Performance Evaluation of Tack Coat Materials

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PERFORMANCE EVALUATION OF TACK COAT MATERIALS

FINAL REPORT

by

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16. Abstract

The main purpose of this project is to assess the bond strength of tack coat materials applied under a variety of conditions, including tack coat material, application rate and uniformity, moisture and temperature, and pavement layer types. To evaluate the bond strength, the research team utilized direct shear and rotational shear tests conducted in controlled laboratory conditions. The rotational shear test was also utilized in the field for one active construction project and one controlled field test section. The results of the study will provide WisDOT officials with the data necessary to make informed decisions concerning the need for the continuation of the current tack coat specifications or to develop new or modified specification requirements.

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Executive Summary

Project Summary

This research evaluated the bond characteristics of tack coat materials currently used in Wisconsin. Conventional SS-1h and CSS-1h emulsions as well as modified CSS-1hm and SS-1hp emulsions were utilized. A neat PG 58-28 binder was also used for comparative purposes. Bond strengths developed over a variety of application conditions were measured by direct shear and rotational shear testing. The data generated in this study were used to evaluate the criteria enumerated in the Section 455 of the Wisconsin Department of Transportation (WisDOT) Standard Specifications for Highway and Structure Construction.

Background

The bond between constructed HMA layers plays a critical role in the performance of the HMA pavement. When a poor bond between layers exists, slippage cracking often occurs where traffic accelerates, decelerates or turns. Poor compaction, top-down cracking and surface delaminations may also be attributed to inadequate interlayer bonding (West, 2006). A variety of asphaltic materials have been used to provide a strong mechanical bond between HMA layers. Asphalt emulsions are the most common choice for tack coat materials and but paving grade asphalts have also been used successfully. The common challenge is to determine the appropriate combination of tack coat material, application rate and application/pavement conditions.

Process

This project included (1) a review of current practice, (2) detailed laboratory testing of fabricated specimens under a variety of application conditions, and (3) field tests to extend the study findings to in situ conditions for newly constructed HMA pavements. The review of current practice identified key protocol to be used during laboratory testing. From this review, an experimental plan for the testing of bond strengths of conventional tack coat materials was developed and executed. Specialized test fixtures and equipment were developed during this study to aid in the testing of the bond strength. The equipment developed for rotational shear testing was successfully utilized in the field to test bond strengths in situ. The data from this study was used to evaluate WisDOT's 2012 criteria for tack coat usage.

Findings and Conclusions

The findings of the initial laboratory testing indicated:

- PG 58-28 provides a better bond strength than the SS-1h materials
- The minimum recommended tack coat application rate is 0.025 gal/yd^2, for both SS-1h and PG 58-28 materials, which supports the current WisDOT specification value.
- Higher air temperatures during application increases tack coat effectiveness, with 37F being the minimum recommended temperature. This supports the WisDOT specification that requires air temperatures of 36F or higher during tack coat application.
- Dry or wet conditions prior to overlay did not significantly affect bond strength. This indicates that as long as the tack material is set, slight rains during paving may not pose a problem with tack coat effectiveness. No testing was conducted to simulate rains during tack coat application, which could delay the setting of the tack coat and/or result in wash-off of the tack materials.
- Results from direct shear testing indicated more instances of statistical differences in group means as compared to the rotational shear results. This result indicates the direct shear test may be more appropriate for differentiating strength differences within the lab. However, the rotational shear test is more suited to field operations where in situ bond strength is being investigated.

The field studies utilized in situ rotational shear testing conducted with the equipment developed during this study. Pavement coring operations necessary to produce the tiered test specimen, using both a 6-inch and 4-inch core barrel, were completed with relative ease at any desired pavement location. Measurement of the rotational shear resistance, using the portable RST, was also completed with little complication. The findings from the field studies indicated that direct comparisons of rotational shear resistance measured in situ and on lab prepared specimens using the same construction materials may differ substantially, indicating the need for field verification of the available bond strength. It is recommended that this equipment be utilized on future construction projects to monitor bond strengths developed under typical construction operations.

Field tack coat application rates computed from available construction data indicate the need for a better understanding of the dilution rates provided by the emulsion suppliers. This research developed application charts and a simple spreadsheet that can be used to determine the appropriate tack coat distribution rates given material data and project specifications. It is recommended that these tools as well as a confirmation patch test be utilized on future construction projects to help ensure that residual tack coat application rates are meeting agency specifications.

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- Ms. Deborah Schwerman for her assistance in organizing the field testing along STH 11 and for collecting patch samples of the tack coat materials.

- Material producers who provided the tack coat materials used in the project.

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Chapter 1. Introduction and Research Approach

1.1 Background

It is widely recognized that the bond between constructed HMA layers play a critical role in the performance of the HMA pavement. When a poor bond between layers exists, slippage cracking often occurs where traffic accelerates, decelerates or turns. Poor compaction, top-down cracking and surface delaminations may also be attributed to inadequate interlayer bonding (West, 2006). A variety of asphaltic materials have been used to provide a strong mechanical bond between HMA layers. Asphalt emulsions are the most common choice for tack coat materials and but paving grade asphalts have also been used successfully. The common challenge is to determine the appropriate combination of tack coat material, application rate and application/pavement conditions.

1.2 Problem Statement and Objectives

Tack coats are commonly used to prevent localized pavement shoving and sliding which may lead to slippage cracking and reduced pavement integrity. Tack coats are intended to bond constructed pavement layers together and ensure that the layers act monolithically when subjected to traffic loads. Insufficient or improper application of tack coat can result in a weak bond between hot mix asphalt (HMA) pavement layers or between HMA and PCC pavement layers, causing the layers to act independently. The type of tack coat used, type and condition of the adhering surfaces, rate of tack coat application, application temperature, and curing conditions are all factors that directly affect the development of the interlayer bond. The intent of this laboratory-oriented study is to investigate tack coat performance using materials and methods common in the Wisconsin paving industry.

Recently completed WHRP Study 0092-02-13 (Mehta and Siraj, 2007) investigated interlayer slippage in several Wisconsin pavements. The results of this study indicated that the probability of slippage could be correlated to the stiffness ratio between HMA pavement layers, and that a higher stiffness ratio indicated lower risk of slippage between pavement layers. It was reported that to achieve a higher stiffness ratio and thus reduce the probability of slippage, the thickness of the surface layer could be increased. The recommendations from this study, which were based primarily on the results of backcalculated pavement layer properties, did not provide any practical guidance for the proper usage of tack coats. To expand on these results, this study will investigate a means to reduce the risk of slippage by the proper utilization of tack coat materials.

The specific objectives of this research study are:

- To evaluate the adhesion characteristics of tack coats approved or proposed for use within Wisconsin.
- To develop qualitative relationships between laboratory test results and expected field performance.
- To recommend the cost-effective combination(s) of tack coat materials and construction procedures which result in satisfactory performance.

1.3 Research Approach

This research investigated the adhesion properties of tack coats, including emulsions, modified emulsions and paving grade binders. The following parameters were evaluated:

- Tack coat application rate
- Tack coat and pavement application temperatures
- Type and condition of adhering surfaces
- Type of laboratory/field test equipment/protocol

This study was completed to provide data necessary for the assessment of current WisDOT Standard Specifications for Highway and Structure Construction, specifically Section 455 as it pertains to the selection and use of tack coat materials. A research factorial was developed and implemented during Phase 1 laboratory testing. Field testing within a controlled test section and along an active construction project was included to compliment and extend the results of the Phase 1 laboratory tests.

Chapter 2. Literature Review

2.1 Introduction

A significant number of research studies have been completed with the aim of investigating the adhesive properties of tack coat layers and/or to establish appropriate test methods for evaluating the bond strength between pavement layers associated with tack coat applications. It is widely recognized that the bond between constructed Hot-Mix Asphalt (HMA) layers plays a critical role in the performance of the HMA pavement. When a poor bond between layers exists, slippage cracking often occurs where traffic accelerates, decelerates and/or turns. A variety of asphaltic materials have been used to provide a strong mechanical bond between HMA layers. Asphalt emulsions are the most common choice for tack coat materials but paving grade asphalts have also been used successfully.

Some common challenges are: 1) to determine the appropriate type of tack coat material, 2) to establish the appropriate application rate for the given pavement conditions, 3) to establish an effective procedure to evenly distribute the tack coat at the desired application rate, 4) to ensure the existing pavement surface has been properly prepared prior to tack coat application, and 5) to develop a plan to account/adjust for environmental conditions during tack coat application. To provide insight to help support effective solutions to the above challenges, numerous lab studies have been undertaken to assess the bond strength of the tack coat layer and to quantify the effects of various parameters (i.e., tack coat type, application rate/uniformity, surface conditions, temperature) on the bond strength.

2.2 Tack Coat Materials

Current WisDOT specifications (2012) allow for the use of MS-2, SS-1, SS-1h, CSS-1, CSS-1h, and modified emulsified asphalts. Original slow-setting emulsions can contain up to 43% water, while rapid-setting emulsions contain up to 35% water (Mohammad et. al. 2012). Slow-setting grade emulsions can be diluted, which provides better flow from the application equipment. A telephone survey of 14 HMA contractor members of the Wisconsin Asphalt Pavement Association indicated all are using emulsions as their tack coat material. When specified, the specific emulsion used includes CSS-1 (2), CSS-1h (2), SS-1 (1) and SS-1h (2). A survey conducted by Cross & Shrestha (2005) also indicates these four emulsion types as the dominant materials currently in use throughout the western U.S. Paul & Scherocman (1998) also indicate these four emulsion types are the dominant tack materials used in their survey of practice reported from 42 states and the District of Columbia.

Current WisDOT specifications (2012) allow for the dilution of tack materials by the contractor with an equal amount of potable water. Texas DOT (2001) does not allow contractors to dilute emulsions on site. Instead, the emulsions must be diluted by the manufacturer. Ohio (2001) indicates that only slow setting emulsion tack materials may be diluted by the addition of an equal amount of water. However, it is not clear if this dilution is allowed on the job site. Several problems arise when slow-setting emulsions are diluted: the emulsions may take hours to break and possibly days to set, also if the overlay is tacked with a slow-setting emulsion there is a vulnerability to slippage during the early life of the pavement (Mohammad et. al. 2012).

2.3 Tack Coat Application Rates

Current WisDOT specifications (2012) indicate an application rate of 0.025 gal/yd^2 after dilution. It is not clearly specified if this target application rate is the actual or residual application rate. Furthermore, project specific application rates are based on the engineer's approval of the rate proposed by the contractor to provide an effective bond with the overlying material. Typical application rates used in Ohio (2001) are based on the underlying pavement type/condition, as shown in **Table 2.1**. It can be seen that lower application rates are recommended for newer surfaces.

Table 2.1. Typical Application Rates in Ohio (2001)

Existing Pavement Condition	Application Rate* (gal/sy)		
	Residual	Undiluted	1:1 Dilution
New Asphalt	0.03 – 0.04	0.05 – 0.07	0.10 – 0.13
Oxidized Asphalt	0.04 – 0.06	0.07 – 0.10	0.13 – 0.20
Milled Asphalt Surface	0.06 – 0.08	0.10 – 0.13	0.20 – 0.27
Milled PCC Surface	0.06 – 0.08	0.10 – 0.13	0.20 – 0.27
PCC	0.04 – 0.06	0.07 – 0.10	0.13 – 0.20

* Rates shown are for slow setting asphalt emulsions (SS1, SS1H) containing approximately 60% bituminous material.

CALTRANS (2006) has developed guidelines on tack coat application rates based on tack coat material, the HMA overlay type, and the type of HMA surface to be tack coated, as shown in **Table 2.2**.

Table 2.2 Tack Coat Application Rates in California (2006)

Type of HMA Overlay	Type of Existing Surface	Application Rate (gal/sy)		
		Slow Set Emulsion (1)	Rapid Set Emulsion (2)	Paving Grade Asphalt
Dense Graded HMA Overlay	Dense, Tight Surface (i.e., between lifts)	0.04 – 0.08	0.02 – 0.04	0.01 – 0.02
	Open Textured or Dry, aged Surface (i.e., milled surface)	0.08 – 0.20	0.04 – 0.09	0.02 – 0.06
Open Graded HMA Overlay	Dense, Tight Surface (i.e., between lifts)	0.06 – 0.11	0.02 – 0.06	0.01 – 0.03
	Open Textured or Dry, aged Surface (i.e., milled surface)	0.11 – 0.24	0.06 – 0.12	0.03 – 0.07

(1) Rates shown are 1:1 diluted slow set asphalt emulsions
(2) Rates shown are for undiluted rapid set asphalt emulsions

The U.S. Army Corps of Engineers (2000) recommends that application rates should be based on the residual asphalt content and that the use of diluted slow set emulsions (1:1) will result in complete coverage and a very thin residual asphalt film. A general target of approximately 0.04 to 0.06 gal/sy is suggested with this amount dependent on the condition of the pavement surface. For milled surfaces, a residual application rate as high as 0.08 gal/sy is suggested.

Tashman, et al. (2006) report that in the U.S., all states typically use residual application rates between 0.013 and 0.058 gal/sy with slow set emulsions. Tashman, et al. also provide the results of various research efforts targeted at determining optimum residual application rates based on material type and test temperature. These results indicate optimum residual rates between 0.02 and 0.22 gal/sy.

Mohammad et. al. (2012) completed a study to determine the best amount of residual tack coat for HMA placement. The results of the study are shown in **Table 2.3**. The results from the study provide a much smaller range of application rates than what is currently being used nationwide. Some states may currently be using more tack coat than what is necessary in order to achieve optimal performance.

Table 2.3. Optimal Residual Tack Coat Application Rates (Mohammad et. al. 2012)

Surface Type	Residual Application Rate (gsy)
New Asphalt Mixture	0.035
Old Asphalt Mixture	0.055
Milled Asphalt Mixture	0.055
Portland Cement Concrete	0.045

Ensuring a uniform placement of tack coat is usually a primary concern. The most common method to check for uniformity is to visually confirm that the entire surface is covered with tack coat. A nationwide study found that if non-uniform tack coat application is discovered, then 70% of respondents will reapply the tack coat (Mohammad et. al. 2012). It was also found that when the tack coat is reapplied, 70% of those respondents lower the application rate in order to not over apply the tack coat.

2.4 Tack Coat Distribution

Current WisDOT specifications (2012) require that tack coat distributors be equipped with a tachometer, pressure gauges, accurate volume measuring devices with a pump power unit and full circulation spray bars that are adjustable laterally and vertically. Washington DOT (2003) recommends that the spray bar height be adjusted throughout the day to account for the lessening weight of the tack material in the tank, thus ensuring the desired double or triple nozzle spray coverage is achieved. Cross & Shrestha (2005) indicate the double overlay is recommended for most applications. If the spray bar is set too low, streaking may occur due to little or no nozzle spray overlay. If the spray bar rises due to a lessened load, excessive overlay may occur. This is reported to result in excessive application rates; however, it is not clear how this is possible using a constant application rate from each spray nozzle. Mohammad et. al. (2012) identified which factors must be addressed in order to ensure uniform tack coat distribution: nozzle spray patterns should be identical, the nozzle needs to be sized based on what is being distributed, spray bar height should remain constant, pressure within the distributor must force the tack coat out at a constant rate, and temperature must be maintained to ensure adequate flow is achieved.

2.5 Pavement Surface Preparation

Current WisDOT specifications (2012) indicate the tack coat may be applied only when the existing surface is dry and reasonably free of loose dirt, dust, or other foreign matter, a condition which must be achieved by sweeping immediately before tack coat application. This requirement is echoed through the literature, typically with stronger wording that the surface be "thoroughly cleaned" prior to tack coat application. In addition to sweeping the pavement surface, high-pressure air or water can be used to thoroughly clean the existing surface. On milled surfaces with large amounts of debris resulting from the milling operations, a broom and vacuum system may be required to completely clean the roadway prior to tack coat application.

2.6 Environmental Conditions

Current WisDOT specifications (2008) indicate the tack coat may be applied only when the air temperature is 36 ^{o}F or more. The Asphalt Institute (MS-19) indicates best results are obtained with pavement surface temperatures above 77 ^{o}F. Current WisDOT specifications (2008) also indicate that tack coats should not be applied if the surface is wet or before impending rains. CALTRANS (2006) suggests that if rain occurs on newly placed tack coat, sand should be applied to blot the tack materials. This sand then should be swept or flushed off with water and a new tack layer reapplied before resuming paving operations.

2.7 Laboratory Testing

West, et al. (2005) focused on the development of a test method for characterizing the bond strength between fine and coarse graded HMA layers which included the evaluation of testing temperature, normal pressure, tack coat type, application rate and mixture type. In this study, CRS-2, CSS-1 and PG 64-22 tack coat materials were investigated using residual application rates of 0.02, 0.05 and 0.08 gal/yd^2. Bond strength tests were conducted on laboratory prepared specimens using a direct shear type test with a loading rate of 2 in/min and test temperatures of 50, 77 and 140 ^{o}F. The study concluded that the PG 64-22 binder provided higher bond strengths than the emulsions, that higher bond strengths were generally evident at the lower application rate, and that bond strength significantly reduces as test temperature increases. The study also recommended a minimum bond strength of 100 psi to ensure good performance.

Al-Qadi, et al. (2008) investigated the interface bond strength of HMA layers placed over Portland Cement Concrete (PCC) pavements. In this study, a direct shear device capable of producing both vertical (shear) loads and horizontal (normal) loads was utilized. Primary testing parameters included three HMA types (9.5mm surface, 19mm standard binder, 19mm stripping-vulnerable binder), three tack coat materials (SS-1hP, SS-1h, RC 70), four residual application rates (0, 0.02, 0.05, 0.09 gal/yd^2), four PCC surface textures (smooth, transverse tined, longitudinal tined, milled), three application temperatures (50, 68, 86 ^{o}F) and two moisture conditions (dry, saturated). The test results indicated the emulsion tack coats provided similar bond strengths, with each being substantially higher than the cutback. The researchers state the 9.5mm surface mix generally provides better interface bond; however, presented data indicate higher bond strengths for the standard binder mix with the SS-1hP tack material. The first round of testing indicated the application rate of 0.05 gal/yd^2 produced the greatest bond strengths. Subsequent testing to refine the optimum application rate yielded a preferred residual application rate of 0.04 gal/yd^2 for the SS-1hP/19mm binder combination. The effects of PCC surface texture (smooth, transverse/longitudinal tined) were negligible at each application rate. However, the milled surface exhibited significantly higher bond strengths for all application rates. Furthermore, the data trends suggest that even with an application rate of 0 (no tack) the milled PCC surface would yield a greater bond strength that all other combinations of tack material/application rate. Using the testing combination of smooth PCC surface, 9.5mm surface mix, SS-1hP at 0.05 gal/yd^2, bond strengths decreased as test temperature and surface moisture were increased.

Tashman, et al. (2006) investigated the bond strength of constructed pavement sections based on a factorial assessment of surface treatment, curing time, residual application rate and pavement location. Surface treatments included milled and non-milled, each with broom cleaning prior to tack coat application. Target residual application rates of 0, 0.018, 0.048 and 0.072 gal/yd^2 were used for the CSS-1tack coat material. A new 2-inch HMA overlay (1/2 inch NMAS) was applied on half of the test sections after the tack coat had enough time to cure and set (approx 2.5 hours) and on the other half with 3 minutes after tack coat application. UTEP Pull-Off tests were conducted on the cured sections before paving. Six-inch pavement cores were extracted on the day after paving and tested using the Torque Bond Test and the FDOT Shear Tester. The study concluded that curing time and pavement location were insignificant factors and that increased residual application rate did not significantly improve the bond shear strength. The study also concluded that the milled sections exhibited significantly higher bond strengths and that the absence of tack coat did not affect the bond strength for the milled sections. The study also indicated that the UTEP Pull-Off test was generally ineffective for testing on milled sections. The overall average bond strength for the milled sections was 176 psi (range from 98 – 267 psi) and for the non-milled section was 60 psi (range from 18 – 117 psi).

