Characterizing the Macrotexture of Asphalt Pavement Designs in Connecticut

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February 2011

Research Project: SPR-2243

Report 2

Report No. CT-2243-2-10-3

Connecticut Department of Transportation
Bureau of Engineering and Construction

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Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipients Catalog No.**
CT-2243-2-10-3		

4. Title and Subtitle
Characterizing the Macrotexture of Asphalt Pavement Designs in Connecticut

5. Report Date
February 2011

6. Performing Organization Code
SPR-2243

7. Author(s)
John W. Henault

8. Performing Organization Report No.
CT-2243-2-10-3

9. Performing Organization Name and Address

Connecticut Department of Transportation
Division of Research
280 West Street
Rocky Hill, CT 06067-3502

10. Work Unit No. (TRIS)

11. Contract or Grant No.
CT Study No. SPR-2243

13. Type of Report and Period Covered
Report 2
2004-2010

12. Sponsoring Agency Name and Address

Connecticut Department of Transportation
2800 Berlin Turnpike
Newington, CT 06131-7546

14. Sponsoring Agency Code
SPR-2243

15. Supplementary Notes
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract
In response to a Federal Highway Administration Technical Advisory entitled *Surface Texture for Asphalt and Concrete Pavements*, the Connecticut Department of Transportation (ConnDOT) has begun to establish targets for pavement texture depth on high-speed facilities by characterizing the macrotexture of different ConnDOT hot mix asphalt (HMA) pavement mixes. The results of this effort are presented in this paper. Pavements evaluated include SuperPave mixes with nominal maximum aggregate sizes of 0.187-inches, ¼-inch, 3/8-inch and ½-inch. The mean profile depth (MPD) and estimated texture depth of each were measured with a high-speed laser sensor (laser profiler) mounted to ConnDOT's Dynatest 1295 Pavement Friction Tester.

Laser profiler and Circular Track Meter (CTMeter) texture measurements were taken and compared at the Virginia Smart Road facility in Blacksburg, Virginia, in order to validate previously taken laser profiler measurements in Connecticut. Validation of the laser profiler measurements was necessary because laser profilers have not been used extensively in practice. The linear association comparing measurements taken with these two devices was relatively strong (R^2=0.80) The laser profiler appears to provide a viable macrotexture measurement.

MPD was the measure used to characterize the macrotexture of the above ConnDOT HMA mixes. The characterizing MPDs measured for the ConnDOT mixes ranged between 21 to 22-mils for the ½-inch mix, 15-mils for 3/8-inch mix, 12 to 15-mils for the ¼-inch mix, and -1 to 4 mils for the 0.187-inch mix.

17. Key Words
Pavement Friction Testing, Skid Testing, Connecticut Department of Transportation, ConnDOT, Locked-Wheel Friction Tester

18. Distribution Statement
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19. Security Classif. (Of this report)	**20. Security Classif.(Of this page)**	**21. No. of Pages**	**20. Price**
Unclassified	Unclassified	47	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Connecticut Department of Transportation (ConnDOT) and the U.S. Federal Highway Administration. The authors extend a special thanks to Messrs. Jeffery Scully and Eric Feldblum for their contributions to the research, which included taking field measurements. Ms. Susan Hulme is acknowledged for providing administrative assistance and Mr. James Sime for providing project oversight. The authors thank Transportation Pooled Fund Study TPF-5(141) participants, the Virginia Department of Transportation, and Virginia Tech. Finally, the authors thank Mr. Edgar de León Izeppi for reviewing a draft of this report.

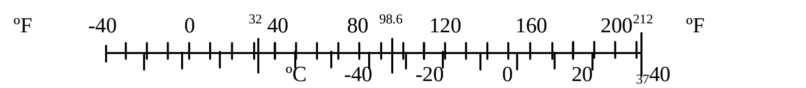
METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
ac	Acres	0.405	hectares	ha
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb.)	0.907	Megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	ºC

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
km^2	square kilometers	0.386	square miles	mi^2
ha	hectares (10,000 m^2)	2.47	acres	ac
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	Megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 (then add 32)	Farenheit temperature	ºF



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INTRODUCTION

Most tire-road interactions are determined by a pavement's surface texture. These interactions include wet friction, splash and spray, noise, rolling resistance, and tire wear *(1)*. Friction is not a natural property of pavement, but is a culmination of many factors that play a specific role in the process. Tire properties such as inflation pressure and the design and condition of the tread play an important role in pavement friction. Environmental factors such as temperature and the presence of water, snow, and ice are also significant *(2)*. The factors that are within a highway agency's control, however, are pavement surface characteristics such as microtexture (wavelength is λ<0.02-inches), macrotexture (λ=0.02 to 2-inches), material properties, and vehicle operating parameters *(2)*. Flintsch et al. provided a thorough explanation of pavement surface texture in a paper published in a 2003 Transportation Research Record *(1).*

Volumetric methods such as the sand patch method *(3)* and the putty method measure the average diameter of a known volume of material spread evenly over the surface of the pavement. The sand patch method uses the measured diameter to calculate the mean texture depth (MTD) of a pavement surface, while the putty method can be used as a relative measurement of pavement macrotexture. The Outflow Meter Test is also a volumetric test, but instead uses water to fill the voids and measures the drainage rate through the surface texture. This test gauges the escape time of water beneath a moving tire and indicates the hydroplaning potential of a surface *(2)*. The sand patch method, however, is the most recognized static method and is still commonly used as the ground-truth standard.

The circular track meter (CTMeter) is a portable surface macrotexture profiling device that uses a charge coupled device (CCD) laser displacement sensor. The CTMeter measures the pavement texture of a static location using a laser mounted on a rotating arm. The arm rotates at a fixed height of 3.15-inches and records the mean profile depth (MPD) and the root mean square (RMS) of eight equal segments of a circle 11.2 inches in diameter or 35 inches in circumference *(4)*. These data are recorded on a laptop computer which processes the average of each of the mean segment depths of all of the segments of the profile, known as the MPD *(5)*. The reported MPD is the average of these eight segments. The software program can process and hold up to eight texture measurements per file. The CTMeter weighs approximately 29-lbs (13 kgs) and it must be connected to a power source at all times in order to collect data *(5)*.

All of these static methods require traffic protection and lane closures. Conversely, dynamic devices, such as laser profilers, allow measurements to be taken at high-speed without protection. The leading high-speed friction testing device in the U.S. is the locked wheel friction tester *(2)*, but this device can also be used to measure pavement texture when equipped with a high-speed laser profiler. The device consists of a locked-wheel skid trailer which is pulled by a tow vehicle and can perform tests using either an ASTM E 501 *(6)* standard ribbed tire or an ASTM E 524 *(7)* standard smooth tire. Measurements are taken by locking the test wheel on wet pavement at 40 mi/hr (64 km/hr) *(8)*. Smooth test tires are more sensitive to pavement macrotexture, while the ribbed tire is more sensitive to microtexture *(2)*. This is because standing water can escape through the ribs of the tire rather than being forced through the voids in the macrotexture *(2)*. The use of texture measurement in combination with friction test results provides a more comprehensive representation of pavement surface characteristics.

The estimated texture depth (ETD), MPD and MTD are the most common texture measurements used to describe pavement texture. For calculating MPD, ASTM E 1845 *(9)* states that the baselength of a segment of pavement macrotexture profile must be 3.94-inches (100mm). The difference between the amplitude measurements of pavement macrotexture and a horizontal line through the top of the highest peak within a given baselength is called the profile depth (PD). The mean segment depth is the average value of the PD of two halves of a segment having a given baselength, and the average of all of the mean segment depths for all of the segments in a profile is called the MPD. By means of a linear transformation of the MPD, an ETD can be derived. The ETD can then be compared to a MTD of the pavement surface macrotexture determined by the volumetric technique of ASTM Test Method E 965. In effect, the MPD is a two-dimensional estimate of the three-dimensional MTD *(1)*.

BACKGROUND

In September 2004, the Connecticut Department of Transportation (ConnDOT) initiated a research study entitled, "Enhancements to ConnDOT's Pavement Friction Testing Program," State Planning and Research (SP&R) study SPR-2243. Objectives of this ongoing research study include developing speed gradients for ConnDOT pavements, investigating the relationship between pavement texture and friction, and evaluating the potential use of the International Friction Index (IFI) in Connecticut *(10)*. The scope of the entire research project is broad; therefore, the focus of this report is concentrated on characterizing pavement macrotexture in Connecticut.

Part of this effort to characterize pavement macrotexture is to begin taking the first steps in establishing texture depth targets for new and in-service pavement surfaces in Connecticut.

A Federal Highway Administration (FHWA) Technical Advisory states "providing adequate texture depth has been shown to improve pavement friction test results at high speeds and reduce crash rates on high speed facilities." The advisory suggests these targets be established by owner-agencies based upon project specific factors, such as roadway geometry *(11)*.

A new Dynatest 1295 Pavement Friction Tester was purchased in 2005 as part of this project. An upgrade from the previous tester includes the addition of a High-Speed Selcom Optocator/SLS5000 Laser Sensor (laser profiler) for measuring pavement texture at high speeds. The sensor is mounted on the driver's side between the front and rear wheels of the tow vehicle. The quality record provided by Dynatest indicates that the sampling frequency of the sensor is 78 kHz, the bandwidth is 30 kHz, and the scale factor is 0.00126 inches/LSB (+/- 1%). It has a stand-off distance of up to 13.35 inches and the measurement range is 5 inches (-0%/+2.4%).

