EVALUATION OF HIGH FRICTION SURFACING FOR REDUCING CRASHES AT HORIZONTAL CURVES

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ABSTRACT

A 2004 National Cooperative Highway Research Program report revealed that nearly one quarter of the United States' highway fatalities occur along horizontal curves, with approximately 76 percent of these being single vehicle roadway departure crashes. In an effort to identify cost-effective ways to enhance safety at horizontal curves, the U.S. Federal Highway Administration initiated the Surface Enhancements at Horizontal Curves (SEAHC) study in 2008 to evaluate the use of using high friction surfacing (HFS) materials for reducing crashes at horizontal curves. Under this effort, HFS treatments have been applied to 16 curves in five different states to date. Treatments have been applied to various pavement types in various climates. Texture depth, profile depth, and skid resistance were measured on each curve just prior to application of the HFS, immediately following treatment, and at one year after installation. Crash data for the three year period preceding HFS application will be compared with crash data for the three year period following treatment to identify potential benefits of HFS treatment in crash reduction along horizontal curves. This paper will discuss the scope of the SEAHC study and present preliminary findings and results from the initial application and testing of the horizontal curves.

1. INTRODUCTION AND BACKGROUND

It has been shown that approximately one quarter of highway fatalities in the United States occur at or near horizontal curves. While contributing factors to these run-off-the-road crashes include excessive vehicle speed, distracted driving, and driver error, at some locations, the deterioration of pavement surface friction may also be a factor, particularly during wet weather.

In an effort to reduce the deaths and injuries that occur along these horizontal curves, in 2008 the United Stated Federal Highway Administration (FHWA) initiated the Surface Enhancements at Horizontal Curves (SEAHC) program for the installation and demonstration of specialty friction enhancing treatments to numerous horizontal curves. The premise behind this study is to isolate and demonstrate the effects of increased surface friction on crash numbers at these select locations. To date, 16 curves in five different states have been treated with friction-enhancing surface treatments under this program. This paper will discuss the demonstration projects completed to date and some of the preliminary findings from the study.

2. HIGH FRICTION SURFACING

One of the strategies identified by a recent National Cooperative Highway Research Program report for reducing collisions on horizontal curves is providing a skid-resistant pavement surface [1]. Likewise, a recent FHWA report on low-cost treatments for horizontal curve safety recommended skid-resistive pavement surface treatments [2]. While there are a number of “skid-resistive” surface treatments that can be used for improving friction of existing pavements, the SEAHC project limited the scope to high friction surfacing or HFS. HFS are thin surface treatments that generally use an epoxy-based binder to bond highly durable aggregates to the pavement surface. Some of the advantages of using HFS for enhancing pavement friction include:

- They can be applied to an existing pavement (most pavement types) with minimal pre-application preparation.
- They can be applied quickly during short (e.g., as little as 4 hour) lane closures, minimizing the impact of installation on traffic.
- They do not significantly affect pavement thickness or cross slope.

HFS has been used for decades with great success in the United Kingdom specifically for enhancing friction on curves with specific characteristics. Australia, Japan, China, and several European countries have also utilized HFS for various friction enhancing applications. Colored HFS has also been used extensively for delineation of bus lanes, pedestrian walkways, medians, roundabouts, intersections, and other applications. In the U.S., HFS has primarily been used for bridge deck treatments, helping to both seal the deck and improve friction. However, use for intersections and horizontal curves has been limited to date.

2.1. Materials

HFS typically consists of proprietary blends of epoxy-based binders used to bond highly durable aggregates to the pavement surface. Binders are typically two-part epoxy blends which may include epoxy resins, bitumen-extended epoxy resins, rosin-esters, polyurethane-resins, acrylic-resins, or other similar materials. In terms of viscosity, the binder is thick enough to hold the aggregate in place, but thin enough to be screeded uniformly over the pavement surface. The binder will typically fill or clog open graded pavement surfaces, but are viscous enough to prevent flowing through the surface and into permeable bases or underdrains.

