

The Use of Polymer Modified Asphalt Binder for High Friction Thin
Lift Overlays in Connecticut

Final Report

Scott Zinke, James Mahoney

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Connecticut Advanced Pavement Laboratory
Connecticut Transportation Institute
School of Engineering
University of Connecticut

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Standard Conversions

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
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 yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
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
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
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
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
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
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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16. Abstract Controlling the frictional characteristics of a roadway is of paramount importance when considering highway safety. Several state highway agencies specify a friction wearing course to be used in high profile or high accident prone areas. The Connecticut Advanced Pavement Lab along with Connecticut DOT investigated a polymer modified high friction wearing course placed in CT in 2012. Laboratory tests including moisture susceptibility and rutting susceptibility indicated no potential for premature failure of the wearing surface. Field testing of both pavement macrotexture and skid testing also show promise that this mix will enhance tire to pavement interface friction. Several field visits to the site have indicated that the surface is performing well to date regarding its durability.			
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Table of Contents

Title Page	i
Disclaimer	ii
Technical Report Documentation Page.....	v
Table of Contents.....	vi
List of Tables.....	vii
List of Figures.....	viii
Executive Summary	ix
Background & Problem Statement	1
Objective	2
Regional Specification Review	3
Review of Skid Testing Literature.....	5
Summary of Skid Testing Method (ASTM E274).....	6
Development of Paver Placed High Friction Thin Overlay for Connecticut.....	9
Construction of the HFTL Sections	9
Problems Encountered.....	12
Collection of the Mixture Materials	13
Hamburg Wheel Track Testing (AASHTO T324)	13
Tensile Strength Ratio Testing	16
Asphalt Pavement Analyzer Testing.....	20
Review of Specified APA Rut Depths.....	21
Skid Testing of HFTL and Control Sections	23
Texture Measurements	26
Results and Discussion.....	31
Conclusions and Recommendations	33
References.....	35
Appendix A. Specification for Paver Placed High Friction Thin Overlay (HFTO).....	37
Appendix B. ADT for High Friction Thin Lift Overlay (HFTL) on Rt. 12 Preston Ledyard.	39

List of Tables

Table 1. Comparison of Film Thicknesses Between Mixes	25
Table 2. MPD Measurements.....	28
Table 3. Wheel Path Texture Comparison (mm)	29
Table 4. Descriptive Statistics Wheel Path and Non-Wheel Path MTD	30
Table 5. Student's T-test Wheel Path and Non-Wheel Path MTD.....	31

List of Figures

Figure 1. ConnDOT Locked Wheel Skid Testing Trailer.....	7
Figure 2. Rt. 12 HFTL Surface Texture	10
Figure 3. Rt. 12 HFTL Surface Texture	10
Figure 4. General Condition of the HFTL Mix.....	11
Figure 5. General Condition of HFTL Mix.....	11
Figure 6. Surface Irregularities at Cardinal Lane Intersection	12
Figure 8. HFTL Hamburg Wheel Track Testing Results Plot.....	14
Figure 9. HFTL Hamburg Test Results.....	15
Figure 10. HFTL Specimens after Hamburg Test.....	16
Figure 11. HFTL Tensile Strength Ratio Test Results	18
Figure 12. Unconditioned HFTL TSR Subset After Testing.....	19
Figure 13. Conditioned HFTL TSR Subset After Testing.....	19
Figure 14. APA Test Configuration.....	20
Figure 15. HFTL APA Rut Depths Plot.....	22
Figure 16. HFTL APA Rut Depths	22
Figure 17. Smooth Tire Friction Numbers	24
Figure 18. Ribbed Tire Friction Numbers	24
Figure 19. Circular Track Meter (CT Meter)	27
Figure 20. Mean Profile Depth Plots.....	28

Executive Summary

Controlling the frictional characteristics of a roadway is of paramount importance when considering highway safety. The tire-pavement surface interface needs to be of a high friction nature so that vehicles are not prone to skidding during wet weather events and in high accident prone areas. Several state highway agencies specify high friction wearing courses for high profile or high accident prone areas. The research team investigated regional state agency specifications, which are summarized in this report. The Connecticut Department of Transportation (ConnDOT) specifies an Ultra-Thin Bonded Wearing Surface, which is partly intended for this purpose; however, it requires the use of specialized paving equipment for construction. It was desired to investigate a high friction mix for use in CT that can be placed with conventional paving equipment. The Connecticut Advanced Pavement Laboratory (CAP Lab) along with ConnDOT investigated a polymer modified high friction wearing course placed in CT in 2012. The mix was designed at the CAP Lab and placed on a state route in southeastern Connecticut. The produced mix was sampled at the plant and tested at the CAP Lab. Laboratory tests, including moisture susceptibility and rutting susceptibility, indicated no potential for premature failure of the wearing surface. The laboratory testing is detailed as part of this report. Locked wheel pavement skid resistance was measured with full-scale ribbed and smooth tires, and pavement texture depth, expressed as Mean Profile Depth (MPD), was measured with a Circular Track Meter (CTMeter). Skid resistance test results show promise that this mix will enhance tire to pavement interface friction, as the average ribbed-tire and smooth-tire skid numbers measured at 40 mph were 55.1 and 53.5, respectively, after 10 months of service. The polymer modified high friction wearing course had an average MPD of 0.78 mm, while an adjacent dense-graded control section had an average MPD of 0.35 mm. It was noted that due to the open texture of the mix, water was held on the surface for a longer time. This required retreatment to prevent water from freezing again. An estimate of the increase in maintenance costs for this section was approximately \$1,600 during the 2012-2013 winter. While it is true that MPD values of greater than 1.00 mm have been measured on ConnDOT's Ultra-thin Bonded Wearing Surface, this level of texture depth (MPD~0.78 mm) for a polymer modified high friction wearing course may provide a better balance between high-speed performance, durability, and winter maintenance requirements than a mix with greater texture depth. Visual inspections during several field visits to the site indicate that the surface is performing well to date. There was one small section of the placement that was troublesome during construction and was subsequently removed and replaced. Recommendations are made for further monitoring of the high friction section.

Background & Problem Statement

Maximizing the friction generated between vehicle tires and pavement is critical for the safety of the motoring public. This is particularly true for roadway sections where vehicles are rapidly accelerating and decelerating, as well as where drivers are forced to navigate through directional changes. These problems are compounded during periods of inclement weather as water reduces the friction between tires and the pavement surface.

The friction between vehicle tires and pavement is dependent upon both the vehicle tire properties and the pavement surface. Tires are continually redesigned to improve their performance by manufacturers. To further enhance the tire-pavement interaction, it is necessary to provide pavement surfaces which will enhance the frictional effects of the tire and pavement interface making the roadway safer.

Advances in asphalt binders, particularly with polymer modifiers, makes it easier to design pavement surfaces that have a high tire-pavement contact friction. Polymer Modified Asphalt Binders (PMAB) have a high degree of elasticity as well as substantial adhesion to the aggregate particles as compared to unmodified asphalt binders. By enhancing these properties, PMAB allow the placement of thin-layers of Hot Mix Asphalt (HMA) with a very open surface texture. This open surface texture increases the friction between vehicle tires and the pavement surface. In addition, the open surface texture reduces the effect of water from a normal rain event since a significant amount of the aggregate remains above the water collecting on the pavement surface.

ConnDOT previously used an open graded friction course (OGFC) as a pavement wearing surface, which was placed approximately one inch thick. Open graded friction courses have a very open aggregate structure that allows water to move vertically into the pavement surface until it reaches a dense-graded asphalt pavement layer underneath, and then the water moves horizontally through the pavement to the shoulder. Standard dense graded HMAs rely on sheet flow to get the water off of the pavement surface. OGFCs have a very open surface texture that enhances the tire-

pavement interaction and reduces the effect of water on tire-pavement friction. An additional benefit of open textured mixes is that they tend to improve visibility on the roadway during rain events as the amount of water spray coming off of vehicle tires is greatly reduced. A disadvantage of open textured mixes is that they tend to be less durable and are more difficult to treat during snow and ice operations. For that reason, ConnDOT discontinued the use of OGFCs several years ago.

Producing a High Friction Thin-Lift (HFTL) overlay using PMAB should provide a very durable wearing surface due to the enhanced mechanical properties of the PMAB. A high friction thin-lift overlay will also avoid the problems with snow and ice operations that were experienced with OGFC because it will not allow water to flow vertically through it. The polymerized binder should prevent massive pavement failures which were also experienced with OGFC. These differences should make a viable option for ConnDOT in areas requiring the highest possible tire-pavement friction.

There is an ultra-thin bonded wearing surface application available in Connecticut that is intended to produce a high friction surface treatment. This application requires specialized equipment to place it. The intent of the proposed PMAB-HFTL is to be able to place a high-friction surface treatment with conventional paving equipment.