The single point, non-contact laser profiler industrial gauging sensor is aligned with the left wheel path and takes measurements over 4-inch (100-mm) segments in accordance with ASTM E 1845. Segment calculations are averaged over a length called a section, with typical section lengths equaling 0.01 miles. For each section, the device calculates and reports MPD, ETD, standard deviation of the texture, mile post and speed of the friction tester as it moves along a driven path. Test data are relayed to a laptop computer inside the cab of the friction tester *(12)*.

For comparison to the aforementioned laser profiler, a Nippo Sangyo Co., Ltd. Circular Track Meter was purchased in 2006. Pavement macrotexture profiles were measured with the CTMeter in accordance with ASTM Standard E 2157. The purpose of comparison was to determine if the laser profiler macrotexture measurements correlated well with the CTMeter measurements obtained in accordance with the above ASTM test method and whether or not the laser profiler could provide viable results.

In the fall of 2007, ConnDOT joined Transportation Pooled Fund Study TPF-5(141), "Pavement Surface Properties Consortium: A Research Program." The Virginia Department of Transportation is the lead agency and the contractor is Virginia Tech. The contract amount is over $720,000 and it has 100% SP&R approval *(13)*. This pooled-fund study compliments ConnDOT's own SPR-2243 study because its objective is to enhance "the level of service provided by the roadway transportation system through optimized pavement surface texture characteristics." Study partners include the FHWA, Georgia, Mississippi, Pennsylvania, South Carolina and Connecticut. The pooling of technical expertise from these other state agencies and Virginia Tech has been extremely beneficial to Connecticut's friction testing program thus far.

As part of this pooled-fund study, ConnDOT participated in an equipment comparison and verification roundup held at the Virginia Tech Transportation Institute's Smart Road facility in Blacksburg, Virginia, in the spring of 2008. While participating in this roundup, ConnDOT engineers were able to measure the macrotexture of several different pavement designs using both their laser profiler and their CTMeter static device. Results of this comparison are presented in this paper.

Validation of the CTMeter with the Sand Patch Method

In a paper published in the Transportation Research Record series in 2005, Hanson and Prowell *(14,15)* concluded that the CTMeter "…produces results comparable with the ASTM E 965 sand patch test." They found that the offset between the CTMeter and sand patch test results was insignificant when open-graded mixtures were excluded.

Flintsch et al. *(1)* concluded that CTMeter macrotexture measurements correlated excellently with sand patch measurements. They found a coefficient of determination (R^2) of 0.94, which is a nearly perfect correlation (R^2=1). They also compared macrotexture measurements taken with a non-contact laser profiler to measurements taken with the sand patch test. They found a strong correlation between the profile-based macrotexture and the sand patch measurements (R^2=0.88). Note that Flintsch et al. indicated that the sand patch test is still widely used as the ground-truth reference because it has been used for many years and significant data are available from earlier studies.

A study on the 2000 National Center for Asphalt Technology (NCAT) Test Track *(14,15)* attempted to evaluate the CTMeter in terms of accuracy, repeatability and reproducibility in comparison with the sand patch method. The results indicated that there is a "strong relationship between the MPD measured by the CTMeter and the MTD determined from the sand patch test" *(14,15)*. Another study by Abe et al. *(16)* put forward this equation describing the relationship between the sand patch and CTMeter test methods: $MTD = 1.03 \times MPD + 0.15$ where MTD and MPD are in mm *(16)*. However, the results from the NCAT test track show that the sand patch method does tend to over estimate open graded friction coarse (OGFC) texture when compared to laser-based methods including the CTMeter *(14,15)*.

In addition, two separate reports based on tests performed at the Virginia Smart Roads test track affirm the remarkable accuracy of the CTMeter to the results obtained by the sand patch method *(1,17)*. The same reports also concluded that a strong agreement existed between the measurements by high-speed laser profile systems and the static sand patch method *(1,17)*. One report *(1)*, however, found that although the correlation was strong, it was different than the one provided in ASTM E-1845. This deficiency was attributed to a possible bias in the particular laser profiler used in the test, or to a difference in the algorithm that was used to calculate the macrotexture*(1).*

In the research study presented here, the CTMeter was used as the ground-truth reference. Considering the lack of repeatability in the sand patch test noted above, perhaps the CTMeter will provide a better ground-truth because it does not appear to be as operator dependent. Additionally, the above-cited research work gives the CTMeter more credibility because it improves the availability of earlier research results that were previously lacking.

OBJECTIVE AND SCOPE

The primary objective of this paper is to characterize the macrotexture of four different ConnDOT SuperPave hot mix asphalt (HMA) pavement designs. The nominal maximum aggregate size for these designs ranged from 0.187 to ½-inch.

The scope of this paper also includes a presentation of the laser profiler versus CTMeter macrotexture measurement comparisons performed at the Virginia Smart Road facility.

CTMeter measurements were taken with the ConnDOT instrument and also with Virginia Tech’s CTMeter on twelve different pavement designs. This paper presents measurements taken with ConnDOT’s CTMeter. Three CTMeter measurements were taken and averaged for each pavement design. These pavement designs encompassed a wide range of textures, from fine to coarse. The goal of these comparisons was to provide some validation of the laser profiler macrotexture measurements as they compared to the CTMeter measurements obtained in accordance with ASTM E 2157.

DATA ANALYIS

Laser Profiler versus CTMeter

Virginia Smart Road

In May of 2008, ConnDOT engineers drove their pavement friction tester to the Virginia Smart Road facility at Virginia Tech to participate in an equipment roundup, as part of Transportation Pooled Fund Study TPF-5(141), along with some of the other participant states: Mississippi, South Carolina, Virginia, and Pennsylvania. Pavement macrotexture profiles were measured for twelve different pavement designs using the CTMeter and the ConnDOT laser profiler. Eastbound and westbound sections were tested for each pavement, so a total of 24 sections were tested. Virginia Tech also measured macrotexture profiles with their CTMeter.

The pavement designs selected for analysis were labeled: Loop, A, B, C, D, I, J, K, L, EP5, Cargill, and CRCP. Table 1 presents a description, MPDs measured with ConnDOT's CTMeter, MPDs measured with VA Tech's CTMeter, and MPDs measured with ConnDOT's high speed laser. Note: the CTMeter MPD values presented are actually an average of three measurements taken for each pavement in the same wheel path traveled by the laser profiler.

Figure 1 below shows the approximate locations of the three CTMeter tests taken on the driver's side wheel path for each section. The high-speed laser measured the macrotexture of each section along the entire length of the section's driver-side wheel path. Therefore, while the CTMeter and the high-speed laser measured the MPD of the same sections, different profiles were examined. Conversely, when comparing the ConnDOT CTMeter to the Virginia Tech CTMeter, the tests where conducted within the same footprint, as the outline of the lead CTMeter was traced onto the pavement for locating the second CTMeter in the same exact location. One would therefore expect the two CTMeters to correlate better to one another than to the high-speed laser.

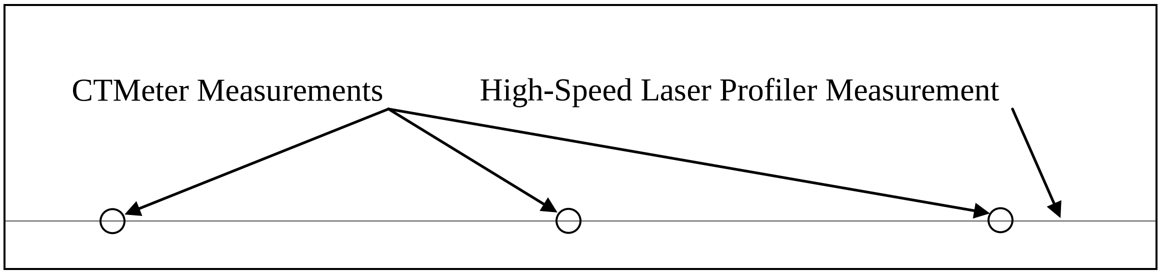

FIGURE 1 Sketch of MPD measurement locations within each test section.

