STATE OF FLORIDA

Preliminary Investigation of a Test Method to Evaluate Bond Strength of Bituminous Tack Coats

Research Report
FL/DOT/SMO/02-459

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October 2002

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ABSTRACT

It is generally recognized that a bituminous tack coat is beneficial for improving the bonding strength between two hot-mix asphalt layers. It is also qualitatively recognized that moisture on the surface of the tack coat can impede the bonding performance of the tack coat. Furthermore, varying tack coat application rates and aggregate interaction between hot-mix asphalt layers are also considered to have an effect on the bonding performance of the tack coat. In an effort to quantify the effects of moisture, tack coat application rate and aggregate interaction on bonding performance, a test apparatus and procedure were developed. Three field projects were also constructed and evaluated at various time intervals. Results indicate that water applied to the surface of the tack coat, representing rainwater, significantly reduced the shear strength of the specimens when compared to equivalent sections without water applied. Varying tack coat application rates within the range of 0.02 to 0.08 gal/sy had less of an effect on shear strengths. The use of a tack coat to increase bonding strength was more effective for fine graded mixtures compared to coarse graded mixtures. Aggregate gradations of the mixtures being bonded together played a critical role in the magnitude of the shear strengths achieved. Fine graded mixtures achieved significantly lower shear strengths than the coarse graded mixtures. A field project containing a milled interface achieved the greatest strengths of the projects tested. The single-operator standard deviation of the test procedure was determined to be 9.6 psi.

INTRODUCTION

Many throughout the transportation industry recognize the importance of applying a bituminous tack coat material between layers of hot-mix asphalt. The Florida Department of Transportation (FDOT) specifies the use of a tack coat in their Standard Specifications for Road and Bridge Construction (1). The tack coat is used to bond the two layers together so that stresses can be transferred from the upper asphalt layer to the lower asphalt layer without slippage or delamination occurring. Uzan et al. (2) has shown through mathematical analysis that the stress distributions at the layer interface region are highly affected by the adhesion conditions at the layer interface. Crescent shaped cracks can form in pavement areas where the interface bond is weak. Hachiya and Sato (3) have shown through computer analysis that separation of the asphalt layers will occur if the shear stress at the interface exceeds the shear strength. They suggest the wearing course will then fail in tension or flexure. The suggested solution is to increase the layer thickness or increase the bond strength through use of a tack coat.

Currently, the FDOT Standard Specifications allow the use of one of three types of tack coat materials. For daytime construction, either of two rapid-set emulsified asphalt tack coat materials (RS-1 or RS-2) can be used. For nighttime construction, a viscosity-graded asphalt cement (AC-5) is specified.

It is qualitatively recognized that placing hot-mix asphalt over tack coat material that has been contaminated by rain is potentially detrimental to the performance of the hot-mix asphalt, possibly resulting in immediate or future slippage or delamination. This is believed to be due to an inability of the two asphalt layers to bond properly because of the interference of the water. In response to this concern, the Standard Specifications require that the paving surface be dry before placing the hot-mix asphalt on the surface (4).

Recently, FDOT Engineers, after discovering that Contractors had placed small quantities of hot-mix asphalt over a tack coat that had been wetted by rain, inquired whether a test method existed for determining the bond strength of roadway cores consisting of two asphalt layers bonded by a bituminous tack material. The FDOT Engineers were interested in finding a quantitative measure for the bond strength of the tack coat to see how detrimental the rainwater was to the tack coat's performance. This type of information would help the FDOT Engineers perform an engineering evaluation to determine whether the hot-mix asphalt should be removed or remain in place.

Upon investigation, an Iowa Department of Transportation test procedure for determining the shearing strength of bonded layers of new and old Portland cement concrete was discovered (5), but no standard published test procedure for determining the bond strength of bituminous tack coats using roadway cores could be found. Subsequently, laboratory and field work was conducted for the purpose of developing a test procedure for this purpose. This report focuses on the work completed to date in the development of the test procedure and presents results for several field test sections.

BACKGROUND

A literature review was conducted to discover what research had been previously conducted on bond strength test procedures. Mohammad et al. (6) performed simple direct shear tests on various types of tack coat materials at several spread rates using laboratory fabricated asphalt specimens. A custom made shearing apparatus was designed and fabricated for use in the Superpave Shear Tester. Specimens were fabricated in the Superpave gyratory compactor in two lifts with a tack coat applied prior to compaction of the second lift. The tests were conducted in constant load mode (50 lb/min). No normal load was applied to the specimens.

Uzan et al. (2) custom built a direct shear device that incorporated a normal load. Samples were rectangular in shape and were compacted with static pressure. The testing apparatus had the capability to measure deformation in the plane perpendicular to the shear plane using two deflectometers. The tests were conducted in constant strain mode (2.5 mm/min).

Mrawira and Damude (7) used a modified version of the test apparatus from ASTM D-143, which is used to test the shear strength of wood samples. The device is of the guillotine style and can apply a uniform lateral load through a pivoting load surface. Test specimens were four-inch diameter roadway cores that were trimmed and had a new hot-mix asphalt overlay compacted over the trimmed surface using a Marshall hammer. Samples were prepared with and without tack coat material. The tests were conducted in constant strain mode (1 mm/min).

Hachiya and Sato (3) tested laboratory prepared cubical and cylindrical hot-mix asphalt samples in tension and flexure to determine tack coat bonding strength. Tests were conducted in constant strain mode (1 mm/min and 100 mm/min).

All of the devices mentioned above were either custom fabricated or adapted from another test procedure. Loading conditions, sample preparation and geometry varied for each of the test methods. Furthermore, each test apparatus focused on testing laboratory prepared samples and not field cores.

OBJECTIVES

In lieu of the test devices and procedures discussed in the previous section, the goal of this research was to develop a test apparatus that is simple in function, tests in direct shear and allows testing parameters to be variable, i.e. loading method (stress or strain controlled), loading rate, test temperature and gap width between shearing plates. Testing parameters would be varied to see which combination of test parameters provided the most meaningful and practical results. The device would also have the flexibility to test untrimmed roadway cores or cylindrical laboratory samples without modification to the device. Subsequent to the development of the test apparatus, testing was conducted to determine the effect of tack coat application rate versus bond strength and the effect that water has on the bonding performance of tack coat material.

INITIAL SHEARING APPARATUS

Upon investigation, it was discovered that the Pavement Evaluation Section of the State Materials Office had custom built a direct shear device for measuring the bonding strength between a thin lift of concrete pavement applied over exiting hot-mix asphalt. The device is shown in Figure 1. The device was a modification of the Iowa Department of Transportation shearing device for Portland cement concrete (5). The FDOT device is of the guillotine type and was designed to be mounted in a rebar/steel-strand breaking machine manufactured by Tinius Olsen (Figures 2 and 3). The machine operates in constant strain mode. The device was built for four-inch diameter cylindrical specimens (either roadway cores or laboratory fabricated specimens). The gap width between shearing platens is fixed at 1/8 inch.

Initially, it was unknown what loading condition would be suitable for this test procedure. Multiple specimens at varying strain rates (0.25, 0.50, 1.0, 2.0 in/min) were tested and the results were analyzed. Specimens were obtained from the Heavy Vehicle Simulator (HVS) test track in Gainesville, Florida. One would expect the specimens tested at the higher strain rates to reach an ultimate load greater than the specimens tested at the lower strain rates

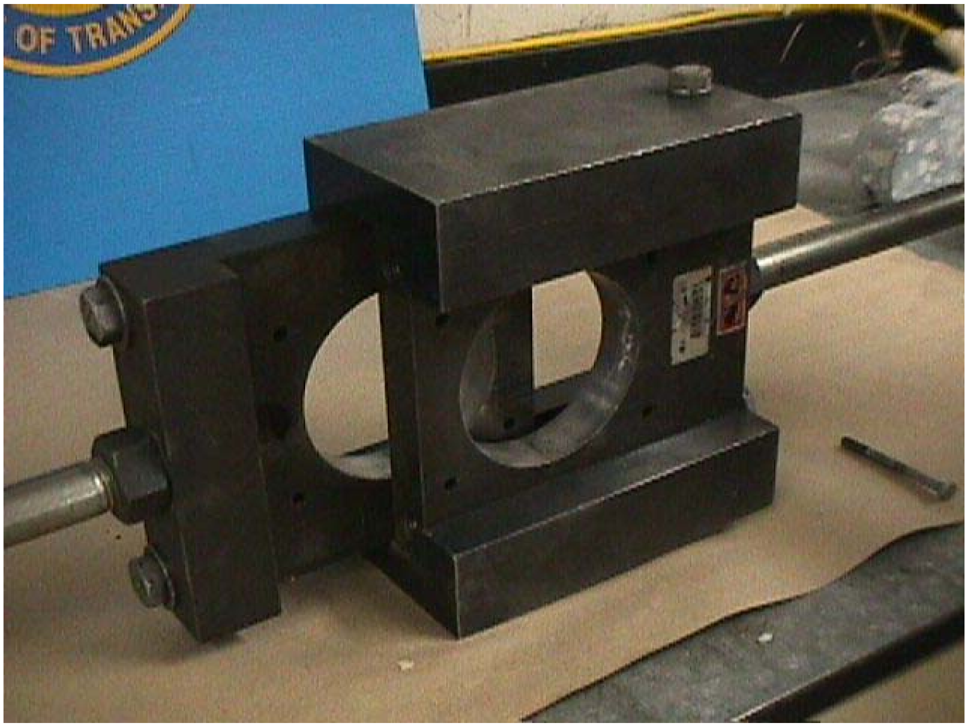

Figure 1 – Initial Shearing Apparatus

Figure 2 – Tinius Olsen Load Frame

Figure 3 – Tinius Olsen Data Acquisition System

due to the viscoelastic nature of asphalt cement. This trend was generally observed, however, the test results within a particular displacement rate were excessively variable (Table 1).

