Recommendations Report for High Friction Surface Treatments

Candidate Sites, Materials, and Construction

FHWA Safety Program

U.S. Department of Transportation
Federal Highway Administration

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16. Abstract

High friction surface treatment (HFST) is a safety-first pavement treatment intended to restore and maintain pavement friction to reduce crashes. The cost of HFST is high compared to typical maintenance treatments; however, HFST is highly effective at reducing wet-weather and run-off road crashes. Improvement in the state of the practice can promote more widespread deployment resulting in more crash reductions and a longer lasting safety countermeasure. This document provides recommendations on the identification of candidate sites, materials selection, and proper construction practices. Much of this guidance is derived from two documents: "High Friction Surface Treatment Curve Selection and Installation Guide," by Atkinson et. al. in 2016, funded by FHWA; and "High-Friction Surface Treatment Guidelines: Project Selection, Materials, and Construction" by Wilson and Holzschuher in 2016, funded by FDOT and FHWA. Relevant recommendations from the recently completed Long-Term Performance Monitoring Study were also incorporated into this document.

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OVERVIEW

High friction surface treatment (HFST) is a safety-first pavement treatment intended to restore and maintain pavement friction to reduce crashes (FIGURE 1). It is a thin layer of high-quality polish-resistant aggregate bonded to the pavement surface with a polymer resin binder.

Photo courtesy of FDOT (*2*)

FIGURE 1 – High Friction Surface Treatment.

The cost of HFST is high compared to typical maintenance projects (unit cost is typically around $25 to $35/sy). Hence, there is incentive to improve the state of the practice to promote more widespread deployment resulting in more crash reductions and to provide a longer lasting safety countermeasure.

The purpose of this document is to provide recommendations on the identification of:

1) candidate sites,
2) proper materials selection, and
3) construction practices.

Many of the recommendations are derived from two documents: "High Friction Surface Treatment Curve Selection and Installation Guide," by Atkinson et. al. in 2016, funded by FHWA (*3*); and "High-Friction Surface Treatment Guidelines: Project Selection, Materials, and Construction" by Wilson and Holzschuher in 2016, funded by FDOT and FHWA (*2*). The relevant recommendations from the recently completed Long-Term Performance Monitoring Study are also incorporated into this document.

CANDIDATE SITES

What to Look for and Avoid

HFST is, first and foremost, a safety treatment used specifically to reduce run-off-the-road and other wet-weather crashes. 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 where stopping sight distance is limited, though the measured safety benefit in these scenarios is still being studied. Other scenarios include approaches to rail crossings, school crossings, and tolling areas, though safety performance data was not available for these locations.

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

The safety-related site criteria that agencies use to assess the appropriateness of an HFST application are locations with:

- High crash frequency.
- Low pavement friction.
- Large speed differential and geometric factors.
- Failure of previously installed lower-cost treatments.

From a materials longevity perspective, agencies also consider:

- Existing pavement condition.

Each of these topics are discussed in this section followed by a guidance summary on where and where *not* to apply HFST in TABLE 1.

High Crash Frequency

The first criterion is a history of high crash frequency. Various network screening methods are outlined in Chapter 4 of the AASHTO Highway Safety Manual (HSM). The HSM provides a network screening process to identify and rank sites on their potential for reducing crash frequency and/or severity. There are five steps in the process: establish the focus of network screening, identify the network and reference population, select the performance measures, select screening method, and screen and evaluate the results. The network screening process as outlined in the HSM is very applicable to identifying sites with the potential for crash reduction with HFST treatment.

The most straight-forward approach is obtaining the total reported crashes per year at a given location or calculating the average crash rate over a number of years (average crash frequency). A more robust method, described in the HSM, is used to estimate expected average crash frequency by using a combination of observed crashes and predicted crashes from carefully calibrated safety performance functions.