TABLE 1 Laser Profiler vs. CTMeter MPD Values at Virginia Smart Road

Pavement Design Sections	Description	MPD Measured with ConnDOT CTMeter mils (mm)	MPD Measured with VTech CTMeter[1] mils (mm)	MPD Measured with Laser Profiler mils (mm)
Eastbound				
Loop	SMA 19.5	36 (0.91)	39 (0.99)	43 (1.09)
A	SM 12.5D	20 (0.51)	21 (0.53)	19 (0.48)
B	SM 9.5D	26 (0.66)	27 (0.69)	19 (0.48)
C	SM 9.5E	27 (0.69)	28 (0.71)	29 (0.74)
D	SM 9.5A	21 (0.53)	22 (0.56)	18 (0.46)
I	SM 9.5A*	37 (0.94)	36 (0.91)	25 (0.64)
J	SM 9.5D	41 (1.04)	41 (1.04)	31 (0.79)
K	OGFC	63 (1.60)	64 (1.63)	68 (1.73)
L	SMA 12.5+	36 (0.91)	39 (0.99)	43 (1.09)
Cargill	Special Surface	67 (1.70)	72 (1.83)	30 (0.76)
EP5	Special Surface	46 (1.17)	47 (1.19)	31 (0.79)
CRCP	Concrete Section	28 (0.71)	28 (0.71)	18 (0.46)
Westbound				
CRCP	Concrete Section	30 (0.76)	32 (0.81)	27 (0.69)
Cargill	Special Surface	75 (1.91)	73 (1.85)	25 (0.64)
EP5	Special Surface	47 (1.19)	46 (1.17)	54 (1.37)
L	SMA 12.5+	41 (1.04)	43 (1.09)	44 (1.12)
K	OGFC	65 (1.65)	71 (1.80)	63 (1.60)
J	SM 9.5D	33 (0.84)	33 (0.84)	56 (1.42)
I	SM 9.5A*	28 (0.71)	29 (0.74)	29 (0.74)
D	SM 9.5A	27 (0.69)	27 (0.69)	27 (0.69)
C	SM 9.5E	31 (0.79)	31 (0.79)	31 (0.79)
B	SM 9.5D	42 (1.07)	40 (1.02)	37 (0.94)
A	SM 12.5D	35 (0.89)	35 (0.89)	28 (0.71)
Loop	SMA 19.5	31 (0.79)	31 (0.79)	49 (1.24)

The CTMeter MPD values ranged from 20 to 73 mils (0.51 to 1.85 mm), while the high-speed laser values ranged from 18 to 68 mils (0.46 to 1.73 mm); therefore, a relatively large range existed for the sample data. It is highly desirable to have a large range of data when trying to identify significant relationships between variables.

First, MPD values measured with the ConnDOT CTMeter were compared to those measured with the Virginia Tech CTMeter. Figure 2 presents a scatter plot with the ConnDOT results on the x-axis and the Virginia Tech results on the y-axis. The coefficient of determination was extremely high (R^2 = 0.99) and the slope was 1.0. This indicates a very strong correspondence between these variables.

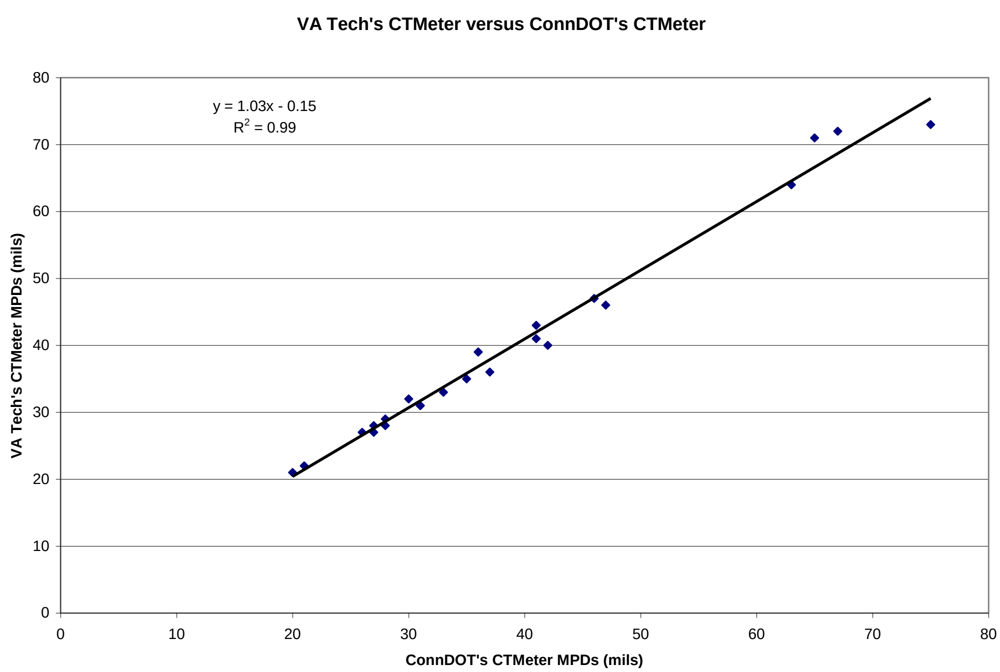

FIGURE 2 VA Tech's CTMeter versus ConnDOT's CTMeter MPD values.

Figure 3 presents a scatter plot showing the relationship between MPD values measured with the high-speed laser profiler and MPD values measured with the ConnDOT CTMeter. When examining the entire dataset, the coefficient of determination was low ($R^2 = 0.21$).

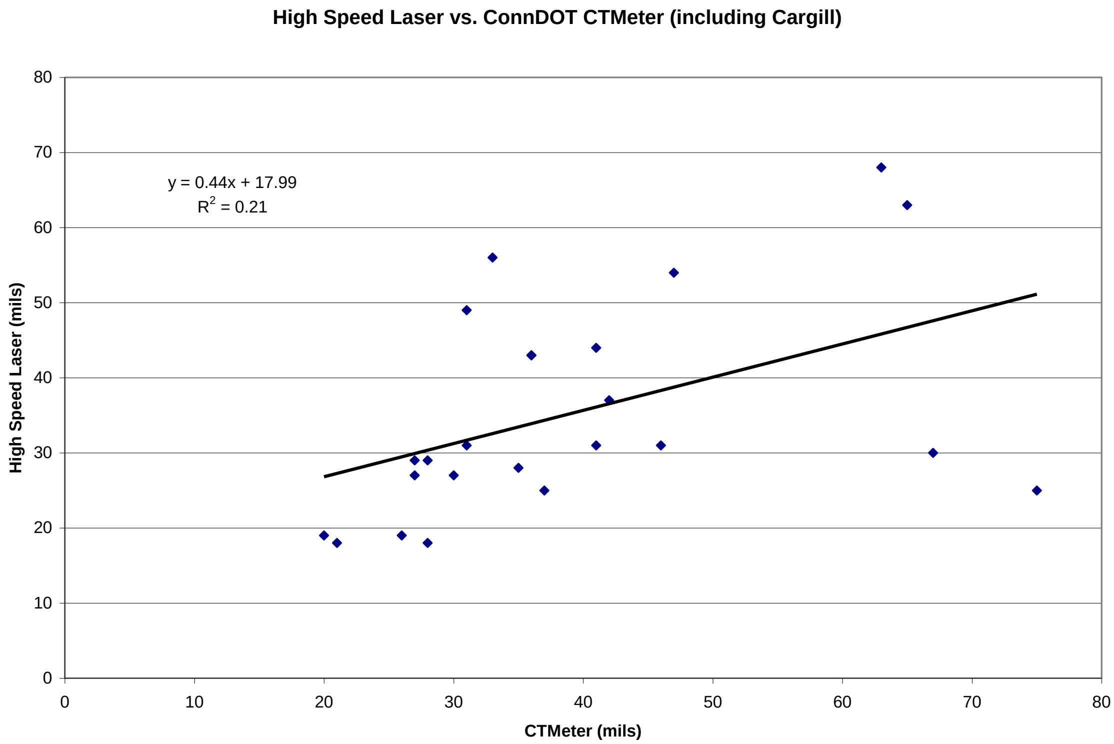

FIGURE 3 Scatter plot of high speed laser MPDs versus ConnDOT CTMeter MPDs for all sections.

The Cargill and EP5 pavement textures were quite different from the other pavements, and the MPD values between the high speed laser and CTMeters differed considerably. Cargill and EP5 pavements are also quite different than any pavements used in Connecticut. Therefore, another trend line was generated with these sections removed from the dataset. This made a significant difference, as the R^2 value increased to 0.65. Since the two devices essentially measure entirely different samples of the same population (every square inch of pavement surface), an R^2 value of 0.65 seems good. However, it depends upon the homogeneity of the pavement sections.

The slope of the trend line also improved from 0.44 to 1.02 after removing the Cargill and EP5 sections from the data set. A slope of 1.02 suggests a better one-to-one correspondence between the instruments.

FIGURE 4 Close-up photo of Cargill pavement.

