Safety Opportunities in High Friction Surfacing

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NATIONAL ASSOCIATION NACE COUNTY ENGINEERS ®

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Overview

Crashes on the nation's roadways continue to be one of the leading causes of fatalities and major injuries in the United States, particularly in rural areas. Roughly half of all fatal crashes occur at intersections or on horizontal curves.[1,2] In horizontal curve crashes, it is often the case that the vehicle speed and curve geometry create a "friction demand" higher than what can be achieved with standard pavement surfaces. Intersection crashes often occur when driver error creates an unexpected need for increased friction demand to serve as a "speed countermeasure." One low cost approach that has been shown to be effective in addressing high "friction demand" locations is the installation of a High Friction Surface Treatment (HFST).

High Friction Surface Treatments are pavement surface treatments that are composed of extremely hard, polish- and abrasion-resistant aggregates bonded to the pavement surface that greatly enhance the skid resistance and frictional characteristics of a road surface. HFSTs address three speed-related crash conditions: low friction, marginal friction (further reduced by weather), and friction values not compatible with approach speeds and geometrics. Originally developed in the United States during the 1950's using epoxy resin, HFST has seen increased use in the U.S. in recent years.[3] It has also been successfully used in Europe and Asia for decades, including on a wide scale in London in the early 1970's.[4]

Through The Federal Highway Administration (FHWA) sponsored projects over the past few years, state agencies are experiencing significant crash reductions at a number of high-crash sites where high friction treatment was installed and monitored.

While HFSTs may not yet be known or understood by many practitioners in the United States, that is about to change. The American Traffic Safety Services Association (ATSSA) is undertaking an effort to promote a better understanding of the benefits of HFSTs. This document provides insights into the benefits and challenges involved in effectively installing HFSTs. It highlights successful applications, and provides readers with contacts and resources to consult when considering their own use of the treatment.

This document is organized into five parts:

- Part one presents an overview of what HFSTs are, where they can be used, the different materials that are available, and other introductory materials.
- Part two presents case studies of successful applications of HFSTs made throughout the United States to address different crash issues.
- Part three presents more in-depth information on the aggregates, binders, and testing methods associated with HFSTs.
- Part four presents national and state contacts that the reader may use to obtain more information on specific HFST installations, and useful website resources that may be consulted.
- Part five provides a glossary of terms used throughout the document, past research results related to the treatment, and a list of the references cited throughout the document for reader reference.

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Identification, review and refinement of the individual case studies were guided by an Expert Panel made up of Industry Professionals listed below.

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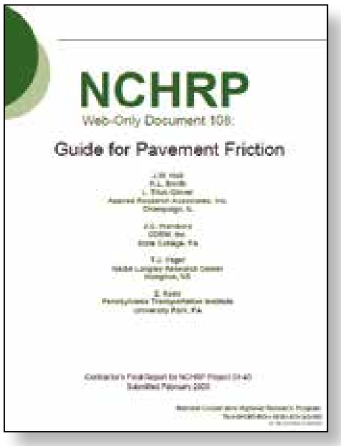
Part 1: Introduction

Crashes on the nation's roadways continue to be one of the leading causes of fatalities and major injuries in the United States, particularly in rural areas. One of the most predominant types of crashes nationwide is roadway departure. In 2010 (the most recent year for which analysis has been completed), there were 32,885 crash-related fatalities throughout the U.S., and 17,389 of these fatalities occurred in lane departure crashes. [5] Federal Highway Administration (FHWA) statistics indicate that 28 percent of fatal crashes occur at horizontal curves, and over 80 percent of these crashes involve some form of roadway departure. [6] Yet horizontal curves make up only a fraction of the nation's roadways. [7] Intersections are another location where a significant number of fatal crashes occur, There were 7,000 intersection crash fatalities in 2009. [8] Clearly there is a need and an opportunity to address crashes at these locations and achieve significant improvements in safety.

Often, increased friction demand is a significant factor resulting in vehicles leaving the roadway or being involved in a skid-related crash at various locations. A Federal Highway Administration 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. [9] Additionally, wet pavement conditions contribute to the loss of friction and increased friction demand. Finally, it has been noted that heavy vehicles with high centers of gravity may overturn before losing control due to skidding, particularly on interchange ramps and downgrade curves. [10] Regardless of the cause, when a vehicle's frictional demand exceeds the frictional force between a tire and the pavement, a skid develops. When friction is reduced and a vehicle is travelling at a high speed or too fast for conditions, the opportunity for lane departure arises, particularly in locations such as horizontal curves.

As one would expect, pavement friction is a widely recognized issue that many agree must be addressed in order to reduce crashes. The National Cooperative Highway Research Program's (**NCHRP)** *Guide for Pavement Friction* (NCHRP Web Document 108) lists HFSTs as one approach to addressing inadequate friction. [11] This point is also stressed in the American Association of State Highway and Transportation Official's (AASHTO) *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan - Volume 6: A Guide for Addressing Run-Off-Road Collisions*. [12] Strategy 15.1 A7 of that document specifically discusses skid resistant pavements, stating that treatments to address the issue "should have high initial skid resistance, durability to retain skid resistance with time and traffic, and minimum decrease in skid resistance with increasing speed." [12] The guide calls for a targeting of spot locations where, under wet or dry conditions due to increased friction demand, skidding is an issue.



(Image: Transportation Research Board)

Clearly, a systematic approach is needed to address locations where lane departure crashes occur. Lane departure crashes are widely recognized as a problem that must be addressed throughout the U.S. They are the only crash type/issue specifically targeted in the Strategic Highway Safety Plans (SHSPs) of all 50 states.

While many lane departure crashes can be attributed to driver inattention, evidence shows that excessive speed and weather are also factors leading to such crashes. In light of this recognition, a number of different approaches to addressing such crashes have been and continue to be pursued.

One reason for the focus on addressing such crashes is that they present an opportunity to achieve significant reductions for relatively low investments. For example, U.S. Department of Transportation (USDOT) statistics indicate that up to 70 percent of wet-pavement crashes can be affected by basic friction improvements. [13] One of the lowest-cost approaches that has been shown to be effective in addressing friction is the use of High Friction Surface Treatments (HFSTs) for critical spot locations.

The FHWA's *Every Day Counts* initiative has cited HFSTs as an emerging technology that can dramatically and immediately reduce crashes, fatalities, and injuries.[7] FHWA's "Low-Cost Treatments for Horizontal Curve Safety" also presents HFSTs as an approach to address skid resistance in curves.[14] The durability of HFST materials and spot-use in critical locations results has proven to be a low cost solution to specific safety issues. HFST represents both a safety treatment and a speed countermeasure, as it often serves to counteract driver behavior (higher speeds) in a manner that prevents crashes without requiring driver intervention.

(Image: FHWA)

High Friction Surface Treatments

High Friction Surface Treatments are pavement surface treatments that are composed of extremely hard, polish- and abrasion-resistant aggregates bonded to the pavement surface using a resin or polymer material (epoxy, acrylic, etc.).[15, 16] They enhance and maintain skid resistance and frictional characteristics at locations where friction demand is greater thanthat provided by the original pavement surface or where the surface has lost its frictional impact due to polishing or loss of aggregate. By amplifying friction, HFSTs serve as a speed countermeasure by enhancing the grip of a pavement. Further detailed information on HFSTs is provided on ATSSA's High Friction Surface website at http://www.highfrictionsurface.net.