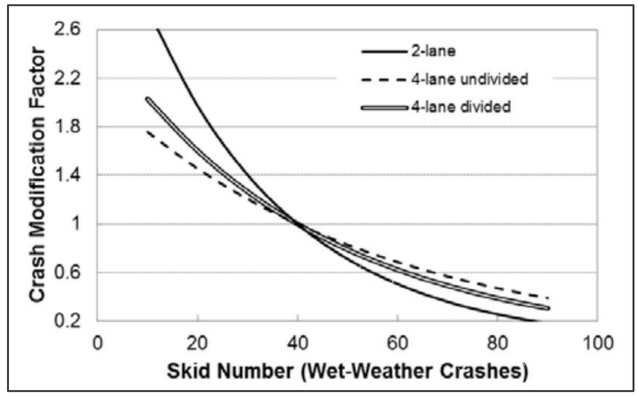
Agencies may focus on specific crash types when identifying candidate sites. Wet-weather crashes, for example, are more indicative of a friction deficiency than total crashes. Agencies may even normalize the wet-weather crash frequency by the percent wet-time, which would highlight how much the wet-weather crashes might be overrepresented in that location. Focusing on run-off-road crashes is also recommended. For example, in 2009, the Kentucky Transportation Cabinet identified over 150 sites with high frequency of crashes, then selected the 30 sites with the highest run-off-road crash rates with a wet/dry crash ratio greater than 50 percent (*4*).

Another consideration is for the crash severity. A property-damage-only crash has a much smaller impact socially and economically than an injury or fatality crash. Agencies may prioritize sites with higher crash severities over other sites to maximize their safety investment. FHWA developed a guide entitled “Crash Costs for Highway Safety Analysis”, which proposed national-level crash costs, as well as provided procedures and a spreadsheet tool to assist states in calculating state-specific values, and update costs over time. The guide and supplemental spreadsheet are available here:

https://safety.fhwa.dot.gov/hsip/planning.cfm

Low Pavement Friction

Wet-weather crashes are largely related to friction deficiencies on the pavement. A study by Pratt et. al. with the Texas A&M Transportation Institute developed crash modification factors that include the effect of skid resistance (*5*). The authors found a significant increase in crashes as the skid number (SN50S) decreased (FIGURE 2). On average, wet-weather run-off-road crashes doubled as the skid number dropped from 40 to 20, and crashes were halved as the skid number increased from 40 to 80.



Graph courtesy of TxDOT (*5*)

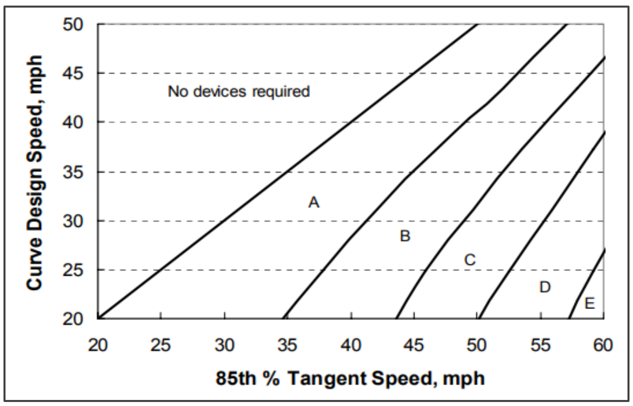
FIGURE 2 – Skid Number Crash Modification Factors for Wet-Weather Crashes.

State agencies with pavement management systems routinely measure the skid number along the roadway network. The skid numbers are often incorporated into decision-making tools for maintenance funds allocation. Skid number, however, is not collected along horizontal curves in most agencies due to the inability of traditional friction measurement devices to operate on horizontal curves without traffic interruption. Instead, skid number is measured at tangent sections ahead of the curve to infer the skid number along the curve section. After a candidate site is identified based on crash frequency, most agencies then collect friction data specifically on the curve. If interested in routinely testing skid on horizontal curves, an agency could use a continuous friction measurement device like a Side-Force Coefficient Routine Investigation Machine (SCRIM) or a Grip Tester. A macrotexture measurement is also important for assessing wet-weather safety.

When the high-crash site skid resistance is sub-standard, the agency decision-makers should explore pavement treatment options to restore or enhance the site friction and reduce the crash rate. Amongst all the pavement treatment solutions, HFST is well-suited when the existing skid numbers are typical for the area but still insufficient to meet the friction demand, or when the agency is concerned traditional materials will not adequately maintain good skid performance due to high friction demand.