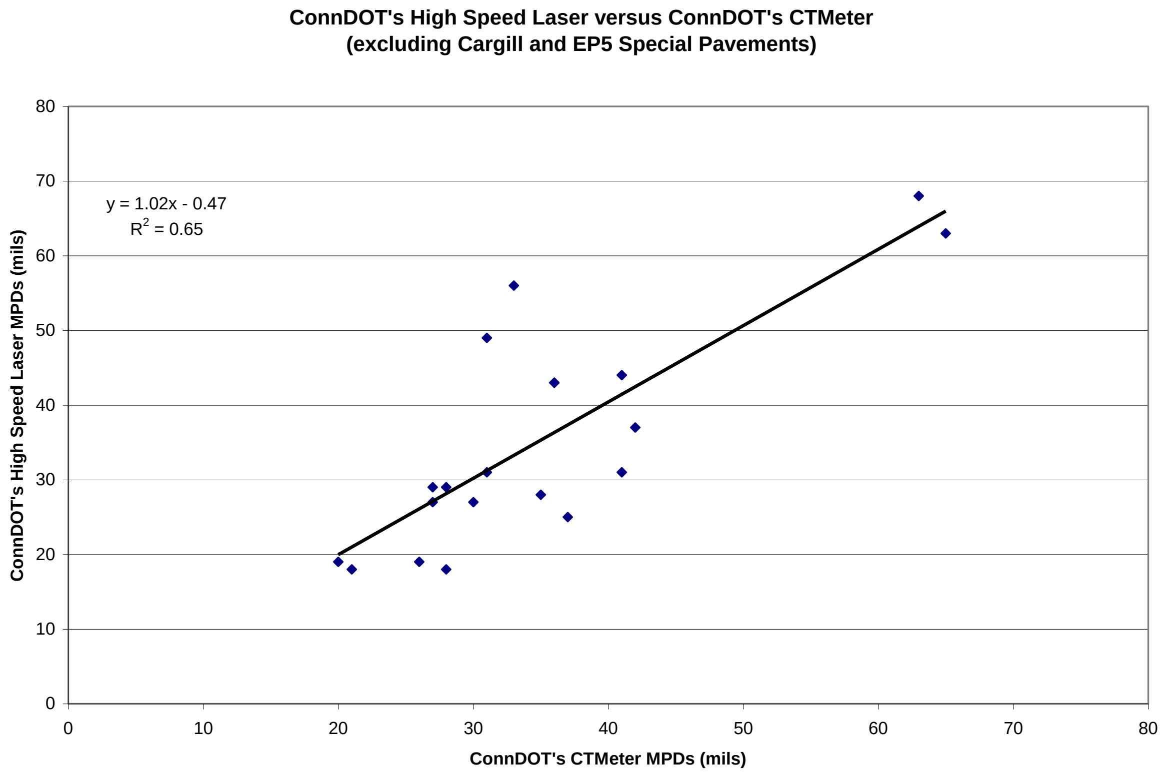

FIGURE 5 Scatter plot of high speed laser MPDs versus ConnDOT CTMeter MPDs (exluding Cargill and EP5 special pavements).

LTPP SPS 9A Test Section

During the fall of 2009, both high-speed laser and CTMeter texture measurements were taken on six different FHWA Long-Term Pavement Performance (LTPP) Special Pavement Study (SPS) 9A Test Sections (090901, 090902, 090903, 090960, 090961, and 090962). These were all located on CT State Route 2 in Colchester, Lebanon, and Bozrah. Each section was 500 feet long. The high-speed laser measurements were taken in the left wheel path of the low-speed lane for the entire 500-ft length, while eight separate CTMeter measurements were taken in the left wheel path of each of the low-speed lanes spread out along the 500-ft length. Note: only six CTMeter measurements were taken at Site 090901. MPD measurements are tabulated in Table 2, and a scatter plot of the high-speed laser measurements versus the CTMeter measurements is presented in Figure 6.

Table 2 Texture Measurements taken on LTPP SPS 9A Test Sections

LTPP Section	Average MPD measured with CTMeter mils (mm)	Average MPD measured with High-Speed Laser mils (mm)
090901	32 (0.81)	19 (0.48)
090902	41 (1.04)	23 (0.58)
090903	36 (0.91)	20 (0.51)
090960	40 (1.02)	22 (0.56)
090961	50 (1.27)	40 (1.02)
090962	52 (1.32)	43 (1.09)

In looking at the scatter plot in Figure 6, it can be seen that the high-speed laser MPD measurements corresponded well with the CTMeter measurements, as the R^2 value was 0.92. Granted, there were only six sites, but this level of correspondence provides a positive indication. Furthermore, when the correspondence found here is considered in combination with that found for the Virginia Smart Road sites (excluding Cargill and EP5 Special Pavements), confidence in the high-speed instrument is realized.

It should be noted that using the formula shown if Figure 6 and solving for x when y = 0, a value of 20.7 mils (0.53 mm) was calculated. This may explain why some very low MPD values were measured with the high-speed laser, and why some values were even negative. So, high-speed laser MPD values of 0 relate to CTMeter MPD values of approximately 20.7 mils (0.53 mm).

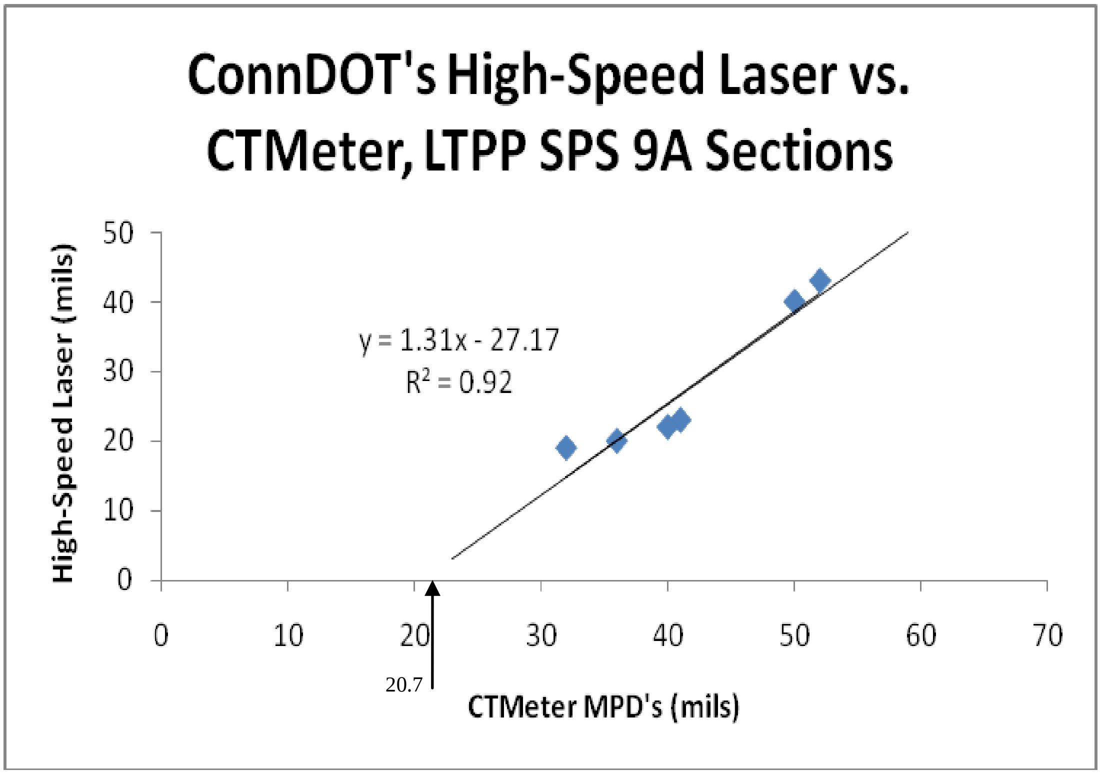

FIGURE 6 Scatter plot of high-speed laser versus CTMeter MPD measurements taken on six LTPP SPS 9A Sections on CT State Route 2 in Colchester, Lebanon, and Bozrah.

ConnDOT Pavements

Macrotexture profiles and skid resistances were measured with ConnDOT's Dynatest 1295 Pavement Friction Tester. Profiles were measured with the laser profiler device mounted to the friction tester, and then MPD and ETD values were calculated programmatically in accordance with ASTM E 1845 from these profiles for each of the pavements examined. MPD values are presented in Table 3. The skid resistances of these paved surfaces were measured using both a full-scale ASTM E 501

Standard Ribbed Tire and an ASTM E 524 Standard Smooth Tire in accordance with ASTM E 274. Friction numbers were calculated based on a corrected speed of 40 mph for the ribbed tire tests using a speed gradient of 0.5. No speed corrections were applied for the smooth tire friction tests; however, the tests were performed at approximately 40 mph. Friction test results are presented in Table 4.

