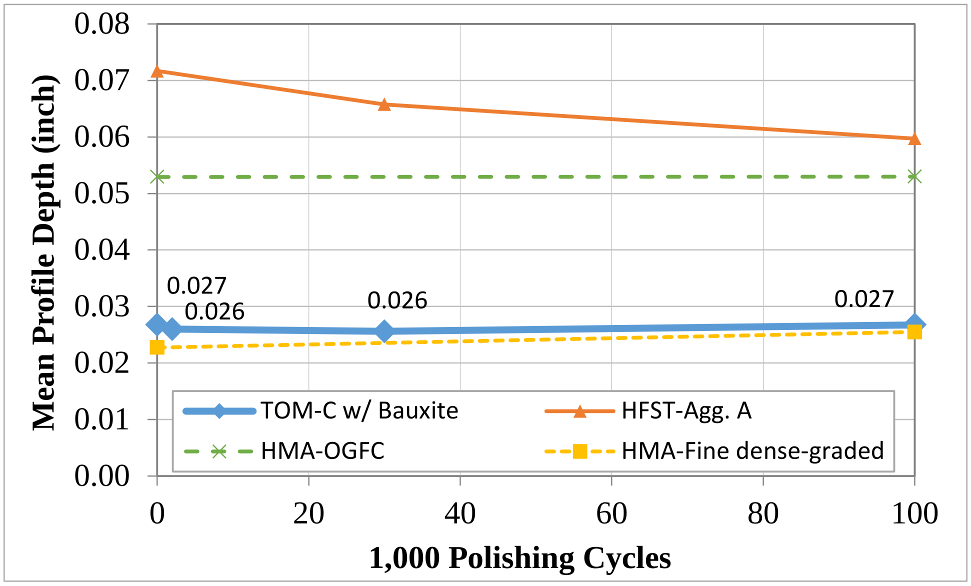


Figure 5.27 – TOM-C design with calcined bauxite

The friction results from slab testing are shown in Figure 5.28. The initial friction coefficient was just under 0.6 and the friction stabilized after 30,000 cycles at just below 0.55. Compared to other HMA designs, this mix had high friction and maintained that friction over time. Compared to HFST, however, the friction was much lower. The texture was similar to other thin overlay designs and much lower than OGFC and HFST. Overall, the friction properties are good, but not comparable to HFST. That said, HFST could have excessive friction capacity and this design may be adequate for crash reduction purposes. Another consideration is to design an open-graded mix with bauxite. This would increase the surface macrotexture.



(a)



(b)

Figure 5.28 – Friction results with polishing: (a) friction coefficient and (b) texture

Chapter 6This thin overlay design with bauxite should perform very well. The question, however, is whether it is economically feasible to produce and construct this mix design in practice. The design would still require importing calcined bauxite, and batching in such a small quantity (less than 100 tons) is a drastic departure for normal production. This would only be feasible if the project was much longer, like a winding rural road.

Experiment #5.2 – Alternative Materials (Aggregate Comparison)

Overview

Another approach to reducing material costs is to use an alternative aggregate. Currently, the specification requires refractory-grade calcined bauxite with a minimum Al_2O_3 content of 87 percent. Since the United States does not have significant sources of bauxite, the aggregate needs to be imported, most often from China. Because of the high Al_2O_3 requirement, other bauxite sources cannot compete in the market. If alternative aggregates were allowed in HFST, it would likely drive down the materials costs.

Aggregate B calcined bauxite is produced in India and has a potential use in HFSTs. This aggregate is refractory-grade, with a reported Al_2O_3 content of 83 percent. Whether the higher Al_2O_3 content is actually required to produce high long-term skid performance is unknown. Aggregate C is a naturally occurring aggregate from the United Kingdom. It has a high silica content and a smaller proportion of Al_2O_3. This aggregate may also be used for HFST. The purpose of this testing, therefore, was to measure the skid resistance potential of these two aggregates and compare them to the standard Aggregate A.

NOTE: The researchers have done preliminary testing of the actual Al_2O_3 content of Aggregates A and B. The results suggest that the both materials have similar contents, right around 87 percent. The precise values need to be verified through further testing.

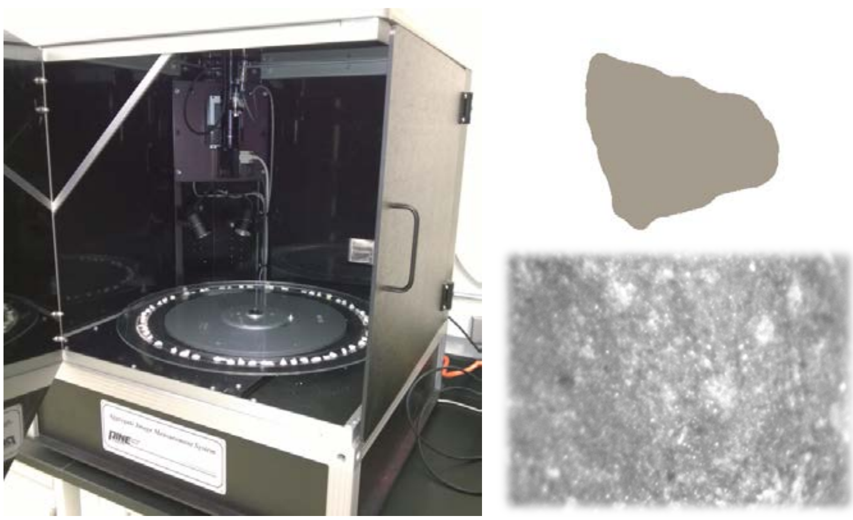
Procedures

Skid resistance is a function of both the microtexture and macrotexture of the pavement surface. The microtexture is mainly dependent on the aggregate microscopic structure; on the other hand, macrotexture is a function of aggregate shape, aggregate gradation, treatment design, and construction method. Over years of traffic, these two properties can change as the aggregate fractures and polishes. In this research, two sets of tests were considered to address micro and macrotexture before and after polishing. The first considers properties of the aggregate alone (micro-deval and aggregate imaging system [AIMS]), and the second set of tests considers the HFST system as a whole (DFT, CTM, and 3-wheel polisher).

Aggregate Specific Testing

The Micro-Deval test was originally developed in the 1960s in France. The Micro-Deval test for coarse aggregate is standardized in AASHTO T 327-05 “Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus”. The test was conducted according to the AASHTO T 327-05 procedure. The aggregate is abraded in a rotating drum filled with steel balls and water. The abraded material is sieved and the mass retained on #16 (1.18 mm) sieve is dried and weighed. The test was modified for this unique aggregate by testing equal amount of aggregate retained on the No. 8 and passing the No. 8 but retained on the No. 16. The test was run for 50 minutes.

The automated aggregate imaging system (AIMS) uses advanced image processing to characterize aggregate shape, angularity and texture (Figure 5.29). The AIMS Angularity Index is based on the 2D aggregate form, while the Texture Index is based on high resolution imagery. Measurements were made on calcined bauxite before and after polishing in the micro-deval. The test methods needed to be modified to consider the smaller aggregate particles used in HFST. Normally, the smallest size aggregate for testing would be retained on the No. 4 sieve. For this testing, however, the aggregate sample was split into two parts: retained on the No. 8 sieve, and passing the No. 8 but retained on the No. 16. 150 and 50 aggregate particles were tested for each size, respectively. The AIMS is not designed to test such small particles, therefore, this required manually adjusting the camera zoom, light level, field of view, and precise aggregate placement.



(a) **(b)**

Figure 5.29 – Aggregate imaging system (AIMS): (a) device and (b) angularity and texture images

HFST Testing

To assess skid resistance of the composite HFST system, the researchers measured macro-texture and micro-texture of lab-fabricated samples before and after simulated traffic. HFST with each aggregate type was applied to concrete slabs. The wet coefficient of friction was measured by a DFT and texture depth was measured by a CTM. After initial testing, the samples were placed in the three-wheel polisher. Testing with the CTM and DFT was conducted before polishing, and after 2,000, 30,000, and 100,000 cycles.

Results

The aggregate specific results are shown in Figure 5.30 and Figure 5.31. The micro-deval loss of both calcined bauxites was very low at 5 percent. In comparison, Aggregate C had a much higher mass loss around 25 percent. This is even higher than the reference aggregates obtained from the rated aggregate source catalogue for TxDOT. This is an indication of low durability and polishing susceptibility.

In the AIMS analysis, the aggregate angularity for all the tested samples was moderate, ranging between 2,750 and 3,500. Angularity decreased after polishing but was still in the moderate category. In the texture analysis, the AIM classified Aggregates A, B, and C as having low, high, and moderate texture, respectively. In all cases, polishing lowered the texture just slightly. Some recent research has suggested the AIMS can be biased with different aggregate colors. In this case, Aggregate A is a lighter-multi-colored aggregate, Aggregate B is dark, and Aggregate C is a light gray. The researchers expect this bias might be manifest here since there is ample evidence that Aggregate A has very high friction properties.

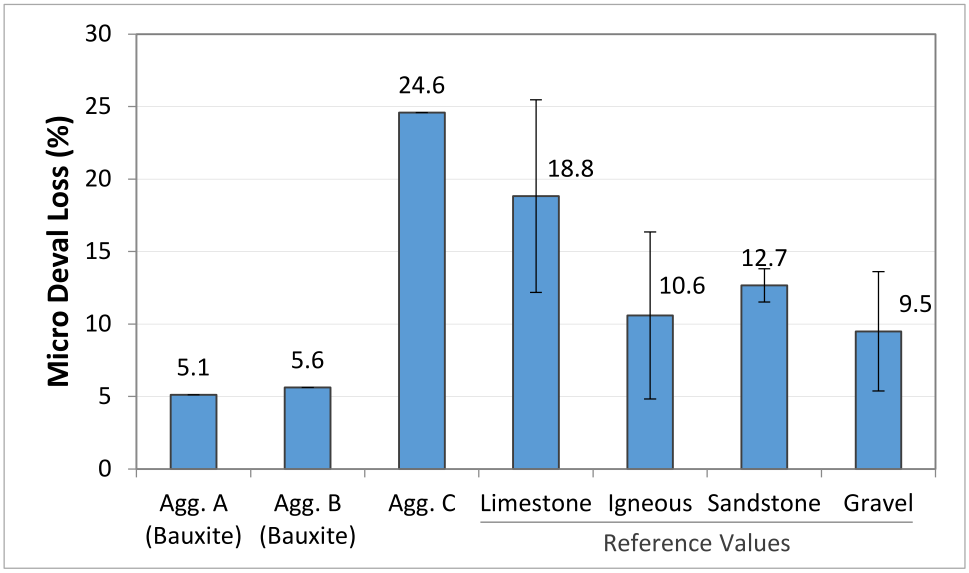


Figure 5.30 – Micro-deval results

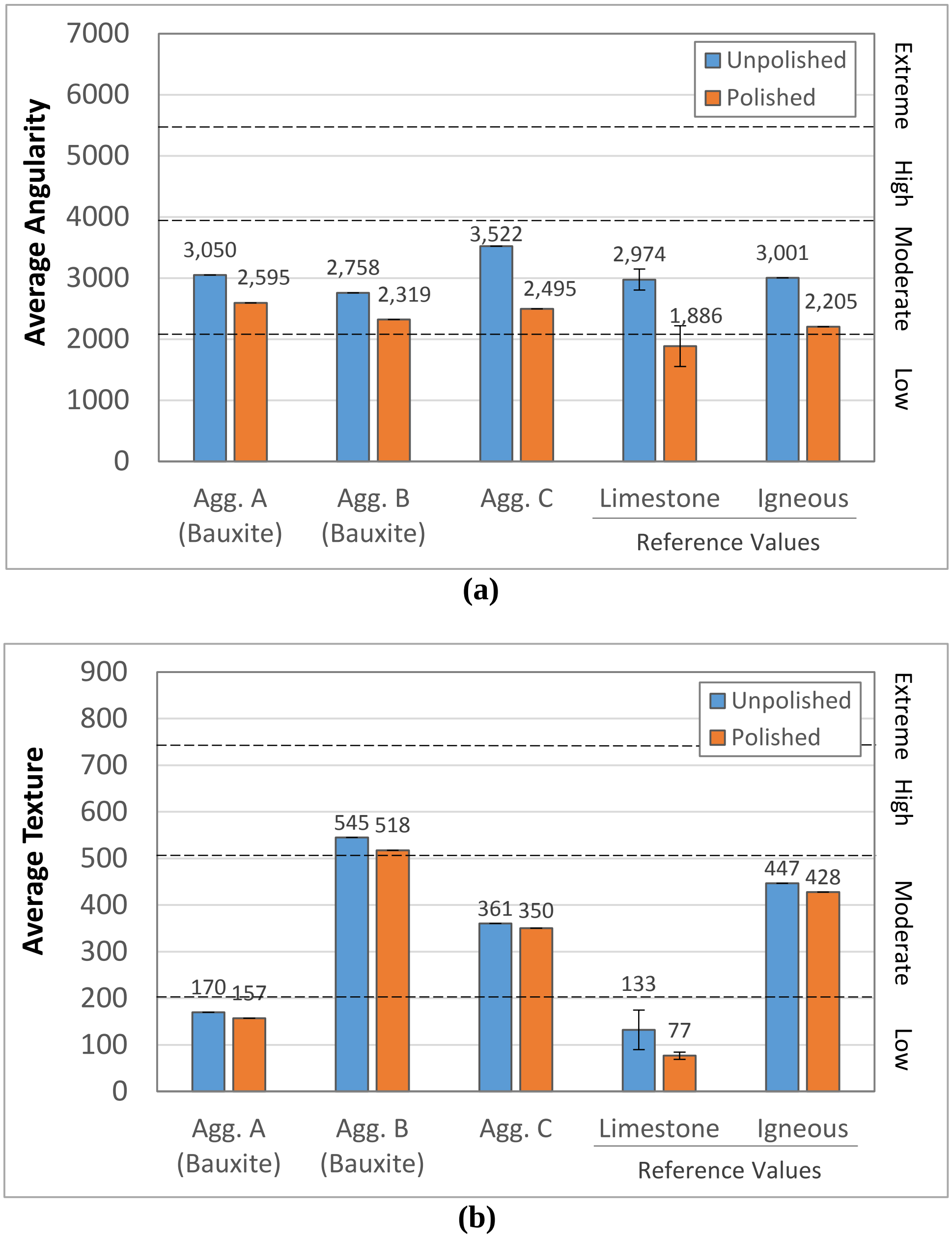
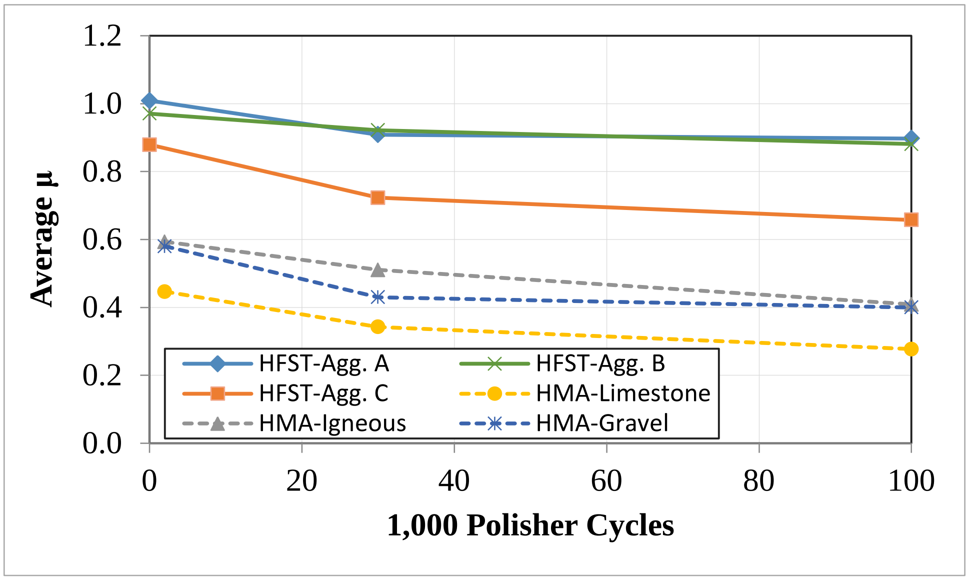


Figure 5.31 – AIMS results: (a) angularity, and (b) texture

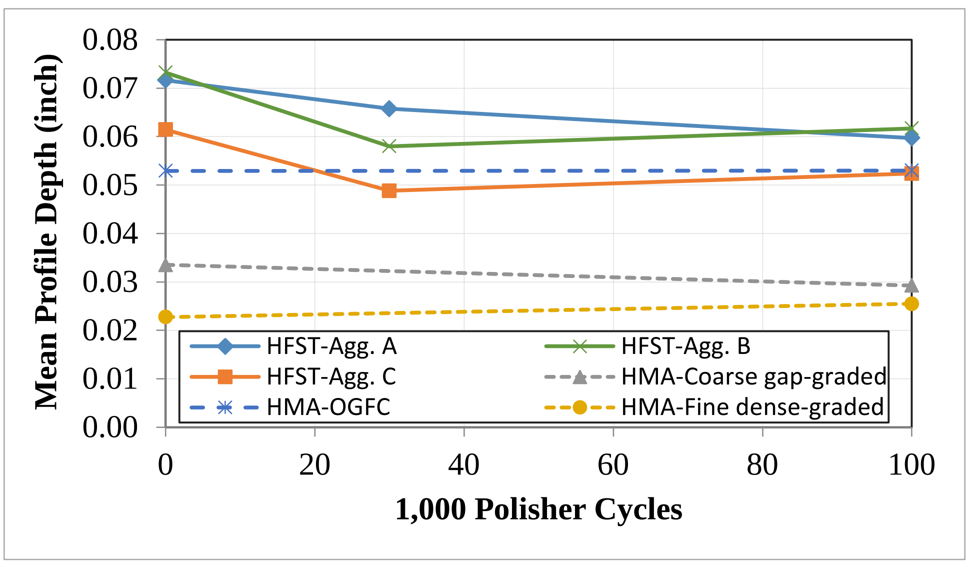
Figure 5.32 gives the HFST friction results. Compared to other mix types, HFST has the highest coefficient initially and in the long-term. Aggregate A and B HFST, both calcined bauxite, had identical friction values. The natural Aggregate C aggregate had lower initial friction performance and polished faster than calcined bauxite. Compared to conventional pavement designs, Aggregate C still had good performance.

The texture of HFST is also very high. Both Aggregate A and B HFSTs started with a mean profile depth of 0.07 inches, and over 100,000 cycles this decreased to 0.06 inches. Aggregate C

HFST also had a high texture (0.06 to 0.05), but slightly lower than the other HFST designs. These values are comparable to OGFC, and considerably higher than typical HMA.



(a)



(b)

Figure 5.32 – Friction results with polishing: (a) friction coefficient and (b) texture

Summary

The purpose of this task was to investigate different aspects of HFST materials and construction practices to improve durability and reduce costs. The topics included the substrate strength, aggregate loss, thermal compatibility, gel time, and alternative materials.

The following are key findings from this task:

Experiment #1 – Substrate Strength

- Substrate tensile strength decreases significantly with moisture conditioning and some with increased air voids.
- The cyclic shear test did not provide consistent results while the pull-off test did.

Experiment #2.1 – Aggregate Loss (Binder Thickness)

- Aggregate loss is a function of binder thickness, where aggregate loss greatly increased for binder thicknesses less than 50 mils.
- A double application of HFST best mitigates issues with aggregate loss. The second application acts as insurance for the first lift.
- Single applications on concrete appear to wear away faster than single applications on HMA, however this phenomenon has not been proven or disproven yet in the field environment.

Experiment #2.2 – Aggregate Loss (Binder Type and Temperature)

- All binders are acceptable for holding aggregate at normal operating temperatures.
- At elevated temperatures (140°F), some binders (Binder C) may become soft and susceptible to accelerated wear.

Experiment #3 – Thermal Compatibility

- Concrete substrate has a relatively low COTE (5×10^{-6}/°F), and asphalt COTE is between 7 and 9×10^{-6}/°F.
- The COTE of HFST is drastically higher for the substrate (between 14 and 30×10^{-6}/°F). High stresses are likely to build up between HFST and the substrate during thermal cycling.
- The COTE values for epoxies were higher than for the acrylic polyester.