Large Speed Differential and Geometric Factors

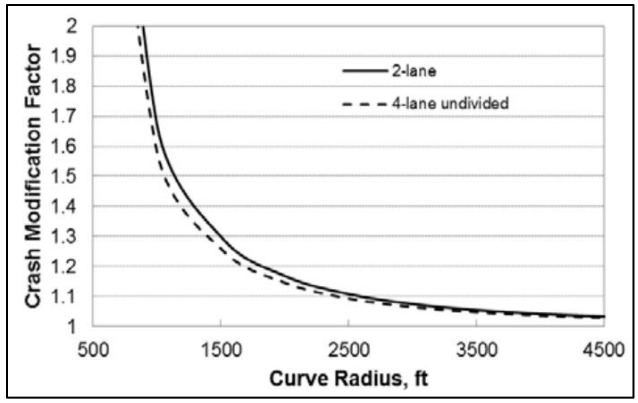
The speed differential in a horizontal curve is defined as the difference between the posted speed limit for the tangential roadway segment and the advisory speed for the curve. The greater the differential, the faster a driver needs to decelerate to safely maneuver through the curve without losing control, and the greater the friction demand will be. Herrstedt and Greibe, from Denmark, evaluated curve risk based on the energy required to change a vehicles speed going into a curve (*6*). They defined curve risk categories based on the 85th percentile tangent speed and the curve design speed (FIGURE 3). HFST can provide additional friction to the motorist when rapid deceleration is required, such as in categories D and E.



Graph courtesy of Traffic Engineering and Control (*6*)

FIGURE 3 – Curve Risk Categories.

The curve radius is a significant factor in setting curve advisory speeds. Pratt et al. related a small curve radius with an increase in crash frequency (*5*). The crash rate increases exponentially as curve radius decreases (FIGURE 4). In the same study, Pratt et al. developed the Texas Curve Margin of Safety spreadsheet program. The Texas Department of Transportation uses this program to compare the friction margin of safety at three key points along a curve's length, which illustrates how the greatest friction enhancement is needed at the beginning and mid-points of the curve.



Graph courtesy of TxDOT (*5*)

FIGURE 4 – Crash Modification Factor as a Function of Curve Radius.

By focusing on wet-weather and run-off-road crashes, the agency will naturally filter down to tight-radius horizontal curves and loop-ramps (FIGURE 5). Sites might also include high-approach speed intersections, and sensitive locations with high pedestrian volumes like in-front of public schools.

Photo courtesy of FDOT (*1*)

FIGURE 5 – HFST on Tight Curve Before Intersection.

Failure of Prior Low-Cost Treatments

Outside of a geometric redesign, HFST is a comparatively expensive treatment for crash reduction. Agencies often employ different low-cost treatments first, such as:

- Horizontal alignment signs (see MUTCD).
- Center line and edge line pavement markings.
- On-pavement or vertical roadside delineators.
- Advanced curve warning pavement markings.
- Audible milled-in rumble strips.
- Guardrail.

Signs, markings, and rumble strips require the driver to first observe and then react to avoid a crash. A guardrail does not prevent crashes but mitigates the crash severity. HFST, on the other hand, is a passive countermeasure that is always acting to help the driver stay on the road as they navigate a curve. If the other countermeasures fail to reduce crashes to an acceptable level, HFST may be the next most cost-effective option.

Existing Pavement Condition and Maintenance

HFST should only be used on structurally sound pavements requiring minimal surface repair. If the pavement surface is in marginal or poor condition, or has any significant non-structural defects, the agency should repair or replace the layer. HFST applications on weak and aged pavement can actually accelerate pavement failure. For asphalt pavement, mill out the deteriorated layer and replace it with an asphalt inlay. For concrete pavement, repair or replace distressed slabs. The types of surface defects that would require surface repair/replacement include:

ASPHALT PAVEMENT

- Moderate-severity cracking.
- Rutting greater than 0.25 inches.
- Raveling.
- Flushed sealcoat.

CONCRETE PAVEMENT

- Moderate or severe:
  - Transverse cracking.
  - Longitudinal cracking.
  - Spalling.
  - Corner cracking.
- Shattered slab in more than three pieces.