TABLE 3 Macrotexture Mean Profile Depth (MPD) Descriptive Statistics

Nominal Max Size Aggregate		0.187-in (#4 Mix)	0.187-in (#4 Mix)	¼-inch (#6 Mix)	¼-inch (#6 Mix)	3/8-inch	3/8-inch	½-inch	½-inch	½-inch
Location		Route 2 EB	Route 9 NB	I-91 NB	I-84 WB	I-91 NB	I-91 NB	Route 411 W	Route 411 W	Route 411 W
Town		Colchester	Haddam	Cromwell	Vernon	North Haven	North Haven	Rocky Hill	Rocky Hill	Rocky Hill
Milepost		20.59 -22.71	17.69 -18.84	27.71-33.68	75.76-75.11	4.80-8.43	4.80-8.43	1.44-1.00	1.44-1.00	1.44-1.00
Date Measured		10/19/05	8/8/06	5/8/07	11/28/07	4/30/07	5/3/07	4/30/07	5/8/07	11/28/07
Year Paved		2004	2004	2006	2007	2004	2004	2005	2005	2005
Case Number		1	2	3	4	5	6	7	8	9
n		234	127	177	427	399	399	45	44	45
Mean	(inches)	0.007	0.002	0.012	0.015	0.015	0.015	0.021	0.022	0.021
	(mm)	0.18	0.05	0.30	0.38	0.38	0.38	0.53	0.56	0.53
Median	(inches)	0.004	-0.001	0.011	0.015	0.015	0.014	0.021	0.022	0.02
	(mm)	0.10	-0.03	0.28	0.38	0.38	0.36	0.53	0.56	0.51
Mode	(inches)	0.003	-0.001	0.011	0.014	0.015	0.014	0.017	0.02	0.018
	(mm)	0.08	-0.03	0.28	0.36	0.38	0.36	0.43	0.51	0.46
Std. Dev.	(inches)	0.0129	0.0088	0.004	0.0029	0.0027	0.0027	0.0039	0.0044	0.0032
	(mm)	0.328	0.224	0.102	0.074	0.069	0.069	0.099	0.112	0.081
Range	(inches)	0.083	0.049	0.020	0.016	0.019	0.023	0.017	0.016	0.014
	(mm)	2.11	1.24	0.51	0.41	0.48	0.58	0.43	0.41	0.36
Minimum	(inches)	0.002	-0.002	0.006	0.008	0.01	0.008	0.016	0.015	0.017
	(mm)	0.05	-0.05	0.15	0.20	0.25	0.20	0.41	0.38	0.43
Maximum	(inches)	0.085	0.047	0.026	0.024	0.029	0.031	0.033	0.031	0.031
	(mm)	2.16	1.19	0.66	0.61	0.74	0.79	0.84	0.79	0.79
25th	(inches)	0.003	-0.001	NA	0.013	0.013	0.013	0.018	0.019	0.018
Percentile	(mm)	0.08	-0.03		0.33	0.33	0.33	0.46	0.48	0.46
75th	(inches)	0.005	0	NA	0.017	0.016	0.016	0.024	0.025	0.023
Percentile	(mm)	0.13	0.00	NA	0.43	0.41	0.41	0.61	0.64	0.58

TABLE 4 Friction Test Results

Nom. Max Size Aggregate	0.187-in (#4 Mix)	0.187-in (#4 Mix)	¼-inch (#6 Mix)	¼-inch (#6 Mix)	3/8-inch	3/8-inch	½-inch	½-inch	½-inch
Location	Route 2	Route 9	I-91	I-84	I-91	I-91	Route 411	Route 411	Route 411
Town	Colchester	Haddam	Cromwell *a*	Vernon	North Haven	North Haven	Rocky Hill	Rocky Hill	Rocky Hill
Direction	EB	NB	NB	WB	NB	NB	WB	WB	WB
Milepost	20.59-22.71	17.69-18.84	27.71-33.68	75.76-75.11	4.80-8.43	4.80-8.43	1.44-1.00	1.44-1.00	1.44-1.00
Date Measured	10/19/05	8/8/06	5/8/07	11/28/07	4/30/07	5/3/07	4/30/07	5/8/07	11/28/07
Year Paved	2004	2004	2006	2007	2004	2004	2005	2005	2005
Case Number	1	2	3	4	5	6	7	8	9
FN_{40R}[a]									
n	15	16	34	19	19	*b*	7	7	7
Mean	63.3	56.4	55.5	58.3	52.4	-	45.7	45.6	47.1
Standard Deviation	1.4	1.7	2.0	1.7	1.6	-	1.8	3.6	2.1
Range	4.4	6.4	9.0	5.5	5.5	-	5.1	10.9	5.7
Minimum	61.6	53.8	53.0	54.5	49.0	-	42.9	39.3	43.8
Maximum	66.0	60.2	62.1	60.0	54.5	-	48.0	50.2	49.5
FN_S[c]									
n	16	25	33	17	*d*	19	*d*	*d*	*d*
Mean	47.8	26.6	45.3	64.3	-	42.0	-	-	-
Standard Deviation	3.8	3.8	3.3	3.2	-	3.2	-	-	-
Range	15.2	16.3	14.7	13.2	-	12.3	-	-	-
Minimum	39.3	17.7	37.0	56.5	-	34.7	-	-	-
Maximum	54.5	34.0	51.7	69.7	-	47.0	-	-	-

[a] friction number based on corrected speed of 40 mph with E501 Standard Ribbed Tire.

[b] friction tests were performed with an E524 Standard Smooth Tire only.

[c] friction number measured with a E524 Standard Smooth Tire.

[d] friction tests were performed with an E501 Standard Ribbed Tire only.

TABLE 5 Job Mix Formulas for Pavement Designs, Percent Passing

Sieve Size	0.187-inch SuperPave (% Passing)	0.25-inch SuperPave (% Passing)	3/8-inch SuperPave (% Passing)	½-inch SuperPave (% Passing)
#200	6.0	5.0	3.0	3.0
#100	11.0	8.0	8.0	8.0
#50	20.0	13.0	14.0	15.0
#30	33.0	20.0	23.0	24.0
#16	50.0	33.0	32.0	33.0
#8	78.0	50.0	47.0	43.0
#4	96.0	69.0	68.0	57.0
3/8"	100.0	97.0	97.0	79.0
½"	100.0	100.0	100.0	98.0
¾"	100.0	100.0	100.0	100.0

ConnDOT 0.187-inch Mix

A SuperPave mix with a 0.187-inch nominal maximum aggregate size was tested on October 19, 2005. This is commonly referred to as the #4 mix because the #4 sieve opening is 0.187-inches. This pavement was constructed in 2004 and was the finest pavement design of the four measured. The pavement tested on this date was located on Route 2 EB in Colchester, CT, from 20.59-22.71 miles as per the ConnDOT Highway Log. The mean MPD measured for this pavement was 7 mils (1 mil=0.001 inch) (0.18mm). In this instance, the mean is not the most descriptive statistic to use because these data were not normally distributed. The 25th percentile for this data set was 3 mils (0.08 mm) and the 75th percentile was 5 mils (0.13 mm). The median was 4 mils (0.10 mm) and appears to characterize the MPD better in this case. The 25th percentile ETD was 7 mils (0.18 mm) and the 75th percentile ETD was 8 mils (0.20 mm). The ETD values were also clustered, and reporting to the nearest one thousandth of an inch, the median was 8 mils (0.20 mm) (same as 75th percentile due to rounding).

The average calculated friction number measured with a ribbed tire and based on a corrected speed of 40 mph (FN_{40R}) was 63.3. FN_{40R} values ranged from 61.6 to 66.0, and the standard deviation was 1.4. The average smooth tire friction (FN_S) was 47.8, and the FN_S values were more variable, as the standard deviation was 3.8. Based on these data, an adequate level of friction existed for this pavement at the time it was tested; however, these tests were performed just one year after construction. The friction has likely decreased since that time, especially the FN_S values considering that the average MPD was just 7 mils (0.18 mm).

Another 0.187-inch mix was tested on August 8, 2006. This pavement section was located on Route 9 NB in Haddam from 17.69-18.84 miles. The same clustering of values was observed for this 0.187-inch pavement, and for the aforementioned reasons, the median seems to be more descriptive of the macrotexture than the mean. The mean MPD and ETD values for this pavement were only 2 mils (0.05 mm) and 9 mils (0.23 mm), respectively; while the median MPD and ETD values were -1 mil (-0.03 mm) and 7 mils (0.18 mm), respectively. These were by far the lowest MPD and ETD values measured of the four different pavement designs investigated, and compared to the other pavements; the 0.187-inch mix has virtually no texture to speak of.

Upon closer examination of the job mix formulas (JMFs) contained in Table 4, it is not surprising that the 0.187-inch mix had such lower MPD and ETD values. There are significant differences between the percents passing the sieves for the 0.187-inch mix and the ¼-inch mix. The 0.187-inch mix is much finer, with 96-percent of the mass passing the #4 sieve for the 0.187-inch mix and only 69-percent passing the #4 sieve for the ¼-inch mix. The difference between the ¼-inch mix and the 3/8-inch mix is much more subtle. In fact, the ¼-inch and the 3/8-inch particle-size distributions are very similar from the #200 sieve up to the ½-inch sieve. Both the ¼-inch and 3/8-inch mixes evaluated in this study fall within the particle-size distribution master ranges of the former ConnDOT Class 2 mix contained in ConnDOT's Standard Specifications *(18)*.

The average FN_{40R} for this pavement was 56.4, and the standard deviation was 1.7. The FN_S values were lower for this 0.187-inch mix, as the average was just 26.6. Studies have shown that pavements with FN_S of less than 25 have higher incidents of wet weather accidents (*19,20)*. Note that the pavement was only 2 years old when these tests were performed. It is surmised that the lower FN_S values owe largely to this pavement's fine macrotexture because, as previously stated, smooth tires are more sensitive to macrotexture *(2)*. Conversely, FN_{40R} values remained relatively high because the ribbed tire is more sensitive to the microtexture *(2)*.

ConnDOT ¼-inch Mix

On May 8, 2007 a SuperPave mix with ¼-inch nominal maximum aggregate size was tested. This is referred to as the SuperPave No. 6 mix in Connecticut because the soft metric conversion from ¼-inch is 6 mm. To avoid confusion, this will be referred to as the ¼-inch mix in this paper. This ¼-inch mix was located on intermittent sections of Interstate 91 NB from 27.71 to 33.68 miles. The mean MPD and ETD values for this pavement were 12 and 18 mils (0.30 and 0.46 mm), respectively, and the median values were 11 and 17 mils (0.28 and 0.43 mm). A histogram of the MPD values is presented in Figure 7. The MPD and ETD values are normally distributed for this pavement. This distribution is typical of the ¼-inch, 3/8-inch, and ½-inch mixes.