Subsequent testing of roadway cores obtained from various construction projects revealed that there was a reduction in testing variability as testing personnel became more experienced with conducting the test.

Despite the reduced variability obtained with increased experience at performing the test procedure and the basic simplicity in theory and design of the testing apparatus, there were several drawbacks to this testing apparatus: 1) the shearing test apparatus was heavy (approximately 75 pounds) and cumbersome to work with, 2) the Tinius Olsen test machine was designed to apply much higher loads than needed for hot-mix asphalt shear testing, 3) the Tinius Olsen machine often induced stresses into the test specimen during test setup, 4) the test temperature could not be controlled, 5) this type of device would never be practical to implement

Table 1 – Displacement Rate Test Data for Initial Shearing Apparatus

Displacement Rate (in/min)	Sample Number	Maximum Load (lbs)
0.25	1	malfunction
	2	822
	3	653
	Average	738
0.50	1	967
	2	510
	3	561
	Average	679
1.0	1	1050
	2	1346
	3	565
	Average	987
2.0	1	998
	2	673
	3	1777
	Average	1149

in the District laboratories. Therefore, it was decided to construct a test apparatus that would better meet the needs previously discussed in the "Objectives" section of this report.

FINAL SHEARING APPARATUS

A simple direct shear device was designed and constructed that would operate in the Materials Testing System (MTS) located in the Bituminous Research Lab (Figures 4 and 5). The device holds six-inch nominal diameter roadway cores or laboratory fabricated specimens. Roadway cores do not need to be trimmed due to the design of the device and the large size of the MTS testing chamber. The device was manufactured so that the gap width between the shearing platens is adjustable. In addition, the MTS equipment has the flexibility of strain or stress modes

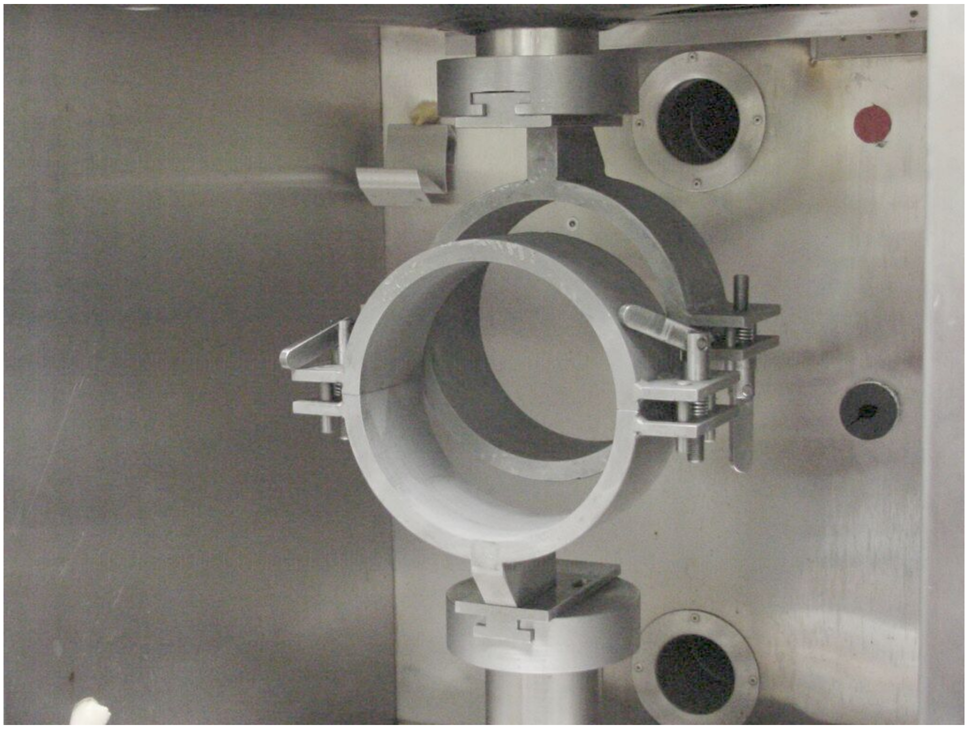

Figure 4 – Final Shearing Apparatus

Figure 5 – Final Shearing Apparatus

of loading, adjustable loading rates and temperature control. The shear device is simple to use and the data acquisition and reporting has been automated with software modified for this application.

One of the goals for this test apparatus was to make it practical enough to be used in District laboratories. It is recognized that in Florida, none of the District laboratories have MTS equipment to operate a test apparatus as used in this study. However, FDOT researchers wanted to have the flexibility to vary testing parameters during the initial development of the test procedure. Once the testing parameters had been selected, then a device could be constructed that was similar to the one used in this study, but would be functional in a loading device that was common to all of the District laboratories. One such device is the Marshall apparatus used to determine stability and flow.

EVALUATION OF TESTING PARAMETERS

The following five testing parameters were examined in the development of the test apparatus and procedure: 1) specimen diameter, 2) mode of loading, 3) rate of loading, 4) testing temperature and 5) gap width between shearing platens. In the examination of the testing parameters, there were two primary concerns: 1) select the final version of the testing parameter so that the most meaningful data is obtained and 2) maintain practicality and simplicity in the test procedure.

As a general note, in the evaluation of the testing parameters, all shear stress values were calculated as the ultimate load obtained divided by the cross-sectional area of the specimen.

Specimen Diameter

During this study, two diameters were considered: four inch and six inch. These two diameters represent the most common size samples used in laboratory testing. The initial shearing device was designed for four-inch diameter specimens. However, it was decided to design the final shearing device to accommodate six-inch diameter specimens for two reasons. First, FDOT specifications require that Contractors cut six-inch diameter roadway cores for density determination. FDOT coring crews also use six-inch diameter coring bits for the roadway cores they obtain for pre-construction pavement evaluation purposes. Second, FDOT researchers believed that the larger shearing surface area provided by using a six-inch diameter specimen versus a four-inch diameter specimen would provide less variable results, especially for mixtures containing a large nominal maximum aggregate size.

Mode of Loading

The MTS equipment has the capability to load either in strain or stress control mode. Ideally, the mode of load chosen for this test would duplicate that encountered in the roadway. The mode of loading experienced in an actual pavement was unknown to the FDOT researchers but it likely is neither strain or stress solely. Initially, the FDOT researchers were going to use stress controlled loading at 400 to 500 psi/min. This was the mode of loading and rate that the Iowa Department of Transportation used in their shear test for bonded concrete (5). However, as identified in the literature search, most of the testing performed by other researchers was conducted in strain control mode. After further consideration, it was decided to use strain controlled loading. The main reason for choosing this mode of loading was not for any mechanistic reason, but because it would be more practical to implement this procedure at other laboratories, especially if the

Marshall apparatus were used. Other common laboratory tests, such as Marshall stability and flow and indirect tension testing, are also tested in strain controlled mode.

Rate of Loading

Since it was decided that strain controlled loading would be used, it was necessary to determine at what displacement rate the test would be conducted. Two displacement rates were chosen for examination: 2.0 and 0.75 in/min. The 2.0 in/min rate is a common displacement rate used for laboratory tests. The 0.75 in/min displacement rate was chosen as a comparison based on experimentation with the initial shearing apparatus that indicated that a displacement rate of 0.75 in/min corresponded to stress rate of 400 to 500 psi/min (same as Iowa DOT specification) for the particular mixture being tested. Cores from the FDOT HVS test track were tested at both displacement rates using the final shearing apparatus and the data is shown in Table 2. The samples tested at the 2.0 in/min displacement rate exhibited a higher average failure shear stress (60 psi) compared to the samples tested at 0.75 in/min (38 psi). This trend agrees with the data shown in Table 1 for the samples tested with the initial shearing apparatus; i.e. samples tested at greater displacement rates require a greater load to fail. This is due to the viscoelastic nature of asphalt cement.

Table 2 – Comparison of Failure Shear Stress for Two Displacement Rates Using Final Shearing Apparatus

Sample #	Failure Stress (psi)	
	2.0 in/min	0.75 in/min
1	37	29
2	62	30
3	56	58
4	92	43
5	53	30
Average	60	38

The displacement rate of 2.0 in/min was selected for the test procedure for two reasons. First, the 2.0 in/min rate is very common in asphalt testing. The Marshall apparatus is currently geared to operate at that displacement rate. If the Marshall apparatus were eventually used to conduct the shear test at District laboratories, then no modification to the gearing would be required. Second, the 2.0 in/min rate provided failure shear stresses of higher magnitude than the 0.75 in/min rate. A larger test value range could allow better discernment between good and poor performing samples, especially if the standard deviation of the test procedure were relatively constant among a range of failure shear stresses.

