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EFFECTIVENESS AND PERFORMANCE OF HIGH FRICTION SURFACE TREATMENTS AT A NATIONAL SCALE

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EFFECTIVENESS AND PERFORMANCE OF HIGH FRICTION SURFACE TREATMENTS AT A NATIONAL SCALE

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ABSTRACT

Although High Friction Surface Treatment (HFST) has been widely installed in recent years, validation efforts considering various materials, installation ages, environmental conditions, and traffic levels are missing primarily due to lacking of high-speed data collection instruments. Utilizing laser imaging technology and fixed-slip friction tester, this study collects comprehensive pavement surface data at 21 HFST sites in 11 states at highway speeds. Measurements on HFST and untreated pavements are compared to determine the effectiveness of HFST. Multivariate analyses are conducted to investigate the impacts of factors on HFST friction. Average temperature and installation age are identified as the significant factors. HFST sites constructed using calcined bauxite aggregates exhibit better friction performance than those using flints. Subsequently, friction models are developed to aid highway agencies in managing HFST.

Keywords: High Friction Surface Treatment (HFST), Effectiveness, Multivariate Analysis, Friction Models

INTRODUCTION

High Friction Surfacing Treatments (HFST) were firstly applied in the United Kingdom in 1960s to maintain pavement skid resistance and reduce the fatalities and injuries from crashes that occur at or near horizontal curves (Brimley and Carlson 2012). Recently, the Federal Highway Administration (FHWA) Office of Pavement Technology has implemented the Surface Enhancements At Horizontal Curves program and Every Day Counts 2 program to install HFST at numerous horizontal curves throughout the U.S. due to higher friction demand of vehicles on curves and intersections than that on other pavement sections (The Trans Tec Group 2015). Through various HFST projects, the effectiveness of HFST in improving skid resistance and reducing crashes has been demonstrated (Bledsoe 2015, Moravec 2013, State of South Dakota Department of Transportation 2015, Bischoff 2008, Izeppi et al. 2010 and Waters 2011).

Generally pavement friction and macro-texture are tested before and after HFST installation to quantify the changes in surface skid resistance. Pavement friction is measured primarily using the Dynamic Friction Testers and agency-owned locked-wheel skid testers, while macro-texture is measured using stationary or low speed devices such as the Circular Track Meter, ASTM E 965 “Sand Patch” Method, or RoboTex (Moravec 2013 and Izeppi et al. 2010). Most of these devices require lane closure to perform the tests, and highway agencies must perform multiple data collection processes to gather different pavement surface characteristics. These limitations have constrained continuous evaluation of the surface characteristics of installed HFST sites in the longer term after they are opened to traffic. In addition, according to the authors' knowledge, no study has

been conducted to evaluate HFST performance at a national scale under various traffic conditions, environments, and HFST materials.

This research applies the state-of-the-art 3D laser imaging based technology named PaveVision3D Ultra with necessary software tools for data collection and subsequent surface characterization for 21 HFST demonstration sites in 11 states as instructed by FHWA. The PaveVision3D Ultra system is capable of automatically conducting comprehensive pavement survey at full-lane coverage at 1mm resolution in three dimensions at highway speed up to 60 mph, measuring pavement surface cracking, profiling, texture, geometric parameters, and reconstructing 3D virtual pavement (Wang 2011). This single-pass and complete lane coverage platform provides an ideal solution to evaluate the surface characteristics of HFST without interrupting traffic. In addition, pavement friction data on HFST is collected using the FHWA continuous fixed-slip friction tester, which uses a standardized smooth-tread test tire to measure friction in terms of a uniteless friction number, μ . Statistical data analysis is conducted to compare the measured surface characteristics before, after, and on the HFST to determine the effectiveness of the HFST. Multivariate analysis is included to identify the significant levels of potential influencing factors on HFST friction performance. Subsequently, pavement friction prediction models are developed for HFST.

HFST DATA COLLECTION AND SURFACE CHARACTERIZATION

HFST Data Collection

The data collection effort described herein includes testing of 21 HFST sites in 11 states as instructed by FHWA. The locations of the HFST sites are shown in FIG. 1.