FN_{40R} values ranged from 53.1 to 62.1, the average was 55.5, and the standard deviation was 2.0. FN_S values ranged from 37.0 to 51.7, the average was 45.3, and the standard deviation was 3.3. Therefore, an adequate level of friction existed for this pavement when it was tested, less than one year after construction.

Another SuperPave ¼-inch mix was tested on November 28, 2007. This pavement was located on Interstate 84 WB in Vernon, Connecticut, from 75.76 to 75.11 miles. The mean MPD for this pavement was 15 mils (0.38 mm) and the mean ETD was 20 mils (0.51 mm). These data sets were also normally distributed, so the mean values seem to adequately characterize the macrotexture.

The average FN_{40R} was 58.3 for this pavement. Surprisingly, the average FN_S value was 64.3, which was actually higher than the average FN_{40R}. It is not clear as to why the FN_S would be higher than the FN_{40R} in this case. The average speed during the 17 smooth tire tests was 40.1 mph, and the average speed during the 19 ribbed tire tests was 40.2 mph, so the ribbed tire friction numbers were not significantly adjusted for tests at 40 mph. Temperatures were also similar, ranging in the mid 40's (Fahrenheit), so it is not explained by temperature either.

This may have been due to the pavement having been recently constructed prior to testing and having experienced minimal wear, however, this is purely speculation because the mean MPD was not especially high. The FN_{40R} and FN_S variances were similar to the other pavement sites, with the standard deviations equal to 1.7 and 3.2, respectively.

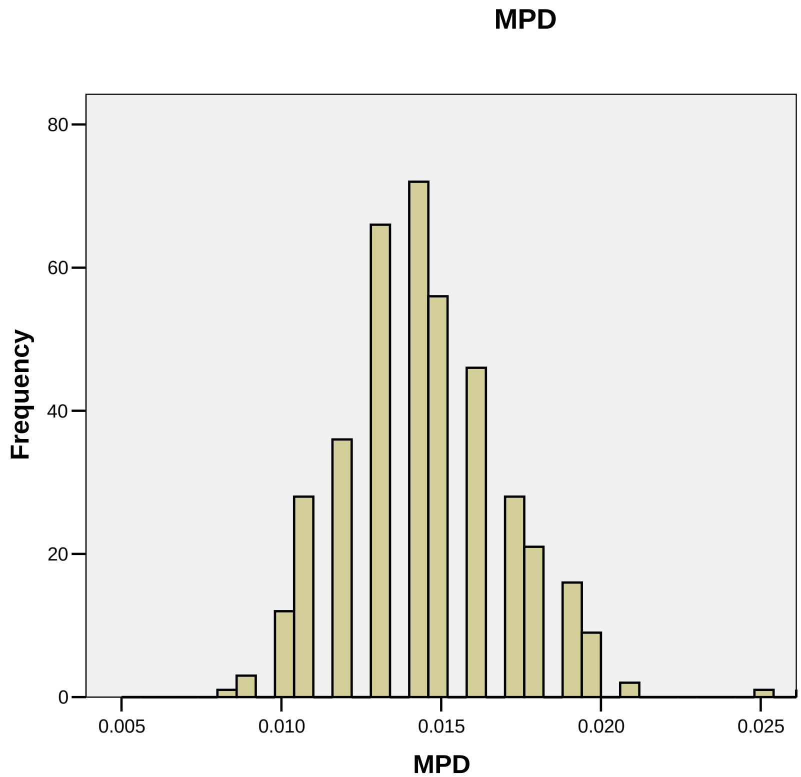

FIGURE 7 MPD Histogram for ¼-inch SuperPave on I-91 NB from 27.71 to 33.68 miles.

ConnDOT 3/8-inch Mix

A SuperPave mix with 3/8-inch nominal maximum aggregate size was tested on April 30, 2007, on I-91 NB in North Haven, Connecticut, from 4.80 to 8.43 miles. The average MPD was 15 mils (0.38 mm), and the average ETD was 20 mils (0.51 mm). The same section of 3/8-inch mix was tested again on May 3, 2007. A certain degree of repeatability was demonstrated, as the average MPD and ETD values were the same at 15 and 20 mils (0.38 and 51 mm), respectively.

Pavement friction was measured with a standard ribbed tire on April 30, 2007, and it was measured with a standard smooth tire on May 3, 2007. FN_{40R} values ranged from 49.0 to 54.5, the average was 52.4 and the standard deviation was 1.6. As should be expected for FN_S values, because smooth tires are more sensitive to the water flow rate *(21)*, they were more volatile than the FN_{40R} values. FN_S ranged from 34.7 to 47.0, the average was 42.0 and the standard deviation was 3.2.

ConnDOT ½-inch Mix

A SuperPave mix with ½-inch nominal maximum aggregate size on Route 411 WB in Rocky Hill, Connecticut, in front of the ConnDOT Central Laboratory from approximately 1.44 to 1.00 miles, was tested during three of the aforementioned dates that other mixes were tested. The particle-size distribution for this ½-inch mix falls within the master ranges contained in the ConnDOT Standard Specifications *(18)* for the former ConnDOT Class 1 Mix. The average MPD and ETD values measured on April 30, 2007, were 21 and 25 mils (0.53 and 0.64 mm), respectively. On May 8, 2007, the values were 22 and 26 mils (0.56 and 0.66 mm), and on November 28, 2007, the values were 21 and 24 mils (0.53 and 0.61 mm), respectively. This again demonstrates a certain degree of repeatability for the laser profiler.

The average FN_{40R} values were 45.7, 45.6 and 47.1. The averages for the other two test dates were within one standard deviation of the mean for each respective test date. For example, the average FN_{40R} plus or minus one standard deviation for April 30, 2007, ranged from 43.9 to 47.5, and the average FN_{40R} for the other two dates fell within this range. Smooth tire skid resistances were not measured for this pavement.

SUMMARY OF RESULTS

The four different HMA mixes compared in this study were classified by their nominal maximum aggregate sizes. Upon examining the JMFs presented in Table 5, it can be seen that the #4 and #8 sieves provide a better representation for the different mixes. Percents of aggregate passing the #8, #4, and 3/8-inch sieves are presented again below in Table 6, along with the Characterizing MPD for each case. The term "Characterizing MPD" refers to whether the median or mean MPD were used to characterize the macrotexture. The median values were used for the 0.187-inch mixes because the data were not normally distributed, while the mean values were used for the other mixes because the data were normally distributed in these instances.

The 0.187-inch mix was considerably finer than the other mixes. This is readily evident, as 96-percent passed the #4 sieve versus 69-percent for the ¼-inch mix. The same was true on the #8 sieve: 78-percent passed for the 0.187-inch mix, while just 50-percent passed for the ¼-inch mix. Conversely, the differences between the ¼-inch mix and the 3/8-inch mix were subtle, as the percents passing the #4 sieve were 69-percent versus 68-percent on the 3/8-inch sieve, and the percents passing the #8 sieve were 50-percent for the ¼-inch mix versus 47-percent for the 3/8-inch mix.

Figure 3 presents the relationship between pavement macrotexture and aggregate gradation. Figure 8 presents a scatter plot comparison between the nominal maximum aggregate size and the characterizing MPD. Figures 9-11 present scatter plot comparisons between sieve sizes and characterizing MPDs for each case. R^2 values are given for each scatter plot. The percents passing the #4 and #8 sieves relate closely to the MPD values, and the R^2 values for these were 0.96 and 0.90, respectively. The R^2 value relating the nominal maximum aggregate sizes and MPD values was 0.81. The R^2 value for the 3/8-inch sieve was only 0.64, so there was not as strong of an association between the percent passing the 3/8-inch sieve and the measured MPD.

