



Tack Coat Testing – Measuring Field Bond Strength

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16. Abstract (Limit: 250 words) <p>This report summarizes lessons learned in evaluating the bonding strength of hot mix asphalt (HMA) layers. Testing included: determining an optimal range for the bond strength of a tacked hot mix asphalt interface, and implementing the findings. The research method used a Florida Bond Test fixture along with a Marshall asphalt mixture testing load frame to evaluate tack bond shear strength and deformation. Specimens were obtained from state, county and city paving projects from around Minnesota. Results were compared to related research conducted in the United States.</p> <p>Recommendations for a tack bond test program:</p> <ul style="list-style-type: none"> • Equipment includes the Marshall load frame already used by many HMA laboratories, HMTS software or similar, and the Florida Bond Test apparatus. • Follow Minnesota modifications of Florida Bond Test protocol <ul style="list-style-type: none"> ○ Compute the average and standard deviation of peak shear stress from specimen sets ○ Cores exhibiting layer separation during coring or during removal will be included in the specimen set and assigned a peak shear stress of 0 psi • Average peak shear stress will be 100 psi or greater • The standard deviation of peak shear stress will be 25 psi or less 			
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Final Report

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Executive Summary

The objective of this research was to determine an optimal range for the bond strength of a tacked hot mix asphalt interface, and implement the findings. The research method used a Florida Bond Test fixture along with a Marshall hot mix asphalt load frame to evaluate tack bond shear strength and deformation. Specimens were obtained from state, county and city paving projects from around Minnesota. Results were compared to related research conducted in the United States.

Recommendations for a Minnesota Tack Bond testing program include the use of a Marshall-style load frame. Rationale is that load frames of this type have been used in asphalt laboratories for many years, and should be readily available at no cost. The load frame capacity should be a load of 10,000 lb (at 2 in/min). Other equipment requirements are a Florida Bond Test fixture and optional test software.

Testing should follow the Minnesota modifications of Florida Bond Test protocol. Compute the average and standard deviation of peak shear stress from specimen sets made of three or more cores. Any cores exhibiting layer separation during coring, or during removal from the core hole will be included in the specimen statistical values and assigned a peak shear stress of 0 psi

Passing tests will have:

- Average peak shear stress of 100 psi or greater
- Standard deviation of peak shear stress of 25 psi or less

Chapter 1: Introduction

Local Road Research Board (LRRB) project number 949, titled, “Tack Coat Testing – Measuring Field Bond Strength”, was sponsored by the Minnesota Local Road Research Board.

Background and Objectives

Bonding of hot mixed asphalt (HMA) layers is a factor in maintaining proper, long term pavement performance. It has been estimated that one third to one half of the pavements in Minnesota may experience up to a 25% reduction of service life due to the de-bonding of HMA layers. When proper bonding occurs between layers of HMA, the pavement structure performs in the manner in which it is designed, facilitating long term performance.

One purpose of this study was to measure the bond strength of many different pavements. State, county and city projects were selected to evaluate the bond strength with the objective to determine criteria for bond strength.

In preparation for this project, the researchers received a 34 page document from the MnDOT Library containing the names of reports and publications that are related to this topic. While there were many studies that have looked at bond strength of the tack coats in controlled laboratory settings, there were none that specifically showed what bond strengths Minnesota achieves in the field both immediately after construction and years after construction.

Researchers used the literature to learn what shear strengths would be considered poor, acceptable, and exceptional. This information helped categorize results from Minnesota construction projects.

A second objective of this project was to demonstrate the performance of properly applied tack coats by testing the bond strengths of a few different tack coat emulsions at a few application rates.

Project Outline

Since the proposed objective of this research was to determine an optimal range for bond strength and implement the findings, it was necessary to study the bond strength of many different pavements. New and old state, county and city projects from around Minnesota were selected and evaluated for bond strength. This project used a laboratory shear test to determine bond strength of the tacked face between two lifts of HMA. Testing was performed on both field cores and laboratory specimens and a practical minimum value of interfacial bond strength was determined from the testing.

Reports were delivered to the LRRB to update the organization on details from each of the following tasks:

1. Coring and testing of existing pavements.
2. Coring and testing of pavements under construction.
3. Construction and testing.
4. Discussion of bond strength test results performed by MnDOT as compared to research performed by others.

Future implementation activities may include training on proper tack application, measuring bond testing, revising standard specifications, presenting at conferences, and participating in webinars.

Chapter 2: Evaluation Methods

Research Approach

Many cores taken from existing pavements were tested for bond strength. When possible, cores were also tested for "mix" strength. Literature search was used to determine the testing method using the Florida Bond Tester and bond strength target values. Current projects were also included in which photos of good tack with measured bond strength are presented.