Considering the directions and number of lanes at each site, 41 data collections are conducted, with each PaveVision3D data collection covering a full traffic lane. With the exception of pavement friction data which are collected separately using FHWA's fixed-slip friction tester, surface characteristics, including pavement rutting and macro-texture, are measured for each HFST site using the 1mm PaveVision3D Ultra technology at posted highway speed without interfering the traffic. To determine the effectiveness of HFST in improving surface properties, all the data sets are collected beginning 300 ft to 500 ft before and through 300 ft to 500 ft after each HFST section.

Pavement Rutting

Rutting is defined as the permanent traffic-associated deformation within pavement layers. The recent provisionally-approved AASHTO Designation PP69-10 (AASHTO 2013) has been implemented into the PaveVision3D system for rutting characterization and cross slope measurements. Rutting in the left and right wheelpaths are averaged into average rutting in inches for each image frame with a dimension of 6.7ft (2, 048mm) in length and 13.4ft (4, 096mm) in width for each data collection. Rutting data are not calculated for rigid pavement sections, which are represented with zero rutting values.

Pavement Friction

Skid resistance is the ability of the pavement surface to prevent the loss of tire traction. The friction value from the HFST was reported every 1 ft over the length of the section tested in order to show any variations in friction. Example friction data plots are shown in FIG. 2. Some sites show clear improvements of skid resistance (as shown in FIG. 2.a) and the differentiation of the HFST section from abutting pavement, while others don't

show any trend (as shown in FIG. 2.b), in part because they are older HFST installations which may loss friction over time.

Pavement Macro-texture

The methodologies for texture measurement can be grouped into two categories: static and high-speed methods. Traditionally the measurement of pavement macro-texture at high-speed is based on single longitudinal or line-of-sight profile in the wheelpath. Mean Profile Depth (MPD) is one of the widely used texture indices. Example MPD data plots from the PaveVision3D Ultra system are shown in FIG. 3. Similar to friction data, some sites show much higher MPD values on HFST surface in contrast to the abutting pavement, while others don't show noticeable differences.

EVALUATION OF HFST EFFECTIVENESS

The 1mm 3D data are collected 300ft to 500ft before and/or after each HFST section so that the measured surface characteristics before, after, and on the HFST sites can be compared and statistical analyses performed to determine the effectiveness of the HFST sites in improving surface characteristics. The beginning and end locations of each HFST section are determined based on “event markers” from the field friction data collection, and visually from collected 3D data sets. A paired t-test with equal variance is performed for each HFST site. The t-test investigates the difference between the means of the non-HFST and HFST treatment sections. At 95% confidence interval, if P-value is smaller than 0.05, the null hypothesis is rejected and the mean of the two groups are significantly different.

The friction and MPD data are reported at 1.0 ft interval. The t-test results for friction number and MPD for each data collection are summarized in Table 1. It is evident that HFST surfaces have significantly different friction numbers (with an average $P = 0.01$ for all the HFST sites) and surface texture MPD values (with an average $P = 0.01$ for all the HFST sites) than those on the abutting pavement. The average friction number of all HFST sites is 86.76, while the friction of non-HFST surface has an average of 56.56. The average MPD of all HFST sites is 0.0522 inches (1.32 mm), while the MPD of non-HFST surface has an average of 0.0410 inches (1.04 mm).

FIG. 4 shows the difference between the two means of friction numbers and MPDs for each HFST data collection. The majority of the HFST sites have much larger friction numbers and MPD values comparing to the non-HFST surfaces. However, there are several exceptions. Sites 25 and 26 have smaller friction numbers on HFST surfaces than those on the non-HFST surfaces. The deicer materials observed on the two HFST locations during data collection may result in the lower friction numbers of the sites. Approximately identical friction numbers are observed for Site 15 on HFST and non-HFST surfaces. In addition, the friction on HFST of Site 30 is slightly higher than that on the non-HFST surface even though the treatment was applied only one year prior to data collection. For MPD, 5 out of 41 collections report smaller MPDs on HFST surfaces, such sections including Sites 3, 4, 22, 23, and 24.