Experiment #4 – Binder Gel Time

- The dixie-cup gel time test was not drastically responsive to changes in proportioning until a 25 percent change.
- The gel time test is very sensitive to temperature.
- The gel time for epoxy resins below 60°F increases exponentially while the gel time of acrylic polyester can be controlled at low temperatures with an additive.
- The FTIR was insensitive to binder proportioning errors.

Experiment #5.1 – Alternative Materials (HMA with Bauxite)

- A thin overlay mix was successfully design using PG 76-22 binder and a coarse-size calcined bauxite.

- The design had good rutting resistance. The friction properties, while better than other HMA designs, are inferior to HFST friction.

Experiment #5.2 – Alternative Materials (Aggregate Comparison)

- Aggregate A and B calcined bauxites had similar Al_2O_3 contents and both performed very well in HFST friction testing.
- Aggregate C has good friction properties, but is not on par with calcined bauxite. Of particular concern is the high micro-deval mass loss.
- The AIMS machine ranked Aggregate A as “low” for texture even when it performed very well in other tests. This may be a fault of the image analysis software because of the aggregate’s light color.

CHAPTER 7
PROJECT CONCLUSION

The State of Florida has successfully used HFST since 2006 to reduce wet weather crashes on tight curves and intersections and to maintain bridge decks; however, the Florida Department of Transportation (FDOT) has reported issues related to premature failure of the treatment. Various sections of HFST have experienced severe cracking and potholing of the pavement, delamination from the existing surface, and raveling of the aggregate from the resin binder. Another issue with HFST is that the high material costs limit the number of sections that can be treated annually. Consequently, there is a need to research the best materials and practices to eliminate premature HFST failures and reduce overall HFST costs, while maintaining or improving treatment life and friction performance.

The scope of this project was to:

- Review the literature and conduct industry interviews on the state of the practice of HFST.
- Document all existing HFST projects in Florida and analyze their performance based on distress, skid resistance, and crash reduction.
- Do field testing on six projects and evaluate their present performance and conduct forensic analyses as needed.
- Perform a range of laboratory tests on different aspects of HFST materials and construction practices to improve durability and reduce costs.
- Develop a revised HFST specification for Florida and an HFST Guidelines booklet.

Findings

Following is a list of key findings from previous chapters:

Chapter 3: Documentation of Existing Projects

- Of the 39 identified HFST sections, 17 were on tight curves, 16 were on wide curves/tangents, and 6 were on intersections/approaches.
- The bid unit cost of HFST in Florida was between \$26 and \$40/yd^2, and the total unit cost (including traffic control, repairs, striping, etc.) was between \$36 and \$113/yd^2. The total cost for a typical tight curve segment was \$171,000.
- Nearly 70 percent of all projects are in good and fair condition. Poor and failed projects constitute 22 percent. Other projects had localized failures.
- The most prominent distress was aggregate loss (raveling), followed by uncured binder failure.

- Raveling occurred on half of all open-graded sections (6 of 12) and all dense-graded sections (2 of 2). Other distresses characteristic of the open-graded surfaces are tearing and stripping.
- The average FN40R of all in-service HFST sections was 73 (compare to 51 for concrete and 35 for asphalt). The initial and long-term FN40R of calcined bauxite HFST was 80 and 63.
- Crashes were most prominent on tight curves and intersections/approaches. Existing crashes on the wide curve/tangent sections were negligible (mostly bridge deck preservation projects).
- Crash reduction from HFSTs was most effective on tight curves, where the average reduction in crash rate was 32 and 75 percent for total and wet weather crashes, respectively. Crash rates increased on average for intersections/approach.
- HFST is a cost-effective treatment for tight curves with a history of crashes. The average BC ratio was between 18 and 26 (depending on calculation method), with some sections as greater than 50 and as high as 118.
- HFST is not cost effective, from a crash reduction perspective, on wide curves/tangents with no history of crashes. The cost effectiveness for bridge deck preservation was not part of this research.
- The cost effectiveness of HFST at intersections/approaches is still inconclusive. Half the observed sections had good BC ratios, and the other sections saw a significant increase in crashes.

Chapter 4: Field Testing

- Several distress types were observed (potholing, aggregate loss, surface cracking, substrate tearing, splotchy texture). Through forensic evaluation, several of the failure mechanisms were identified as discussed in the background section.
- Average tensile strength values for the good-condition HFST ranged from 77 to 260 psi. Values near distressed HFST ranged from 37 to 110 psi, including some cores that failed during sample preparation. Most tests failed within the substrate.
- The average friction coefficients in and between the wheel paths were 0.69 and 0.75, respectively.
- The average texture (MPD)values in and between the wheel paths were 0.049 and 0.054 inches, respectively.
- The average decrease in friction and MPD due to aggregate loss was 13 and 21 percent, respectively.

Chapter 5: Laboratory Testing

Experiment #1 – Substrate Strength

- Substrate tensile strength decreases significantly with moisture conditioning and some with increased air voids.
- The cyclic shear test did not provide consistent results while the pull-off test did.

Experiment #2.1 – Aggregate Loss (Binder Thickness)

- Aggregate loss is a function of binder thickness, where aggregate loss greatly increased for binder thicknesses less than 50 mils.
- A double application of HFST best mitigates issues with aggregate loss. The second application acts as insurance for the first lift.
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- At elevated temperatures (140°F), some binders (Binder C) may become soft and susceptible to accelerated wear.

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- The COTE values for epoxies were higher than for the acrylic polyester.

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- The standard gel time test was not drastically responsive to changes in proportioning until a 25 percent change.
- The gel time test is very sensitive to temperature.
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- The AIMS machine ranked Aggregate A as "low" for texture even when it performed very well in other tests. This may be a fault of the image analysis software because of the aggregate's light color.

Recommendations

Candidate Projects

The researchers recommend that agencies strongly consider applying HFST on tight crash-prone curves. Agencies should carefully consider if HFST would be effective at reducing crashes at intersection approaches and within intersections (i.e., identify if a significant source of accidents is skid related). When applied on wide curves and tangent sections (i.e., for maintenance of bridge decks), agencies should not expect to see economic benefits from crash reduction. Further research should be done to identify what variables will best predict a high BC ratio (e.g. exact radius size, present crash rate, nature of crashes, etc.).

As concerns the existing surface type, the researchers do not recommend placing HFST on OGFC pavements. While some projects have successful performance over OGFC, the material often causes more problems like excessive draindown, requirement of double-lift HFST, substrate cracking, and stripping. These surfaces should rather be milled out and inlayed with dense-graded mix instead.

The department may consider a minimum substrate strength requirement, but stricter requirements on the existing surface type and distress condition should resolve issues with substrate failure. The researchers do not recommend excessively stringent requirements on surface condition as it could unnecessarily drive up the costs of HFST application with marginal benefits to long-term performance.

Materials

The researchers recommend lowering the minimum required Al_2O_3 content for calcined bauxite to 86 percent. The minimum required content could likely be lowered further with negligible effect to performance; however, the data are not yet available to support this decision. The unknown aggregate tested may be suited for bridge-deck preservation.

The current specification for polymer resin binders is adequate. In the future, the department may consider a specification with greater flexibility to mitigate problems with thermal incompatibility. This change would need to be balanced with the binder strength and hardness.

An alternative approach to HFST could be incorporating calcined bauxite into HMA design. While a successful design can be created, it is likely an infeasible option considering the economics of producing and constructing such small quantities. It may only be feasible if paving a winding rural road. Even then, the friction performance of this design is inferior to HFST.

Construction

The researchers recommend a contractor requirement to place an HFST test section before full-scale application. This gives the contractor a chance to identify and fix problems, and of equal importance, the FDOT inspector will become familiar with the process and potential issues.

Surface preparation of all projects should include a high-pressure air wash after sweeping to remove remaining dust and debris. Concrete surfaces should require shot blasting to a texture level of concrete surface profile (CSP) 5.

Many problems associated with poor mixing, uneven resin binder thickness, and insufficient aggregate coverage could be solved by using automated application equipment. The researchers recommend FDOT adopt this requirement into their specification. This is expected to increase the cost of HFST early on, especially since very few companies have this capability. With time, as more vendors enter to compete, the costs are expected to decrease.

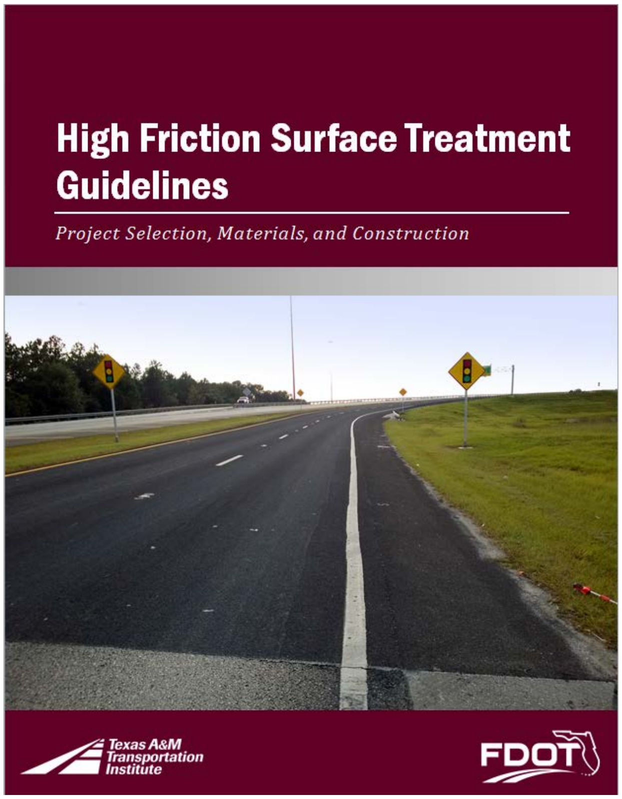
Neither the gel time test nor the FTIR test are recommended as quality control methods. The tests are not sensitive enough to misproportioning except at extremes, and therefore the tests are not substitutes for proper maintenance and calibration of the application equipment. Still the simple gel time test does have a place to ensure against major problems. The required mil thickness in the current HFST specification is adequate and the researchers recommend that contractors and inspectors check the actual mil thickness from time to time with a thin film thickness gauge.

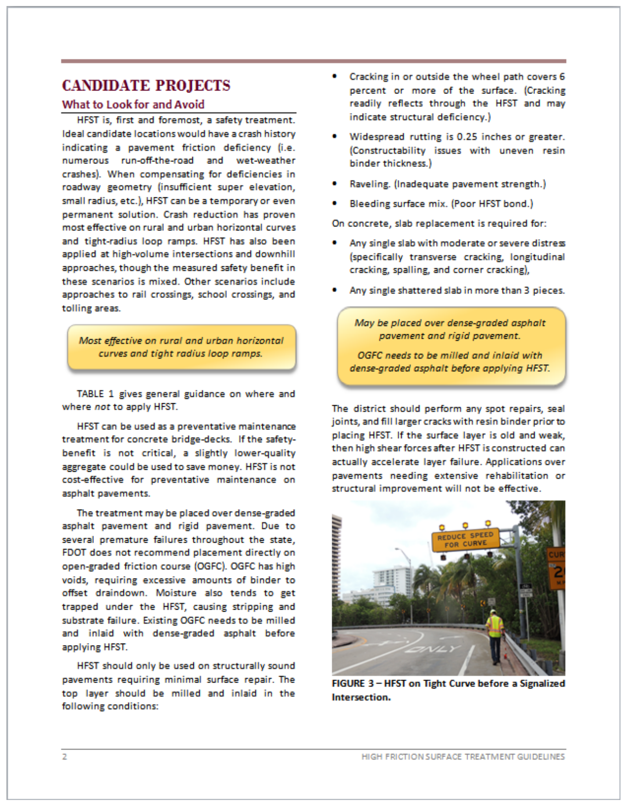
Currently the contractor is required to sweep after the initial cure and do follow-up sweeping after 2 weeks. The researchers recommend another follow-up sweep between 24 to 48 hours on high-volume roadways.

HFST Specification and Guidelines

After discussing with FDOT and industry leaders, many of these recommendations have been incorporated into a revised FDOT specification for HFST (Section 333). The latest recommended specification is contained in Appendix E

In addition, a user-ready booklet, titled “High Friction Surface Treatment Guidelines: Project Selection, Materials, and Construction,” was developed to mirror the FDOT specification and provide additional insight into many requirements and recommendations. The cover and an example page are shown below (Figure 7.1). The document can be obtained by contacting the FDOT State Materials Office (Charles Holzschuher. charles.holzschuher@dot.state.fl.us).





CANDIDATE PROJECTS

What to Look for and Avoid

HFST is, first and foremost, a safety treatment. Ideal candidate locations would have a crash history indicating a pavement friction deficiency (i.e. numerous run-off-the-road and wet-weather crashes). When compensating for deficiencies in roadway geometry (insufficient super elevation, small radius, etc.), HFST can be a temporary or even permanent solution. Crash reduction has proven most effective on rural and urban horizontal curves and tight-radius loop ramps. HFST has also been applied at high-volume intersections and downhill approaches, though the measured safety benefit in these scenarios is mixed. Other scenarios include approaches to rail crossings, school crossings, and tolling areas.

Most effective on rural and urban horizontal curves and tight radius loop ramps.

TABLE 1 gives general guidance on where and where *not* to apply HFST.

HFST can be used as a preventative maintenance treatment for concrete bridge-decks. If the safety-benefit is not critical, a slightly lower-quality aggregate could be used to save money. HFST is not cost-effective for preventative maintenance on asphalt pavements.

The treatment may be placed over dense-graded asphalt pavement and rigid pavement. Due to several premature failures throughout the state, FDOT does not recommend placement directly on open-graded friction course (OGFC). OGFC has high voids, requiring excessive amounts of binder to offset draindown. Moisture also tends to get trapped under the HFST, causing stripping and substrate failure. Existing OGFC needs to be milled and inlaid with dense-graded asphalt before applying HFST.

HFST should only be used on structurally sound pavements requiring minimal surface repair. The top layer should be milled and inlaid in the following conditions:

- Cracking in or outside the wheel path covers 6 percent or more of the surface. (Cracking readily reflects through the HFST and may indicate structural deficiency.)
- Widespread rutting is 0.25 inches or greater. (Constructability issues with uneven resin binder thickness.)
- Raveling. (Inadequate pavement strength.)
- Bleeding surface mix. (Poor HFST bond.)

On concrete, slab replacement is required for:

- Any single slab with moderate or severe distress (specifically transverse cracking, longitudinal cracking, spalling, and corner cracking),
- Any single shattered slab in more than 3 pieces.

May be placed over dense-graded asphalt pavement and rigid pavement.

OGFC needs to be milled and inlaid with dense-graded asphalt before applying HFST.

The district should perform any spot repairs, seal joints, and fill larger cracks with resin binder prior to placing HFST. If the surface layer is old and weak, then high shear forces after HFST is constructed can actually accelerate layer failure. Applications over pavements needing extensive rehabilitation or structural improvement will not be effective.

FIGURE 3 – HFST on Tight Curve before a Signalized Intersection.

2 HIGH FRICTION SURFACE TREATMENT GUIDELINES

Figure 7.1 – HFST guidelines booklet

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APPENDIX A
INTERVIEWS

FHWA Comments

10/31/14

Polymer Resin Binder

- Proper binder performance is CRITICAL for a successful HFST project
- Epoxy is ~2/3 the cost of the HFST materials.
- 2-Part product mixed (Binder and the activating agent). A plasticizer is added to the binder portion
- If the plasticizer is not reactive, it just becomes a filler in the final polymer resin.
    - The filler can be UV sensitive and leaves the resin system over time, making the system more brittle.
    - A REACTIVE plasticizer will not have UV degradation. (cresole is an option).
    - One idea is to use UV conditioning on a sample, then do an elongation test.
- Quick bonded products are competitive with epoxy products
- Use of byproducts from Nylon Industry as a filler to reduce the cost – may not be a good idea
- Quality control for materials and adequate mixing.
    - Need quality control at the epoxy manufacturer.
    - Testing at 70 F may not give the minimum tensile strength
        - This is very different than in the field. When placing epoxy at lower temperature (55 F), the strength gain is slowed down, and the FULL strength is never achieved.
    - Not cured properly
    - Not having a good quality control measures and maintaining the consistency
    - FHWA quality control procedure – small "Dixie cup" sample and monitor the setting before applying. If it doesn't gel, something is wrong (material or mixing)
    - Kansas take one sample at every 100 gallons and check the consistency
    - Illinoi DOT conduct IR finger print using binder sample if the field. They also test binder sample in the lab way before (2 months back) field application. IR finger print is to verify whether the lab measured properties are achieved in the field.
    - Colored epoxy to visually identify good mixing.
- Benzene additive? In the epoxy eating the pavement.

Construction Methods

- Proper mixing and application rate of epoxy is CRITICAL for a successful HFST project.
- Poor mixing has been a problem for FDOT,
    - FDOT did lots of hand applications. Compare this to California which exclusively does a fully automated application process.
    - When manually mixing, need to use a Jiffy mixer, not a mortar mixer.
    - Dixie-cup test may catch poor mixing.
    - Colored epoxy may catch poor mixing.
- Application thickness is important, target of 50% embedment of aggregate
    - Aggregate is 3 mm, epoxy layer should be 1.5 mm (in addition to filling in the surface texture.)

    - Concrete bridge deck uses less epoxy than an asphalt surface.
    - Open-graded asphalt takes a lot more binder. One job was using 3x the amount of binder….this actually isn't what you want. Too thick of binder can cause problems.
    - Crews moving from concrete to asphalt often apply too little binder…leads to failure.
    - Rubber serrated squeegees often lead to thin/inconsistent binder thickness (thickness can change with application pressure.)
- Double-application of HFST has had better performance.
    - Caltrans only does double applications. High success rate.
    - FDOT first did single application on open graded. Didn't perform well.
    - Double layer application is the most common practice in Bridges
        - A thin application of binder in the first layer followed by applying aggregates
        - Apply the second layer (binder plus aggregate). The binder from the 2nd application covers the first layer nicely and makes a durable long lasting HFST in bridges
    - Double layer application with fully automated system will provide FDOT a better solution
- Fully-automated systems
    - Three identified contractors located in East, Central and Western U.S.

Aggregate

- HFST failures are generally not related to the aggregate. But there are improvements that can be made to make HFST more economical.
- Calcined Bauxite.
    - Different types.
        - Refractory grade – Higher grade, made at ~1400 C in the kiln. In rest of industry it's used as an insulator.
        - Abrasive grade – Lower grade, made at 1100 C in the kiln. Not as polishing resistant.
    - Upcoming price reduction
        - Higher demand for HFST applications
        - Many deposits in the world - China (both refractory and abrasive grades), Guyana (South America), India (mostly abrasive grade, high Fe-content may be an issue, 87% CB is needed but 86% is produced mostly here), Australia (max. producer), and Brazil (biggest deposit).
        - Most HFST agg is from China right now. Other countries mine Bauxite for aluminum.
        - When bauxite has more iron impurities, it's not as good for aluminum…but we could still use it.
        - "Buff" bauxite is gone, used to be made in vertical kilns in China…now everything is rotary kiln.
- Taconite is high in friction…but not as good with polishing.
- Flint, three types.
- Recycled ceramic aggregate (didn't work)
- Blending aggregate
    - May be an effective option…however also some issues.
    - Vancouver WA (recycled ceramic agg blend with bauxite…polished out)
    - Wisconsin w/ basalt and CB blend, didn't perform well.
    - UK report…blending does not work
    - AASHTO spec says 87% alumina oxide…but people are still blending aggregates.
    - Idea of using softer aggregate in the bottom of the double layer system.
- Tests

    - Resistant to polishing is more important than high initial friction. Calcined bauxite shows high resistance to polishing.
    - LA is not a meaningful test, does not relate to long-term polish resistance.
    - UK actually started using PSV/AAV ratio instead of PSV alone and this approach is similar to micro-deval method.
    - Aggressive micro-deval (50 minutes instead of 15 minutes) used by NCAT is a good test to qualify an aggregate for HFST.
    - Require a skid trailer value of 60. (tire type not specified)
- Friction demand unique on project-by-project basis. Calculate the friction demand in a particular location based on geometry and other parameters and select the type of binder and aggregate to meet that friction demands. Performance based approach.
- Other states use different aggregates because of "Low-Bid" jobs. Whoever used the cheaper aggregate won the job, but these projects are polishing out. Flint included.
- Aggregate polishing especially a problem on curves with insufficient superelevations. But if superelevation is just about right, polishing might not be an issue.

