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Friction Testing of Pavement Preservation Treatments: Friction Measurements on Fog Seal Trials Using Six Rejuvenators, State Route KER58

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Abstract:
This technical memorandum describes an investigation (1) to measure the change in pavement surface friction at three hours and at three days after application of six rejuvenators as fog seals and (2) to compare friction values obtained using the California Skid Tester (CST), the British Pendulum Tester (BPT), and the Dynamic Friction Tester (DFT). Statistical correlations among the CST, BPN, and DFT are presented.

Keywords:
Friction, skid resistance, British Pendulum Tester, BPT, British Pendulum Number, BPN, California Skid Tester, CST, Dynamic Friction Tester, DFT, Circular Track Meter, CTM, texture depth, variability, temperature correction

Proposals for implementation:
In the near future, Caltrans should perform a field shadowing study measuring surface friction for approximately six months using the DFT and BPT in conjunction with the Lock Wheeled Skid Trailer and the CST units. With development of a database of pavement friction measurements, this study should enable Caltrans to decide which of the three units (CST, DFT, or BPT) can be used in the field for surface friction measurements after a prescribed time to determine if the established minimum friction requirements are met. If these measurements do not meet the minimum requirements, Caltrans should determine what action or actions are necessary to open the treated surface to traffic as soon as practicable.

Related documents:

- Lu, Q. and Steven, B. 2006. *Friction Testing of Pavement Preservation Treatments: Literature Review.* UCPRC-TM-2006-10. Technical memorandum. University of California Pavement Research Center, Berkeley and Davis,
- Steven, B. 2008. *Friction Testing of Pavement Preservation Treatments: Temperature Corrections and Operator/Machine, Variability.* UCPRC-TM-2008-05. Technical memorandum. University of California Pavement Research Center, Berkeley and Davis.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PROJECT OBJECTIVES

The Office of Pavement Preservation of the Division of Maintenance of the California Department of Transportation (Caltrans) has identified a need to establish a correlation between the California Skid Tester (CST) (CTM 342) and the British Pendulum Tester (BPT) (ASTM E303-93). The UCPRC was then requested by the Division of Maintenance to conduct an investigation to meet this need, if possible, so that fog seals applied to roadways can be tested prior to opening to traffic to determine whether the pavement surfaces meet minimum friction requirements. If these requirements are not met, the contractor would be required to perform actions that would improve friction values to the required levels.

The first goal of this research is to attempt to establish a correlation between friction values measured using the CST and the BPT together with the correlation's level of significance. A relationship of this type with minimal error would be especially useful to permit use of the BPT because of its ease of measuring friction values, defined by the British Pendulum Number (BPN), just after application of a fog seal. The BPN could then be readily converted to a Skid Number (SN), the established specification parameter.

A second goal of the study is to investigate the change in friction resulting from the application of fog seals by measuring it immediately before and soon after the seals are applied. Additional goals to be completed (if time and budget permit) are (1) to investigate changes in friction soon after the fog seals are applied and after two months of traffic and (2) to compare the friction values obtained using the CST, the BPT, and the Dynamic Friction Tester (DFT), the latter of which was developed by the Federal Highway Administration (FHWA).

This technical memorandum presents results of the study associated with the second goal, i.e., to investigate the change in pavement surface friction resulting from the application of fog seals by friction measurements immediately prior to and after their application and to compare the friction values obtained using the CST, the BPT, and the DFT. Six rejuvenators were used as the fog seals in this investigation.

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ABBREVIATIONS AND TERMS USED IN THE TEXT

BPT	British Pendulum Tester (ASTM E 303)
BPN	British Pendulum Number
DFT	Dynamic Friction Tester (ASTM E 1911-98)
CTM	Circular Track Meter (ASTM E2157-01)
CST	California Skid Tester (CTM 342)
HMA	Hot-mix Asphalt
HVS	Heavy Vehicle Simulator
IFI	International Friction Index
F60	Friction coefficient at 60 km/h (associated with IFI)
MPD	Mean Profile Depth
PPTG	Pavement Preservation Task Group
SN	Skid Number
Sp	Speed coefficient (associated with IFI)
TRRL	Transport and Road Research Laboratory

1 INTRODUCTION

This technical memorandum presents the results of friction tests undertaken by the University of California Pavement Research Center (UCPRC) on behalf of the California Department of Transportation (Caltrans) for a study investigating the benefits of various rejuvenator products used as fog seals on the performance of hot mix asphalt (HMA) pavements.

The UCPRC conducted British Pendulum Tester (BPT), Dynamic Friction Tester (DFT), and Circular Track Meter (CTM) measurements prior to the application of the rejuvenator products, three hours after the application of the products and three days after the application of the products. In parallel with the UCPRC measurements, Caltrans staff conducted California Skid Tester (CST) and Locked Wheel Skid measurements.

The fog seal trial using the six rejuvenators was organized and conducted by the joint Caltrans and Industry Pavement Preservation Task Group (PPTG). Friction testing was undertaken to measure the surface friction prior to application of the rejuvenators, then three hours and three days afterward. This report presents the results of the field measurements and the analyses of the resulting data.

2 SITE DESCRIPTION

The test site was located in the rolling hill topography of Caltrans District 8, east of the township of Mojave on eastbound State Route 58 in Kern County. In the vicinity of the site, SR 58 is a divided highway with four lanes, two in each direction, with HMA surfaces. The test section, beginning at Post Mile 123.295 and ending at Post Mile 125.095, is located on a tangent downgrade (gentle hill).

Six rejuvenators supplied by five producers were used in the trial; each material was applied in the Number 2 lane (outside lane) over a 1,000-foot length with a 500-foot long buffer zone between each test section. A control zone 1,000 feet long immediately preceded the first section containing a rejuvenator. The six materials and the beginning and end post miles of each of their sections are listed in Table 2.1.

Table 2.1: Start/End Post Miles for Test Sections

Product	Start Post Mile	End Post Mile
Reclamite®	124.905	125.095
CRF®	124.621	124.811
Styraflex®	124.337	124.527
Pass QB®	124.053	124.242
Cationic quick setting emulsion (CQS)	123.769	123.958
Topein®C	123.485	123.674
Control	123.295	123.485

No friction measurements were taken on the control section, however it could be assumed that its friction properties and characteristics were similar to those from the other sections prior to the application of the rejuvenating seals on them. This assumption was supported by skid measurements using the Caltrans Skid Trailer (ASTM E 274). Appendix A contains a summary of skid measurements expressed as Skid Numbers (SN) for both the control section and the six sections tested prior to application of the rejuvenating seals. Accordingly, the various friction measurements taken prior to application of the rejuvenating seals could serve as the baseline for the sections on which the seals were applied. Moreover, these measures of skid resistance could be considered representative for the control section had they been taken based on the information included in Appendix A.

3 FRICTION MEASUREMENTS

Friction measurements were completed on June 18, 2007, the day prior to application of the rejuvenators. The rejuvenators were then applied on June 19, 2007, and the +3-hours measurements were completed. Measurements at +3 days were completed on June 22, 2007.

Two UCPRC staff participated in the test program, one to operate the BPT and the other to operate the DFT and the CTM. Both staff members were experienced in the operation of the equipment used for the testing.

For each test section, five measurements were obtained during each test series. The first measurement for a section was taken 500 ft from its start; successive measurements were then obtained at intervals of 76.2 ft (25 m). The center of each instrument was located in the outside wheelpath, 2.4 ft (0.8 m) from the shoulder stripe. At each location the CTM was used first to measure the surface texture and followed in order by the DFT and the BPT. Both the CTM and DFT were set up and operated from the rear of a van since both units required power and the DFT required water operation.

Pavement and air temperatures were recorded by the BPT operator. The BPT was equipped with Transport and Road Research Laboratory (TRRL) rubber sliders (pads) that were less then 12 months old. Rubber pads on the DFT and BPT were changed in accordance with their standard test procedures, i.e., for the DFT after 12 tests, and for the BPT when the wear on the striking edge of the slider exceeded 1/8 in. (3.2 mm) (1/8 in. reduction in length of striking surface) or 1/16 in. (1.6 mm) vertical to the slider (1/16 in. reduction in thickness of the pad). Data obtained with the BPT were corrected to a standard temperature of 20°C using the relationship previously developed by the UCPRC *(1, 2)*.

All the testing conducted three hours after application of the rejuvenator agents was done directly on the surface of the freshly treated pavement, except for the Reclamite section which was treated with an application of sand prior to testing. This is in conformance with the Caltrans specification that requires application of a sand blotter layer when Reclamite is used as a fog seal.

Caltrans staff performed the measurements with the CST; these measurements were made at the same locations and at the same times as the UCPRC devices. On June 19 (the day of application of the rejuvenators) the CST broke down after testing the Topein C material and no further measurements were obtained with this equipment for the +3-hours measurements. A replacement CST device was made available on June 22 for the +3-days testing. In addition to the CST tests, Caltrans staff also conducted friction tests on August 7, 2007 (about seven weeks following application of the rejuvenators), using the Caltrans Locked Wheel Skid Trailer. Results of all of the measurements except the Locked Wheel Skid Trailer Tests are summarized in Table 3.1 through Table 3.4.