The comparisons of the average rutting on HFST and non-HFST of asphalt pavement surfaces are shown in FIG. 5. No consistent statistical conclusion can be made based on the t-test results: some sections have significantly different rutting while others

don't between HFST and non-HFST segments. This is logical since HFST treatments do not correct rutting problems on existing pavement surfaces. The rutting on an HFST surface is dependent on the pavement condition before the treatment. The average rutting are 4.24 mm and 4.53 mm for HFST and non-HFST respectively. The average P-value is 0.14, which indicates that on average no significant difference is observed for rutting on non-HFST versus HFST surfaces.

HFST FRICTION PERFORMANCE

Potential Influencing Factors

Influencing factors relating to pavement friction are generally categorized as pavement surface characteristics, vehicle operational parameters, tire properties, and environmental factors (Hall et al. 2009). The influence of asphalt mixture type and Portland cement concrete surface textures on pavement friction has been widely researched (Asi 2007, Ahammed and Tighe 2008). Several pavement friction models has been developed, some of which are established based on macro- and micro-texture of mix aggregates (Ergun et al. 2005). Operational factors including water film thickness, test speed, or temperature are found to affect friction measurement (Flintsch et al. 2012 and Henry 2000). Studies also find that temperature could affect pavement friction in short-term and long-term (Ahammed and Tighe 2010, Luo 2003, and Fuentes 2009).

Based on data availability in this study, precipitation, average temperature, HFST installation age, aggregate type, and annual average daily traffic (AADT) for each HFST site are identified as the potential influencing factors to evaluate the HFST friction performance in the long-term and at a wider scale. Precipitation and average temperature

data are obtained from the climate station close to each HFST site. Two indicators, friction number on HFST (FN_{HFST}) and the ratio of friction number (FN Ratio) are used to evaluate HFST pavement friction performance. Herein, FN Ratio is the friction number on HFST (FN_{HFST}) divided by the friction number on Non-HFST ($FN_{Non-HFST}$).

$$FN\ Ratio = \frac{FN_{HFST}}{FN_{Non-HFST}} \quad (1)$$

The potential influencing factors and corresponding friction information for each data collection are provided in Table 2. FN Ratio, FN_{HFST} , and $FN_{Non-HFST}$ for each data collection are evaluated considering the aforementioned factors:

- As shown in FIG. 6, FN Ratio and FN_{HFST} show decreasing trends with the increase of HFST installation age and average temperature.
- For HFST sites with more than 60 month of installation age, FN Ratio in FIG. 6(b) approaches approximately 1.0, which indicates that the average life of a HFST surface is around 5 years and the benefit of HFST in friction effectiveness is nearly lost by that time.
- HFST sites installed with calcined bauxite aggregates exhibit better friction performance than those with flints (FIG. 7).
- No trend is observed between friction performance (FN Ratio and FN_{HFST}) and precipitation, AADT respectively, neither does the accumulated traffic volume (which is AADT times 365 days and HFST installation age).
- There is no obvious relationship between $FN_{Non-HFST}$ and the five influencing factors.

Even though HFST sections in colder regions experience more frequent snow plowing and deicing activities, it demonstrates that the effect of winter maintenance on HFST performance has been minimal. On the contrary, higher temperature seems to cause a softening effect on the HFST resin and possibly the underlying asphalt binder, which would allow HFST aggregate to penetrate into the softened surface with reduced macro-texture or lead to the loss of aggregate due to reduced bonding strength. As a result, lower FN Ratio and FN_{HFST} are measured on HFST sections in warmer regions. In addition, HFST is subject to deterioration through climate and traffic wear, and therefore older HFST sections show lower FN Ratio and FN_{HFST} .