HFSTs can be used in a variety of settings including interchange ramps (Image: South Carolina DOT)

HFSTs address three conditions of concern: low friction, marginal friction affected by weather, and friction values not compatible with approach speeds and geometrics.[17] In addition to horizontal curves and intersection approaches, HFSTs are available to address friction-related issues for a minimal cost at a number of locations, including:

- Transition lanes;
- Bridge decks;
- High speed roadway entrance/exit ramps;
- Steep grades;
- Approaches to rail, school, and trail crossings; and
- Tolling areas.[18]

While horizontal curves and intersections are generally the focus of this document, these examples are provided to the reader for consideration in addressing different concerns specific to their locale.

What is a High Friction Surface?

A High Friction Surface is comprised of a thin application of rosin-based products into which an aggregate with a characteristic of wear-resistance is embedded onto an existing asphalt or concrete pavement (or steel surface). It is different from other pavement treatments (chip seal, slurry, micro-surfacing, milling, grooving, etc.) since High Friction Surface treatments are designed to enhance pavement friction to approach a British Pendulum Number (BPN) in a range that begins at 65 and often reaches the upper 90's. (Note that a friction number (FN) is a number calculated using measurements from a locked wheel testing device that represents the average coefficient of friction measured across a test interval.[11])

One of the best performing and commonly used aggregates is calcined bauxite, but other less expensive aggregates have been successful for some less severe geometric conditions. These aggregates include certain types of steel slag and granite materials with high polished stone values (PSV). The aggregate size used in HFSTs is typically less than six millimeters (more typically two to four millimeters), and its rough texture and greater surface area act together to increase friction. The aggregate is bonded to the roadway surface using different binders such as bitumen-extended epoxy, epoxy resin, rosin-ester, polyurethane resin or acrylic resin.

What does a High Friction Surface do?

The combined aggregate-binder treatment forms a pavement surface that is resistant to polishing and provides improved friction and skid resistance. This improvement provides an additional opportunity for a motorist to regain control of a vehicle in situations of excess speed. Given the durability of the aggregate material and the strength of the binder, the combination is able to withstand heavy braking and snowplowing. This makes HFSTs an ideal solution to address friction concerns in any climate.

HFSTs (right) provide additional surface microtexture (Image: South Carolina DOT)

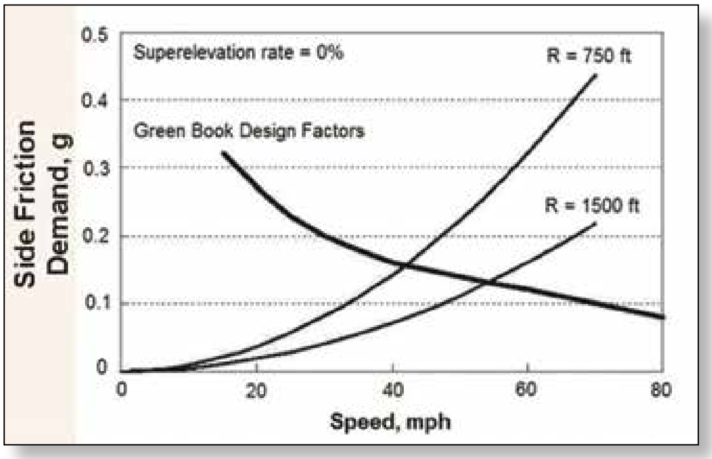
Since added friction is typically needed at spot locations such as horizontal curves or at intersections, often it may be adequate to treat only short sections of the pavement. Or, if the problem is high approach speed (pavement friction demand), the treatment may be needed in only one direction or approach lane.

Simply stated, HFSTs work by increasing the ability of the roadway surface to prevent the loss of tire traction. This is accomplished by the surface of the selected aggregate that provides appropriate microtexture for the pavement. Microtexture is the surface texture of the aggregate, and in the case of HFSTs, the resistance of the aggregate to polishing and abrasion allows microtexture to be maintained providing friction between the pavement surface and a tire.[15] When tire friction is maintained, vehicles are better able to maintain their course on the pavement and are capable of better braking performance when necessary. Industry figures indicate that at 60 miles per hour (mph), an HFST can reduce stopping distances by up to 40 percent on wet or dry pavement.[18]

How should High Friction Surfaces be used?

The correlation between speed and crashes in horizontal curves has been well documented. Of course this could be said for approach speeds at intersections as well. Speed is a major component of increased friction demand in curves and for stopping at intersections. Since HFSTs work well for both conditions in reducing stopping distance and loss of control, they should be considered a "speed countermeasure" and used at locations where friction demand exceeds the friction provided by traditional pavements.

The key to cost-effectively employing High Friction Surfaces is to identify sites where they will achieve the greatest impact. One approach is to look for sites with high occurrences of skid related crashes, including during wet conditions. Agencies may also explore crash locations where curve geometry combined with excessive speed result in side friction demand and kinetic energy beyond the capacity of the best pavements. A higher friction surface amplifies braking and expedites the reduction in vehicle speeds, helping drivers retain control.[19] Furthermore, it meets the need underscored by AASHTO's *2011 Greenbook* to provide skid resistant pavements for wet, snow and ice covered surfaces to address side friction needs.[20] An agency can also perform field measurements of pavement friction, should testing equipment be available.



Relationship between curve speed and side friction demand for two radii

What materials are used for High Friction Surfaces?

As stated earlier, a number of different aggregate and binder materials are available to use when applying an HFST. The following paragraphs briefly introduce these materials, specifically aggregates and binders. Part 3 of this document will discuss them in greater detail. A list of manufacturers and suppliers of different aggregate and binder products is provided on the ATSSA High Friction Surface Treatments website at www.highfrictionsurface.net. Typically, however, HFSTs use:

Aggregates

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.

Calcined Bauxite – An aggregate derived from aluminum ore that, when heated to a high temperature, increases in physical hardness and stability, resulting in polished stone values in the upper 60s and lower 70s. [21]

Calcined bauxite is the most commonly used HFST aggregate (Image: David Merritt)

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.[21]

Steel Slag – An impurity 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.[21]

Taconite – An iron bearing sedimentary rock that contains quartz, chert, or carbonate.

Of course, there are other proprietary products that are also derivatives of these materials, but these have been presented for initial reader familiarization.

Binders

Epoxy-Resin – A 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).[21]

Rosin-Ester – A thermoplastic binder that is applied to the aggregate during a manufacturing process. The dry aggregate is heated on site for placement on the pavement surface, typically with a handheld box.[21]

Polyurethane-Resin – A multi-component binder system consisting of a resin for flow and polyurethane for hardening, which was designed for faster curing times.[21]

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.

How are High Friction Surfaces installed?

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 or weaknesses. HFST applied to defective pavements will peel away if preexisting conditions are not addressed prior to installation. In general, cracks smaller than one-quarter inch in width can be sealed. Larger cracks and weakened pavement will need to be repaired by patches or other means. Addressing these conditions prior to installation will help to ensure an HFST that will remain durable for years.