- Coring and testing of existing pavements. The number of cores per project, and number of projects was determined by the TAP. This information was used to establish a database of tack strength.
- Coring and testing pavements under construction. Also collected mix samples to determine the shear strength of the mix. This information was also used to establish a database of tack strength. The number of cores per project, and number of projects was determined by the LRRB technical assistance panel.
- Based, on preliminary findings, “properly” applied tack materials were constructed at different applications rates, and then tested. Emulsified asphalts such as CSS-1h and CRS-2P were included as tack coat material.
- Discussion of bond strength as it relates to pavement performance based on data collected and research performed by others.
- Draft and Final reporting.
- Implementation Plan. Recommendation for implementation plan based on the findings from the research.

Tack Coat Construction Practice

A survey of literature produced the following results.

AASHTO and other collaborating organizations published best practices for constructing asphalt pavement (1). They stated that the function of tack coat is to ensure a bond between the existing surface and new pavement, and that slippage-type distresses occur without proper bonding. Quality application is important, so personnel should ensure that nozzles function, are set at the same angle, and at proper height. Proper application rate and uniformity are also important. Application should be based on residual asphalt of 0.04-0.06 gal/yd² for non-milled and up to 0.08 gal/yd² for milled surfaces.

The Asphalt Emulsion Manufacturers Association recommended that emulsion for tack coat conforms to ASTM D997 for SS-1h D2397 for CSS-1 or CSS-1h (2). Dilution prior to spraying enhances the covering properties of the emulsion. When diluting, the water should be clean and potable. The final tack product should be a thin, tacky, adhesive film.

Minnesota specifications for tack coat (3) permit the use of CSS-1 or CSS-1h emulsified asphalts as well as use of MC-250 medium cure cutback asphalt in special cases when cold temperatures are anticipated. Minnesota does not permit dilution of tack in the field. The minimum residual asphalt content of emulsions must be 57% when undiluted, and 40% if diluted by the supplier at a rate of seven parts emulsion to three parts water. Rates of application are specified for

combinations of tack product and surface type. Rates fall between 0.05 to 0.1 gal/yd² (0.03 to 0.06 gal/yd² residual asphalt) when tacking with undiluted emulsion for asphalt overlays.

The FHWA Central Federal Lands Highway Division (CFLHD) studied prime and tack coats, and published a guideline for project development and field personnel (4). In a survey of agencies, no DOT's recalled specific pavement failure associated with tack coat, but listed insufficient tack as a cause of debonding. The survey found that in no instance was too much tack listed as the cause of slippage. CFLHD reported on various tack coat application rates of several agencies, including the U.S. Army Corps of Engineers specification of 0.05 to 0.15 gal/yd² residual asphalt. The range accounts for lower rates used for bonding new pavement layers as well as higher rates for preparing for overlays on PCC or milled HMA surfaces. Their literature search also found:

- Debonding of HMA layers can cause slippage cracks and reduced pavement life.
- Laboratory interface shear strength was affected by rate of shear, size of normal force, temperature, and joint construction.
- Monolithic construction provided the highest shear strength.
- In reports where the statistical significance of the differences in interface shear strength was evaluated, tacked interfaces were either stronger or not significantly different from untacked interfaces.
- Higher the viscosity of the bituminous binder related to higher interface shear strength.
- Application rate typically had little effect on interface shear strength. Higher than typically recommended application rates resulted in slightly lower interface shear strengths.

Tests that Quantify Tack Coat Quality

A survey of literature produced the following results.

At the time of this report, NCHRP 9-40A Field Implementation of the Louisiana Interface Shear Strength Test (LISST) was an ongoing national research effort (5). Projects selected and tested for NCHRP 9-40A included relatively thin overlays ranging from 1.25 to 1.75 in. Quarterly report 7 found no issues with testing overlays of those dimensions with the LISST. Specimens were taken from a variety of Missouri and Louisiana paving projects where Trackless Tack and SS-1h were applied at residual rates of 0.05 gal/yd². New HMA was paved over several surface types:

- a. new HMA
- b. PCC
- c. existing HMA
- d. milled HMA
- e. tacked HMA leveling course

The researchers generally found an LISST coefficient of variation below 30%, except the COV increased to 70% when testing SS-1h tack over existing HMA. Trackless Tack was more consistent overall than SS-1h. In terms of LISST, averages were generally between 35 and 80 psi. Several poor performers included Trackless Tack over milled HMA (6 psi), as well as SS-1h and Trackless Tack over PCC (7 and 14 psi).

Academic and corporate researchers experimented with an energy-based bond tests (6). Specimens came from spray paver construction projects and laboratory produced specimens. The Interface Bond Test has similarities with the DCT asphalt mixture test. The laboratory phase showed fracture energy attained between 97 and 131 J/m² resulting from tack application rates between 0.1 and 0.2 gal/yd². Tests on field cores from Missouri showed the spray paver applications were superior to the distributor-applied tack that attained only 9 J/m² from CSS emulsion applications of 0.08 gal/yd². Tests on the spray paver applications attained 33 to 38 J/m² when CSS was applied at 0.10 to 0.15 gal/yd². Similar tests using polymer modified asphalt emulsion attained 164 to 199 J/m² using tack rates of 0.10 to 0.15 gal/yd². Direct tension tests showed the same trends, but energy values were of somewhat greater magnitude.