Testing Temperature

Since pavement temperature can vary widely depending on the region and time of year and because the exact temperature conditions at which a shear failure may occur in a roadway are unknown, it was decided to test specimens at four different temperatures and select the temperature which provided the most meaningful test results and would be the most practical to achieve. The four temperatures selected for testing were 77, 100, 120 and 140°F. Five cores from the HVS test track were tested at each temperature range. Cores were brought to the required temperature by placing them in a temperature control chamber for a minimum of two hours. Cores were then removed from the chamber one at a time and immediately tested. It required approximately two to three minutes to remove each specimen from the temperature control chamber, mount the specimen in the testing apparatus and test the specimen. Test results are presented in Table 3 and Figure 6. Higher failure shear stresses were observed at lower testing temperatures where asphalt binder behaves more like an elastic material than a viscous material. Increasing the testing temperature from 77 to 100°F decreased the failure shear stress

Table 3 – Failure Shear Stress vs. Temperature

Sample #	Failure Stress (psi)			
	Test Temperature (F)			
	77	100	120	140
1	105	48	16	7
2	90	47	15	11
3	105	45	17	12
4	110	38	13	4
5	94	40	11	7
Average	101	44	14	8

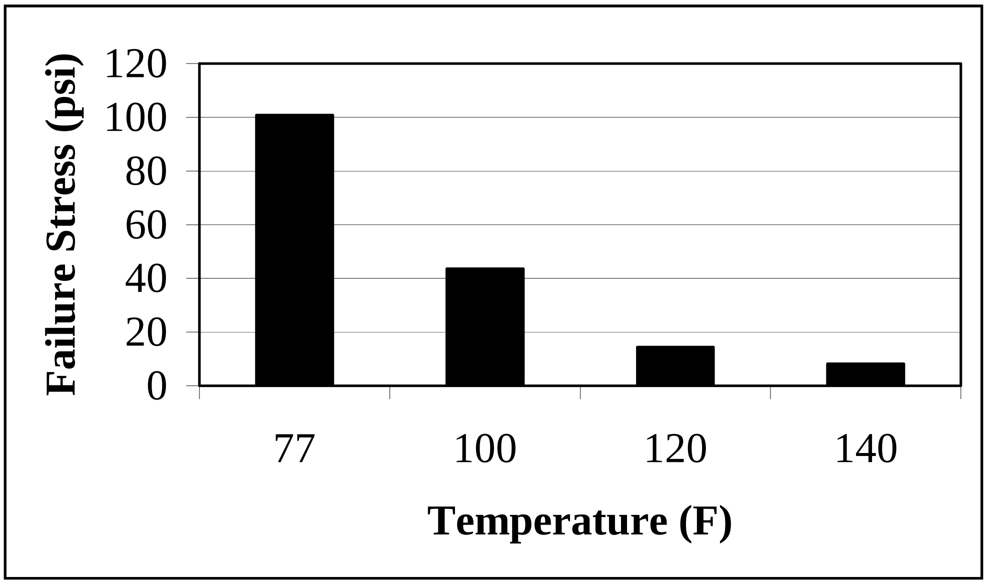

Figure 6 – Failure Shear Stress vs. Temperature

by more than half (101 psi at 77°F and 43 psi at 100°F). Very low failure shear stresses were observed at 120 and 140°F (14 and 8 psi respectively).

The testing temperature selected for the test procedure was 77°F. The higher obtained stresses would allow better discernment between good and poor performing samples. If 120 or 140°F were selected, it may be difficult to determine if a difference exists between average failure shear stresses due to low mean values obtained at these higher temperatures combined with standard deviations that may overwhelm the difference in means. Furthermore, 77°F is a relatively easy temperature to achieve in a laboratory. Specimens can be placed in sealed watertight plastic baggies in a water bath maintained at 77°F or in a temperature controlled air chamber as done in this study.

Gap Width Between Shearing Platens

It is necessary to have a gap between the shearing platens large enough to account for roadway cores that are not cored exactly perpendicular to the roadway surface. Cores obtained in this manner will result in a layer interface plane that is not exactly perpendicular to the sides of the cylindrical core. Therefore, the layer interface plane (shear plane) will be at a slight angle within the shearing apparatus and the apparatus must have a gap wide enough to accommodate this skewness. The roadway core should be rotated within the apparatus so that the skewness is in the horizontal plane. This should eliminate or minimize the effect of the skewness on the strength values obtained.

It is also imperative that the gap width not be too large. This would result in bending stresses in the sample during shearing due to the cantilever effect of the unsupported edges. Considering the above factors, the gap width chosen for the test apparatus is 3/16 inches. No adverse testing results or affects were observed using this gap width. Mrawira and Damude (6) also found that the gap width of their shear-testing device needed to be widened to accommodate irregularities in the planar surface of the asphalt layers and skewness of core samples obtained and therefore, chose a gap width of 5/16 inches.

Summary of Test Parameters

The final testing parameters chosen are: 1) specimen diameter; 6 inches, 2) mode of loading; strain controlled, 3) rate of loading; 2 in/min, 4) testing temperature; 77°F and 5) gap width between shearing platens; 3/16 inch.

FIELD TEST PROJECTS

After the laboratory testing parameters for the shearing apparatus were selected, three field research projects were evaluated, one on United States Highway 90 (US-90) and two on Interstate 95 (I-95). These projects provided a means to use the new shearing apparatus to evaluate several variables that would be encountered in real construction projects that might affect the bonding strength between hot-mix asphalt layers.

US-90 Project

Project Description

This project was located on US-90 in Madison County, approximately one mile west of the town of Madison. The eastbound lane of the two-lane roadway was tested for this research project. The project consisted of milling the exiting distressed asphalt pavement and replacing it with hot-mix asphalt constructed in two layers. The lower layer was a 12.5 mm fine graded traffic level C Superpave mixture. (A traffic level C mixture design corresponds to 3 million to < 10 million equivalent single axle loads (ESALs) as the design traffic level.) The mixture contained Georgia granite and reclaimed asphalt pavement. The upper layer was a friction course mixture (FC-6), which was also a 12.5 mm fine graded traffic level C Superpave mixture containing a large proportion of Georgia granite and a small proportion of local sand. A rapid set (RS-1) emulsified asphalt tack coat was used to bond the two layers together. RS-1 is typically applied at 160°F. RS-1 has a minimum residue by distillation of 55% and a minimum specified penetration value of 60.

Description of Test Sections

The purpose of this field study was to examine the effects of tack coat application rate and water on bond strength. Six test sections of varying lengths were laid out consecutively (Figure 7). The following conditions were examined: 1) 0.05 gal/sy tack coat application rate, 2) 0.02 gal/sy, 3) 0.02 gal/sy, then water applied, 4) 0.08 gal/sy, 5) 0.08 gal/sy, then water applied and 6) no tack coat applied. These six test sections are summarized in Table 4.

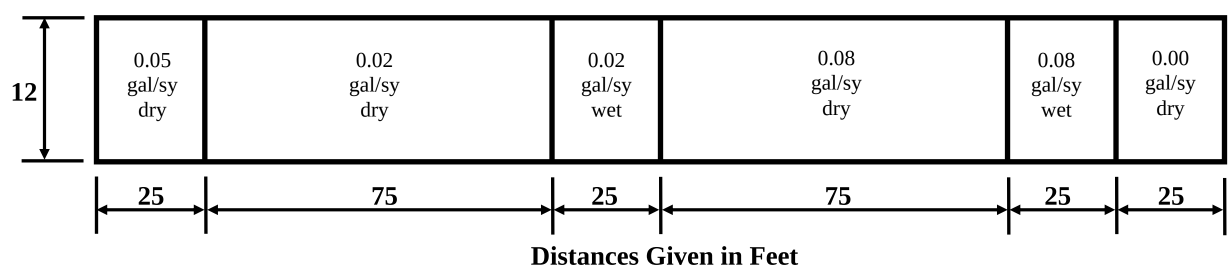

Figure 7 – US-90 Test Section Layout

Table 4 – US-90 Test Section Conditions

Section #	Tack Coat Spreadrate (gal/sy)	Wet or Dry
1	0.05	Dry
2	0.02	Dry
3	0.02	Wet
4	0.08	Dry
5	0.08	Wet
6	0.00	Dry

The tack coat application rates chosen for this study include the minimum (0.02 gal/sy), midpoint (0.05 gal/sy) and maximum (0.08 gal/sy) values for the allowable tack coat application rate range specified in the FDOT's Standard Specifications. The tack distributor truck was relatively new and was able to apply the tack application rates using electronic controls within the cabin of the truck. There was no other independent verification of the application rates other than a visual inspection. For the two sections that were wetted, a water supply truck with a garden hose was used to apply a uniform spray of water to the surface of the tack coat to the extent that slight water runoff occurred. At the time the water was applied, the tack was "broken" or "set". The quantity of water used at both test sections appeared visually to be the same. The hot-mix asphalt was placed over this wetted tack coat surface.

Performance

Roadway cores were obtained in a stratified pattern from each of the six test sections and tested in the laboratory to determine the shear strength of the tack coat. Roadway cores were obtained at four different times covering a total time period of slightly more than three months to examine the effect of time on the shear strength of the tack coat. Five cores were obtained for each test section at each time period. Table 5 lists the coring and testing dates for each of the four time periods.