Aggregates bonded to the surface are typically 1-3 mm uniformly sized stone. They should be polish and abrasion resistant such that they will not readily polish or abrade away under traffic. Ideal aggregates are those which maintain microtexture over time and “chip” (on a microscopic level) as they wear, rather than polishing. Calcined bauxite has traditionally been the preferred aggregate for HFS, but due to a very limited number of sources for the material, other locally available materials have also been used. In the U.S., flint, slag, and granite aggregates have been used as alternatives to calcined bauxite, although calcined bauxite is still used extensively.

2.2. Properties

A strict definition of HFS has not been established yet in the U.S. However, the British Board of Agrément (BBA), which provides guidelines for assessment and certification of HFS in the UK, defines HFS as a surface "having a minimum skid resistance value (SRV) of 65 measured using the portable Skid-Resistance Pendulum Tester." [3] This high level of friction is also expected to be maintained over time. For certification purposes, the BBA requires HFS to maintain a minimum skid resistance value of 65 (measured using the portable Skid-Resistance Pendulum Tester) up to two years after installation.

In terms of texture depth, it is not uncommon for HFS surfaces to have an initial mean texture depth of 3-4 mm, as measured with the ASTM E965 "Sand Patch" test, before exposure to traffic. The BBA requires HFS to have a minimum mean texture depth of 1.4 mm after installation, and 1.0 mm after two years of traffic wear.

2.3. Installation

Depending on the binder, HFS systems may utilize either hot-applied or cold-applied processes. Cold-applied HFS are most commonly used in the U.S., and were utilized for the SEAHC demonstrations described herein. With a cold-applied system, the two components of the binder may be heated slightly to lower viscosity, but not to the extent of hot-applied HFS systems. The two components are mixed together just prior to being applied to the pavement surface.

HFS systems have traditionally been installed manually by mixing the binder components in large buckets or barrels and spreading it on the pavement surface with squeegees, followed by hand-broadcasting of the aggregate. However, in the U.S. most HFS vendors have now developed proprietary application machines to significantly improve the consistency of the mixed binder and rate of application of both the binder and aggregate.

HFS does have some limitations for installation. Most HFS binders are hydrophobic, and therefore the pavement must be at least surface dry before applying the binder. In general, HFS systems must be installed when pavement surface temperatures are 5ºC and rising to ensure that the binder fully cures in a reasonable amount of time. Certain HFS binders can also be tailored to the ambient conditions, permitting them to be installed in lower temperatures if necessary. Depending on surface temperature and ambient conditions, HFS requires anywhere from 30 minutes to four hours to cure sufficiently for exposure to traffic. Excess aggregate should be removed with a power broom or vacuum followed by compressed air to ensure all loose stone is removed from the surface before opening to traffic.

3. SEAHC DEMONSTRATION PROJECTS

The focus of the FHWA SEAHC demonstration projects is to evaluate the viability of HFS as a cost-effective treatment for reducing crashes at horizontal curves by improving or restoring pavement friction. Crash reduction is the primary goal for the program, with a secondary goal of evaluating the viability of HFS as a skid-resistive surface treatment. To evaluate crash reduction, crash data before and after HFS application are compared. To evaluate the viability of HFS, friction, texture, and material performance properties are monitored over time. Through this evaluation, the use and analysis of results for various friction and texture testing methodologies along with contractor-chosen installation technologies and procedures will be demonstrated. This is a three-year evaluation study, and therefore crash data, texture, friction, and material performance data are evaluated over a three-year period after installation.

3.1. Site Selection

Selection of the horizontal curves to receive treatment in each state is based on crash data provided by the state and a field investigation of the site itself. Crash data are required for at least the three years preceding installation. Crash data of interest is both wet and dry crashes (icy/snowy crashes are excluded), single vehicle run-off-road and multiple vehicle sideswipe and run-off-road crashes.