Mechanical installation of HFST (Image: David Merritt)

HFSTs can be installed on different surfaces, including jointed pavements when proper masking is used (Image: Michigan DOT)

The installation of High Friction Surfaces can be accomplished mechanically or manually. As the technology and application has evolved, the process has become more mechanized and easier to complete. However, for smaller treatment projects (ex. those 100 to 200 feet in length), a manual approach may be more practical. Using this approach, an area of 200 to 300 square yards per hour can be completed. [22]

The installation of High Friction Surfaces is completed through a thin overlay process.[16] Following implementation of any necessary traffic control, the pavement surface is swept clean and dried as needed using brooms, compressed air or shot-blasting. Surface temperatures must be taken to ensure that they meet the specification of the chosen binder. Finally, drains, joints, and expansion devices must be covered with duct tape or plastic to prevent epoxy and aggregates from filling them.

The chosen binder is mixed and spread over the treatment area using squeegees (manually) or a mechanical spreader. Note that squeegees wear quickly during installation, so multiple squeegees should be available to ensure a manual installation can be completed without interruption. Aggregate is then spread over the binder by hand or mechanically, with the excess swept away by brooms or sweepers. When spread manually, a grid system should be laid out to prevent the binder from fanning out. The binder takes two to four hours to set, depending on temperature, allowing for vehicles to drive on the treated area shortly after completion. Maintenance needs are not a significant issue, as aggregate materials have been observed to retain high friction numbers (exceeding 60) in long-term testing under heavy traffic conditions. [23]

While the approaches to installing HFSTs are straightforward, it is important to strictly follow installation guidelines related to surface preparations, pavement, and weather conditions.[21] When preparing the binder, incorrect product mixing and composition can result in a failure of the binder to adhere the aggregate to the pavement surface once installed. Failure to spread the binder out homogeneously or to apply a proper amount of aggregate can also lead to a non-uniform surface and lower friction than intended.[21] The existing pavement may also negate the use of an HFST, For example, applied to porous asphaltthe binder will seep into crevices and not provide proper adhesion. Finally, temperature, as well as humidity and moisture, either on the pavement surface or in the selected aggregate, can lead to lower adhesion and eventual raveling and peel-off.[21] These aspects of HFST should be taken into consideration, particularly when planning and performing each installation.

Evaluation of High Friction Surface products

New products are being developed that will enhance the performance of HFST binders even more. Consequently, the AASHTO has incorporated the evaluation of High Friction Surface treatments into their National Transportation Product Evaluation Program (NTPEP). The Polymer Concrete Overlays (PCO) technical committee developed a test deck where material manufacturers can install their products and be evaluated and compared to similar products. The first of these test decks were installed in October 2012. For more information on the test deck process and results, go to http://www.ntpep.org/Pages/PCO.aspx.

Cost-benefit analysis

Past work by the Virginia Tech Transportation Institute (VTTI) found that HFSTs produce high cost-benefit ratios. These have ranged between 2.23 and 8.45, indicating a positive return on investment for each dollar spent on the treatment.[21] The exact nature of each particular installation and the problem it addresses will have a direct bearing on the exact cost-benefit ratio that can be achieved, but in general, HFSTs have shown to produce a significant return on investment in a short period of time.

There is also money eligible for HFST projects through FHWA Highway Safety Improvement Program (HSIP) funds, which are geared toward reducing crashes, fatalities, and injuries along public roads. The exact cost of an HFST will vary by the amount of surface being treated, labor costs, the aggregate and binder selected, and locale. As indicated earlier, treatments can be applied to limited lengths of roadway manually or mechanically, providing an opportunity to achieve safety improvements quickly once a site has been identified and materials acquired.

Part 2: Case Studies

The value of High Friction Surface treatments in reducing roadway crashes has been discussed in the prior sections. This section focuses on specific examples of successful applications in the field to address friction demand issues throughout the United States. Each case study includes contact information for agency personnel associated with the project, should the reader wish to follow up and learn more about a specific application.

CASE STUDY: Northampton County, Pennsylvania Sr 611, Horizontal Curve[24]

The Pennsylvania Department of Transportation (PennDOT) applied an HFST to the southbound lane of a horizontal curve along SR 611 at a location referred to as "Groundhog Locks." The southbound lane had experienced a number of wet weather crashes in the horizontal curve. The site could not be improved through widening due to historic structures on either side of the right of way. Alternative safety treatments had been applied prior to HFST installation, including the use of chevrons, additional signage, and improved pavement markings; however, none of these treatments had an impact on crashes.

Prior to the installation of the HFST, 21 southbound wet weather crashes were recorded at the location over five years. During the 5.2 years since the installation, there have been zero wet weather crashes. Based on the historical crash experience at the site, PennDOT believes that crashes would have continued to occur at a similar frequency had the HFST not been installed in the southbound lane. Furthermore, as a result of the crash reduction results observed in the three years following the installation, HFSTs have become an approved crash treatment since 2011.

Installation of HFST on SR 611 southbound lane and overall view of the site and its limited right of way (Images: Pennsylvania DOT)

The HFST used was calcined bauxite for the aggregate and epoxy resin for the binder. The application was completed manually through squeegeeing the binder out and hand-spreading the aggregate. To date, the site has held up well and maintained high friction numbers. The experience with HFST on SR 611 has led to the identification of eleven future sites where the treatment will be used.

Skid test measurements performed prior to the HFSTinstallation found that the pavement had an average skid number of 24. After the HFST installation, the friction numbers were in the mid-70s. The most recent measurement taken in July of 2010 found an average skid number of 71, illustrating the durability of the calcined bauxite surface over time.

Location: SR 611, Segment 4 (Groundhog Locks), 5 miles south of Easton
Problem: Wet weather crashes in the southbound lane (due to low friction numbers and geometrics)
Material: Calcined bauxite
Installation: June 2007

Agency Contact:
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Agency: Pennsylvania Department of Transportation
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Email: spohowsky@state.pa.us

CASE STUDY: Bellevue, Washington Downgrade Intersection Approach

The Forest Drive westbound approach, at its intersection with Cole Creek Parkway, regularly had vehicles sliding down the hill during icy weather. In 2011, the average daily traffic at the approach was 4,941 vehicles. In an effort to combat the problem, a High Friction Surface treatment was applied on this approach in 2004. From 1995 to October of 2004, the City of Bellevue had recorded 2.7 accidents per year that were attributed to grade, skidding, driving too fast for conditions, or run off the road. Subsequent to the installation, the average went down to 0.5 accidents per year. In 2007, due to a surface water problem at the bottom of the hill, the pavement was resurfaced. To determine if the HFST should be reapplied, the City of Bellevue analyzed the effect of it on the crash cost. They found an annual accident cost reduction of about $25,000 per year to the public. Hence, the City recommended that the HFST be reapplied.