Table 5 – Coring and Testing Dates for US-90 Field Project

Paving Date	Round #	Coring Date	# Days to Coring	Testing Date	# Days to Testing
03/20/02	1	03/21/02	1	03/27/02	7
	2	04/02/02	13	04/04/02	15
	3	04/29/02	40	05/01/02	42
	4	06/27/02	99	07/03/02	105

Shear strength test results are presented in Table 6 and Figures 8 and 9. The data in Table 6 was evaluated for outlying test results in accordance with ASTM E 178-94 (8). A significance level of 5% was used. The outliers shown in Table 6 are not included in the calculations. The outlier analysis is displayed in Table 7.

It was not possible to obtain testable roadway cores for the 0.02 gal/sy wet section at the round one time period because all of the cores sheared at the layer interface during coring due to a very weak tack coat bond. The weak bond was caused by a low tack coat application rate, the application of water before paving and the short time period between paving and coring for round one. Therefore, no data is presented for this section at round one. Furthermore, during the subsequent rounds for this test section, some roadway cores continued to shear during coring or would come apart at the layer interface during handling.

The following inferences can be deduced from the US-90 test data:

1. With respect to tack coat application rate, there is a general trend that higher tack coat application rates result in higher strengths when comparing the 0.02, 0.05 and 0.08 gal/sy dry test sections.

2. At round four, the bond strengths for the 0.02, 0.05 and 0.08 gal/sy dry test sections started to equalize, indicating that the application rate has less effect in a long term situation.

3. Bond strengths for all of the test sections increased with time. This conclusion agrees with research conducted by Hachiya and Sato (3) showing that greater strengths were achieved with longer curing times for the tack coat prior to testing.

4. Two sections (0.00 gal/sy dry and 0.08 gal/sy wet) showed a decrease in strength at round four compared to round three. It is possible by examining the slopes of the lines in Figure 9 for these two sections, that the round three test results may be high due to an unexplainable reason.

Table 6 – US-90 Shear Strength Values

Round #	Core #	Shear Strength Values (psi)					
		Test Section Number and Test Condition					
		6	2	3	1	4	5
		0.00 gal/sy	0.02 gal/sy	0.02 gal/sy	0.05 gal/sy	0.08 gal/sy	0.08 gal/sy
		Dry	Dry	Wet	Dry	Dry	Wet
1	1	13	NA	NA	37	69	23
	2	10	27	NA	35	76	16
	3	NA	31	NA	22	71	24
	4	NA	21	NA	NA	76	14
	5	NA	NA	NA	46	70	11
	Average	12	26	NA	35	72	18
	Std. Dev.	2	5	NA	10	3	6
	C.O.V.	18	19	NA	28	5	32
	Variance	4.5	25.3	NA	98.0	11.3	32.3
2	1	NA	62	27	52	93	27
	2	41	59	19	47	78	31
	3	43	58	26	NA	91	42
	4	35	55	20	69	89	33
	5	37	50	NA	61	101	50
	Average	39	57	23	57	90	37
	Std. Dev.	4	5	4	10	8	9
	C.O.V.	9	8	18	17	9	25
	Variance	13.3	20.7	16.7	94.9	68.8	86.3
3	1	107	102	33	85	145	101
	2	76	119	14	85	117	108
	3	93	81	45	***95****	119	85
	4	80	110	NA	85	130	126
	5	86	105	38	NA	127	127
	Average	88	103	33	85	128	109
	Std. Dev.	12	14	13	0	11	18
	C.O.V.	14	14	41	0	9	16
	Variance	149.3	198.3	176.3	0.0	123.8	313.3
4	1	80	124	59	152	123	75
	2	82	140	29	156	164	74
	3	93	128	49	156	141	***47****
	4	49	118	NA	130	146	72
	5	84	127	NA	147	143	70
	Average	78	127	46	148	143	73
	Std. Dev.	17	8	15	11	15	2
	C.O.V.	22	6	33	7	10	3
	Variance	280.3	64.8	233.3	117.2	213.3	4.9

*** Outlier; excluded from calculations.**

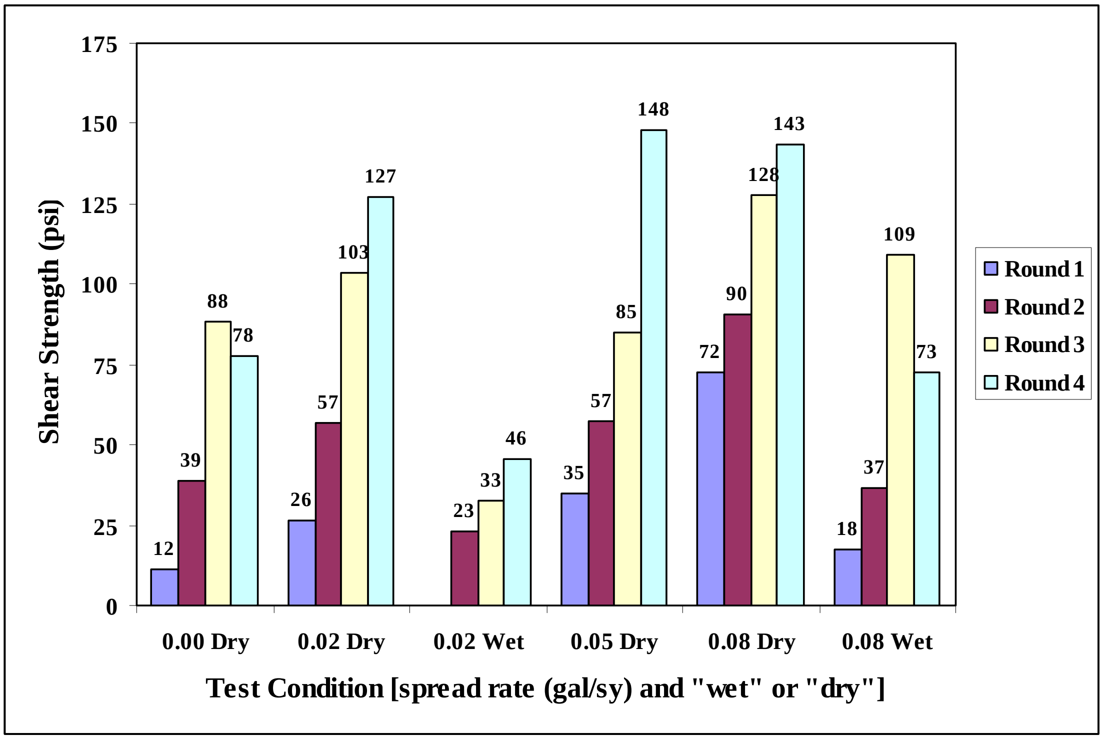

Figure 8 – Shear Strength Test Data for US-90 Project

5. The bond strength for the section with no tack coat never reached the same magnitude as the strengths for the 0.02, 0.05 and 0.08 gal/sy dry test sections, indicating that tack coat is effective at increasing bond strength. Research conducted by Hachiya and Sato (3) also indicates adhesion between layers of asphalt can be improved by using a tack coat.

6. The presence of water on the surface of the tack coat reduced the bond strength compared to equivalent sections without the addition of water.

7. The bond strengths of the wet sections increased with time, but not to the same magnitude as the equivalent sections without the addition of water.

8. Wet test sections with a greater tack coat application rate performed better than wet test sections with a lower tack coat application rate.