Comparison of other States

- California (high success rate)
    - Caltrans uses modified polyester acrylic for all HFST projects
    - Modified polyester acrylic. Sets up faster and can be used in cooler temperatures.
    - Equipment is good
    - Open-graded mixes likely higher-quality than FDOT open-graded.
    - Big projects, high number of projects, multi-lanes, more money involved
- South Carolina (some issues)
    - One vendor used on several projects – 7 failures have been reported
    - The types of failures are (i) pop-outs (like Tampa), (ii) raveling, (iii) water percolation because the shoulders were not sealed
    - A local contractor employed to do the job and HFST vendor leases their equipment w/ a truck operator.
    - South Carolina specifications later changed.
- Kentucky (more successful projects)
    - Two lane projects
    - Small projects
    - Cheaper models
    - Not having raveling problems FDOT is having.
- Illinois
    - Requires binder materials submitted months in advance. During testing, the binder needs to match the "IR fingerprint" to be acceptable.
- NCAT (2003 - 2005):
    - One epoxy incorporated a reactive filler (plasticizer). Earlier practice was to use cresole. Cresole was banned but it's possible the name changed and is still in use.
    - Acrylic polyester resin is much better at low temperature applications
    - Looking for cheaper asphalt binder (modified asphalt) for HFST applications

Specifications

- Need a revamped AASHTO spec. Current one came out just to get the ball rolling, but it's not adequate.
    - Tighten up aggregate spec

- More tests for the binder
- LA abrasion test does not relate to long-term polish resistance under tire traffic. Look more at micro-deval (modified). In the UK, they're looking at a PSV/AAV ratio. (AAV was not defined.)

- Dixie-cup field test.

New High-Friction Systems

- Polymer modified asphalt could be a potential alternative binder
    - Compatible with the existing pavement surfaces
    - Cheaper price – binder is the most costly element in HFST and not the aggregate
    - Needs to have HIGH resistance to shear
- Epoxy modified asphalt (New Zealand) could be another alternative binder
- Rapid set high strength mortar with calcined bauxite
- Thin gap-graded overlay using calcined bauxite or blend.
- Slurry using calcined-bauxite fines.

Other Contacts

- Dave Merrit (Transtec).
- Julien Yen, Cornerstone in Missouri.
- ATSSA a good community. But most contractors don't know what they're doing.
- Dallas based manufacturing company for the applicator equipment.

Industry Comments

CONTRACTOR 1

11/12/14

- FDOT, took a while to refine their specification.
- Use waste nylons
- 2 or 3 epoxy guys do a good job (use non-reactive fillers)
- Hybrid Polyester resin hybrid Cost all the same
- Lab tests very different at different temperatures
- Solvent bases (blended coal tar) melts pavements
    - Watch mil thickness
- Maintain viscosity control especially in hot temps and superelevated
- Don't put epoxy on chip-less seal coat
- Be cautious for use in geometric corrections
- \$19-25 / yd^2 (complete)
- For very site specific treatments, seal coat isn't as cost effective.

CONTRACTOR 2

3/27/15

Pure Epoxies

- Safety Grip by Epoplex – 2:1 ratio.

- E-Bond 526 by Transpo Industries, 1:1 ratio.
- Unitex Pro-Poxy by Dayton Superior.
- Flexolith by Euclid Chemical, 1:1 ratio.
- Mark 154 by Polycarb (DOW).
- TyreGrip by Enise-Flint (formerly Ennix Prismo Traffic Safety Solutions).
- Sika Corp, a manufacture, focuses more on bridges.
- Conren product has cresole.

Others

- Epoxy Urethane
- Hitex by Hitex Traffic Group is UK-based.

VENDOR 1

2/25/15

- Thermal incompatibility
    - Problem is having 1) thermal incompatibility, then 2) excessive stiffness.
    - Stiffness may be made worse with thick applications.
    - To reduce this problem, use polymer with lower stiffness (more flexible) but maintain tensile strength. (Like epoxy-urethane)
    - Measurement idea…place HFST on metal and use strain gauges.
- Issues with competing epoxy
    - Add non-reactive stuff, need to add some filler to lower the viscosity.
    - Nenephenol added to dilute the system…non-reactive
- Modified polyester resin
    - Cross-linking faster. Much slower for epoxy.
- Thoughts on FTIR
    - Use it as a finger-print to verify epoxy components and mixing
    - Not feasible. Not sensitive enough to catch subtle variations in proportioning.
    - Requires advanced testing in the lab.
    - Dixie cup method much better suited (Kansas 202)
    - Bradenton never set up.
- CalTrans tests with dog-bone sample.

APPENDIX B
FDOT HFST PROJECT DATA

Table B.1 – Curve Section Geometries and Friction Demand.

District	Section Type	Section Description	Radius (ft)	Cross-Slope (%)	Speed (mph)	Hypothetical Friction Demand*
4	Bridge	EB I-595, SB I-75	2546	6.40	60	0.03
4	Mainline	Royal Palm, I-75	310	10.00	25	0.03
4	Bridge	EB I-595, NB I-95	1432	7.30	50	0.04
4	Bridge	NB I-75, to EB I-595	1910	7.90	60	0.05
4	Bridge	SB SR 869, WB I-595 over I-75 Ramp	1763	8.30	60	0.05
4	Bridge	SB I-95, EB I-595	1146	8.40	50	0.06
4	Bridge	SB SR 869, WB I-75	1432	9.30	60	0.07
4	Bridge	Park and Ride, SB I-95	330	4.60	25	0.08
4	Bridge	NB I-95, Park and Ride	330	4.60	25	0.08
4	Mainline	I-95, Belvedere	213	10.00	25	0.10
1	Bridge	US 301, US 41	674	8.00	45	0.12
7	Mainline	SR 60, I-75	500	9.00	40	0.12
1	Mainline	Memorial Blvd, I-4	583	9.90	45	0.13
4	Bridge	SB I-95, WB I-595	716	10.00	50	0.13
4	Bridge	I-595, Ft L Airport	509	6.00	40	0.15
4	Mainline	SR 810, I-95	230	10.00	30	0.16
4	Mainline	I-95, SR 810	230	10.00	30	0.16
6	Mainline	SR A1A, 27 St	104	2.50	20	0.23
4	Mainline	I-75, Royal Palm	425	10.00	50	0.29

* Calculation:

$$\boldsymbol{f = \frac{(V/1.47)^2}{32.2 * R} - \frac{e}{100}}$$

f = Hypothetical friction demand
V = Velocity (mph)
R = Curve radius (ft)
e = Cross-slope or super-elevation (%)

Table B.2 – HFST Performance Issues.

Location		Performance Issues	Follow-Up Work
District 1			
13010000	US 41 and SR 684 Intersection	• Binder failure during construction. (mixing or material problem) • Several weeks of raveling.	• Mill-out, resurface, and replace HFST on EB SR 684. • Several weeks of sweeping aggregate.
16180301	WB US 192 to SB US 27	• Block cracking and potholes. Possibly related to thermal incompatability (thickness difference).	• Ramps reconstructed 2014
16100102	WB Memorial Blvd to I-4 Ramps	• Minor raveling before bridge.	
13121000	US 301 over US 41	• Raveling after construction. Over asphalt, yes. Over bridge, maybe. • Thermal plastic striping came off with aggregate.	• Restriping.
District 4			
86075037	EB Royal Palm to NB I-75	• Some reflective cracking. • Delamination w/ pothole?	
86075038	NB I-75 to WB Royal Palm	• Losing aggregate in first year. • May not be a critical issue. Section is still performing well.	
86230000	Sheridan St	• Raveling, aggregate did not embed properly.	• Reapply treatment in 2010 with mechanical method. • Reconstructed section in 2014 w/o HFST.
86010006	I-595 to Ft L Airport	• Raveling on some OGFC locations.	• Reapplication in localized areas.
93220143	SB I-95 Off-Ramp to Congress Ave.	• Substrate tearing at intersection (transverse then random) • Agg loss and epoxy loss over concrete at the light.	
93220000	I-95 (6th Ave S and Lake Worth Blvd)	• Splotchy areas not setting up on SB ramp.	• SB ramp was redone (date?)
District 6			
87060002	SR A1A and 27 St	• Some small areas losing aggregate, exposing epoxy. • Localized areas patched with HFST. Too much epoxy on patches (high embedment depth) • Random cracking (possibly thermal incompatability.)	• HFST patching where aggregate was lost.
District 7			
10075033	WB SR 60 to NB I-75	• Many random localized binder failures. • Exposed substrate then stripped and potholed.	• Planned for reconstruction soon.
10190051	SB I-275 to WB SR 60	• First half has many localized binder failures. • Exposed substrate then stripped and potholed. About 3-inch by 3-inch.	• Second segment was reconstructed. HFST and OGFC were removed and replaced with dense mix and new HFST. • Scheduled for reconstruction in 2015.
Turnpike			
16470002	WB Polk Co. Pkwy to WB I-4	• Some areas with binder failure immediately after installation. • Epoxy bleeding and tracking. • Some aggregate raveling	• HFST removed, replaced with FC-5. (date?)

Table B.3 – Crash Statistics.

Section		Total Crashes/MV		Wet Weather Crashes/MV	
		Before HFST	After HFST	Before HFST	After HFST
Curves, Curve Ramps, and Loop Ramps					
10075011	SB I-75 to Big Bend Rd	1.5	0.1	0.9	0.1
10075033	WB SR 60 to NB I-75	1.8	0.7	0.8	0.0
10190051	SB I-275 to WB SR 60	1.3	0.3	1.0	0.0
13121000	US 301 over US 41	0.5	0.0	0.3	0.0
16180301	WB US 192 to SB US 27	1.7	0.2	0.9	0.0
86010006	I-595 to Ft L Airport	0.3	0.0	0.3	0.0
86070088	WB SR 810 to NB I-95	1.6	0.0	1.0	0.0
86070090	NB I-95 to WB SR 810	2.0	0.0	1.4	0.0
86070143	Park and Ride, NB I-95	1.8	0.0	1.8	0.0
86070144	SB I-95, Park and Ride	0.0	5.2	0.0	0.0
86070146	NB I-95, Park and Ride	0.0	1.5	0.0	1.5
86070156	Park and Ride, SB I-95	0.7	0.0	0.0	0.0
86075037	EB Royal Palm to NB I-75	1.2	0.6	0.8	0.5
86075038	NB I-75 to WB Royal Palm	0.2	0.2	0.1	0.1
86095055	SB I-95, WB I-595	0.1	0.3	0.0	0.1
93220159	SB I-95 to Belvedere Rd	1.4	0.9	0.1	0.1
All Curved Sections*		1.0	0.6	0.6	0.1
Crash rate reduction (%)		-38.2		-74.5	
Tangents, Tangent Ramps, and Large curve ramps (radius > 1,000 ft)					
70120000	Eau Gallie Blvd, Indian River	0.0	0.0	0.0	0.0
86070130	NB I-95, EB SR 84	0.2	0.0	0.0	0.0
86075039-5	SB SR 869, SB I-75 over NB I-75	0.0	0.1	0.0	0.0
86075039-5	SB SR 869, SB I-75 over EB SR 84	0.1	0.0	0.0	0.0
86075039-5	SB SR 869, SB I-75 over WB SR 84	0.0	0.0	0.0	0.0
86075040-5	NB I-75, SR 869 over SR 84 and I-595	0.0	0.0	0.0	0.0
86075040-5	NB I-75 over WB SR 84 and N New Riv	0.0	0.0	0.0	0.0
86075042	SB I-75, NB SR 869	0.0	0.0	0.0	0.0
86075043	SB SR 869, WB I-75	0.0	0.1	0.0	0.0
86075046	SB I-75, EB I-595	0.0	0.2	0.0	0.0
86075048	NB I-75, to EB I-595	0.0	0.0	0.0	0.0
86080500	EB SR 84 over I-75	0.0	0.0	0.0	0.0
86081000	SR 84 WB over I-95 NB Ramps	0.1	0.3	0.0	0.0
86095056	SB I-95, EB I-595	0.2	0.3	0.1	0.0
86095062	EB I-595, NB I-95	0.5	0.5	0.1	0.3
93220000	I-95 (6th Ave S and Lake Worth Blvd)	0.5	0.4	0.3	0.2
All Tangent and Large Curve Sections		0.1	0.1	0.0	0.0
Crash rate reduction (%)		28.1		-16.3	
Approaches/Intersections					
13010000	US 41 and SR 684 Intersection	2.2	1.9	0.2	0.3
16100102	WB Memorial Blvd to I-4 Ramps	2.5	5.5	0.5	1.1
86080000, -	SR 84 WB and I-95 Intersection	1.9	2.9	0.4	1.0
86210000	SR 736, I-95 and CSX RR	2.1	5.4	0.3	0.5
87060002	SR A1A and 27 St	0.8	0.8	0.2	0.1
93220143	SB I-95 Off-Ramp to Congress Ave.	2.2	1.3	0.3	0.1
All Approach Sections*		2.0	3.0	0.3	0.5
Change in crash rate** (%)		50.6		69.4	

* Values without "After HFST" data omitted

** Positive value indicates an increase in crashes

APPENDIX C
FDOT HFST CASE STUDIES

Tampa, I-275 Off-Ramp to SR 60

Site Description

This HFST project is located on the off ramp from southbound I-275 to westbound SR 60 (Co. section #10190051) (Figure C.1). The ramp carries an average of 38,000 vehicles each day, with 5 percent trucks. The site had an average of 17.6 crashes per year.

The ramp consists of two 12-ft lanes, a 6-ft inside shoulder, and a 12-ft outside shoulder. The shortest curve radius is 492 ft and the curve length is 570 ft. The existing surface was an open-graded friction course constructed in 2004.

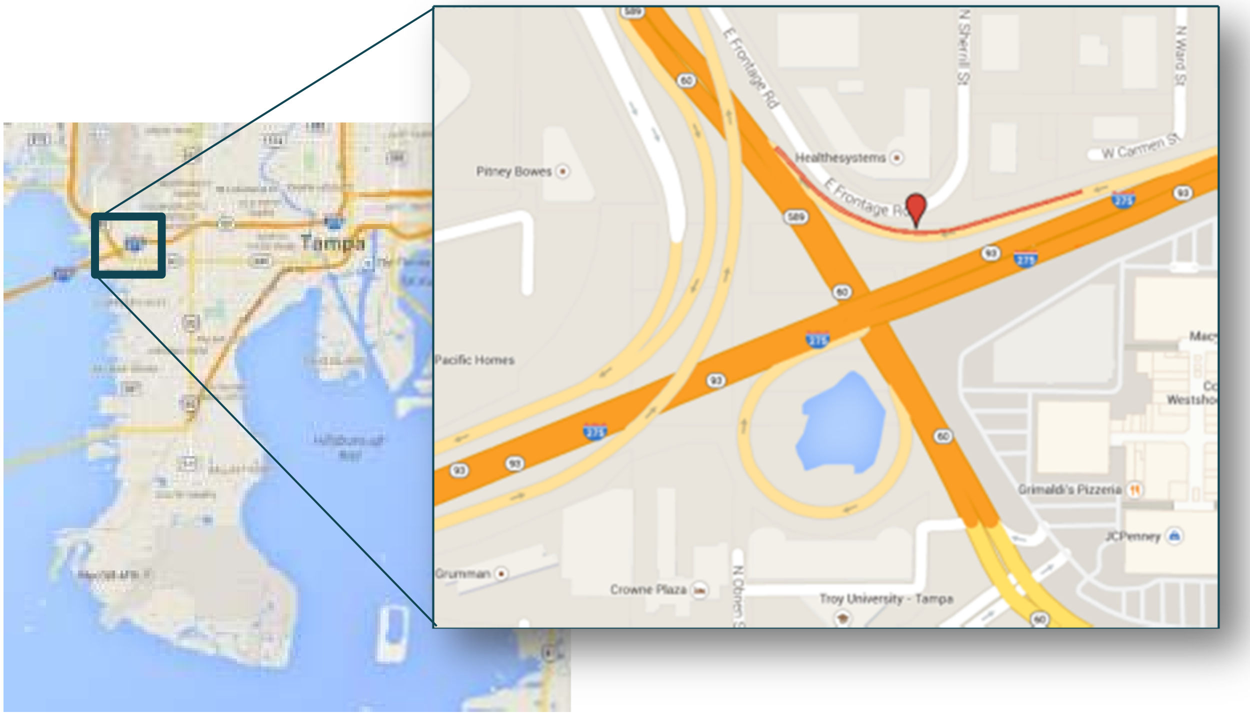


Figure C.1 – Project Location.
(www.google.com/maps/)

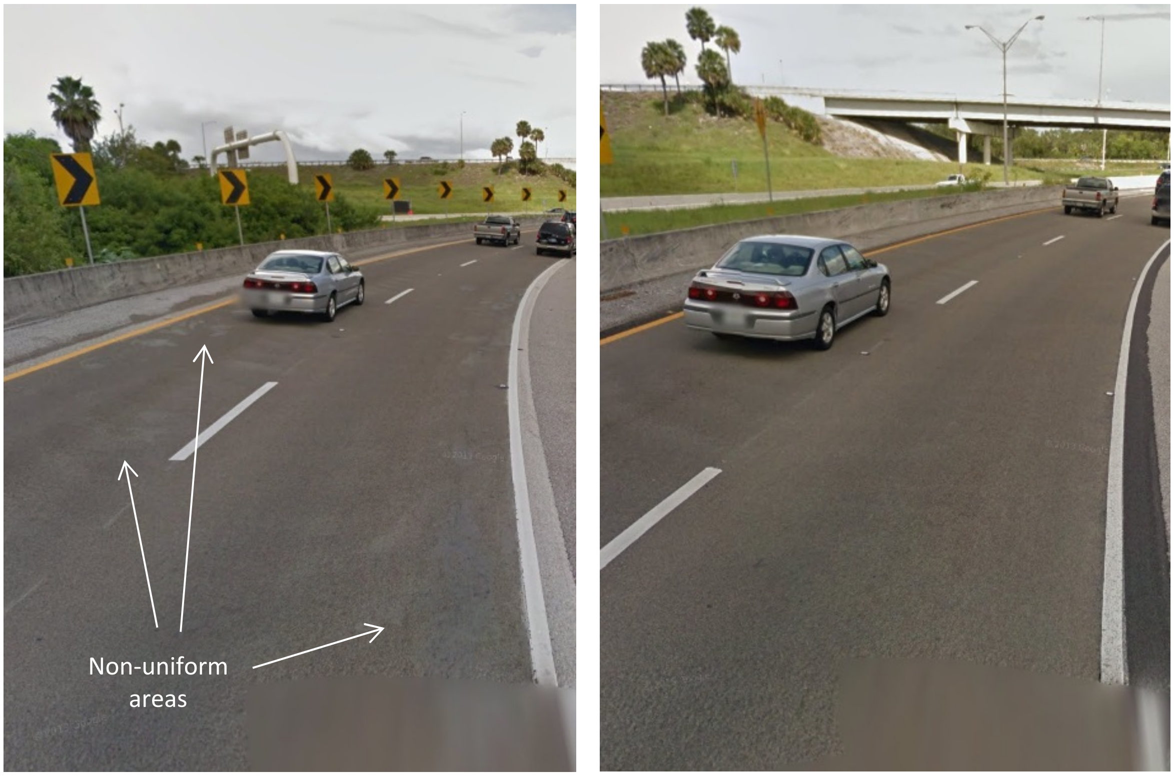
Construction

The HFST was constructed in mid-December 2011 by Florida Safety Contractors. The HFST product, *MARK 154 Safe-T-Grid* was supplied by PolyCarb (subsidiary of Dow), and used calcined bauxite aggregate. FDOT Special Specification Dev 333 (9/13/2010) was used. The bid price was $11.44/sq-yd. It turns out the contractor was inexperienced and underbid the project. HFST is normally between $25 and $35/sq yd.

The existing surface was cleaned with a vacuum-sweeper and a blower as needed. During construction, the contractor had problems with proportioning/mixing the epoxy, despite using an automated epoxy mixing and applicator truck. This resulted in several spots that did not set-up. The second half of the project was particularly bad. Subsequently, the next month, the HFST and existing HMA surface course on this half were milled out and replaced with FC-5 and a new

HFST. The aggregate was applied by hand and with a mechanical applicator truck. Loose aggregate was swept away after the epoxy had set up.