Sholar, et al. (2002) investigated the HMA interlayer bond strength of constructed pavement sections using a direct shear apparatus at a strain rate of 2 in/min and a test temperature of 77 ^{o}F. Test sections were constructed using an RS-1 emulsified asphalt tack coat at application rates of 0, 0.02, 0.05 and 0.08 gal/yd^2. Water was also applied to the surface of the set tack coat on 2 sections (0.02 and 0.08 gal/yd^2) to simulate the effects of rain during paving. Six inch pavement cores were extracted at four time periods ranging from 1 to 99 days after paving. This study concluded that HMA interlayer bond strengths for the dry pavements increased with application rate and generally increased with time and that the presence of water reduced the bond strengths. A limited number of tests were also conducted on a milled HMA section, with the results indicating significantly higher bond strengths as compared to the non-milled sections and general insensitivity to application rate.

Mohammad, et al. (2005) investigated the HMA interlayer bond strength of laboratory prepared 19 mm NMAS specimens using the Superpave Shear Tester. The research factorial included 8 different tack coat materials (PG 64-22, PG 76-22M, SS-1, SS-1h, CRS-2P, CSS-1, CRS-2L, SS-1L), 2 test temperatures (77, 131 ^{o}F), five application rates (0, 0.02, 0.05, 0.1, 0.2 gal/yd^2) and 6 normal pressures (0, 20, 40, 60, 80, 100 psi). Based on paired analysis of the various test results, this study concluded that increased application rates generally decreased interface bond strength, especially at the higher test temperature, and that the CRS-2P and CRS-2L were identified as the best tack coat types with an optimal residual application rate of 0.02 gal/yd^2.

Willis and Timm (2006) conducted a forensic investigation of a rich-bottom HMA test section which exhibited premature fatigue cracking attributed to interlayer slippage. Direct shear tests were conducted on 6-inch cores extracted from sections exhibiting distress and from sections without distress (control). Interlayer bond strengths between the SMA surface and

HMA middle layer and between the HMA middle layer and the Rich-bottom layer were determined using a strain rate of 2 in/min. For analysis purposes, shear stresses at the outside edge of a loaded tire were computed at various depths using the WESLEA program assuming full and no bonding between layers. Figure 2.1 presents the results of this analysis.

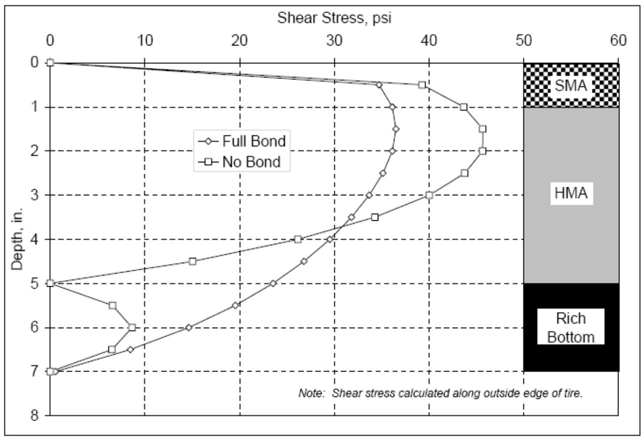

Figure 2.1. WESLEA Analysis Results (Willis & Timm, 2006)

Bond strengths measured between the HMA middle and rich-bottom layers were substantially higher than comparable measures between the SMA and HMA middle layers for all coring locations. However, the interlayer bond strengths measured for the distressed sections were comparable to those from the control section.

Eedula and Tandon (2006) conducted pull-off tests using the UTEP Pull-Off Device (UPOD) to measure the cohesive strengths of PG64-22, SS-1h and CSS-1h tack coat surfaces. Tests were conducted using residual application rates of 0.04 and 0.10 gal/sy at test temperatures of 50, 77, 95 and 140 ^{o}F. Pull-off tests were conducted at times of 10, 20, 30, 40, 50, and 60 minutes after tack coat application. The primary focus of the tests were to develop equipment and procedures suitable for field acceptance testing. The initial series of tests conducted with a residual application rate of 0.04 gal/sy indicated increased cohesive strength at elevated temperatures. Subsequent laboratory testing over the full factorial indicated cohesive strengths for all tack materials increased as temperature, time delay after application, and residual application rate increased. Cohesive strength was maximized for the CSS-1h material.

Mohammad et. al. (2012) developed two distinct methods for determining tack coat strength. The Louisiana Tack Coat Quality Tester (LTCQT) was created to evaluate the quality of the bond strength in the field. In addition, the Louisiana Interlayer Shear Strength Tester (LISST) was created to evaluate the interface shear strength of specimens in the laboratory. The study involved four different pavement surfaces (old HMA, new HMA, milled HMA, and grooved PCC), five types of tack coat (SS-1h, SS-1, CRS-1, Trackless, PG 64-22), and three separate application rates (0, 0.031, 0.062, 0.155 gal/sy). In addition to the varying materials that were used testing was done for wet and dry conditions, dusty and clean conditions, 0 and 20 psi confinement pressure, and 50% and 100% tack coat coverage. Only one test temperature was considered throughout the study, which was 25 ^{o}C. The study determined that cleaning and sweeping of the surface is necessary for adequate performance. Confined specimens produced higher shear strengths, indicating that a confinement of zero can be considered in design for a conservative estimate. Water was not observed to provide much of a difference in the performance of the tack coat; however the researchers still recommended that dry conditions be utilized. Table 2.3 shows the findings of the study in relation to different pavement types and optimal residual application rates.

2.8 Field Testing

Eedula and Tandon (2006) conducted controlled field pull-off tests with the UPOD to measure the cohesive strengths of PG 64-22, SS-1h ans CSS-1h tack coat surfaces. Tests were conducted using a residual application rate of 0.04 gal/sy at test temperatures of 60 and 95 ^{o}F. Pull-off tests were conducted 30 minutes after tack coat application. The field tests indicated increased cohesive strengths at the elevated test temperature, which was consistent with previous laboratory test results. However, the field tests indicated reduced strengths and increased variability as compared to laboratory results. Additional field tests were conducted on selected paving projects using residual application rates of 0.08 to 0.20 gal/sy, pavement surface temperatures of 90.6 to 126.0 ^{o}F, and delay times of 10 to 60 minutes after tack coat application. Using the results of previous lab studies, all field test results were converted to an estimated strength at an application rate of 0.04 gal/sy. The results were utilized to develop a field acceptance test procedure using the UPOD device. Figure 2.2 provides an example nomograph developed for acceptance of the SS-1h tack material. For any given prevailing temperature and time since application, the nonograpgh provides the minimum test strength (measured stress) needed for acceptance.

Tashman, et al. (2006) conducted a controlled field experiment to investigate the influence of surface treatment, residual application rate, delay time, and pavement location on bond strength for a non-diluted CSS-1 tack material. Surface treatments included milled and broomed and non-milled and broomed. Residual application rates were varied from 0.0 to 0.072 gal/sy. Delay time was 2.5 hours (full set) and 3 minutes (unbroken sections). Test locations were selected in the wheel path and middle of the lane. The UTEP Pull-Off Device (UPOD) was

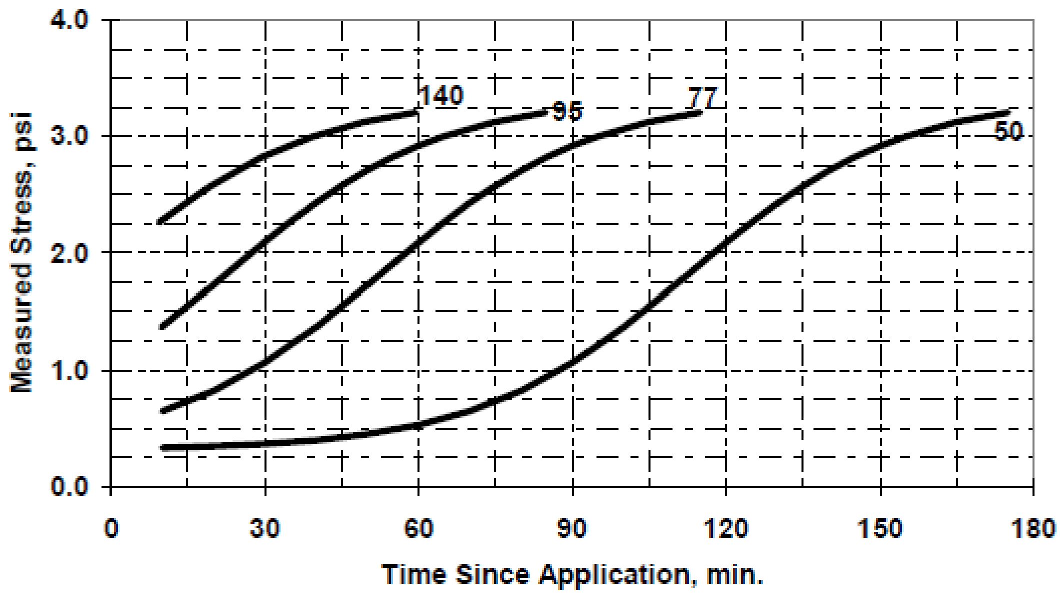

Figure 2.2 Nomograph for SS-1h Tack Coat Acceptance (Eedula and Tandon, 2006)

used to test the broken sections prior to paving. Cores were extracted after pavement and tested in the laboratory using direct shear and torque bond test equipment. The UPOD tests indicated higher cohesion for the unmilled sections while the direct shear and torque tests both indicated significantly higher shear strengths for the milled sections. The delay time was found to be an insignificant factor for both the direct shear and torque bond strengths. Also, the absence of tack coat did not affect the shear strength of the milled sections. The researchers also concluded that the direct shear test seems to better simulate the state of stress encountered in the field that leads to debonding at the interface.

Accelerated loading tests were conducted by Al-Qadi, et al. (2009) to investigate the development of asphalt tensile strains and HMA layer rutting based on tack material, application rate, coverage uniformity, HMA mix type, PCC surface texture and surface cleaning method.

The field tests did not include any direct measurements of the tack coat bond strengths after pavement. However, the field results were reported to validate the optimum SS-1hP application rate of 0.04 gal/sy and the fact that the PG64-22 binder provides the highest HMA-PCC interface bonding.

2.9 Summary and Recommendations from Literature Review

The research results presented herein generally support the WisDOT Standard Specifications application rate of 0.025 gal/yd^2 and the restriction of applications before impending rains. The cited research also indicates that tack coat applications on milled surfaces, a common practice in Wisconsin and surrounding states, may be less critical than tack coat applications between HMA paving layers. While the cited research provides general recommendations on required bond strength, preferred materials and application rates, more specificity is needed to quantify interlayer bond strengths resulting from allowable combinations of materials and applications within Wisconsin.

Based on the key parameters identified through the literature review and the telephone survey, a research factorial was developed to include the following considerations when tack coat materials are applied:

1- Tack Material Type (5) – CSS-1, CSS-1h, SS-1, SS-1h, PG-58-28

2- Residual Application Rate (4) – 0, 0.010, 0.025, 0.040 gal/sy

3- Distribution Quality (2) – Uniform, streaked

4- Interface Type (2) – Aged HMA-19mm lower layer, 19mm lower layer-12.5mm upper layer

5- Surface Preparation (2) – None, broom sweep

6- Pavement Temperature at Application (3) – 37, 70, 110 ^{o}F

7- Moisture Conditions (2) – Surface dry, surface dry with water spray prior to overlay

8- Bond Strength Test (2) – Direct shear, rotational shear

It should also be noted that the proposed testing does not include any tests on milled HMA surfaces. This choice was made based on published research which indicates bond strength on this surface type is independent of tack material type and application rate, primarily due to the aggressive mechanical bond provided by the milled surface texture.

Chapter 3 Phase 1 Laboratory Testing

3.1 Introduction

Phase 1 laboratory testing was conducted at Marquette University to assess the bond strength of tack materials under a variety of conditions, including tack coat material, application rate and uniformity, moisture and temperature conditions, and pavement layer types. The lab tests were focused to assess the current protocols for tack coat applications, as enumerated in Section 455 of the WisDOT Standard Specifications (2012). Consideration was given to the following parameters:

Tack Coat Type **–** Current WisDOT specifications allow for the use of MS-2, SS-1, SS-1h, CSS-1 and CSS-1h emulsified asphalts. The SS-1h material was chosen for the laboratory studies in addition to a paving grade PG 58-28 binder.

Tack Coat Application Rate **-** Current WisDOT specifications indicate an application rate of 0.025 gal/yd^2. To provide for meaningful comparisons, application rates of 0.01, 0.025 and 0.04 gal/yd^2 were utilized to provide quantitative data on the effects of application rates compared to the baseline condition of no tack coat application. In addition to application rate, uniformity of coverage may play a critical role in the quality of the interlayer bond. For each selected application rate, 2 levels of uniformity representing both uniform and streaked coverage were simulated.

Application Temperatures **–** The base temperature of the HMA supporting layer was varied to simulate varying paving environments which may impact the activation of the tack coat and ultimately its adhering properties. Current WisDOT specifications require a minimum air temperature of 36 ^{o}F, which may be considered equal to the average base layer temperature. The refrigeration equipment in the Asphalt Lab at Marquette University allowed for a minimum temperature of 37 ^{o}F. Additional base layer temperatures of 70 ^{o}F and 110 ^{o}F were utilized to simulate a broad range of paving environments. Specimens were conditioned for a minimum of 24 hours at these temperatures prior to the application of tack coat materials and held at these temperatures during the curing period.

***Adhering Surfaces* –** Current WisDOT specifications indicate the tack coat may be applied only when the existing surface is dry and reasonably free of loose dirt, dust, or other foreign matter, a condition which must be achieved by sweeping immediately before tack coat application. For the laboratory prepared specimens, the surface of the base specimens was either dry or wetted with a water spray immediately before the tack coat application.

Mixture Type - The mixture types for the base and overlying HMA layers affects the quality of the bond provided by the tack coat. For the initial laboratory study, WisDOT standard 19.0 mm NMAS (lower layer) and 12.5 mm NMAS (upper layer) were utilized. Materials for each of these mixture types were obtained from Payne & Dolan during actual production.

***Test Type* –** The conducted shear strength tests included the direct shear and rotational shear tests. A special direct test fixture and a portable rotational shear tester were designed and fabricated for this study. For comparative purposes, replicate tests were conducted using both test devices to determine which test is most suitable for implementation.

3.2 Test Specimen Fabrication

The interface type considered during initial laboratory testing was a standard 19 mm NMAS lower pavement layer surfaced with a 12.5 mm NMAS upper pavement layer. Lab specimens were prepared with a portable gyratory compactor using HMA materials donated by Payne & Dolan, Inc. Figures 3.1 and 3.2 provide the mix designs for the E-3 mixtures used for this project.

Lower layer specimens were compacted to a nominal thickness of 3 inches. A spray of white paint was then applied to the top perimeter of the specimens to aid in the subsequent identification of the layer interface after complete fabrication. The marked specimens were then temperature conditioned for a minimum of 24 hours. Tack coat materials were applied and the lower layer specimens were returned to the conditioning environment until the tack material was completely set. The lower layer specimens were then returned to the gyratory compactor and a 12.5 mm NMAS surface layer was then compacted to a nominal thickness of 1 inch. During initial specimen fabrication, the compacted lower layer specimens could not be re-inserted into the gyratory mold without significant downward pressure. To minimize disturbance of the specimens, the perimeter surface of the specimens were sanded to slightly reduce the diameter, allowing for easier re-insertion. This process proved to be extremely labor and material intensive. It was then decided to mill away the interior of one of the gyratory molds, slightly increasing its internal diameter and allowing for easy re-insertion of the lower layer specimens

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REPORT OF SUPERPAVE VOLUMETRIC MIX DESIGN
(AASHTO MP-2, PP-28, T312 & ASTM D-4867)

Issued Date: 3/31/2005
Amended Date: 8/1/2006

DESIGN NUMBER: 502405 — JOB: 40002 (1060-05-71)
PLANT: 40002 — MIX TYPE: E-3 — MIX TEMPERATURE: 135°C - 149°C
MIX SIZE: 19.0 mm — Design ESAL Range (mil.): 1 to < 3

Compactive Effort: (Gyrations) Ni: 7 Nd: 75 Nm: 115

Binder Data: GRADE: PG 58-28 SOURCE: CRM, Milwaukee Gb: 1.028 **RAP Pb:** 4.47

AGGREGATE SOURCE DATA

AGG	AGGREGATE	SOURCE	TEST#	LOCATION
AGG #1	RAP	40002	13-B-05	
AGG #2	#1 Stone	WLS-EQ	16-A-05	SW1/4 SW1/4 S18 T5N R20E Waukesha Co.
AGG #3	1/2" Chip	WLS-EQ	17-A-05	SW1/4 SW1/4 S18 T5N R20E Waukesha Co.
AGG #4	3/8" Chip	WLS-EQ	18-A-05	SW1/4 SW1/4 S18 T5N R20E Waukesha Co.
AGG #5	MFGD Sand	WLS-EQ	20-A-05	SW1/4 SW1/4 S18 T5N R20E Waukesha Co.
AGG #6	Natural Sand	Honey Creek	21-A-05	NW1/4 S26 T7N R19E Racine Co.
AGG #7	Deg	Honey Creek	1	NW1/4 S26 T7N R19E Racine Co.

AGGREGATE GRADATION

		Agg #1	Agg #2	Agg #3	Agg #4	Agg #5	Agg #6	Agg #7	JMF	SPECIFICATION MIN	SPECIFICATION MAX
% BLEND		15.0	10.0	10.0	10.0	45.0	9.5	0.5			
2	50.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
1-1/2	37.5 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
1	25.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4	19.0 mm	100.0	78.7	100.0	100.0	100.0	100.0	100.0	97.9	90.0	100.0
1/2	12.5 mm	100.0	9.4	87.9	100.0	100.0	100.0	100.0	89.7	0.0	90.0
3/8	9.5 mm	96.0	4.0	11.9	95.6	100.0	100.0	100.0	80.6	0.0	0.0
#4	4.75 mm	78.0	3.1	1.1	2.1	89.5	90.7	100.0	61.7	0.0	0.0
#8	2.36 mm	59.1	2.5	1.1	1.5	55.8	74.7	100.0	42.1	23.0	49.0
#16	1.18 mm	45.0	2.1	1.0	1.4	32.2	59.4	100.0	27.8	0.0	0.0
#30	0.60 mm	33.6	2.1	1.0	1.3	18.5	41.1	100.0	18.2	0.0	0.0
#50	0.30 mm	21.4	2.1	1.0	1.3	10.6	15.8	100.0	10.4	0.0	0.0
#100	0.15 mm	15.2	2.0	0.9	1.3	6.4	5.9	100.0	6.6	0.0	0.0
#200	0.075 mm	12.1	1.8	0.9	1.2	4.4	4.3	100.0	5.1	2.0	8.0
	FAA	42.7	0.0	0.0	0.0	46.5	41.1	0.0	44.9		
	Gsb	2.673	2.776	2.760	2.762	2.756	2.653	2.653	2.736		

AGGREGATE DATA FOR BLENDED DESIGN JMF

CRUSH 1F/2F: 97.9 / 97.1 — FAA: 44.9 — SE: 89
Gsb: 2.736 — Gsa: 2.810 — Gse: 2.803
Moist. Absorption: 1.0 — Dust Proportion: 1.0 — Soundness: 0.0
L.A. WEAR: 0.0 (100) 0.0 (500) — Freeze-Thaw: 0.0
ELONGATED: 1.0 (5/1)

VOLUMETRIC DATA

Point	Added Pb	Total Pb	Gmm	Gmb	Va	VMA	VFB	Unit Wt.	%Gmm Ni	%Gmm Nm	TSR
A	3.7	4.4	2.605	2.472	5.1	13.6	62.7	2465			
B	4.2	4.9	2.584	2.491	3.6	13.4	73.3	2484			
C	4.7	5.4	2.564	2.505	2.3	13.4	82.8	2498			
JMF	4.1	4.8	2.588	2.484	4.0	13.6	70.6	2477	88.2	97.3	92.8
		Corr. Factor:	0.000								TSR N = 28
SPECIFICATION					4.0	13.0	65 - 75		89.0	98.0	

Comments: Eliminate Deg. Natural Sand = 10.0%
WisDOT aggregate test number 217-105-04
WisDOT Verifcation number 250 - 0010 - 2005
A change in binder grade or source is recognized without the need for additional mix design testing. (per WisDOT 1559)

M. Noel Fortier

M. Noel Fortier
Wisconsin Certified Hot Mix Asphalt Technician IIIS
THE TEST DATA SHOWN ON THIS REPORT PERTAIN ONLY TO THE MATERIAL SUBMITTED FOR DESIGN.
AASHTO MP2 MODIFIED TO MEET CUSTOMER REQUIREMENTS.