9. The test method was able to distinguish between different tack coat application rates and also the presence of water.

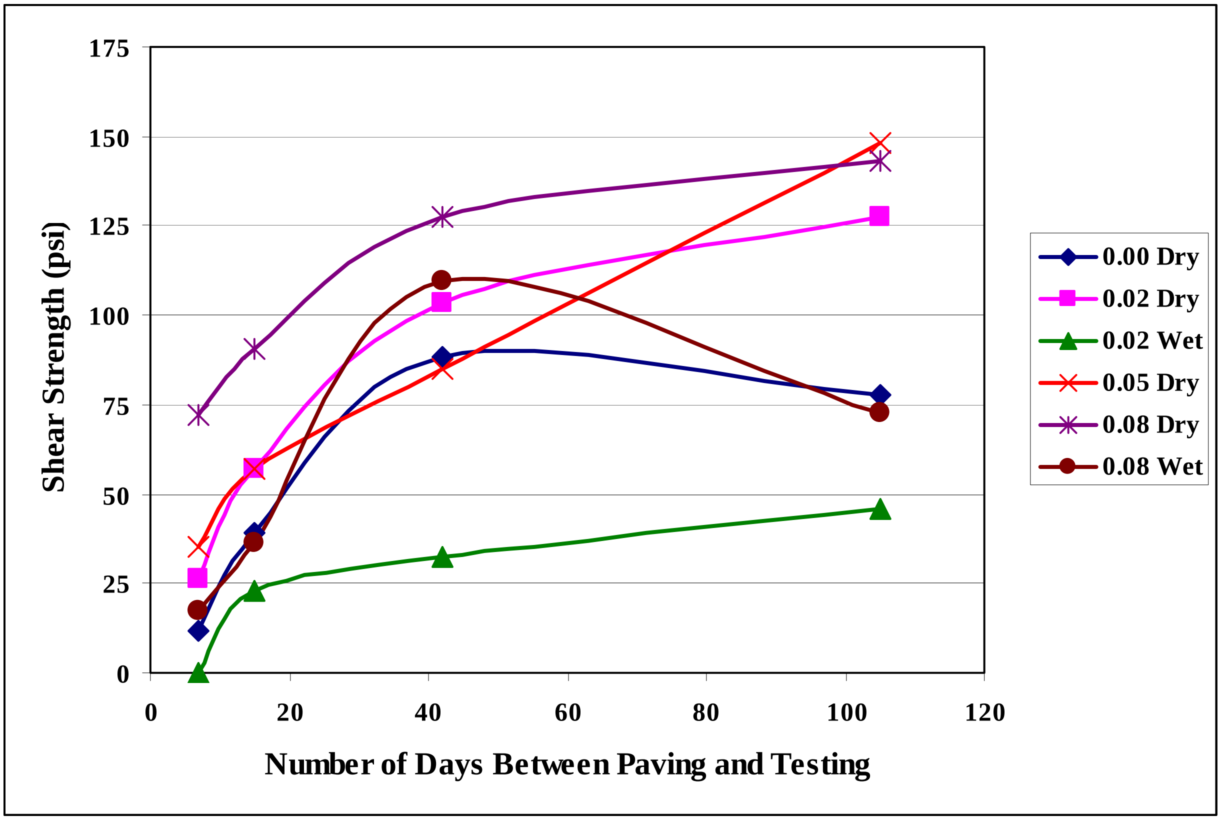

Figure 9 – Shear Strength Test Data vs. Time for US-90 Project

I-95 Project

Project Description

This project was located on I-95 in Nassau County, south of SR-200. The project consisted of the addition of a new inside lane constructed in three layers of hot mix asphalt. The northbound inside lane of the six-lane divided highway was tested for this research project. The first layer of hot mix asphalt was a 19.0 mm coarse graded traffic level E Superpave mixture. (A traffic level E mixture design corresponds to ≥ 30 million equivalent single axle loads (ESALs) as the design traffic level.) The mixture contained a combination of Nova Scotia granite, South Florida limestone, Georgia granite and reclaimed asphalt pavement. The second layer was a 12.5 mm

Table 7 – US-90 Test Data Outlier Analysis

Round #	Statistic	Test Section Number and Test Condition					
		6	2	3	1	4	5
		0.00 gal/sy	0.02 gal/sy	0.02 gal/sy	0.05 gal/sy	0.08 gal/sy	0.08 gal/sy
		Dry	Dry	Wet	Dry	Dry	Wet
1	Max	13	31	NA	46	76	24
	Min	10	21	NA	22	69	11
	Average	12	26	NA	35	72	18
	Std. Dev.	2	5	NA	10	3	6
	T_1	0.707	1.060	NA	1.313	1.011	1.161
	T_n	0.707	0.927	NA	1.111	1.071	1.126
	T_{max}	0.707	1.060	NA	1.313	1.071	1.161
	n	2	3	NA	4	5	5
	T_{crit}	NA	1.155	NA	1.481	1.715	1.715
	Pass/Fail	Pass	Pass	NA	Pass	Pass	Pass
2	Max	43	62	27	69	101	50
	Min	35	50	19	47	78	27
	Average	39	57	23	57	90	37
	Std. Dev.	4	5	4	10	8	9
	T_1	1.095	1.495	0.980	1.052	1.495	1.033
	T_n	1.095	1.143	0.980	1.206	1.278	1.442
	T_{max}	1.095	1.495	0.980	1.206	1.495	1.442
	n	4	5	4	4	5	5
	T_{crit}	1.481	1.715	1.481	1.481	1.715	1.715
	Pass/Fail	Pass	Pass	Pass	Pass	Pass	Pass
3	Max	107	119	45	95	145	127
	Min	76	81	14	85	117	85
	Average	88	103	33	88	128	109
	Std. Dev.	12	14	13	5	11	18
	T_1	1.015	1.591	1.393	0.500	0.953	1.379
	T_n	1.522	1.108	0.941	1.500	1.564	0.994
	T_{max}	1.522	1.591	1.393	1.500	1.564	1.379
	n	5	5	4	4	5	5
	T_{crit}	1.715	1.715	1.481	1.481	1.715	1.715
	Pass/Fail	Pass	Pass	Pass	***Fail***	Pass	Pass
4	Max	93	140	59	156	164	75
	Min	49	118	29	130	123	47
	Average	78	127	46	148	143	68
	Std. Dev.	17	8	15	11	15	12
	T_1	1.708	1.168	1.091	1.681	1.397	1.764
	T_n	0.920	1.565	0.873	0.720	1.410	0.634
	T_{max}	1.708	1.565	1.091	1.681	1.410	1.764
	n	5	5	3	5	5	5
	T_{crit}	1.715	1.715	1.155	1.715	1.715	1.715
	Pass/Fail	Pass	Pass	Pass	Pass	Pass	***Fail***

coarse graded traffic level E Superpave mixture. The mixture contained the same aggregates as the 19.0 mm mixture but was proportioned differently. The third and final layer was an FC-5 open graded friction course. For this research project, the tack coat bond strength was evaluated for the interface between the first and second layer. A rapid set (RS-2) emulsified tack coat was used to bond the first and second layer together. RS-2 is typically applied at 160°F. In comparison, RS-2 has a minimum residue by distillation of 63% and RS-1 has a minimum residue by distillation of 55%. RS-2 has a penetration range of 100 to 200 and RS-1 has only a minimum specified value of 60.

Description of Test Sections

Similar to the US-90 field study, the purpose of this field study was to examine the effects of tack coat application rate and water on bond strength. Six test sections of varying lengths were laid out consecutively in the same pattern as for the US-90 field study (Figure 7). The following conditions were examined: 1) 0.05 gal/sy tack coat application rate, 2) 0.02 gal/sy, 3) 0.02 gal/sy, then water applied, 4) 0.08 gal/sy, 5) 0.08 gal/sy, then water applied and 6) no tack coat applied. These six test sections are summarized in Table 4.

The tack coat application rates chosen for this study include the minimum (0.02 gal/sy), midpoint (0.05 gal/sy) and maximum (0.08 gal/sy) values for the allowable tack coat application rate range specified in the FDOT's Standard Specifications. The tack distributor truck was able to apply the tack application rates accurately using controls within the cabin of the truck. There was no other independent verification of the application rates other than a visual inspection. For the two sections that were wetted, a water supply truck with a garden hose was used to apply a uniform spray of water to the surface of the tack coat to the extent that slight water runoff occurred. At the time the water was applied, the tack was “broken” or “set”. The quantity of water used at both test sections appeared visually to be the same. The hot-mix asphalt was placed over this wetted tack coat surface.

Performance

Similar to the US-90 field study, roadway cores were obtained in a stratified pattern from each of the six test sections and tested in the laboratory to determine the shear strength of the tack coat. Roadway cores were obtained at three different times covering a total time period of slightly more than one month to examine the effect of time on the shear strength of the tack coat. Five cores were obtained for each test section at each time period. Table 8 lists the coring and testing dates for each of the three time periods.

Table 8 – Coring and Testing Dates for I-95 Field Project (non-milled area)

Paving Date	Round #	Coring Date	# Days to Coring	Testing Date	# Days to Testing
04/04/02	1	04/05/02	1	04/10/02	6
	2	04/16/02	12	04/22/02	18
	3	05/06/02	32	05/13/02	39

Shear strength test results are presented in Table 9 and Figures 10 and 11. The data in Table 9 was evaluated for outlying test results in accordance with ASTM E 178-94 (8). A significance level of 5% was used. The outlier analysis is displayed in Table 10. The analysis revealed no outlying data at the 5% significance level, though some values were marginally close.

The following inferences can be deduced from the I-95 test data:

Table 9 – I-95 Shear Strength Values (non-milled area)

Round #	Core #	Shear Strength Values (psi)					
		Test Section Number and Test Condition					
		6	2	3	1	4	5
		0.00 gal/sy	0.02 gal/sy	0.02 gal/sy	0.05 gal/sy	0.08 gal/sy	0.08 gal/sy
		Dry	Dry	Wet	Dry	Dry	Wet
1	1	94	113	65	134	116	89
	2	100	122	73	132	119	104
	3	84	89	74	131	133	91
	4	104	110	NA	131	129	83
	5	93	119	52	NA	112	85
	Average	95	111	66	132	122	90
	Std. Dev.	8	13	10	1	9	8
	C.O.V.	8	12	15	1	7	9
	Variance	58.0	168.3	103.3	2.0	78.7	67.8
2	1	82	97	81	132	129	81
	2	100	122	65	127	123	91
	3	89	107	81	125	129	76
	4	91	100	91	124	128	80
	5	104	95	51	126	117	88
	Average	93	104	74	127	125	83
	Std. Dev.	9	11	16	3	5	6
	C.O.V.	9	10	21	2	4	7
	Variance	77.7	119.7	249.2	9.7	27.2	37.7
3	1	130	NA	122	138	123	107
	2	118	111	96	137	136	119
	3	130	124	116	134	118	109
	4	113	116	97	130	134	111
	5	118	109	78	145	124	123
	Average	122	115	102	137	127	114
	Std. Dev.	8	7	18	6	8	7
	C.O.V.	6	6	17	4	6	6
	Variance	60.2	44.7	308.2	30.7	59.0	47.2

1. With respect to tack coat application rate, there is no significant difference between the 0.05 and 0.08 gal/sy dry test sections in terms of shear strength. These two sections provided only a marginal improvement over the 0.02 gal/sy dry test section.