Intuitively, AADT should have an impact on pavement friction development since pavement wears and friction values decrease with repetitive traffic applications. However, majority of the HFST sites are located either on ramps or multiple-lane highways. Detailed traffic data on ramps and for each lane of multiple-lane sections are not available and the AADT values have to be estimated based on engineering judgment. With more accurate traffic data, the relationship between AADT and friction may be better revealed. It should also be noted that only one data collection was performed for each HFST site and no time-series comparisons are available for each site. Most sites on ramps are older in age but with much lower estimated AADT values, while sites on mainline highways are younger in age but with higher traffic volumes. As a result, the accumulated traffic volumes of HFST sites on ramps are less than that of the sites installed more recently on mainline roads. Therefore, the friction number does not decrease with the increase of accumulated traffic volume if various levels of traffic

volumes on all the tested HFST sites are considered simultaneously in the analysis. When time-series data are available, the deterioration of friction for each site should be noticeable as the site ages and carries more accumulate traffic.

Multivariate Analysis Results

Multivariate analysis is conducted to analyze the effect of the influencing variables on FN Ratio, FN_{HFST} , and $FN_{Non-HFST}$. Precipitation, average temperature, HFST installation age, AADT are continuous independent variables, while aggregate type is a categorical variable and should be properly coded and quantified before multivariate analysis could be performed. Herein bauxite aggregate is represented as '1' while flint is coded as '0' in data preparation of model development. P-value is used to evaluate the significant level of each influencing variable on the dependent outcomes (which are the two friction performance measures). The multivariate analysis result is shown in Table 3.

At 95% confidence interval, if P-value is smaller than 0.05, the corresponding variable has significant effect on the dependent variables. The P-values for average temperature and HFST installation age are much smaller than 0.05, which means they have significant effect on FN Ratio and FN_{HFST} . The corresponding coefficient of those two dependent variables are negative, which indicates that FN Ratio and FN_{HFST} decrease as those two variables increase. P-value of aggregate type (larger than 0.05) shows that it is not a significant factor for FN Ratio and FN_{HFST} . However the corresponding coefficients of aggregate type are positive, which implies HFST using bauxite (coded as '1') will add a positive number into the predicted FN Ratio or FN_{HFST} while HFST using flint (coded as '0') doesn't include such positive contribution to friction numbers. This

statistic results support the data shown in FIG. 7 that FN Ratio and FN_{HFST} for HFST using bauxite are generally greater than those using flint. For $FN_{Non-HFST}$, P-values for all the five variables are greater than 0.05, which indicates that the independent variables have insignificant impacts on pavement friction for non-HFST sections.

Subsequently, multivariate analysis considering only the two significant influencing factors (average temperature and installation age) is conducted and the results are appended in Table 3. Both factors remain to be significant for the prediction of FN Ratio. However, the P-value of average temperature on FN_{HFST} is larger than 0.05, which indicates that the impact of average temperature on FN_{HFST} is not as significant as that of installation age, which supports the data shown in FIG. 6(c) that FN_{HFST} decreasing trend is not as significant as that of installation age. The multiple linear regression models are therefore developed as shown in Equation (2) to predict FN Ratio and FN_{HFST} :

$$\begin{aligned} FN \text{ Ratio} &= 2.912 - 0.019 * \text{Average Temperature} - 0.013 * \text{Age} \\ FN_{HFST} &= 130.027 - 0.507 * \text{Average Temperature} - 0.575 * \text{Age} \end{aligned} \quad (2)$$

The predicted and measured FN Ratio and FN_{HFST} for all the 41 data collections are plotted in FIG. 8. The predictions follow similar development trend as the actual measured FN Ratio and FN_{HFST} , and the R-squared values are 0.55 and 0.50 respectively. There are several potential reasons may cause the moderate R-squared values. Several factors of many HFST sites may take the same values, which reduces the variability of the data sets. For example, if HFST sites are close to each other in distance, the climate data for these sites are obtained from one weather station and the same values of precipitation and average temperature are used. For HFST sites with multiple lanes,

AADT data remains the same for the site for all lanes. More detailed and accurate data could result in better friction prediction models with higher R-squared values.