Table 3.1: DFT Measurements

Product	Post Mile	DFT Measurement		
		Prior	+3 hrs	+3 days
Topein C	123.580	0.603	0.418	0.488
	123.595	0.629	0.413	0.461
	123.611	0.634	0.393	0.477
	123.629	0.643	0.405	0.523
	123.642	0.636	0.472	0.453
CQS	123.864	0.631	0.300	0.419
	123.879	0.622	0.324	0.394
	123.895	0.629	0.343	0.419
	123.926	0.628	0.344	0.414
PASS QB	124.148	0.624	0.140	0.279
	124.163	0.641	0.292	0.274
	124.179	0.627	0.183	0.278
	124.194	0.625	0.158	0.274
	124.210	0.642	0.180	0.272
StyraFlex	124.432	0.635	0.221	0.328
	124.447	0.648	0.226	0.361
	124.463	0.657	0.222	0.329
	124.478	0.624	0.229	0.351
	124.494	0.621	0.211	0.335
CRF	124.716	0.620	0.213	0.450
	124.731	0.625	0.228	0.404
	124.747	0.626	0.263	0.404
	124.763	0.633	0.246	0.384
	124.778	0.636	0.186	0.363
Reclamite + sand	125.000	0.617	0.440	0.376
	125.016	0.638	0.417	0.389
	125.031	0.641	0.433	0.378
	125.047	0.653	0.489	0.373
	125.062	0.650	0.428	0.330

Table 3.2: BPT Measurements (Reported as BPN Values) Corrected to 20°C

Product	Post Mile	BPN Values at 20°C		
		Prior	+3 hrs	+3 days
Topein C	123.580	68	56	55
	123.595	75	52	49
	123.611	75	53	51
	123.629	78	50	55
	123.642	75	53	46
CQS	123.864	70	62	44
	123.879	70	75	43
	123.895	69	77	48
	123.926	67	85	50
PASS QB	124.148	69	38	37
	124.163	62	53	39
	124.179	67	57	42
	124.194	65	38	46
	124.210	69	49	36
StyraFlex	124.432	69	49	43
	124.447	72	45	46
	124.463	69	42	47
	124.478	68	46	44
	124.494	64	37	45
CRF	124.716	63	36	64
	124.731	71	35	62
	124.747	66	34	61
	124.763	65	34	60
	124.778	61	35	54
Reclamite + sand	125.000	59	72	55
	125.016	67	70	56
	125.031	69	70	57
	125.047	55	76	52
	125.062	55	66	50

Table 3.3: Raw BPT Measurements (BPN Values) and Air/Surface Temperatures

Product	Post Mile	Air and Surface Temperatures and Unadjusted BPN Values								
		Prior			+3 hrs			+3 days		
		Temperature°C		BPN	Temperature°C		BPN	Temperature°C		BPN
		Air	Surface		Air	Surface		Air	Surface	
Topein C	123.580	39.6	54.8	53	33.0	40.5	49	41	34.5	50
	123.595	41.7	55.8	59	33.8	43.8	44	32	43.1	42
	123.611	38.7	52.9	60	34.4	45.5	45	32	39.8	45
	123.629	44.6	58.2	60	33.3	42.1	43	32.0	42.7	47
	123.642	42.2	53.1	59	34.9	41.6	46	38.3	44.7	39
CQS	123.864	43.0	53.1	56	34.5	45.9	52	30.5	37.6	39
	123.879	37.4	52.9	56	36.4	44.9	63	28.0	35.9	39
	123.895	40.5	53.5	55	34.4	44.9	65	30.2	37.6	43
	123.926	37.4	50.5	54	39.0	47.5	70	30.3	38.6	44
PASS QB	124.148	39.4	52.0	55	35.5	52.5	31	29.7	35.6	33
	124.163	37.9	47.8	51	37.7	51.3	43	27.4	33.0	36
	124.179	38.6	48.8	55	37.8	53.2	46	28.1	33.8	38
	124.194	36.6	48.4	54	37.5	53.6	30	28.6	33.7	42
	124.210	35.0	48.4	57	39.5	52.1	39	28.2	34.8	33
StyraFlex	124.432	34.2	47.5	57	41.7	56.1	38	27.4	31.1	40
	124.447	33.1	47.2	60	37.9	52.6	36	25.2	29.6	44
	124.463	35.8	41.8	60	39.3	54.7	33	25.5	31.0	44
	124.478	34.5	41.8	59	38.0	54.4	36	23.8	31.0	41
	124.494	34.8	44.5	54	41.6	54.0	29	26.3	32.5	42
CRF	124.716	33.2	43.3	54	39.4	54.7	29	26.8	31.3	60
	124.731	33.4	44.4	61	38.9	53.3	27	23.3	30.5	58
	124.747	32.5	40.4	58	39.7	51.1	27	26.4	27.9	58
	124.763	33.0	40.7	57	39.6	53.5	27	23.1	26.8	58
	124.778	35.7	43.2	53	39.3	56.7	27	25.1	28.1	51
Reclamite + sand	125.000	35.0	38.4	53	38.5	55.8	56	24.0	27.2	53
	125.016	34.5	39.5	59	38.0	53.2	56	20.5	25.8	54
	125.031	31.6	37.4	61	38.4	53.1	56	20.4	25.3	55
	125.047	27.6	31.4	51	40.1	49.5	62	21.4	24.9	50
	125.062	30.5	33.5	51	37.3	53.1	53	24.3	25.4	49

Table 3.4: California Skid Tester (CST) Measurements

Product	Post Mile	CST Measurements		
		Prior	+3 hrs	+3 days
Topein C	123.580	0.33	0.35	0.30
	123.595	0.37	0.34	0.30
	123.611	0.36	0.33	0.29
	123.629	0.34	0.33	0.27
	123.642	0.37	0.33	0.30
CQS	123.864	0.37	No data due to equipment breakdown.	0.30
	123.879	0.38		0.28
	123.895	0.36		0.26
	123.926	0.38		0.29
PASS QB	124.148	0.35		0.30
	124.163	0.35		0.32
	124.179	0.36		0.26
	124.194	0.35		0.28
	124.210	0.35		0.29
StyraFlex	124.432	0.38		0.28
	124.447	0.38		0.29
	124.463	0.36		0.28
	124.478	0.38		0.26
	124.494	0.36		0.30
CRF	124.716	0.36		0.27
	124.731	0.38		0.27
	124.747	0.36		0.26
	124.763	0.35		0.27
	124.778	0.36		0.26
Reclamite + sand	125.000	0.35		0.29
	125.016	0.36		0.30
	125.031	0.34		0.27
	125.047	0.38		0.30
	125.062	0.33		0.27

4 MEAN PROFILE DEPTH

Mean profile depths (MPD) using the CTM were obtained for all of the test sections. These results are summarized in Table 4.1 for the sections in which the rejuvenators were applied. Prior to the application of the rejuvenators, MPD values were measured over the length of the project since the pavement surface was the same (aged HMA) throughout. From these data (not included in this memo) the average MPD value was determined to be 0.77 mm, with a standard deviation of 0.10 mm and a coefficient of variation of 13 percent. Actual measured values ranged from 0.63 mm to 1.01 mm. It was expected that measurements taken three hours after application of the rejuvenator products would show decreasing MPD values, as residual binder collected at the bottom of the surface voids. The average reduction of MPD for each section ranged from 0.01 mm (Topein C) to 0.14 mm (Pass QB). However, at five test locations, the MPD value increased (see Table 4.1). This apparent anomaly may have resulted from misalignment of the CTM on the pavement at the points of measurement. After three days, the average change in MPD for each section, compared with the "before" condition, ranged from 0 mm (Topein C) to 0.12 mm (Pass QB). In general, the application of the rejuvenator resulted in a small reduction of the surface macrotexture, which is more critical for surface friction at higher speeds.

The MPD values have been used to determine International Friction Index (IFI) values presented subsequently in Chapter 5.