TABLE 6 Nominal Maximum Size Aggregate; Percents Passing #8, #4, and 3/8-inch Sieves; and Characterizing MPDs

Case Number	Nominal Maximum Size Aggregate (inches)	Percent Passing the #8 Sieve (%)	Percent Passing the #4 Sieve (%)	Percent Passing the 3/8-inch Sieve (%)	Characterizing MPD (mils)
1	0.187	78	96	100	4
2	0.187	78	96	100	-1
3	0.25	50	69	97	12
4	0.25	50	69	97	15
5	0.375	47	68	97	15
6	0.375	47	68	97	15
7	0.5	43	57	79	21
8	0.5	43	57	79	22
9	0.5	43	57	79	21

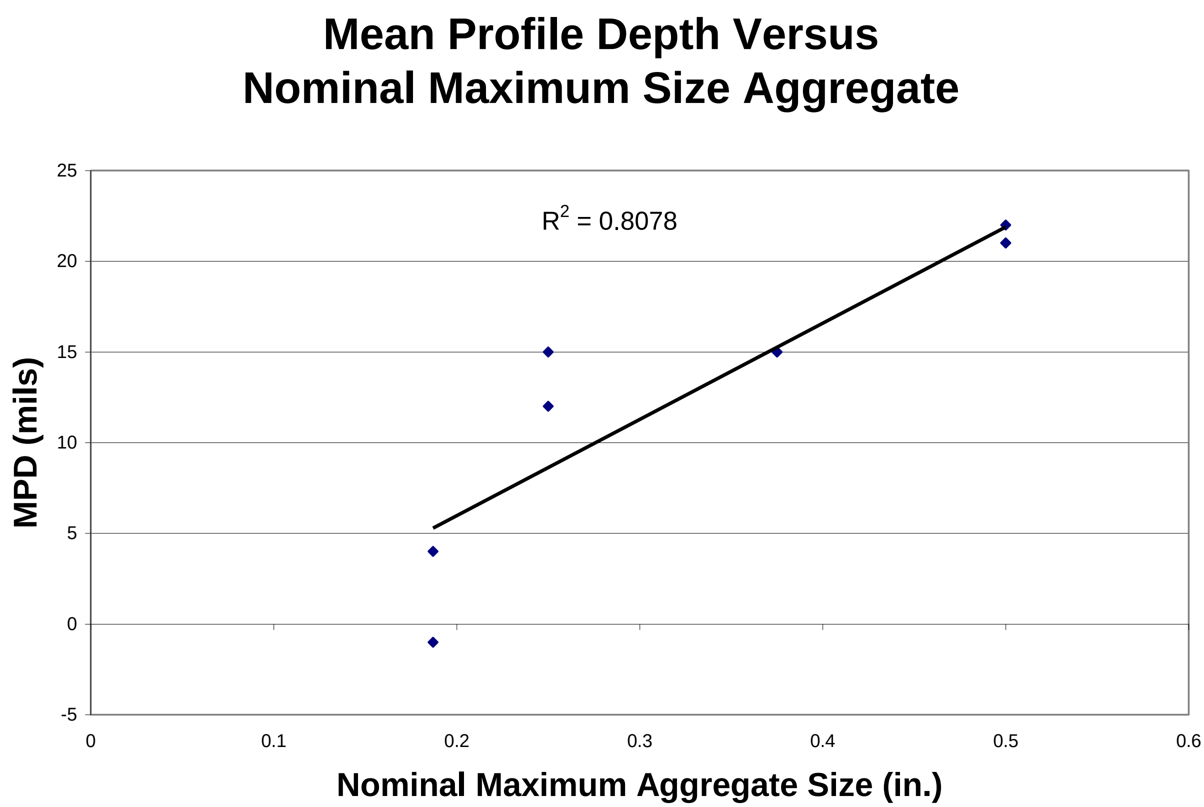

FIGURE 8 Scatter plot relating MPD versus nominal maximum size aggregate

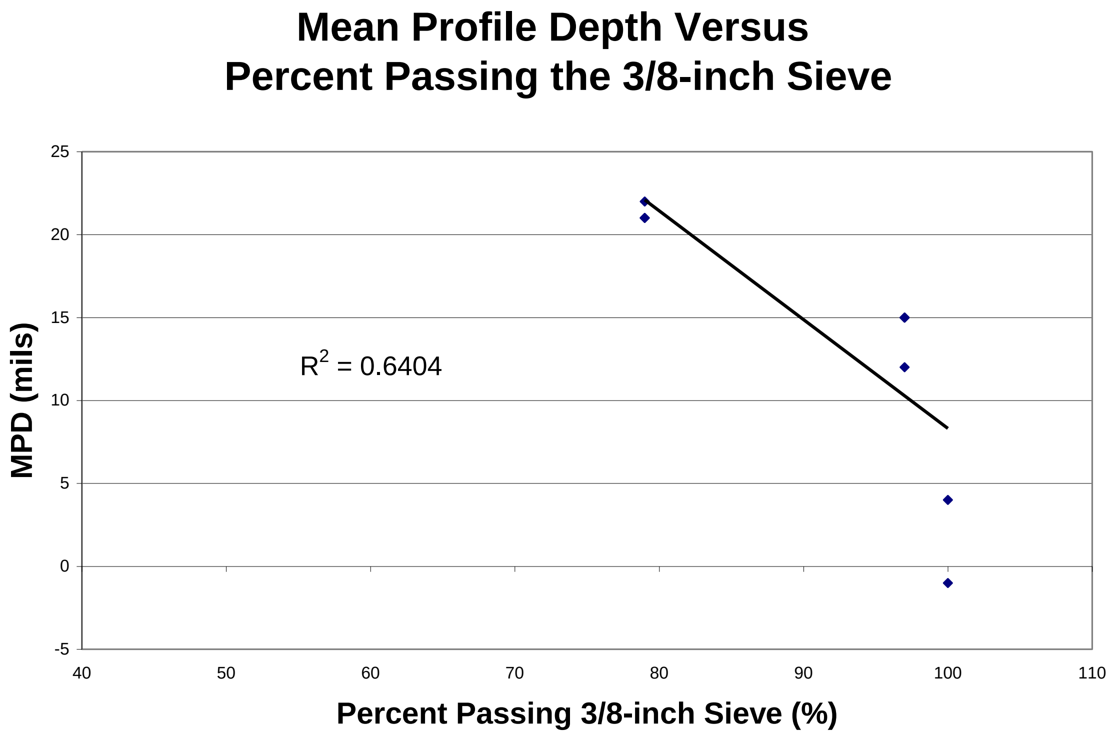

FIGURE 9 Scatter plot relating MPD versus percent passing the 3/8-inch sieve.

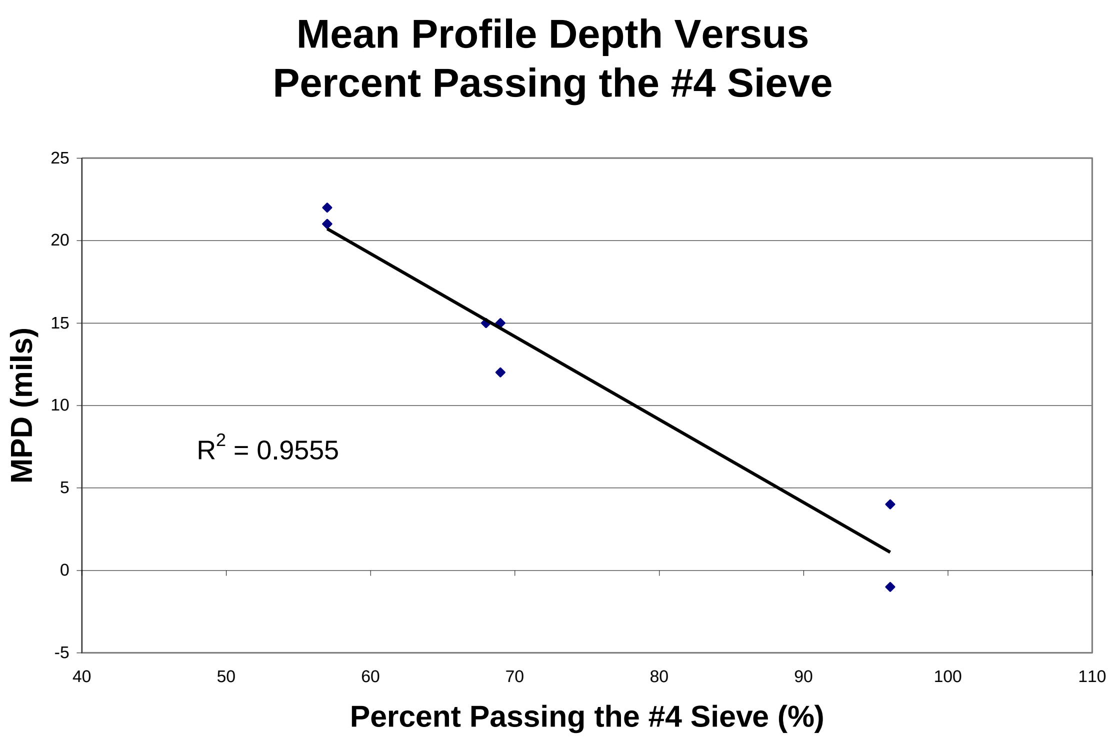

FIGURE 10 Scatter plot relating MPD versus percent passing the #4 sieve.