In an investigation of 4.75-mm mixtures in Kansas, researchers found that different tack rates did not affect Hamburg Wheel Track test results (7). They did find that pull-off test results were affected by properties of the existing pavement; including density, mixture design, and aggregate source.

A New Brunswick study used FWD field testing along with direct and indirect laboratory testing to evaluate a variety of tack rates during the first and fourth season after construction (8). Results showed there was no statistically significant structural difference between overlays constructed with and without tack. Laboratory tests supported conclusions from the field testing. The conclusions stated that tack coat should be used only when “there are other tangible benefits beyond structural strength and integrity of the pavement”.

Texas DOT’s Thin Surface Mix (TSM) is an asphalt overlay used on structurally sound pavement beginning to show signs of aging distress. A key construction issues with TSMs is a good bond to the existing surface (9). The researchers recommend evaluating the tack application using a pull-off test (ASTM C1583) in the field or laboratory, but an acceptance range was not included. Non-tracking tack was recommended at application rates of 0.03 to 0.06 gal/yd². Spray-applied underseals were recommended when overlaying in circumstances having unsealed cracks or pavement with high voids.

A study on bonding found that dynamic shear modulus was useful in evaluating bonding. In-house equipment modifications were used to perform dynamic loading and shear strength tests. High shear reactions showed that the current tack methods used in Kansas were the optimum for constructing coarse-fine and fine-fine interfaces (10). Dynamic shear was superior to shear strength for distinguishing effects of application rate.

Washington researchers used a literature search to compare and contrast other research results and also performed an extensive evaluation of bond testing methods (11): 1) a field experiment tested the results of milling, varying tack rates, and paving over broken and unbroken tack. Field measurements of tack rates found material was under-applied at high target rates and over-applied at low target rates. Analysis of cores from wheel paths showed that no pick-up occurred. 2) UTEP Pull-Off, Florida Shear, and Torque Bond testing was used to evaluate the experimental sections. It was found that the pull-off produced results opposite to the torque and shear methods. None of the methods were recommended for in-situ testing, but the Florida Shear test was recommended for laboratory work.

The project activities for NCHRP 712 (12) included development of a pull-off type test of tack quality (LTCQT) and an interface shear-type test of bond strength (LISST). Test parameters for the LTCQT field test include an approximate one hour evaporation time. Output is in terms of load and time. The LISST provides load and displacement output. Based on the project activities, the minimum recommended tack shear strength was 40 psi. NCHRP Report 712 is comprehensive, including sections on the state of the practice, the project experiment and results, and appendices for recommended test standards as well as a tack coat training manual. Experimental results found good correlations between tack bond strength and tack properties; viscosity and softening point. Although shear tests were highest for all of the tested materials when the residual application rate was 0.155 gal/yd², it was reportedly difficult to determine an optimum value. It was recommended to use residual rates of 0.035 gal/yd² on new asphalt, 0.055 gal/yd² on milled and old asphalt, and 0.045 gal/yd² on Portland cement.

A study of tack at NCAT (13) included development of a shear device in a laboratory study followed by field validations. Conclusions from the laboratory work stated that intermediate test temperatures were the most practical (77°F). Normal-loading is not necessary at intermediate test temperatures, but normal loads of 20 psi should be used at high temperatures. The study found bond strengths were higher at lower application rates, and that test temperature was the most influential factor on bond strength.

In the field phase of this study, milled HMA surfaces produced higher tack bond strengths. Bond strength was also greater for a section placed with a spray paver. The researchers observed a wide range of tack coat application practices.

The study recommended a minimum bond shear of 100 psi averaged from at least three tests. Bond strength results below 50 psi were considered poor. The study also generated a draft specification for coring and testing bond strength specimens. Other recommendations included using ASTM D 2995 to check the tack coat application rate.

Illinois researchers used interfacial shear testing to develop recommendations for optimum tack coating (14). The study also included optimal application rate, placement method, and pavement cleaning technique. The optimum residual application rate of 0.04 gal/yd² was recommended for SS-1vh emulsion. Other optimums were not clear. 0.06 gal/yd² was recommended as optimum for milled surfaces, but the highest strengths for SS-1h on milled surfaces occurred at rates below 0.06 gal/yd². Data plots of shear strength of milled surfaces showed SS-1h materials attaining values between 120 and 140 psi at rates between 0.02 and 0.06 gal/yd². Strength declined to approximately 80 psi as application increased to 0.08 gal/yd².

Florida DOT developed an interface shear test of bond strength (15) in response to questions over what tacking and paving practices were appropriate. Florida wanted to quantify bond strength of tack coats using a test that was meaningful and also easily implemented so a test was developed using concepts from an Iowa DOT test that measures shear strength between new and old Portland cement concrete. FDOT performed laboratory and field work, and found test rates and temperatures would produce measurement results of a magnitude that would allow differentiation. The final parameters included testing 6 in. diameter specimens using strain controlled loading rate of 2 in/min at a temperature of 77°F. The nominal gap width between shearing platens was 3/16 inch.