Once a “short list” of sites has been identified, field visits are made to each site to determine whether it is a suitable candidate. Some of the criteria used to determine whether a site is suitable are:

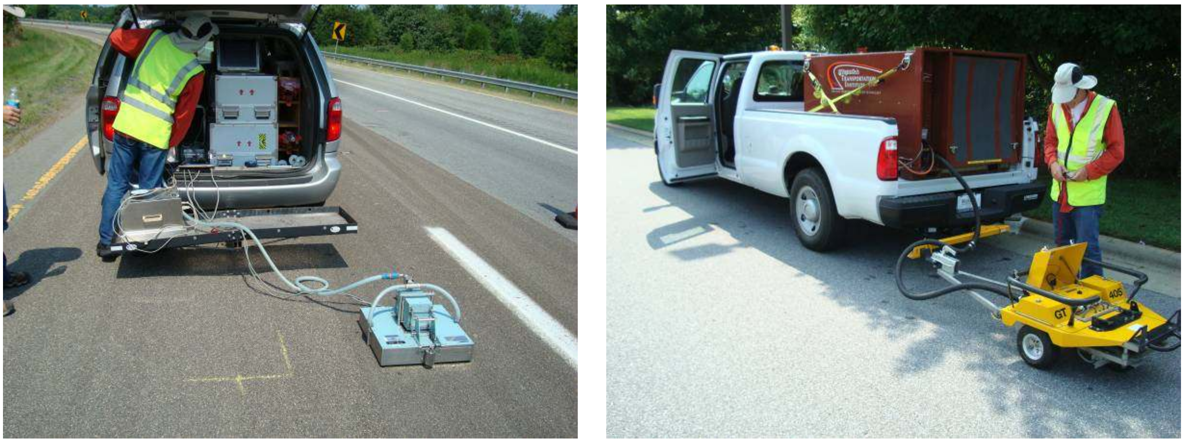
- High rate of run-off-road or sideswipe crashes per average daily traffic volume (high accident reduction opportunity).
- No other readily apparent causes of crashes, such as site distance issues, presence of driveways/intersections, inadequate superelevation, or other societal (e.g., intoxication) causes.
- Pavement in good condition structurally – no major distresses or surface defects that would affect the performance of the HFS.
- No plans by the state highway agency for pavement rehabilitation, other surface treatments, or other safety treatments (e.g., additional signage, striping, delineation, etc.) during the three year period following installation.

The SEAHC effort has sought to include a variety of pavement types and roadway types (rural and urban, high volume and low volume, mainline and ramps). Of the 16 demonstrations completed to date, eight have been on asphalt pavement, six have been concrete pavement, and two on bituminous chip seal pavement surface treatment. Eleven of the projects have been in urban areas and five in rural areas. Eight of the projects have been on ramps, seven on mainline pavement, and one on a curve at an intersection approach.

3.2. Testing

In order to quantify the effect of HFS on friction and texture, a number of friction and texture tests are conducted on each SEAHC demonstration. Testing is conducted just prior to HFS application, immediately following HFS application (before exposure to traffic for the stationary tests), and at approximately one year after installation. If deemed appropriate, sites may also be tested at three years after installation.

Friction testing (Figure 1) consists of the Dynamic Friction Tester (DFT), GripTester, and if provided by the state highway agency, locked-wheel friction trailer. The DFT is a stationary device which provides a complete speed vs. friction curve from 0 km/hr to 80 km/hr. The GripTester is a fixed-slip device which operates at highway speed and measures friction at a 14.5 percent slip ratio using a small scale smooth test tire. The locked wheel trailer provides friction readings for a fully-locked test wheel (100 percent slip) using ribbed and/or smooth tires. Friction measurements with the DFT are taken at 2-4 locations along each curve (depending on the length of the curve) in both the right wheel path and center-lane. GripTester measurements are conducted in both wheel paths and center-lane over the full length of the HFS section. Locked-wheel trailer measurements are generally collected in the right wheel path only, with 1 3 measurements per site, depending on the length of the section.