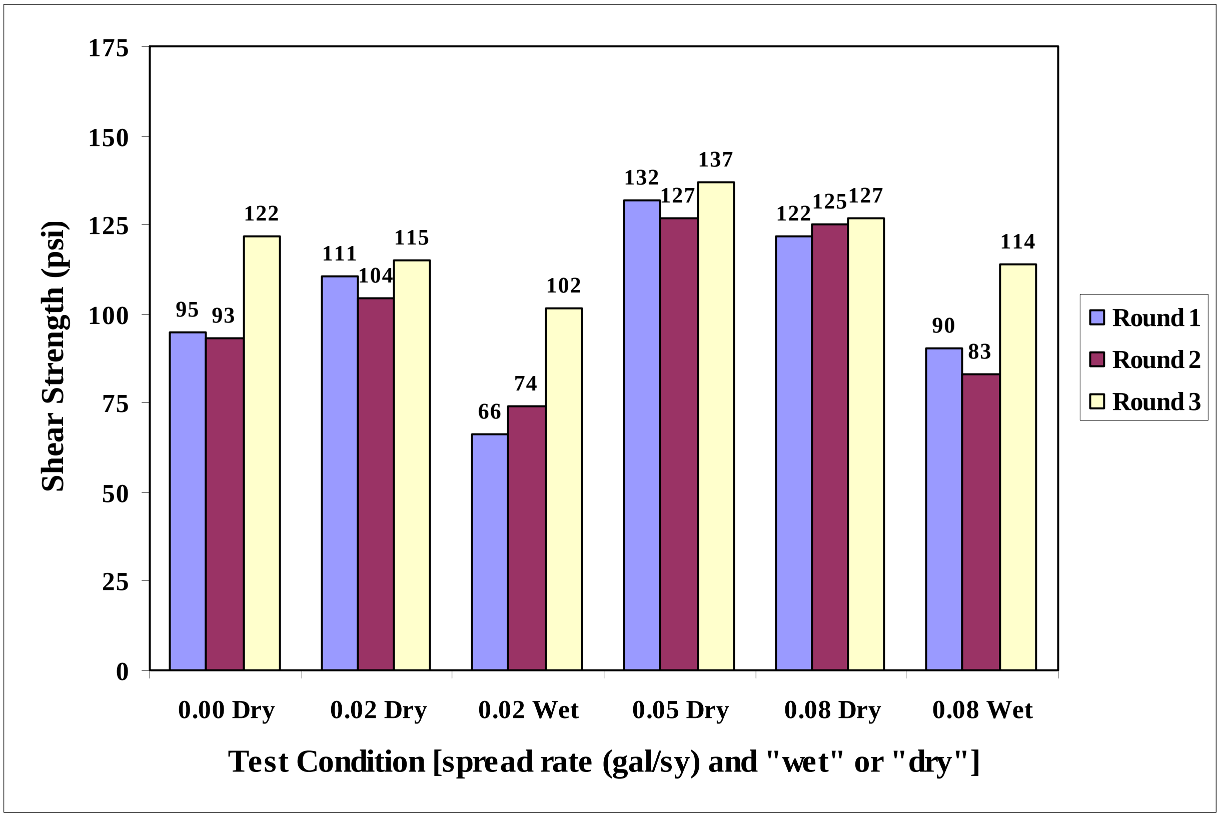

Figure 10 – Shear Strength Test Data for I-95 Project (non-milled area)

2. There was an insignificant increase in shear strength with time for the 0.02, 0.05 and 0.08 gal/sy dry test sections.

3. The 0.02 and 0.08 gal/sy wet test sections had lower shear strengths than all of the other sections but the shear strength values appeared relatively high compared to the wet test sections on the US-90 project.

4. Shear strength values increased with time for the 0.02 and 0.08 gal/sy wet test sections. At round three (tested 39 days after paving), the average shear strength values were 102 and 114 psi, respectively, for these two sections. These values are approaching the round three shear strength values of the 0.02, 0.05 and 0.08 gal/sy dry sections (115, 137 and 127 psi respectively).

5. The bond strength for the section with no tack coat performed very well (122 psi at round three). The shear strength of this section increased with time.

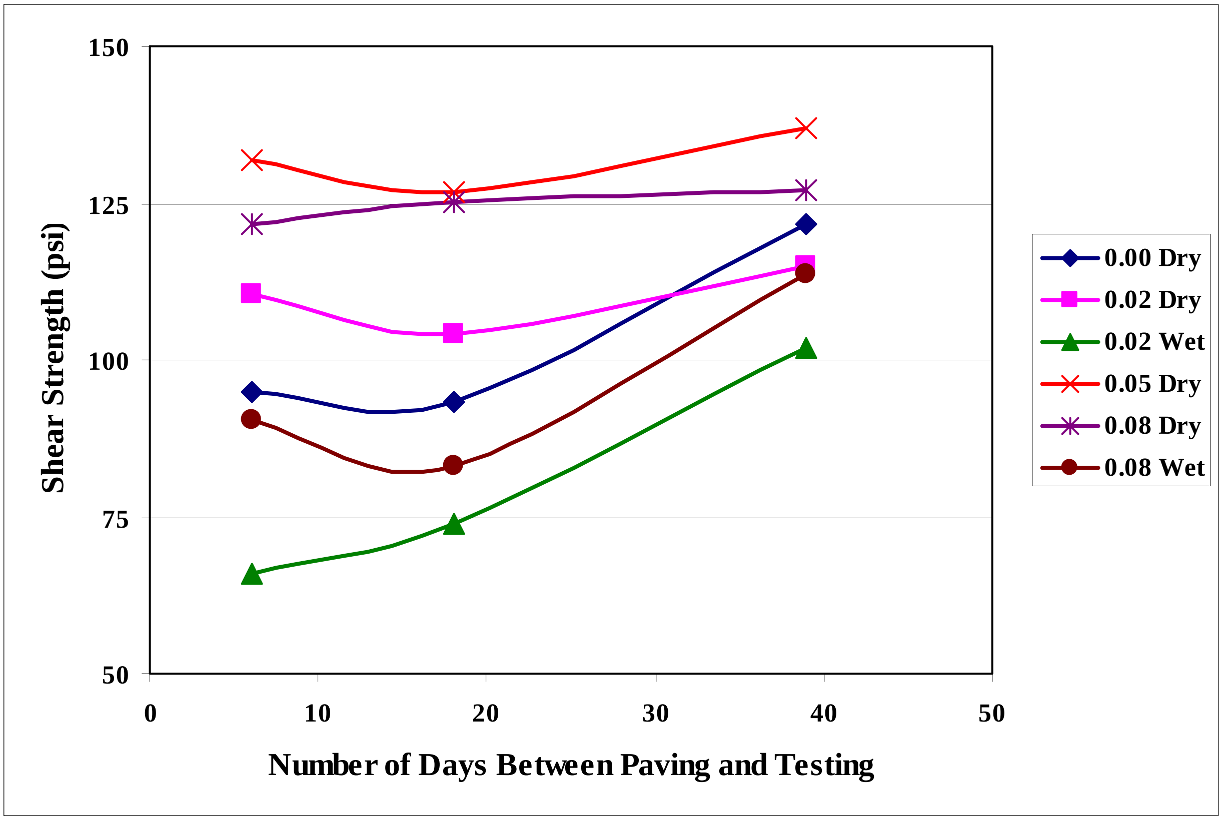

Figure 11 – Shear Strength Test Data vs. Time for I-95 Project (non-milled area)

6. It appears that the coarse aggregate gradations of both the 19.0 mm lower layer and the 12.5 mm upper layer provided aggregate interlock that dominated the effect of the tack coat in terms of shear strength. This is explained by the high strength values of the section without tack coat and the minimal difference between the shear strength values for the 0.02, 0.05 and 0.08 gal/sy dry test sections.

7. Despite the aggregate interlock effect, the presence of water on the tack coat surface at the time of paving reduces the shear strength values in the short term. As time passes, the shear strength values increase.

8. Wet test sections with a greater tack coat application rate performed better than wet test sections with a lower tack coat application rate.