Figure 3.1. Mix Design for E-3 19 mm NMAS Lower Layer

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REPORT OF SUPERPAVE VOLUMETRIC MIX DESIGN
(AASHTO MP-2, PP-28, T312 & ASTM D-4867)

Issued Date: 8/18/2006
Amended Date: 8/18/2006

DESIGN NUMBER: 503205 | JOB: 40007 (2040-02-73)
PLANT: 40007 | MIX TYPE: E-3 | MIX TEMPERATURE: 135°C - 149°C
MIX SIZE: 12.5 mm | Design ESAL Range (mil.): 1 to < 3

Compactive Effort: (Gyrations) Ni: 7 Nd: 75 Nm: 115

Binder Data: GRADE: PG 58-28 SOURCE: CRM, Milwaukee Gb: 1.029 RAP Pb: 4.02

AGGREGATE SOURCE DATA

AGG	AGGREGATE	SOURCE	TEST#	LOCATION
AGG #1	Cr. RAP	40007	15-B-05	
AGG #2	1/2" Chip	Franklin Quarry	35-A-05	NE1/4 S10 T5N R21E Milwaukee Co.
AGG #3	CA 16	Franklin Quarry	36-A-05	NE1/4 S10 T5N R21E Milwaukee Co.
AGG #4	MFG'D Sand	Franklin Quarry	38-A-05	NE1/4 S10 T5N R21E Milwaukee Co.
AGG #5	Natural Sand	Gander Mountain	39-A-05	S1/2E1/2 S9 T46N R9E McHenry Co. IL
AGG #6	Deg	Gander Mountain	1	S1/2E1/2 S9 T46N R9E McHenry Co. IL

AGGREGATE GRADATION

		Agg #1	Agg #2	Agg #3	Agg #4	Agg #5	Agg #6	JMF	SPECIFICATION MIN	SPECIFICATION MAX
% BLEND		8.0	12.0	19.0	35.0	25.5	0.5			
2	50.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
1-1/2	37.5 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
1	25.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
3/4	19.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2	12.5 mm	100.0	75.4	100.0	100.0	100.0	100.0	97.0	90.0	100.0
3/8	9.5 mm	93.7	25.6	97.8	100.0	100.0	100.0	90.2	0.0	90.0
#4	4.75 mm	72.0	3.7	24.0	98.2	93.9	100.0	69.6	0.0	0.0
#8	2.36 mm	54.9	2.6	5.2	69.4	74.9	100.0	49.6	28.0	58.0
#16	1.18 mm	42.3	2.2	3.8	42.2	57.1	100.0	34.2	0.0	0.0
#30	0.60 mm	32.3	2.1	3.4	24.9	38.7	100.0	22.6	0.0	0.0
#50	0.30 mm	22.5	2.1	3.3	14.3	16.7	100.0	12.4	0.0	0.0
#100	0.15 mm	15.7	2.1	3.2	7.5	7.1	100.0	7.1	0.0	0.0
#200	0.075 mm	9.8	2.0	3.1	5.0	5.1	100.0	5.2	2.0	10.0
	FAA	43.4	0.0	0.0	46.7	40.8	0.0	44.1		
	Gsb	2.666	2.647	2.626	2.683	2.675	2.675	2.664		

AGGREGATE DATA FOR BLENDED DESIGN JMF

CRUSH 1F/2F: 95.4 / 95.3 | Gsb: 2.664 | Moist. Absorption: 1.6 | L.A. WEAR: 0.0 (100) | ELONGATED: 0.8 (5/1)
FAA: 44.1 | Gsa: 2.784 | Dust Proportion: 1.1 | 0.0 (500)
SE: 81 | Gse: 2.737 | Soundness: 0.0 | Freeze-Thaw: 0.0

VOLUMETRIC DATA

Point	Added Pb	Total Pb	Gmm	Gmb	Va	VMA	VFB	Unit Wt.	%Gmm Ni	%Gmm Nm	TSR
A	4.9	5.2	2.520	2.384	5.4	15.2	654.5	2378			
B	5.4	5.7	2.500	2.399	4.0	15.1	73.5	2393			
C	5.9	6.2	2.482	2.420	2.5	14.8	83.1	2413			
JMF	5.4	5.7	2.500	2.400	4.0	15.0	73.3	2394	88.3	97.2	93.2
	Corr. Factor:		0.000								TSR N = 22
SPECIFICATION					4.0	14.0	65 - 75		89.0	98.0	

Comments: Eliminate Deg Natural Sand Gander Mountain= 30.0%
WisDOT Aggregate Test number 217 - 27 - 2003 WisDOT Verification number 250-0124-2005
A change in binder grade or source is recognized without the need for additional mix design testing. (per WisDOT 1559)

Gail Hoard

Gail Hoard
Wisconsin Certified Hot Mix Asphalt Technician IIIS
THE TEST DATA SHOWN ON THIS REPORT PERTAIN ONLY TO THE MATERIAL SUBMITTED FOR DESIGN.
AASHTO MP2 MODIFIED TO MEET CUSTOMER REQUIREMENTS.

Figure 3.2. Mix Design for E-3 12.5 mm NMAS Surface Layer

The completed specimens were allowed to cool to ambient laboratory temperatures for a minimum of 24 hours. A 4 inch core barrel was then penetrated through the surface layer and into the lower layer to a depth of approximately ¼ inch. The annular ring of the HMA surface layer was then removed at the interface using a specially designed apparatus equipped with a diamond saw blade, resulting in a tiered specimen ready for shear testing. Figures 3.3 through 3.10 illustrate the basic steps in the specimen fabrication process.

3.3 Direct Shear Testing

Direct shear testing was conducted at Marquette University using a Riehle Universal Testing Machine (UTM). A special 2-part test fixture was designed and fabricated at Marquette to allow for the correct positioning of the intended shear plane. Test specimens were randomly selected from within the batch of specimens fabricated with the desired tack coat application conditions. In some instances, the tiered portion of the fabricated specimens was off-center due to wandering of the core barrel during fabrication. These specimens were preferentially tested in direct shear as this offset could be accounted for during placement of the specimen within the test fixture. After the specimen was secured within the test fixture, the test fixture was mounted within the UTM. Figures 3.11 through 3.16 provide photos of the test preparations. The actual direct shear test was conducted using a crosshead movement of 2 inches per minute with the peak load (P_{max}) prior to specimen failure recorded. The bond strength is computed from the peak load as:

$$\text{Bond Strength (psi)} = \frac{P_{\max}}{\pi r^2}$$

Figure 3.3. Compacted 19 mm NMAS Lower Layer With ID and Marking Paint

Figure 3.4. Compacted 19 mm NMAS Lower Layer After Tack Application (Note: Perimeter Sanded to Allow for Re-Insertion Into Gyratory Compactor)

Figure 3.5. Compacted 19 mm NMAS Lower Layer Returning to Gyratory Compactor

Figure 3.6. Extruded Specimen After Addition of 12.5 mm NMAS Surface Layer

Figure 3.7. Specimen After Coring with 4-inch Core Barrel

Figure 3.8. Specimen Mounted for Removal of Annular Ring

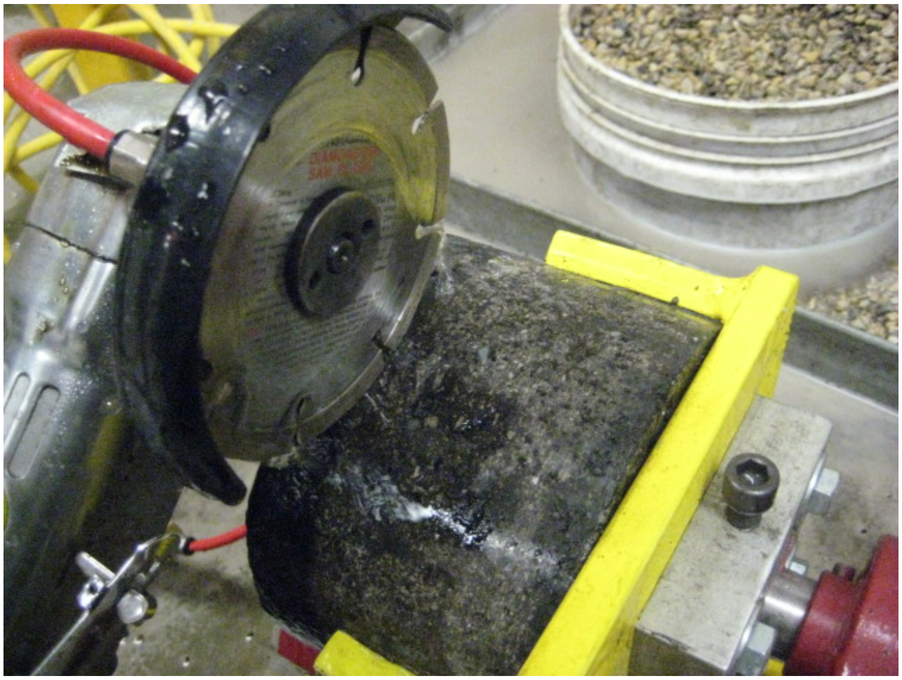

Figure 3.9. Diamond Blade for Removal of Annular Ring

Figure 3.10. Completed Tiered Specimen

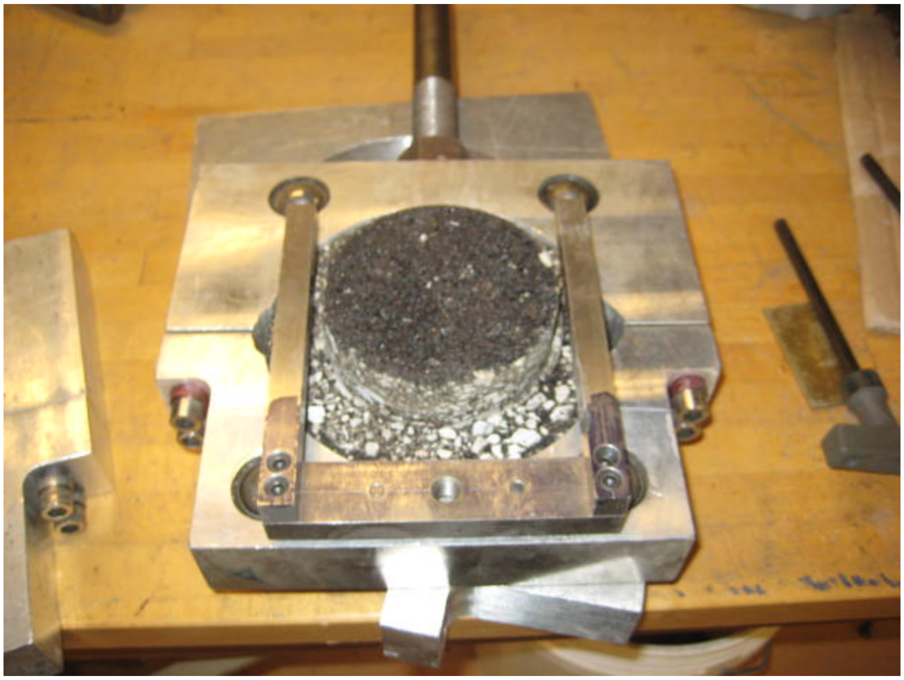

Figure 3.11. Tiered Specimen Placement Within Bottom Portion of Direct Shear Fixture

Figure 3.12. Side View of Specimen Within Bottom Portion of Direct Shear Fixture

Figure 3.13. Alignment Jig for Top Portion of Direct Shear Test Fixture

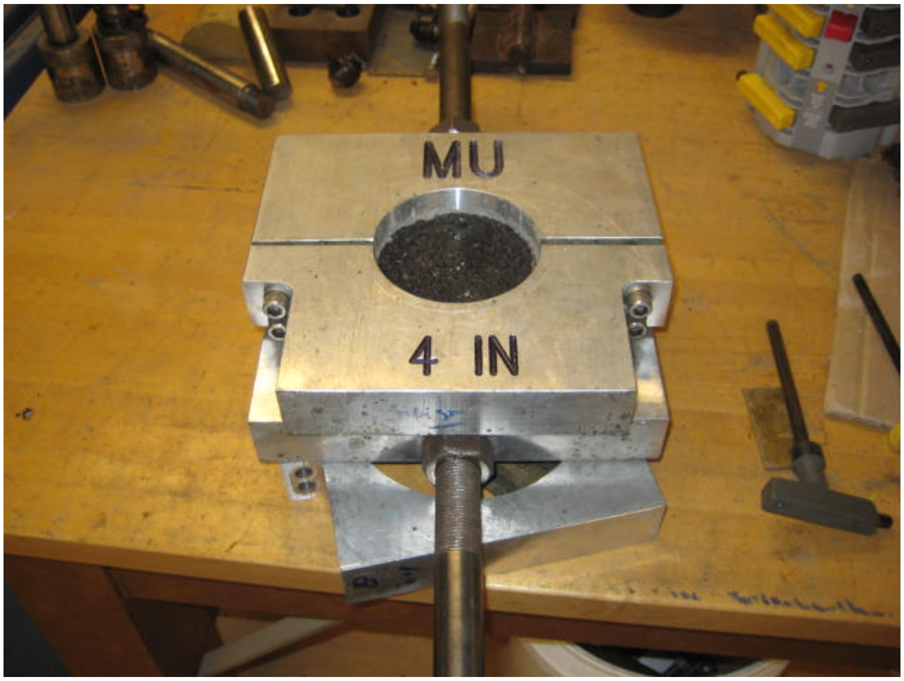

Figure 3.14. Tiered Specimen With Top Portion of Direct Shear Fixture Attached

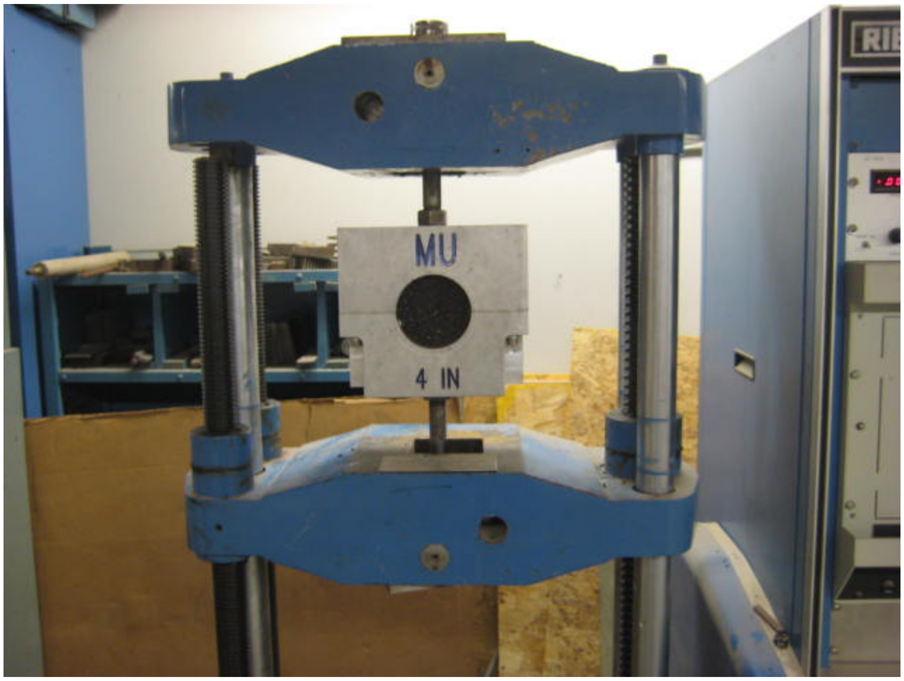

Figure 3.15. Direct Shear Fixture Mounted in Riehle UTM

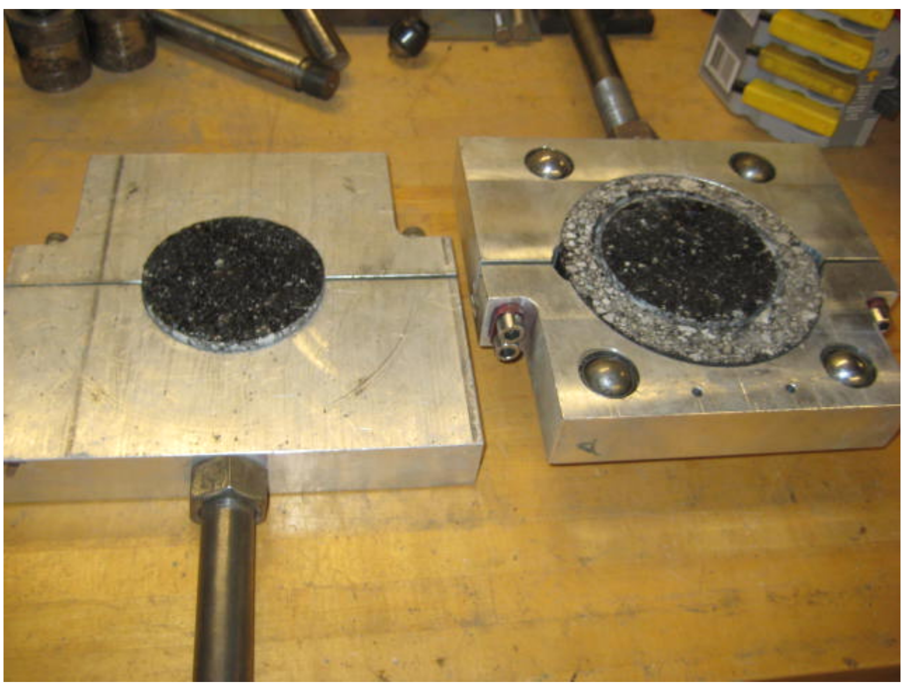

Figure 3.16. Tiered Specimen After Direct Shear Failure

3.4 Rotational Shear Testing

Rotational shear testing was conducted at Marquette University using a test device specially designed and fabricated for this project. The rotational shear tester (RST) can be operated as a bench-top device within the laboratory or re-configured as a field device capable of testing pavement layers in situ. Tiered test specimens were randomly selected from within the batch of specimens fabricated with the desired tack coat application conditions. After the specimen was secured within the test fixture, the test fixture was mounted within the RST. Figures 3.17 through 3.20 provide photos of the test preparations. The actual rotational shear test was conducted using a rotational movement of 0.25 revolutions per minute, which approximates a shear rate of 2 inches per minute along the circumferential path at a distance of 1.33 inches (2/3 of the radius) from the center of the test specimen.