A pilot section of a PMAB-HFTL treatment was placed a part of a resurfacing project in 2012. This placement was monitored and a portion of the mix was collected from the plant and tested in the laboratory for durability related issues. Skid testing was also conducted immediately following placement and at specified intervals after that. Finally, in December 2013, pavement texture depths of the PMAB-HFTL treatment and control sections were measured with a Circular Track Meter (CTMeter).

Objective

Develop a non-proprietary polymer modified HFTL wearing surface specification that can be placed with conventional paving equipment.

Regional Specification Review

The goal of the regional specification review was to gain insight as to what surrounding agencies were doing as a means of dealing with the need for increased friction in designated areas. A few of the reviewed specifications involved the use of open-graded friction courses (OGFCs). It should be noted that the goal of this research is not to produce or specify an OFGC mix. It does turn out, however, that some other surrounding agencies are deploying OGFC treatments to solve the need for increased friction. Those treatments are included in this review for maintenance of continuity.

The Massachusetts Department of Transportation (MassDOT) has a specification for the production and use of OGFC [1]. The specification also has a modified version of the OGFC (OGFC-M). The modified version is slightly coarser and allows for the inclusion of up to 5% ½-inch stone. The standard OGFC requires 100% passing the ½-inch sieve. The OGFC-M is required to be produced and placed at higher material temperatures and used when the ambient temperature is less than 60 °F and falling. The OGFC mix is specified in more favorable ambient conditions. That is, when the temperature is 60 °F and rising. The OGFC-M is also specified for greater thicknesses due to the increase in stone size. In both cases, the specification suggests covering the mix during hauling in addition to minimizing the haul time in order to meet temperature requirements. In June, 2001, an engineering directive [2] instructed that all projects using OGFC be replaced with Polymer Modified Open-Graded Friction Course (OGFC-P). The directive suggests that the inclusion of PMAB would increase the service life of open graded mixes by minimizing raveling and issues related to delamination.

The Rhode Island Department of Transportation (RIDOT) also has a specification for the use of a friction course on overlay projects. [3], [4]. The mix is designated as Modified Class 9.5 HMA. [4]. The binder must meet PG 64-28 requirements. There are provisions within the specification for the use of an approved WMA additive as well.

The New Jersey Department of Transportation (NJDOT) has a specification for the use of an OGFC, a Modified Open Graded Friction Course (MOGFC), an Ultra-thin Friction Course, Stone Matrix Asphalt (SMA), and an Asphalt Rubber Open Graded Friction

Course (AR-OGFC). [5] The following materials are not permitted as coarse aggregates for use in OGFC and MOGFC mixes: crushed recycled container glass (CRCG), ground bituminous shingle material (GBSM), remediated petroleum contaminated soil aggregate (RPCSA), and RAP. PG 76-22 binder is specified for the OGFC and MOGFC mixes.

NJDOT's MOGFC mixes are required to contain a stabilizing additive consisting of mineral or cellulose fiber. If using mineral or cellulose fibers, the required dosing rate is 0.4 percent or 0.3 of the mix by weight, respectively. It is also required that a technical representative from the supplier of the additive technology be present on the first day of production and placement of the MOGFC in case the need arises for technical assistance.

Open graded mixes are also subject to moisture susceptibility testing via AASHTO T 283, [6] with the following exceptions: there is no required air void content, specimens are compacted via Superpave gyratory compactor using 50 gyrations, and there is no required specific saturation level. Adjustments to the mix, possibly including an anti-strip additive, must be made if the measured tensile strength ratio of the mix falls below 80 %.

The MOGFC mixes are tested for abrasion and impact susceptibility in addition to moisture susceptibility.

The gradation master ranges for both the 9.5 mm OGFC and MOGFC mixes are similar; however, the MOGFC is slightly coarser. There is also a designation for a MOGFC 12.5 mm mix. The 9.5 mm OGFC and MOGFC air void requirements are 15% and 18%, respectively, while the 12.5 mm MOGFC air void requirement is 20 %.

The Ultra-Thin Friction Course and SMA (gap-graded) mixes are also not allowed to contain any recycled materials similar to the open graded mixes. The specified binder grade for both the Ultra-thin and SMA mixes is PG 76-22, and the binder must be polymer modified.

NJDOT's AR-OGFC mixture is composed of both coarse and fine aggregate combined with asphalt-rubber binder. There are no recycled products allowed in the mix, similar to the mixes previously discussed. Fine aggregate is specified to be manufactured stone sand. The rubber is ground tire rubber with a specific gravity of 1.15 ± 0.05 and must have a moisture content of not more than 0.75 %. To prevent particles from sticking together, the contractor is allowed to add up to 4 % calcium carbonate by weight of the total rubber. All ground tire rubber must pass the #8 sieve. The binder used is to be either a PG 64-22 or PG 58-28. An approved blend of both grades is also allowed. It is also required that a WMA technology be used. This can include the use of paraffin wax, esterified wax, or a surfactant type chemical additive. Foamed WMA technologies or any additive which incorporates steam in the mix is prohibited. Acceptance testing of AR-OGFC mixes consists of air voids measurement, testing of the composition of the mix and drain down testing.

The New York State Department of Transportation (NYSDOT) has a specification for a paver placed surface treatment [7]. While not referred to as a *friction* surface, the coarse aggregates are required to meet standards which contribute to high friction characteristics in a road surface. The treatment consists of the application of a warm PMA emulsion coat which is immediately followed by an application of an ultra-thin HMA wearing surface. This treatment requires the use of a paver which is capable of applying both the PMA emulsion and the HMA surface. This is similar to the ultra-thin bonded wearing surface treatment which is currently available in Connecticut but requires specialized equipment to place.

Review of Skid Testing Literature

There are multiple ways of measuring the frictional characteristics of pavement surfaces such as the British Pendulum Tester, Locked Wheel/Full-Scale Tire test and Variable Slip Measurements among other available tests. Locked wheel skid testing (ASTM E274 [8]) is the measure by which ConnDOT (Figure 1) and most other agencies quantify the level of friction on a roadway surface.

Summary of Skid Testing Method (ASTM E274)

The standard test method used for quantifying skid resistance on a paved surface is with a full-scale tire and is outlined in ASTM E274. This test is used to evaluate the skid resistance of a pavement surface compared to that of other surfaces or to assess the changes in skid resistance of a wearing surface over time. The information presented in this section is intended to summarize that which is contained in ASTM E274.

The measured skid resistance is reported as a skid number (SN). Reported along with the skid number are the speed, the units of speed, and the type of tire used. The letters R and S denote ribbed and smooth tires respectively. Parentheses are used if the test is reported in km/hr, while there are no parentheses used in the reported skid number if the speed units are in mph. For example, if the number reported is SN40R, then the test was conducted at 40mph with a ribbed tire. SN(65)S indicates it was tested at 65km/h with a smooth tire.

The apparatus used is a trailer fitted with one or more test wheels to be towed by a vehicle (Figure 1). There are different types of tires used depending on the specifications they must meet. Ribbed tires meet the E501 specifications for Pavement Skid-resistance Tests and the smooth tires meet the E524 specifications for Pavement Skid-resistance Tests. Agencies may specify which tires are to be used for their purposes.



Figure 1. ConnDOT Locked Wheel Skid Testing Trailer

The friction force of the locked test wheel is measured as it is dragged over a pavement surface that has been wetted down via a water applicator, which is fixed directly in front of the test wheel while the test team attempts to maintain the apparatus at a constant speed. The speed at which the skid resistance test is intended to be conducted is 40 mph (65km/h), but the speed will vary dependent upon the conditions of the roadway. In this case the friction values are back corrected to the value which corresponds to 40 mph.

Before the test begins, the apparatus is brought as close to the designated speed as conditions permit. Water is applied 1 to 4 inches above the pavement at an angle of 20 to 30° about 10 to 18 inches in front of the tires (Figure 1) at the assigned rate. The water is simply clean water which is free of any added chemicals. The break for the test wheel is then applied to lock the tire in position. It is then dragged over the wetted

pavement as the instruments measure and record the values for the skid for time intervals of 1.0 to 3.0 seconds.

The skid number is generally calculated from Equation 1, below, where F is the tractive or horizontal force applied to the test tire and W is the dynamic vertical load on the test wheel. Both variables are expressed in units of pound-force [lbf] or in Newtons [N] to give a unitless SN. Depending on the exact testing method, other variables may be taken into account, and so equation 1 may vary.

$$SN = (F/W) * 100 \quad (1)$$

While exact values of acceptable and unacceptable skid numbers vary from agency to agency, the underlying principle is evident in Equation 1, lower SN indicate less friction between the tires and the road and are a possible safety concern while higher numbers indicate a higher level of friction.