Table 10 – I-95 Test Data Outlier Analysis (non-milled area)

Round #	Statistic	Test Section Number and Test Condition					
		6	2	3	1	4	5
		0.00 gal/sy	0.02 gal/sy	0.02 gal/sy	0.05 gal/sy	0.08 gal/sy	0.08 gal/sy
		Dry	Dry	Wet	Dry	Dry	Wet
1	Max	104	122	74	134	133	104
	Min	84	89	52	131	112	83
	Average	95	111	66	132	122	90
	Std. Dev.	8	13	10	1	9	8
	T_1	1.444	1.665	1.377	0.707	1.105	0.899
	T_n	1.182	0.879	0.787	1.414	1.262	1.652
	T_{max}	1.444	1.665	1.377	1.414	1.262	1.652
	n	5	5	4	4	5	5
	T_{crit}	1.715	1.715	1.481	1.481	1.715	1.715
	Pass/Fail	Pass	Pass	Pass	Pass	Pass	Pass
2	Max	104	122	91	132	129	91
	Min	82	95	51	124	117	76
	Average	93	104	74	127	125	83
	Std. Dev.	9	11	16	3	5	6
	T_1	1.271	0.841	1.444	0.899	1.572	1.173
	T_n	1.225	1.627	1.090	1.670	0.729	1.270
	T_{max}	1.271	1.627	1.444	1.670	1.572	1.270
	n	5	5	5	5	5	5
	T_{crit}	1.715	1.715	1.715	1.715	1.715	1.715
	Pass/Fail	Pass	Pass	Pass	Pass	Pass	Pass
3	Max	130	124	122	145	136	123
	Min	113	109	78	130	118	107
	Average	122	115	102	137	127	114
	Std. Dev.	8	7	18	6	8	7
	T_1	1.134	0.898	1.356	1.227	1.172	0.990
	T_n	1.057	1.347	1.151	1.480	1.172	1.339
	T_{max}	1.134	1.347	1.356	1.480	1.172	1.339
	n	5	4	5	5	5	5
	T_{crit}	1.715	1.481	1.715	1.715	1.715	1.715
	Pass/Fail	Pass	Pass	Pass	Pass	Pass	Pass

9. The test method was able to distinguish between the dry and wet test sections.

Milled Test Section

Approximately one thousand feet south of the above referenced test section, a portion of the northbound inside lane was milled to remove 12.5 mm coarse graded mix that did not meet construction specifications. It was decided that a field study would be conducted in this area to examine the effects of the milled surface on the shear strength values. Six test sections of varying length were laid out consecutively in the same pattern as for the US-90 and I-95 non-milled field studies (Figure 7).

Performance of Milled Test Section Similar to the US-90 and I-95 non-milled field studies, roadway cores were obtained in a stratified pattern from each of the six test sections and tested in the laboratory to determine the shear strength of the tack coat. Roadway cores were obtained at two different times covering a total time period of two weeks. Five cores were obtained for each test section at each time period. Table 11 lists the coring and testing dates for each of the two time periods. All cores were oriented so that the shearing motion was in the same direction as the milling striations.

Table 11 – Coring and Testing Dates for I-95 Field Project (milled area)

Paving Date	Round #	Coring Date	# Days to Coring	Testing Date	# Days to Testing
04/04/02	1	04/05/02	1	04/11/02	7
	2	04/12/02	8	04/17/02	13

Shear strength test results are presented in Table 12 and Figure 12. The data in Table 12 was evaluated for outlying test results in accordance with ASTM E 178-94 (8). A significance level of 5% was used. The outlier shown in Table 12 is not included in the calculations. The outlier analysis is displayed in Table 13.

Table 12 – I-95 Shear Strength Values (milled area)

Round #	Core #	Shear Strength Values (psi)					
		Test Section Number and Test Condition					
		6	2	3	1	4	5
		0.00 gal/sy	0.02 gal/sy	0.02 gal/sy	0.05 gal/sy	0.08 gal/sy	0.08 gal/sy
		Dry	Dry	Wet	Dry	Dry	Wet
1	1	156	147	84	***168****	150	116
	2	161	145	NA	156	135	100
	3	150	144	104	155	149	97
	4	154	140	102	159	137	100
	5	152	152	107	156	135	NA
	Average	155	146	99	157	141	103
	Std. Dev.	4	4	10	2	8	9
	C.O.V.	3	3	10	1	5	8
	Variance	17.8	19.3	107.6	3.0	58.2	74.3
2	1	155	142	111	146	128	99
	2	150	138	99	152	144	95
	3	153	149	65	155	127	83
	4	151	147	88	158	126	92
	5	160	140	84	157	136	108
	Average	154	143	89	154	132	95
	Std. Dev.	4	5	17	5	8	9
	C.O.V.	3	3	19	3	6	10
	Variance	15.7	21.7	296.3	23.3	59.2	84.3

*** Outlier; excluded from calculations.**

The following inferences can be deduced from the I-95 milled section test data:

1. For every equivalent test section condition and equivalent round of testing, the shear strength values for the milled area are significantly higher than for the non-milled area. Intuitively, this is logical since the rough striations in the surface created by the milling machine would provide greater shear resistance at the layer interface.

2. With respect to tack coat application rate, the shear strength values for the 0.02, 0.05 and 0.08 gal/sy dry test sections were nearly equivalent.

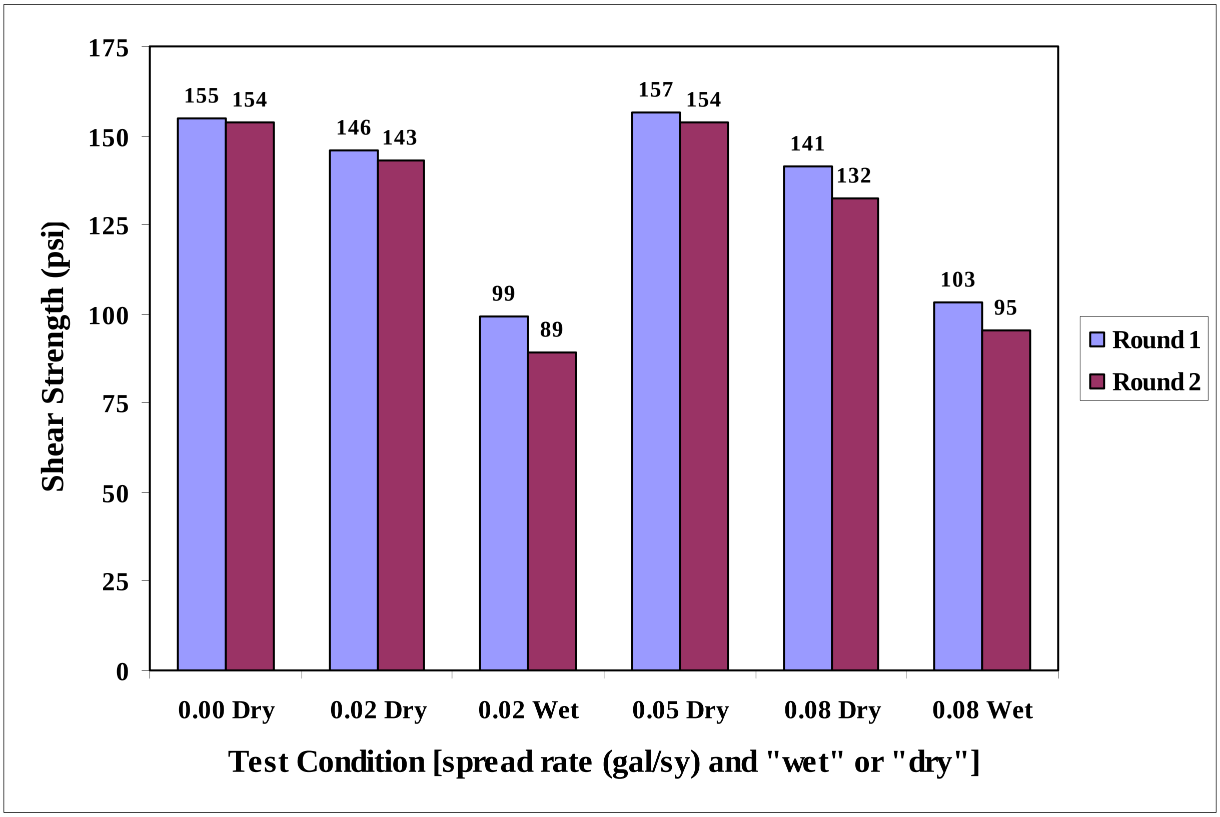

Figure 12 – Shear Strength Test Data for I-95 Project (milled area)

3. Shear strength values declined very slightly for all test sections during the one-week period between round one and round two. The explanation of this is uncertain, but could possibly be the result of testing variability.

4. The 0.02 and 0.08 gal/sy wet test sections had lower shear strengths than all of the other sections but the shear strength values appeared relatively high compared to the wet test sections on the US-90 project.

5. The bond strength for the test section with no tack coat performed as well as any other test section indicating the ineffectiveness of using a tack coat on this milled surface.

Table 13 – I-95 Test Data Outlier Analysis (milled area)

Round #	Statistic	Test Section Number and Test Condition					
		6	2	3	1	4	5
		0.00 gal/sy	0.02 gal/sy	0.02 gal/sy	0.05 gal/sy	0.08 gal/sy	0.08 gal/sy
		Dry	Dry	Wet	Dry	Dry	Wet
1	Max	161	152	107	168	150	116
	Min	150	140	84	155	135	97
	Average	155	146	99	159	141	103
	Std. Dev.	4	4	10	5	8	9
	T_1	1.090	1.275	1.470	0.709	0.813	0.725
	T_n	1.517	1.457	0.747	1.717	1.154	1.480
	T_{max}	1.517	1.457	1.470	1.717	1.154	1.480
	n	5	5	4	5	5	4
	T_{crit}	1.715	1.715	1.481	1.715	1.715	1.481
	Pass/Fail	Pass	Pass	Pass	***Fail***	Pass	Pass
2	Max	160	149	111	158	144	108
	Min	150	138	65	146	126	83
	Average	154	143	89	154	132	95
	Std. Dev.	4	5	17	5	8	9
	T_1	0.959	1.116	1.418	1.574	0.806	1.351
	T_n	1.565	1.245	1.255	0.912	1.534	1.372
	T_{max}	1.565	1.245	1.418	1.574	1.534	1.372
	n	5	5	5	5	5	5
	T_{crit}	1.715	1.715	1.715	1.715	1.715	1.715
	Pass/Fail	Pass	Pass	Pass	Pass	Pass	Pass

6. Despite the effect of the milling striations, the presence of water on the tack coat surface at the time of paving reduced the shear strength values compared to the test sections where water was not present.
7. The test method was able to distinguish between the dry and wet test sections.