Location: Cole Creek Parkway and Forest Drive
Problem: Forest Drive WB approach; during icy weather, vehicles would slide down the hill
Material: Calcined bauxite
Installation: October 2004

Agency Contact:

Name: Mark Poch, PE, PTOE
Position: Traffic Engineering Manager
Agency: City of Bellevue – Transportation Department
Telephone: 425-452-6137
Email: mpoch@bellevuewa.gov


Installation of HFST on westbound Forest Drive (Images: City of Bellevue, Washington)

CASE STUDY: Milwaukee, Wisconsin Marquette Interchange

In 2008, the new Marquette Interchange was completed in Wisconsin. This is a heavily utilized ramp with annual daily traffic of 31,000 vehicles. Part of the design included a ramp connection from I-94 eastbound to I-43 northbound. Unfortunately, during every rain or snow event, vehicles were leaving the traveled way so frequently that the connection was shut down. In just a three-year period, 81 crashes occurred on this ramp. Mike Burns with the Wisconsin Department of Transportation described the walls surrounding the roadway as having "every vehicle paint color you could imagine." In October 2011, a high surface friction treatment of calcined bauxite was installed. Since this time, only two crashes have occurred. Wisconsin DOT was able to review a video recording of the first crash and observed the vehicle's wheels drifting into the shoulder area which did not have the High Friction Surface treatment. On a later installation at another site, the HFST was extended out an additional 5 feet onto the shoulder. This was based on experiences from the Marquette Interchange installation, where vehicles were observed to drift onto the untreated shoulder area.

Problem: Any snow or rain event resulted in numerous vehicles leaving the traveled way of the I-94 WB to I-43 EB ramp causing the DOT to shut down the ramp.
Material: Calcined Bauxite
Installation: October 2011
Location: Milwaukee, Wisconsin; I-94 to I-43

Overview of the Marquette Jct. ramp (Image: Wisconsin DOT)

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Agency: Wisconsin Department of Transportation
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CASE STUDY: Kentucky Horizontal Curves

Recognizing that nearly 70 percent of their roadway crashes were related to road departure Kentucky identified a need to address road departure accidents. Roadway departure crashes are a priority for the Kentucky Transportation Cabinet (KTC) because they have found that these crashes tend to lead to injuries or fatalities. If a half-mile roadway section had eight or more wet weather crashes over a five-year period, the KTC proactively applied a High Friction Surface treatment if the pavement was in a good condition. All of the locations used calcined bauxite for the aggregate.

Location 1: Madison County, Kentucky; KY-21, MP 6.25-6.8

Installation: In November 2010, two horizontal curves were located within these mileposts. Prior to the High Friction Surface treatment installation, 10 wet weather crashes and 10 dry weather crashes were recorded at this location over three years. Since the installation, over a period of 1.9 years, five wet-weather crashes and five dry-weather crashes have occurred. Taking into account the relative periods of time before and after, the data suggests a comparable number of 6.67 crashes in the before period and 5.26 crashes in the after period. However, relativetraffic volume was not taken into account, and the after-period is short.

Overview of the KY-21 site at milepost 6.25-6.8 (Image: Kentucky Transportation Cabinet)

Overview of the KY-21 site at milepost 11.3-13.6 (Image: Kentucky Transportation Cabinet)

Location 2: Madison County, Kentucky; KY-21, MP 11.3-13.6

Installation: April 2011

The roadway within this segment was divided into five sections, each containing a horizontal curve. Prior to the High Friction Surface treatment, 57 wet-weather crashes and 16 dry-weather crashes were recorded over a three-year period. After the treatment, nine wet-weather crashes and five dry-weather crashes were observed over 1.5 years. This data suggests a rate of 24.3 crashes per year in the before-period and 9.33 crashes per year in the after-period. Traffic volume was not taken into account, and the after-period is short.

Location 3: Oldham County, Kentucky; KY-22, MP 4.36-4.44

Installation: August 2009

One horizontal curve was contained within this section. Prior to the High Friction Surface treatment, 53 wet weather crashes and three dry weather crashes were observed over a three year period. After the treatment, five wet weather and zero dry weather crashes were observed over a period of 3.18 years – a rate of 18.67 average crashes per year before the installation and 1.57 average crashes per year after the installation.

Overview of the KY-22 site at milepost 4.36-4.44 (Image: Kentucky Transportation Cabinet)

Overview of the US 25 - KY 1629 intersection site (Image: Kentucky Transportation Cabinet)

Location: Knox County, Kentucky; US 25 SB Lane, at its intersection with KY 1629

Installation: April 2011

District 11 within the Kentucky Transportation Cabinet requested a treatment to address rear-end crashes at the intersection of US 25 and KY 1629 in Knox County, Kentucky. A High Friction Surface treatment was only applied on US 25 in the southbound lane. This particular direction has a downgrade. During the three years prior to the installation, there were six wet-weather crashes and 27 dry-weather crashes. Almost all of the crashes were rear-end crashes. During the 1.3 years after the installation, there were two wet weather crashes and five dry weather crashes—a rate of 11 average crashes per year prior to the treatment and about 5.38 crashes after the treatment.

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CASE STUDY: California Interchange Ramps

The California Transportation Department (Caltrans) has installed only about 10 High Friction Surface treatments around the state to date. Two locations are on Route 50, near Sacramento, California. The first is the westbound On-Ramp from Folsom Blvd to Route 50. The second is the westbound On-Ramp from NB 65th St. A third was on Route 20 near Nevada City. Another location, which will be discussed further below, was the Route 105 Sepulveda Boulevard on-ramp in Los Angeles, Caltrans is planning to install fifty more applications throughout the state over the next few years, including one at a high speed signalized intersection.

The major focus area for additional applications is the end of on-ramps and on curves of two-lane roadways. Caltrans' specification for HFSTs requires the use of calcined bauxite as an aggregate. Prior to the decision to install HFSTs, Caltrans mainly used open grade asphalt concrete (OGAC) to reduce wet pavement collisions along with grinding and grooving. However, OGAC could not be installed at locations where there were freezing temperatures. Two additional benefits of High Friction Surface treatments when compared with OGAC are that they can be placed on any pavement surface and there are no concerns with cross drainage.

The I-105 Sepulveda Boulevard On-Ramp, a primary egress point from Los Angeles International Airport, was notorious for closures when it rained since based on experience Caltrans had a high expectation that crashes would occure. The average daily traffic on the on-ramp is 31,000. Crashes were occurring as a result of the tight curvature, the low friction, and the aggressive driving of motorists. Caltrans received numerous calls of complaint when this highly-used on-ramp was closed. Collision records showed that 80 percent of the collisions occurred during wet pavement conditions. As a result, Caltrans applied a High Friction Surface treatment. Since the application, it has not been necessary to close the ramp. The pre-application skid number was 32. The post-application friction value was around 60, but as the installation just occurred recently, post-application crash experience data is not available.