The agency must still ensure that the surface distress is not related to larger structural problems through a forensics investigation. A pavement engineer could:

- Review the as-built pavement design.
- Collect field cores to assess:
  - Cracking patterns.
  - Debonding.
  - Deeper layer deterioration.
- Measure deflections with non-destructive falling-weight equipment.

If there is a structural problem, the pavement would require extensive rehabilitation, at which time realigning the curve or correcting the superelevation may be more cost effective to improve safety.

HFST applications over open-graded pavement present unique challenges which may discourage this approach. Because of the high voids content, open-graded asphalt pavement requires significantly more resin binder and often a two-layer application. This thick application may increase problems with thermal incompatibility between the HFST and the asphalt. Moisture may also get trapped under the HFST, causing stripping and substrate failure. Due to several premature failures, the Florida Department of Transportation does not allow placement directly on open-graded friction course (*1*). In Florida, existing open-graded layers need to be milled and inlaid with dense-graded asphalt before applying HFST. Other agencies may consider a similar approach. In contrast, applications over open-graded pavement in California have generally been successful (7).

May be placed over dense-graded asphalt pavement and rigid pavement. Applications on open-graded pavement present unique challenges. Agencies may opt to mill and inlay with dense-graded asphalt before applying HFST.

Thin polymer overlays are a common concrete bridge deck preservation treatment. The materials and application of this treatment and HFST are very similar, except that HFST must have high-friction calcined bauxite aggregate and may warrant slightly different resin binder properties. Therefore, the agency may consider applying an HFST treatment in lieu of a traditional thin polymer overlay for bridge deck treatment if safety is a major concern.

Other important maintenance operations could govern the use of HFST. Agency decision-makers should communicate with the maintenance office to coordinate the timing of other resurfacing operations around the candidate site. An agency may delay HFST construction if the road is scheduled for a mill and inlay, or the maintenance operation could be expedited.

Based on interviews with northern region states, snow removal operations through ploughing and deicing have no effect on HFST performance.

TABLE 1 – General Recommendations on Candidate Pavements.

Scenario	Where to Use HFST	Where NOT to Use HFST
Roadway Applications	• Locations with a high crash rate related to a friction deficiency. (i.e. Run-off-the-road crashes, and wet-weather crashes) • On rural horizontal curves where drivers tend to drive too fast for the road conditions and super elevations are inadequate. • On tight-radius freeway loop ramps. • At a downgrade signalized or stop controlled intersection approaches. • On roadways that may need geometric corrections to meet the friction demand, but the agency lacks the funding. • On concrete pavements and bridge decks where both preservation and safety are a concern.	• If less-expensive traffic control devices (chevrons, curve-warning signs, etc.) are expected to adequately reduce crashes. • Tangent sections where crashes are related to driver errors. • Following the curve beyond the PT or more than 1,000 ft before a curve. (No benefit here.) • As a preventative maintenance treatment on asphalt pavement.
Pavement Condition	• Dense-graded asphalt or concrete. • Pavement condition rating of “Good” and higher. • Polished surface. • Few low-severity cracks. Very few cracks greater than 0.25 inch Wide. • Minor rutting ≤ 0.25 inch. • No structural damage.	• Caution against open-graded asphalt without previous experience or appropriate pre-construction measures. • Asphalt pavements with 6+ percent of cracking in or outside the wheel paths. • Widespread rutting > 0.25 inch deep. • Raveling surface. • Bleeding pavement. • Areas where layer debonding or subsurface stripping is suspected. (Verify with coring and other pavement forensics.) • Concrete single slab with moderate or severe distress, patching, or shattered in more than 3 pieces.

Site Verification

In addition to the factors mentioned above, once candidate sites have been identified, the agency should do a thorough, in-person, review of the site conditions to verify that the site is still a suitable candidate for HFST. Much of the following check list was recommended by Atkinson et. al. (*3*):