Skid testing results are presented as a value known as the skid number (SN). As such, the research team sought to find what levels of friction were deemed as acceptable. *Jayawickrama et al*, [10] conducted a survey of 48 State DOTs inquiring of their friction control practices. At a 74% response rate, they concluded that a SN of ≥ 30 for low volume roads was generally considered acceptable. The reader should note that these values are threshold minimum SN at which point improvements must be made to increase friction. DOT's do not target these values at the time of construction or maintenance, they target much higher SN such that the result is superior friction at the road to tire interface. If these minimum numbers are approached as pavement surfaces are monitored over time, corrective action is deemed necessary. They also concluded that a SN of $\geq 35-38$ for high volume roads was generally considered acceptable. At the time of the survey, 3 state DOTs were using a value of 40 as the minimum threshold value for a safe SN. It is stated in the results of the survey that skid testing results with a SN of < 30 are generally considered unacceptable and corrective action must be taken to increase skid resistance in an effort to reduce susceptibility to skid related traffic incidents. While it was unclear upon review of the survey literature whether these were

ribbed-tire or smooth-tire values, it is assumed that these were for ribbed-tire values because the ribbed tire was the only standard tire used until ASTM E 274 was amended in 1990 to give the smooth tire equal status [9]. Up until that time, the smooth tire was considered an “alternative” test tire. Considering that the Jayawickrama et al [10] was published in 1996, it is likely that they were referring to ribbed-tire skid numbers.

Development of Paver Placed High Friction Thin Overlay for Connecticut

Several trials of high friction mixes were designed at the Connecticut Advanced Pavement Laboratory (CAP Lab). The underlying principal behind the design was a surface texture which was slightly more open than the traditional densely graded Superpave mixes used in Connecticut in an effort to increase the level of friction at the interface of tire and pavement. Given ConnDOT’s history with open-textured mixes, it was desired to use a PMA binder in order to mitigate the durability issues that were encountered in the past. The minimum binder content was specified at 6% and the target air voids level during design of the mix was increased from 4% to 5% to account for the reduction of finer particles in the mix. The asphalt binder was required to meet PG 76-22. Draindown testing (AASHTO T305) was also a requirement as part of the mix design. The specification for the developed mix is detailed in Appendix A.

Construction of the HFTL Sections

The HFTL mix was placed on several nights during resurfacing of CT Route 12 (Project #58-325) in Preston/Ledyard Connecticut in August/September 2013. During these nights, trial sections of the HFTL were placed as part of a larger overlay project that included a dense graded Superpave mix from which the control section was selected. The HFTL section extends from CT Rt. 12 MP 6.93 to MP 8.56. The HFTL mix was placed at a thickness of 1 inch in accordance with the specification (Appendix A). Images 2 and 3 give an indication of the surface texture of the mix the day following construction of the first section while images 4 and 5 show the general condition of the overlay. The Average Daily Traffic for this site ranges between 11,200 and 11,900 as shown mapped in Appendix B.



Figure 2. Rt. 12 HFTL Surface Texture



Figure 3. Rt. 12 HFTL Surface Texture



Figure 4. General Condition of the HFTL Mix



Figure 5. General Condition of HFTL Mix

Problems Encountered

On the southern end of the HFTL placement, there were some thermal (end load) segregation areas observed after construction. This is likely due to the cooler material from the end of the load on the haul unit as a material transfer vehicle was not used for placement. After several visits to the project location by the research team, these areas are no longer visible. It remains to be seen if there are any cyclic failures as a result of end load segregation in that area.

There was a fairly short section of the HFTL trial mix placed on the second night at the intersection with Cardinal Lane that displayed some clear problems. The paver appeared to drag the mix. This resulted in surface irregularities as seen in Figure 6. Possible causes include low mixture temperature or equipment related issues. That section of pavement was removed by the contractor and subsequently replaced in the days following construction.



Figure 6. Surface Irregularities at Cardinal Lane Intersection

Collection of the Mixture Materials

CAP Lab personnel were on hand at the facility during production of the mix in order to sample materials from haul units immediately following production. Materials were collected for testing in the Asphalt Pavement Analyzer (APA), the Hamburg Wheel Tracking Device and also for testing of resistance to moisture induced damage via tensile strength ratio.

Hamburg Wheel Track Testing (AASHTO T324)

The Hamburg test is a destructive test which is used to indicate the mixture's structural integrity in the presence of water and repeated loading. The primary concern with respect to the Hamburg test is the determination of the stripping inflection point. The stripping inflection point is the point where damage to the specimen is due to the asphalt binder stripping from the material as a result of moisture and repeated loading. When this happens, it is evident when viewing the plot of rutting verses the number of passes of the wheel over the specimen. As damage becomes permanent, the slope of rutting depth verses the number of passes changes. An example of this is shown in Figure 7.

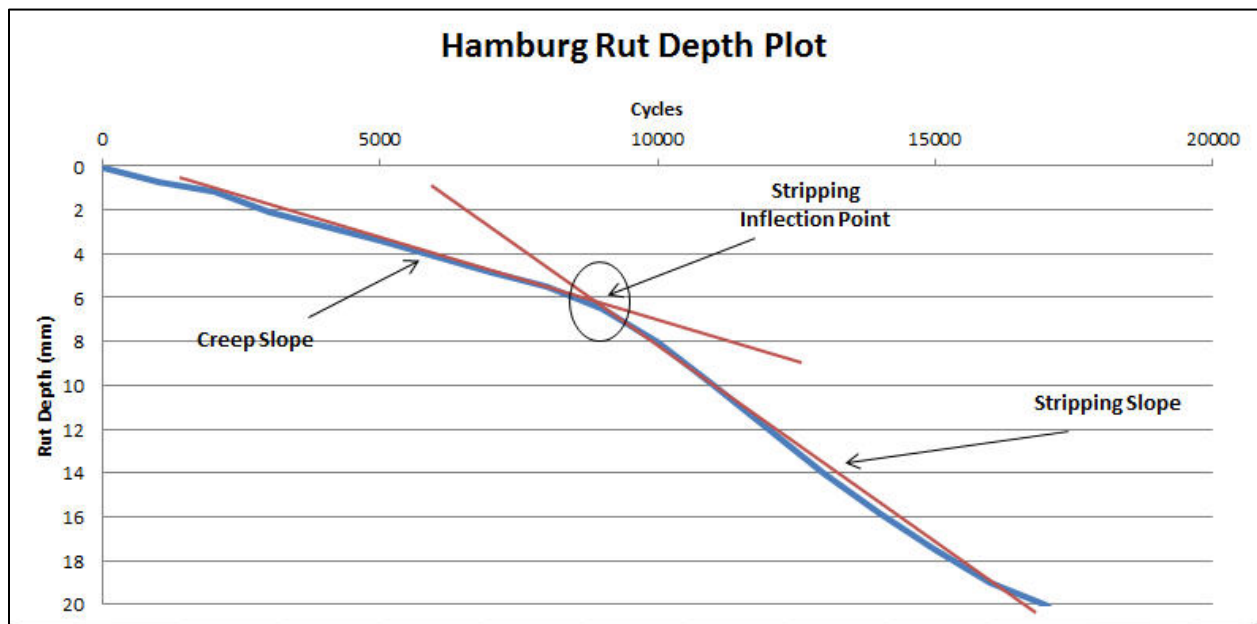


Figure 7. Example of Stripping Inflection Point

As seen in Figure 7, damage accrues at an increased rate when the slope of rutting (creep slope) changes and is elevated (stripping slope). This point on the plot coincides with the point during testing, when damage increases due to stripping. The longer a specimen lasts without this slope increase taking place, the less prone to moisture induced damage the mixture will be in place in the field.

Results of the HFTL mixture test show that this material isn't susceptible to a notable degree of moisture induced damage. Once the creep slope was established, after the test was initiated, there was no discernible change in slope from the beginning to the end of the test (Figure 8).

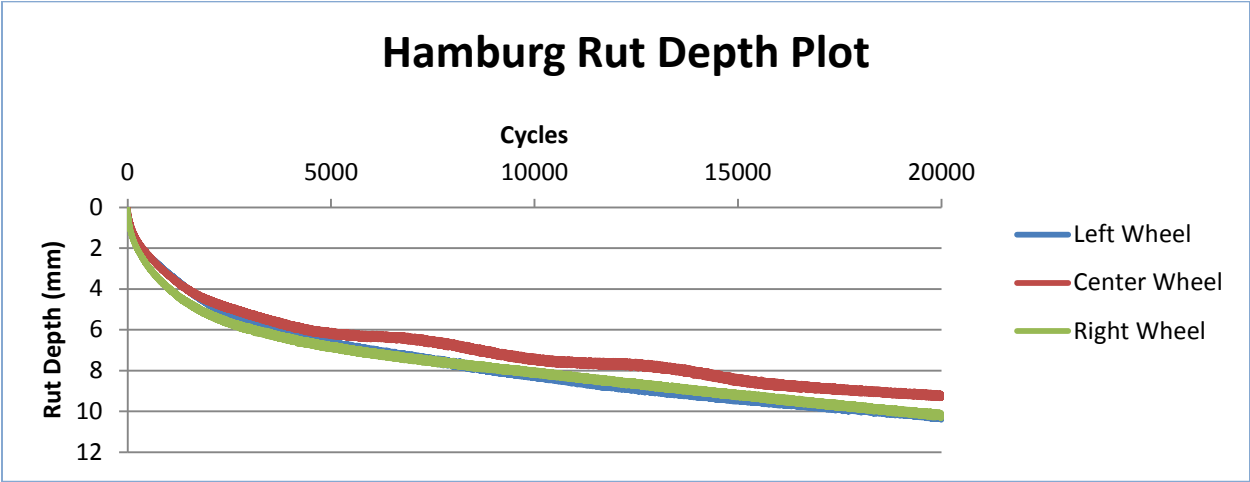


Figure 8. HFTL Hamburg Wheel Track Testing Results Plot

In addition to the lack of a notable stripping inflection point, it can also be seen from Figure 8 that the material lasted the full length of the test, which is 20,000 cycles. This is a positive indication that this material is also quite durable from a rutting perspective. This is also evident as the maximum rut depth of those specimens was 10.35 mm (Figure 9).