Specimens from construction project cores found strength trends for milled, non-milled, and various wet-versus-dry tack scenarios. It was found that shear bond strength generally increased as the time interval between paving and testing increased. Researchers determined that the standard deviation was more useful than coefficient of variation, and that test results from the specimen pool had a standard deviation of 9.6 psi.

In an update of their prior report (16,15) Florida restated previous research results along with additional information, and updated and reiterated the project recommendations, including future research needs.

- Contaminated tacked surfaces occur often during construction. Testing should be conducted to quantify the effect of dirt on the bond strength between paving layers.
- Testing of pavements with failed bond need to be investigated before setting shear strength specification limits. Minimum shear strength values were unknown.
- Investigate other applications for the shear device. Shear tests of slippage failures could identify locations in projects that need to be milled and replaced.

Tack Bond Strength

Collaborating engineers from MnDOT and counties identified a number of projects and provided background data for the following matrix (Table 1). Findings from individual case studies are located in the appendix.

Table 1 Projects for Study of Bond Strength

Agency	Highway	Location	Cores	Gyratory	Remark
MnDOT	MNTH 95	Metro	x		Bituminous slide
MnDOT	USTH 10	D3	x		2 RAP+shingles sections
Beltrami County	CSAH 22	Beltrami	x		Texas underseal
Chisago County	CR 63	Chisago	x		Hot to Hot HMA
MnDOT	I-35 and CR 61	Carlton Co.	x		Dirty/clean conditions
MnDOT	Parking lot	Metro	x		Tack/no-tack, Dirty/clean conditions
Otter Tail County	CR 11, 21, 31, 73	Otter Tail	x		Tightblade level course
MnDOT	MNTH 33	D1	x	x	Tack rates
MnDOT	USTH 10	Metro	x	x	Tack rates/methods

Chapter 3: Evaluation of Contaminate and Tacked HMA

This chapter summarizes the layout, construction, and evaluation of an experimental unmilled HMA overlay. Work was performed during the fall season. The plan intentionally included areas with and without dirt contaminate.

Construction

Construction of a tack and paving experiment was performed on the north lane of Cell 84 located at the MnROAD Farm Loop near Albertville, MN. Coordinates for east end of Cell 84 are near 45°14'59.66"N, 93°41'7.54"W. The original dense-graded asphalt on Cell 84 was constructed in 2007 as part of a farm implement load study. In 2014 Cell 84 condition was free of cracking and other distress.

Construction details: On October 22, 2014 the contractor supplied a MnDOT level 2 super pave mix at MnROAD as requested. See sketch (Figure 1).

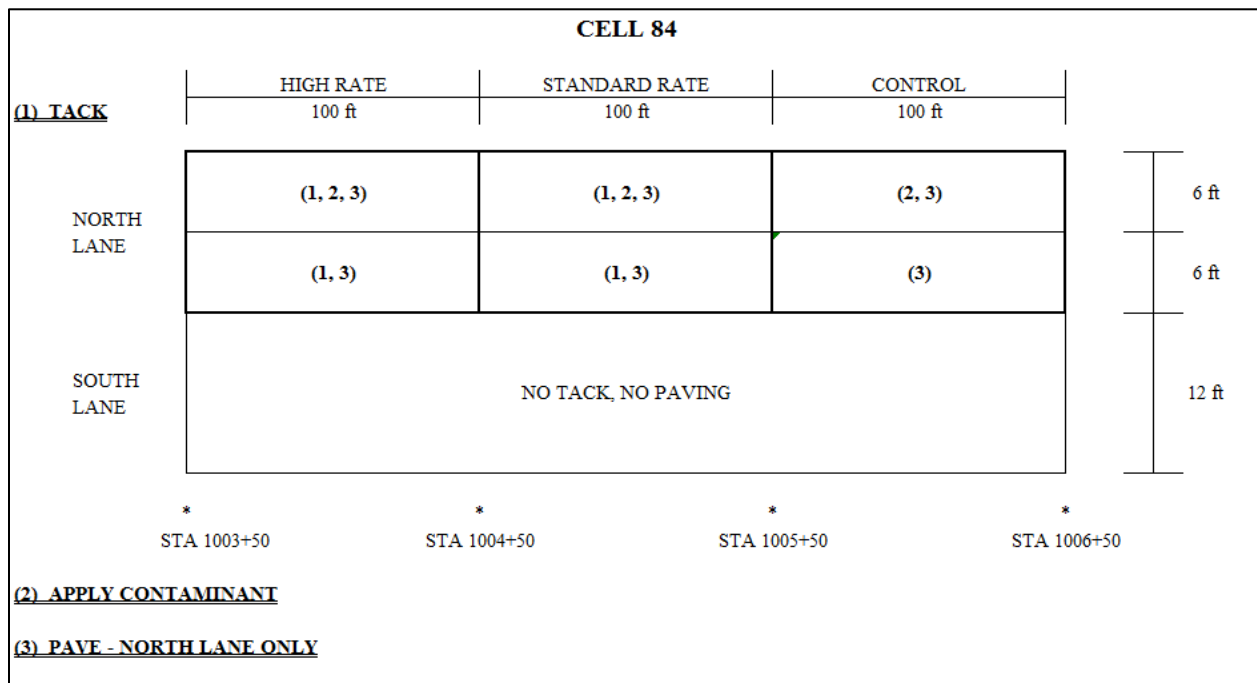


Figure 1 Layout of Tack Experiment on MnROAD Cell 84.