Table 4.1: Mean Profile Depth (Surface Texture) Measurements

Product	Post Mile	Mean Profile Depth (mm)		
		Prior	+3 hrs	+3 days
Topein C	123.580	0.75	0.68	0.77
	123.595	0.78	0.59	0.59
	123.611	0.64	0.62	0.67
	123.629	0.75	0.85*	0.73
	123.642	0.63	0.76*	0.78*
CQS	123.864	0.82	0.65	0.65
	123.879	0.87	0.82	0.82
	123.895	1.01	0.80	0.75
	123.926	0.84	0.81	0.79
PASS QB	124.148	0.69	0.54	0.57
	124.163	0.82	0.63	0.65
	124.179	0.72	0.63	0.54
	124.194	0.72	0.57	0.68
	124.210	0.86	0.72	0.75
StyraFlex	124.432	0.66	0.69*	0.78
	124.447	0.84	0.91*	0.81
	124.463	0.79	0.75	0.70
	124.478	1.01	0.83	1.05
	124.494	0.68	0.65	0.69
CRF	124.716	0.73	0.71	0.67
	124.731	0.65	0.57	0.65
	124.747	0.79	0.78	0.80
	124.763	0.90	0.72	0.72
	124.778	0.85	0.65	0.70
Reclamite + sand	125.000	0.65	0.54	0.61
	125.016	0.78	0.69	0.72
	125.031	0.78	0.65	0.71
	125.047	0.75	0.76*	0.77
	125.062	0.72	0.65	0.66

* Increase in MPD

5 INTERNATIONAL FRICTION INDEX

The measurements for the DFT and CTM values were used to determine the International Friction Index (IFI) (ASTM E 1960 – 07) values (Speed coefficient [Sp] and Friction coefficient at 60 km/h [F60]) and are listed in Table 5.1. By comparing the DFT measurements from Table 3.1 and the F60 values from Table 5.1 at +3 days, it can be seen that the range of values for each rejuvenator is more consistent for the F60 values than for the DFT measurements. For example, the range of measured DFT values for the Topein C was 0.070 units while for the same material the range for F60 values was 0.042 units. Ranges in measured DFT and F60 values for each of the six rejuvenators are shown in Table 5.2. The range in measured F60 values varies from 0.021 (PASS QB) to 0.042 units (Topein C) while the range in individual DFT measurements varies from 0.007 (Topein C) to 0.087 units (CRF). Based on these data it would be reasonable to assume that a suitable spread of measured F60 values for a particular product could be set at 0.04 units.

Coefficients to calculate the F60 value of the IFI from CST measurements could be developed by calculating the linear shift required to transform the F60 values from the CST to the F60 value as calculated by the DFT at the same location. The ASTM standard for the DFT (E 1911–07) states that test results from this equipment have been correlated with the ASTM E 274 skid test procedure, resulting in a correlation coefficient (R) of 0.86. Also, ASTM E 1960 includes a procedure for the DFT and the CTM (macrotexture MPD determination) that can be used for calibrating other friction testers.

There is a difficulty in calculating the F60 value for the CST, in that the *slip speed* is difficult to determine. At the moment the spinning tire contacts the ground, its rotating velocity or slip speed is 50 mph. However, the speed immediately begins to drop toward a value of zero as the carriage starts moving. The reported value for the CST measurement is an empirical function of the distance that the carriage moves along the ground. The reported value for the CST measurement is an empirical function of the distance which the carriage moves along ground.

Table 5.1: IFI Values for the DFT Measurements

Product	Post Mile	Prior		+3 hrs		+3 days	
		Sp (km/h)	F60	Sp (km/h)	F60	Sp (km/h)	F60
Topein C	123.580	76.9	0.343	69.4	0.253	79.1	0.296
	123.595	80.2	0.361	59.7	0.236	59.7	0.254
	123.611	65.1	0.332	63.0	0.233	68.3	0.275
	123.629	76.9	0.352	87.7	0.300	74.8	0.275
	123.642	64.0	0.333	78.0	0.213	80.2	0.267
CQS	123.864	84.5	0.371	66.2	0.211	66.2	0.239
	123.879	89.9	0.377	84.5	0.237	84.5	0.272
	123.895	104.9	0.392	82.3	0.233	76.9	0.259
	123.926	86.6	0.371	83.4	0.237	81.3	0.266
PASS QB	124.148	70.5	0.340	54.3	0.130	57.6	0.183
	124.163	84.5	0.373	64.0	0.195	66.2	0.191
	124.179	73.7	0.348	64.0	0.153	54.4	0.178
	124.194	73.7	0.347	57.6	0.139	69.4	0.194
	124.210	88.8	0.380	73.7	0.158	76.9	0.199
StyraFlex	124.432	67.3	0.337	70.5	0.173	80.2	0.227
	124.447	86.6	0.380	94.2	0.189	83.4	0.245
	124.463	81.2	0.375	76.9	0.178	71.6	0.219
	124.478	104.9	0.393	85.5	0.186	109.2	0.259
	124.494	69.4	0.336	66.2	0.165	70.5	0.220
CRF	124.716	74.8	0.347	72.6	0.171	68.3	0.264
	124.731	66.2	0.331	57.6	0.164	66.2	0.243
	124.747	81.2	0.361	80.2	0.198	82.3	0.263
	124.763	93.1	0.382	73.7	0.186	73.7	0.244
	124.778	87.7	0.376	66.2	0.155	71.6	0.233
Reclamite + sand	125.000	66.2	0.328	54.3	0.235	61.9	0.225
	125.016	80.2	0.365	70.5	0.254	73.7	0.246
	125.031	80.2	0.366	66.2	0.254	72.6	0.241
	125.047	76.9	0.365	78.0	0.295	79.1	0.246
	125.062	73.7	0.358	66.2	0.252	67.3	0.214

Table 5.2: Range of Values for DFT and F60 Measurements

Product	DFT Range	F60 Range
Topein C	0.070	0.042
CQS	0.025	0.033
PASS QB	0.007	0.021
Styraflex	0.033	0.040
CRF	0.087	0.031
Reclamite + sand	0.059	0.032

6 DATA ANALYSES

The friction measurements reported in Chapter 4 were subjected to statistical analyses. A correlation table was established for measurements made prior to treatment, three hours after treatment, and three days after treatment. Results of these analyses are shown in Table 6.1; also included are comparisons for the computed values associated with the IFI, i.e., Sp and F60. Appendix A includes an explanation of the use of Table 6.1. Its purpose is essentially to measure the strength of the linear relationships between pairs of variables, in this instance friction values, by the various types of equipment used in the investigation.

Results of the statistical analyses have been plotted in Figure 6.1 through Figure 6.13. Box plots of the DFT, BPT, and CST measurements are included in Figure 6.1 through Figure 6.3. Regression analysis results for the DFT versus BP, DFT versus CST, and BP versus CST are illustrated in Figure 6.4 through Figure 6.6, while similar correlations are shown in Figure 6.7 through Figure 6.10 for the IFI values, Sp and F60, with the CST and BP measurements.

In Figure 6.4 through Figure 6.10 it will be noted that none of the relationships comparing results of the different equipment would be considered robust. Nevertheless, as will be seen subsequently, the DFT and BP equipment could be used to assess the friction characteristics of freshly applied fog seals. The relationship between the DFT and CST (Figure 6.5) shows the highest R^2 value, i.e., 0.69. Using the same data and additional data from SR 33 (2007), the warm mix Heavy Vehicle Simulator (HVS) test pavement at the Granite Rock Quarry site (2007), and concrete sections from SR 58 (2006), Dr. James Lee[1] of Caltrans developed an equation of the same form:

$$DFT = -0.280 + 2.127\ CST \qquad \textbf{(1)}$$

which exhibited a higher R^2 value of 0.90. This difference could be attributed in part to differences in the interpretation of the speed at which the friction value from the CST is determined. In addition, recognizing spatial variation in pavement surface characteristics, Caltrans has recommended the use of three to five measurements to determine friction values. Equation (1) is based on DFT and CST values using this recommendation.

Additional analyses were conducted in which the intercepts of the relationships for DFT versus BP, DFT versus CST, and BP versus CST were not used. Results for the DFT versus BPT and BPT versus CST measurements were improved as seen in Table 6.2. The relationship between the DFT versus CST

[1] Dr. James Lee, along with other Caltrans staff, participated with the UCPRC staff in this test program on SR 58 in Kern County. Caltrans measured surface friction characteristics using their skid trailer (ASTM E274) and the CST. Dr. Lee reported this relationship in October 2007 in a Microsoft *PowerPoint* presentation.

measurements was not improved; accordingly, only the relationship for regression including the intercept has been included.

Figure 6.11 through Figure 6.13 contain the relationships discussed in the previous paragraph. Also shown on these figures are the 95 and 50 percent confidence bands which contain the true probabilities of the regression expressions. For example, in Figure 6.12, for a DFT measurement of 0.46 the resulting estimate of the CST value would be in the range of approximately 0.30 to 0.32. Similarly, in Figure 6.13, for a BP measurement of 60 the CTS value would be in the range of approximately 0.32 to 0.35. These results suggest that either the DFT or BP equipment could be used to assess the friction characteristics of fog seals after placement to insure that the pavement would meet the minimum surface friction requirements to permit traffic operations. (It should be noted that 0.3 is the minimum acceptable value for the CST measurements.)

It might be argued that the products evaluated in this investigation likely influence the surface friction characteristics of the pavement differently, and therefore one might question the comparison of friction measurements using the different types of equipment. In this case, however, the main purpose of the regression analysis has been to measure the strength of linear relationships among different instrument methods (i.e., the CST, BP, and DFT). That is to say, three distributions based on the measurements of CST, BP, and DFT were used to evaluate the mutual strength of linear relationships between any two instrument methods by regression analysis. The distribution of instrument measurements (instrument distribution) can be regarded as the population with two characteristics—in this case, product type and curing time. Hence, the variation of product type was considered as the population variation and was included in the error term of the regression analyses. For example, the “prior” measurements appear to be reasonably consistent and invariable for the various products using the DFT, BP, and CST. However, both the DFT and BP test data indicate more differences between the products for the “+3-days” measurements, which is not observed with the CST data.