CONCLUSIONS

This project applies the 3D laser imaging based PaveVision3D Ultra technology with necessary software tools for data collection and subsequent surface characterization and evaluation of the HFST demonstration sites. The 1mm 3D data for 21 HFST sites in 11 states with a total of 41 sections are collected for each traffic lane at the posted highway speeds. Pavement rutting and macro-texture data are calculated from collected 1mm 3D data sets, while pavement friction data are collected using FHWA's continuous fixed-slip friction tester.

The measured surface characteristics on the HFST sites and untreated existing pavements are compared and paired t-tests are performed to determine the effectiveness of the HFST sites in improving surface characteristics. Strong evidence is found that the HFST surfaces have statistically significant higher friction numbers and surface macro-texture MPD values than those on the adjacent pavements without HFST. There exist several exceptions to such trend, 2 sections for friction data and 5 sections for MPD data, probably due to the long installation age and use of winter maintenance. Subsequently, multivariate analysis are conducted to investigate the impacts of five independent variables: precipitation, average temperature, HFST installation age, aggregate type, and AADT, on HFST friction performance. Average temperature and HFST installation age are identified to have significantly impact on friction number on HFST (FN_{HFST}) and the ratio of friction on HFST to that on non-HFST (FN Ratio). Based on the trend between

FN Ratio and installation age, the benefit of HFST in friction effectiveness is lost after approximate 60 months (5 years) of service. HFST sites using calcined bauxite aggregates exhibit higher friction performance than those using flints. The regressional friction prediction models are therefore developed for HFST, which can be used to predict the service life of HFST installation and aid decision making within a highway agency. However, it should be noted that the models don't consider the pavement conditions before HFST application and HFST construction quality variations as the dependent variables due to the unavailability of data. In addition, detailed traffic data for ramps and each lane of sites with multiple lanes are not available and have to be estimated during the model development.

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Table 2. Potential Influencing Factors of HFST Friction Performance

Table 3. Multivariate Analysis Results

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Table 1. Paired T-Test Results for Friction Numbers and MPDs

Data Collection ID	Friction Number					MPD (Inch)				
	Mean - HFST	Mean - Non HFST	df	P value	Sig. Diff?	Mean - HFST	Mean - Non HFST	df	P value	Sig. Diff?
1	98.08	51.79	1060	0	Yes	0.0498	0.0345	1274	0	Yes
2	103.49	58.04	990	0	Yes	0.0514	0.0284	1172	0	Yes
3	87.89	68.3	1540	0	Yes	0.0548	0.0677	1739	0	Yes
4	81.69	70.38	1541	0	Yes	0.0526	0.0581	991	0	Yes
5	107.86	63.86	1477	0	Yes	0.0625	0.0465	1184	0	Yes
6	112.42	63.85	1499	0	Yes	0.0634	0.0459	957	0	Yes
7	104.05	60.55	1088	0	Yes	0.0513	0.0342	978	0	Yes
8	98.74	57.76	984	0	Yes	0.0497	0.0321	1454	0	Yes
9	100.6	55.84	1113	0	Yes	0.0517	0.0346	1075	0	Yes
10	91.35	44.1	826	0	Yes	0.0501	0.03	691	0	Yes
11	102.39	61.77	1019	0	Yes	0.049	0.036	1243	0	Yes
12	94.59	49.12	1194	0	Yes	0.0496	0.0351	1119	0	Yes
13	57.64	43.83	1272	0	Yes	0.0383	0.0283	1132	0	Yes
14	83.17	52.64	768	0	Yes	0.043	0.0192	285	0	Yes
15	65.55	64.93	925	0.38	No	0.0362	0.0217	351	0	Yes
16	64.28	53.3	1677	0	Yes	0.0456	0.0332	1600	0	Yes
17	59.14	52.73	1767	0	Yes	0.0291	0.0289	2143	0.41	No
18	73.12	54.51	831	0	Yes	0.0419	0.0313	616	0	Yes
19	94.98	60.43	791	0	Yes	0.09	0.0825	1181	0.03	Yes
20	72.81	54.5	471	0	Yes	0.0351	0.0323	645	0	Yes
21	68.93	54.32	367	0	Yes	0.0397	0.0257	418	0	Yes
22	64.49	45.09	244	0	Yes	0.0423	0.0812	303	0	Yes
23	64.14	37.95	253	0	Yes	0.0539	0.1083	365	0	Yes
24	84.14	76.23	524	0	Yes	0.0384	0.0498	399	0	Yes
25	52.1	69.09	1940	0	Yes	0.041	0.0356	1308	0	Yes
26	56.5	76.24	1995	0	Yes	0.038	0.0383	1814	0.01	Yes
27	74.62	60.83	900	0	Yes	0.0548	0.0449	844	0	Yes
28	72.79	55.66	267	0	Yes	0.0562	0.0402	859	0	Yes
29	101.45	66.22	310	0	Yes	0.0579	0.0465	429	0	Yes
30	59.5	55.74	414	0	Yes	0.0548	0.0514	769	0	Yes
31	90.25	41.1	2543	0	Yes	0.0572	0.0293	2100	0	Yes
32	93.37	42.45	2561	0	Yes	0.0581	0.027	1981	0	Yes
33	107.81	53.06	1968	0	Yes	0.0592	0.0313	588	0	Yes
34	108.33	55.36	1734	0	Yes	0.0734	0.0382	1376	0	Yes
35	102.6	57.24	1069	0	Yes	0.0671	0.0452	1306	0	Yes
36	92.68	49.37	1635	0	Yes	0.0526	0.0397	1286	0	Yes
37	111.46	51.08	1468	0	Yes	0.0474	0.035	489	0	Yes
38	97.06	54.02	969	0	Yes	0.0692	0.0354	1803	0	Yes
39	124.28	50.44	1962	0	Yes	0.0588	0.0354	1840	0	Yes
40	88.41	58.68	1864	0	Yes	0.0608	0.0381	1054	0	Yes
41	88.32	66.57	1369	0	Yes	0.0663	0.0419	989	0	Yes