Dynamic Friction Tester *GripTester*

Figure 1: Friction testing devices for SEAHC demonstrations.

Texture testing (Figure 2) consists of measuring the mean profile depth (MPD) using the circular track meter (CTM) and RoboTex device, and mean texture depth (MTD) using the ASTM E965 “Sand Patch” test [4]. CTM measurements are collected at the same locations as the DFT tests. RoboTex measurements, which provide a continuous, 100 mm wide texture profile of the pavement surface, are collected in the right wheel path and center lane over the full length of the section. The RoboTex texture profile can then be used to compute a more comprehensive MPD.

Circular Track Meter *RoboTex*

Figure 2: Texture testing devices for SEAHC demonstrations.

In addition to the tests described above, two sites were selected for tire-pavement noise testing using the on-board sound intensity (OBSI) method in order to quantify any possible changes in tire-pavement noise due to HFS. One dense graded hot-mix asphalt pavement surface and one chip seal surface were selected for OBSI testing.

3.3. Completed Demonstrations

Demonstration projects completed in four states in August-September 2009 included North Carolina, Kansas, Montana, and Colorado. Projects in a fifth state, Michigan, were completed in September 2010. Demonstration projects for each state were completed by a single HFS vendor using the same HFS product for all sites. Table 1, below, summarizes the demonstration projects for each state.

As Table 1 shows, three different HFS products have been used on the demonstration sites to date. All three products had been used extensively elsewhere in the U.S., ensuring that the materials and installation procedures had already been established. The majority of the projects utilized flint aggregate. However, to help establish a performance comparison, both bauxite and flint were used for the projects in Michigan, with approximately equal quantities of each split amongst the five projects.

Table 1 also shows the variety of pavement surface types (portland cement concrete, hot-mix asphalt, or chip seal) and roadway types, mentioned previously. This has provided a wide cross-section of horizontal curves for comparison of performance based on pavement type, climatic conditions, and traffic volumes.

All installations and testing have been completed during short (6-10 hour) closures of the lane or ramp. Six of the installations were completed during nighttime closures in order to minimize the impact of installation on traffic. All installations to date have utilized machine application, as shown in Figure 3. While installation procedures and processes have varied between HFS vendors, virtually no problems have been experienced with installation, and the final product at each site has been very consistent and uniform. Figure 4 shows some typical pavement surfaces before and after HFS application.

Table 1: Summary of SEAHC Demonstrations completed to date.

State	Route	Roadway Type	Pavement Type	Rural/ Urban	HFS Product	Aggregate Type	Area (m^2)
North Carolina	US 311	Ramp	HMA	Urban	Ennis Paint TyreGrip	Bauxite	2,230
Kansas	K-5	Mainline	HMA	Rural	PolyCarb SafetyGrip	Flint	558
	K-99	Mainline	HMA	Rural			1,003
	I-635	Ramp	PCC	Urban			1,037
	K-96	Ramp	PCC	Urban			1,105
Colorado	I-25 NB	Mainline	HMA	Urban	Crafco HFS	Flint	1,394
	I-25 SB	Mainline	HMA	Urban			1,227
	CO 119	Mainline	HMA	Rural			1,338
	US 36	Mainline	HMA	Rural			1,783
Montana	I-15/I-90	Ramp	Chip Seal	Rural	PolyCarb SafetyGrib	Flint	2,081
	US 93	Mainline	Chip Seal	Urban			3.314
Michigan	I-85/SB Baldwin Rd.	Ramp	PCC	Urban	PolyCarb SafetyGrip	Bauxite	1,717
	I-85/NB Baldwin Rd.	Intersection Approach	PCC	Urban		Bauxite	245
	I-85/ Rochester Rd	Ramp	HMA	Urban		Bauxite	613
	I-69/I-75	Ramp	PCC	Urban		Flint	1,450
	I-96/US 311	Ramp	PCC	Urban		Flint	1,040

Figure 3: Machine application techniques used for SEAHC demonstrations.