Table 6.1: Correlation Table

	DFT (prior)	DFT (+3 hrs)	DFT (+3 days)	BPT (prior)	BPT (+3 hrs)	BPT (+3 days)	CST (prior)	CST (+3 hrs)	CST (+3 days)	Sp (prior)	Sp (+3 hrs)	Sp (+3 days)	F60 (prior)	F60 (+3 hrs)	F60 (+3 days)
DFT (prior)	1.000														
DFT (+3 hrs)	-0.218	1.000													
DFT (+3 days)	0.136	0.591	1.000												
BPT (prior)	-0.068	0.446	-0.005	1.000											
BPT (+3 hrs)	0.095	0.168	0.675	-0.139	1.000										
BPT (+3 days)	-0.149	0.585	0.304	-0.128	-0.101	1.000									
CST (prior)	0.050	0.031	-0.149	0.194	0.072	-0.137	1.000								
CST (+3 hrs)	NA	NA	NA	NA	NA	NA	NA	1.000							
CST (+3 days)	0.029	-0.037	0.279	0.028	0.193	-0.379	0.024	NA	1.000						
Sp (prior)	0.081	-0.057	-0.157	-0.010	0.164	-0.127	0.141	NA	-0.305	1.000					
Sp (+3 hrs)	0.294	0.283	0.097	0.232	0.176	0.012	0.337	NA	-0.234	0.553	1.000				
Sp (+3 days)	0.027	0.151	0.055	0.098	0.081	-0.008	0.368	NA	-0.214	0.534	0.751	1.000			
F60 (prior)	0.356	-0.153	-0.121	-0.070	0.188	-0.168	0.154	NA	-0.224	0.946	0.572	0.472	1.000		
F60 (+3 hrs)	0.200	0.625	0.914	0.023	0.696	0.323	-0.133	NA	0.150	0.047	0.320	0.180	0.080	1.000	
F60 (+3 days)	-0.232	0.904	0.529	0.357	0.212	0.539	0.189	NA	-0.102	0.159	0.511	0.508	0.055	0.599	1.000

Notes: CST measurements for +3-hours data are unavailable.
A value of 1 indicates two variables are highly correlated.
A value of 0 indicates two variables are not correlated.
A positive value indicates two variables are positive-correlated.
A negative value indicates two variables are negative-correlated.
See Appendix A for further discussion.

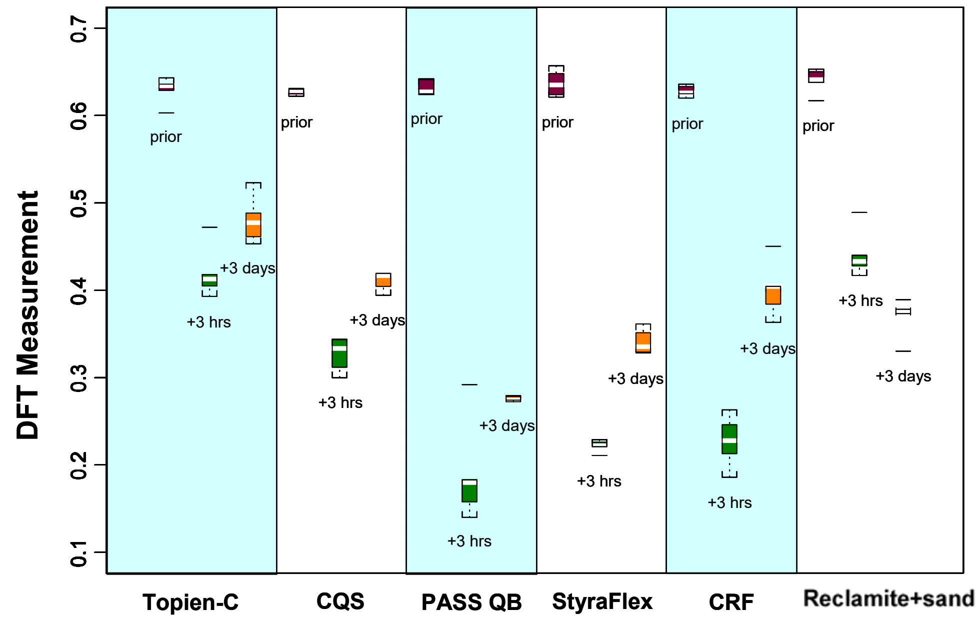

Figure 6.1: Box plots of DFT measurements.

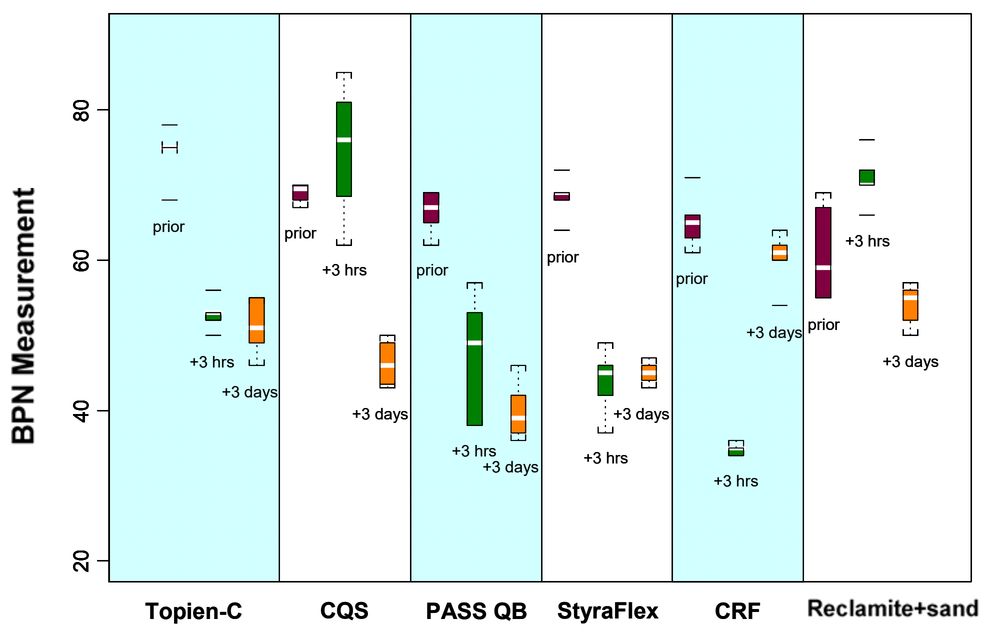

Figure 6.2: Box plots of BP measurements.

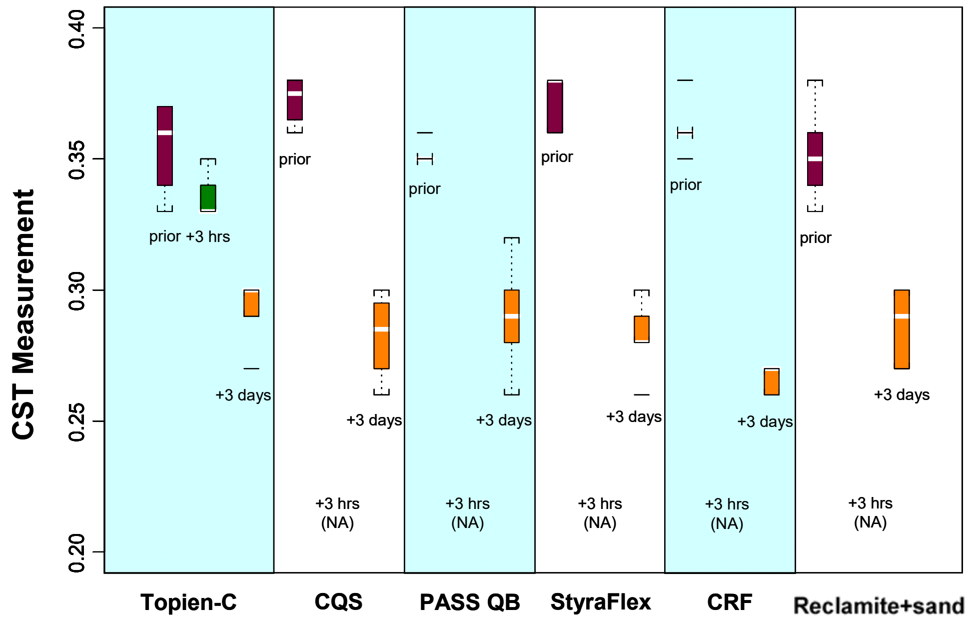

Figure 6.3: Box plots of CST measurements.