Table 2. Potential Influencing Factors of HFST Friction Performance

ID	Precipitation (Inch)	Air Temperature (°F)	Data Collection Speed (MPH)	Installation Age (Month)	Aggregate	AADT	FN _{HFST}	FN _{Non-HFST}	FN Ratio
1	34.6	51.3	40	30	Bauxite	14167	104.05	60.55	1.72
2	34.6	51.8	40	30	Bauxite	14167	98.74	57.76	1.71
3	34.6	51.9	40	30	Bauxite	14167	100.6	55.84	1.8
4	34.6	51.4	40	30	Bauxite	14167	91.35	44.1	2.07
5	34.6	52.3	40	30	Bauxite	14167	102.39	61.77	1.66
6	34.6	51.8	40	30	Bauxite	14167	94.59	49.12	1.93
7	37.7	86.2	40	30	Bauxite	13500	87.89	68.3	1.29
8	37.7	85.2	40	30	Bauxite	13500	81.69	70.38	1.16
9	12.8	38.5	30	63	Flint	2760	84.14	76.23	1.1
10	14	39	40	63	Flint	5955	52.1	69.09	0.75
11	14	38.5	40	63	Flint	5955	56.5	76.24	0.74
12	35.5	33.9	40	64	Flint	26165	57.64	43.83	1.32
13	35.5	33.7	30	64	Flint	1717	83.17	52.64	1.58
14	35.5	33.8	30	64	Flint	1717	65.55	64.93	1.01
15	34.3	36.5	40	64	Flint	6350	64.28	53.3	1.21
16	27.2	50	40	4	Bauxite	400	102.6	57.24	1.79
17	27.2	50.9	40	4	Bauxite	400	92.68	49.37	1.88
18	27.2	50.7	40	4	Bauxite	400	111.46	51.08	2.18
19	27.2	37.5	40	4	Bauxite	1720	97.06	54.02	1.8
20	27.2	37.8	40	4	Bauxite	1720	124.28	50.44	2.46
21	26.4	31.4	40	4	Bauxite	8420	90.25	41.1	2.2
22	26.4	32.1	40	4	Bauxite	8420	93.37	42.45	2.2
23	26.4	32.4	40	4	Bauxite	8420	107.81	53.06	2.03
24	26.4	31.9	40	4	Bauxite	8420	108.33	55.36	1.96
25	48.4	53.1	30	4	Bauxite	6400	98.08	51.79	1.89
26	48.4	51.7	30	4	Bauxite	9810	103.49	58.04	1.78
27	55.4	43.8	40	17	Bauxite	2100	107.86	63.86	1.69
28	55.4	44	40	17	Bauxite	2100	112.42	63.85	1.76
29	30.7	44.5	30	51	Flint	10510	59.14	52.73	1.12
30	34	50.8	30	51	Flint	4291	73.12	54.51	1.34
31	30.2	41.7	30	51	Bauxite	3300	94.98	60.43	1.57
32	30.2	44.3	30	51	Bauxite	3400	72.81	54.5	1.34
33	30.2	44.2	30	51	Bauxite	3400	68.93	54.32	1.27
34	30.2	49.4	20	51	Bauxite	2750	64.49	45.09	1.43
35	30.2	45.1	20	51	Bauxite	2750	64.14	37.95	1.69
36	44	58.6	30	9	Bauxite	1300	74.62	60.83	1.23
37	44	58.6	30	9	Bauxite	1300	72.79	55.66	1.31
38	44	55.8	30	9	Bauxite	1300	101.45	66.22	1.53
39	44	55.3	30	9	Bauxite	1300	59.5	55.74	1.07
40	36.8	47	40	39	Bauxite	15500	88.41	58.68	1.51
41	36.8	46.3	40	39	Bauxite	15500	88.32	66.57	1.33