(a) (b)

(c)

(d) (e)

Figure 4: Pavement surfaces before and after prior to HFS application: (a) dense graded hot-mix asphalt pavement; (b) portland cement concrete; (c) bituminous chip seal; (d) calcined bauxite aggregate HFS surface; (d) flint aggregate HFS surface.

4. PRELIMINARY FINDINGS

Of the 16 demonstrations completed to date, eight have been re-tested after approximately one year in place. Unfortunately, three sites were removed due to failure of the underlying asphalt pavement which required the HFS to be milled off with the underlying pavement.

Summarized below are some of the key findings from the installation, testing, and evaluation of the projects to date.

4.1. Crash Reduction

Being a three-year study, crash reduction due to the HFS installations is mostly anecdotal at this point. Maintenance personnel from some agencies have reported no crashes at certain sites since the HFS was installed. Ultimately, crash data will be compiled for each site after the HFS has been in place for at least three years. This data will then be compared with crash data from the three years prior to HFS installation to determine crash reduction.

4.2. Friction and Texture

Table 2, below shows the average before and after HFS installation texture values and associated percent improvement based on pavement type. Also shown are the average values for the one-year evaluation of the 2009 demonstration projects. Note that the 2010 demonstration project data were included in the “Pre-HFS” and “Post-HFS” average values, but not the “1-Year”average values. Table 3 shows the results for friction measurements in a similar manner. Note that all concrete surfaces were transversely tined and all asphalt surfaces were dense graded hot-mix asphalt.

As these results indicate, concrete pavement showed the most significant improvement in both friction and texture from the application of HFS, particularly for texture. Asphalt pavement also showed significant increase in texture and friction, but to a lesser extent than concrete. Chip seal surfaces showed the least improvement in both friction and texture over the other surfaces, which was not unexpected due to the fairly aggressive nature of chip seal surfaces.

The one-year texture and friction values are significantly lower than the post-HFS installation values. The primary reason for this is that the post-installation tests were conducted immediately following installation, before any traffic wear had occurred. HFS has been found to be a very aggressive surface immediately following installation and exhibits a certain “wear in” period during the first few weeks and months following installation wherein traffic breaks off aggregate that are only loosely held in the epoxy matrix until the surface stabilizes. This is evidenced by the amount of loose aggregate generally found on the shoulder within weeks after installation. Measuring texture and friction after a few weeks of traffic wear will likely provide the best indication of true post-installation texture and friction.

One result of note is the apparent decrease in friction and texture for the chip seal surfaces after one year. Unfortunately, the change in friction and texture that would have occurred without the HFS could not be measured, so it is not known whether this is truly a decrease in friction and texture over what would have normally occurred with the chip seal surface. The friction and texture values are still very high, however, and therefore the HFS is still providing the benefits of high friction.

Table 1: Summary of texture data by pavement type.

Surface Type	Mean Profile Depth (MPD) *Circular Track Meter*				Mean Texture Depth (MTD) *ASTM E 965 "Sand Patch" Test*			
	Pre-HFS	Post-HFS	Pct. Increase	1-Year	Pre-HFS	Post-HFS	Pct. Increase	1-Year
Asphalt	0.78	1.81	132%	1.09	1.25	2.76	121%	1.34
Concrete	0.52	2.00	285%	1.15	0.70	3.28	369%	1.70
Chip Seal	1.19	2.57	116%	1.00	1.45	3.17	119%	1.41

Table 2: Summary of friction data by pavement type.