MOISTURE TEST DATA SHEET (HAMBURG TYPE WHEELS @ 50 Passes Per Minute)

Project No. Thin Friction Test No. 1
 Mix ID No. Thin Friction Test Date 18-Sep
 Mix Type RT 12 Data File _____
 Mold Type _____ Operator JD

Temperature 50
 Wheel Load 158
 Lab ID CAP lab

Left Sample ID 4, 8			Bulk S Gravity	% Air Void 7.0	ate Of Rutting		
Temperature			Depth Reading (mm's)				
PASS COUNT	F	C	Left Value 0.044556 10.35253 0	Man Depth Reading	REMARKS	MM/HR	
0	32	0					
1	122	50					133.667
20000	122	50					1.548
20001	122	50					-31057.594
20000	32	0					

Center Sample ID 9, 13			Bulk S Gravity	% Air Void 7.1	ate Of Rutting		
Temperature			Depth Reading (mm's)				
PASS COUNT	F	C	Center Value 0.014954 9.222782 0	Reading	REMARKS	MM/HR	
0	32						
1	122	50					44.861
20000	122	50					1.381
20001	122	50					-27668.348
20000	32						

Right Sample ID 7, 15			Bulk S Gravity	% Air Void 7.4	ate Of Rutting		
Temperature			Depth Reading (mm's)				
PASS COUNT	F	C	Right Value 0.074448 10.1844 0	Man Depth Reading	REMARKS	MM/HR	
0	32						
1	122	50					223.343
20000	122	50					1.517
20001	122	50					-30553.196
20000	32						

Figure 9. HFTL Hamburg Test Results

The specimens after testing are shown in Figure 10.



Figure 10. HFTL Specimens after Hamburg Test

Tensile Strength Ratio Testing

In addition to measuring the HFTL mixture's susceptibility to moisture induced damage via the Hamburg Wheel Track test, it was tested via AASHTO T 283, Resistance of Compacted Bituminous Mixtures to Moisture-Induced Damage. This is a test that is utilized by ConnDOT to approve mixture designs and changes to the JMF on different projects. The tensile strength test measures the potential of a sample for stripping and moisture damage. The principles behind the test are similar in theory to those of the Hamburg test. Water tends to weaken the cohesive bond between the asphalt binder and the surface of the aggregate. The TSR is the ratio of the tensile strength of a conditioned set of specimens to that of a set that has not been subjected to moisture or freezing. A high TSR value then would be indicative of a mix that is not very susceptible

to moisture induced damage, while a lower value would be indicative of mix that is susceptible to moisture damage. ConnDOT specifications currently require a TSR value of no less than 80%, which is also the Superpave standard.

This test is performed by partially saturating a set of 3 samples in a vacuum container for 5-10 minutes, and then running those samples through a freezing cycle for a minimum of 16 hours. Once the freezing cycle is complete, the sample is directly placed in a 60° C soaking cycle for 24 ± 1 hours. After the 60° soaking phase, the sample is placed in a 25° C bath for 2 hours and finally tested for strength. Strength testing is conducted in a compression testing apparatus. The sample is locked in place on its side and then an increasing load is applied at a constant rate until the sample shows bearing of permanent damage. That is, when the displayed load resistance either begins to decrease or no longer elevates. This is the point that is indicative of the specimen's maximum indirect tensile strength.

The specimens that are not subject to the freezing cycle, are conditioned to a temperature of 25° C and then broken in the testing head.

As previously stated the TSR requirement for both Superpave and ConnDOT is a minimum of 80%. As seen in Figure 11, the measured TSR for the HFTL mix is 94.3%. This result is an indication that this mix is not readily susceptible to moisture induced damage.

Moisture Susceptibility T283

ConnDOT Modified Method

Project	Project Number							
Date	9/18/2012							
Mix	Thin Friction Wearing Surface							
Technician	John DaDalt							
Specimen #	1	2	5	6	10	11	12	16
Wair	3773.8	3781.9	3759.5	3750.1	3763.6	3769.8	3761	3768.9
Wwater	2187.5	2184.9	2173.1	2159.6	2173.3	2183.7	2176.1	2171.5
Wssd	3804.6	3803.9	3777.4	3773.4	3788.6	3793.6	3785.6	3790.4
Gmb	2.334	2.336	2.343	2.324	2.330	2.342	2.337	2.328
Gmm	2.518	2.518	2.518	2.518	2.518	2.518	2.518	2.518
% Air Voids	7.320	7.230	6.934	7.714	7.467	7.004	7.198	7.543
Air Voids, Vol	118.371	117.054	111.250	124.483	120.622	112.759	115.854	122.117
	Conditioned			Unconditioned				
Specimen #	1	5	12	2	10	11		
Wair	3773.8	3759.5	3761					
Wwater2								
Wssd2	3861.4	3845.6	3844.5					
Gmb2		0.978	0.978					
Water Pickup	87.6	86.1	83.5					
Air Voids, Vol	118.371	111.250	115.854					
Saturation %	74.00	77.39	72.07					
Strength, lbs	4530	4177	3599	5007	4051	3990		
Average, lbs	4102			4349				
TSR, %	94.3							

Figure 11. HFTL Tensile Strength Ratio Test Results

AASHTO T 283 test results indicate a very low potential for stripping and moisture damage. What may appear to be exposed aggregate in the images are, in fact, fractured aggregates.



Figure 12. Unconditioned HFTL TSR Subset after Testing



Figure 13. Conditioned HFTL TSR Subset After Testing

Asphalt Pavement Analyzer Testing

To test for susceptibility to rutting, CAP Lab personnel conducted rut testing via the Asphalt Pavement Analyzer (APA). This machine is quickly interchangeable with the Hamburg Wheel Track testing apparatus at the CAP Lab. The APA test involves laying a rubber pneumatic tube which is pressurized to 100 psi, across the top center of the test specimens as shown in Figure 14.

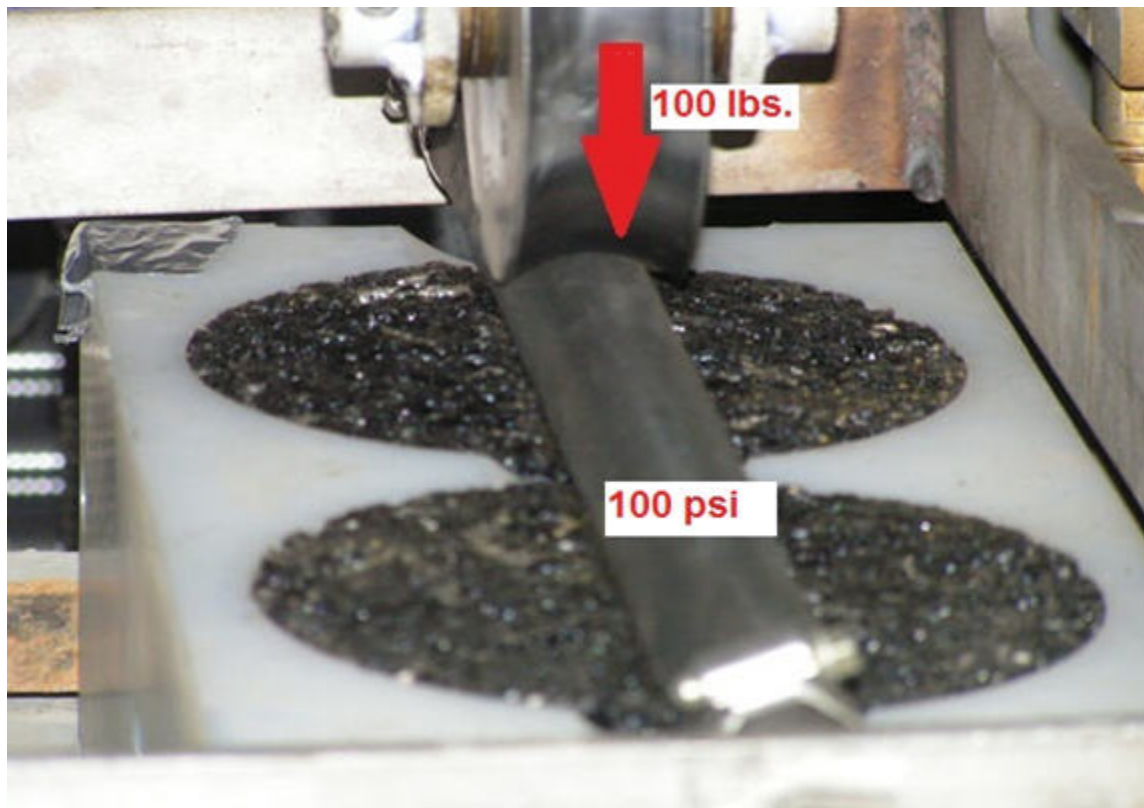


Figure 14. APA Test Configuration

The specimens are conditioned to temperature inside the unit for 6 to 24 hours. Once this has been achieved, the testing consists of applying a 100 lb. downward force onto the overlying pneumatic tubes via the wheels as shown in Figure 14. The wheels are then passed across the hoses a maximum of 8000 cycles. Rut depth measurements are taken via LVDTs at different locations on the specimen.