The final surface in Figure C.2 shows with locations without and with milling/resurfacing, respectively. The HFST in Part A was non-uniform and splotchy, a result of poor epoxy mixing and possibly incorrect binder thickness. The image in Part B is notably more uniform.



(a) (b)

Figure C.2 – Completed HFST (July 2012): a) over existing surface, b) over milling/resurfacing.
(www.google.com/maps/)

Performance

Since installation, accidents along this ramp have decreased dramatically. Crashes per year dropped from an average of 14.0 to 0.5—a reduction of 96 percent (Table C.1.)

Table C.1 – Crashes Before and After HFST Installation.

Data Range	Total Crashes/ Yr	Wet Weather Crashes/Yr	Crashes/Yr by Injury				
			K (fatal)	A (serious)	B (moderate)	C (minor)	O (none)
Before (2007-2011)	17.6	14.0	0.0	1.0	1.6	4.2	10.8
After (2012-2013)	3.5	0.5	0.0	0.0	0.0	0.5	3.0

The ramp previously had a skid resistance (FN40R) of 30 in 2010. After the installation, in 2012, the FN40R was 84, and in 2013 was 64. The mean profile depth of the new treatment was 0.048 inches.

From a durability standpoint, the first half of the project, which was not reconstructed, is experiencing a large number of uncured binder failures and potholes. In some cases, the aggregate was lost from the binder. They also had delaminations and OGFC stripping under the HFST (Figure C.3). On the section that was milled and replaced, the small pop-out failures are non-existent. This can be attributed to correcting epoxy problems, placing HFST on an undamaged surface, and lower traffic stress on the trailing side of the curve. Since this study, the project has been removed and reconstructed.

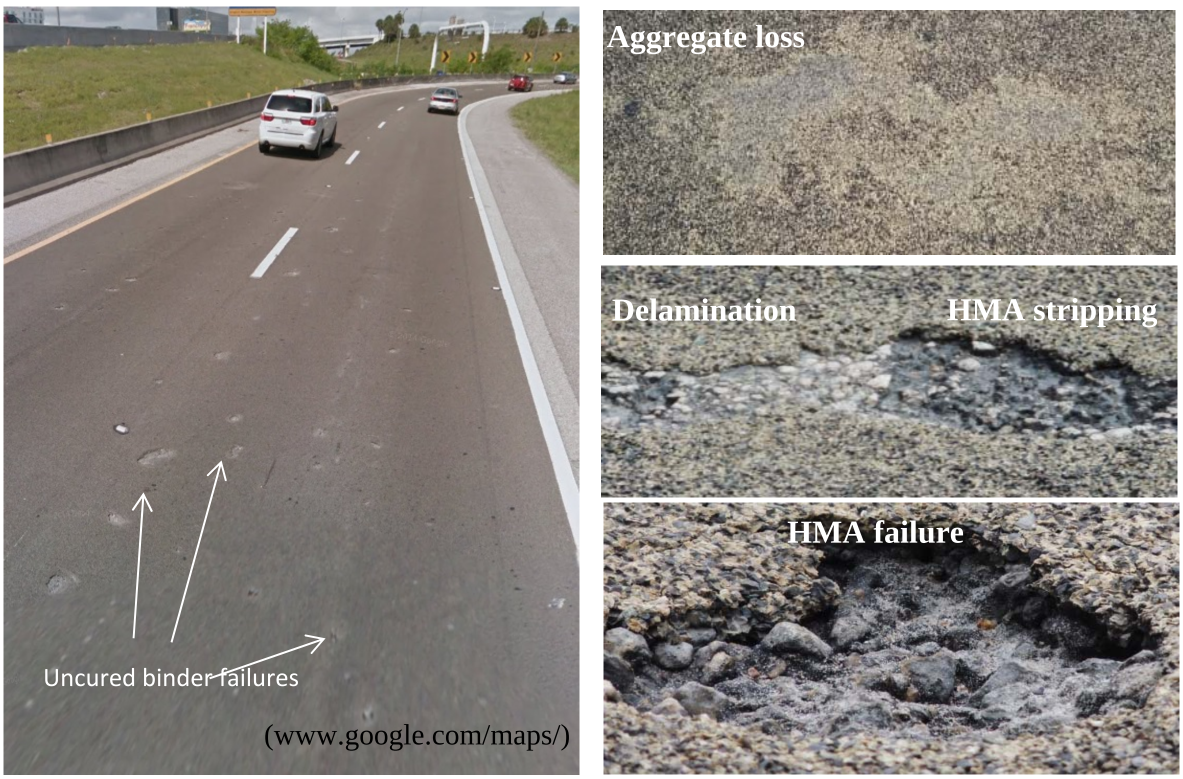


Figure C.3 – Failed locations on HFST (2014)

Brandon, SR 60 Off-Ramp to I-75 NB

Site Description

This is very similar to the Tampa project just described. The project is located on the off ramp from westbound SR 60 to northbound I-75 (Co. section #10075033) (Figure C.4). The ramp carries an average of 17,500 vehicles each day, with 7.2 percent trucks. The site had an average of 11.6 crashes per year.

The ramp consists of two 12-ft lanes, a 6-ft inside shoulder, and a 12-ft outside shoulder. The shortest curve radius is 492 ft and the curve length is 570 ft. The existing surface was an open-graded friction course constructed in 2004.

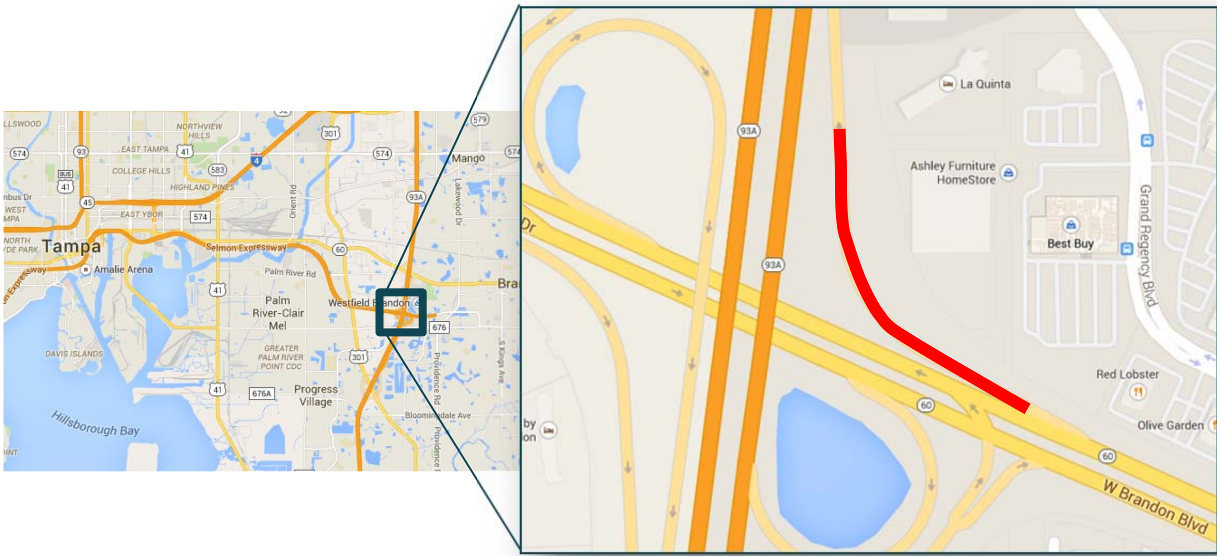


Figure C.4 – Project Location.
(www.google.com/maps/)

Construction

The HFST was constructed in mid-December 2011 by Florida Safety Contractors. The HFST product, *MARK 154 Safe-T-Grid* was supplied by PolyCarb (subsidiary of Dow), and used calcined bauxite aggregate. FDOT Special Specification Dev 333 (9/13/2010) was used. The bid price was $11.44/sq-yd. It turns out the contractor was inexperienced and underbid the project. HFST is normally between $25 and $35/sq yd.

The existing surface was cleaned with a vacuum-sweeper and a blower as needed. During construction, the contractor had problems with proportioning/mixing the epoxy, despite using an automated epoxy mixing and applicator truck. This resulted in several spots that did not set-up. Unlike the Tampa project, no sections were reconstructed. The aggregate was applied by hand and with a mechanical applicator truck. The completed surface is shown in Figure C.5.

Performance

Since installation, accidents along this ramp have decreased dramatically. Crashes per year dropped from an average of 5.2 to 0.0—a 100 percent reduction (Table C.2.) These data, however, have not been adjusted as per crash analysis procedures.

Table C.2 – Crashes Before and After HFST Installation.

Data Range	Total Crashes/ Yr	Wet Weather Crashes/Yr	Crashes/Yr by Injury				
			K (fatal)	A (serious)	B (moderate)	C (minor)	O (none)
Before (2007-2011)	11.6	5.2	0.0	0.6	1.4	2.6	7.0
After (2012-2013)	4.5	0.0	0.0	0.5	2.0	0.5	1.5

Figure C.5 – Completed HFST (May 2011).

The ramp previously had a skid resistance (FN40R) of 34 in 2010. After the installation, in 2013, the FN40R was 62. The mean profile depth of the new treatment was 0.053 inches.

In February 2015, the researchers assessed the pavement distress, measured friction and texture, and took cores for pull-off strength testing.

From a distress perspective, the project has severe performance problems. In scattered locations where the epoxy was not blended, the HFST has failed and the weak substrate has since developed into potholes (Figure C.6 and Figure C.7). Failure development was noted by 1) dark sunken depressions, 2) aggregate loss and delamination from the substrate, and then 3) stripping and raveling of the substrate out from under the HFST. Pull-off strength tests were performed on cores from good and near failed locations. This project is scheduled for reconstruction in the near future.

The friction and texture results are shown in Figure C.8. Friction on the approach tangent was slightly higher than in the curve. This is expected because aggregate polishing is more aggressive under turning traffic. The friction in the wheel paths was not significantly different than between the wheel paths. Texture depth was higher in the tangent and again there was no statistical difference in or between the wheel paths. Both friction values and texture values are exceptional.

Figure C.6 – Uncured binder failure and potholing.

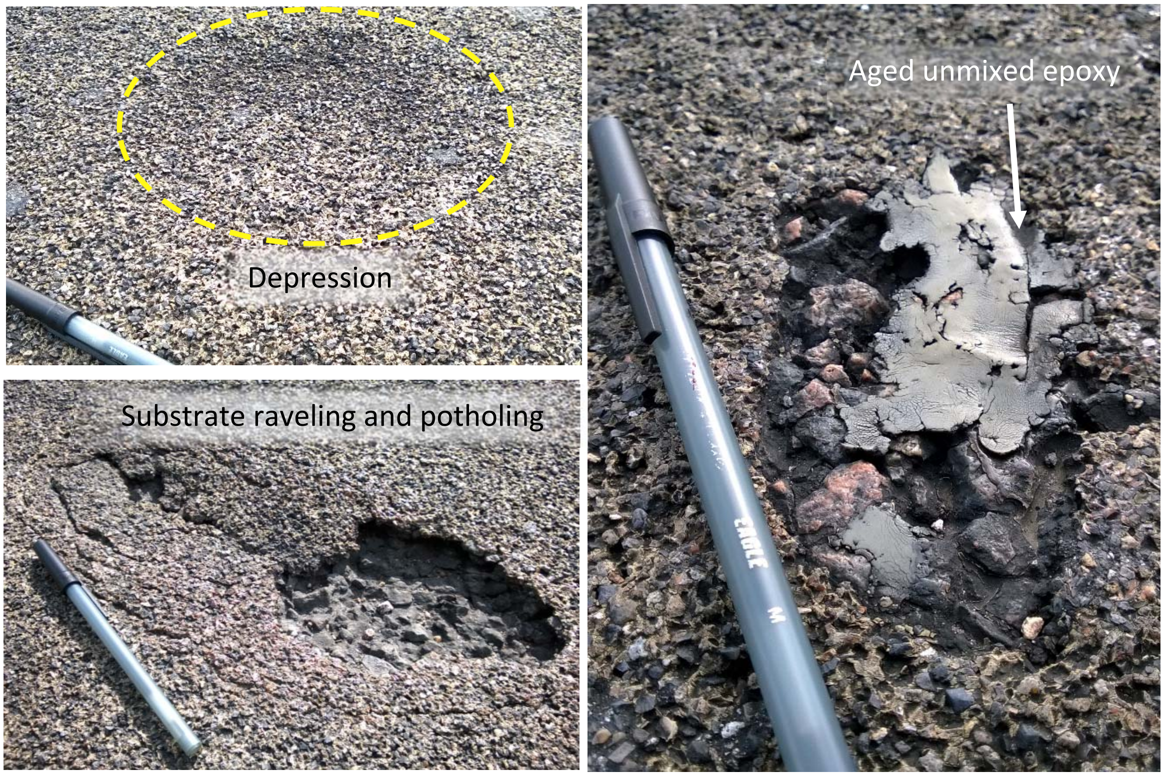
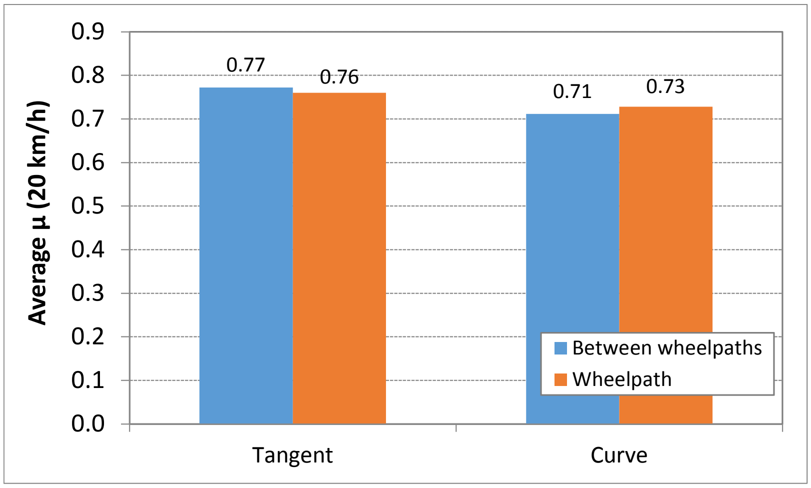
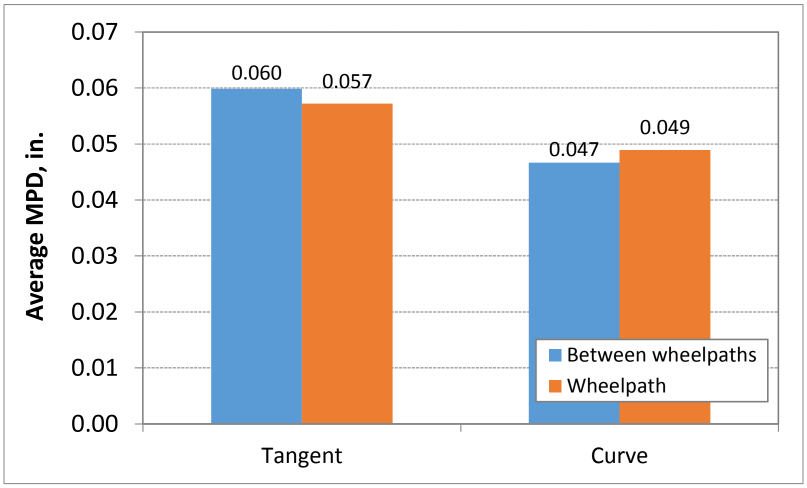


Figure C.7 – Stages of HFST failure.



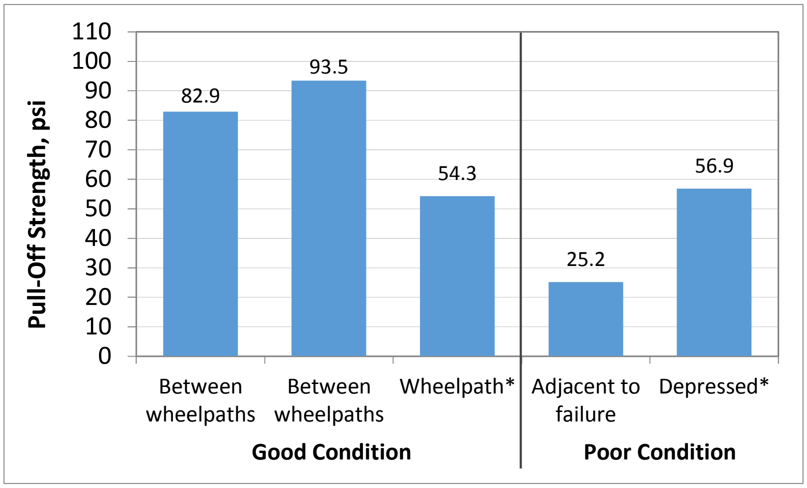
(a)



(b)

Figure C.8 – Results of DFT and CTM testing: a) Friction and b) texture.

Three cores were taken in good locations and two from poor locations for pull-off testing. The results of the test are shown in Figure C.9. All results are the average of three readings, expect those marked by an asterisk which experienced some failures during sample preparation. “Good Condition” samples between the wheel paths had high bond strengths above 80 psi. The “Good” sample in the wheel path had low strength, under 55 psi, and also had two readings that failed in sample preparation. The “Poor Condition” samples had average strengths around 25 and 55 psi. All failures were in the FC-5 substrate.



* Failed readings during sample preparation

Figure C.9 – Pull-off test results.

Lakeland, SR 546 (Memorial Blvd) at I-4 Ramp Connection

Site Description

This HFST project is located on SR 546 on a ramp and overpass at the I-4 connection (Co. section #16100102) (Figure C.10). The project only involves the west-bound lanes and shoulder. The ramp carries an average of 5,200 vehicles each day, with 10 percent trucks. The site had an average 1.4 crashes per year.

The ramp consists of two 12-ft lanes, and a 7 to 14-ft shoulder. There is a traffic signal after the curve at the end of the overpass. The shortest curve radius is 583 ft. The existing surface before the overpass was FC-5 placed in 2009. The shoulders were likely dense-graded and the overpass is concrete. The pavement just before the bridge deck had an uneven texture, caused by removal of old pavement markings and a lane shift. (Figure C.11)

Construction

The HFST, Tyregrip, was constructed in October 2011 by Better Roads. The HFST product, was supplied by DBi Services, and used calcined bauxite. FDOT Special Specification Dev 333 (5/3/2010) was used over asphalt sections, and TSP 403 (1/24/2011) over the bridge deck. The bridge deck had a double HFST application. Based on observation, the asphalt section may have had a double application but not in the shoulder.