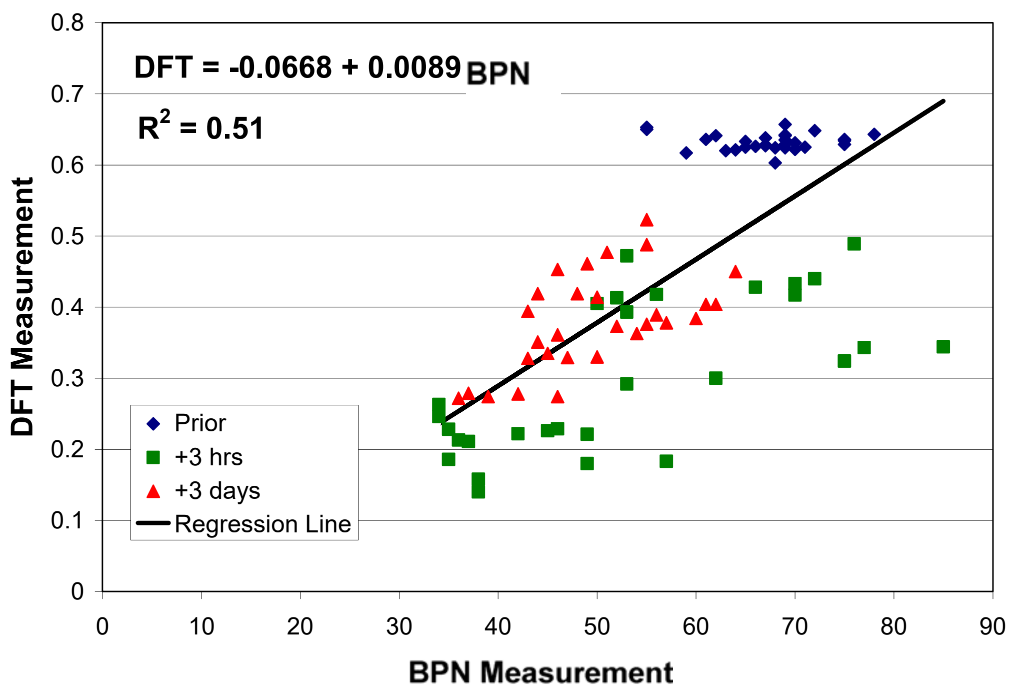

Figure 6.4: DFT measurements versus BPT measurements.

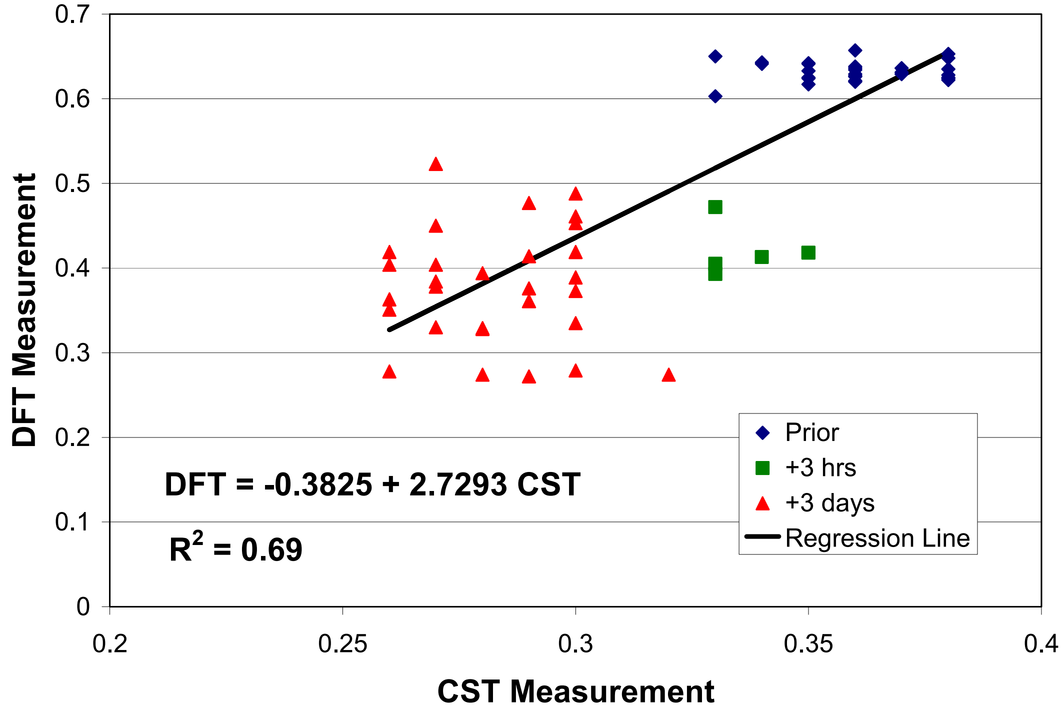

Figure 6.5: DFT measurements versus CST measurements.

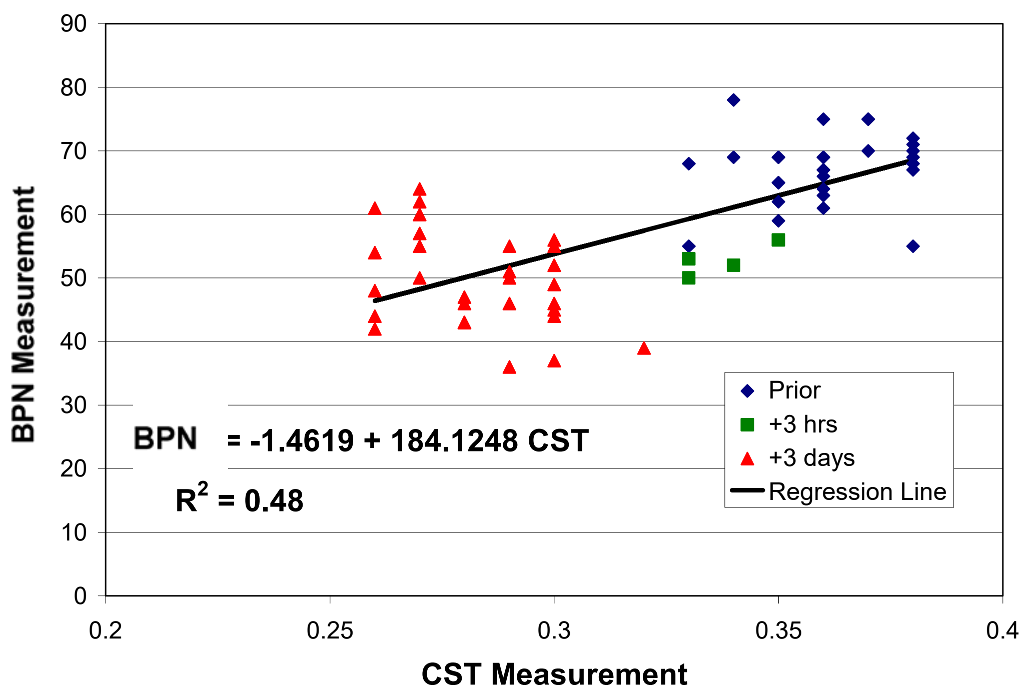

Figure 6.6: BPT measurements versus CST measurements.

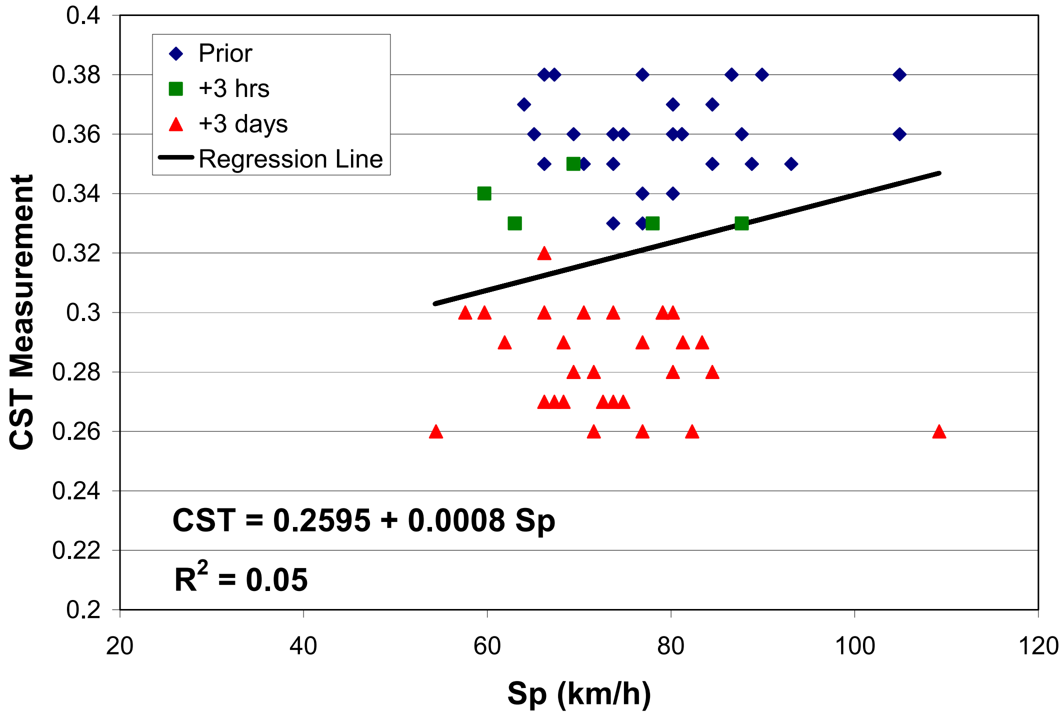

Figure 6.7: CST measurements versus Sp.