Review of Specified APA Rut Depths

The research team also investigated what some State Departments of Transportation are using as specified maximum rut testing values using the APA for basis of comparison.

The Virginia Department of Transportation uses a maximum rut depth of 3.5 mm on roadways designed to be in service for more than 10 million ESALs, 5.5 mm for 3 to 10 million ESALs and 7.0 mm for 0 to 3 million ESALs. [11]

The Arkansas Department of Transportation specifies maximum rut depth based on the number of gyrations used in the mix design; maximum of 8.0 mm for 75 & 115 Gyration, 5.0 mm for 160 & 205 Gyration. [12]

The Georgia Department of Transportation specifies a maximum of 5.0 mm for most mixes. They specify higher maximum rut depths for lower volume mixes. [13]

The North Carolina Department of Transportation has specifications for APA rut depths ranging from 4.5 mm to 11.5 mm depending on the mix type. [14]

The HFTL APA specimens tested for this research were done so at a temperature of 64 °C, which represents the design high climatic temperature for the Connecticut region. Even though the PG Grade of the asphalt binder used for the HFTL mix was 76-22, the high temperature which is critical for determining rutting susceptibility is 64 °C for the Connecticut region. The test results for the HFTL are plotted in Figure 15. The final rut depth for each of the tested specimens is shown in Figure 16. As each of the resulting average values for rut depth testing came in under 5.0 mm, and, in light of the reviewed rut depth specifications, it is the opinion of the research team that this mix is not susceptible to rutting.

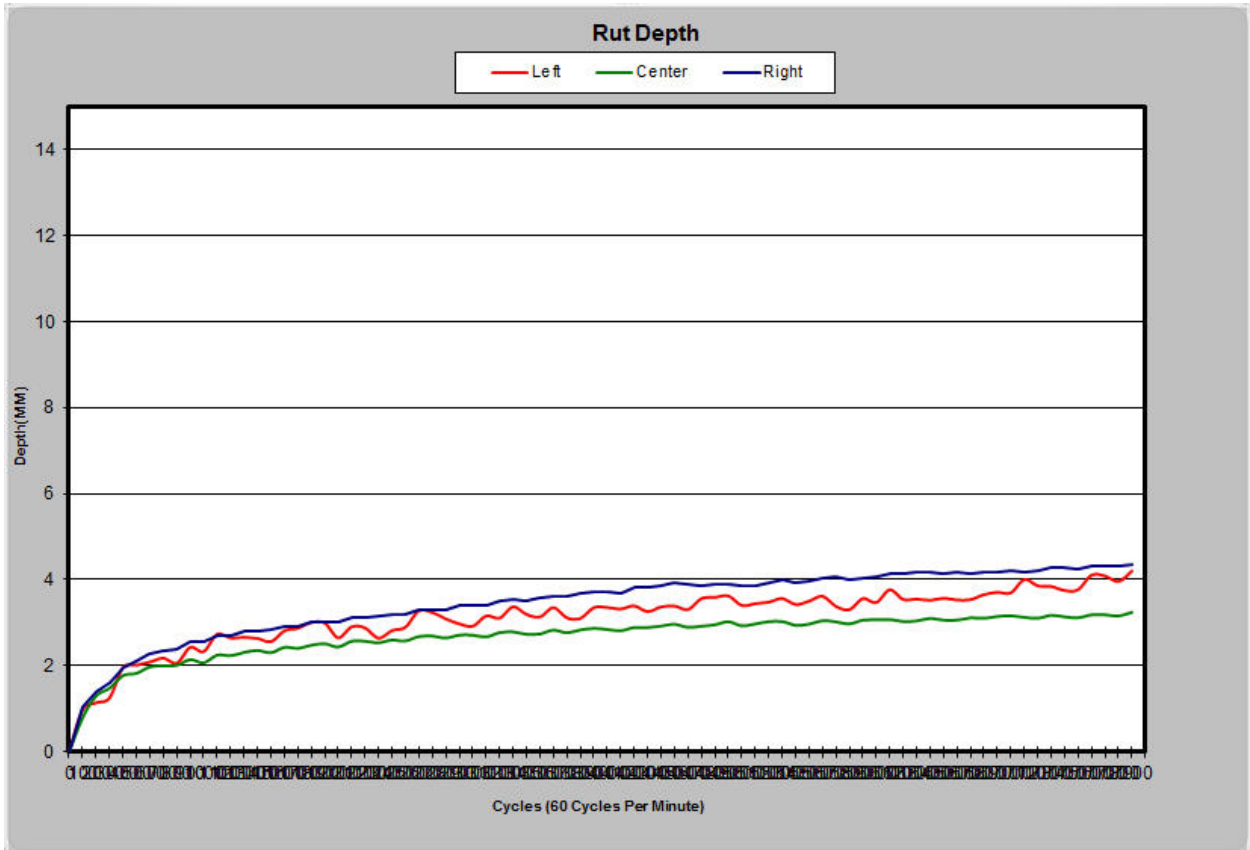


Figure 15. HFTL APA Rut Depths Plot

RUTTING TEST DATA SHEET (60 Cycles Per Minute)

Project No. Thin Friction Test No. 1 Temperature 64
 Mix ID No. Test Date 17-Apr Wheel Load
 Mix Type Thin Friction Data File Hose Pressure 100
 Mold Type Operator JD Lab ID CAP lab

Left Sample ID 17 20			Bulk S Gravity					% Air Void		7.5 Rate Of Rutting	
Temperature			Depth Gauge Reading					Man Average Depth	APA Average	Percent Change	MM/HR
STROKE COUNT	F	C	1	2	3	4	5				
0	32	0						0			
25	145.4	63	0.238	0.223	0.238	0.238	0.387		0.265		38.121
4000	145.4	63	2.960	2.945	2.989	4.893	2.989		3.355	92.11%	2.799
8000	145.4	63	4.075	4.001	4.105	5.205	3.198		4.117	18.50%	0.685
8000	32	0						0			

Center Sample ID 18 21			Bulk S Gravity					% Air Void		6.9 Rate Of Rutting	
Temperature			Depth Gauge Reading					Man Average Depth	APA Average	Percent Change	MM/HR
STROKE COUNT	F	C	1	2	3	4	5				
0	32							0			
25	145.4	63	0.224	0.254	0.254	0.224	0.239		0.239		34.450
4000	145.4	63	2.766	2.796	2.841	2.916	2.886		2.841	91.58%	2.356
8000	145.4	63	3.155	3.095	3.185	3.230	3.215		3.176	10.55%	0.301
8000	32							0			

Right Sample ID 22 23			Bulk S Gravity					% Air Void		6.8 Rate Of Rutting	
Temperature			Depth Gauge Reading					Man Average Depth	APA Average	Percent Change	MM/HR
STROKE COUNT	F	C	1	2	3	4	5				
0	32							0			
25	145.4	63	0.328	0.358	0.313	0.372	0.372		0.349		50.193
4000	145.4	63	3.694	3.649	3.769	3.858	3.575		3.709	90.60%	3.043
8000	145.4	63	4.350	4.275	4.424	4.528	4.230		4.362	14.96%	0.587
8000	32							0			

Figure 16. HFTL APA Rut Depths

Skid Testing of HFTL and Control Sections

The two most imperative aspects of the HFTL mix are structural integrity and the level of skid resistance. It should be noted that ASTM E274 [8] provides for the use of both a ribbed tire and smooth tire in the measurement of pavement surface friction. The reason for the two different methods is that two different things are being quantified: pavement micro-texture and pavement macro-texture. Hall et al, defines micro-texture in pavement as a roughness quality at the sub-visible/microscopic level while defining macro-texture as a surface roughness quality that results from the mixture properties such as aggregate grading, size and shape as well as the manner in which the pavement was finished [15]. Hall et al go on to state that the ribbed tire test does not adequately measure a pavement's macro-texture due the movement of water into the tire grooves. Thus the smooth tire test gives the best indication of the macro-texture of the pavement surface, while the ribbed tire is useful in measuring the micro-texture.