The RST provides a record of the measured torque, in ft-lbs, and rotational speed taken at a sampling rate of 2 Hz. Figure 3.21 provides an example plot of the RST test results. The bond strength was computed from the maximum measured torque, T_{max} , prior to failure using:

$$\text{Rotational Shear Bond Strength (psi)} = \frac{24T_{\max}}{\pi r^3}$$

Figure 3.17. Tiered Specimen Mounted Within Lower RST Fixture

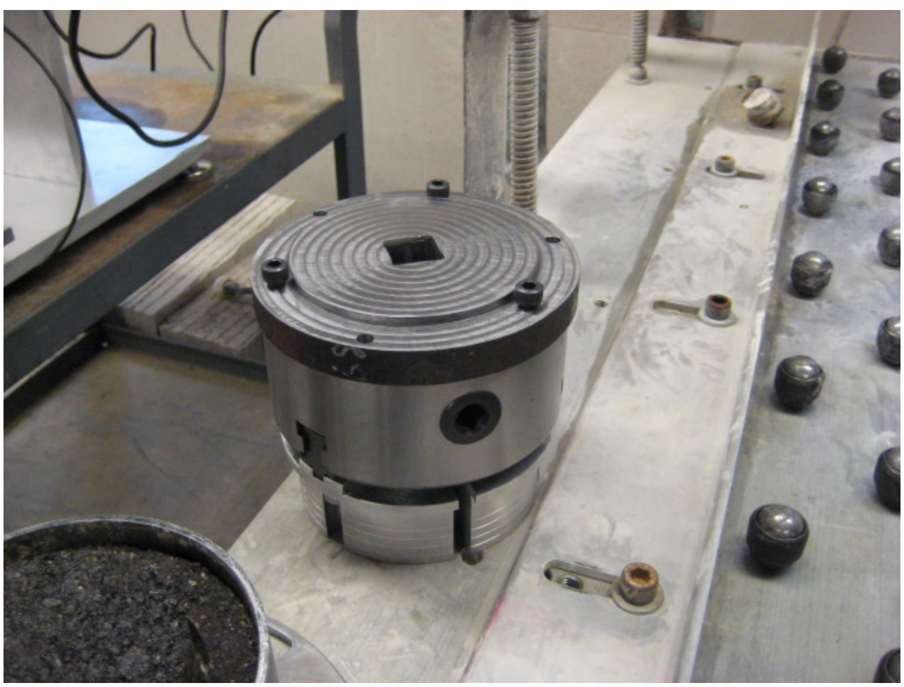

Figure 3.18. Upper RST Fixture

Figure 3.19. Specimen and Fixtures Mounted Within RST

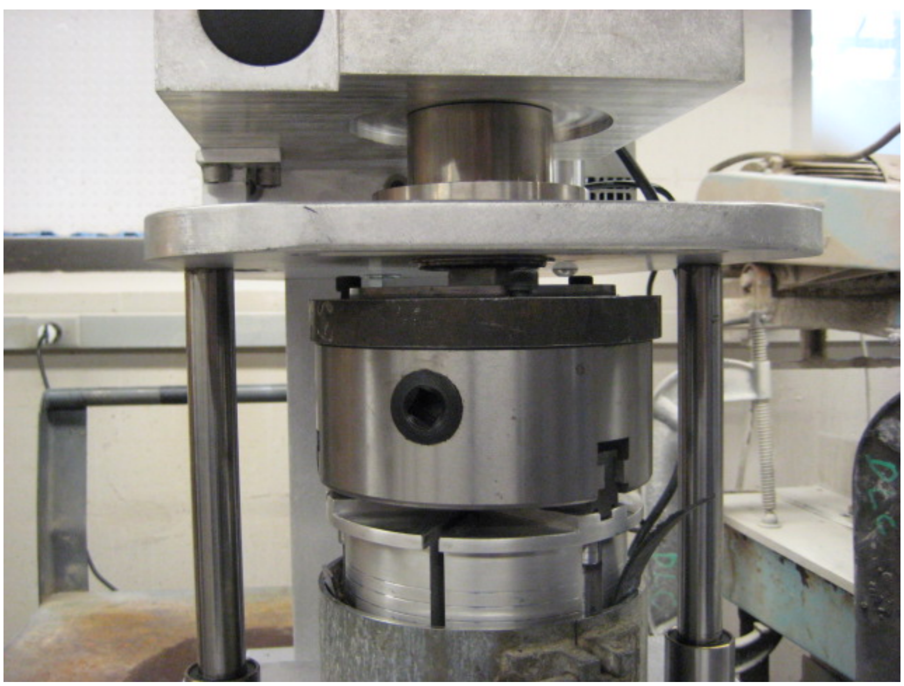

Figure 3.20. RST Ready for Testing

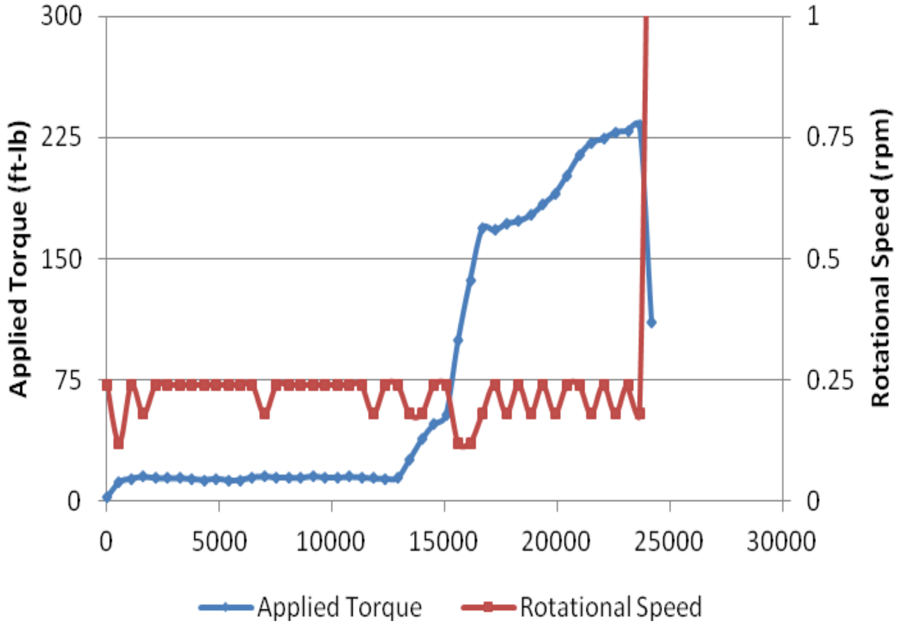

Figure 3.21. Sample RST Test Result

3.5 Discussion of Test Results

The test results from the Phase 1 laboratory testing are provided in **Table 3.1**. As shown, the average bond strength from direct shear testing of nearly all of the test groups was above 100 psi, the minimum recommended value from previous research. The instances where average bond strengths were less than 100 psi were primarily confined to the CSS-1h material applied at 37F.

Because of the many variables included within the testing matrix, a wide range of comparisons can be made with regards to tack coat application conditions, including tack coat material, application rate and uniformity, moisture and temperature conditions. The following discussions will compare and contrast these results in both qualitative and quantitative measures. The replicate test measures for each application condition have been assigned into a unique group number to aid in the discussions. Paired comparisons between groups were used to identify if there was a statistical difference between group means at the 90% confidence level. The F-Test was used to determine if the variances between groups could be considered equal, as noted by a calculated $P(F<=f)$ value GREATER than 0.05. The t-Test was then used to determine if the group mean could be considered to be statistically different, as noted by a $P(T<=t)$ value LESS than 0.05. The F-Test and t-Test values were both computed using Microsoft Excel Data Analysis Tools.

Figures 3.22 through 3.31 provide comparative plots illustrating data trends for a wide range of comparisons. The statistical analysis outlined above was applied to a broad range of group pairs to determine if the observed trends were quantitatively different at the 90% significance level. **Tables 3.2 through 3.6** provides the results of these analyses, with those comparisons having statistically different group mean values highlighted.

Table 3.1. Phase 1 Laboratory Test Results

Test Group	Application Temp F	Surface Wet/Dry	Tack Type	Coverage Type	Residual gal/sy	Shear Test	Peak Shear Stress psi	psi	psi	Average psi
1	37	D	SS1h	Uniform	0	D	69.6	81.2		75.4
2	37	D	SS1h	Uniform	1	D	87.9	97.5	115.4	100.3
3	37	D	SS1h	Uniform	2	D	151.6	133.7	107.4	130.9
4	37	D	SS1h	Uniform	4	D	198.5	112.2	196.6	169.1
5	70	D	SS1h	Uniform	0	D	97.1	117.8	128.5	114.5
6	70	D	SS1h	Uniform	1	D	147.6	125.3	115.4	129.4
7	70	D	SS1h	Uniform	2	D	153.6	115.4	117.4	128.8
8	70	D	SS1h	Uniform	4	D	158.0	158.0	111.8	142.6
9	110	D	SS1h	Uniform	0	D	119.0	126.9	116.6	120.8
10	110	D	SS1h	Uniform	1	D	139.3	161.1	113.0	137.8
11	110	D	SS1h	Uniform	2	D	145.6	158.8	112.6	139.0
12	110	D	SS1h	Uniform	4	D	164.7	193.0	170.3	176.0
13	37	W	SS1h	Uniform	0	D	58.9	110.2		84.6
14	37	W	SS1h	Uniform	1	D	150.8	95.1	93.5	113.1
15	37	W	SS1h	Uniform	2	D	159.2	157.6	116.2	144.3
16	37	W	SS1h	Uniform	4	D	167.9	181.0	119.0	156.0
17	70	W	SS1h	Uniform	0	D	94.3	79.6		86.9
18	70	W	SS1h	Uniform	1	D	81.6	126.5	158.0	122.0
19	70	W	SS1h	Uniform	2	D	137.3	151.2	127.7	138.7
20	70	W	SS1h	Uniform	4	D	150.0	150.0	191.4	163.8
21	110	W	SS1h	Uniform	0	D	132.5	140.5	151.6	141.5
22	110	W	SS1h	Uniform	1	D	91.9	147.2		119.6
23	110	W	SS1h	Uniform	2	D	133.7	94.3		114.0
24	110	W	SS1h	Uniform	4	D	113.0	183.0	172.7	156.2
25	37	D	SS1h	Uniform	0	R	207.1	134.4	212.5	184.7
26	37	D	SS1h	Uniform	1	R	191.6	180.7	189.1	187.1
27	37	D	SS1h	Uniform	2	R	202.1	236.9	169.6	202.9
28	37	D	SS1h	Uniform	4	R	191.7	274.6	251.0	239.1
29	70	D	SS1h	Uniform	0	R	219.3	134.8	177.4	177.2
30	70	D	SS1h	Uniform	1	R	155.5	152.6	162.1	156.7
31	70	D	SS1h	Uniform	2	R	191.2	296.2		243.7
32	70	D	SS1h	Uniform	4	R	185.0	252.5	285.2	240.9
33	110	D	SS1h	Uniform	0	R	216.1	238.4	192.5	215.7
34	110	D	SS1h	Uniform	1	R	245.7	225.3		235.5
35	110	D	SS1h	Uniform	2	R	205.1	293.1	311.0	269.7
36	110	D	SS1h	Uniform	4	R	251.1	288.6	292.5	277.4
37	37	W	SS1h	Uniform	0	R	105.3	104.2	156.5	122.0
38	37	W	SS1h	Uniform	1	R	155.5	265.6	246.3	222.4
39	37	W	SS1h	Uniform	2	R	173.5	241.1	214.3	209.6
40	37	W	SS1h	Uniform	4	R	179.7	252.5	224.0	218.7
41	70	W	SS1h	Uniform	0	R	162.5	140.5	186.8	163.3
42	70	W	SS1h	Uniform	1	R	157.9	268.4	213.4	213.3
43	70	W	SS1h	Uniform	2	R	142.8	259.3	185.8	196.0
44	70	W	SS1h	Uniform	4	R	257.3	280.1	263.6	267.0
45	110	W	SS1h	Uniform	0	R	217.6	271.8	233.6	241.0
46	110	W	SS1h	Uniform	1	R	167.2	245.4	181.0	197.9
47	110	W	SS1h	Uniform	2	R	318.3	200.6	295.9	271.6
48	110	W	SS1h	Uniform	4	R	237.0	293.4		265.2
49	37	D	SS1h	Streaked	1	D	148.4	174.7	205.3	176.1
50	37	D	SS1h	Streaked	2	D	187.4	178.3	159.6	175.1
51	37	D	SS1h	Streaked	4	D	150.8	139.3	144.4	144.8
52	70	D	SS1h	Streaked	1	D	147.2	167.9	177.9	164.3
53	70	D	SS1h	Streaked	2	D	162.7	194.6	196.6	184.6
54	70	D	SS1h	Streaked	4	D	209.3	195.4	208.5	204.4
55	110	D	SS1h	Streaked	1	D	154.4	176.7		165.5

Table 3.1. Phase 1 Laboratory Test Results

Test Group	Application Temp F	Surface Wet/Dry	Tack Type	Coverage Type	Residual gal/sy	Shear Test	Peak Shear Stress psi	psi	psi	Average psi
56	110	D	SS1h	Streaked	2	D	179.4	161.9		170.7
57	37	D	SS1h	Streaked	1	R	318.1	223.8		271.0
58	37	D	SS1h	Streaked	2	R	200.2	245.9	214.7	220.3
59	37	D	SS1h	Streaked	4	R	340.9	269.7	230.4	280.3
60	70	D	SS1h	Streaked	1	R	296.6	331.5	406.9	345.0
61	70	D	SS1h	Streaked	2	R	302.8	230.6	341.0	291.5
62	70	D	SS1h	Streaked	4	R	271.9	249.0	214.0	245.0
63	110	D	SS1h	Streaked	1	R	229.7	270.5	301.2	267.1
64	110	D	SS1h	Streaked	2	R	279.9	296.8	310.4	295.7
65	110	D	SS1h	Streaked	4	D	150.4	171.9		161.1
66	110	D	SS1h	Streaked	4	R	278.5	292.7	311.8	294.3
67	37	D	58-22	Uniform	1	D	134.5	103.8	124.1	120.8
68	37	D	58-22	Uniform	2	D	189.8	229.6	193.4	204.2
69	37	D	58-22	Uniform	4	D	138.1	202.9		170.5
70	70	D	58-22	Uniform	1	D	205.7	197.0		201.3
71	70	D	58-22	Uniform	2	D	142.8	168.7	203.3	171.6
72	70	D	58-22	Uniform	4	D	159.2	154.4		156.8
73	110	D	58-22	Uniform	1	D	151.6	202.9	183.0	179.2
74	110	D	58-22	Uniform	2	D	152.8	186.2	170.3	169.8
75	110	D	58-22	Uniform	4	D	214.5	148.4	205.7	189.5
76	37	W	58-22	Uniform	1	D	153.2	177.9	190.6	173.9
77	37	W	58-22	Uniform	2	D	170.3	132.9	163.9	155.7
78	37	W	58-22	Uniform	4	D	169.5	213.3		191.4
79	70	W	58-22	Uniform	1	D	205.3	108.6		157.0
80	70	W	58-22	Uniform	2	D	244.7			244.7
81	70	W	58-22	Uniform	4	D	214.1	161.1		187.6
82	110	W	58-22	Uniform	1	D	152.4	136.5	192.2	160.3
83	110	W	58-22	Uniform	2	D	161.1	156.0	163.1	160.1
84	110	W	58-22	Uniform	4	D	164.7	188.2	206.9	186.6
85	37	D	58-22	Uniform	1	R	22.2	180.3	158.6	120.4
86	37	D	58-22	Uniform	2	R	208.9	155.6	212.1	192.2
87	37	D	58-22	Uniform	4	R	223.7	291.2	248.6	254.5
88	70	D	58-22	Uniform	1	R	303.3	180.4		241.8
89	70	D	58-22	Uniform	2	R	302.4			302.4
90	70	D	58-22	Uniform	4	R	210.7	253.9		232.3
91	110	D	58-22	Uniform	1	R	251.5	223.5	285.1	253.4
92	110	D	58-22	Uniform	2	R	242.4	263.3	356.1	287.2
93	110	D	58-22	Uniform	4	R	263.2	279.3	226.6	256.4
94	37	W	58-22	Uniform	1	R	227.4	233.9	199.2	220.1
95	37	W	58-22	Uniform	2	R	273.6	280.3	218.7	257.5
96	37	W	58-22	Uniform	4	R	239.6	211.8	251.2	234.2
97	70	W	58-22	Uniform	4	R	242.7	223.2		233.0
98	110	W	58-22	Uniform	1	R	169.0	184.7	222.9	192.2
99	110	W	58-22	Uniform	2	R	232.1	267.8	295.0	265.0
100	110	W	58-22	Uniform	4	R	227.1	172.1	207.3	202.2
101	70	D	58-22	Streaked	1	D	191.0			191.0
102	70	D	58-22	Streaked	4	D	157.2			157.2
103	70	W	58-22	Streaked	1	D	202.5			202.5
104	70	W	58-22	Streaked	2	D	152.0	200.1	184.6	178.9
105	70	D	58-22	Streaked	1	R	186.0	293.4	282.5	253.9
106	70	D	58-22	Streaked	4	R	249.5			249.5
107	70	W	58-22	Streaked	1	R	329.9			329.9
108	70	W	58-22	Streaked	4	R	357.8			357.8