- Cleared the north (westbound) lane of Cell 84 for work. No milling was performed. MnROAD staff swept the asphalt surface in preparation for paving.
 - Sweeping was completed by 8:30 AM
 - Falling weight deflection measurements were performed in the center of the lane immediately after sweeping
 - By 11:15 the contractor was prepared to pave with three HMA trucks in queue.
- At 11:35 **the contractor tacked** with CSS-1h at three different rates. Figure 3 and Figure 4 show the tack application. Note the amount leaving the spray nozzles and the difference in coverage.

- Observed the distributor applied single nozzle coverage in the standard section and double coverage in the high rate section.
- Researchers verified that tack application began at Station 1005+50 and ended at Station 1003+50. Minor pooling was observed at the border between standard and high tack sections.
- Appropriate tack coverage levels were achieved; either none or total.
- Immediately after tacking the **researchers applied contaminant** to the outside half of the lane and paving began (Figure 2, Figure 5).
- The contaminates used in each 6-ft by 100-ft section were 6200 g (13.7 lb) minus #8 material and 4250 g (9.4 lb) fine sand.

Table 2 Tack and Contaminant Layout: MnROAD Cell 84

Cell	Lane	Begin Station	End Station	Offset from Centerline, ft	Tack Rate	Contaminant
84	North	1003+50	1004+50	0-6	High (0.10)	None
84	North	1003+50	1004+50	6-12	High (0.10)	Sanded Surface
84	North	1004+50	1005+50	0-6	Standard (0.03)	None
84	North	1004+50	1005+50	6-12	Standard (0.03)	Sanded Surface
84	North	1005+50	1006+50	0-6	0	None
84	North	1005+50	1006+50	6-12	0	Sanded Surface

- **Contractor paved** 300 feet approximately 2.5 inches thick by 12 feet wide in the north lane of Cell 84 (Figure 6). According to truck tickets, the mixture was a 9.5-mm recycled wear mix containing 6.1 percent total asphalt binder. Performance Grade 58-28 asphalt binder grade was added at 5.1 percent to the mix, making the new/total binder ratio 83.6 percent. The MnDOT mixture designation for this material would be SPWEA230B.
 - During paving, the trucks dumped HMA into the paving machine, and drove along with it until empty. At that point trucks would exit and enter through the tack; these equipment movements are common to paving operations.



Figure 2 Appearance of the No Tack section before and after contaminant.



Figure 3 Distributor operations on the Standard Tack section.



Figure 4 Distributor operations on the High Tack section.



Figure 5 Appearance of tack sections before and after contaminant.



Figure 6 Paving the High Tack section.

Testing and Sampling

The objective of this testing was to look at the effect of Tack Application Rate, Contamination, and Cure Time on the interlayer bond strength of tacked pavement.

The core area of each section was selected to reduce any edge effects, so omitted the 5 feet at each end and 1 foot at each side. The 10 feet adjacent to falling weight deflectometer (FWD) test points were also marked off in order to avoid coring at FWD sensor locations.

When sampling cores, the direction of tack application was noted and a minimum of three replicates were cut at each core test location. It was preferred that cores should be taken in areas away from tack distributor start-up.

Coring Observations

Coring was performed on the Cell 84 tack study sections in two phases. An initial round of core cutting was performed in October of 2014 that did not produce any bonded specimens. A second round was planned for the April of 2015 after the emulsified tack had been exposed to warm weather. The rationale was these additional core areas received less HMA delivery truck tracking during construction.

Initial Coring

During the initial coring it was observed that the structure was a nominal 9-in. thickness. In all cases the overlay detached from the underlying pavement during coring. The Cell 84 core log is shown in Table 3.

Secondary Coring

During the second round of coring the cutting rate was as kept as low as possible by reducing the down force of the cutting barrel to self-weight only. The self-weight method was successful and attempts using additional force were not. During the second round a number of additional cores

were attempted between the wheel paths. They were added in order to increase the chance of producing bonded specimens.