Sepulveda ramp HFST installation (Image: California Department of Transportation)

Problem: Ramp closures during rain. The problems developed primarily as a result of aggressive driving and low surface friction. The ramp is a primary egress point from LAX.
Material: Calcined bauxite
Installation: February 2011
Location: Sepulveda Ramp; Los Angeles, California

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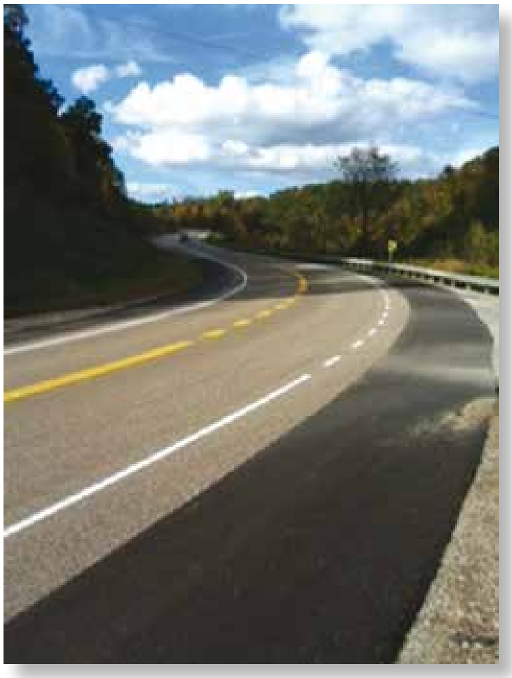
CASE STUDY: West Virginia Horizontal Curves

West Virginia was experiencing a high number of run-off-the-road crashes throughout their highway network. To combat this problem, West Virginia has applied a High Friction Surface treatment to more than 20 sites. Although the after-data is still limited due to the recentness of installations, indications thus far are that the High Friction Surface treatments have reduced the number of crashes. Two locations are highlighted in this case study: West Virginia 14 and West Virginia 20. They have average daily traffic values of 3,400 and 7,200, respectively. To ensure that sites are performing as expected, West Virginia requires skid testing 90 days after a project is completed. The surface must have maintained a value greater than or equal to 69. Both sites mentioned above have fulfilled this requirement.

A High Friction Surface treatment was installed at milepost 15.48 on WV14, in Wirt County, north of six- degree horizontal curve. Prior to the application of the High Friction Surface treatment, four wet-weather crashes occurred over the course of three years. After- accident data is still forthcoming.

Problem: A sharp horizontal curve with a crash history.
Material: Calcined Bauxite
Installation: October 2012
Location: West Virginia 14, north of Elizabeth



WV14, north of Elizabeth (Image: West Virginia Department of Transportation)

A High Friction Surface treatment was installed at milepost 16.42 on WV20, in Mercer County, between Princeton and Athens, West Virginia. It is a two-lane road in southern West Virginia, frequented by commuters. The site is located at a series of horizontal curves. Prior to the application of the High Friction Surface treatment, four run-off-the-road crashes occurred over the course of three years. The West Virginia Department of Transportation is waiting for three years to elapse to analyze the before- and after-accident experience at the site.

Problem: West Virginia has a high number of run off the road crashes.
Material: Calcined Bauxite
Installation: August 2011
Location: West Virginia 20, Between Princeton and Athens

WV20, Between Princeton and Athens (Image: West Virginia Department of Transportation)

Agency Contact:
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CASE STUDY: Florida Interchange Ramps and Intersection

The Florida Transportation Department (FDOT) has installed a number of High Friction Surface treatments around the state to date. Among the sites with HFST installed are the northbound interchange ramp at Royal Palm Boulevard and I-75 (Broward County), the I-595 interchange ramp to the Ft. Lauderdale airport, and the west leg (downgrade) of Sheridan St. at the North 29th Ave. intersection (Broward County). These locations are discussed further below. Note that for legal reasons, the Florida DOT could not provide specific crash figures or friction numbers for the cases discussed here. However, according to Patrick Upshaw, state pavement performance engineer, there has been an "across the board reduction of crashes at each [HFST] site and friction numbers have met the [FDOT] specification requirements."

HFST installations in Florida are guided by *Developmental FDOT Specification Section 333*. This specification directs the use of epoxy-resin binder and calcined bauxite in HFST applications. Specific requirements pertaining to the epoxy binder's characteristics are also outlined, including different strengths, viscosities, curing times, and so forth. The specification also outlines different installation requirements.

Both the Royal Palm Blvd. and I-75 northbound ramp location and the I-595 ramp to the Ft. Lauderdale airport location involved sharply curved ramps with increased friction demands. The Royal Palm Blvd. and I-75 ramp has an average daily traffic rate of14,500, while the I-595 ramp to the airport had an average daily traffic rate of 6,400. The Royal Palm Blvd. and I-75 northbound ramp was installed in 2006 and has performed well. The I-595 - Ft. Lauderdale airport location was installed in 2011 and the airport is pleased with its performance.

The Sheridan St. and North 29th Ave. intersection HFST was installed on the west leg approach of

I-595 ramp to the Ft. Lauderdale airport HFST installation (Image: Florida Department of Transportation)

Sheridan St. to address a history of wet weather crashes on the downgrade approaching the stop bar. The site had an average daily traffic rate of 45,500 and was installed in 2010. This site has performed well to date.

Problem: Restrictive geometries requiring increased friction demand (interchanges); wet weather friction crashes on intersection approach (intersection).
Material: Calcined bauxite
Installation: 2006 and 2011 (interchanges); 2010 (intersection)
Location: Royal Palm Boulevard and I-75 (Broward County); I-595 interchange ramp to Ft. Lauderdale airport; Sheridan St. and North 29th Ave. intersection (Broward County)

Agency Contact:

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Part 3: Materials and Test Methods

The case studies outlined in the previous section provide excellent examples of how HFSTs have been used to address different safety problems related to friction. While the aggregate and binder materials used in the different case studies have been identified, this section provides more specific details on how the different materials used in HFSTs are classified, characterized, and tested.

Aggregate Materials

A number of different aggregate materials are available when applying an HFST. In general calcined bauxite is the most widely used aggregate in HFST projects, with slag also used in some cases.[25] When selecting an aggregate, polish and abrasion resistance are important metrics to consider. These provide an indication of how well an aggregate will hold up over time. Unfortunately, the measurement of these metrics is not necessarily made by agencies for normal pavements; consequently, polished stone values are provided when available for each of the aggregates discussed in this section to provide the reader with a point of reference.

The use of a specific aggregate may be influenced by local availability; for example, steel slag is readily available in regions where steelmaking operations are present and may be available at a more competitive price than other materials. A list of manufacturers/suppliers of the different aggregate products discussed in the following text can be found on the ATSSA High Friction Surface website at http://www.highfrictionsurface.net. Terms used throughout this section of text are defined in the glossary section.

Basalt

Basalt is a volcanic rock formed by the rapid cooling of lava which is rich in magnesium and calcium oxides. It is one of the most common rocks found on Earth. It has a polished stone value of between 52 and 68, depending on the particular variations throughout a basalt flow.[26] It is used as a surfacing aggregate in many regions where it is readily available. Basalt tends to weather faster than other rock types, which may be of concern for use in High Friction Surfaces over time. While the use, performance and effectiveness of basalt in HFSTs have not yet been reported, it does present an option (particularly if locally available) for use in friction surfacing projects with low average daily travel (ADT).

Calcined Bauxite

Calcined bauxite is the most widely used aggregate in HFSTs. It is derived from aluminum ore that, when heated to a high temperature, increases in physical hardness and stability, resulting in polished stone values from the lower 70s.[21] These characteristics ensure that calcined bauxite will maintain its microtexture and will not polish over time. When correctly bonded with the selected binder, calcined bauxite can withstand a great deal of abuse, including abrasive actions such as snow plowing.

Calcined bauxite is the most commonly used HFST aggregate (Image: David Merritt)

Emery

Emery is a rock containing corundum (aluminum oxide) and iron oxide that has been used as an abrasive in products such as sandpaper (hence the name emery boards). No polished stone values appear for this material in literature.