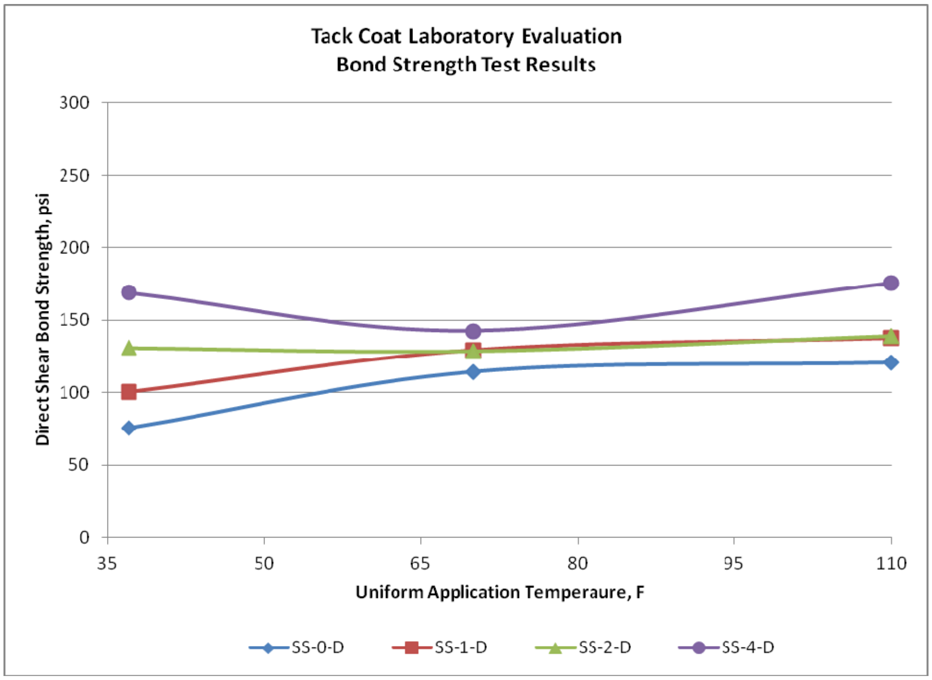

Figure 3.22. Example DST Test Results for the Dry SS-1h Material

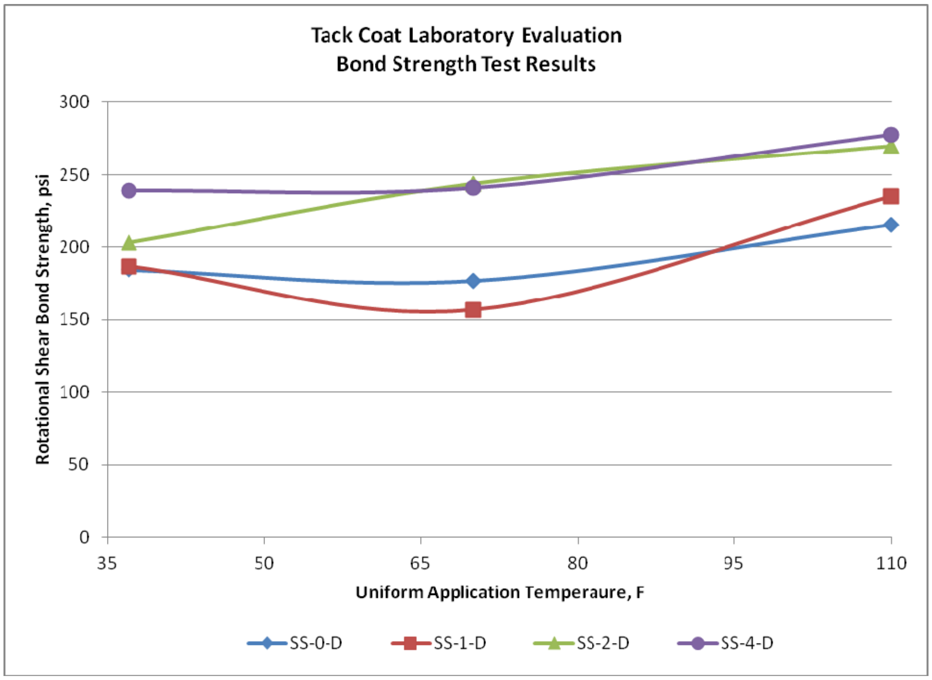

Figure 3.23. Example RST Test Results for the Dry SS-1h Material

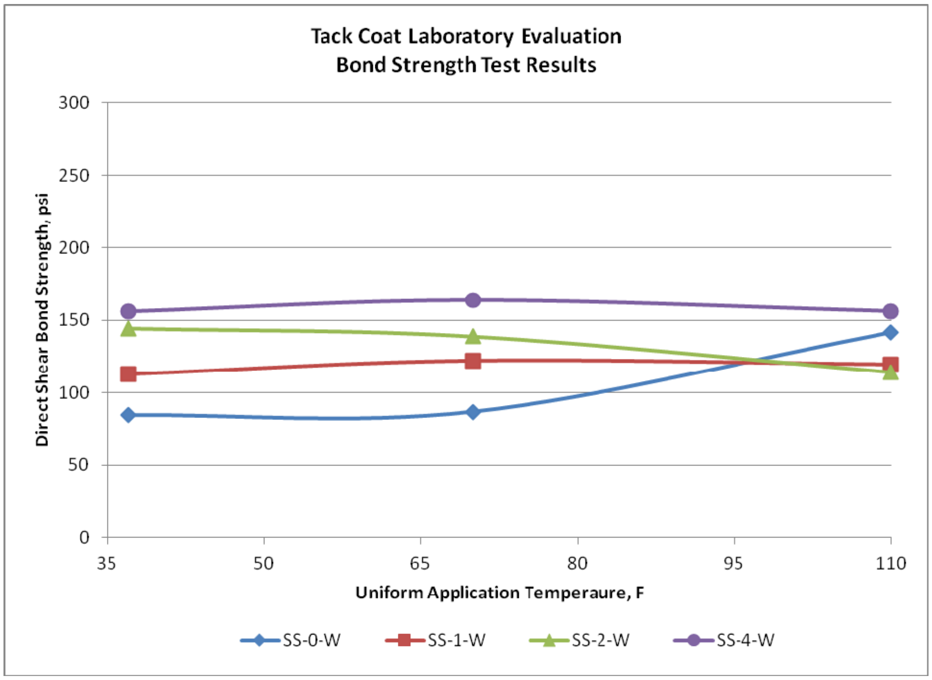

Figure 3.24. Example DST Test Results for the Wet SS-1h Material

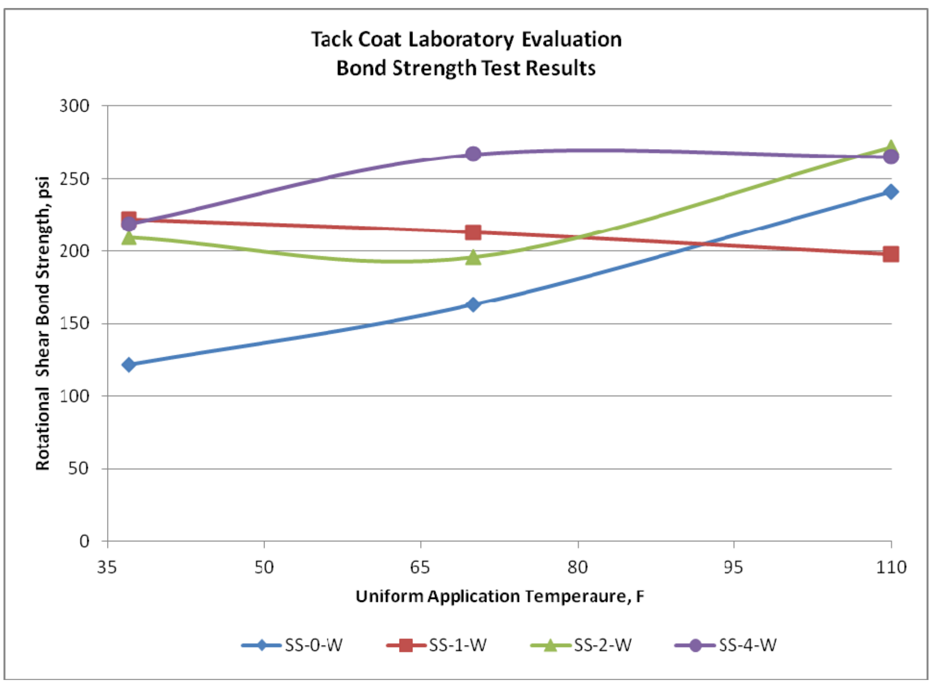

Figure 3.25. Example RST Test Results for the Wet SS-1h Material

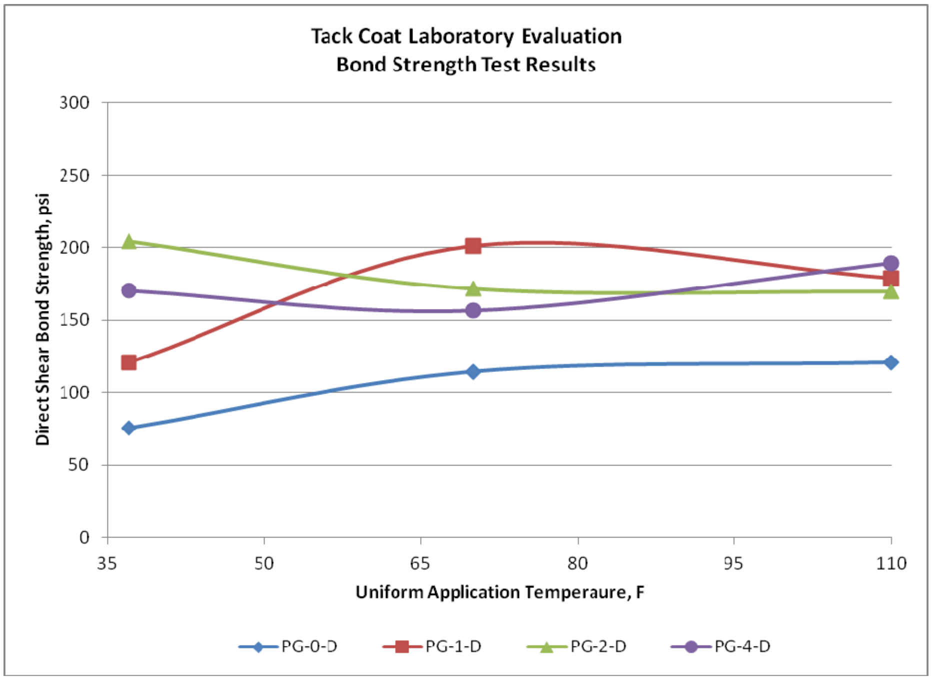

Figure 3.26. Example DST Test Results for the Dry PG 58-28 Material

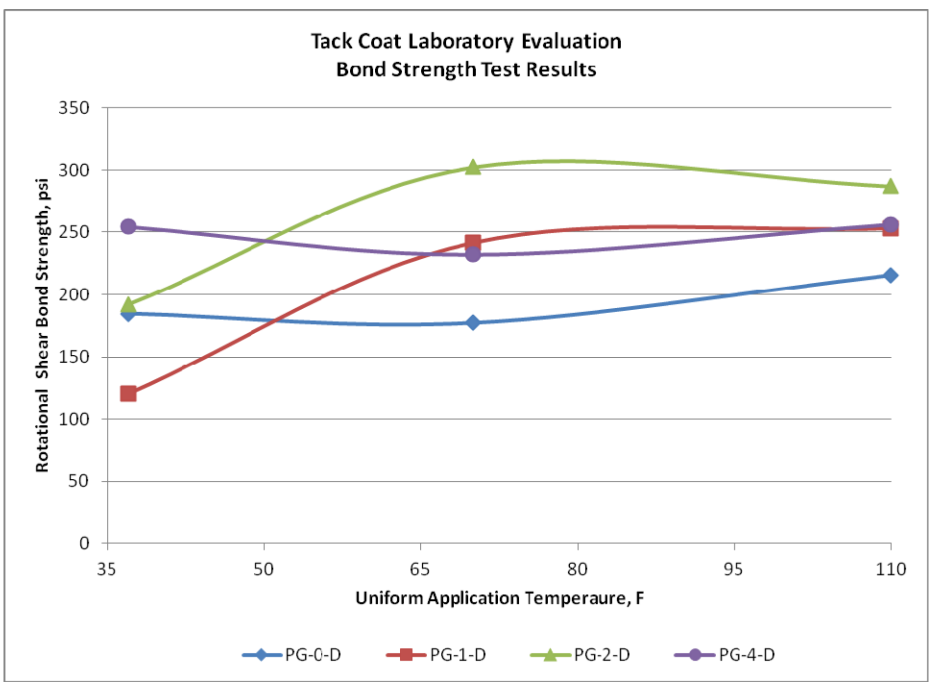

Figure 3.27. Example RST Test Results for the Dry PG 58-28 Material

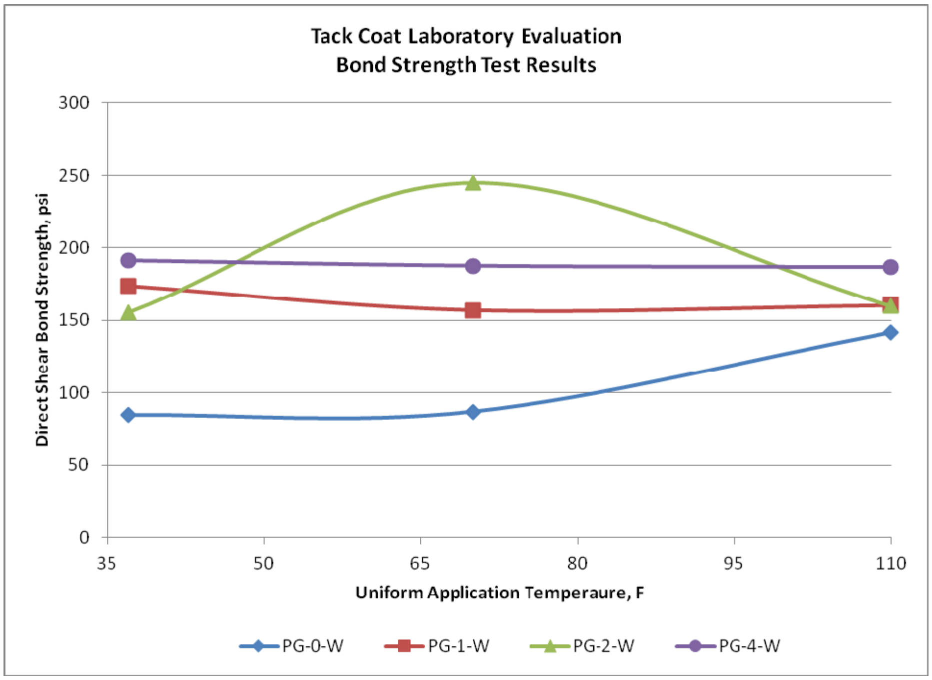

Figure 3.28. Example DST Test Results for the Wet PG 58-28 Material

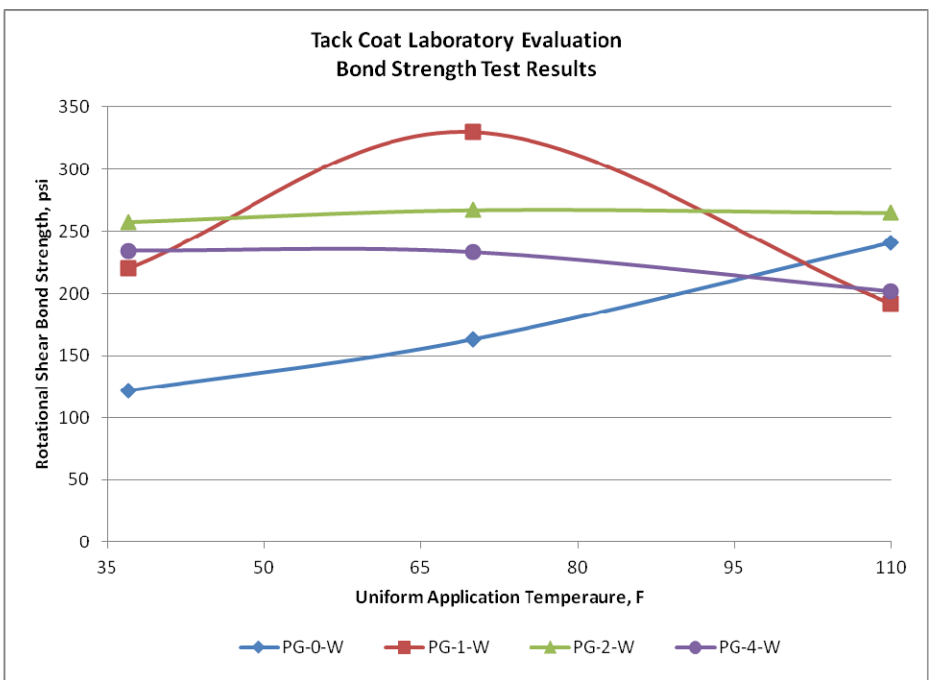

Figure 3.29. Example RST Test Results for the Wet PG 58-28 Material

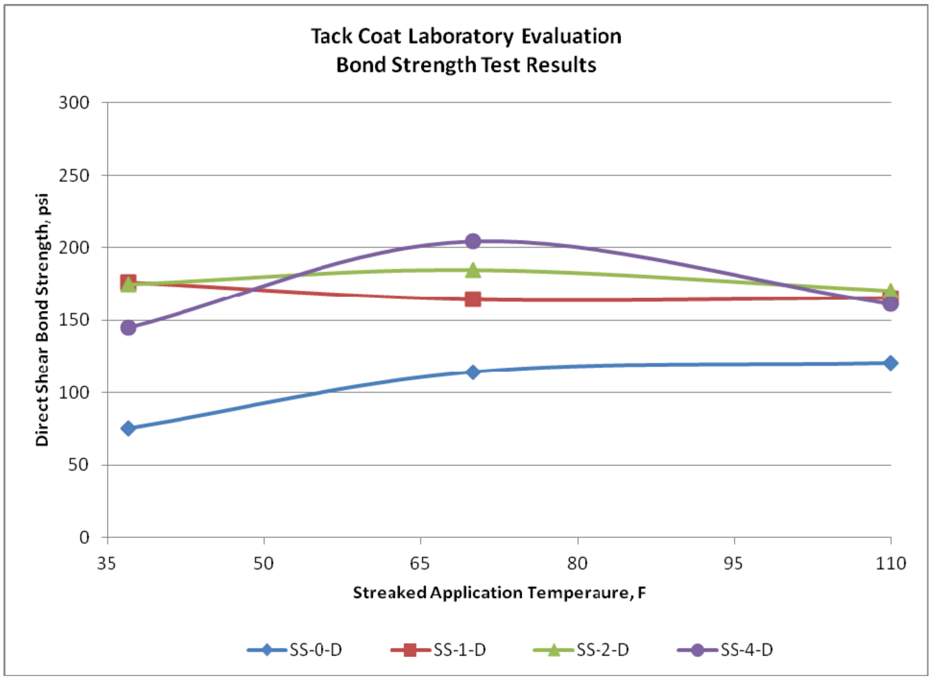

Figure 3.30. Example DST Test Results for the Dry Streaked SS-1h Material

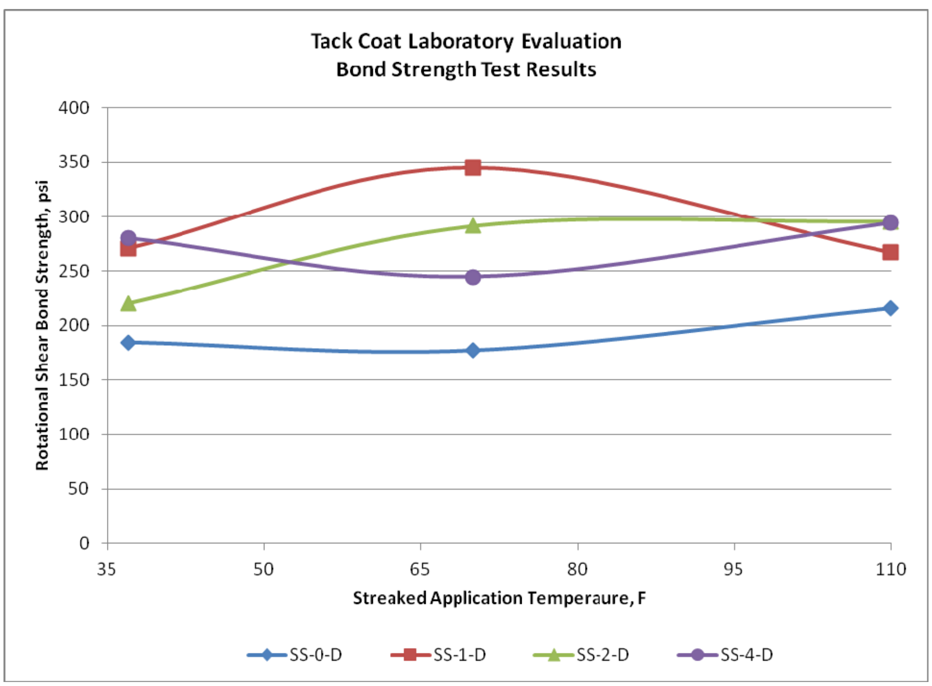

Figure 3.31. Example RST Test Results for the Dry Streaked SS-1h Material

Table 3.2. Statistical Analysis Results for SS-1h vs PG 58-28

Group Comparison	Group IDs	F-Test Result	Stat Diff Variance	t-Test Result	Stat Diff Mean
Uniform App Dry DST	2 - 67	0.444	N	0.163	N
	3 - 68	0.495	N	0.0153	Y
	4 - 69	0.55	N	0.977	N
	6 - 70	0.256	N	0.011	Y
	7 - 71	0.334	N	0.1167	N
	8 - 72	0.0892	N	0.528	N
	10 - 73	0.4646	N	0.1127	N
	11 - 74	0.331	N	0.141	N
	12 - 75	0.1482	N	0.5791	N
Uniform App West DST	14 - 76	0.2535	N	0.0495	Y
	15 - 77	0.403	N	0.5649	N
	16 - 78	0.556	N	0.3139	N
	18 -79	0.2169	N	0.5028	N
	20 - 81	0.2579	N	0.4363	N
	22 - 82	0.306	N	0.2633	N
	23 - 83	0.0172	Y	0.2584	N
	24 - 84	0.2381	N	0.2913	N
Uniform App Dry RST	26 - 85	0.1151	N	0.1487	N
	27 - 86	0.471	N	0.7103	N
	28 - 87	0.3894	N	0.6515	N
	30 - 88	0.0031	Y	0.3983	N
	32 - 90	0.3896	N	0.8485	N
	34 - 91	0.3145	N	0.5129	N
	35 - 92	0.4671	N	0.7331	N
	36 - 93	0.4167	N	0.361	N
Uniform App Wet RST	38 - 94	0.0894	N	0.9517	N
	39 - 95	0.4963	N	0.1589	N
	40 - 96	0.2339	N	0.5572	N
	44 - 97	0.3611	N	0.0587	N
	46 - 98	0.3057	N	0.8543	N
	47 - 99	0.2028	N	0.8772	N
	48 - 100	0.289	N	0.1225	N