Table 3 Cell 84 Core Inventory

No	Date	Section	Location	Paving Condition	Core #	Condition
1	10/24/2014	High Tack	LWP	Clean	NA	†
2	10/24/2014	High Tack	LWP	Clean	NA	†
3	10/24/2014	High Tack	LWP	Clean	NA	†
4	10/24/2014	High Tack	LWP	Clean	NA	†
5	10/24/2014	High Tack	RWP	Dirty	NA	†
6	10/24/2014	High Tack	RWP	Dirty	NA	†
7	10/24/2014	High Tack	RWP	Dirty	NA	†
8	10/24/2014	Standard Tack	RWP	Dirty	NA	†
9	10/24/2014	Standard Tack	RWP	Dirty	NA	†
10	10/24/2014	Standard Tack	RWP	Dirty	NA	†
11	10/24/2014	Control	RWP	Dirty	NA	†
12	10/24/2014	Control	RWP	Dirty	NA	†
13	10/24/2014	Control	RWP	Dirty	NA	†
14	4/28/2015	High Tack	BWP	No Truck Tracking	1/3	Bonded
15	4/28/2015	High Tack	BWP	No Truck Tracking	2/3	Bonded
16	4/28/2015	High Tack	BWP	No Truck Tracking	3/3	Bonded
17	4/28/2015	High Tack	BWP	No Truck Tracking	NA	†
18	4/28/2015	High Tack	LWP	Clean	1/3	Bonded
19	4/28/2015	High Tack	LWP	Clean	2/3	Bonded
20	4/28/2015	High Tack	LWP	Clean	3/3	Bonded
21	4/28/2015	High Tack	LWP	Clean	NA	†
22	4/29/2015	High Tack	RWP	Dirty	1/3	Bonded
23	4/29/2015	High Tack	RWP	Dirty	2/3	Bonded
24	4/29/2015	High Tack	RWP	Dirty	3/3	Bonded
25	4/29/2015	Standard Tack	BWP	No Truck Tracking	1/3	Bonded
26	4/29/2015	Standard Tack	BWP	No Truck Tracking	2/3	Bonded
27	4/29/2015	Standard Tack	BWP	No Truck Tracking	3/3	Bonded
28	4/29/2015	Standard Tack	LWP	Clean	1/3	Bonded
29	4/29/2015	Standard Tack	LWP	Clean	2/3	Bonded
30	4/29/2015	Standard Tack	LWP	Clean	3/3	Bonded
31	4/29/2015	Standard Tack	RWP	Dirty	1/1	Bonded
32	4/29/2015	Standard Tack	RWP	Dirty	2	†
33	4/29/2015	Standard Tack	RWP	Dirty	3	†
34	4/29/2015	Standard Tack	RWP	Dirty	4	†
35	4/29/2015	Standard Tack	RWP	Dirty	5	†

Table 3 continued						
No	Date	Section	Location	Paving Condition	Core #	Condition
36	4/29/2015	Standard Tack	RWP	Dirty	6	†
37	4/29/2015	Control	LWP	Clean	1/3	Bonded
38	4/29/2015	Control	LWP	Clean	2/3	Bonded
39	4/29/2015	Control	LWP	Clean	3/3	Bonded
40	4/29/2015	Control	RWP	Dirty	1/3	Bonded
41	4/29/2015	Control	RWP	Dirty	2/3	Bonded
42	4/29/2015	Control	RWP	Dirty	3/3	Bonded
43	4/29/2015	Control	RWP	Dirty	NA	†
44	4/29/2015	Control	BWP	No Truck Tracking	1/3	†
45	4/29/2015	Control	BWP	No Truck Tracking	2/3	‡
46	4/29/2015	Control	BWP	No Truck Tracking	3/3	‡
† - No bond						
‡ - Slight bond that did not survive removal from the core hole						

Factors Influencing Core Survival and Performance

The performance measure of any core having an interface that does not survive cutting or removal from a core hole is an interfacial-shear-strength value of zero. Survivors may be tested for bond strength.

Emulsion Break and Bond Cure

Results of coring showed that there were 13 cores attempted during the fall of 2014; all tacked interfaces failed during coring. During the spring of 2015 there were 33 cores attempted and only 11 bond interfaces failed during coring or core removal. This result occurred for a pavement that had received no traffic during the time interval. Recall that construction notes reported the paving proceeded prior to breaking of the tack emulsion. The improvement supports a theory that the tack application may have been insufficiently broken during construction, and that insufficient curing of the tack coat may have contributed to the short term tack failures.

Presence of Contamination

Because of the initial total failure rate, the first round of coring provided insufficient data to draw conclusions about the short term effect of contamination on bond strength. The data from the second round of coring provided a data set of 33 cores, including three duplicates. Duplicates were excluded in a comparison of second-round success rates that showed that clean, tacked surfaces were most likely to deliver cores with bonded interfaces (90% success within group), while dirty tacked surfaces were only 40% successful. Intermediate levels of contamination from the between-the-wheel paths group showed a 60% rate of success.

Tack Rate

In this experiment a comparison of the data for effect of tack application quantity showed that, regardless of contamination level, tacked surfaces had a slightly higher rate of success than non-tacked surfaces. High and standard rate tack applications produced 93% and 90% success rates while the non-tacked controls were 87%.