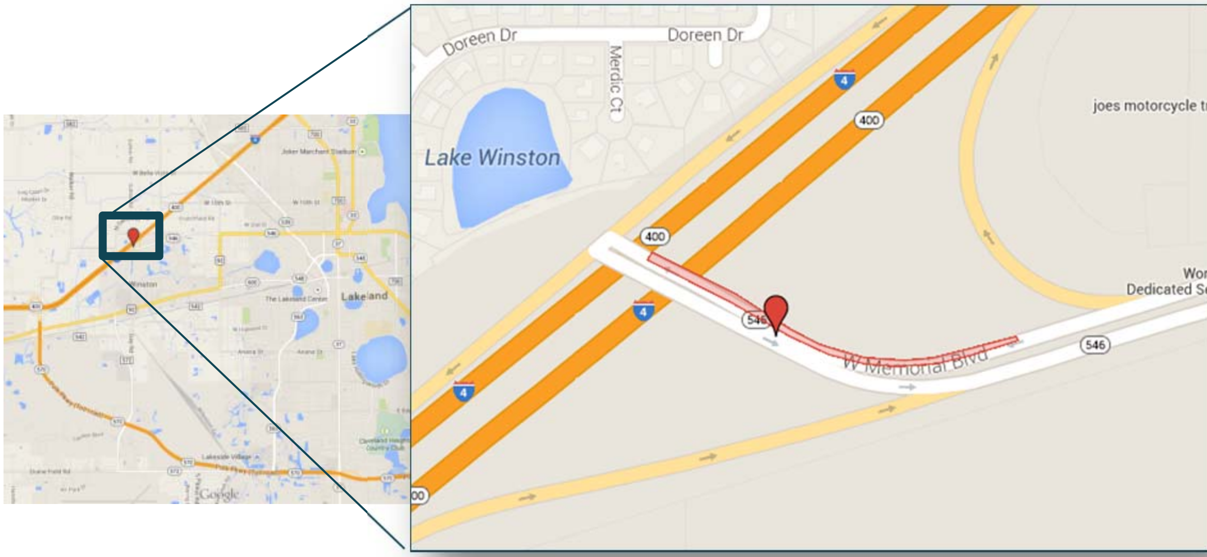


Figure C.10 – Project Location.
(www.google.com/maps/)

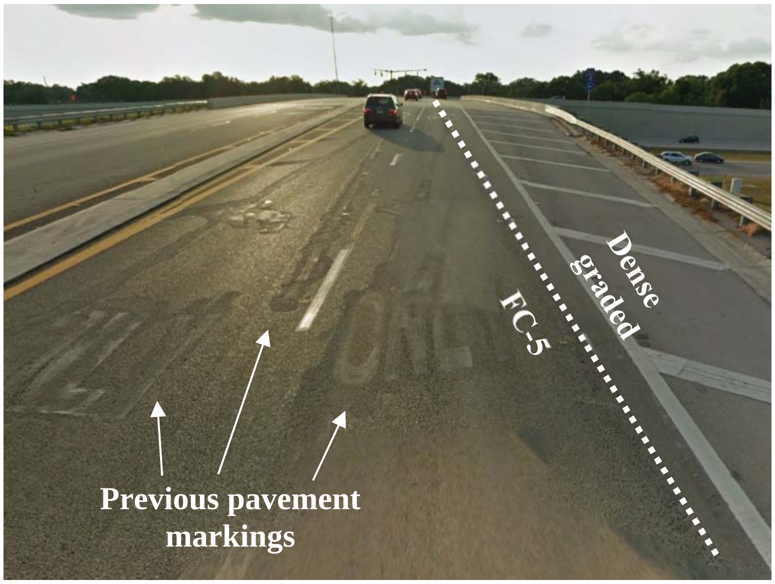


Figure C.11 – Uneven texture of existing surface before bridge deck (May 2011).
(www.google.com/maps/)

Performance

Since installation, accidents along this ramp have increased from 0.2 to 1.0 crashes per year (Table C.3). This increase may be explained by the following considerations.

1. The estimated traffic volume here has increased dramatically after construction (about 2,500 AADT before to about 7,000 AADT after). With more traffic, the crash rate will also rise.

2. Over 50 percent of accidents are just before and inside the intersection, not at the curve. These accidents are likely caused by the unique and unexpected intersection geometry (high-speed approaches, unexpected signal, and poor sight-distance.) Higher friction would marginally reduce these accidents.
3. For accidents before the HFST, about 20 percent *might* be related to a friction deficiency (run off-the road, wet-weather rear-end, non-DUI). After the HFST, about 18 percent of crashes still fell into this category. Of note, five of these later crashes occurred on the same section just before the bridge within three months of each other. The HFST in this area was raveling, and perhaps most raveling happened in a short span of time (spring-summer 2013). Though friction here was still high, the loose aggregate may have acted like ball-bearings under the tires. In the 2014 visit, loose aggregate was found in the shoulders and little noted in the travel lanes.

Table C.3 – Crashes Before and After HFST Installation.

Data Range	Total Crashes/ Yr	Wet Weather Crashes/Yr	Crashes/Yr by Injury				
			K (fatal)	A (serious)	B (moderate)	C (minor)	O (none)
Before (2006-2011)	1.4	0.2	0.0	0.0	0.8	0.0	0.6
After (2011-2014)	4.4	1.0	0.0	0.3	1.0	0.3	2.7

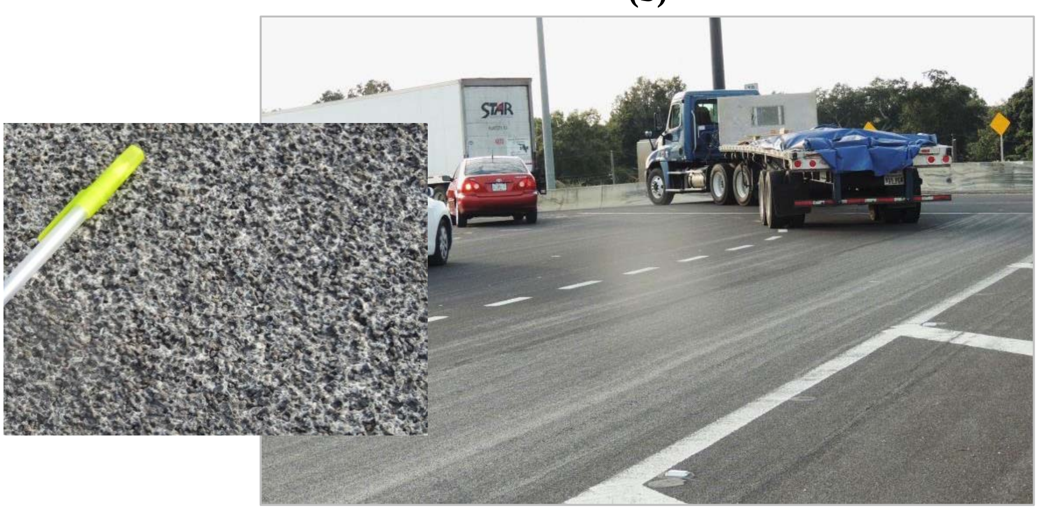
In December 2011, after construction, the ramp had FN40R values of 82. The mean profile depth of the new treatment was 0.061 inches. The friction before construction is unknown.

The project is generally performing well. Most of the HFST is intact with uniform texture. There is a 190 ft portion just before the bridge that is raveling and corresponds to the preexisting area with pavement marking removal. It is likely that the uneven texture made it difficult to achieve the correct epoxy thickness, which lead to the aggregate loss. Portions of the shoulder are also raveled, which was likely caused by lower attention to construction quality in a non-critical area. The double application on the bridge is performing very well, even under heavy turning traffic.

In January 2015, testing was performed at different locations both in and out of the wheel path. The first location was in the curve where there was no aggregate loss. The second location was after the curve on a raveling section. The last location was on the bridge deck just before the stop light and had no aggregate loss. The results are shown in Figure C.13. In all cases friction was lower in the wheel path. Friction is over asphalt areas with and without aggregate loss was not different. And friction in front of the stop light was lower than in the curve. In all cases, friction in this project is very high. Texture depth over asphalt was highest outside the wheel path. All other values were essentially the same. Surface texture on this project was high all around.

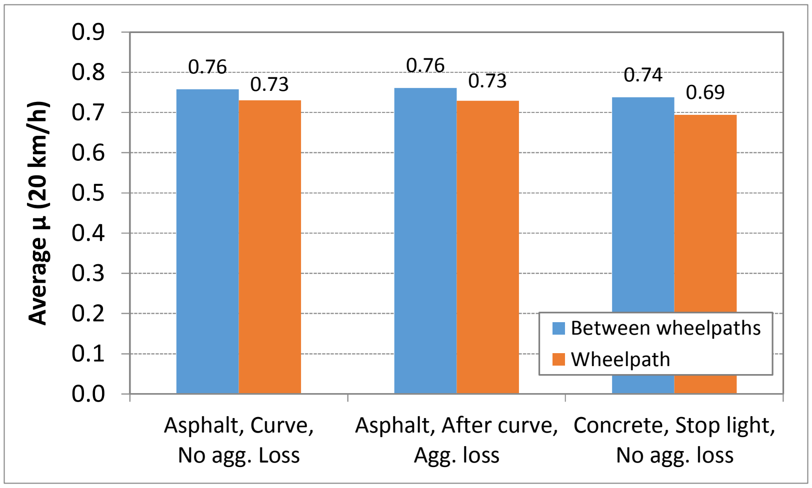
(a)

(b)

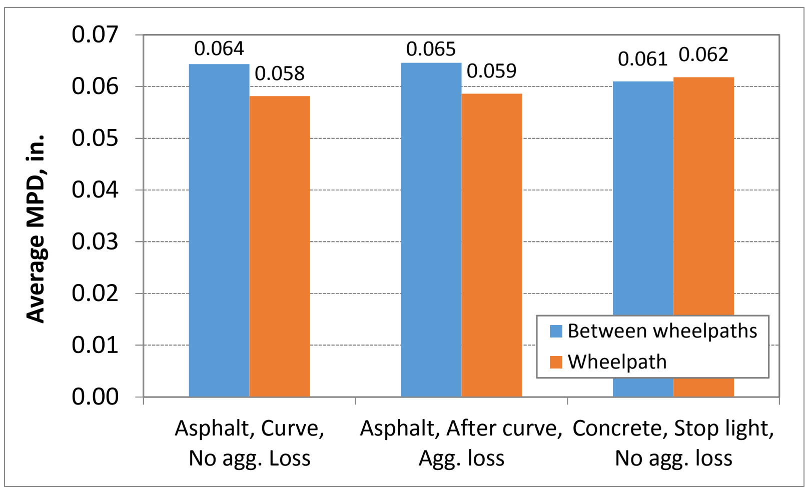


(c)

Figure C.12 – In-service HFST (November 2014): a) Intact over asphalt, b) raveling over asphalt, c) intact over concrete.



(a)



(b)

Figure C.13 – Results of DFT and CTM testing: a) Friction and b) texture.

Two cores were taken from the project for pull-off strength testing: one at the curve and one after in the raveling section. The first sample failed at an average of 64.0 psi in the asphalt. This value is often considered low. Under harsher conditions we expect this location would show signs of HMA tearing. The second sample also failed in the asphalt at an average of 91.3 psi.

Lake Worth, I-95 Mainline and Ramps

Site Description

This HFST project is located on the I-95 viaduct between 6th Avenue South and Lake Worth Road (Co. section #93220000) (Figure C.14). The highway has an AADT of 185,000 and 7.5 percent trucks. The site had an average of 32.2 crashes per year.

The main line has five 12-ft lanes in each direction and the ramps have two lanes each. The existing pavement was transversely-tined concrete (Figure C.15).

Construction

As is the case with many bridge applications, this HFST was applied more as a maintenance treatment (seal the bridge deck) rather than to reduce accidents.

The HFST was constructed in April and May of 2014 by Ram Construction. The HFST product was *520 HFS*, supplied by E-Bond, and used calcined bauxite aggregate. The bridge specification TSP T400 (5/15/13) was used. The unit bid cost is not available, but the lump sum project cost was \$1.7 million (approx. \$39/yd^2).

Construction was done with an automated epoxy mixer and applicator followed by hand distribution with serrated squeegees. The aggregate was spread using a mechanical blower. Construction went smoothly for most part except for an epoxy mixing malfunction on the southbound exit ramp. This left random splotchy areas that did not set up, as will be discussed shortly

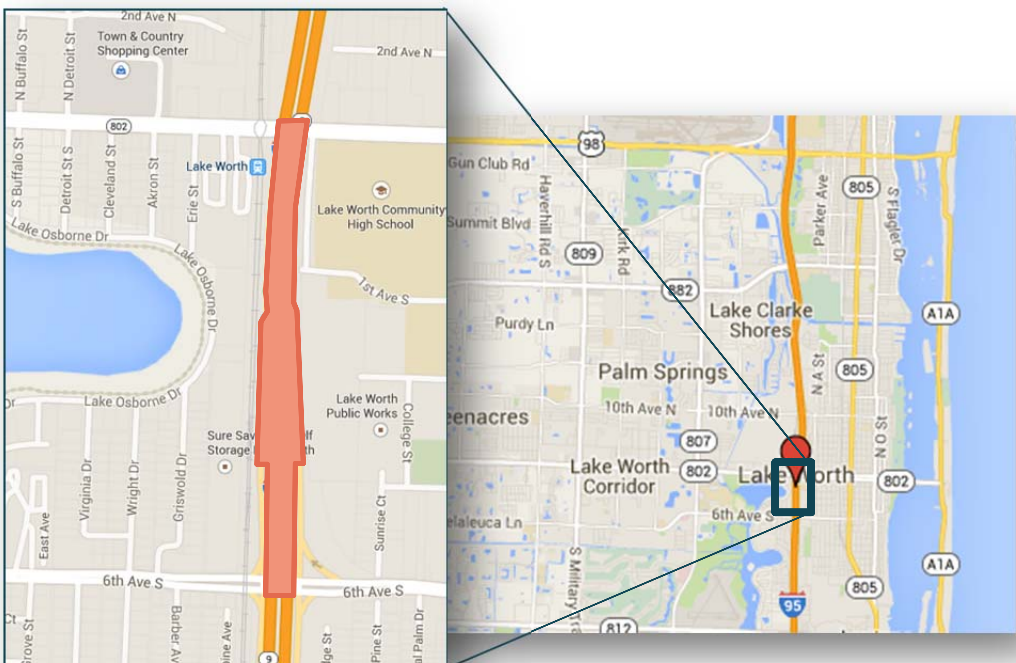


Figure C.14 – Project Location.
(www.google.com/maps/)

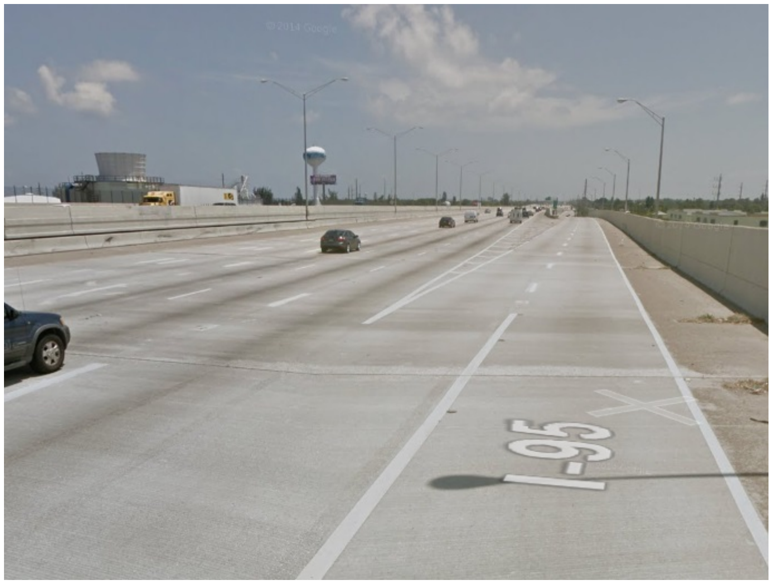


Figure C.15 – Existing surface.
(www.google.com/maps/)

Performance

Since installation, accidents have decreased from 23.0 to 12.3 crashes/yr, a reduction of 46 percent. The complete data is shown in Table C.4. These numbers represent the raw data and have not been analyzed or corrected according to crash analysis procedures. This project was not placed with the purpose of reducing crashes, therefore reduction statistic may not be reliable.

Table C.4 – Crashes Before and After HFST Installation.

Data Range	Total Crashes/ Yr	Wet Weather Crashes/Yr	Crashes/Yr by Injury				
			K (fatal)	A (serious)	B (moderate)	C (minor)	O (none)
Before (2007-2011)	32.2	23.0	0.2	1.4	6.6	5.4	18.6
After (2012-2013)	24.7	12.3	0.0	2.5	0.0	2.5	22.2

Prior to the treatment, the average skid number (FN50R) was 43 in 2011 (min: 39, max: 50). The average MPD was 0.028 inches, (min: 0.016, max: 0.043). Shortly after installation, the average FN50R was 77, (min: 73, max: 80), and the average MPD was 0.043 inches (min: 0.040, max: 0.046). The average DFT friction values in 2014 were 0.82 on average and the macrotexture from the CTM was 0.061 inches on average. There was very little difference in results in vs between the wheel path.

The project was less than a year old when visited, and was in very good condition. The only area of concern was the southbound exit ramp, which was spotted with loose splotchy areas (Figure C.16). These spots were caused by improper proportioning and/or mixing of the two part epoxy within the mixing truck. The binder in each of these spots never set up and was loose and sticky when assessed. The black color comes from the accumulation of dirt. A few spots are starting to delaminate and this is expected to continue if the material is not removed and replaced. When sampling the HFST with a core rig, the splotchy areas sheared off under the force of the barrel (Figure C.17), while normal areas remained intact. Bond strength testing in the field was unsuccessful due to rain and cool temperatures, but we expect the normal areas had good bond strength.

Figure C.16 – Splotchy areas on southbound exit ramp.

Figure C.17 – Weak bond of splotchy area.

Boca Raton, I-95 Off-Ramp to Congress Ave.

Site Description

This HFST project is located on the off-ramp from I-95to the Congress Ave. exit in Boca Raton (Co. section #93220143) (Figure C.18). The ramp has an AADT of 9,300 and 3.5 percent trucks. Before the HFST, the site had a low average of 7.6 crashes per year.

There are two 12-ft wide lanes and a shoulder. There is a stop light at the end of the ramp, just before the curve. The existing ramps surface is OGFC. The intersection shortly after the stop bar, is a concrete bridge deck. A little after the turn, the bridge deck ends and transitions to a dense-graded asphalt surface. The ramp approach is on a vertical grade. Though the condition of the existing pavement is not known, areas before and after the current treatment are good with some occasional cracking in the wheel path.

At the time the District was considering placing a trial section of HFST, there was an accident at this location. A vehicle exiting highway ran through the red light and struck the median barrier on Peninsula Corp Dr. Though the accident itself does not suggest a friction deficiency, and the crash rate here was not considerably high, the District decided to use this location to trial the HFST.

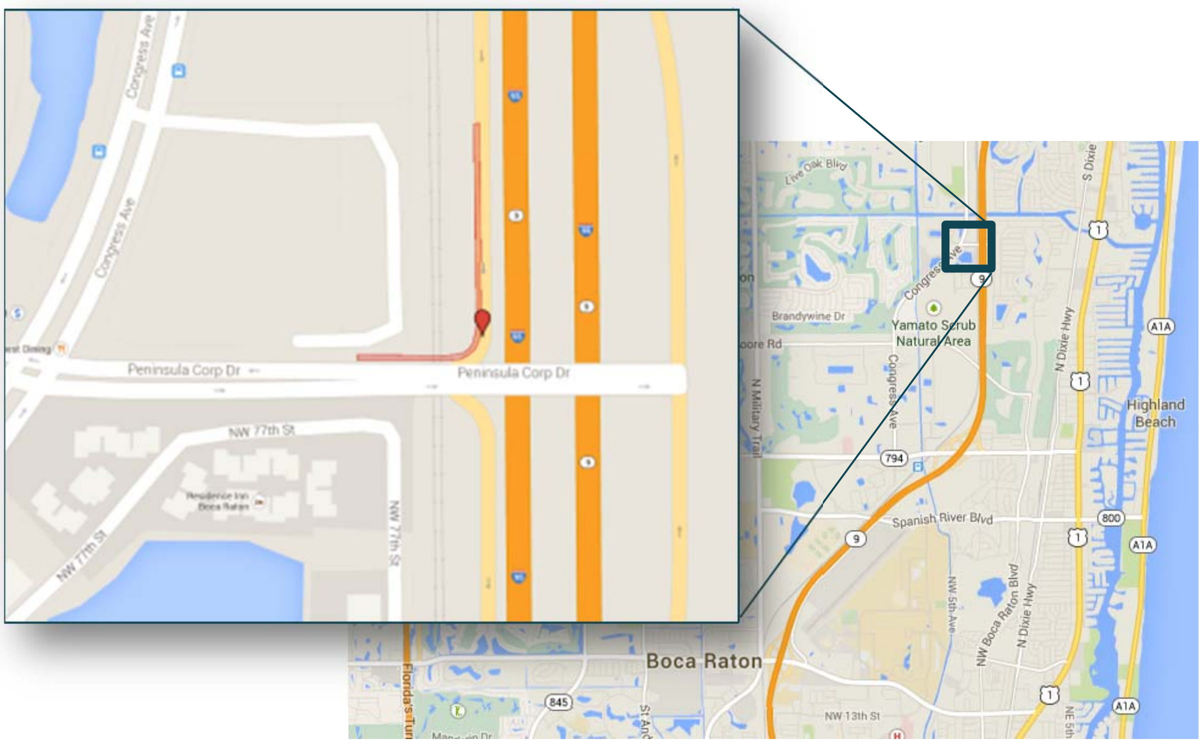


Figure C.18 – Project Location.
(www.google.com/maps/)

Construction

The HFST was constructed in October 2010. The product was named *Safe-T-Grip* and was supplied and constructed by Traffic Calming. The supplied epoxy was known for being stiff, and prone to cause cracking failures. The section was constructed with the specification Dev 333, 3/2/2010. Even though there was a small portion of bridge deck section, only the mainline specification was used. The project length was 700 ft and total treated area was 2,300 sy. The unit price of the HFST was $34.47/sy.