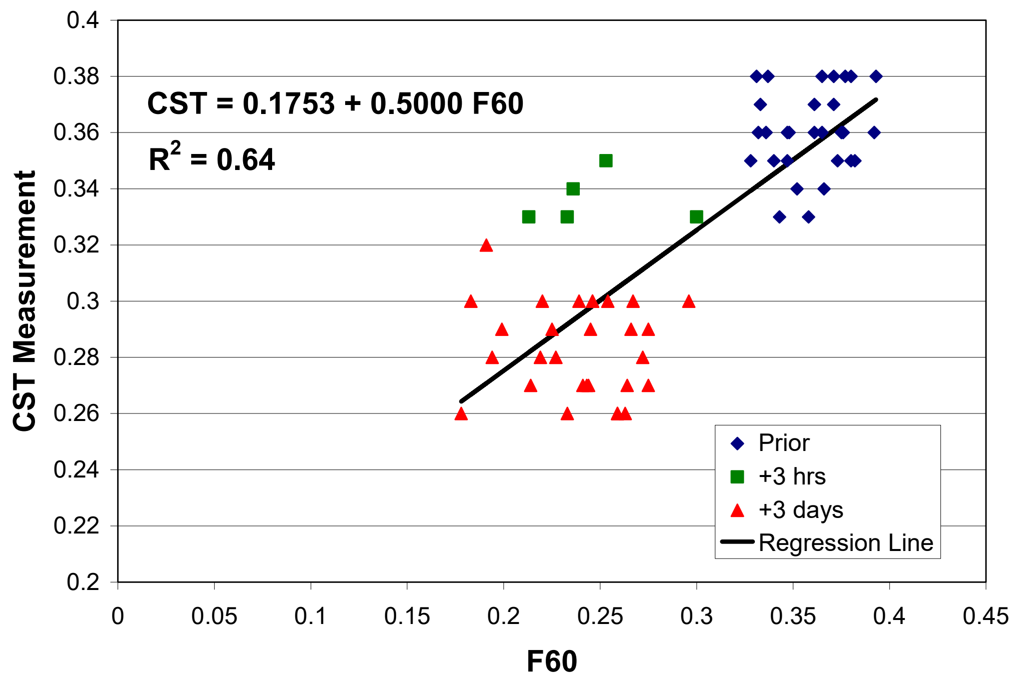

Figure 6.8: CST measurements versus F60.

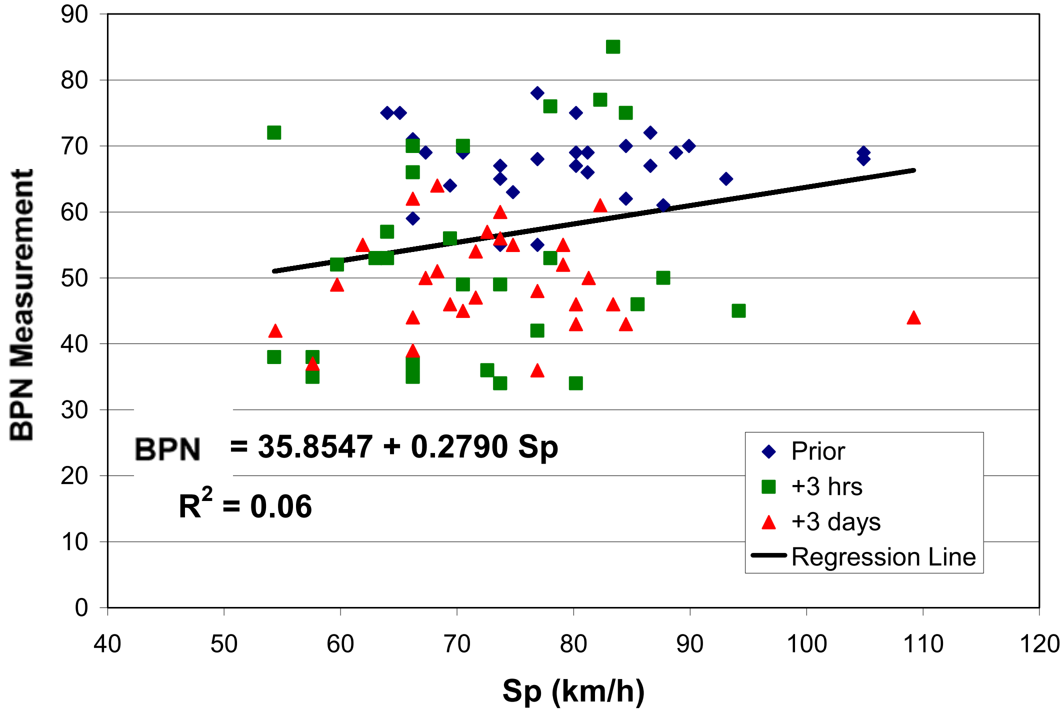

Figure 6.9: BPT measurements versus Sp.

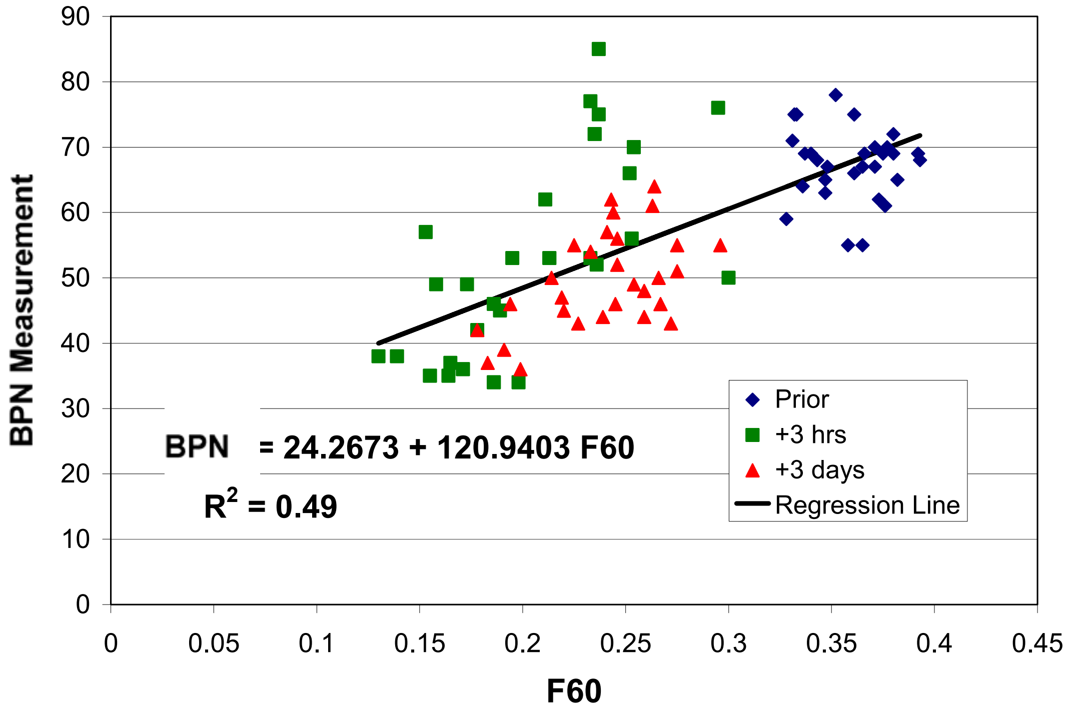

Figure 6.10: BPT measurements versus F60.