Surface Type	Friction at 20 km/hr *Dynamic Friction Tester*				GripNumber (GN) at 65 km/hr, 14.5% slip *GripTester*			
	Pre-HFS	Post-HFS	Pct. Increase	1-Year	Pre-HFS	Post-HFS	Pct. Increase	1-Year
Asphalt	0.47	0.83	77%	0.65	0.50	0.89	78%	0.69
Concrete	0.45	0.84	87%	0.60	0.45	0.95	111%	0.65
Chip Seal	0.74	0.96	30%	0.68	0.70	0.92	31%	0.70

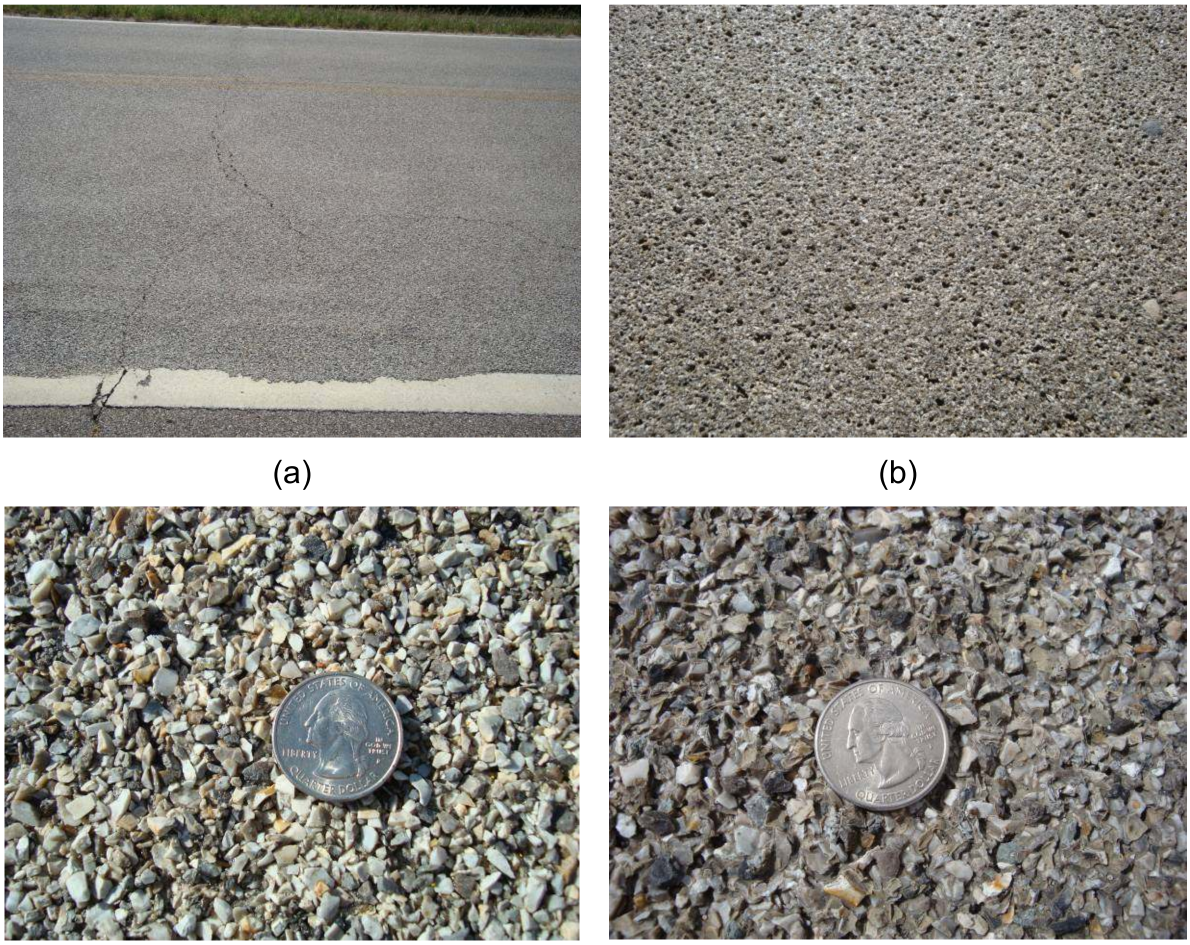
4.3. Material Performance

Overall, the HFS products used for this study have performed well in varying climates and under varying levels of traffic. Most of the demonstrations were exposed to heavy snowfall and snow plow wear in winter, and experience relatively hot temperatures in the summer. Below are summarized some of the key observations regarding material performance based on the one-year evaluations of the projects installed in 2009.