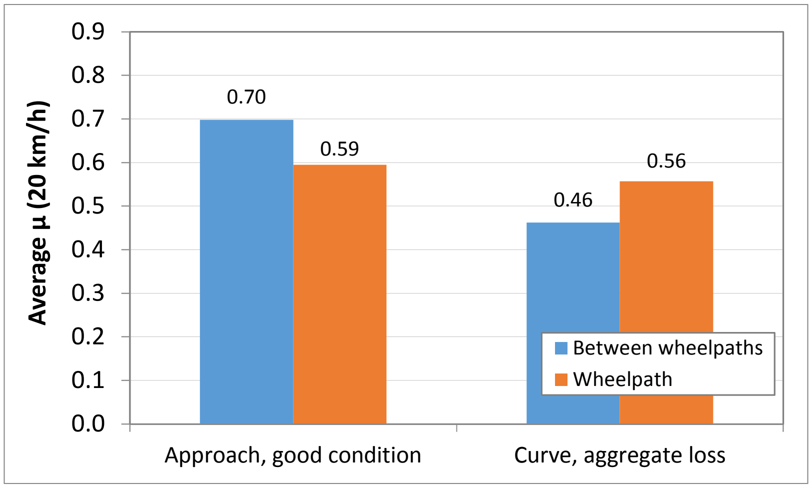
Performance

Since installation, wet weather crashes along this ramp have dropped from an average of 1.0 to 0.5 crashes per year—a reduction of 50% (Table C.5). These numbers represent the raw data and have not been analyzed or corrected according to crash analysis procedures. Whether these accidents are skid related is unknown.

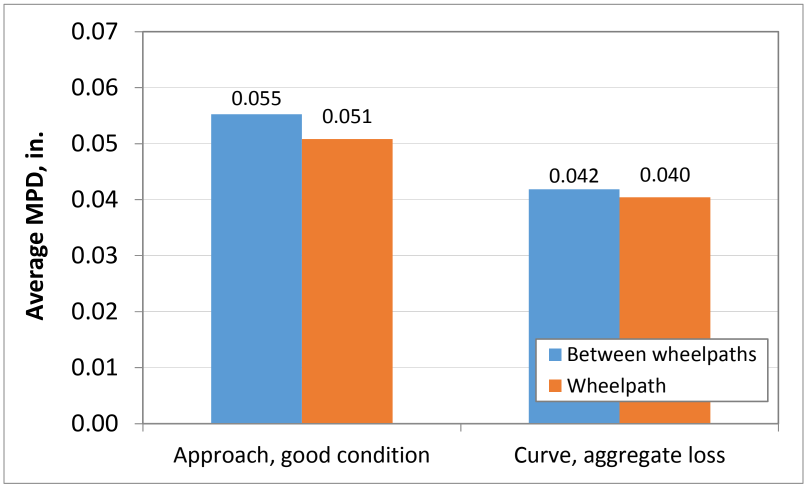
Table C.5 – Crashes Before and After HFST Installation.

Data Range	Total Crashes/ Yr	Wet Weather Crashes/Yr	Crashes/Yr by Injury				
			K (fatal)	A (serious)	B (moderate)	C (minor)	O (none)
Before (2005-2010)	7.6	1.0	0.2	1.2	1.8	1.2	3.2
After (2010-2014)	4.4	0.5	0.2	0.0	1.0	0.7	2.5

The skid numbers (FN30R) shortly after construction was 83 and 75 for the two lanes. Three years later, in 2013, the skid numbers (FN40R) were 60 and 71, and then FN40R of 60 in 2015. The average MPD values after construction and were 0.042 and 0.039 inches. In the 2014 site visit, the friction and texture were measured with the DFT and CTM (Figure C.19). Measurements were made on the approach in good condition and in the curve which was experiencing aggregate loss. The friction was considerably higher in the approach between the wheel paths (0.70). The loss of friction from polishing and aggregate loss at this site was significant, though higher than 0.5 is still much better than most roads. The texture depth also decreased at the curve (from >0.05 inches to 0.04 inches).



(a)



(b)

Figure C.19 – Results of DFT and CTM testing: a) friction and b) texture.

This project has some interesting distresses, as shown in the diagram in Figure C.20. Distresses include transverse cracking, random cracking, and raveling. Descriptions and our hypotheses of the causes for each distress follow.

The HFST approaching the stop light is transversely cracked, with crack severity and frequency greatest near to the stop bar (Figure C.21). The cracking pattern becomes more block-like after the stop bar, heading into the turn. Before the HFST, there is no sign of cracking, except an occasional longitudinal crack. To confirm that the distress was not reflective cracking from the existing pavement, cores were taken at the edge of developing cracks to see if the cracks originated from the top or bottom. Pull-off strength tests on the approach broke within the OGFC and failed during sample preparation, confirming the very weak condition of the substrate. After the stop bar, where distress was more severe, the average strength was 74 psi. These samples, however, failed at both the epoxy-asphalt interface and in the OGFC. This was not expected but suggest the repeated high-shear forces at the intersection have also weakened the HFST bond.

Around the turn, traffic moves onto the concrete bridge deck. The first section here has significant HFST raveling and wearing away (Figure C.22); roughly 30% of the HFST is gone. This is only apparent in the right-hand lane, which has a tighter turning radius and more traffic. Initially, the aggregate is raveled/plucked out of the epoxy, after which the exposed epoxy also wears away. After the turn, the wearing away of the HFST on the bridge deck is much less severe. We believe this problem was caused by 1) using a single-lift HFST, and 2) possibly no shot-blasting. This does not appear to be a traditional delamination issue.

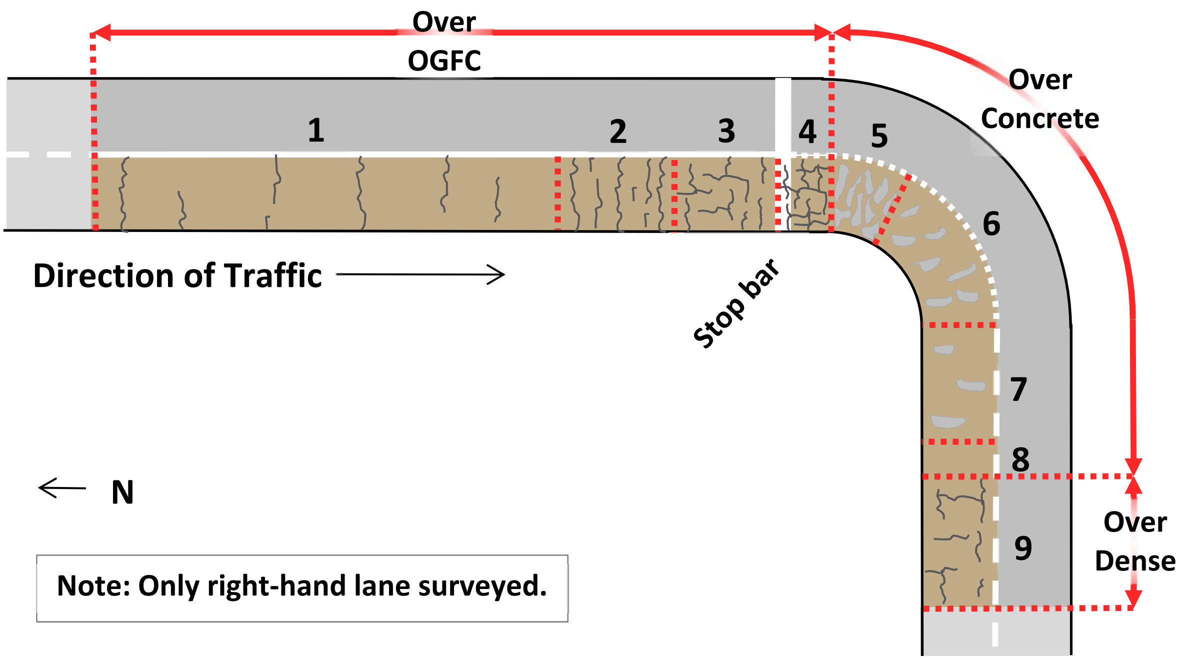


Figure C.20 – Distress map.

Table C.6 – Distress Type, Severity, and Extent.

Section #	Section Length (ft)	Distress	Severity	Rate/ Percentage
1	280	Transverse Cracking	Low-Mod	18*
2	70		High	28*
3	60	Random Cracking	Mod-High	100%
4	30		High	100%
5	20	Raveling	High	30%
6	50		Mod	20%
7	70		Low-Mod	10%
8	20	None	-	-
9	80	Random Cracking	Low	75%

* Number of cracks per 100 linear feet of HFST.

Figure C.21 – Distress near stop bar over OGFC: a) transverse and b) random cracking.

Figure C.22 – Wearing away of HFST around the curve over concrete.

After the bridge deck, the HFST is over asphalt again, likely a dense-graded mix. The section has low-severity random cracking. This area is after the curve and far from the next light, though cars in the area may still be accelerating and changing lanes. From pull-off testing, the average tensile strength of the existing asphalt was 97 psi, but with a wide variation from 36 to 145 psi. All samples broke in the asphalt.

Figure C.23 – Random cracking of HFST after the curve and over HMA.

Miami Beach, SR A1A (Indian Creek Dr.) to Collins Ave

Site Description

This HFST project is located on SR A1A (Indian Creek Dr.) at the intersection with Collins Ave in Miami Beach (Co. section #87060002) (Figure C.24). The road has an AADT of 9,700 and 6.4 percent trucks. Before the HFST, the site had a low average of 2.8 crashes per year.

There are two 12-ft lanes and a bike lane that divides that changes into three 12-ft lanes at a signalized intersection. The existing surface was a 3-year old dense-graded FC-9.5.

Construction

The HFST was constructed in August 2011. The product was named *Safe-T-Grip* and was constructed by Traffic Calming under the contractor Horizon Contractors, Inc. The supplied epoxy is known for being stiff, and prone to cause cracking failures. The section was constructed with the specification Dev 333, 4/28/2009. The project length was 360 ft and total treated area was 1,233 sy. The unit price of the HFST was $38/sy.

Shortly after construction, the project was losing aggregate in some random locations, possibly due to uncured binder failure (poor mixing) or poor aggregate embedment. These locations were repaired manually, and the result was a functional, but splotchy surface. The aggregate in these areas had a much deeper embedment depth, resulting in lower macrotexture.

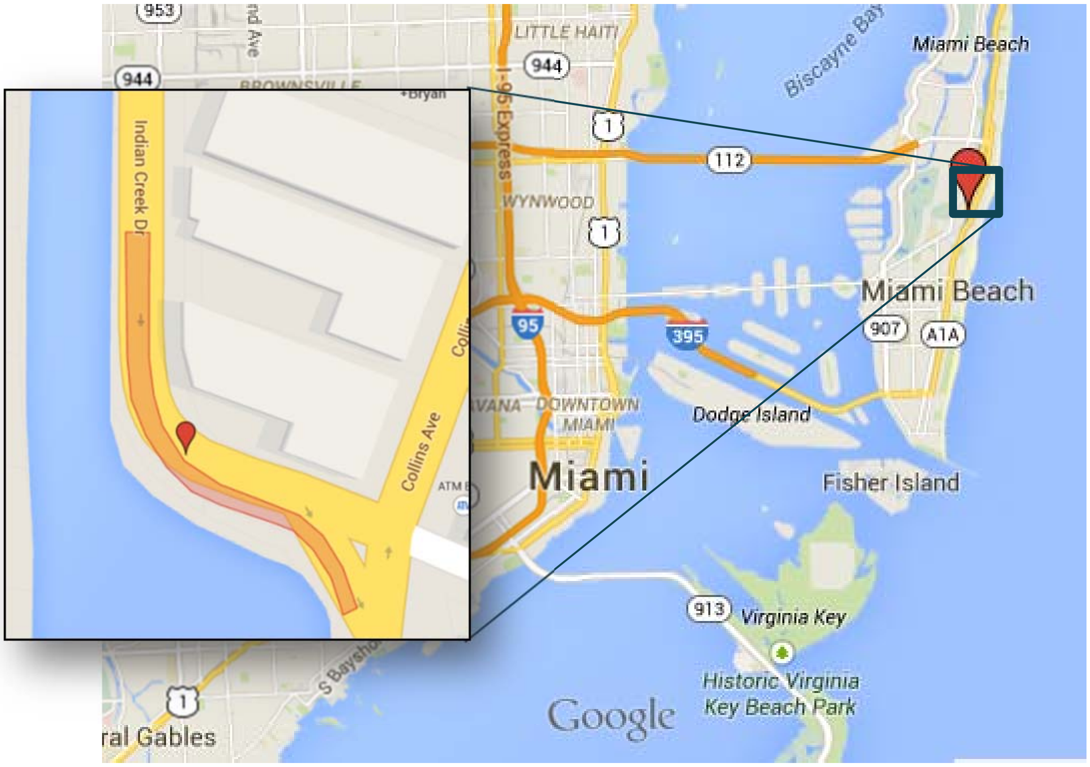


Figure C.24 – Project Location.
(www.google.com/maps/)

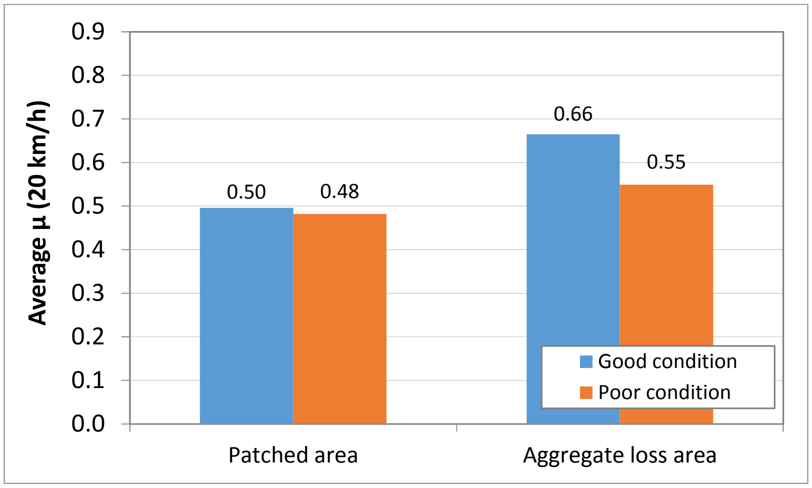
Performance

Since installation, the total crashes at this location remained the same and wet-weather crashes, and wet weather crashes went from 0.6 to 0.3/yr. (Table C.7). When the initial crash rate is this low, the potential to observe any further reduction is limited.

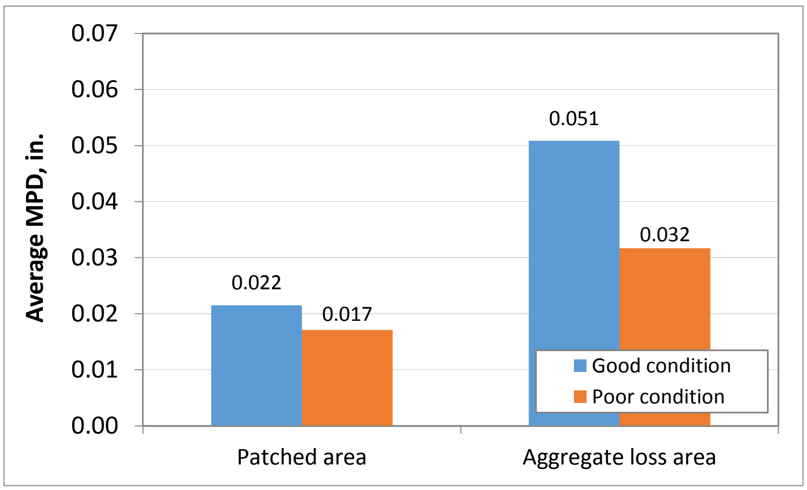
Table C.7 – Crashes Before and After HFST Installation.

Data Range	Total Crashes/ Yr	Wet Weather Crashes/Yr	Crashes/Yr by Injury				
			K (fatal)	A (serious)	B (moderate)	C (minor)	O (none)
Before (2004-2009)	2.8	0.6	0.0	0.0	0.4	0.0	2.4
After (2011-2014)	2.8	0.3	0.0	0.3	0.6	0.6	1.2

The average skid number (FN30R) before construction was 36. In 2012, a few months after construction, the SN was 69. The following year, the SN was 57 and the MPD was 0.028 (quite low for an HFST). In the 2014 site visit, the friction and texture were measured with the DFT and CTM (Figure C.25). Measurements were made on an area with patching and on an area with aggregate loss. In both cases, tests were made on "good" and "poor" condition surfaces. Friction was highest (0.66) where the aggregate was intact and not patched. This spot was also outside the wheel paths. Areas with patching and experiencing aggregate loss had a friction coefficient around 0.5. Texture was also much higher in the "good" non-raveled area (0.051 inches). The patched areas had low texture (~ 0.02 inches).



(a)



(b)

Figure C.25 – Results of DFT and CTM testing: a) friction and b) texture.

This project had prominent random cracking throughout (Figure C.27). In two of three cores taken, cracking was in the HFST and just entering the top of the asphalt. Considering the underlying HMA was new, the researchers believe most cracking is top-down in nature, and indicates either thermal incompatibility. A substrate tearing failure is not expected since the average tensile strength of the substrate in pull-off testing was over 200 psi. Other distresses include light aggregate raveling and then splotchy HFST patching (Figure C.28).

Figure C.26 – Project overview.

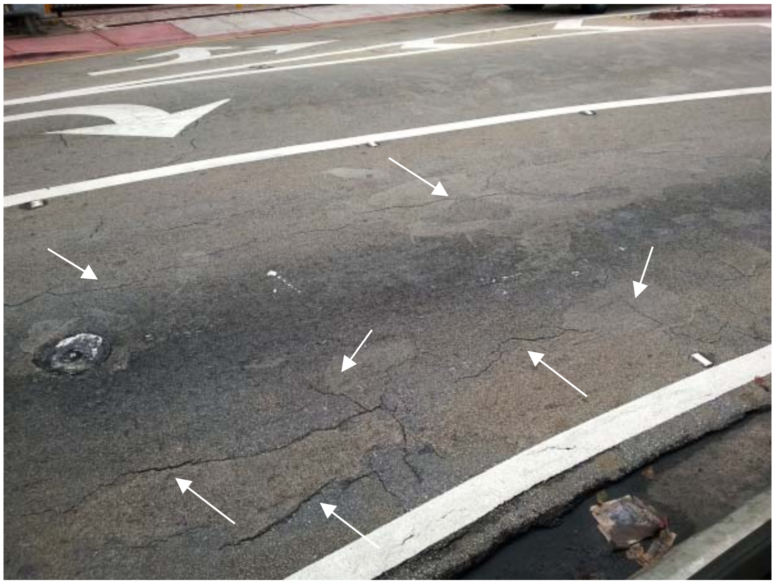


Figure C.27 – Random cracking (likely thermal incompatibility).

(a) (b)

Figure C.28 – Other distress: a) raveling and b) subsequent HFST patching.

Fort Lauderdale, I-595 Off-Ramp to FLA (Airport)

Site Description

This HFST project is located on the off-ramp from I-595 to the Fort Lauderdale International Airport terminal (Co. section #86010006) (Figure C.29). The road has an AADT of 39,500 and 5.3 percent trucks. Before the HFST, the site had a low average of 4.0 crashes per year.