The research team requested skid testing to be performed on the sections immediately following construction and then also at intervals following construction. Skid testing was performed by ConnDOT personnel. Skid testing was conducted on these sections five (5) times. Following construction, skid testing took place during the month of construction and then at 3 months, 10 months, 14 months and 21 months. The skid testing plots over time are shown in Figures 17 and 18 (*Plots courtesy J. Henault, ConnDOT*).

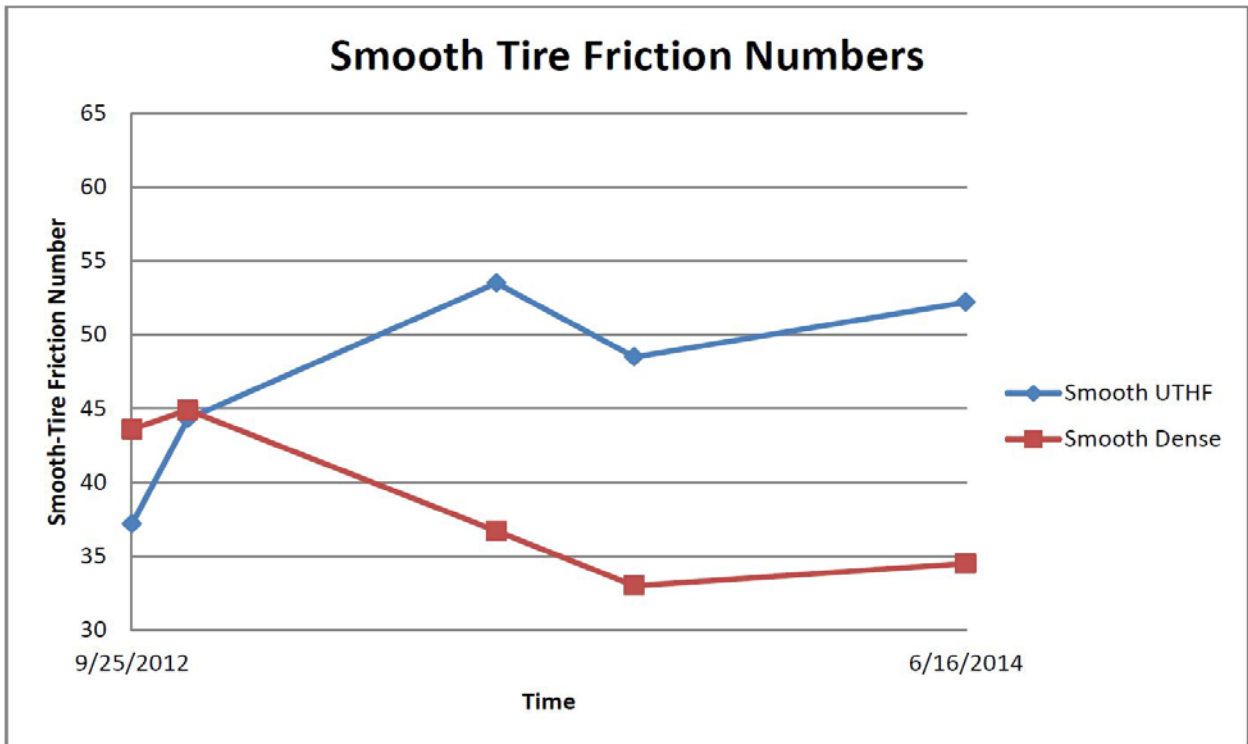


Figure 17. Smooth Tire Friction Numbers

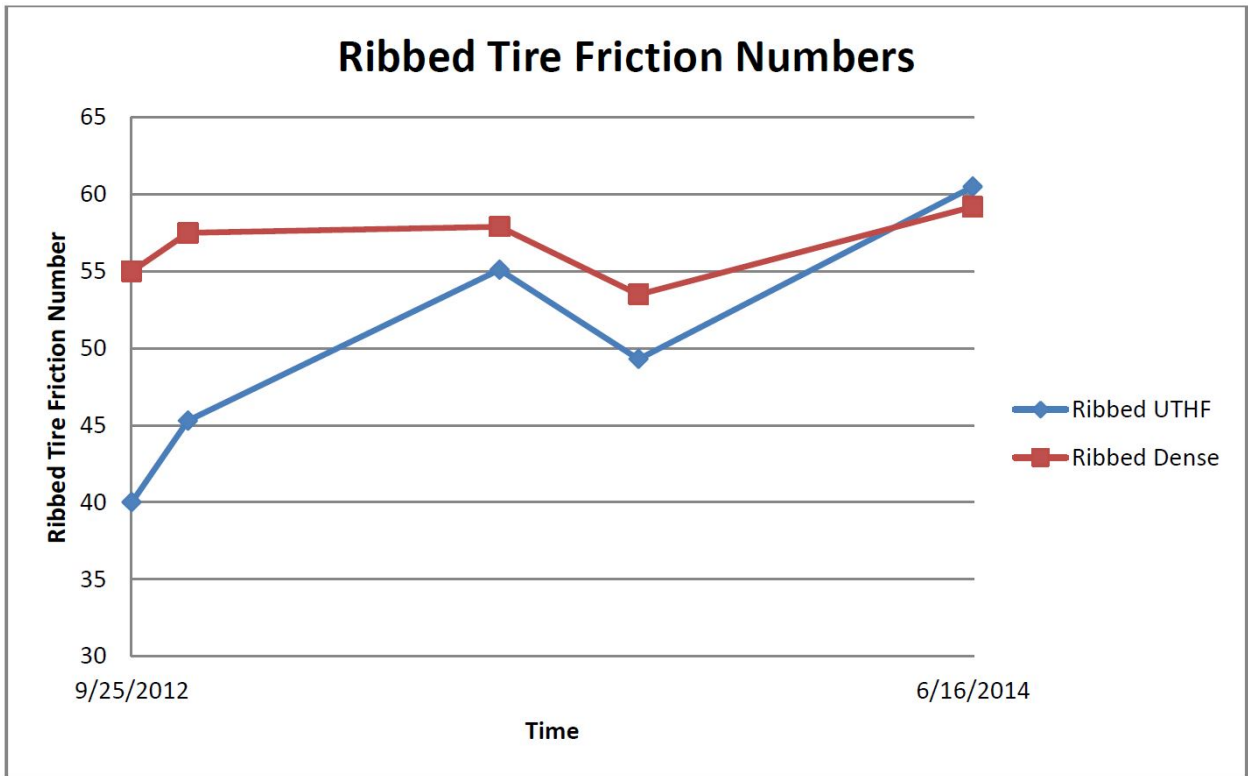


Figure 18. Ribbed Tire Friction Numbers

In both plots, the red series represents the dense graded control section and the blue series represents the HFTL mix sections. It can be readily seen that the HFTL sections began with a lower SN than the dense graded sections. This was the case for test results utilizing both the smooth and the ribbed tire. This may be a direct result of the increase in asphalt binder with the HFTL mixture.

It was desired to compare the binder film thickness values between the mixes. CAP Lab calculated the binder film thickness for both the control sections as well as the HFTL sections utilizing a number of different approaches. The surface area of the mix aggregates was calculated using the Hveem mix design section of the Asphalt Institute's MS-2 [16] manual. Then the film thicknesses were checked and compared to the resulting ConnDOT values which were the same as the calculated values. The ConnDOT film thickness values from the acceptance sheets from the nights of production were used. It should be noted that the film thicknesses are averages from 24 acceptance test values during production of both mixes. The values are shown in Table 1.

Mix Type	Film Thickness (microns)
HFTL	13.9
SuperPave 1/2" (dense)	7.0

Table 1. Comparison of Film Thicknesses Between Mixes

The HFTL mix has nearly twice the calculated film thickness as the control section during production. This increase in film thickness may play a role of reducing the friction effects of the surface aggregate immediately after construction and until repeated traffic loading and environmental damage (UV light and oxidation) cause the asphalt binder to wear at the contact interface between tire and pavement. It is possible that as some of the surface binder wears, the friction effects of the textured surface prevail, which would explain the increase in skid resistance over time.

The reduction in skid resistance between months 10 and 14 after construction needed to be investigated to determine if the numbers continued to drop after further skid testing. It is possible that the drop was simply an anomaly as the skid resistance

increased during the 21 month measurements however the section should continue to be monitored. The SN for the HFTL after the last set of skid testing was just over 50 for the smooth tire test and just over 60 for the ribbed tire test.

Texture Measurements

In 2006, ConnDOT purchased a Circular Track Meter (CT Meter) for purposes of classifying the surface texture of pavements in Connecticut. Henault et al, [17] refer to research which was conducted to verify the accuracy and repeatability of the CT Meter. This work was conducted utilizing ASTM E 965 *Standard Test method for Measuring Pavement Macrotexture Using a Volumetric Technique* [18] (*sand patch test*) as the standard for comparison. The statistical tool which was used to analyze the difference in the results from the two tests was the coefficient of determination, commonly simply noted as *R-squared* which is the resultant value of the statistical test. Results showed there is a near perfect correlation between results of the two tests. This is further stated in ASTM E 2157-09 [19] which is the designation which details the CT Meter test method. It is stated in the designation that the CT Meter results are extremely highly correlated with the mean texture depth results for the volumetric test and that the CT Meter results can replace those results obtained with the volumetric method.