Granite

Granite is 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.[21] These characteristics have led to its use as a High Friction Surface aggregate in past applications.

Granite is another commonly used HFST aggregate (Image: David Merritt)

Silica

Silica is an oxide in the form of sandstone, silica sand, or quartzite. It possesses high abrasion resistance and thermal stability. No polished stone values appear for this material in literature. While the use, performance and effectiveness of silica in HFSTs has not yet been reported (it is currently under testing at the National Center for Asphalt Technology (NCAT) test track) it does present an option (particularly if locally available) for use in friction surfacing projects.

Steel Slag

Steel slag is an impurity 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.[21] Depending on the chemical composition of the slag itself, it can have a varying polished stone value. Tests have shown on average, the PSV of steel slag is 63 to 64.[27] This is another material that may be locally available for use in some regions.

Taconite

Taconite is an iron bearing sedimentary rock that contains quartz, chert or carbonate. No polished stone values appear for this material in literature. Taconite is mainly found in the Messabi Iron Range of Minnesota, making it a HFST product that can be considered in that region.

Binder Materials

A number of different binder materials are available for use in HFSTs, and their use is typically determined by factors such as aggregate, climate, and vendor. In general, epoxy-resin is a commonly used binder, although other materials have also been used. Manufacturerssuppliers of the different binder products discussed in the following text can be found on the ATSSA High Friction Surface website at http://www.highfrictionsurface.net. Terms used throughout this section of text are defined in the glossary.

Binder materials can be applied mechanically or by hand, as shown (Image: Pennsylvania DOT)

Epoxy-Resin

Epoxy-resin is a 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).[21] It is the binder that has been in use the longest for HFSTs and has shown good performance over time. The two components used in the binder are mixed together at the treatment site at equal quantities by weight. Once it has been applied to a surface, the curing time for the binder is between three to four hours at an average ambient temperature.

Rosin-Ester

Rosin-ester is a thermoplastic binder that is applied to the aggregate during a manufacturing process. In other words, it is already applied to the aggregate prior to delivery and installation at the treatment site. The dry aggregate is heated on site for placement on the pavement surface, typically with a handheld box.[11] While care must be taken to ensure the correct surface application thickness, the thermoplastic nature of the binder allows for rapid curing. This allows the roadway to reopen to traffic once the roadway surface reaches an ambient temperature.[21]

Polyurethane-Resin

Polyurethane-resin is a multi-component binder system consisting of a resin for flow and polyurethane produce for hardening, designed for faster curing times.[21] The components are combined on site and mixed together mechanically before being spread on the pavement surface. Once applied, the binder can set in as quickly as two and one-half hours, depending on ambient temperature. Once set, it retains some flexibility, reducing issues with brittleness and breakage.

Acrylic-Resin

Acrylic-resin is a two component system in which the aggregate contains the curing agent that was designed to offer a faster curing time than epoxy-resin. The binder is spread over the treated surface, and curing begins when the aggregate is spread over that surface. The binder is of such a consistency that it wets the aggregate and activates the curing agent, providing bonding to the pavement surface without submerging the aggregate itself. The binder can set in as quickly as one and one-half hours, depending on ambient temperature.

Polyester-Resin

Polyester-resin is a multi-component binder system consisting of a resin for flow and polyester produce for hardening. The binder is mixed and spread either mechanically or manually over the treatment surface and curing begins when the aggregate is spread. The binder can set in as quickly as two hours, depending on ambient temperature.

Friction Measurement Devices

The key to effectively employing High Friction Surfaces is to identify the sites where they will achieve the greatest impact. Given that HFSTs target areas of low friction or where there may be high friction demand, an understanding of friction conditions before and after installation is essential both to identify locations where friction numbers are low, as well as to determine how friction numbers have increased following HFST installation --both immediately and over time. This does not take into account the additional friction needs of vehicles in horizontal curves.[11] The following section discusses the different measurement devices that are available to measure friction at a particular site. Note that some devices such as skid trailers do not measure friction in horizontal curves well. In light of this, other approaches such as the identification of most severe curves for treatment based on estimates of different aspects such as side friction demand and kinetic energy should perhaps be considered. [28]

British Pendulum Test (BPT)

The British pendulum test measures skid resistance of a pavement surface (typically within the wheel tracks) using a pendulum of known mass,rotating around a vertical spindle. When released from a horizontal position, the pendulum head strikes the pavement surface being tested at a constant velocity. [29] The distance travelled by the pendulum after striking the surface determines the friction resistance and is reported by a scale directly attached to the test apparatus. The result of the BPT is a calculatedskid resistance value between zero and 100 (zero being a no friction condition). For more information on this test approach, the reader should consult ASTM (formerly the American Society for Testing and Materials) Standard E303 - 93(2008): *Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester*. [30]

Dynamic Friction Tester (DFT)

The dynamic friction tester is a device that measures friction using a horizontal disk fitted with three spring-loaded rubber sliders that are in contact with a paved surface. The disk's rotational speed decreases due to the friction generated between the sliders and a wet pavement (wetted by a component of the apparatus).[21] The torque generated by the sliding is measured during the spin and used to calculate friction as a function of speed. Grip measurements are typically collected at speeds of 12, 25, 37 and 50 miles per hour.[21] The result of the DFT is a calculation of the friction coefficient of a surface, reported as a value between zero and one (zero being a no friction condition). For more information on this test approach, the reader should consult ASTM Standard E1911-09ae1: *Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester*. [31]

Griptester

A griptester is a device that measures continuous skid resistance through a fixed slip device, where a test tire is connected to a trailer wheel axle by a chain, allowing the system to measure the rotational resistance of a constantly slipping smooth tire.[21] The device reports a grip number, which is a measure of resistance obtained by the device in terms of the friction force observed between a partially locked wheel and the wet pavement that ranges between zero and 100 (zero being a no friction condition). For more information on this test approach, the reader should consult ASTM Standard E2340/E2340M-11: *Standard Test Method for Measuring the Skid Resistance of Pavements and Other Trafficked Surfaces Using a Continuous Reading, Fixed-Slip Technique*.[32]

Locked Wheel Skid Trailer

This device is the one most commonly used for friction measurement in the U.S, particularly for HFSTs. The locked wheel skid trailer is a device that records the steady state friction force of a locked wheel on a wet pavement as the wheel slides along at constant speed, with skid resistance reported as a friction or skid number (typically called a friction number, although the terms are interchangeable).[27] The friction number is reported in a range between zero and 100 (zero being a no friction condition). The measurements can be collected by a vehicle towing the trailer in the travel lane without closing the roadway. It should be noted that skid trailers do not easily measure friction in curves, and alternative approaches to friction measurements may need to be considered depending on the characteristics of a particular site. For more information on this test approach, the reader should consult ASTM Standard E274/E274M-11: *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*.[33] Table 1 provides guidance related to friction numbers for normal (not HFST) pavements for reference purposes.