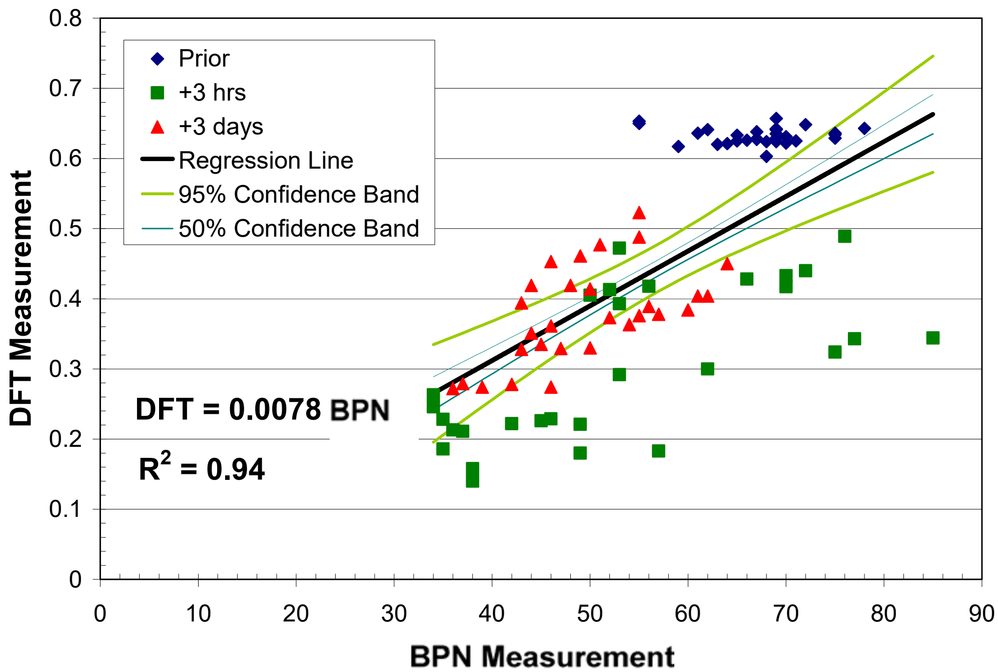

Figure 6.11: DFT measurements versus BPT measurements (model without intercept) and associated confidence bands.

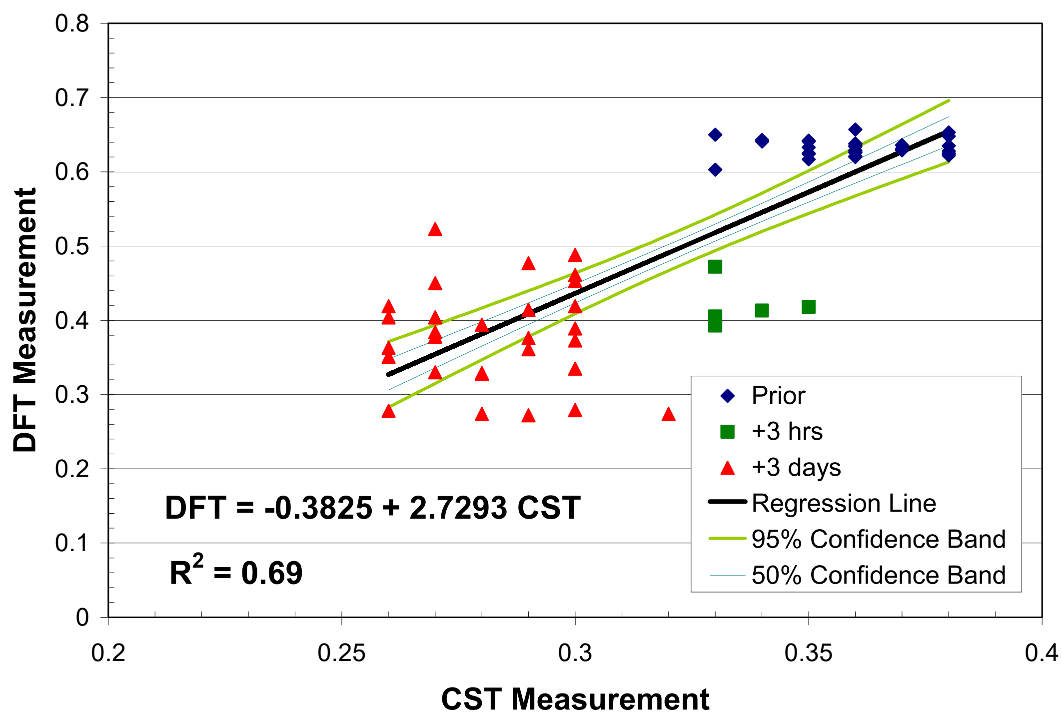

Figure 6.12: DFT measurements versus CST measurements and associated confidence bands.

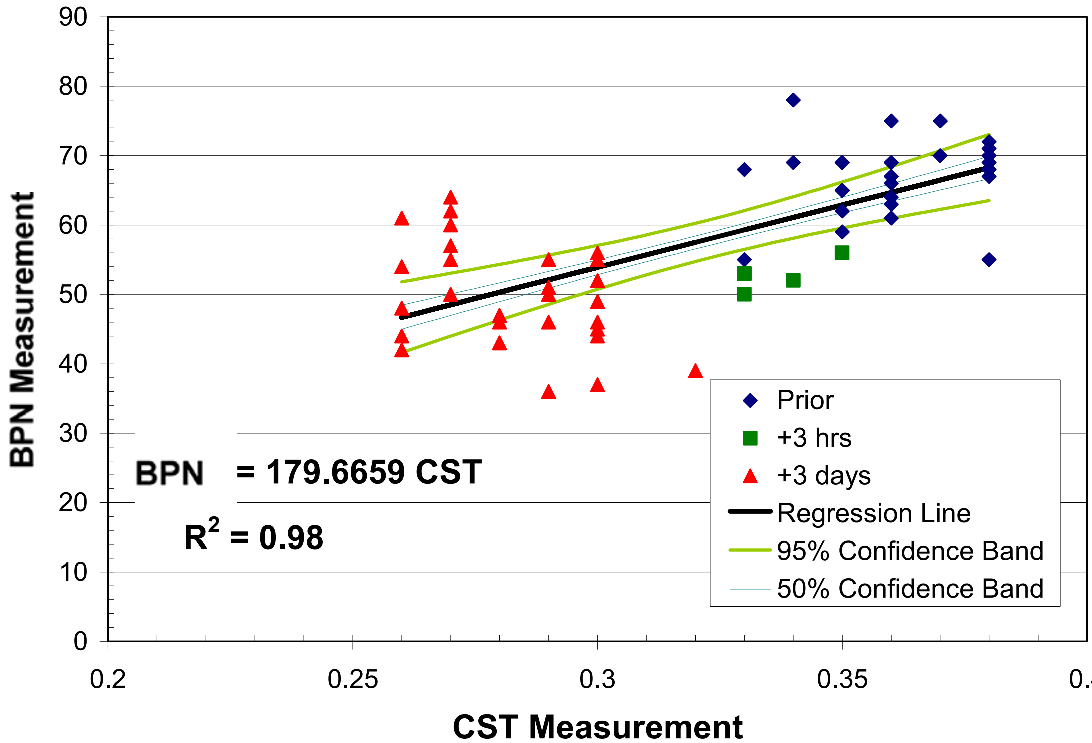

Figure 6.13: BPT measurements versus CST measurements (model without intercept) and associated confidence bands.

Table 6.2: Summary of Regression Analysis

Model Specification	R^2	Residual Standard Error	DOF
$DFT = \underset{(0.0551)}{-0.0668} + \underset{(0.0009)}{0.0089}\, BPN$	0.51	0.1119	85
$DFT = \underset{(0.0002)}{0.0078}\, BPN$	0.94	0.1122	86
$DFT = \underset{(0.0770)}{-0.3825} + \underset{(0.2365)}{2.7293}\, CST$	0.69	0.0754	61
$BPN = \underset{(7.9199)}{-1.4619} + \underset{(24.3429)}{184.1248}\, CST$	0.48	7.7630	61
$BPN = \underset{(2.9825)}{179.6659}\, CST$	0.98	7.7021	62
$CST = \underset{(0.0355)}{0.2595} + \underset{(0.0005)}{0.0008}\, S_P$	0.05	0.0398	61
$CST = \underset{(0.0144)}{0.1753} + \underset{(0.0476)}{0.5000}\, F60$	0.64	0.0244	61
$BPN = \underset{(9.2239)}{35.8547} + \underset{(0.1221)}{0.2790}\, S_P$	0.06	12.4300	85
$BPN = \underset{(3.7089)}{24.2673} + \underset{(13.3349)}{120.9403}\, F60$	0.49	9.1290	85

7 SUMMARY AND RECOMMENDATIONS

This report has summarized the results of an investigation (1) to evaluate the influence of six different rejuvenators used as fog seals on pavement surface friction characteristics over a short time following application and (2) to provide a comparative study of the use of different equipment to evaluate surface friction characteristics. Equipment used in the study included the California Skid Tester (CST), the British Pendulum Tester (BPT), the Dynamic Friction Tester (DFT), and the Circular Track Meter (CTM). Tests using the BPT, DFT, and the CTM were performed by UCPRC staff while Caltrans staff operated the CST. In addition, friction values were determined by the Caltrans staff using their Locked Wheel Skid Trailer (data from these measurements were not used in this study). The purpose of the comparative equipment study was in part to evaluate the suitability of relatively portable equipment to determine pavement surface friction following application of the fog seal. There has been concern that the application of a rejuvenator could reduce pavement friction to a level lower than the minimum permitted by Caltrans. Portable devices like the DFT and BPT offer a suitable alternative to current Caltrans friction measuring devices to provide relatively rapid answers for the level of surface friction following fog seal applications.