Table 3.3. Statistical Analysis Results for SS-1h and PG 58-28, Wet vs Dry

Group Comparison	Group IDs	F-Test Result	Stat Diff Variance	t-Test Result	Stat Diff Mean
SS-1h DST Uniform App	1 - 13	0.1426	N	0.7611	N
	2 - 14	0.1547	N	0.5641	N
	3 - 15	0.4541	N	0.5196	N
	4 - 16	0.3054	N	0.7201	N
	5 - 17	0.4182	N	0.1265	N
	6 - 18	0.1558	N	0.7744	N
	7 - 19	0.2319	N	0.5218	N
	8 - 20	0.4454	N	0.3632	N
	9 -21	0.2399	N	0.0311	Y
	10 - 22	0.0773	N	0.3763	N
	11 - 23	0.3623	N	0.3571	N
	12 - 24	0.1359	N	0.4471	N
SS-1h RST Uniform App	25 - 37	0.3122	N	0.108	N
	26 - 38	0.0094	Y	0.4116	N
	27 - 39	0.9853	N	0.7963	N
	28 - 40	0.421	N	0.5622	N
	29 - 41	0.2321	N	0.6441	N
	30 - 42	0.0077	Y	0.2178	N
	31 - 43	0.3321	N	0.4783	N
	32 - 44	0.049	Y	0.4823	N
	33 - 45	0.4176	N	0.2945	N
	34 - 46	0.235	N	0.327	N
	35 - 47	0.4489	N	0.1534	N
	36 - 48	0.1188	N	0.0462	Y
PG 58-28 DST Uniform App	67 - 76	0.4026	N	0.0201	Y
	68 - 77	0.4523	N	0.0474	Y
	69 - 78	0.3784	N	0.6465	N
	70 - 79	0.05712	N	0.4569	N
	72 - 81	0.0575	N	0.3666	N
	73 - 82	0.4483	N	0.4467	N
	74 - 83	0.0458	Y	0.4295	N
	75 - 84	0.2576	N	0.9088	N
PG 58-28 RST Uniform App	85 - 94	0.5068	N	0.04939	Y
	86 - 95	0.461	N	0.072	N
	87 - 96	0.2468	N	0.4338	N
	90 - 97	0.2663	N	1	N
	91 - 98	0.4419	N	0.0643	N
	92 - 99	0.2158	N	0.6022	N
	93 - 100	0.481	N	0.0726	N

Table 3.4. Statistical Analysis Results for SS-1h and PG 58-28 Application Rates

Group Comparison	Group IDs	F-Test Result	Stat Diff Variance	t-Test Result	Stat Diff Mean
SS-1h @ 37F	1 - 3	0.2524	N	0.0478	Y
Dry DST	2 - 3	0.2827	N	0.1133	N
Uniform App	3 - 4	0.1691	N	0.2882	N
SS-1h @ 70F	5 - 7	0.3554	N	0.4064	N
Dry DST	6 - 7	0.3705	N	0.9696	N
Uniform App	7 - 8	0.0609	N	0.7175	N
SS-1h @ 110F	9 - 11	0.04879	Y	0.3262	N
Dry DST	10 - 11	0.494	N	0.954	N
Uniform App	11 - 12	0.284	N	0.0849	N
SS-1h @ 37F	13 - 15	0.2751	N	0.1083	N
Wet DST	14 - 15	0.3582	N	0.2553	N
Uniform App	15 - 16	0.3575	N	0.647	N
SS-1h @ 70F	17 - 19	0.5282	N	0.0155	Y
Wet DST	18 - 19	0.0865	N	0.5113	N
Uniform App	19 - 20	0.1964	N	0.1788	N
SS-1h @ 110F	21 - 23	0.1009	N	0.1904	N
Wet DST	22 - 23	0.3941	N	0.8851	N
Uniform App	23 - 24	0.4622	N	0.2758	N
SS-1h @ 37F	25 - 27	0.3715	N	0.6098	N
Dry RST	26 - 27	0.0277	Y	0.5304	N
Uniform App	27 - 28	0.3836	N	0.3052	N
SS-1h @ 70F	29 - 31	0.2217	N	0.2806	N
Dry RST	30 - 31	0.0042	Y	0.3483	N
Uniform App	31 - 32	0.283	N	0.9625	N
SS-1h @ 110F	33 - 35	0.1465	N	0.2009	N
Dry RST	34 - 35	0.1777	N	0.4873	N
Uniform App	35 - 36	0.1421	N	0.8397	N
SS-1h @ 37F	37 - 39	0.4308	N	0.0274	Y
Wet RST	38 - 39	0.2522	N	0.76599	N
Uniform App	39 - 40	0.4649	N	0.7742	N
SS-1h @ 70F	41 - 43	0.1368	N	0.4204	N
Wet RST	42 - 43	0.4681	Y	0.7247	N
Uniform App	43 - 44	0.0378	N	0.1104	N
SS-1h @ 110F	45 - 47	0.1631	N	0.4792	N
Wet RST	46 - 47	0.3123	N	0.1665	N
Uniform App	47 - 48	0.4034	N	0.9081	N
PG 58-28 Dry DST	67 - 68	0.3347	N	0.005859	Y
37F Uniform App	68 - 69	0.1728	N	0.3312	N
PG 58-28 Dry DST	70 - 71	0.1419	N	0.284	N
70F Uniform App	71 - 72	0.0788	N	0.5608	N
PG 58-28 Dry DST	73 - 74	0.2944	N	0.6249	N
110F Uniform App	74 - 75	0.0526	N	0.4359	N
PG 58-28 Wet DST	76 - 77	0.4748	N	0.317	N
37F Uniform App	77 - 78	0.2616	N	0.205	N
PG 58-28 Wet DST	82 - 83	0.01602	Y	0.9873	N
110F Uniform App	83 - 84	0.0526	N	0.0989	N
PG 58-28 Dry RST	85 - 86	0.1207	N	0.2419	N
37F Uniform App	86 - 87	0.4545	N	0.0836	N
PG 58-28 Dry RST	91 - 92	0.2088	N	0.4425	N
110F Uniform App	92 - 93	0.1645	N	0.4674	N
PG 58-28 Wet RST	94 - 95	0.2245	N	0.1683	N
37F Uniform App	95 - 96	0.2518	N	0.3662	N
PG 58-28 Wet RST	98 - 99	0.4316	N	0.0414	Y
110F Uniform App	99 - 100	0.4357	N	0.0625	N

Table 3.5. Statistical Analysis Results for SS-1h and PG 58-28, Uniform vs Streaked

Group Comparison	Group IDs	F-Test Result	Stat Diff Variance	t-Test Result	Stat Diff Mean
SS-1h Dry DST Uniform vs Streaked	2 - 49	0.194	N	0.014	Y
	3 - 50	0.289	N	0.044	Y
	4 - 51	0.014	Y	0.486	N
	6 - 52	0.474	N	0.057	N
	7 - 53	0.439	N	0.028	Y
	8 - 54	0.079	N	0.017	Y
	10 - 55	0.420	N	0.255	N
	11 - 56	0.345	N	0.193	N
	12 - 65	0.417	N	0.359	N
SS-1h Dry RST Uniform vs Streaked	26 - 57	0.054	N	0.098	N
	27 - 58	0.325	N	0.488	N
	28 - 59	0.367	N	0.368	N
	30 - 60	0.007	Y	0.029	Y
	31 - 61	0.314	N	0.468	N
	32 - 62	0.250	N	0.904	N
	34 - 63	0.272	N	0.349	N
	35 - 64	0.071	N	0.485	N
	36 - 66	0.350	N	0.355	N
PG 58-28 Dry DST Uniform vs Streaked	88 - 105	0.275	N	0.865	N

Table 3.6. Statistical Analysis Results for SS-1h and PG 58-28 Application Temperatures

Group Comparison	Group IDs	F-Test Result	Stat Diff Variance	t-Test Result	Stat Diff Mean
Dry SS-1h DST	1 - 5	0.3396	N	0.0539	N
	2 - 6	0.4163	N	0.0794	N
	3 - 7	0.4837	N	0.9111	N
	4 - 8	0.2262	N	0.4582	N
	1 - 9	0.271	N	0.00455	Y
	2 -10	0.2505	N	0.0798	N
	3 - 11	0.466	N	0.6889	N
	4 - 12	0.0844	N	0.828	N
Wet SS-1h DST	13 - 17	0.1778	N	0.9368	N
	14 - 18	0.419	N	0.7753	N
	15 - 19	0.1902	N	0.7396	N
	16 - 20	0.3479	N	0.7547	N
	13 - 21	0.0633	N	0.06845	N
	14 - 22	0.3535	N	0.853	N
	15 - 23	0.3712	N	0.2851	N
	16 - 24	0.4282	N	0.9931	N
Dry PG 58-28 DST	67 - 70	0.2704	N	0.006864	Y
	68 - 71	0.3448	N	0.2062	N
	69 - 72	0.0467	Y	0.7457	N
	67 - 73	0.2662	N	0.0287	Y
	68 - 74	0.3658	N	0.0968	N
	69 - 75	0.3294	N	0.634	N
Wet PG 58-28 DST	76 - 79	0.0694	N	0.6341	N
	78 - 81	0.4397	N	0.9221	N
	76 - 82	0.3053	N	0.5333	N
	77 - 83	0.0324	Y	0.7257	N
	78 - 84	0.2806	N	0.846	N

As indicated in **Tables 3.2 through 3.6**, the vast majority of group comparisons resulted in no statistical difference in the group means at the 90% significance level. For those comparisons with a statistical difference between group means, the following conclusions can be drawn:

- The PG 58-28 tack coats have a statistically significant improvement in bond strength over the SS-1h materials when tested in direct shear at the following conditions:
    - 37F, dry, uniform coverage, and 0.025 gal/yd^2
    - 70F, dry, uniform coverage, and 0.010 gal/yd^2
    - 37F, wet, uniform coverage, and 0.010 gal/yd^2

- The tests on the wetted surfaces prior to overlay have a statistically significant improvement in bond strength over the dry surfaces for the following:
    - direct shear at 110F, at uniform coverage, with no tack coat applied.
    - direct shear at 37F, at uniform coverage, applied at 0.01 gal/yd^2

- The tests on the dry surfaces prior to overlay have a statistically significant improvement in bond strength over the wet surfaces for the following:
    - SS-1h tested in direct shear at 110F, at uniform coverage, applied at 0.025 gal/yd^2
    - PG 58- tested in direct shear at 37F, at uniform coverage, applied at 0.025 gal/yd^2

- The application rate of 0.025 gal/yd^2 displays statistical significance when tested in direct shear at the following conditions:
    - SS-1h at 37F, dry, and uniform coverage
    - SS-1h at 70F, wet, uniform coverage
    - PG 58-28 at 37F, dry, and uniform coverage

- The application rate of 0.025 gal/yd^2 displays statistical significance when tested in rotational shear at the following conditions:
    - SS-1h at 37, wet, uniform coverage

- Increasing the application temperature to 110F demonstrated a statistically significant improvement in bond strength for the following conditions:
    - SS-1h, dry, no tack coat applied
    - PG 58-28, dry, uniform coverage, applied at 0.010 gal/yd^2

- For the application temperature of 70F, a statistically significant improvement in bond strength was noted for the following condition:
    - PG 58-28, dry, uniform coverage, applied at 0.010 gal/yd^2

Based on the above findings, the following general observations are noted:

- PG 58-28 provides a better bond strength than the SS-1h materials
- The minimum recommended tack coat application rate is 0.025 gal/yd^2, for both SS-1h and PG 58-28 materials, which supports the current WisDOT specification value.
- Higher temperatures increases tack coat effectiveness, with 37F being the minimum recommended temperature. This also supports the WisDOT specification and Asphalt Institute results that the best results are obtained above 70F.
- Dry or wet conditions prior to overlay did not significantly affect bond strength. This indicates that as long as the tack material is set, slight rains during paving may not pose a problem with tack coat effectiveness.
- Uniform coverage is expected and preferred; however, streak coverage did not show any statistical difference in bond strength.
- Results from direct shear testing indicated more instances of statistical differences in group means as compared to the rotational shear results. This result indicates the direct shear test may be more appropriate for differentiating strength differences within the lab. However, the rotational shear test is more suited to field operations where in situ bond strength is more of a concern.

A comparison of the test group average rotational shear strength versus direct shear strength is provided in **Figure 3.32**. Although the R^2 value for the simple linear model is quite low, the data suggests a minimum rotational shear bond strength of 193 psi would be appropriate to ensure the minimum direct shear bond strength requirement of 100 psi.

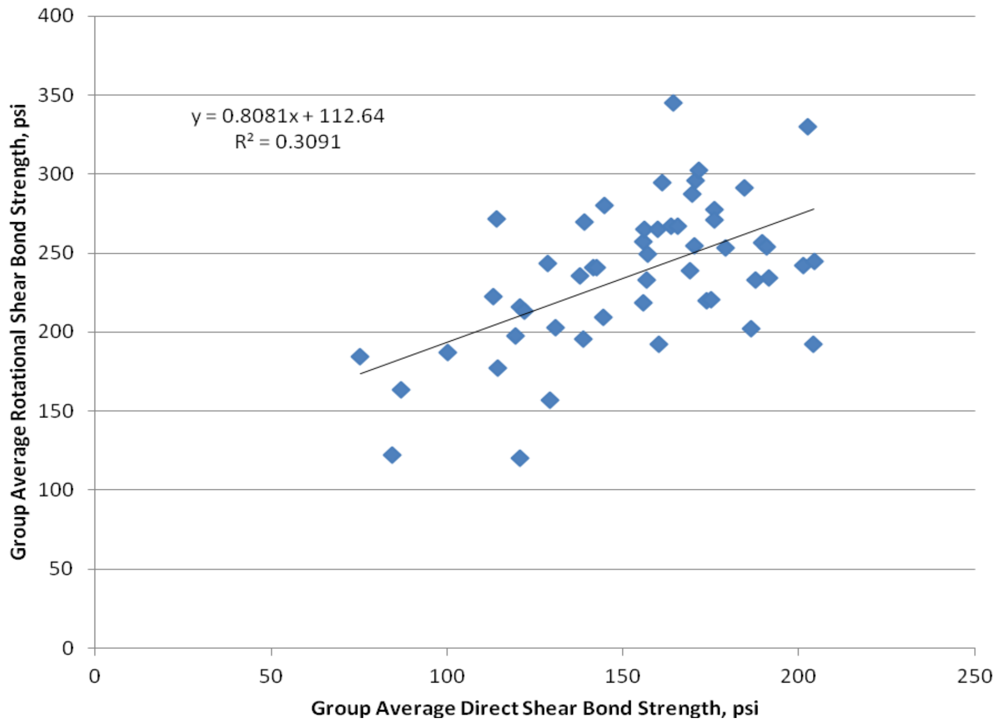

Figure 3.32. Comparison of Group Average Bond Strength Values

Chapter 4 Field Testing

4.1 Introduction

Field testing was conducted within an aged Marquette University parking lot and along the STH 11 Burlington Bypass construction project. The Marquette tests were conducted to assess the bond strength of CSS-1h and NTSS-1hm Trackless tack materials under a variety of conditions, including application rate, moisture conditions, and pavement surface cleanliness. The STH 11 field tests were focused to assess the bond strength of standard SS-1h and latex modified SS-1hp tack materials at various application rates.

4.2 Marquette University Field Test

A controlled field test was set up within Lot Z at Marquette University, located at the corner of North 18th St. and West Clybourn St. This lot was scheduled for removal to make way for a new day-care center and offered the opportunity to test the bond strength of tack materials placed between an existing, aged surface and a new, 19 mm NMAS lower layer. A sand patch test, conducted on a representative location of the existing surface, provided an average reading of 13.5 inches.

4.2.1 Test Cell Layout

A 9 ft x 20 ft test area was laid out to include five major test cells, each 9 ft x 4 ft in dimension. The major cells were further subdivided into four separate sub-cells, each 9 ft x 1 ft in dimension. **Figure 4.1** provides a sketch of the test area layout used for this study. As indicated in **Figure 4.1**, each major test cell included the same four target residual application rates utilized during the Phase 1 laboratory study. Test Cells A & B were established to examine

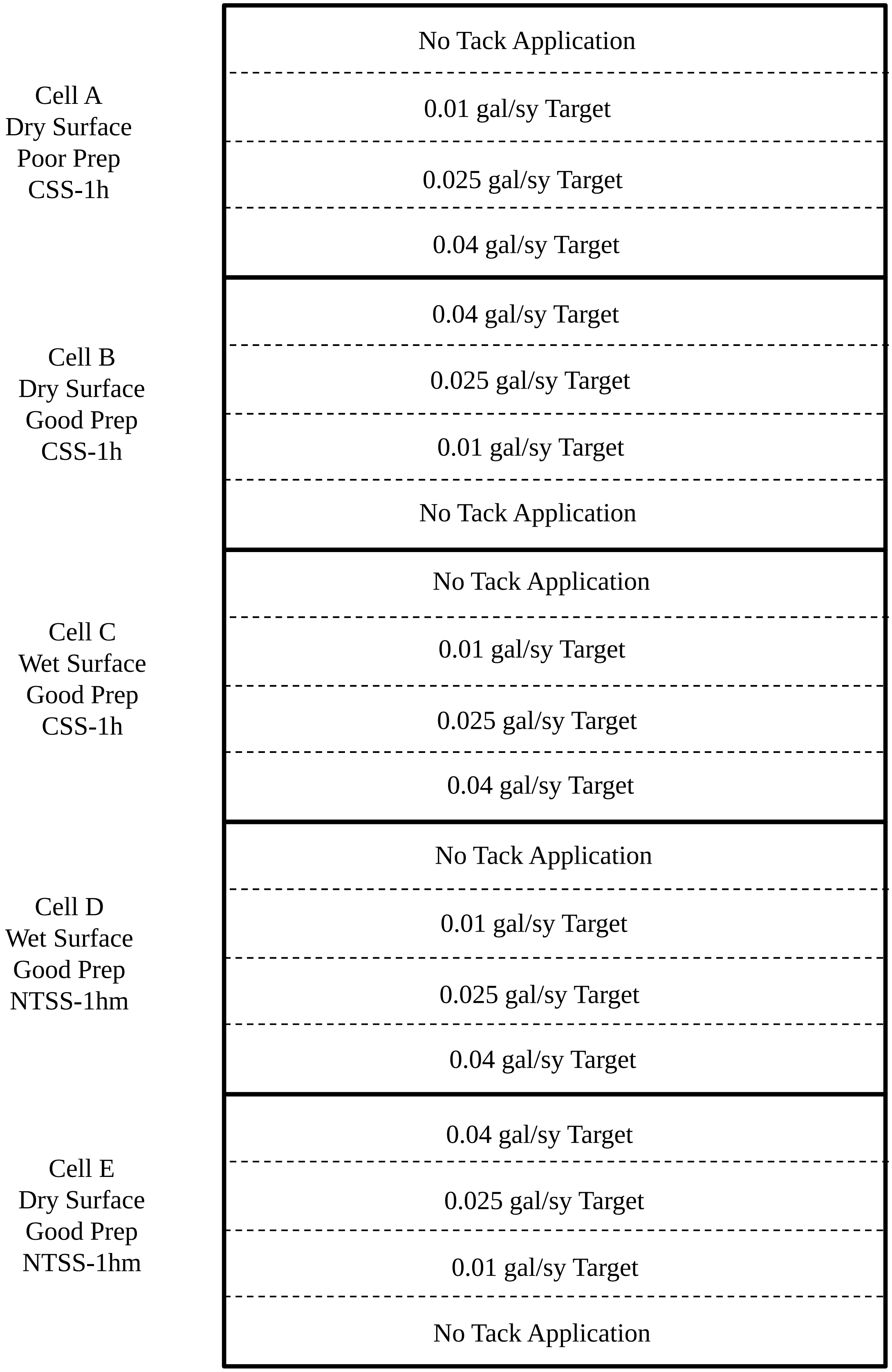

Figure 4.1. Schematic of Marquette Parking Lot Test Section

the influence of surface prep prior to the CSS-1h tack coat application. For Test Cell A, only a minimal sweep was conducted to remove loose gravels and coarse sand particles. The surface of Test Cell B (also C, D, E) was thoroughly swept clean of all loose gravel, sand and dust particles. Test Cell C was established to further examine the effect of surface moisture during paving operations. For this Cell, water was sprayed onto the surface of the base pavement immediately before paving operations began.