FWD Testing

Figure 8 shows results from several series of falling weight deflectometer (FWD) measurements that were performed on Cell 84 before and after paving:

- Prior to paving on 10/22/14
 - Mid-lane only
- One day after paving on 10/23/14
 - Mid-lane
 - Inner wheel path
 - Outer wheel path
- Two weeks after paving on 11/6/2014
 - Mid-lane
 - Inner wheel path
 - Outer wheel path
- Five months after paving on 4/3/2015
 - Mid-lane
 - Inner wheel path
 - Outer wheel path

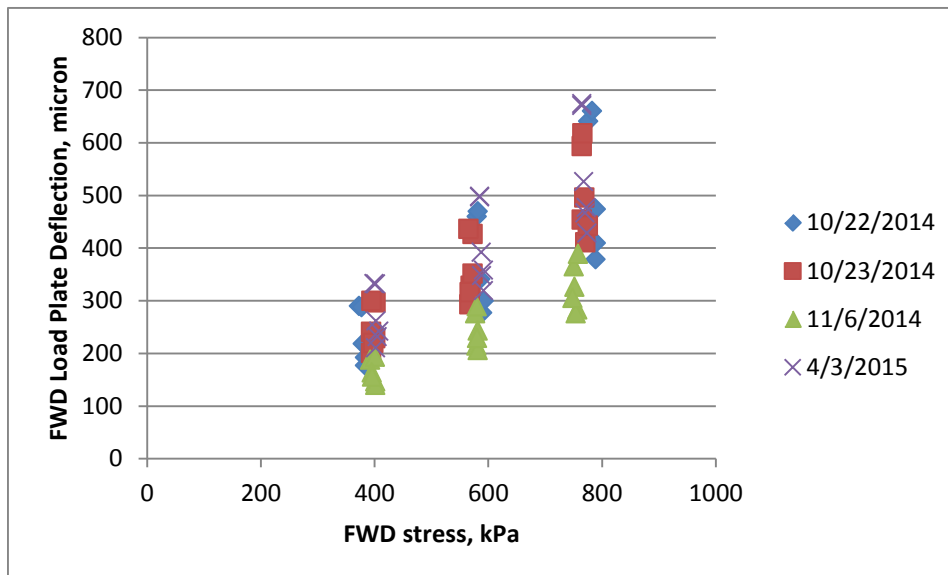


Figure 7 FWD at mid-lane: plate deflection versus applied stress.

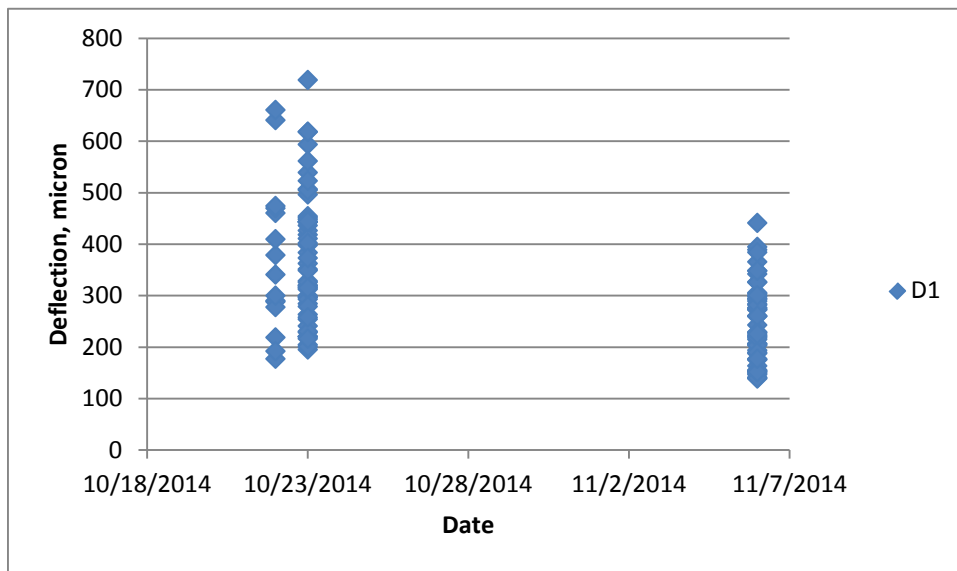


Figure 8 Deflection at load plate versus test date.

A normalized Area Factor (A36) was calculated from the FWD deflection basin and used to compare the structure before and after overlay. It is well documented that FWD results for bituminous pavement are influenced by base condition (saturated, frozen, unfrozen) and temperature. Inspection of the equation shows that values near 36 will be produced when similar measurements are obtained throughout the deflection basin, and values near 6 will be produced when the load point deflection is much greater than the rest. Therefore, a hypothesis is offered that a well-tacked structural improvement like an overlay should cause A36 to increase.

$$\text{Area Factor}_{36} = 6 \left(1 + 2 \left(\frac{D_{12}}{D_0} + \frac{D_{24}}{D_0} \right) + \frac{D_{36}}{D_0} \right) \quad \text{Equation 1}$$

Where:

D0 = Deflection measured at the center of FWD load plate

D12 = Deflection measured 12 in. (305 mm) from the center of FWD load plate

D24 = Deflection measured 24 in. (610 mm) from the center of FWD load plate

D36 = Deflection measured 36 in. (914 mm) from the center of FWD load plate

Figure 9 plots the calculated basin area for measurements taken mid-lane, offset six feet from the centerline joint. Note that on the day after paving the A36 decreased on average by 6 percent, but after two weeks had increased by 8 percent relative to the initial measurement. This increase coincided with a reduction of deflection magnitude at the load plate. Measurements were also taken after six months, but there appeared to be some reduction relative to prior testing. It is possible that the behavior at six months was influenced by spring thaw conditions.