The test pavement, located on SR 58 near Mojave, California, included seven 1,000 ft long test sections. These sections included a control section (no rejuvenator applied) and six others, each with a different rejuvenator. Tests were conducted prior to the application of the rejuvenators on June 19, 2007, three hours after application on June 20, and three days later on June 22. The data obtained from the tests are summarized in Chapters 3, 4, and 5. These data were then subjected to regression analyses.

Results of these analyses suggest that both the DFT and BPT could be very useful to check the friction characteristics of fog seals after application to provide guidance as to whether the pavement could be opened directly to traffic or require a light sand application to the pavement surface.

Based on the field study on SR 58 and the resulting analyses, it is recommended that in the near future Caltrans perform a field shadowing study for an approximately six-month period when surface friction measurements are obtained. (N.B. While the control section was not included in the three-hour and three-day friction tests reported herein, it should be included in the six-month program). Accumulated data on pavement friction gathered with DFT, BPT, and CTM—in conjunction with the Lock Wheeled Skid Trailer and the CST units—would provide a suitable basis for deciding whether to use either one or three of the units employed in this study to quickly determine if a fog seal–treated roadway can opened to traffic soon after application. It should be noted that in October 2007, Dr. James Lee of Caltrans proposed a similar one-year study using the DFT and CTM along with the current Caltrans pavement surface friction test equipment (*PowerPoint* presentation by Dr. Lee referred to earlier in this memo).

REFERENCES

1. Lu, Q. and Steven, B. 2006. *Friction Testing of Pavement Preservation Treatments: Literature Review.* Technical memorandum for the California Department of Transportation by the University of California Pavement Research Center, Davis and Berkeley. (UCPRC-TM-2006-10).
2. Steven, B. 2008. *Friction Testing of Pavement Preservation Treatments: Temperature Corrections and Operator/Machine Variability.* Technical memorandum for the California Department of Transportation by the University of California Pavement Research Center, Davis and Berkeley. (UCPRC-TM-2008-05).

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The Authors wish to acknowledge the significant contribution of Mr. David Spinner for his editorial efforts and patience in the preparation of this report.

APPENDIX A: SKID MEASUREMENTS CONDUCTED USING THE CALTRANS SKID TRAILER (ASTM E 274)

In addition to the various skid-measuring equipment used to measure the surface characteristics of the sections to which the rejuvenating agents were applied, the Caltrans skid trailer was used to measure the Skid Number (SN) (ASTM E 274) of the test sections. In the initial measurements obtained with the skid trailer on 6/13/07, SNs were reported only for the six test sections. However, when follow-up measurements were made on 6/20 (24 hours after application), 6/21 (48 hours after application), and 7/03/07 (14 days after application), SNs were obtained for the control section as well as for the six test sections. Table A.1 summarizes skid trailer friction measurements taken on the control section following application of the rejuvenating seals. For comparison, SNs obtained on the six test sections prior to application of the rejuvenating seals are also included. Inspection of this table provides the basis for the statement made in Chapter 2 of this memo that the control section exhibited the same friction characteristics as the six test sections. Accordingly, one can conclude that the initial measurements made using the DFT (Table 3.1), the BPT (Table 3.2), and the CST (Table 3.4) would be representative of the control section had these tests been conducted.

Table A.1: Friction Measurements on SR 58 Using the Caltrans Skid Trailer (ASTM E 274), 6/13 – 7/03/07

	SN40									
	Before Product Application							Control Section		
	All Sections (except the control section)	Section 2 (PM123.485–123.674)	Section 3 (PM123.769–123.958)	Section 4 (PM124.053–124.242)	Section 5 (PM124.337–124.527)	Section 6 (PM124.621–124.811)	Section 7 (PM124.905–125.095)	24 Hours After Product Application	48 Hours After Product Application	14 Days After Product Application
Avg.	51.1	51.2	51.2	51.9	50.7	51.7	52.0	47.6	49.1	51.6
Stdev.	1.105	0.883	1.669	1.345	1.506	0.816	1.549	2.504	3.271	2.56
Min.	48	49	48	50	48	51	50	45	45	48
Max.	53	52	53	53	52	53	54	52	54	55

APPENDIX B: DISCUSSION OF THE USE OF THE CORRELATION TABLE (TABLE 6.1)

The correlation matrix shown in Table 6.1 measures the strength of the linear relationship between pairs of variables. Figure B.1 presents a series of scatter plots of 500 independent pairs of bivariate normal random variables with several correlation coefficients to indicate how the plots look when two normal random variables exist with a certain correlation coefficient.

The corresponding algorithm regarding the generation of correlated random numbers is briefly described in the following discussion making use of a simulation. Its purpose is to present a visual relationship of the correlation coefficient and the random variables. To do this, two correlated random variables with a normal distribution $N(0,1)$, with a mean $\mu = 0$ and a standard deviation $\sigma = 1$, are utilized. The theoretical procedure for generating the correlated random variables is as follows (Spector 1994)[2]:

If $E(X) = \Theta$ and $Var(X) = \Omega$,

then $E(u'X) = u'\Theta$ and $Var(u'X) = u'\Omega u$.

If random variables with $E(X) = \Theta$ and $Var(X) = \mathrm{I}$, i.e., no correlation,

then $E(u'X) = u'\Theta$ and $Var(u'X) = u'u$.

If random variables with $Var(Y) = \Omega$ are selected,

A Cholesky decomposition can be used on $\Omega \Rightarrow u'u$.

Therefore, $Y = u'X$ has $E(u'X) = u'\Theta$ and $Var(u'X) = u'u = \Omega$.

Note that the above-illustrated symbols are in matrix form and *u* represents an upper triangular matrix. The correlation (ρ) of two jointly distributed random variables *X* and *Y* is defined as $\rho = \frac{Cov(X,Y)}{\sqrt{Var(X)} \cdot \sqrt{Var(Y)}}$. Note that *X* and *Y* are random variables with a normal distribution $N(0,1)$, i.e., $Var(X) = Var(Y) = \mathrm{I}$, i.e., $\rho = Cov(X,Y)$.

[2] Spector, Phil. *An Introduction to S and S-Plus*, Duxbury Press, 1994.

Note that the clouds of points in Figure B.1 are roughly elliptical. In Table 6.1, the marginally visible pattern was set at a correlation coefficient value of 0.5 based on a subjective judgment; hence the correlation values greater than 0.5 were highlighted. This shows that the greater the correlation coefficient, the stronger the linear relationship. For example, the Sp (prior) is highly positive-correlated with the F60 (prior) with correlation 0.964.

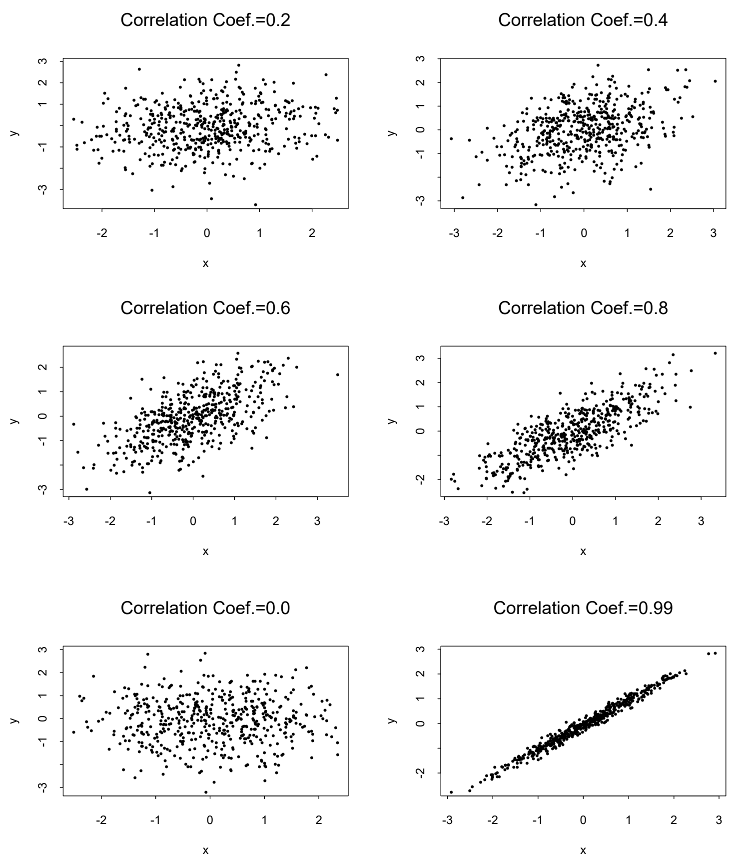

Figure B.1: Scatter plots of 500 independent pairs of bivariate normal random variables. (with correlation coefficients ρ= 0.2, ρ= 0.4, ρ= 0.6, ρ= 0.8, ρ =0.0, and ρ= 0.99).