Table 3. Multivariate Analysis Results

Variables	FN Ratio		FN HFST		FN Non-HFST	
	Coefficients	P-value	Coefficients	P-value	Coefficients	P-value
<i>Considering All Five Independent Factors</i>						
Intercept	3.113	0.000	146.258	0.000	40.368	0.012
Precipitation (Inch)	0.016	0.074	1.027	0.020	-0.210	0.495
Average Temperature (°F)	-0.037	0.003	-1.626	0.005	0.459	0.250
Installation Age (Month)	-0.011	0.000	-0.473	0.001	0.061	0.523
Aggregate AADT	0.064	0.684	1.978	0.791	-1.517	0.780
	0.000	0.265	0.000	0.462	0.000	0.619
<i>Considering only the Two Independent Factors that have Significant Influence</i>						
Intercept	2.912	2.62E-10	130.027	2.07E-09	42.056	0.000
Average Temperature (°F)	-0.019	0.006	-0.507	0.111	0.229	0.272
Installation Age (Month)	-0.013	1.05E-07	-0.575	4.07E-07	0.094	0.141

LIST OF FIGURES

FIG. 1. HFST Sites

FIG. 2. Example Friction Data

FIG. 3. Example MPD Data

FIG. 4. Average Friction Numbers and MPDs for HFST Sites

FIG. 5. Average Rutting for HFST Sites

FIG. 6. HFST Friction Performance vs. Installation Age and Average Temperature

FIG. 7. HFST Friction Performance vs. Aggregate Type

FIG. 8. HFST Friction Performance Prediction

175x95mm (300 x 300 DPI)

(a) With Distinct Difference

(b) With Minor Difference

93x111mm (300 x 300 DPI)

(a) With Distinct Difference

(b) With Minor Difference

91x111mm (300 x 300 DPI)

186x113mm (300 x 300 DPI)

186x51mm (300 x 300 DPI)

Draft

186x114mm (300 x 300 DPI)

(a) FN_{HFST} vs. Aggregate Type

(b) FN Ratio vs. Aggregate Type

98x115mm (300 x 300 DPI)

(a) Predicted vs. Measured FN_{HFST}

(B) Predicted vs. Measured FN Ratio

184x114mm (300 x 300 DPI)