This gave the research team confidence in the results of the CT Meter and macrotexture measurements were carried out in accordance with ASTM E 2157 [19]. This test utilizes a laser surface profiler (Figure 19) called the CT Meter to measure the pavement surface profile. The laser is mounted on an arm which travels in a circular pattern (track) and measures the displacement of the surface or profile. The device reports the mean profile depth (MPD). It also reports the root mean square (RMS) of the measurements since profile measurements can be both positive and negative. For purposes of this analysis, the MPD was the statistic which was used.



Figure 19. Circular Track Meter (CT Meter)

Measurements were taken at randomly determined locations on both the HFTL sections and the dense graded sections. It was originally desired that there would be about 16 measurements taken on each section of pavement. Due to time constraints, 16 measurements were taken on the HFTL sections and only 8 on the dense graded surface. Results of those measurements are shown in Table 2 and Figure 20.

Reading	Dense MPD	UTHF MPD
1	0.23	0.81
2	0.43	0.69
3	0.37	1.05
4	0.45	0.62
5	0.34	0.64
6	0.36	0.98
7	0.27	0.83
8	0.37	0.82
9		0.86
10		0.68
11		0.62
12		0.65
13		0.81
14		0.89
15		0.74
16		0.75
Average	0.35	0.78

Table 2. MPD Measurements

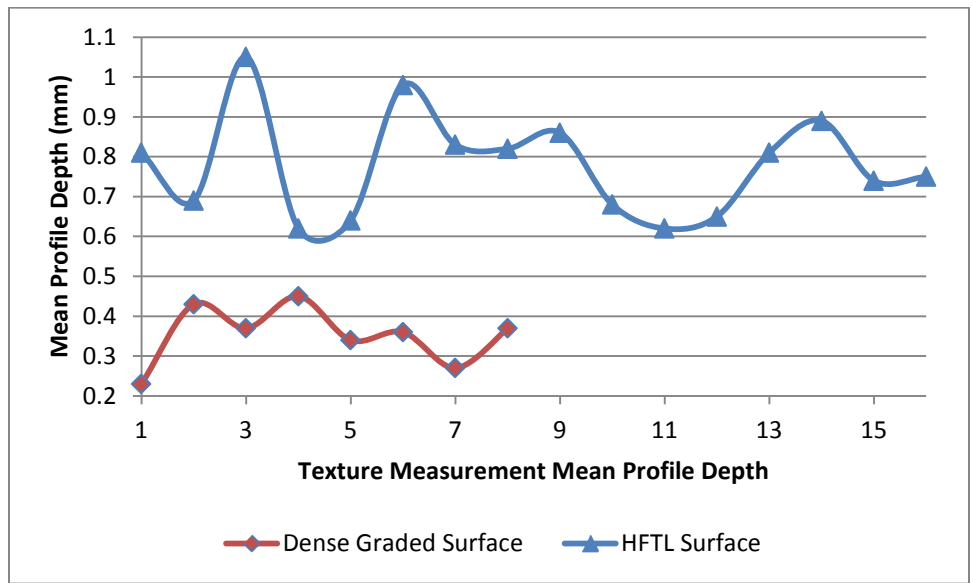


Figure 20. Mean Profile Depth Plots

The average of the dense graded surface readings was less than half the HFTL readings. This provides more than adequate confidence that the HFTL section, from a comparative standpoint, has a much higher degree of surface texture relative to the dense graded section.

During field measurements of the HFTL section, there was a suspected difference in surface texture between the wheel paths and non-wheel paths. The research team decided to examine whether the effects of traffic loading were in any way causing differences in the level of texture across the pavement surface. Specifically, the concern was whether traffic loading was causing a decrease in texture in the wheel paths in the HFTL sections.

As stated previously, there were 16 total texture measurements taken within the HFTL section. 8 of them happened to fall within the visible wheel path while 8 of them did not. The research team did a brief examination of the texture measurement results, comparing wheel path to non-wheel path results in the HFTL section. The data points are shown below in Table 3. The research team also ran brief descriptive statistics on the two sets of data utilizing an Excel™ Spreadsheet. Those are shown in Table 4.

Reading	Non-Wheelpath	Wheelpath
1	0.81	0.69
2	1.05	0.62
3	0.83	0.64
4	0.62	0.98
5	0.65	0.82
6	0.81	0.86
7	0.89	0.68
8	0.75	0.74
Average	0.80	0.75

Table 3. Wheel Path Texture Comparison (mm)

<i>Non-Wheelpath</i>	<i>Descriptive Statistics</i>	<i>Wheelpath</i>	<i>Descriptive Statistics</i>
Mean	0.80125	Mean	0.75375
Standard Error	0.04801181	Standard Error	0.043790797
Median	0.81	Median	0.715
Mode	0.81	Mode	#N/A
Standard Deviation	0.135797907	Standard Deviation	0.123859079
Sample Variance	0.018441071	Sample Variance	0.015341071
Kurtosis	0.64593872	Kurtosis	-0.091664227
Skewness	0.499484813	Skewness	0.856529301
Range	0.43	Range	0.36
Minimum	0.62	Minimum	0.62
Maximum	1.05	Maximum	0.98
Sum	6.41	Sum	6.03
Count	8	Count	8
Confidence Level(95.0%)	0.113529891	Confidence Level(95.0%)	0.103548781

Table 4. Descriptive Statistics Wheel Path and Non-Wheel Path MTD

The data and statistics show that the wheel path measurement averages are slightly lower than those of the non-wheel path measurements. Because of a small sample size, the research team chose to determine whether the difference was statistically significant. A simple Student's T-test was used to compare the sets of data. The data was assumed to be distributed normally and the variances were considered equal. Results of the T-test are shown below in Table 5.

t-Test: Two-Sample Assuming Equal Variances		
	<i>Non- Wheelpath</i>	<i>Wheelpath</i>
Mean	0.80125	0.75375
Variance	0.018441071	0.015341071
Observations	8	8
Pooled Variance	0.016891071	
Hypothesized Mean Difference	0.05	
df	14	
t Stat	-0.038471702	
P(T<=t) one-tail	0.484927406	
t Critical one-tail	1.761310136	
P(T<=t) two-tail	0.969854812	
t Critical two-tail	2.144786688	

Table 5. Student’s T-test Wheel Path and Non-Wheel Path MTD

Given the t-statistic and critical value shown in the results in Table 5, it can be stated at this point that the slight decrease in the average texture measurements in the wheel path in comparison to the non-wheel path measurements is due purely to chance and is not significant.

Results and Discussion

The results of the Moisture susceptibility testing, via both the Hamburg method as well as the Tensile Strength Ratio method, show evidence that the HFTL mix is not susceptible to moisture induced damage. The lack of an evident stripping inflection point on the Hamburg plot (Figure 8) in addition to the high TSR value (Figure 11) and no evidence of stripping after testing (Figure 12 &13) give confidence that this mix will fare well from an environmental damage standpoint.

The results of the rut testing (Figure 15 &16) in comparison with the reviewed specification standards from other state agencies indicate that there should be confidence in this mix to hold up to ConnDOT Traffic Level 2 loading. Note: this is the traffic level that exists on Route 12 where this HFTL mix was placed.

Laboratory test results indicate that this mix will perform well in the field regarding its durability and structural integrity. It should be cautioned at this time that this was a single mix with one asphalt binder source. There is a possibility that the use of an alternative binder source or aggregate source could yield different laboratory test results.

Results of skid testing over the course of time are positive, as the skid resistance increased significantly from the time of placement until the last test was performed 14 months later. The average SN_{40S} value increased from approximately 37 to 48 during that time, and the average SN_{40R} value increased from approximately 40 to 49. What may be of concern is the drop of about 5 skid numbers for both the smooth- and ribbed-tire tests from month 10 to month 14 following placement. It is yet to be seen if this trend will continue or if both SN_{40S} and SN_{40R} stabilize at approximately 50.

The results of macrotexture measurements indicate that the HFTL surface should provide an adequate texture depth for high-speed (50 mph or greater) facilities, and the superior SN_{40S} values discussed above bear this out. The average MPD for the HFTL surface was 0.78 mm. This was significantly greater than for the control section (MPD=0.35 mm).

ConnDOT division of maintenance was contacted to determine if there were any problems encountered in this area with respect to winter maintenance operations that may have been a result of the of HFTL mix. It was noted that due to the open texture of the mix, water was held on the surface for a longer period of time. This required

retreatment to prevent the held water from freezing again. An estimate of the increase in maintenance costs for this section was \$1586.52 during the 2012-2013 winter.