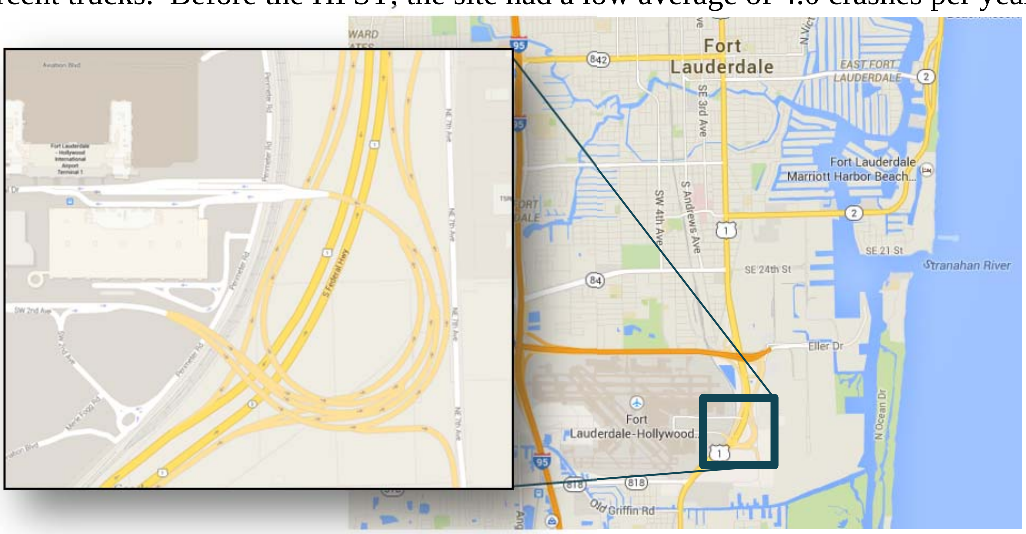


Figure C.29 – Project Location.

There are three to six 12-ft lanes in this large loop ramp, including various merging lanes. The existing surface is a combination of open-graded FC-5 and two concrete bridge decks.

Construction

The HFST was constructed in November and December 2011. The product was *Mark-154 Safe-T-Grid* and was constructed by POLY-CARB under the contractor Kiewit Infrastructure. The bridge spec TSP 403 (5/19/2011) was used and it is unknown if Dev 333 was used for asphalt sections. The project length was 3,260 ft and total treated area was 17,950 sy. The unit price of the HFST was $40/sy.

Details on the application technique were not confirmed, though the researchers believe the binder was mixed in a mixing truck, applied and spread manually, and aggregate spread manually.

Some areas shortly after construction had notable problems with aggregate loss. This was likely a result of insufficient film thickness over the uneven open-graded surface. The contractor returned to do touch-up work in these areas.

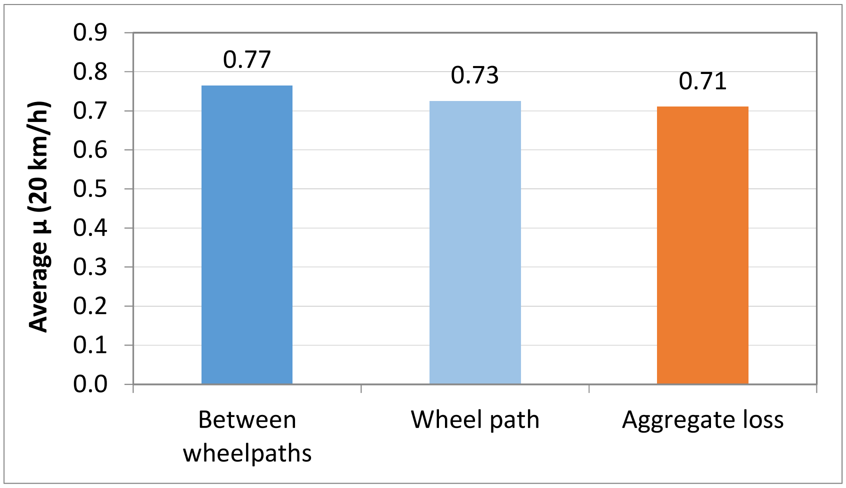
Performance

Crash data after construction is not available, but wet weather crashes before construction was 3.8/yr. When the initial crash rate is this low, the potential to observe any further reduction is limited.

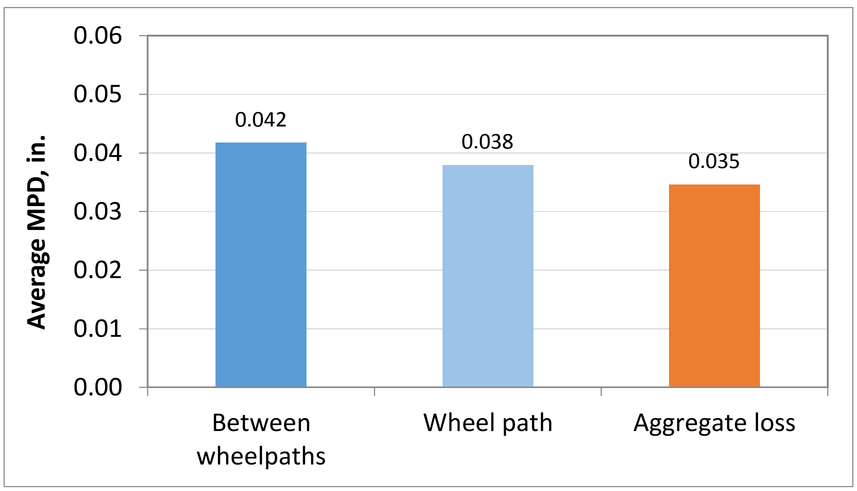
Table C.8 – Crashes Before HFST Installation.

Data Range	Total Crashes/ Yr	Wet Weather Crashes/Yr	Crashes/Yr by Injury				
			K (fatal)	A (serious)	B (moderate)	C (minor)	O (none)
Before (2006-2011)	4.0	3.8	0.0	0.0	0.4	1.0	2.6

The average skid number (FN40R) in 2008 was 44. Immediately after construction, the average SN was 88 and the MPD was 0.047 inches. The following year (2013), the SN was 77 and MPD was 0.043 inches, and in 2015 FN40R was 69. In the 2014 site visit, the friction and texture were measured with the DFT and CTM. Measurements were made on an asphalt section in a good area and an area with aggregate loss. More measurements were made over the bridge in and between the wheel paths. The highest friction (0.77) was located between the wheel paths. Locations in the wheel path and experiencing aggregate loss had lower friction (0.73 and 0.71, respectively). This is still exceptional. Texture depth was greatest between the wheel path (and also over the asphalt) (0.042 inches). The lowest texture was in an area with aggregate loss (0.035 inches). These trends are reasonable and expected.



(a)



(b)

Figure C.30 – Results of DFT and CTM testing: a) friction and b) texture.

Pull-off testing was attempted in the field on concrete sections and done on asphalt cores in the lab. Field testing was not successful due to precipitation and cold temperatures. The pull-off results from the asphalt sections are shown in Figure C.31.In nearly every case, the FC-5 substrate failed before the HFST bond. Before the first bridge, the average strength was between 100 and 120 psi. After the bridge, the strength was much higher, between 200 and 325 psi. These values help us understand what kind of tensile strengths we can expect from FC-5.

There were two distress types apparent on this project: raveling and irregular depressions Figure C.32. The raveling was an issue during construction, inadequate film thickness, and is still apparent. The irregular depressions were noted at the lane edge and in some random locations within the lane, not necessarily associated with the wheel path. These depressions appear similar to the areas that potholed out on the Bradenton WB US 60 to NB I-75 ramp. Those potholes were caused by 1) poor epoxy mixing and 2) substrate stripping. Though not certain, we think these sections may be a result of stripping. Perhaps moisture is getting trapped beneath the HFST and in the summer heat is causing the problem shown here. The researchers believe these sections may pothole in the near future.

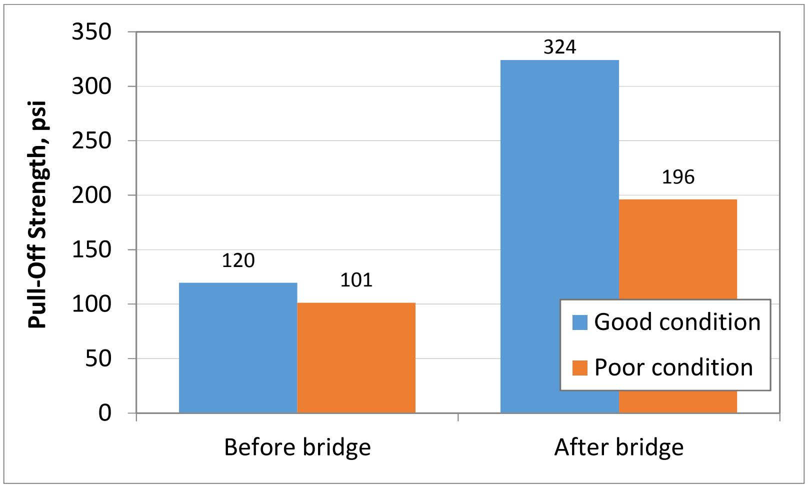


Figure C.31 – Pull-Off Strength Results.

(a) **(b)**

Figure C.32 – Surface distress: a) Aggregate loss and b) irregular depressions.

APPENDIX D
LABORATORY TESTING DETAILS

Materials

Concrete Design

Product *Product Name*	*Quantity*		*Producer* *Plant #*	*QPL #* *Spec:*	*SSD*	*FM*	*Geological Type*
Cement: Type II Cement MH	400	LB	ARGOS CEMENT-NEWBERRY CMT09	AASHTO M85 II LS (MH)	3.15		
Fly Ash: Class F Fly Ash	100	LB	SEPARATION TECHNOLOGIES-CRYSTAL RIVER FA01	ASTM C 618 - Class F	2.36		
Coarse Aggregate: # 67 Stone	1850	LB	VULCAN MATERIALS COMPANY 10645		2.33		
Fine Aggregate: Silica Sand	1128	LB	VULCAN MATERIALS COMPANY 16659		2.63	2.19	
Air Ent Admixture: ConAir 260	3.08	OZ	PREMIER CONCRETE ADMIXTURES	S924-0030 AASHTO M 154 - AEA			
Type A Admixture: OptiFlo MR	15.0	OZ	PREMIER CONCRETE ADMIXTURES	S924-0137 AASHTO M 194 - Type A			
Water: Water for Concrete	26.4	GA					
Water: Water for Concrete	220	LB					

Specification Limits

Compressive Strength	Greater than or equal to 4000	avgpsi
Heat of Hydration	Less than or equal to 88	cal/g
Temperature	Less than or equal to 100	degree F
W/CM Ratio	Less than or equal to 0.44	LB per LB

Producer Data

W/cm Ratio	0.44	LB per LB
Temperature		degree F
Heat of Hydration	79	cal/g
Compressive Strength	4080	avgpsi 6 DAY
Aggregate Correction Factor		

FC-5

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

ASPHALT MIX DESIGN

SUBMIT TO THE DIRECTOR, OFFICE OF MATERIALS, CENTRAL ASPHALT LABORATORY, 5007 NE 39TH AVE, GAINESVILLE, FL 32609

Contractor: Community Asphalt Corp. Address: 7795 Hooper Road, West Palm Beach, FL 33411

Phone No. (561) 790-3993 Fax No. (561) 515-0269 E-mail ssurvis@ctilabs.net

Submitted By: CTI, Inc. Type Mix: FC-5 Intended Use of Mix: Friction Course

Product Description	Product Code	Producer Name	Product Name	Plant/Pit Number	Terminal
1. S1A Stone	C41	White Rock Quarries	S1A Stone	87339	
2. S1B Stone	C53	White Rock Quarries	S1B Stone	87339	
3. S1B Stone	C51	White Rock Quarries	S1B Stone	87339	
4. Screenings	F22	White Rock Quarries	Screenings	87339	
5.					
6.					
7. PG Binder	916-76PMA		PG 76-22 (PMA)		

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	40%	40%	16%	4%			JOB MIX	CONTROL	
	Number	1	2	3	4	5	6	FORMULA	POINTS	
S	3/4" 19.0mm	100	100	100	100			100	100	
I	1/2" 12.5mm	83	100	100	100			93	85 - 100	
E	3/8" 9.5mm	45	94	97	100			75	55 - 75	
V	No. 4 4.75mm	9	24	41	100			25	15 - 25	
E	No. 8 2.36mm	7	4	13	86			10	5 - 10	
	No. 16 1.18mm	6	3	8	68			8		
S	No. 30 600µm	5	3	6	52			6		
I	No. 50 300µm	4	3	5	35			5		
Z	No. 100 150µm	3	3	3	12			4		
E	No. 200 75µm	2.5	2.5	2.5	3.0			3.8	2 - 4	
S	G_{sb}	2.407	2.416	2.412	2.527			2.416		

The mix properties of the Job Mix Formula have been conditionally verified, pending successful final verification during production at the assigned plant, the mix design is approved subject to F.D.O.T. specifications.

JMF reflects aggregate changes expected during production

SPM 13-11643A (FC-5)

Director, Office of Materials: Timothy J. Ruelke, P.E.

Original document retained at the State Materials Office

Effective Date: 07 / 23 / 2013

Expiration Date: 07 / 23 / 2016

FC-9.5

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
ASPHALT MIX DESIGN
SUBMIT TO THE DIRECTOR, OFFICE OF MATERIALS, CENTRAL ASPHALT LABORATORY, 5007 NE 39TH AVE, GAINESVILLE, FL 32609

Contractor: Weekley Asphalt Paving, Inc. Address: 20855 SW 36th St., Ft. Lauderdale, FL 33332

Phone No. (954) 389-5849 Fax No. (954) 659-9395 E-mail asphaltskippy999@aol.com

Submitted By: Weekley Asphalt Paving, Inc. Type Mix: Fine FC-9.5 Intended Use of Mix: Friction Course

Design Traffic Level: C Gyrations @ Ndes: 75

Product Description	Product Code	Producer Name	Product Name	Plant/Pit Number	Terminal
1. S1B Stone	C51	White Rock Quarries	S1B Stone	87339	
2. Screenings	F22	White Rock Quarries	Screenings	87339	
3.					
4.					
5.					
6.					
7. PG Binder	916-76PMA		PG 76-22 (PMA)		

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	53%	47%					JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
SIEVE SIZE	3/4" 19.0mm	100	100					100		
	1/2" 12.5mm	100	100					100	100	
	3/8" 9.5mm	95	100					97	89 - 100	
	No. 4 4.75mm	40	100					68	- 89	
	No. 8 2.36mm	7	92					47	32 - 67	47
	No. 16 1.18mm	5	74					37		
	No. 30 600µm	4	59					30		
	No. 50 300µm	3	41					21		
	No. 100 150µm	2	14					8		
	No. 200 75µm	1.0	2.0					4.0	2 - 10	
	G_{sb}	2.412	2.527					2.465		

The mix properties of the Job Mix Formula have been conditionally verified, pending successful final verification during production at the assigned plant, the mix design is approved subject to F.D.O.T. specifications.

JMF reflects aggregate changes expected during production

SPM 13-12014A (TL-C)

Transferred from SPM 10-8922A (TL-C)

Director, Office of Materials: Timothy J. Ruelke, P.E.
Original document retained at the State Materials Office

Effective Date: 11 / 08 / 2013

Expiration Date: 11 / 08 / 2016

Results

Table D.1 – Substrate Strength Results (Overlay Tester).

Sample ID	Material	Density	MIST	Cycles	Peak Load	Avg. Cycles	Avg. Peak Load	Comments
1-1.1	FC-5	81	Y	1995	836	1193	1055	
1-1.2	FC-5	81	Y	1175	1233			
1-1.3	FC-5	81	Y	408	1095			
1-2.1	FC-5	86	Y	-	-	144860	232	Material missing
1-2.2	FC-5	86	Y	104417	243			
1-2.3	FC-5	86	Y	185302	220			
1-3.1	FC-5	86	-	2997	834	1874	1064	
1-3.2	FC-5	86	-	1380	1129			
1-3.3	FC-5	86	-	1245	1230			
1-4.1	FC-9.5	91.8	Y	282	841	218	708	
1-4.2	FC-9.5	91.8	Y	35	542.6			
1-4.3	FC-9.5	91..8	Y	337	740			
1-5.1	FC-9.5	94.8	Y	895	404	8372	442	
1-5.2	FC-9.5	94.8	Y	15849	480			
1-5.3	FC-9.5	94.8	Y	297	1187			Omit outlier
1-6.1	FC-9.5	94.8	-	910	789	645	839	
1-6.2	FC-9.5	94.8	-	379	888			
1-6.3	FC-9.5	94.8	-	1000	374			Omit outlier
1-7.1	Concrete	-	-	11749	1841	37132	1663	
1-7.2	Concrete	-	-	62514	1484			
1-7.3	Concrete	-	-	597	1833			Omit outlier

Table D.2 – Substrate Strength Results (Pull-Off Test).

Sample ID	Material	Desnity	MIST	Results (psi)			Avg. Result
1-1.4	FC-5	81	Y	63.2	56.5	56.9	59
1-2.4	FC-5	86	Y	61.7	66.5	Test failed	64
1-3.4	FC-5	86	-	156.2	187.9	182.4	176
1-4.4	FC-9.5	91.8	Y	10	8	Sample failed	9
1-5.4	FC-9.5	94.8	Y	23.7	20.6	21	22
1-6.4	FC-9.5	94.8	-	117	125	Test failed	121
1-7.4	Concrete	NA	-	219.3	224.7	206.4	217

Table D.3 – Aggregate Loss Results (Binder Thickness).

Slab				Weights (g)			Texture/MPD, mm		
ID	Substrate	Application Type	Binder thickness (mils)	Pre Test	Post Test	Mass loss	Pre Test	Post Test	% Change
2.1-1	FC-5	Double	50	-	24669	NA	1.94	1.39	28.4
2.1-2	FC-5	e w/ 5-minute	50, much less at 5 min.	24163	24111	52	1.94	1.38	28.9
2.1-3	FC-9.5	Single	30	22859	22769	90	1.79	1.27	29.1
2.1-5	FC-9.5	Single	70	23491	23423	68	1.97	1.35	31.5
2.1-6	FC-9.5	Double	50	25335	25090	245	1.91	1.34	29.8
2.1-11	Concrete	Single	20	28065	27889	176	1.87	0.23	87.7
2.1-7	Concrete	Single	30	27936	27608	328	1.76	0.74	58.0
2.1-8	Concrete	Single	50	28687	28495	192	1.89	1.30	31.2
2.1-9	Concrete	Single	70	27922	27850	72	2.01	1.03	48.8
~~2.1-10~~	Concrete	Double	50	31213.0	31564	<0	1.97	1.79	9

Table D.4 – Aggregate Loss Results (Binder Type and Temperature).

Slab			Weights (g)			Texture/MPD, mm		
ID	Binder	Temp	Pre Test (USE)	After Testing	Mass loss	Pre Test	Post Test	% Change
2.2-1	A	72	31213.0	31564	<0	1.97	1.79	9
2.2-3	B	72	31484.0	31442	42	2.00	1.72	14
2.2-6	C	72	32049.0	32371	<0	2.08	1.65	21
2.2-7	D	72	29611	29459	152	1.92	1.72	11
2.2-2	A	140	28187	28032	155	1.90	1.32	31
2.2-4	B	140	32469	32307.4	162	1.92	1.21	37
2.2-5	C	140	33503	32902	601	2.08	0.74	65
2.2-8	D	140	31711	31782	<0	1.98	1.48	25

Table D.5 – COTE Results (ASTM C531).

		Comparator (in.)							Length (in.) (Final at 22°C)	COTE
		Initial		Final			Change			
Sample Type	Sample	(22°C)	Temp (°C)	Len (in.)	Temp (°C)	Len (in.)	Temp (°C)	Len (in.)		(10^{-6}/°C)
HFST-A	1	0.0298	45.4	0.0456	10.7	0.0234	34.7	0.0222	11.240	56.9
HFST-A	2	-0.0004	45.4	0.0144	10.7	-0.0064	34.7	0.0208	11.243	53.3
HFST-A	3	0.0116	45.4	0.0271	10.7	0.0051	34.7	0.0220	11.251	56.4
HFST-A	4	0.0001	45.4	0.0139	10.7	-0.0063	34.7	0.0202	11.246	51.8
HFST-B	1	0.0068	45.4	0.0181	10.6	0.0003	34.8	0.0178	11.254	45.5
HFST-B	2	0.0046	45.4	0.0165	10.6	-0.0011	34.8	0.0176	11.252	44.9
HFST-B	3	0.0873	45.4	0.0137	10.7	-0.0030	34.7	0.0167	11.249	42.8
HFST-B	4	0.0561	45.4	-0.0184	10.7	-0.0351	34.7	0.0167	11.252	42.8
HFST-C	1	0.0391	40.0	0.0485	10.5	0.0320	29.5	0.0165	11.280	49.6
HFST-C	2	-0.0365	40.0	-0.0262	10.5	-0.0431	29.5	0.0169	11.250	50.9
HFST-C	3	0.0347	40.0	0.0432	10.5	0.0270	29.5	0.0162	11.284	48.7
HFST-C	4	0.0070	40.0	0.0155	10.5	-0.0008	29.5	0.0163	11.253	49.1
HFST-D	1	0.0909	45.4	-0.0006	10.6	-0.0109	34.8	0.0103	11.237	26.3
HFST-D	2	0.0850	45.4	-0.0029	10.6	-0.0128	34.8	0.0099	11.240	25.3
HFST-D	3	0.0848	45.4	-0.0039	10.6	-0.0134	34.8	0.0095	11.240	24.3
HFST-D	4	0.0869	45.4	-0.0048	10.6	-0.0145	34.8	0.0097	11.240	24.8

Table D.6 – COTE Results (AASHTO T336).