- ☑ **Physically Locate Crashes.**
- ☑ **Record Roadway and Traffic Conditions.**
  - Presence of skid marks.
  - Damaged roadside barriers and other objects.
  - Presence and condition of previous low-cost countermeasures.
  - Superelevation if applicable.
  - Driver speed and general behavior.
  - Speed advisory measurements.
  - Point of curvature and point of tangent.
  - Horizontal and vertical sight distances.
  - Intersections near or within the curve.
  - Heavy vehicle use (winter chains).
  - Speed differentials.
- ☑ **Determine HFST Start and End Points.**
  - Start at or before where vehicles start to brake (observe brake lights).
  - Additional guidance suggested by Brimley and Carlson with Texas A&M Transportation Institute (8). The recommended starting point for HFST is based on the curve speed differential. (See Table 5.)
- ☑ **Conduct a Friction Test.**
- ☑ **Check Pavement Condition.**
- ☑ **Screening Sample Questions.**
  - Are the collisions related to physical conditions of the location?
  - Are existing signs, delineation, and pavement markings accomplishing their purpose?
  - Are there any specific traffic movements to be prohibited or favored?
  - Is special nighttime enhancement needed (i.e. lighting, delineation, and sign visibility)?
  - Are selective enforcement or maintenance procedures needed?
  - Is parking contributing to collisions?
  - Are there adequate advance guide signs so that motorists may choose proper lanes and directions well in advance of need?

MATERIALS

Quality Counts

HFST is composed of hard, polish and abrasion-resistance aggregate bonded to the pavement using a polymer resin binder. These components are detailed in this section.

High-Friction Aggregate

FHWA considers calcined bauxite as the aggregate of choice for use in HFST applications. Other aggregates like flint, basalt, and granite may only be used for preventative maintenance applications that are not safety-critical.

Calcined bauxite is the aggregate of choice.

The aggregate gradation is a very fine gravel (FIGURE 6). The maximum size is 3 to 4 mm and the minimum size is about 1 mm (95% passing No. 6 sieve and 5% passing No. 16). If a larger gradation were used, the HFST would require more resin binder without any added safety benefits.

Photo courtesy of FDOT (*1*)

FIGURE 6 – Calcined Bauxite Crushed & Graded.

The critical aggregate properties are a low aggregate abrasion value (20% max) and a high aluminum oxide (Al_2O_3) content (usually 87% minimum).

In storage and transportation, the aggregates MUST be stay clean and dry. Any moisture in the aggregate could result in a poor bond and eventual aggregate loss.

Where does calcined bauxite come from?

Calcined bauxite is an imported product in the United States, though there is one domestic source at the time of this report. Raw bauxite is primarily mined to produce aluminum. The leading bauxite producers are Australia, China, Brazil, India, Guinea, and Jamaica. When raw bauxite is heated to high temperatures (1,000 to 1,500°C), it undergoes calcination, increasing in physical hardness. Calcined bauxite is then crushed to size, washed, dried, and bagged before shipping to regional business like the HFST installer.

Polymer Resin Binder

The role of the resin binder system is to hold the high friction aggregate in place. Because traditional bituminous binders are soft (especially in the summer), they are not suitable under the extreme shear forces inherent to curves and approaches. A polymer resin binder system with high bond strength and other key mechanical properties is vital for the longevity of the HFST installation.

Polymer resin binders are multi-component systems that react chemically upon mixing and throughout the curing phase. The resin binder system includes a base resin, a curing agent, and often additives to help with meeting flexibility, strength, and cure time requirements. The critical characteristics of the resin binder for HFST applications are summarized in TABLE 2.

TABLE 2 – Key Characteristics of Polymer Resin Binder.

Characteristic	Importance
Viscosity	Spreadable without being too runny
Gel Time	Adequate time to mix and apply
Cure Rate	Need to open to traffic quickly
Strength	Must not crush or get torn apart under traffic
Hardness	Must not yield under traffic
Elongation	Needs flexibility to resist cracking
Low Water Absorption	Resistant to moisture-related damage
Adhesive Strength	Bond to the pavement and to the aggregate

There most common HFST resin binders are:

- **Epoxy-Resin** - Good durability and bond strength. Short to long curing times, depending on temperature. Cannot be applied at temperatures below 60°F. May be susceptible to UV aging.
- **Polyester-Resin** - Good durability and bond strength. Short to long curing times depending on additive use. May be applied at lower temperatures. Resistant to UV aging.
- **Polyurethane-Resin** – Good durability and bond strength. Variable curing time. May be applied at lower temperatures. Resistant to UV aging.