Test Cells D & E were established to examine the benefits of using a trackless tack material, in this instance an NTSS-1hm material manufactured by Blacklidge Emulsions, Inc. in Gulfport, MS. Both Test Cells were thoroughly swept clean of all loose gravel, sand and dust particles prior to tack coat application. Test Cell D was sprayed with water immediately before surface paving while Test Cell E was left dry during paving operations.

4.2.2 Pre-Paving Operations

On the day before paving, the test cells were laid out and an application guide was spray painted onto the surface of the lot. **Figure 4.2** provides a photo of the marked test cells. Cut portions of fabric sample bags, approximately 10 inches x 12 inches each, were taped to the surface of the pavement, leaving approximately a 10 inch x 10 inch exposed area. **Figure 4.3** provides a photo of these patch samples taped to the surface. The tack coat materials were then applied across the full width of each sub-cell during the afternoon prior to paving operations. Initially, the CSS-1h material was applied using a spray paint gun following a method successfully trialed within the asphalt lab. However, during applications over the larger areas of

Figure 4.2. Layout of Test Cells and Application Guide

Figure 4.3. Patch Samples in Place in Test Cells A & B

the test cells, the spray gun repeatedly clogged, making targets difficult to attain within the CSS-1h test cells A & B. The quick drying nature of the trackless tack material made it unsuitable for the spray gun applicator. The application method was changed to utilize a 9 inch long foam brush roller, which allowed for more targeted coverage within the CSS-1h test cell C and the CSS-1hm test cells D & E. Approximately 2 hours after the start of tack coat applications, the patch samples were removed from the pavement, bagged and preserved for subsequent testing. **Figures 4.4** through **4.7** provide photos of the tack coat applications. **Table 4.1** provides the results of the patch sample testing.

4.2.3 Placement of the 19 mm Lower Layer

The 19 mm NMAS lower layer was placed on the morning of June 3, 2011 by Frank Armstrong Enterprises, Inc. Immediately prior to paving, Test Cells C & D were thoroughly wetted with a water spray from a portable tank sprayer. The HMA materials were placed to an uncompacted thickness of approximately 2.25 inches and the compacted to a nominal thickness of 2 inches using a vibrating plate compacter and a small steel wheeled roller. **Figures 4.8** through **4.11** provide photos of the paving operations. The entire paving operations, from first dump to final rolling, were completed in approximately 20 minutes.

Figure 4.4. Spray Gun Application of CSS-1h

Figure 4.5. Spray Gun Application Over Cell A

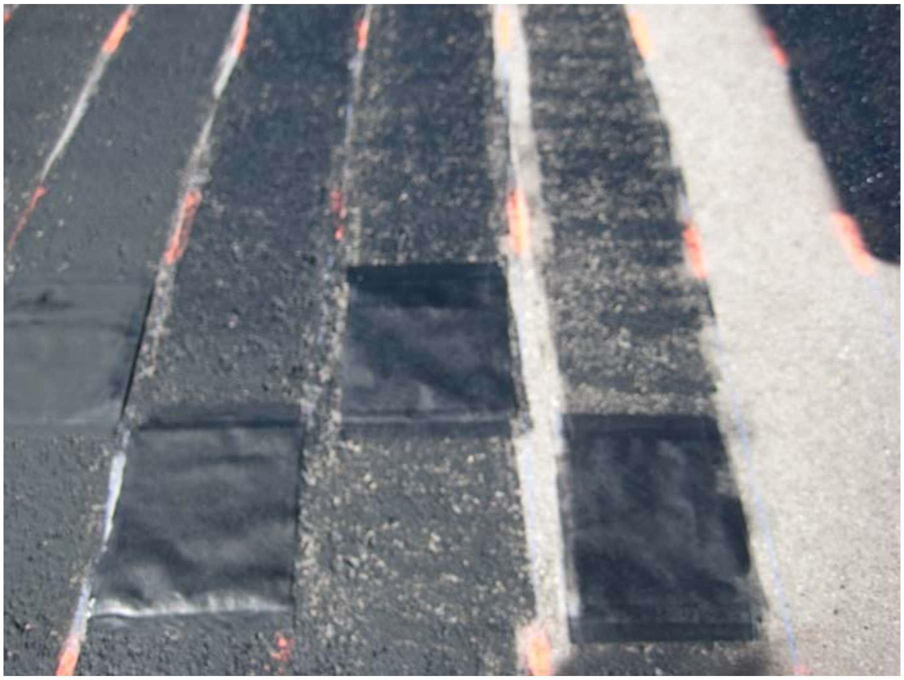

Figure 4.6. Spray Gun Application Over Cell C (Right Side) and Roller Application of NTSS-1hm (Left Side)

Figure 4.7. Completed Tack Coat Application With Patches Removed

Table 4.1. Patch Samples From Marquette University Test Section

Test Sub-Cell	Patch Area, in^2	Patch Mass, g	Patch + Tack, g	Tack Mass, g	Application Rate, g/in^2	Application Rate, gal/SY
A1	103.77	7.74	9.17	1.43	0.014	0.005
A2	102.20	7.62	10.73	3.11	0.030	0.010
A4	90.65	6.76	10.79	4.03	0.044	0.015
B1	89.62	6.69	8.67	1.98	0.022	0.007
B2	89.93	6.71	9.38	2.67	0.030	0.010
B4	89.60	6.68	10.71	4.03	0.045	0.015
C1	90.00	6.71	8.88	2.17	0.024	0.008
C2	88.44	6.60	9.24	2.64	0.030	0.010
C4	88.99	6.64	12.25	5.61	0.063	0.021
D1	70.03	5.22	8.12	2.90	0.041	0.014
D2	90.94	6.78	13.00	6.22	0.068	0.023
D4	75.38	5.62	14.55	8.93	0.118	0.040
E1	75.74	5.65	10.04	4.39	0.058	0.019
E2	69.06	5.15	11.44	6.29	0.091	0.030
E4	68.04	5.08	14.97	9.89	0.145	0.049

Figure 4.8. Start of Paving Operations

Figure 4.9. Spread of HMA Materials

Figure 4.10. Edge Compaction with Plate Compactor

Figure 4.11. Final Compaction With Steel Wheel Roller

4.2.4 Pavement Coring

The week following paving operations, coring operations began to provide samples for direct shear testing in the lab and for field testing with the RST. Prior to coring, a grid pattern was painted and chalked onto the surface of the 19 mm NMAS lower layer to provide a reference for where cores should be extracted. The grid of coring locations is illustrated in **Figures 4.12 and 4.13**. 6 inch diameter cores for direct shear testing were generally taken from alternate core locations, as shown in **Figure 4.14**. For the remaining locations, rotational shear testing was conducted in the field. For these locations, the pavement was first cored with the 6 inch core barrel to a depth approximately 1 inch below the interface between the existing surface and the 19 mm NMAS lower layer. A four inch diameter core barrel was then used to cut to a depth of approximately ½ inch below the interface. The annular ring was then removed in preparation for the RST. **Figures 4.15 and 4.16** provide photos taken during the field coring operations for the RST.

4.2.5 Direct Shear Test Results

Phase 2 direct shear tests were conducted following the same protocol used during Phase 1 testing. The results of all Phase 2 direct shear tests are provided in **Table 4.2**. For those locations with entries of n.a under the base HMA thickness heading, the 19 mm NMAS layer separated from the base HMA during coring. For these locations, bond strength between the 19 mm NMAS and base layers is assumed negligible. For those locations with entries of n.a. under the Peak Shear to Failure heading, the 19 mm NMAS layer separated from the base HMA during coring, transport or during placement within the direct shear test fixture. For these locations, bond strength between the 19 mm NMAS and base layers is again assumed negligible.

Figure 4.12. Grid for Coring Operations

Figure 4.13. Coring for Location E0-3

Cell A Dry Surface Poor Prep CSS-1h	A0-6	A0-5	A0-4	A0-3		A0-2	A0-1
	A1-6	A1-5	A1-4	A1-3		A1-2	A1-1
	A2-6	A2-5	A2-4	A2-3		A2-2	A2-1
	A4-6	A4-5	A4-4	A4-3		A4-2	A4-1
Cell B Dry Surface Good Prep CSS-1h	B4-6	B4-5	B4-4	B4-3		B4-2	B4-1
	B2-6	B2-5	B2-4	B2-3		B2-2	B2-1
	B1-6	B1-5	B1-4	B1-3		B1-2	B1-1
	B0-6	B0-5	B0-4	B0-3		B0-2	B0-1
Cell C Wet Surface Good Prep CSS-1h	C0-6	C0-5	C0-4	C0-3		C0-2	C0-1
	C1-6	C1-5	C1-4	C1-3		C1-2	C1-1
	C2-6	C2-5	C2-4	C2-3		C2-2	C2-1
	C4-6	C4-5	C4-4	C4-3		C4-2	C4-1
Cell D Wet Surface Good Prep NTSS-1hm	D0-6	D0-5	D0-4	D0-3		D0-2	D0-1
	D1-6	D1-5	D1-4	D1-3		D1-2	D1-1
	D2-6	D2-5	D2-4	D2-3		D2-2	D2-1
	D4-6	D4-5	D4-4	D4-3		D4-2	D4-1
Cell E Dry Surface Good Prep NTSS-1hm	E4-6	E4-5	E4-4	E4-3		E4-2	E4-1
	E2-6	E2-5	E2-4	E2-3		E2-2	E2-1
	E1-6	E1-5	E1-4	E1-3		E1-2	E1-1
	E0-6	E0-5	E0-4	E0-3		E0-2	E0-1

Figure 4.14. Grid of Coring Locations in Marquette Parking Lot Test Section
Note: Shaded Cells Represent Core Locations for Direct Shear Testing

Figure 4.15. Coring Operations for Field RST

Figure 4.16. Close-Up of Prepared Core for Field RST

Table 4.2. Direct Shear Test Results From Marquette Test Section

Base HMA	Tack Material	Test Sub-Cell	Application Rate, gal/SY	Core Location	19mm NMAS Thickness, in	Base HMA Thickness, in	Direct Shear Bond Strength, psi	Average Bond Strength, psi
Poor Prep Dry Surface	CSS-1h	A0	0	2	1.875	n.a.	n.a.	n.a.
				3	2	n.a.	n.a.	
				5	1.875	2.5	n.a.	
		A1	0.005	1	2.125	3	27.1	16.9
				4	2	2.75	23.6	
				6	2	2.5	n.a.	
		A2	0.010	2	2.125	3	34.5	11.5
				3	2.125	2.25	n.a.	
				5	2.25	2.5	n.a.	
		A4	0.015	1	2.25	2.5	29.3	31.9
				4	2.25	2.25	15.0	
				6	2.25	2.5	51.6	
Good Prep Dry Surface	CSS-1h	B0	0	1	2.125	n.a.	n.a.	n.a.
				4	2	n.a.	n.a.	
				6	1.875	n.a.	n.a.	
		B1	0.007	2	2	2.5	48.7	36.6
				3	2	2.75	24.8	
				5	2	3	36.1	
		B2	0.010	1	2	2.5	42.0	33.4
				4	2	2.5	32.3	
				6	2	2.25	25.8	
		B4	0.015	2	2.125	2.5	44.7	43.9
				3	2.5	2.75	45.7	
				5	2.25	2.5	41.4	
Good Prep Wet Surface	CSS-1h	C0	0	2	2.25	2.5	n.a.	n.a.
				3	2.25	n.a.	n.a.	
				5	2.25	n.a.	n.a.	
		C1	0.008	1	2.125	2.5	47.0	46.2
				4	2.375	3	38.0	
				6	2	2.75	53.5	
		C2	0.010	2	2.25	2.5	37.1	44.1
				3	2.25	3	58.4	
				5	2.25	2.75	36.8	
		C4	0.021	1	2.125	2.5	64.1	67.0
				4	225	2.75	69.4	
				6	2	2.75	67.3	
Good Prep Wet Surface	NTSS-1hm	D0	0	5	2.125	n.a.	n.a.	n.a.
				2	2.375	2.5	n.a.	
				3	2.25	n.a.	n.a.	
		D1	0.014	1	2.125	2.75	52.7	54.6
				4	2.125	2.75	55.4	
				6	1.875	2.75	55.9	
		D2	0.023	2	2.5	2.25	49.5	57.4
				3	2.25	3	81.5	
				5	2	2.75	41.2	
		D4	0.040	1	2.5	2.25	54.0	58.2
				4	2.25	2.75	66.8	
				6	2.25	2.5	53.8	
Good Prep Dry Surface	NTSS-1hm	E0	0	1	2.25	2.5	n.a.	n.a.
				3	2.5	n.a.	n.a.	
				5	2.25	n.a.	n.a.	
		E1	0.019	2	2.25	2.25	59.8	55.1
				4	2.5	2.5	51.9	
				6	2.125	3	53.6	
		E2	0.030	1	2.25	2.125	36.9	40.1
				3	2.375	2.75	44.2	
				5	2.25	2.75	39.0	
		E4	0.049	2	2.25	2.25	62.7	54.7
				3	2.375	2.5	56.0	
				5	2.375	2.75	45.4	

4.2.6 Rotational Shear Test Results

Phase 2 rotational shear tests were conducted following the same protocol used during Phase 1 testing, with the exception that these tests were conducted in the field. The results of all Phase 2 rotational shear tests are provided in **Table 4.3**. For those locations with entries of n.a under Peak Shear to Failure heading, the 19 mm NMAS layer separated from the base HMA during coring. For these locations, bond strength between the 19 mm NMAS and base layers is assumed negligible.

4.2.7 Discussion of Shear Test Results

The results of the laboratory direct shear tests and in situ rotational shear tests provided in Tables 4.2 and 4.3 indicate all values are well below the recommended threshold values of 100 psi for direct shear and 16 psi for rotational shear strengths developed from Phase 1 lab testing. DST and RST data trends are provided in **Figures 4.17 and 4.18**, respectively. In each figure, the coding for the trend lines uses the X-Y-Z notation, with X representing the surface preparation (P=Poor, G=Good), Y representing the surface moisture during paving (W=Wet, D=Dry), and Z representing the tack material (CSS-1h or CSS-1hm). Considering the direct shear trends for the 1h tack material applied to the clean, dry surface (G-D-1h), the data suggests a significant drop in strength for the poorly prepared surface (P-D-1h) and an increase in strength for the wet surface (G-W-1h). However, due to the large variances in the data sets, paired T-tests reveal no statistical difference at the 90% confidence level for the group means when comparing groups constructed with similar residual application rates. Similarly, although the trends for each preparation group suggest an increase in strength for increased residual application rates, paired T-tests do no indicate any statistical difference in the group means for

Table 4.3. Rotational Shear Test Results From Marquette Test Section

Base HMA	Tack Material	Test Sub-Cell	Application Rate, gal/SY	Core Location	Peak Load to Failure, ft-lb	Average Bond Strength, psi
Poor Prep Dry Surface	CSS-1h	A0	0	1	n.a.	n.a.
				4	n.a.	
				6	n.a.	
		A1	0.005	2	14.5	9.2
				3	7.1	
				5	7.4	
		A2	0.010	1	19.4	18.9
				4	6.6	
				6	33.4	
		A4	0.015	2	21.1	15.4
				3	12.0	
				5	15.3	
Good Prep Dry Surface	CSS-1h	B0	0	2	n.a.	n.a.
				3	n.a.	
				5	n.a.	
		B1	0.007	1	16.5	16.6
				4	9.3	
				6	26.4	
		B2	0.010	2	41.6	25.7
				3	20.8	
				5	18.4	
		B4	0.015	1	22.4	33.5
				4	46.1	
				6	36.7	
Good Prep Wet Surface	CSS-1h	C0	0	1	n.a.	n.a.
				4	n.a.	
				6	n.a.	
		C1	0.008	2	8.6	16.3
				3	17.0	
				5	25.7	
		C2	0.010	1	15.3	27.4
				4	30.9	
				6	39.9	
		C4	0.021	2	21.0	28.8
				3	37.2	
				5	32.3	
Good Prep Wet Surface	NTSS-1hm	D0	0	1	n.a.	n.a.
				4	n.a.	
				6	n.a.	
		D1	0.014	2	27.7	35.0
				3	51.3	
				5	31.0	
		D2	0.023	1	25.3	35.6
				4	34.8	
				6	51.8	
		D4	0.040	2	33.1	35.2
				3	43.8	
				5	33.8	
Good Prep Dry Surface	NTSS-1hm	E0	0	2	n.a.	n.a.
				4	n.a.	
				6	n.a.	
		E1	0.019	1	30.4	26.3
				3	24.6	
				5	8.1	
		E2	0.030	2	40.1	47.7
				4	59.7	
				6	24.5	
		E4	0.049	1	57.2	61.5
				4	71.6	
				6	33.2	

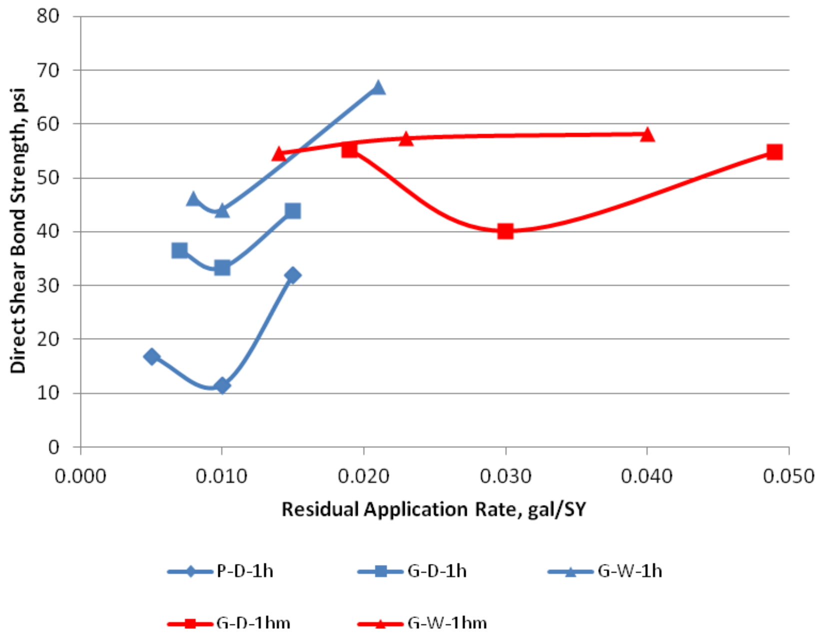

Figure 4.17. Direct Shear Test Results for Marquette Test Section

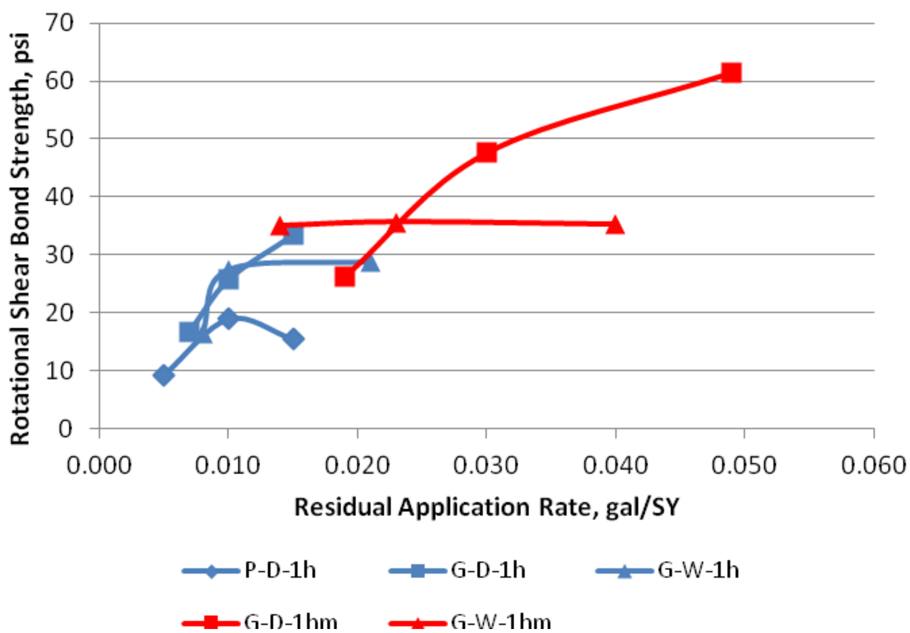

Figure 4.18. Rotational Shear Test Results for Marquette Test Section

each residual application rate. For the trackless tack material (SS-1hm) at the lowest application rate, there is a statistical increase in strength over the conventional tack material.