Locked wheel skid trailers are the most commonly used friction measurement device (Image: International Cybernetics)

Table 1: Typical friction numbers (Noyce, et al. [34])

Skid Number	Comments
<30	Take measures to correct
≥30	Acceptable for low volume roads
31 – 34	Monitor pavement frequently
≥35	Acceptable for heavily traveled roads

Texture Measurement Devices

Texture depth is another critical aspect of producing a High Friction Surface. The texture of an aggregate takes on two dimensions: macrotexture and microtexture. These aspects of an aggregate contribute to its friction characteristics. Different devices can be used to measure the characteristics of an aggregate and these are discussed in the following sections.

Circular Track Meter

The circular track meter is a laser displacement sensor that measures the mean profile depth and root mean square values of the macrotexture profiles of a pavement.[27] In other words, it is measuring the roughness of the aggregates based on the characteristics of their size and shape. For more information on this test approach, the reader should consult ASTM E2157: *Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter*.[35]

Sand Patch Method

The sand patch method is a test method that spreads a known volume of glass beads in a circle on a cleaned pavement surface, measuring the diameter of the resultant circle.[11] The volume of beads divided by the area of the circle determines the mean texture depth (typically reported in millimeters). For more information on this test approach, the reader should consult ASTM E965-96(2006): *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique*.[36]

Outflow meter

The outflow meter is a test method that measures water drainage rates through surface texture and interior voids, indicating the hydroplaning potential of the surface by relating the escape time of water beneath a moving tire.[11] The device consists of a cylinder with a rubber ring on the bottom and an open top, equipped with sensors to measure the time for a known volume of water to pass into the pavement. For more information on this test approach, the reader should consult ASTM E2380/E2380M-09: *Standard Test Method for Measuring Pavement Texture Drainage Using an Outflow Meter*.[37]

Other Considerations

In addition to the different aggregate and binder materials that comprise a High Friction Surface and the tests to characterize that surface before and after installation, other aspects related to HFSTs should be considered. For example, the application of a binder is just as important as its selection -- particularly the way that the binder is applied to the pavement surface. When manually applying a binder, care should be taken to follow manufacturer's instructions and use the proper equipment, such as a squeegee rather than a paint roller. This will result in a proper binder thickness and prevent the binder from wicking into the aggregate when it is spread.

Different mechanical means can be used to install HFST (Image: David Merritt)

When considering a binder, some testing aspects to consider include its tensile strength, tensile elongation, pull up test results, hardness, and abrasion resistance.[25] While these may not be directly reported in product literature, they may be items that an agency should ask a manufacturer about when considering a particular product. This is particularly true for agencies that have developed or are following product and installation specifications for HFSTs.

Once installed, it is helpful to monitor the performance of an HFST over time. For example, a rule of thumb might be to take friction measurements after one year of service or when wear or surface peeling is observed.[25] Once a surface is installed, a locked wheel friction tester is preferable for taking measurements. Of course, the performance of this device on curves is once again an aspect that must be considered.

Wear and surface peeling (delamination) are two common issues facing HFSTs once installed. Wear is directly related to a selected aggregate's characteristics and the environment where the HFST is installed. A particular aggregate may perform adequately in a southern climate where it is not exposed to snow plowing, but it may wear quickly when installed in a northern climate. Delamination is another potential issue for HFSTs. It may occur as the result of a surface binder being installed on a dirty or wet surface, on a pavement that is in poor general condition (cracking, potholes, etc.), under incorrect temperatures or because of an improper mixing of binder components (improper ratios, for example). Regardless of the cause, delamination results in a compromised High Friction Surface that will not meet its intent and must be corrected as soon as possible. ■

Part 4: Resources and References

This section provides resources that the reader is encouraged to consult to learn more about High Friction Surfaces. It includes contacts at the federal and state level, as well as websites that the reader may visit to obtain more information on specific projects.

Federal Contacts

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West Virginia Department of Transportation

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Wisconsin Department of Transportation

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Websites

High Friction Roads: http://www.highfrictionroads.com/

ATSSA High Friction Surface Treatments:
http://www.highfrictionsurface.net

FHWA Every Day Counts Initiative:
http://www.fhwa.dot.gov/everydaycounts/

National Center for Asphalt Technology (NCAT):
http://www.ncat.us/

Road Surface Treatments Association (United Kingdom):
http://www.rsta-uk.org/

Part 5: Key Terms, Definitions and Reports

This section provides a summary of different HFST terms and their definitions. This glossary is provided for reader familiarization with the different terms they may encounter during the course of considering HFSTs for a particular application. A brief summary of research reports pertaining to HFSTs tested throughout the U.S. is also provided. Finally, a list of the references cited throughout this document is presented. The reader is also encouraged to visit the ATSSA High Friction Surface website for further information and details at http://www.highfrictionsurface.net/.

Terms

Acrylic-Resin – A two-component binder system in which the aggregate contains a curing agent that was designed to offer a faster curing time than epoxy-resin.

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

Calcined Bauxite – An aggregate derived from aluminum ore that, when heated to 2900° F, increases in physical hardness and stability, resulting in polished stone values in the upper 60s and lower 70s.[21]

Cost-Benefit Analysis – The process employed to calculate a cost-benefit ratio, which shows the value of benefits achieved for every dollar of cost incurred on an item. Cost-benefit ratios greater than 1.0 are generally desired. This may also be referred to as a benefit-cost ratio.

Emery – A rock containing corundum (aluminum oxide) and iron oxide that has been used as an abrasive in products such as sandpaper.

Epoxy-Resin – A 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).[21]

Friction – The force resisting the motion of objects against one another.

Friction Number (FN) – A number calculated using measurements from a locked wheel testing device that represents the average coefficient of friction measured across a test interval. The reporting values range from 0 to 100, with 0 representing no friction and 100 representing complete friction. This is also referred to as a Skid Number (SN). A friction number is calculated as follows:

$$FN(V) = 100\mu = 100\times(F/W)$$

Where:

$FN(V)$ = Velocity of the test tire, mi/hr.

μ = Coefficient of friction.

F = Tractive horizontal force applied to the tire, lb.

W = Vertical load applied to the tire, lb.[11]

In the case of friction numbers, studies have indicated that numbers less than 35 to 40 (measured at 40 mph using a ribbed tire) are associated with increased crashes. Note that this does not take into account the additional friction needs of vehicles in horizontal curves.[11] Friction numbervalues are generally designated by the speed at which the test is conducted and by the type of tire used in the test. For example, *FN40R* = 36 indicates a friction number of 36, as measured at a test speed of 40 mph (64 km/hr) and with a ribbed (*R*) tire.[11]

Gradation – The particle size distribution of aggregates.

Granite – A combination of quartz and potassium feldspar, its mineral composition and interlocking crystals results in hardness and abrasion resistance, producing polished stone values greater than 62.[21]

High Friction Surface Treatments (HFST) – Pavement surface treatments that are composed of tough, polish- and abrasion-resistant aggregates bonded to the pavement surface using a resin material (epoxy, acrylic, etc.). They restore or enhance the skid resistance and frictional characteristics of a pavement where the original pavement surface has lost these characteristics due to polishing or loss of aggregate.