Methyl methacrylate resin and other polymer binders are not widely accepted due to cost or durability concerns. The specific properties for a given resin binder can vary from one formulation to another. In time, new products are likely to emerge with superior properties for constructability and long-term performance. Also, note that some products produce caustic fumes or contain certain components that, if improperly handled, may cause irritation during application.

The HFST installer will likely prefer a certain product and their installation equipment will be calibrated accordingly. Their equipment may be adaptable to different resin-binder types.

Material Certifications

The proposed aggregate and resin binder materials need to be certified by the producers. The certifications are typically acceptable for 90 days to 12 months and whenever a new source or batch is used.

CONSTRUCTION

Tips for Success

If installed properly, HFST could last for at least 10 years with superior skid resistance. The success of HFST is dependent on proper surface preparation, mixing/application techniques, and service conditions. Overlooking any of these considerations could jeopardize the longevity of the installation.

The success of HFST is dependent on proper surface preparation and mixing/application techniques.

Test Strip

It is recommended that the contractor place a test strip a minimum of 20-ft long before full-scale application. Most often this is the same day as full construction. The contractor will have a chance to identify and fix problems, and of equal importance, the agency inspector will become more familiar with the process and potential issues. If the contractor is prequalified and the inspector has overseen several successful projects, the test strip may be waived.

Both parties should identify the following:

- **Surface preparation** - Adequate sweeping and air-washing to produce a clean, dry, dust-free surface. On concrete, correct shot blasting techniques (and subsequent cleaning) to produce the specified texture (FIGURE 8).
- **Resin binder proportioning** – Equipment settings to achieve the correct binder proportioning. Generally, the gel-time test is not sensitive enough to misproportioning to substitute for proper maintenance and calibration of the equipment. Still, this simple test does have a place to ensure against major mixing problems. A 2-oz sample in a small paper cup will typically gel within 10 to 25 minutes (temperature dependent).
- **Resin binder application rate** – Equipment settings to achieve correct resin binder thickness. In production, the application rate will be measured by material weights and flow rates in the equipment. A wet film thickness gauge (FIGURE 7) may be helpful to verify the flow rate before spreading aggregate; however, the proper use of the gauge is very subjective on uneven pavement surfaces.

Photo courtesy of TTI

FIGURE 7 – Wet Film Thickness Gauge.

- **Cure time** – The initial cure time when traffic is permitted. Time will vary by product, ambient temperature, and surface temperature.

Surface Preparation

Without adequate surface preparation, the HFST is liable to de-bonded and delaminate, especially on concrete. This issue is often caused by changes in temperature. HFST wants to expand and contract much more than asphalt or concrete and will pop-off under thermal stress if the bond is insufficient.

On asphalt pavements, first clean with a mechanical sweeper or vacuum sweeper, then follow-up with a high-pressure air wash to dry. Experience has shown that sweepers alone can leave a lot of dust on the road. Vacuum sweepers, when not properly maintained, can even make the dust situation *worse*. Follow these procedures for air washing:

- Use dry compressed air
- Use a minimum of 180 cfm
- Compressor oil traps must be functioning (or compressor may start misting oil!)
- Maintain air lance perpendicular and within 12 inches of the surface.

On concrete pavement, the surface first needs to be shot blasted to remove curing compounds, loosely bonded mortar, surface carbonation, etc.

Sand blasting will be inadequate. The shot blasted surface should again be cleaned with a sweeper and a high-pressure air wash.

Don’t rush shot blasting. The rate that the shot-blasting equipment moves will affect the final surface profile of the pavement. A fast brush-off blasting will not be adequate. The final surface must have a minimum texture of Concrete Surface Profile (CSP) 5 as specified by the International Concrete Repair Institute (ICRI). (See FIGURE 8.) The texture should not go beyond CSP 7. Reference CSP chips can be purchased online directly from the ICRI website.

Don’t rush shot blasting.