The rotational shear test results presented in **Figure 4.18** for the conventional CSS-1h tack material are similar to those presented for the direct shear tests in **Figure 4.17,** namely the apparent decrease in bond strength for the poorly prepared surface (P-D-1h) and increase in strength for the wet surface. However, again due to the increased variances in the data sets, paired T- tests reveal no statistical difference at the 90% confidence level for the group means when comparing groups constructed with similar residual application rates. Similarly, although the trends for each preparation group suggest an increase in strength for increased residual application rates, paired T-tests do no indicate any statistical difference in the group means for each residual application rate.

4.3 STH 11 Burlington Bypass Field Test

The STH 11 Burlington Bypass was constructed during the late summer of 2010 by BR Amon and Sons using a 12.5 mm NMAS surface layer over a 19 mm NMAS lower layer. During construction, the contractor proposed a trial use of latex modified SS-1hp tack material applied at a proposed residual application rate of 0.04 gal/SY. This SS-1hp tack material reportedly improves compaction of the overlaying HMA layer and reduces rutting (Al-Qadi, et al., 2009). In addition to the latex modified section, it was also proposed to construct comparative test sections using the standard SS-1h tack material at residual application rates of 0.04 gal/SY (Heavy) and 0.020 gal/SY (Control). WisDOT personnel requested information from this project to be included into this research project. In response to this request, Marquette research staff worked with Deborah Schwerman from WisDOT and Joe Kyle from BR Amon & Sons to lay out test sections and to plan for pre- and post-construction testing activities. Because this was a project being constructed on a new alignment without public traffic, no provisions for traffic control were needed during the conduct of coring operations and in situ shear testing.

4.3.1 STH 11 Test Section Layout

Within each of the three proposed test sections, three sub-sections were established to provide replicate test results. The initial 450 ft of the SS-1hp latex modified section was removed from consideration due to potential start-up problems, with the remaining 6,000 ft divided into the three 2,000 ft sub-sections. For the SS-1h sections, the leading and ending 300 ft of each 3,000 ft test section was removed due to potential start-up and transition problems, resulting in three 800 ft sub-sections. Within each of the nine sub-sections, two random locations were selected for tack material sampling, pavement coring and subsequent shear testing. **Table 4.4** provides information on the established test sections.

Table 4.4. STH 11 Test Section Information – Westbound Outer Lane

Tack Material Type	Proposed Application Rate, gal/SY	Section Length ft	Sub-Section ID	Sub-Section Length ft	Start Station	End Station	Random Number	Subsection Test Station
SS-1hp	0.04	6450	L1	2000	102150	100150	0.17558	100974
			L2	2000	100150	98150	0.47001	99210
			L3	2000	98150	96150	0.47839	97193
SS-1h	0.04	3000	H1	800	95700	94900	0.61606	95207
			H2	800	94900	94100	0.28858	94669
			H3	800	94100	93300	0.06516	94048
	0.02	3000	C1	800	92700	91900	0.25386	92497
			C2	800	91900	91100	0.15025	91780
			C3	800	91100	90300	0.47928	90717

4.3.2 STH 11 Pre-Construction Testing

Prior to tack coat application and subsequent surface layer paving, blank tack coat sample patches were taped to the existing HMA lower layer. The patch samples, each approximately 14 inches x 14 inches, were cut from fabric sample bags and taped across their corners near the mid-lane position at each randomly selected test location. The patch samples were removed from the pavement after the tack material was applied and set and placed within individual marked plastic bags. The samples were then transported to the WisDOT SE Region Materials Lab and ultimately to the Marquette University Asphalt Lab. The dried patch samples were removed from their bags, trimmed to remove the tape used to affix the corners to the pavement, and then measured and weighed to determine the patch area and recovered tack material mass. The emptied plastic sample bags were also weighed to determine the mass of any tack material that had been transferred during placement and transport.

Table 4.5 provides the results of the STH 11 patch sample tests. As shown, the residual application rates are significantly lower than the target rates proposed before construction and the contractor computed residual application rates. This reduction was investigated by drying back samples of the SS-1h and SS-1hm tack materials sampled during construction. Tests conducted at Marquette University indicated residual solid mass ratios of 0.418 and 0.548 for the CSS-1h and NTSS-1hm materials, respectively. Using a specific gravity of 1.03 for each residuum material results in volumetric ratios of 0.405 and 0.532 for the SS-1h and SS-1hm materials, respectively, which are significantly lower than the contractor assumed values of 0.65 and 0.80. The contractor assumed values, which were based on the dilution rates provided by the supplier, did not account for the basic dilution rate of the emulsion stock which can vary between 0.57 and 0.70. To reduce the risk of computational errors of this type during construction projects, a tack coat application table was developed to aid in the determination of a tack coat application rate, in gallons per lane-mile, based on materials information and specified project targets. A simple spreadsheet was also developed to provide this information as well as the expected residuum mass that should be recovered on a 1 ft^2 patch sample. **Table 4.6** provides a sample output from this spreadsheet. The values highlighted in yellow are input by the contractor while the cell highlighted in green as well as the cells in the lower table are computed based on these inputs.

Table 4.5. STH 11 Patch Sample Results

Sample ID	Sub Section	Total Mass g	Plastic Bag g [(1)]	Trimmed Patch g	Patch Area cm^2	Clean Mass g [(2)]	Tack Mass g	Residual App Rate g/cm^2	Residual App Rate gal/sy	Ave Res App Rate gal/sy	Target Res App Rate gal/sy	Contractor Computed gal/SY
1	L1	89.23	64.66	22.13	1225.7	13.76	9.75	0.008	0.017			
2	L2	95.21	65.83	26.67	1195.1	13.41	15.81	0.013	0.028			
3	L3	96.36	66.47	27.29	1231.3	13.82	16.66	0.014	0.029	0.025	0.040	0.044
4	H1	90.93	66.14	22.06	1235.4	13.87	11.05	0.009	0.019			
5	H2	90.15	65.69	22.25	1239.6	13.91	10.75	0.009	0.019			
6	H3	88.83	65.06	22.20	1241.4	13.93	10.05	0.008	0.017	0.018	0.040	0.029
7	C1	85.18	64.57	17.65	1200.4	13.47	5.47	0.005	0.010			
8	C2	86.67	65.40	19.63	1281.1	14.38	7.37	0.006	0.012			
9	C3	84.90	64.35	17.54	1248.5	14.01	4.60	0.004	0.008	0.010	0.020	0.015

[(1)] Clean plastic bag with no residual tack materials = 63.28 g

[(2)] Clean mass of trimmed patch with no tack materials measured at 0.0112 g / cm^2

Table 4.6. Example Output From Tack Coat Application Spreadsheet

Specific Gravity of Emulsion =	1.01
Specific Gravity of Binder Residue =	1.03
Target Residual Application rate (gal/sy) =	0.025
Target Residual Application rate (lb/sy) =	0.2184
Target Residual Application rate (gal/lane-mile) =	176
Residual Weight on 1 ft^2 Patch Sample (grams/patch) =	11.0

% Residue in Emulsion	Secondary Dilution Rate										
	100/0	95/5	90/10	85/15	80/20	75/25	70/30	65/35	60/40	55/45	50/50
57	309	325	343	363	386	412	441	475	515	561	618
58	303	319	337	357	379	405	433	467	506	552	607
59	298	314	331	351	373	398	426	459	497	542	597
60	293	309	326	345	367	391	419	451	489	533	587
61	289	304	321	339	361	385	412	444	481	525	577
62	284	299	315	334	355	378	406	437	473	516	568
63	279	294	310	329	349	372	399	430	466	508	559
64	275	289	306	324	344	367	393	423	458	500	550
65	271	285	301	319	338	361	387	417	451	492	542
66	267	281	296	314	333	356	381	410	444	485	533
67	263	277	292	309	328	350	375	404	438	478	525
68	259	272	288	304	324	345	370	398	431	471	518
69	255	268	283	300	319	340	364	392	425	464	510
70	251	265	279	296	314	335	359	387	419	457	503

Note: Values in table represent application rates for diluted emulsions in gallons per lane mile.

4.3.3 STH 11 Laboratory Shear Testing

Approximately 1 week after construction, 6-inch full-depth cores were extracted from each test section to provide specimens for laboratory testing of the shear strength of the tack layer. Two mid-lane cores were extracted from each test section, approximately 6 ft upstream and downstream of the locations of the patch tests, resulting in a total of 18 cores. During coring, seven of the cores separated between the 12.5 mm surface layer and the 19 mm lower layer, indicating a weak tack bond strength. **Table 4.7** provides summary results of the coring operation.

Table 4.7. Summary of STH 11 Coring Operations

Sub Section	Core ID	Total Core Thickness (in)	12.5 mm Surface Thickness (in)	Top Layer Separated Yes/No
L1	L1A	6.5	1.9	Y
	L1B	6.2	1.6	N
L2	L2A	6.6	1.8	N
	L2B	6.3	1.7	N
L3	L3A	5.6	1.7	N
	L3B	6.6	1.7	N
H1	H1A	5.9	1.9	N
	H1B	5.9	1.9	N
H2	H2A	5.7	1.8	N
	H2B	6.1	1.9	Y
H3	H3A	6.4	1.9	N
	H3B	6.6	1.9	Y
C1	C1A	5.9	1.9	N
	C1B	6.0	1.9	Y
C2	C2A	5.9	1.9	Y
	C2B	6.0	1.9	N
C3	C3A	6.1	1.8	Y
	C3B	6.3	1.9	Y

The recovered cores were transported to the Marquette University Asphalt Lab for direct and rotational shear testing. The cores were randomly grouped and tested following the same protocol used for previous shear tests. **Table 4.8** provides the shear test results. As shown, the peak direct and rotational shear stress values for the latex modified SS-1hp are significantly higher than the SS-1h values, which may be the result of improved material characteristics and/or increased residual application rates (See **Table 4.5**). However, all values are below recommended minimum values for direct and rotational shear bond strengths.

Table 4.8. Summary of STH 11 Lab Shear Test Results

Sub Section	Core ID	Total Core Thickness (in)	12.5 mm Surface Thickness (in)	Shear Test Type	Direct Shear Bond Strength psi	Rotational Shear Bond Strength psi
L1	L1A	6.5	1.9	n.a. (1)		
	L1B	6.2	1.6	DST	94.3	
L2	L2A	6.6	1.8	RST		116.4
	L2B	6.3	1.7	RST		144.0
L3	L3A	5.6	1.7	DST	45.4	
	L3B	6.6	1.7	RST		121.2
H1	H1A	5.9	1.9	RST		16.8
	H1B	5.9	1.9	DST	21.5	
H2	H2A	5.7	1.8	DST	n.a. (2)	
	H2B	6.1	1.9	n.a. (1)		
H3	H3A	6.4	1.9	RST		3.6
	H3B	6.6	1.9	n.a. (1)		
C1	C1A	5.9	1.9	DST	27	
	C1B	6.0	1.9	n.a. (1)		
C2	C2A	5.9	1.9	n.a. (1)		
	C2B	6.0	1.9	RST		14.4
C3	C3A	6.1	1.8	n.a. (1)		
	C3B	6.3	1.9	n.a. (1)		

(1) Core separated in Field
(2) Core separated during placement in test fixture

4.3.4 Field Shear Testing

Approximately 2 weeks after construction, field testing with the portable RST was conducted at each previously cored pavement location, with a single field RST test conducted within 6 feet of the previous coring locations. Table 4.9 provides the results of the field RST results. As shown, the trends in shear strength values are similar to the laboratory results but the field results from the latex modified sub sections are significantly lower than the lab results.

Table 4.9. Summary of STH 11 Field RST Results

Sub Section	Rotational Shear Bond Strength, psi	Average Rotational Shear Bond Strength, psi (2)
L1	8.3	29.4
L2	18.5	
L3	61.5	
H1	n.a. (1)	7.7
H2	13.1	
H3	9.9	
C1	n.a. (1)	5.9
C2	9.2	
C3	8.6	

(1) Surface layer separated during coring
(2) Averages assume value of 0 psi for separated cores

4.3.5 Laboratory Testing of Lab-Prepared STH 11 Specimens

The results of the STH laboratory and field tests were significantly lower than expected based on the results of Phase 1 laboratory testing. To better understand if these differences were due to sample preparation techniques, samples of HMA and tack materials used during construction for the lower and upper layers were obtained. These materials were used to fabricate tiered specimens with residual tack application rates similar to those measured from the patch samples. It was intended to produce six specimens at each tack material / target application rate combination used during actual construction. However, prior to the conduct of shear testing, it was determined that the actual application rate used of the latex modified specimens was slightly lower than the field application rate. **Table 4.10** provides the results of laboratory testing for the lab-prepared STH 11 specimens. As shown, the test results are significantly higher than those obtained from the lab and field tests on the actual pavement. Additionally, all average group values exceed the recommended minimum values for direct and rotational shear strength. Furthermore, there is no statistical difference between any group average based on paired T-test results from the three sample sets for each shear test type. This variation in strength results highlights the need for conducting in situ testing to accurately measure the bond strength of constructed pavement sections.

Table 4.10. Summary of Shear Test Results From Lab-Prepared STH 11 Specimens

Test Section	Target Residual Application Rate gal/SY	Actual Residual Application Rate gal/SY	Shear Test Type	Direct Shear Bond Strength psi	Rotational Shear Bond Strength psi	Group Average Bond Strength psi
Latex Modified SS-1hp	0.025	0.022	DST	225.6		
				162.7		
				160.3		182.9
			RST		220.9	
					206.2	
					251.6	226.2
Heavy SS-1h	0.018	0.018	DST	176.3		
				191.0		
				191.0		186.1
			RST		179.5	
					284.8	
					217.6	227.3
Control SS-1h	0.010	0.010	DST	183.4		
				145.6		
				165.1		164.7
			RST		219.3	
					235.7	
					255.5	236.8

4.4 Summary of Field Tests

The field tests conducted as part of this study provided valuable information regarding tack coat application procedures and measurements of tack coat bond strength. Direct comparisons of rotational shear resistance measured in situ and on lab prepared specimens using the same construction materials indicate the need for field verification of the available bond strength.

Field application rates computed from the STH 11 construction data indicate the need for a better understanding of the dilution rates provided by the emulsion suppliers. The current WisDOT specifications allow for the use of diluted emulsions. Section 455.2 contains the following:

455.2.4.3 Emulsified Asphalts

(1) Furnish material conforming, before dilution, to the following:
Anionic emulsified asphalts ....AASHTO M 140
Cationic emulsified asphalts ....AASHTO M 208
Polymer-modified cationic emulsified asphalts ....AASHTO M 316

(2) If diluting emulsified asphalt, mix thoroughly with an equal amount of potable water. If undiluted samples are not available, test the diluted material and modify AASHTO M 140, M 208, or M 316 to reflect properties resulting from dilution of the asphalt.

It is suggested that the first sentence of Item (2) be modified to read:

If using a diluted emulsified asphalt, manufacturers information on the dilution rate and the percent residue in the undiluted emulsion should be provided.

It is also suggested that the WisDOT specifications regarding the desired tack coat application rate be revised to provide a clearer meaning of the intended ***residual*** tack coat application rate. Section 455.3 of the current WisDOT Standard Specifications contains the following:

455.3.2.1 General

(1) Apply tack coat only when the air temperature is 36 F (2 C) or more and the existing surface is dry and reasonably free of loose dirt, dust, or other foreign matter. Do not apply if weather or surface conditions are unfavorable or before impending rains.
(2) Use tack material of the type and grade the contract specifies. The contractor may, with the engineer's approval, dilute tack material as allowed under 455.2.4. Apply at 0.025 gallons per square yard (1L/10m²), after dilution, unless the contract designates otherwise. Limit application each day to the area the contractor expects to pave during that day.

(3) Unless the contract specifies otherwise, keep the road open to all traffic during the work. Plan and prosecute tacking operations to adequately provide for traffic without damaging the work.

It is suggested that Item (2) be revised to read:

Use tack material of the type and grade the contract specifies. The contractor may, with the engineer's approval, use a diluted tack material as allowed under 455.2.4. Apply at a residual application rate of 0.025 gallons per square yard (0.113 ℓ/m²), unless the contract designates otherwise. Limit application each day to the area the contractor expects to pave during that day.

The field tests conducted as part of this study also provided valuable insight regarding the in situ measurement of tack coat bond strength. Pavement coring operations necessary to produce the tiered test specimen, using both a 6-inch and 4-inch core barrel, were completed with relative ease at any desired pavement location. Measurement of the rotational shear bond strength, using the portable RST, was also completed with little complication.

5.0 Conclusions and Recommendations

This research evaluated the bond characteristics of tack coat materials currently used in Wisconsin. Conventional SS-1h and CSS-1h emulsions as well as modified NTSS-1hm and SS-1hp emulsions were utilized. A neat PG 58-28 binder was also used for comparative purposes. Bond strengths developed over a variety of application conditions were measured by direct shear and rotational shear testing. The data generated in this study were used to evaluate the criteria enumerated in the Section 455 of the Wisconsin Department of Transportation (WisDOT) Standard Specifications for Highway and Structure Construction.

The findings of the initial phase of laboratory testing indicated:

- PG 58-28 provides a better bond strength than the SS-1h materials. It is recommended that the PG 58-28 binder be approved for usage as a tack coat material.
- The minimum recommended tack coat application rate is 0.025 gal/yd^2, for both SS-1h and PG 58-28 materials, which supports the current WisDOT specification value.
- Higher ambient air temperatures increase tack coat effectiveness, with 37F being the minimum recommended temperature. This supports the WisDOT specification that requires air temperatures of 36F or higher during tack coat application.
- Dry or wet conditions prior to overlay did not significantly affect bond strength. This indicates that as long as the tack material is set, slight rains during paving may not pose a problem with tack coat effectiveness, provided the tack material is completely set. Tack coat materials should not be applied during rainfall as this may result in wash-off or uneven coverage.
- Results from direct shear testing indicated more instances of statistical differences in group means as compared to the rotational shear results. This result indicates the direct shear test may be more appropriate for differentiating strength differences within the lab. However, the rotational shear test is more suited to field operations where in situ bond strength is more of a concern.

The field studies utilized rotations shear testing conducted with the equipment developed during this study. Pavement coring operations necessary to produce the tiered test specimen, using both a 6-inch and 4-inch core barrel, were completed with relative ease at any desired pavement location. Measurement of the rotational shear bond strength, using the portable RST, was also completed with little complication. The findings from the field studies indicated that direct comparisons of rotational shear bond strengths measured in situ and on lab prepared specimens using the same construction materials may differ substantially, indicating the need for field verification of the available bond strength. It is recommended that this portable equipment be utilized on future construction projects to monitor bond strengths developed under typical construction operations and to refine the acceptance protocol for bond strangths.

Field tack coat application rates computed from available construction data indicate the need for a better understanding of the dilution rates provided by the emulsion suppliers. This research developed application charts and a simple spreadsheet that can be used to determine the appropriate tack coat distribution rates given material data and project specifications. It is recommended that these tools as well as a confirmation patch test be utilized on future construction projects to help ensure that residual tack coat application rates are meeting agency specifications.

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