While it is true that MPD values of greater than 1.00 mm have been measured on ConnDOT's Ultra-thin Bonded Wearing Surface, this level of texture depth (MPD~0.78 mm) for a polymer modified high friction wearing course may provide a better balance between high-speed performance, durability, and winter maintenance requirements than a mix with greater texture depth. Increasing the texture depth may require more winter retreatments to prevent freezing.

Conclusions and Recommendations

In light of the laboratory test results as well as the skid testing results and texture measurements, the research team makes the following recommendations:

- Develop and investigate this mix for use in areas where both friction and durability are concerns.
- Continue to monitor the skid resistance on the HFTL trial section placed on Rt. 12.
- Perform follow-up macro-texture measurements to accompany measurements of skid resistance to investigate trends and relationships between the two with respect to high friction pavement surfaces.
- Perform visual inspections to evaluate the overall condition of the HFTL trial section placed on Rt. 12 to ensure durability in place.
- Pave a second trial section of the HFTL mix with a slightly lower asphalt content along with a control section mix identical to the 2012 HFTL. Monitoring of these two sections could serve as an indication as to whether the increased asphalt content and film thickness contributed to the initially lower skid resistance values measured immediately following construction.

- In addition to the second trial section, it would be advantageous to place a section of the Ultra-thin Bonded Wearing Surface as part of the same project for investigative and comparative purposes.
- Consider a thinner lift (~3/4 inch) application of the HFTL mix.
- Investigate whether the HFTL mix would perform at the same level if different aggregate and/or liquid binder sources were used.
- Continue to refine the HFTL mix to achieve the best balance between high-speed performance (skid resistance and texture), durability, and winter maintenance requirements.

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Appendix A. Specification for Paver Placed High Friction Thin Overlay (HFTO)

1. Asphalt Binder

- A. The asphalt binder used for (HFTO) shall meet the requirements of a PG 76-22 modified with SBS polymer.
- B. The stability of the modified binder shall be verified in accordance with ASTM D7173 using the Dynamic Shear Rheometer (DSR). The DSR $G^*/\sin(\delta)$ results from the top and bottom sections of the ASTM D7173 test shall not differ by more than 10%. The results of ASTM D7173 shall be included on the Certified Test Report.
- C. The supplier of the modified asphalt binder shall provide a maximum temperature the material can be heated without damaging the polymer modification as part of the material certification provided to the Engineer.

2. Tack Coat

- A. The tack coat shall be either CRS-2P or CRS-2L emulsion that meets the requirements for AASHTO M316. The application rate shall be the same as is used for conventional HMA placed on an unmilled surface.

3. Aggregate

- A. The aggregates used for the HFTO shall meet aggregate property requirements for ConnDOT Superpave HMA Level 3 mixes.

4. HFTO Mixture

- A. The JMF shall conform to the following master range:

<u>Sieve Size</u>	<u>Percent Passing</u>
½"	100%
3/8"	90-95%
#4	35-50%
#8	24-36%
#30	8-20%
#50	5-12%
#200	3-7%

- B. The target JMF asphalt content of the mixture shall not be less than 6.0%. With a production tolerance of $\pm 0.3\%$.
- C. The mixture shall be tested using a Superpave gyratory compactor with 75 gyrations. The specimens shall have air voids at 50 gyrations of $5 \pm 1.0\%$ and a minimum VMA of 18%.
- D. The mixture shall be tested in accordance with AASHTO T283 with a minimum Tensile Strength Ratio of 80%. The specimens shall be fabricated using a Superpave Gyratory compactor to a height of 95 mm. If the mixture does not achieve the minimum required Tensile Strength Ratio, then a liquid anti-strip additive shall be blended with the SBS modified asphalt binder at the terminal or refinery and tested to ensure the asphalt binder still meets the required PG 76-22.
- E. Drawdown testing shall be conducted as part of the mix design process in accordance with AASHTO T305. This testing shall be conducted at the anticipated production temperature as well as 25 degrees above the anticipated production temperature. The maximum draindown shall not exceed 0.2% at the production temperature and 0.4% at the elevated temperature.
- F. The production tolerances for the HFTO shall be the same as for standard ConnDOT Superpave mixtures.
- G. As part of the mix design submittal, 12 specimens compacted to 75 mm in height with air void content between 4-6% shall be submitted to the Engineer.

5. Placement

- A. The final compacted thickness of the HFTO shall be 1.0 inch ± 0.25 inches.
- B. Placement shall be done with conventional paving equipment and a minimum of 2 rollers.
- C. Surface temperatures at the time of placement shall be 50 degrees and rising.
- D. All joint construction shall be butt joints.
- E. The contractor shall furnish at least two (2) 10 ton rollers, one of which is capable of operating in vibratory modes. A minimum of 4 passes shall be made across the material before it cools below 200 ° F. The first two passes shall be made in vibratory mode and the final 2 passes shall be made in static mode. All rolling must be completed before the surface temperature of the mat drops below 200 ° F.
- F. Cores shall be taken from the mat and longitudinal joint at frequency that meets ConnDOT's coring requirements for Superpave. The densities obtained from these cores will be used for informational purposes only.

Appendix B. ADT for High Friction Thin Lift Overlay (HFTL) on Rt. 12 Preston Ledyard.

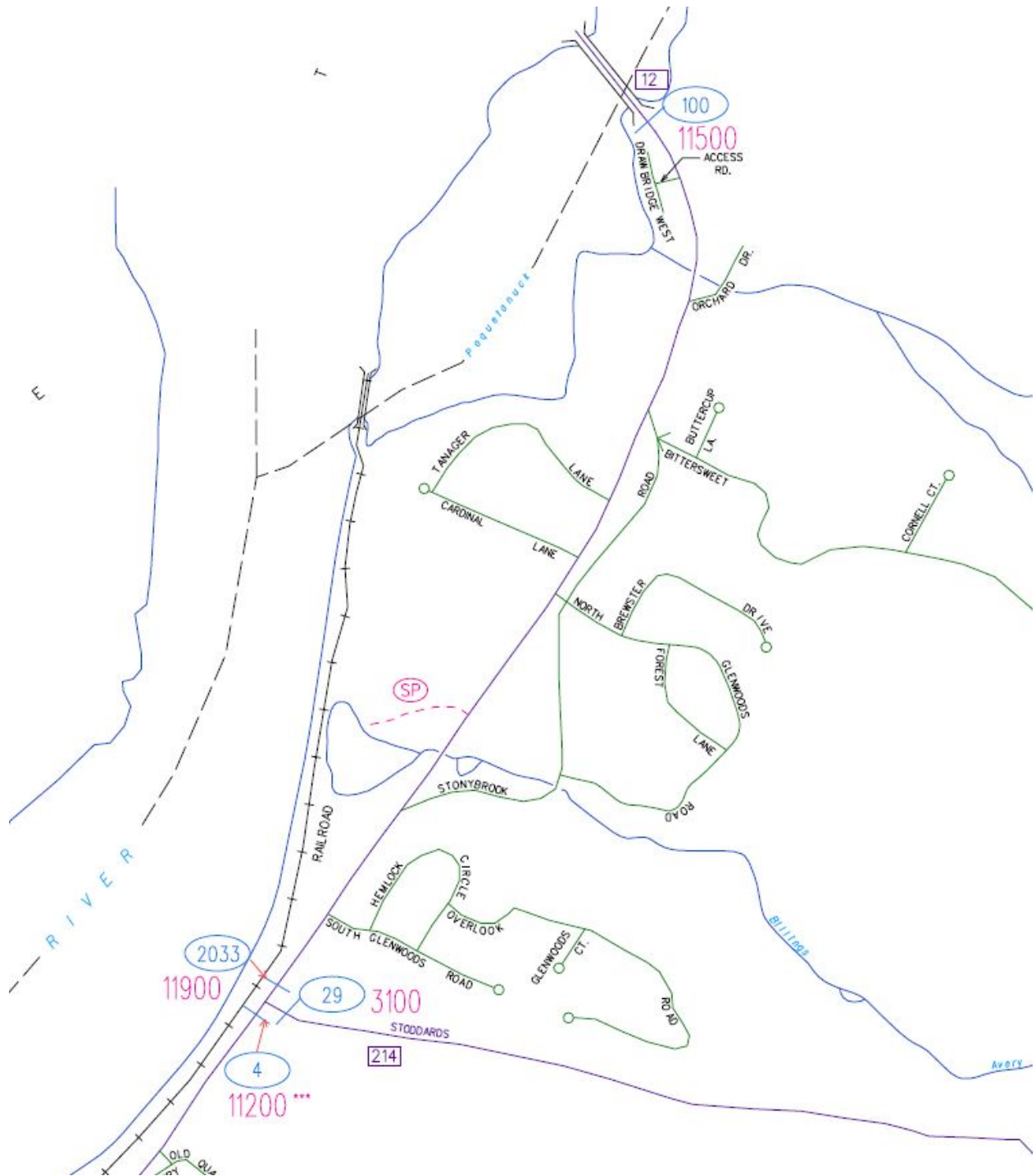


Image Courtesy Connecticut Department of Transportation