MISCELLANEOUS FIELD PROJECTS

In addition to the US-90 and I-95 field studies, two additional construction projects were investigated. Each of the two projects contained sections of the roadway that were not constructed per specification requirements in relation to the tack coat. Each project will be discussed separately below.

SR-19 Project

The SR-19 project was located in Putnam County. This project consisted of milling the existing distressed asphalt pavement and replacing it with hot-mix asphalt constructed in two layers. The lower layer was a 12.5 mm fine graded traffic level C Superpave mixture. The mixture contained South Florida limestone, Georgia granite, local sand and reclaimed asphalt pavement. The upper layer was a friction course mixture (FC-6), which was also a 12.5 mm fine graded traffic level C Superpave mixture containing South Florida limestone, Georgia granite and local sand.

During the paving operation of the upper lift, rain fell on a portion of the roadway and the contractor continued paving over the wetted tack coat. Six cores were obtained from the project, three in the wetted area of the lane and three in a nearby portion of the lane that was paved the same day but did not receive rain. The cores were tested in the shear apparatus to determine the shear strength of the tack coat. The average shear strength of the cores obtained in the wetted area was 66 psi and the average shear strength of the cores obtained in the dry area was 86 psi. The shear strength of the cores obtained in the wetted area was 23% less than the shear strength of the cores obtained in the dry area.

SR-2 Project

The SR-2 project was located in Jackson County. This project consisted of milling the existing distressed asphalt pavement and replacing it with hot-mix asphalt constructed in two layers. The lower layer was a 12.5 mm fine graded traffic level B Superpave mixture. The mixture contained Northwest Florida limestone and local sand. The upper layer was a friction course mixture (FC-6), which was a 12.5 mm fine graded traffic level C mixture containing Georgia granite and local sand.

Similar to the SR-19 project, rain fell on a portion of the roadway during the paving operation of the upper lift and the contractor continued paving over the wetted tack coat. Two cores were obtained from the project, one in the wetted area of the lane and one in a nearby portion of the lane that was paved the same day but did not receive rain. The cores were tested in the shear apparatus to determine the shear strength of the tack coat. The shear strength of the core obtained in the wetted area was 52 psi and the shear strength of the core obtained in the dry area was 100 psi. The shear strength of the core obtained in the wetted area was 48% less than the shear strength of the core obtained in the dry area

Both the SR-19 and SR-2 projects provide further evidence of the effects of water on the effectiveness of the tack coat to bond two layers of hot mix asphalt together. For both of these projects, a reduction in shear strength was observed for the cores obtained from the areas of the roadway that had been wetted by rain as compared to the areas of the roadway that had not been wetted by rain.

TESTING VARIABILITY

Since the shear testing apparatus developed during this research project is only a prototype and no other such devices exist, it was not appropriate to conduct any formal ruggedness or variability studies. However, the test data for the US-90 and I-95 projects was evaluated to obtain an estimate of the repeatability of the test procedure. It is also noted that this estimate of repeatability comes from field samples, which are typically more variable than laboratory fabricated samples for other test methods.

Examination of the standard deviations from the US-90 project, I-95 non-milled project and I-95 milled project (Tables 6, 9 and 12, respectively) show that 39 of 53, i.e. 74%, of the standard deviations are less than or equal to 10 psi. This is a fairly constant standard deviation despite the range of shear strength values encountered.

The coefficient of variation, defined as the standard deviation divided by the average for a set of measurements, is occasionally a better parameter to define variability of a test method if the standard deviation is not relatively constant for a range of averages. Even though the standard deviation did appear to be relatively constant for the range of averages observed, the coefficient of variation was examined for the same US-90 and I-95 projects. Analysis of the coefficient of variation data reveals that it is much less consistent that the standard deviation values. The trend is for the coefficient of variation values to be greater for the lower average values. This further demonstrates the consistency of the standard deviation values.

To determine an appropriate standard deviation for the entire data set of all three projects, the standard deviations were converted to variances. The variances were then pooled and then the pooled variance was converted back to a pooled standard deviation, which would represent the entire data set. The pooled standard deviation for the entire data set is 9.6 psi. The pooled standard deviation multiplied by $2*\sqrt{2}$ equals 27.2 psi, which would be the within-laboratory allowable difference between two test results. The authors would like to note that this value of within-laboratory precision was determined based on the data set from this research report and may not exactly represent the same precision value developed from a round robin study.

CONCLUSIONS

1. A test apparatus was developed that can measure the direct shear strength of roadway or laboratory specimens. The testing conditions are 1) specimen diameter; 6 inches, 2) mode of loading; strain controlled, 3) rate of loading; 2 in/min, 4) testing temperature; 77°F and 5) gap width between shearing platens; 3/16 inch.

2. Three research field projects were constructed and evaluated at multiple time periods after construction. The three projects evaluated the effects of tack coat application rate and the effects of water for three layer interface conditions: 1) 12.5 mm fine graded Superpave mixture placed over a 12.5 mm fine graded Superpave mixture, 2) 12.5 mm coarse graded Superpave mixture placed over a 19.0 mm coarse graded Superpave mixture and 3) 12.5 mm coarse graded Superpave mixture placed over a milled 19.0 mm coarse graded Superpave mixture.

3. Results of this research have shown the effects of water on the bonding ability of tack coat. Water applied to the surface of the tack coat, to represent rainwater, reduced the shear strength of the specimens compared to equivalent sections without water applied. As weeks passed, the strengths of the specimens from the sections with water increased but never reached the same strength as the equivalent sections without water applied. Wet sections with a 0.08 gal/sy application rate performed better than wet sections with a 0.02 gal/sy application rate.

4. Tack coat application rate within the FDOT's specified range (0.02 to 0.08 gal/sy) had a slight effect on shear strength. It was generally observed, especially for the test project consisting of a 12.5 mm fine graded Superpave mixture over a 12.5 mm fine graded Superpave mixture, that shear strengths would increase slightly as the tack coat application rate was increased. As weeks passed, the strengths essentially equalized regardless of the application rate.

5. The gradations of the asphalt mixtures being bonded by the tack coat played a critical role in the shear strengths achieved. Fine graded mixtures achieved significantly lower shear strengths than the coarse graded mixtures. The project containing the milled interface achieved the greatest strengths of the projects tested.

6. The application of tack coat at a application rate of 0.02 gal/sy provided slightly higher shear strength results compared to the test section without tack coat for the test project consisting of a 12.5 mm fine graded Superpave mixture over a 12.5 mm fine graded Superpave mixture. Higher application rates (0.05 and 0.08 gal/sy) did provide greater bonding shear strength compared to the sections without tack coat applied. For the test project consisting of a 12.5 mm coarse graded Superpave mixture placed over a 19.0 mm coarse graded Superpave mixture, the benefits of using a tack coat were less noticeable, especially at the 0.02 gal/sy application rate. For the milled interface project, the shear strengths for the sections with and without tack coat were comparable, indicating that tack coat was not effective at increasing the bonding shear strength for this type of interface condition.

7. The standard deviation of the test procedure was determined to be 9.6 psi as determined by pooling the entire data set from the three test projects. Based on data from this research report, an estimate of the within-laboratory allowable difference between two test results is 27.2 psi.

RECOMMENDATIONS

1. A shear device that could be used in a common piece of test equipment, such as the Marshall apparatus, needs to be evaluated and compared to the results of the device developed in this research study prior to implementation at the District Materials Office level.

2. Testing needs to be conducted for an AC-5 material, which is the third product allowed for use for tack coat applications per the FDOT's specifications.

3. Testing of pavements that have failed due to an inadequate bond need to be investigated prior to setting a shear strength specification limit. It is not known at this time what minimum shear strength value is needed to assure adequate bonding. Factors such as mixture type, application rate, location in project (curve or intersection) will also need to be considered.

4. This research has shown that water has the effect of reducing bonding shear strength values, therefore, FDOT specifications that prevent paving in the rain should be adhered to.

5. The FDOT should consider setting a minimum tack coat application rate higher than 0.02 gal/sy. Results of this research show that a 0.05 gal/sy application rate can be more effective than a 0.02 gal/sy application rate for increasing bonding shear strength.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Frank Suarez, Susan Andrews and William Dillon of the State Materials Office for their work in obtaining, preparing and testing samples. The authors also wish to acknowledge Gene Pettyjohn, Brian Phillips and John Dolan of District 2 for their assistance and cooperation.

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