Property		Value												
Material		Concrete			FC 9.5			FC 5			HFST-A	HFST-B	HFST-C	HFST-D
Sample		1	2	3	1	2	3	1	2	3	1	1	1	1
Length (in.)	1	6.8220	6.8270	6.8180	6.2250	6.8000	6.7300	6.7825	6.8040	6.6450	6.9570	6.9030	6.8040	6.7645
	2	6.8005	6.8280	6.8195	6.2330	6.7630	6.7795	6.8125	6.7995	6.6360	6.9560	6.9260	6.8195	6.7530
	3	6.8000	6.8320	6.8125	6.2500	6.8190	6.8475	6.8010	6.8100	6.5790	6.9680	6.9030	6.8150	6.7610
	Average	6.8075	6.8290	6.8167	6.2360	6.7940	6.7857	6.7987	6.8045	6.6200	6.9603	6.9107	6.8128	6.7595
Temp (°C)	1	11.3	11.3	9.5	25.7	25.7	8.7	30.0	30.0	8.7	10.1	10.1	10.1	10.1
	2	60.1	60.1	60.1	11.0	11.0	27.4	12.0	12.0	27.4	44.5	44.5	44.5	44.5
	3	10.1	10.1	9.8	25.4	25.4	11.2	30.0	30.0	11.2	10.0	10.0	11.7	11.7
LVDT (in.)	1	0.1510	0.1507	0.1337	0.1559	0.1519	0.1608	0.2123	0.2158	0.1589	0.1464	0.1680	0.1685	0.1441
	2	0.1477	0.1476	0.1307	0.1573	0.1533	0.1628	0.2147	0.2181	0.1584	0.1381	0.1581	0.1607	0.1382
	3	0.1509	0.1506	0.1335	0.1561	0.1521	0.1646	0.2130	0.2165	0.1604	0.1470	0.1684	0.1697	0.1444
dTemp (°C)	1-2	48.8	48.8	50.6	-14.7	-14.7	18.7	-18	-18	18.7	34.4	34.4	34.4	34.4
	2-3	-50	-50	-50.3	14.4	14.4	-16.2	18	18	-16.2	-34.5	-34.5	-32.77	-32.77
dLength (in.)	1-2	-0.0033	-0.0030	-0.0030	0.0014	0.0013	0.0019	0.0024	0.0023	-0.0005	-0.0083	-0.0099	-0.0077	-0.0059
dLen2	2-3	0.0032	0.0030	0.0028	-0.0012	-0.0011	0.0018	-0.0017	-0.0016	0.0020	0.0088	0.0103	0.0090	0.0062
COTE (initial)	1	9.96E-06	9.10E-06	8.68E-06	1.51E-05	1.33E-05	-1.53E-05	1.92E-05	1.85E-05	4.08E-06	3.46E-05	4.18E-05	3.30E-05	2.55E-05
	2	9.36E-06	8.82E-06	8.15E-06	1.38E-05	1.15E-05	1.65E-05	1.35E-05	1.29E-05	1.88E-05	3.67E-05	4.31E-05	4.01E-05	2.78E-05
	Average	9.66E-06	8.96E-06	8.42E-06	1.44E-05	1.24E-05	6.05E-07	1.64E-05	1.57E-05	1.14E-05	3.56E-05	4.24E-05	3.66E-05	2.66E-05
Frame		1	2	1	1	2	1	1	2	2	1	2	1	2
Correction Factor		3.15E-07	-2.75E-07	3.15E-07	3.15E-07	-2.75E-07	3.15E-07	3.15E-07	-2.75E-07	-2.75E-07	3.15E-07	-2.75E-07	3.15E-07	-2.75E-07
COTE (Corrected) 10^-6/°C	ndividua	10.0	8.7	8.7	14.8	12.1	0.9	16.7	15.5	11.2	36.0	42.2	36.9	26.3
	Average	9.1			13.4			16.1			36.0	42.2	36.9	26.3
	St. Dev.	0.7			1.9			0.9			-	-	-	-

Table D.7 – Gel Time Results (Temperature).

Resin Binder Type	Temperature (F)	Percent by Weight			Percent by		Gel Time (min)
		Part A	Part B	Additive (g)	Part A	Part B	
A	100	55	45		50	50	8
A	90	55	45		50	50	9
A	80	55	45		50	50	13
A	72	55	45		50	50	20
A	60	55	45		50	50	30
A	50	55	45		50	50	60+
B	100	53	47		50	50	8
B	90	53	47		50	50	12
B	80	53	47		50	50	17
B	72	53	47		50	50	25
B	60	53	47		50	50	45
B	50	53	47		50	50	60+
C	100	53	47		50	50	7
C	90	53	47		50	50	11
C	80	53	47		50	50	17
C	72	53	47		50	50	24
C	60	53	47		50	50	36
C	50	53	47		50	50	60+
D	100	98	2	0.07	-	-	22
D	90	98	2	0.08	-	-	18
D	80	98	2	0.18	-	-	13
D	72	98	2	0.32	-	-	20
D	60	98	2	0.75	-	-	11
D	50	98	2	1.25	-	-	10

Table D.8 – Gel Time Results (Proportioning).

Resin Binder Type	Temperature (F)	Percent by Weight			Percent by Volume		Gel Time (min)
		Part A	Part B	Additive (g)	Part A	Part B	
A	72	29	71		25	75	60
A	72	59	41		35	65	21
A	72	45	55		40	60	16
A	72	55	45		50	50	17
A	72	65	35		60	40	20
A	72	68	22		65	35	21
A	72	79	21		75	25	60
B	72	25	75		22	78	60
B	72	40	60		36	64	26
B	72	43	57		39	61	19
B	72	53	47		50	50	17
B	72	60	40		56	44	16
B	72	63	37		59	41	15
B	72	65	35		63	37	24
B	72	75	25		72	28	60
C	72	-	-		25	75	25
C	72	-	-		35	65	21
C	72	-	-		40	60	21
C	72	53	47		50	50	24
C	72	57	43		60	40	21
C	72	62	38		65	35	21
C	72	73	27		75	25	21
D	72	97.1	2.9	0.19	-	-	16
D	72	97.4	2.6	0.19	-	-	17
D	72	97.6	2.4	0.19	-	-	18
D	72	98.0	2.0	0.19	-	-	20
D	72	98.4	1.6	0.19	-	-	25
D	72	98.6	1.4	0.19	-	-	26
D	72	99.0	1.0	0.19	-	-	25

Table D.9 – Friction Results (Aggregate Only).

Materials	Micro Deval (% loss)			AIMS								
				Texture				Angularity				Sample size
			Sample size	Before		After		Before		After		
	Average	St Dev		Avg	St Dev	Avg	St Dev	Avg	St Dev	Avg	St Dev	
Agg. A (Bauxite)	5.12	-	1	170	-	157	-	3050	-	2595	-	1
Agg. B (Bauxite)	5.6	-	1	545	-	518	-	2758	-	2319	-	1
Agg. C	24.6	-	1	361	-	350	-	3522	-	2495	-	1
Limestone	18.8	6.6	47	133	42	77	8	2974	172	1886	335	4
Igneous	10.6	5.8	10	447	-	428	-	3001	-	2205	-	1
Sandstone	12.7	1.2	3	-	-	-	-	-	-	-	-	-
Gravel	9.5	4.1	30	-	-	-	-	-	-	-	-	-

Table D.10 – Friction Results (HFST System).

Material	Polisher Cycles (k)	DFT (mu)					CTM	
		Speed (k/hr)			Overall		MPD	
		20	40	60	Avg.	St. Dev.	Avg.	St. Dev.
HFST-A (Bauxite)	0	1.00	1.01	1.02	1.01	0.01	1.82	0.12
	30	0.90	0.90	0.93	0.91	0.02	1.67	0.17
	100	0.89	0.88	0.92	0.90	0.02	1.52	0.11
HFST-B (Bauxite)	0	0.95	0.98	0.99	0.97	0.02	1.86	0.03
	30	0.93	0.93	0.91	0.92	0.01	1.47	0.13
	100	0.87	0.87	0.90	0.88	0.02	1.57	0.07
HFST-C	0	0.86	0.89	0.89	0.88	0.02	1.56	-
	30	0.71	0.72	0.74	0.72	0.01	1.24	-
	100	0.65	0.65	0.67	0.66	0.01	1.33	-

APPENDIX E
PROPOSED HFST SPECIFICATION

.

HIGH FRICTION SURFACE TREATMENT.
(REV 2-11-16) (TTI recommendations 5-30-16)

The following new Section is added after Section 330:

SECTION 333
HIGH FRICTION SURFACE TREATMENT

333-1 Description.

This work consists of furnishing and applying a high friction surface treatment (HFST) in accordance with this Section and in conformity with the lines and details shown on the plans.

The Contractor shall be responsible for providing a manufacturer's representative at the construction site in order to train FDOT, Construction, Engineering & Inspection (CEI), and Contractor personnel prior to surface treatment and shall require the manufacturer's representative to be available during application of the surface treatment as necessary.

333-2 Materials.

333-2.1 General: Use a two part polymer resin binder treatment capable of retaining a bauxite aggregate topping under vehicular traffic conditions.

333-2.2 Polymer Binder: The polymer resin binder shall consist of a thermosetting modified polymer compound and shall meet the following requirements:

Table 333-1 POLYMER RESIN BINDER REQUIREMENTS		
Property	**Requirement**	**Test Method**
Viscosity	7 – 30 poises	ASTM D-2556
Gel Time	10 minutes min.	ASTM C-881 (60 gram mass)
Ultimate Tensile Strength	2,000 – 5,000 psi	ASTM D-638 (Type 1 Specimen)
Elongation at break point	30 – 70%	ASTM D-638 (Type 1 Specimen)
Durometer Hardness (shore D)	60 - 80	ASTM D-2240
Compressive Strength	1,000 psi min 3 hours, 5,000 psi min at 7 days	ASTM C-579
Cure Rate (dry time)	3 hours max	ASTM D-1640
Water Absorption	1.0% max	ASTM D-570
Adhesive Strength at 24 hrs	250 psi min or 100% substrate failure	ASTM C-1583

333-2.3 Aggregate: The aggregate shall be a calcined bauxite consisting of a 1-3mm gradation. The aggregate shall be clean, dry, and free from foreign matter. The aggregate will be delivered to the construction site in appropriate packaging that is clearly labeled which protects the aggregate from any contaminates on the jobsite and from exposure to rain or other moisture. The aggregate shall meet the following requirements:

Table 333-2 AGGREGATE REQUIREMENTS			
Property		Requirement	Test Methods
Aggregate Abrasion Value		20% max	AASHTO T-96
Aggregate Grading	No. 4 Sieve Size	100% min Passing	AASHTO T-27
	No. 6 Sieve Size	95% min Passing	AASHTO T-27
	No. 16 Sieve Size	5% max Passing	AASHTO T-27
Moisture Content		0.2% max	AASHTO T-255
Aluminum Oxide		86% min	ASTM C-25

333-2.4 Certified Test Results: Provide to the Engineer certified copies of complete test results from the producers documenting that the polymer resin binder meets the requirements of Table 333-1 and that the aggregate meets the requirements of Table 333-2. The test results shall be within 12 months of project letting date and must be representative of the material used on the project and must document source of origin.

333-3 Vendor Qualification.

The HFST vendor will provide a list of similar projects with owners contact information / project location on which a minimum of 3,000 square yards of high friction aggregate and polymer resin binder has been placed within the past three years from the date of the submittal of bid. Include documentation that indicates the in-place friction characteristics of these projects met a minimum FN40R of 65 when tested in accordance with AASHTO T-242.

333-4 Quality Control Plan.

The vendor shall submit an HFST Quality Control Plan (QCP) and provide a copy to SMO for approval at least 30 days prior to placement of HFST. The QCP shall contain a minimum:

1. Schedule for the trial HFST work and the production HFST work.
2. Description of equipment for placing HFST.
3. Method of application for measuring, mixing, placing, and finishing HFST.
4. Method for protecting areas not to receive HFST.
5. Description of acceptable environmental conditions for placing HFST.
6. Cure time and time to bear traffic estimates for HFST.
7. Storage and handling of HFST components.
8. Disposal and recycling of excess HFST and containers.
9. Contingency plan for possible failure during the HFST application.
10. Name of the certified independent testing laboratory.
11. Key personnel and contact information.
12. All project certifications and test results.

The QCP shall designate a Project Administrator who shall have full authority to institute any action necessary for the successful operation of the Plan.

333-4 Application.

333-4.1 General: Do not apply the two part polymer resin binder on a wet surface, when the ambient or surface temperature is below or above the manufacturer's recommendation, or when the anticipated weather conditions would prevent the proper application of the surface treatment as determined by the manufacturer’s representative. HFST application is not allowed on open graded surface course, unless approval is granted by the Engineer.

333-4.2 Test Strip. Complete a trial test strip prior to starting HFST production work. Surface preparation on the rest of the project may be completed prior to the test strip or during the cure time.

The trial HFST shall:

- Be at least 20 feet long and equal to the production width.
- Be constructed using the same equipment as the production work.
- Replicate field conditions, including ambient and surface temperatures, anticipated for the production work.
- Demonstrate surface preparation requirements.
- Document the settings on the applicator equipment, initial quantities of resin and aggregate, and unused quantities of resin and aggregate remaining in the applicator equipment after applying the HFST.
- On a small area, verify the polymer resin binder film thickness using a wet film thickness gauge prior to aggregate placement.
- Determine the initial set time for polymer resin binder in HFST.
- Have temporary or permanent pavement markers and delineation in place when lanes are open to public traffic.
- Determine that work can be completed within time permitted in Lane Requirement Charts.

Remove and dispose of the HFST test strip if quality is unacceptable. No payment will be made for disposed material. Do not begin HFST production until successful completion of the trial HFST and authorized by the Engineer in writing.

The test strip requirement may be waived by the engineer if the contractor is prequalified and the inspector has overseen several successful projects.

333-4.3 Preparation: Surfaces shall be clean, dry, and free of all dust, oil, debris and any other material that might interfere with the bond between the polymer resin binder material and existing surfaces. For applications on new pavements, install the HFST a minimum of 30 days after the placement of the underlying and adjacent asphalt pavement.

Clean asphalt pavement surfaces using a mechanical sweeper to remove dirt, loose aggregate, debris, and deleterious material. Then air wash the surface with clean and dry air using a compressor with a minimum of 180 cfm and sufficient oil traps. Maintain the air lance perpendicular to the surface and the tip of the air lance within 12 inches of the surface.

Clean concrete pavement surfaces by shot blasting to remove all curing compounds, loosely bonded mortar, surface carbonation, and deleterious material. The final surface must have, at minimum, the texture of Concrete Surface Profile (CSP) 5 as specified by the International Concrete Repair Institute (ICRI). The texture should not go above CSP 7. After shot blasting, vacuum sweep or air wash, with a minimum of 180 cfm of clean and dry compressed air. Maintain the air lance perpendicular to the surface and the tip of the air lance within 12 inches of the surface.

Utilities, drainage structures, curbs and any other structure within or adjacent to the treatment location shall be protected against the application of the surface treatment materials. Cover and protect all existing pavement markings that are adjacent to the application surfaces as directed by the Engineer. Pavement markings that conflict with the surface application shall be removed by grinding or other methods approved by the Engineer and the surface shall be swept clean prior to the polymer binder application.

Pre-treat joints and cracks greater than 1/4 inch in width and depth with the mixed polymer specified herein. Once the polymer in the pre-treated areas has gelled, the high friction polymer binder and aggregate topping installation may proceed.

The top layer of flexible pavement should be milled and inlaid prior to HFST application in the following conditions: cracking covering 6 percent or more of the surface; widespread rutting of 0.25 inches or greater; raveling; or bleeding surface. On concrete, slab repair or replacement is required for any single slab with: moderate or severe distress (specifically transverse cracking, longitudinal cracking, spalling, or corner cracking); or a shattered slab in more than 3 pieces.

333-4.4 Automated Mixing and Application: Apply HFST with a continuous automated method using an applicator vehicle. The applicator vehicle shall mechanically mix, meter, monitor, and apply the binder resin system and spread the high friction aggregate a minimum of 12 ft wide in one uniform and continuous pass. If recommended by the manufacturer, metering pumps shall be heated.

The applicator vehicle must have continuous pumping and proportioning devices that blend the binder components within a controlled system and can blend and mix per the manufacturer’s specification (+/- 2% by volume). The polymer resin binder must be continuously applied once blended. The applicator vehicle must be capable of applying the minimum polymer resin binder spread rate.

Dense-graded asphalt and rigid pavement surfaces will require one course layer of HFST following the application rates in Table 333-3. Open graded asphalt surfaces are not suitable for HFST. All HFST layers must be constructed to a minimum of the drivable lane width.

Table 333-3 Course Layer Requirements	
Polymer Resin Binder Application Rate	High Friction Aggregate Application Rate
50-65 mils (25 to 32 sf/gal)	12 to 15 lbs/sy

The aggregate shall be applied less than 30 seconds of the polymer resin binder application. Completely cover the “wet” polymer binder with aggregate until refusal. The high friction aggregate shall be uniform in color and texture for the full application. Recovered aggregate may only be reused once and must be blended with new aggregate at a rate of 2:1 (two parts new aggregate to one part recovered aggregate). Provide a written record of the recovered aggregate and clearly label storage containers with “Recovered HFST Aggregate” and the project number.

333-4.5 Manual Mixing and Application: Manual mixing and application are only allowed for areas less than 200 square yards or upon approval by the Engineer where truck mounted application machines are not applicable to the specified locations because of construction constraints. Hand-mix the polymer resin binder in accordance with the manufacturer’s recommendations. Uniformly spread the binder using serrated edge squeegees, and within 5 minutes broadcast the aggregate until refusal. All other conditions apply.

333-4.6 Curing: Allow each course of the HFST to cure in accordance with manufacturer recommendations for approximately two hours. Protect treated surfaces from traffic and environmental effects until the area has cured. After the initial cure, the inspector may perform a visual inspection to verify that the polymer resin binder has cured properly and that there are no uncured spots. HFST that does not cure properly is subject to removal at the contractor’s expense.

Before opening to traffic, remove the excess aggregate by hand brooms, mechanical sweeping, or vacuum sweeping. Excess aggregate that can be reused shall be reclaimed by a Vacuum Sweeper. The recovered aggregate must be clean, uncontaminated, and dry, as approved by the Engineer. No more than two weeks after final placement of HFST, the contractor must conduct additional mechanical or vacuum sweeping to remove excess shedding HFST aggregate.

Restripe the pavement surface and reinstall pavement markers as directed in the contract documents after the HFST has been completed and approved by the Engineer. Temporary striping may be necessary as described by the contract documents or as directed by the Engineer.

333-5 Warrantee and Friction Acceptance Testing.

All HFST applications require a minimum 1-year warrantee from surface defects. Within 90 days after construction of the HFST, the Department will measure the friction characteristics in accordance with AASHTO T-242. The minimum acceptable friction number (FN40R) is 65 or the contractor must remove and replace all materials at no additional expense to FDOT.

333-6 Method of Measurement.

The quantities to be paid for will be the plan quantity, in square yards, completed and accepted. No deduction will be made for the areas occupied by manholes, inlets, drainage structures, pavement markings or by any public utility appurtenances within the area.

333-7 Basis of Payment.

Price and payment will be full compensation for all work specified in this Section. Payment will be made under:

Item No. 908-333-1 High Friction Surface Course – per square yard.