Macrotexture – Pavement surface deviations with wave lengths between 0.5 mm and 50 mm. This is the surface roughness of an aggregate defined by the mixture properties (shape, size, and gradation).[11]

Microtexture – Pavement surface deviations with wavelengths less than 0.5 mm.[15] This is the microscopic roughness quality of an aggregate.[11]

Mean profile depth – A mean (average) measure of macrotexture where a pavement surface is divided into given base lengths which are analyzed and the mean segment depths averaged to give a value for a specific length of profile.[38]

Polished stone value – A measure of resistance to the polishing action of vehicle tires under conditions similar to those occurring on the surface of a road.[39] Higher PSV values indicate aggregate that is more resistant to polishing.

Polyester-Resin – Polyester-resin is a multi-component binder system consisting of a resin for flow and polyester for hardening.

Polyurethane-Resin – A multi-component binder system consisting of a resin for flow and polyurethane for hardening, which was designed for faster curing times.[21]

Root mean square – A statistical measure of the magnitude of a varying quantity.

Rosin-Ester – A thermoplastic binder that is applied to the aggregate during a manufacturing process. The dry aggregate is heated on site for placement on the pavement surface, typically with a handheld box.[21]

Silica – An oxide in the form of sandstone, silica sand, or quartzite that possesses abrasion resistance and high thermal stability.

Skid Number (SN) – A value representing the skid of a surface obtained from using the locked-wheel trailer.[15] Calculated as the force required to slide the locked test tire at a given speed divided by the effective wheel load and multiplied by 100.[21] Also referred to as a Friction Number (FN).

Skid Resistance – The capacity of a surface to prevent a loss of traction.

Skid Resistance Value – A measure of skid from the actual road surface that is dependent on the polished stone value of the aggregate and the macrotexture of the surface.[15]

Steel Slag – An impurity 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.[21]

Taconite – An iron bearing sedimentary rock that contains quartz, chert or carbonate.

High Friction Surface Treatment Reports and Literature

The use of High Friction Surface is not new and has shown to be effective over time, both internationally and in the U.S. The following sections provide a summary of the various reports and literature that are available discussing the testing and effectiveness of High Friction Surface Treatments in the U.S.

Evaluation of a High Friction Pavement Surface Treatment (Florida)

A number of state transportation departments began experimenting with high friction surfacing to address speed related crashes. Reddy, et al. in *Evaluation of Innovative Safety Treatments* and *Evaluation of a High Friction Pavement Surface Treatment*, evaluated the use of calcined bauxite installed by the Florida DOT (FDOT) to reduce run-off-the-road crashes on a 300 foot section of on-ramp to Interstate 75. [40,41] The site was selected based on a history of 12 run-off-the-road crashes between 2002 and 2004. In the 12 month period following installation in 2006, the site experienced only 2 crashes. However, due to the limited post-installation time period there is insufficient crash data available for statistical analysis. Instead, surrogate measures were used to better understand the impact and effects of calcined bauxite.

Skid tests performed by FDOT indicated the friction number of the pavement was much higher following the calcined bauxite installation. Prior to installation, the friction number at the site was 35, while after installation of the HFST, the measured friction number was 104. [1] Spot speed studies were also performed before and after installation. Under dry-pavement conditions, mean speeds decreased by an average of 3.72 mph. Under wet-pavement conditions, mean speeds decreased by an average of 2.62 mph. These drops in mean speeds were attributed to the difference in pavement texture and sound following the installation of the HFST, which prompted drivers to slow down.

Field Performance of High Friction Surfaces (Virginia)

Research sponsored by the Federal Highway Administration (FHWA) and Virginia DOT examined the durability of High Friction Surface treatments. Izeppi, et al., in *Review of High-Surface Friction Technologies – Constructability and Field Performance* and *Field Performance of High Friction Surfaces*, evaluated the field performance of High Friction Surfaces texture properties using a Dynamic Friction Tester, a CircularTrack Meter (CTMeter) and a GripTester (testing procedures are discussed earlier in this document).[21, 42] A simplified cost-benefit analysis of different products was also conducted. The HFST products identified by the researchers included granite/bauxite, a flexible polymer-aggregate system, steel slag, an epoxy-aggregate system, and calcined bauxite. During the course of field evaluation, the researchers observed that there was no correlation between texture and friction performance, contrary to what previous studies had claimed.[21] This indicated greater emphasis should be placed on material selection than on texture depth. Overall, HFSTs provided high initial friction levels and could be expected to retain high levels for at least 10 years of service if properly installed. Cost-benefit ratios ranged between 2.23 and 8.45, indicating a positive return on investment for each dollar spent on the treatment.

High Friction Surfaces for Horizontal Curves (Texas)

The Texas Transportation Institute (TTI) examined the use of HFSTs to improve safety on horizontal curves in *Using High Friction Surface Treatments to Improve Safety at Horizontal Curves*. [43] While the work was primarily an overview of past research findings, it did provide a comprehensive summary of the value of HFSTs. This included a summary of observed crash reductions from past installations (those summarized elsewhere in this section), with the researchers concluding that HFSTs offered the potential to reduce all crashes by 20 to 30 percent and wet-weather crashes by 50 percent.[43] Based on past observations of crash reductions, the researchers estimated the financial benefits of HFSTs. Using FHWA's average cost of crashes of $158,177 from the KABCO scale (K=Killed; A=Incapacitating Injury; B=Non-Incapacitating Injury; C=Possible Injury; O=No Injury), if a 20 percent reduction in crashes over the course of one year was achieved, crash savings of between $31,635 and $221,448 could be produced. It should be noted that this was for observed-crash frequencies of between 1 and 7, respectively.[43] For longer timeframes and higher expected crash reductions, these figures topped $2,000,000, easily exceeding the cost of most HFST installations. Finally, the researchers provided recommended distances upstream of the point of curvature to begin HFST installations based on approach and curve speed limits. These distances ranged from 35 to 360 feet, depending on the respective speed limits at a site.[43]

1 A friction number greater than 100 was measured in this case as a result of adjustments made for temperature and skid.

Evaluation of Calcined Bauxite High Friction Surfaces (Washington)

Anderson, et al. are currently (2012) evaluating the calcined bauxite with epoxy used on interchange ramps in Washington for the Washington State Department of Transportation. The work seeks to measure the long-term performance and crash reductions of the treatment, and to develop guidance for future applications in Washington. Prior to HFST application, the roadway had friction numbers ranging between 43.2 and 52.0 as cited in the report *Evaluation of Tyregrip® High-Friction Surfacing*. [44] Initial applications of the HFST did not produce the expected increase in friction numbers. This was attributed to difficulties in evenly applying the selected binder. A third application was successful, producing friction numbers ranging between 75.7 and 79.3. At the time this document was being written, the long-term crash reduction and material performance evaluations remained ongoing.

Evaluation of Steel Slag (Wisconsin)

Bischoff, in *Investigative Study of the Italgrip™ System*, examined whether HFST was suitable, durable, and cost-effective for the Wisconsin Department of Transportation (WisDOT) in 2008. [45] Initial tests conducted before and after installation showed that friction numbers at the application sites increased on average from 42.9 to 72.6. After 5 years in service, additional measurements found an average friction number of 59.4 for the application sites-- still significantly greater than the friction number present before the treatments were installed. Accidents at the site were observed to decrease by 93 percent following installation. Finally, the results indicated that four mm aggregates produced better friction levels over time compared to three mm aggregates. In terms of cost, the product was found to be comparable to other alternatives available on the market.

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