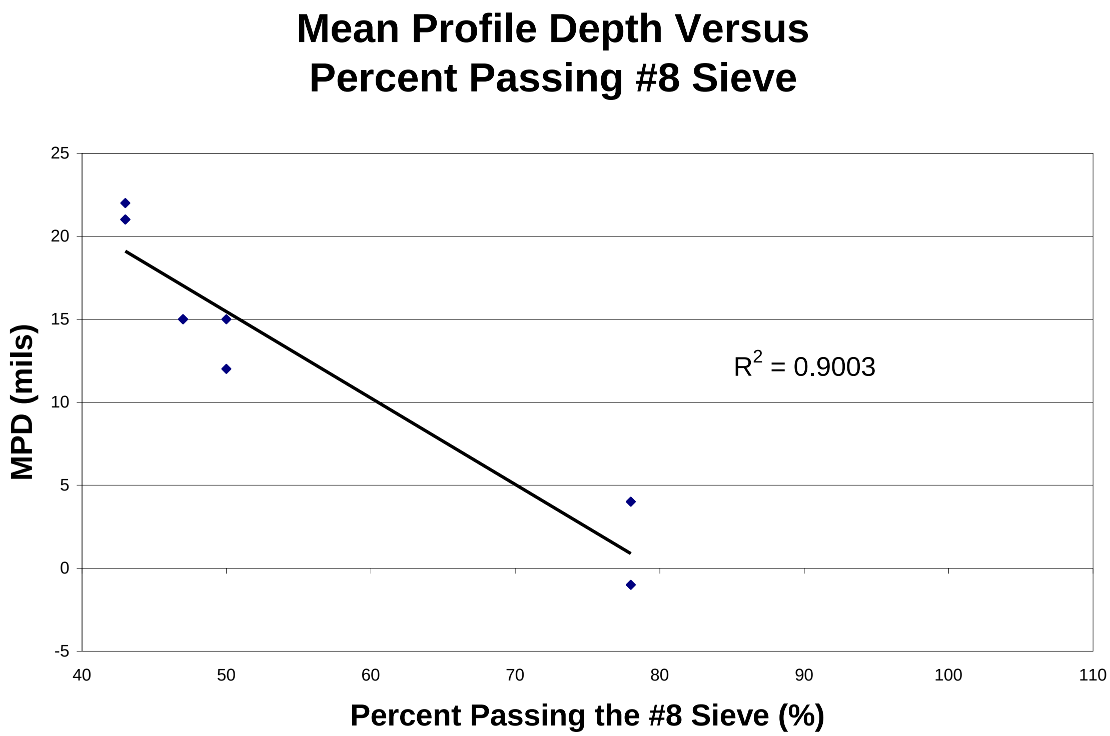

FIGURE 11 Scatter plot relating MPD versus percent passing the #8 sieve.

CONCLUSIONS

The following conclusions were drawn from this study:

- Scatter plots showing the relationship between MPD values measured with the high-speed laser instrument versus values measured with the CTMeter were analyzed. The linear association between these variables was relatively strong, as coefficients of determination (R^2 coefficients) of 0.65 and 0.87 were calculated for the Smart Road and SPS 9A sites, respectively. As such, the high-speed laser instrument appears to provide viable macrotexture measurements.

- In response to a FHWA Technical Advisory titled *Surface Texture for Asphalt and Concrete Pavements*, ConnDOT has begun to establish targets for pavement texture depth on high-speed facilities by characterizing the macrotexture of a few different ConnDOT HMA pavement mixes. The mean profile depth or MPD appears to be the best measure for characterizing pavement macrotexture, since it can be measured using either the high-speed laser instrument or CTMeter.
- The characterizing MPDs measured for the ConnDOT mixes ranged between 21 to 22 mils (0.53 to 0.56 mm) for the 1/2-inch mix, 15 mils (0.38 mm) for 3/8-inch mix, 12 to 15 mils (0.30 to 0.38 mm) for the ¼-inch mix, and 0 to 4 mils (0 to 0.10 mm) for the 0.187-inch mix. These characterizing values are still preliminary and more research is needed to determine the best application(s) for each mix.
- There was a linear association between measured MPD values and the percents passing the #4 and #8 sieves for a respective pavement's particle-size distribution. MPD values tended to increase as less material passed these sieves, i.e. mixes became coarser.
- Laser profiler macrotexture measurements were repeatable from one day to the next. 399 macrotexture measurements were taken on the same 3/8-inch mix on I-91 NB in Connecticut, and the mean MPD for these measurements was 15 mils (0.38 mm) on both

days. The standard deviation was also identical on both days at +/- 2.7 mils (+/- 0.07 mm).

- The ConnDOT CTMeter compared almost identically to the Virginia Tech CTMeter at the Smart Road facility in Blacksburg, VA.

RECOMMENDATIONS

- Mean profile depths (MPDs) measured with the high-speed laser instrument are adequate for providing relative values for characterizing pavement macrotexture on typical HMA pavements used in Connecticut. These typical pavements include but are not limited to ½-inch, 3/8-inch, ¼-inch, and 0.187-inch HMA mixes. Care should be taken in exercising these measurements for other pavements. To that end, it is recommended that further comparative testing be performed between the high-speed laser instrument and other proven instruments, such as the CTMeter, prior to exercising high-speed laser measurements for other pavements less-frequently constructed on Connecticut State highways. These pavements in Connecticut include but are not limited to portland cement concrete (PCC) pavements, open-graded friction courses, and various surface treatments.
- Until demonstrated otherwise, the 0.187-inch (#4) mix should not be used to pave high-speed (50-mph or greater) facilities because it does not appear to have adequate texture depth in

comparison to the other mixes evaluated. This mix should be used only on low-speed facilities that require very thin pavement lifts, but an evaluation of the site geometrics, traffic levels, and vehicle speeds should be conducted before selecting this mix.

- Until demonstrated otherwise, ConnDOT should continue to use the ½-inch mix for high-speed facilities because it appears to provide the most texture depth of the pavements evaluated.
- The ¼-inch and 3/8-inch mixes had particle-size distributions that were similar to one another, and each provided approximately the same level of surface texture. These mixes appear to provide marginal levels of surface texture for high-speed roadways in comparison to the ½-inch mix evaluated in this study. These mixes should provide an adequate level of surface texture for low-speed roadways, although an evaluation of the site geometrics, traffic levels, and vehicle speeds should be conducted before selecting these mixes. Continued use for high-speed roadways for special applications should be monitored by performing periodic friction (smooth and ribbed tire) and texture measurements.

REFERENCES

1. Flintsch, G.W., E. De Leon, K.K. McGhee, and I.L. Al-Qadi. Pavement Surface Macrotexture Measurement and Applications. In *Transportation Research Record No. 1860*, TRB, National Research Council, Washington, D.C., 2003, pp. 168-177.
2. Hall, J.W., L. Titus-Glover, K.L. Smith, L.D. Evans, J.C. Wambold, T.J. Yager, and Z. Rado. *Guide for Pavement Friction – Final Guide*, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, August 2006.
3. *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique,* ASTM Designation E 965-96 (Reapproved 2006), American Society for Testing and Materials, 2006.
4. *Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter,* ASTM Designation E 2157-01 (Reapproved 2005), American Society for Testing and Materials, 2005.
5. *Nippo Sangyo Co., Ltd., Product Guide – CTMeter, 2006.* http://www.nippou.com/en/products/ct.html. Accessed July 25, 2007.
6. *Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests*. ASTM Designation E 501-06, American Society for Testing and Materials, 2006.

7. *Standard Specification for Standard Smooth Tire for Pavement Skid*-Resistance Tests. ASTM Designation E 524-06, American Society for Testing and Materials, 2006.
8. *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire.* ASTM Designation E 274-06, American Society for Testing and Materials, 2006.
9. *Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth*. ASTM Designation E 1845-01 (Reapproved 2005), American Society for Testing and Materials, 2005.
10. Larsen, D.A., and E.G. Feldblum. *Enhancements to ConnDOT's Pavement Friction Testing Program*. CT SP&R Work Program Proposal P-04-1. Connecticut Department of Transportation, 2004.
11. *Surface Texture for Asphalt and Concrete Pavements*. FHWA Technical Advisory, Classification Code T 5040.36, http://www.fhwa.dot.gov/legsregs/directives/techadvs/t504036.htm#materials, Accessed July 25, 2008.
12. *Dynatest 1295 Pavement Friction Tester Operation Manual,* Version 1.01, Dynatest, Westland, MI, April 2003.
13. Transportation Pooled Fund Program, TPF-5(141), *Pavement Surface Properties Consortium: A Research Program*, NCHRP, http://www.pooledfund.org/projectdetails.asp?id=371&status=4, Accessed July 27, 2008.

14. Prowell, B.D., and D.I. Hanson. *Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements,* National Center for Asphalt Technology, NCAT Report 04-05. 2004.

15. Prowell, B.D., and D.I. Hanson. Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements. In *Transportation Research Record No. 1929*, TRB, National Research Council, Washington, D.C., 2005, pp. 88-96.

16. Abe, H., A. Tamai, J.J. Henry, and J. Wambold. *Measurement of Pavement Macrotexture with Circular Texture Meter*, In *Transportation Research Record No. 1764*, TRB, National Research Council, Washington, D.C., 2002, pp. 201-209.

17. Flintsch, G.W., and K.K. McGhee. High-Speed Texture Measurement of Pavements – Final Report, Virginia Transportation Research Council, Charlottesville, Virginia. 2003.

18. *State of Connecticut Department of Transportation Standard Specifications for Roads, Bridges and Incidental Construction*, Connecticut Department of Transportation, FORM 816, 2004.

19. Ganung, G.A. and F.J. Kos. *Wet Weather, High-Hazard Accident Locations: Identification and Evaluation*, Report FHWA-CT-RD403-F-794, Connecticut Department of Transportation, Newington, CT 1979.

20. Hewett, D.L. and W.G. Milery. *Use of the Smooth Tire in Evaluation of Friction Characteristics of Surface Courses in Florida*, Presented at the meeting of TRB Committee A2B07 on Surface Properties-Vehicle Interaction, Transportation Research Board, National Research Council, Washington, D.C., 1992.

21. *NCHRP Synthesis 291: Evaluation of Pavement Friction Characteristics – A Synthesis of Highway Practice*, TRB, National Research Council, Washington D.C., 2000.