- Any cracking in the underlying pavement will reflect into the HFS shortly after construction (Figure 5a). Epoxy-based HFS binders are high modulus materials which will not accommodate the expansion or opening of cracks and joints. Even hairline cracks in underlying asphalt pavement tend to reflect into the HFS. However, the HFS shows excellent adhesion to the pavement on either side of a crack, and reflective cracks in the HFS do not appear to cause any deterioration (e.g., delamination) of the HFS.
- Performance of single-layer HFS under high volumes of studded tires has been unsatisfactory. Studded tires tend to abrade and polish the aggregates and pull aggregate out of the epoxy matrix, leaving a "pockmarked" appearance typical of studded tire wear (Figure 5b). Studded tire wear appears to also diminish the texture and friction achieved with HFS.
- HFS installed on concrete pavement appears to exhibit the best performance in terms of cracking, delamination, and general deterioration. As with asphalt

pavement, cracks in concrete pavement will reflect through. However as long as the crack does not spall, no further deterioration occurs.

Figure 5c and Figure 5d show a typical flint aggregate HFS surface after installation and after one year of traffic wear, respectively. As might be expected, wear was typically more noticeable in the wheel paths than center of the lane.



(a) (b)

(c) (d)

Figure 5: HFS surface performance: (a) reflective cracking over asphalt pavement; (b) studded tire wear; (c) new flint aggregate HFS surface; (c) flint aggregate HFS surface after one year.

As mentioned previously, three of the original HFS installations (US 311 in North Carolina, and I 25 NB & SB in Colorado) were removed less than one year after installation due to failure of the underlying pavement. All three were installed over existing dense graded hot-mix asphalt pavement which was in fair condition at the time of installation. The Colorado sites exhibited minor to moderate levels of alligator cracking in certain areas, but the North Carolina site did not exhibit any major distresses. Further investigation of the North Carolina installation revealed a history of problems with asphalt pavements along this curve, which likely led to the rapid deterioration of the HFS installation under this study.

Observations prior to removal of the HFS and underlying asphalt pavement revealed that the HFS adhered well to the pavement. However, as the underlying asphalt deteriorated, and in some cases delaminated, the HFS material broke away with the asphalt. It is still undetermined as to whether the HFS material contributed in any way to deterioration of the asphalt pavement. There has been speculation that the HFS material may help water in the asphalt layer, which could have accelerated deterioration of the asphalt pavement. However, this has not been confirmed by any further investigations. As a result of these prematurely deteriorated sections, subsequent HFS installations have been limited to pavement which does not exhibit any major surface deterioration (alligator cracking, block cracking, map cracking, etc.).

5. CONCLUSIONS

The HFS demonstration projects completed under the SEAHC program have provided a broad-based opportunity to evaluate the use of high friction surfacing for reducing crashes at horizontal curves. To date, demonstration projects have been constructed throughout the U.S. on a variety of roadways and pavement types, in a variety of climates. The preliminary findings from the SEAHC effort indicate the HFS is a viable material for improving or restoring friction to pavements on horizontal curves in order to reduce crashes. Although crash reduction due to HFS is primarily anecdotal thus far, feedback from state highway agencies indicates that the HFS is having an impact.

There is still much to be learned about HFS materials so that they can be utilized appropriately. The condition of the existing pavement is a primary factor affecting the performance of HFS. Heavily-distressed pavement surfaces should not be treated as the HFS cannot be expected to perform over the long term. Climatic and traffic conditions to which the HFS will be exposed are also an important factor in the performance of the surfacing. Customized blends of epoxy will likely need to be developed by HFS vendors based on the conditions where the HFS is to be used.

The ultimate goal of this effort is to determine whether HFS is a truly cost-effective solution for enhancing safety at horizontal curves, such that highway agencies will have a better understanding of whether this is another tool.

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