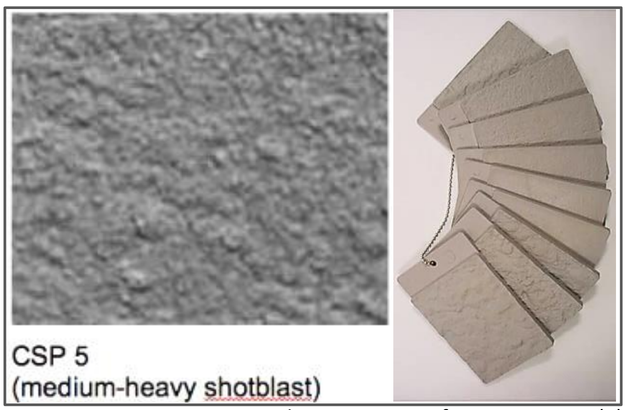


Photo courtesy of KTA-Tator, Inc (9)

FIGURE 8 – Concrete Surface Profiles.

Cover utilities, drains, and curbs to protect them from the HFST treatment. Tape and plastic sheeting work well. Pavement markings should be covered or removed if within the intended treatment area. Fix any outstanding pavement distresses. Pre-treat any joints and cracks greater than 1/4-inch wide with resin binder.

Applications over new asphalt pavement should be installed a minimum of 30 days after asphalt placement. In that time, any asphalt binder still coating the surface will likely wear away under traffic and UV exposure. In addition, the surface texture will be more compact, reducing the amount of resin binder required for the HFST. Applications on new concrete pavement should also be delayed 30 days so the concrete can fully cure.

Equipment

Some states mandate the use of continuous automated or semi-automated applicator vehicles for all projects (FIGURE 9). This automated method minimizes or eliminates problems often associated with manual application methods: inadequate binder mixing, improper and uneven binder thickness, delayed aggregate placement, and inadequate aggregate coverage. In addition, the automated process is considerably faster (2,000+ sy/hr), permitting a quicker return to traffic.

Purely manual application methods can also produce treatments with adequate performance and durability; however, it is critical that all members of the crew have adequate experience with the process. Even when automated applications are mandated, manual application may still be required for small spot applications up to 200 sy and where automated equipment cannot reach.

Photo courtesy of DBi Services (10)

Photo courtesy of WSDOT (11)

FIGURE 9 – Continuous Automated and Semi-Automated HFST Applicator Vehicles.

In a fully-automated method, the applicator must mechanically meter, mix, monitor and apply the resin binder and apply the aggregate in one uniform and continuous pass. Automated monitoring gauge and print-outs are typically available. This should help to minimize the potential for human errors. With some automated application systems, the resin binder can be heated. The heating process can help control the viscosity of the resin in cooler temperatures. In comparison, a semi-automated applicator will carefully mix the resin system, but aggregate distribution and/or binder spreading is still done manually.

At present, there are several HFST application companies that own automated and semi-automated equipment. These companies develop and operate their equipment in-house. New equipment suppliers and contractors are expected to enter the market as the popularity of HFST continues to grow. Equipment for the manual method includes:

- Containers for mixing.
- Electric mixer.
- A "Jiffy Mixer" type mixer attachment can help minimize air entrainment. It is best practice to mix each component separately prior to mixing them together.
- V-notched neoprene squeegees (FIGURE 10). Select design that spreads resin at specified rate.
- Spiked shoes.
- Broadcast system or blower for spreading aggregate (optional).

FIGURE 10 – V-Notched Squeegee.

Mixing

The resin binder must be proportioned correctly and mixed thoroughly. This is a particular problem when applying HFST manually. Mix for as long as the manufacturer recommends. Resin stored at cooler temperatures may require mixing for longer than recommended. Thoroughly work the sides and bottom of the container. Inadequate mixing can also occur with automated systems if not properly maintained and monitored.

Poor mixing will be very apparent as soft spots of uncured binder in the final HFST. These spots can be small (<1 sf) or substantial (several sy). Uncured HFST will need to be removed and replaced at the contractor's expense.

Application

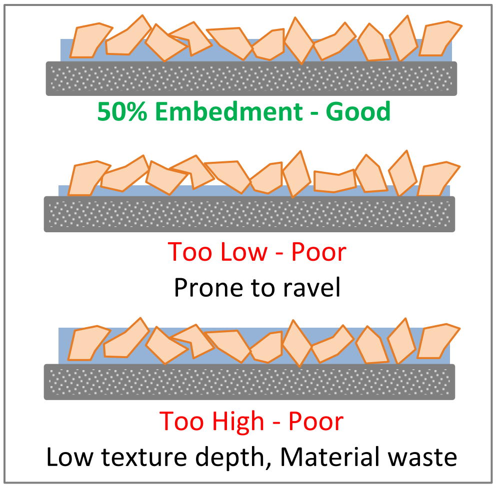
Applications on dense-graded HMA and rigid pavement require one layer of HFST. A double-layer HFST application may be required when placed over open-graded pavement.

The resin binder should be applied to achieve a film thickness of 50-65 mils. The goal is to achieve 50% embedment depth of the aggregate (FIGURE 11). With too little binder, the risk for aggregate loss becomes much greater. Too much binder, and the surface macrotexture is decreased. Besides wasting material, too much binder can contribute to premature failure of the HFST triggered by thermal stresses at the bond interface.

The typical yield rate of the resin binder is between 25-32 sf/gal. Yield rates are dependent upon the surface texture of the pavement. Beforehand, walk the project and identify if there are any changes in the surface texture. Adjust the resin-binder rate whenever the surface texture changes significantly.

Aggregate is spread immediately following the resin binder. For automated systems, this should be in less than 10 seconds, and for manual methods should be done within 5 minutes. It is important that full embedment of the aggregate is achieved prior to the initial setting, or thickening, of the resin binder. The aggregate should completely cover the binder, leaving no "wet" spots. The typical rate is between 12 to 15 lbs/sq-yd.

The goal is to achieve 50% embedment depth of the aggregate.



Graphic courtesy of FDOT (*1*)

FIGURE 11 – Aggregate Embedment.

Some agencies allow the reuse of recovered aggregate. When allowed, the aggregate must be dust-free, reused only once, and be blended with new aggregate. The ratio of new aggregate to recovered aggregate should be about 2 to 1. This will ensure the HFST color and texture remain uniform and that contaminated aggregate is not applied. The contractor should clearly label storage containers of recovered aggregate and include the project and date when it was fist applied.

Curing, Sweeping, and Restriping

The HFST must be allowed to cure according to manufacturer recommendations. The time will vary depending on the type of resin binder and the temperature. Protect the treatment from all traffic until cured.

After curing, excess aggregate must be removed by sweeping. If the contractor wants to reuse the aggregate, they must use a vacuum sweeper. Ensure that the system is clean and dry and will not contaminate the aggregate.

As required by the Engineer, restriping should be done after aggregate removal. This striping may be temporary or permanent, according to the contract.

HFST will continue to shed loose aggregate for several days and weeks. This is normal. The contractor must do additional follow-up sweeping within a specified period like 2 weeks.

Acceptance Testing and Warranty

Agencies often have an acceptance criterion for friction within 30 to 90 days after installation. HFST requires a wear-in period under traffic before friction values stabilize and any premature testing will result in artificial results. The standards for friction testing are the locked-wheel skid trailer (ASTM E274) or the Dynamic Friction Tester (ASTM E1911) (FIGURE 12). Some agencies also require testing for macrotexture depth as this is critical for reducing wet-weather crashes.

Photos courtesy of TTI

FIGURE 12 – Locked-Wheel Skid Trailer (top) and Dynamic Friction Tester (bottom).

Some agencies have adopted 1-year and multi-year warranties as part of the bid document to ensure any pre-mature failures can be replaced. This will affect the overall bid price of the HFST installation. Surface defects may include:

- Delamination.
- Raveling.
- Soft spots of uncured binder.
- Excessive cracking.

The agency would define the extent of each distress that is unacceptable. Corrective action usually involves removal of the existing HFST with grinding, removing an area a bit larger than the distress, and then reapplication of the HFST.

CONCLUSION

This document synthesized the noteworthy practices for HFST based on federal agency, state agency, and industry experience. By properly identifying candidate sites, selecting the best materials, and implementing high-quality construction practices, agencies will have the best return-on-investment for their HFST installations. Agencies can see more widespread HFST deployment and a longer lasting safety countermeasure, resulting in greater crash reductions.

The authors acknowledge that much of this information was previously reported by Atkinson et. al. (*3*) and by Wilson and Holzschuher (*2*). Relevant recommendations from the recently completed Long-Term Performance Monitoring Study were also incorporated into this document.

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