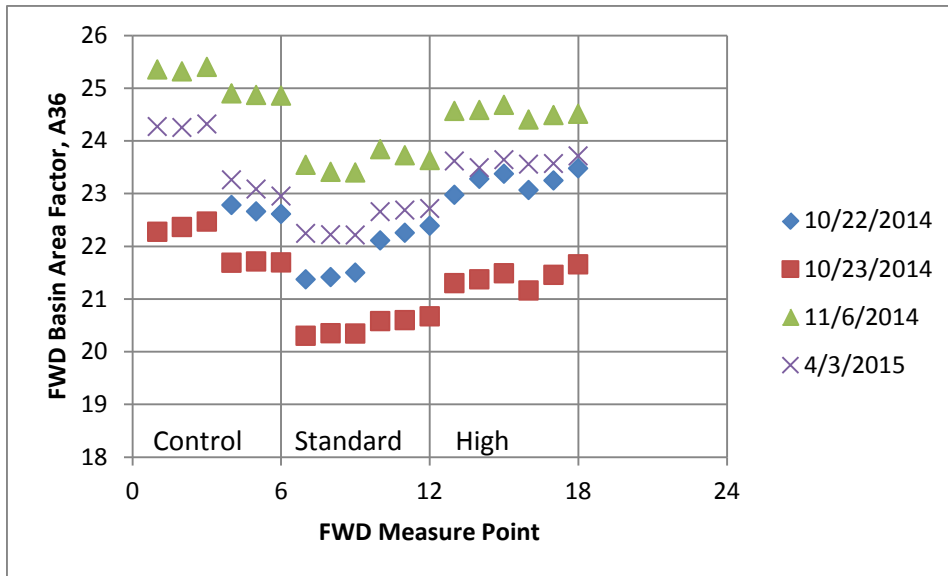


Figure 9 Cell 84 deflection basins before and after overlay.

Figure 10 shows weather data beginning one week prior to testing and construction. Historical climate data from the Minnesota Department of Natural Resources was used to construct the figure. Darkened data points indicate the FWD test dates. During testing the daily highs were all above freezing, while low temperatures fluctuated between 20 and 45 degrees Fahrenheit.

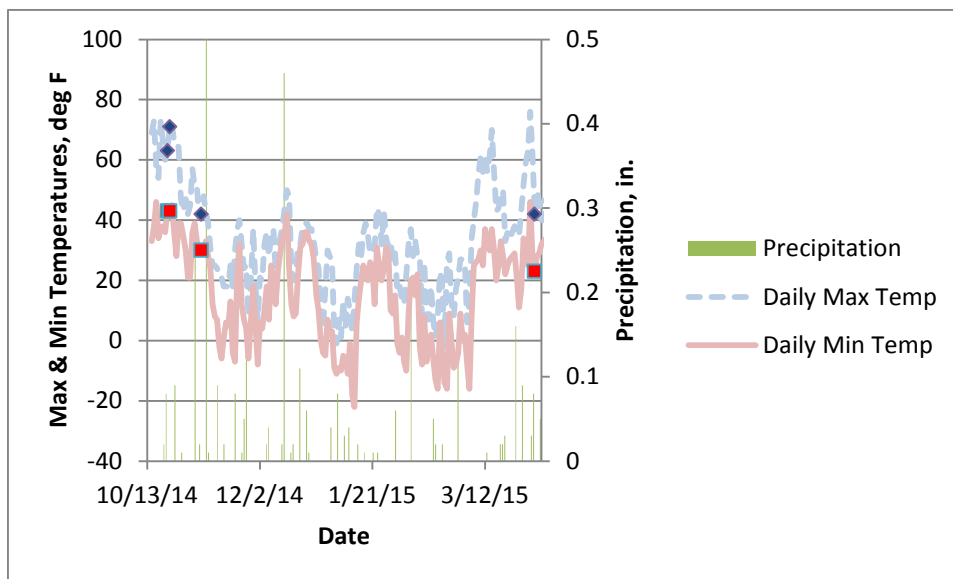


Figure 10 Weather summary for St. Cloud region.

Recall that prior to overlay, contaminate was applied to the tacked surface in the outside wheel path of Cell 84. Figure 11 and Figure 12 show that A36 increased over time in all of the subsections, regardless of contamination.

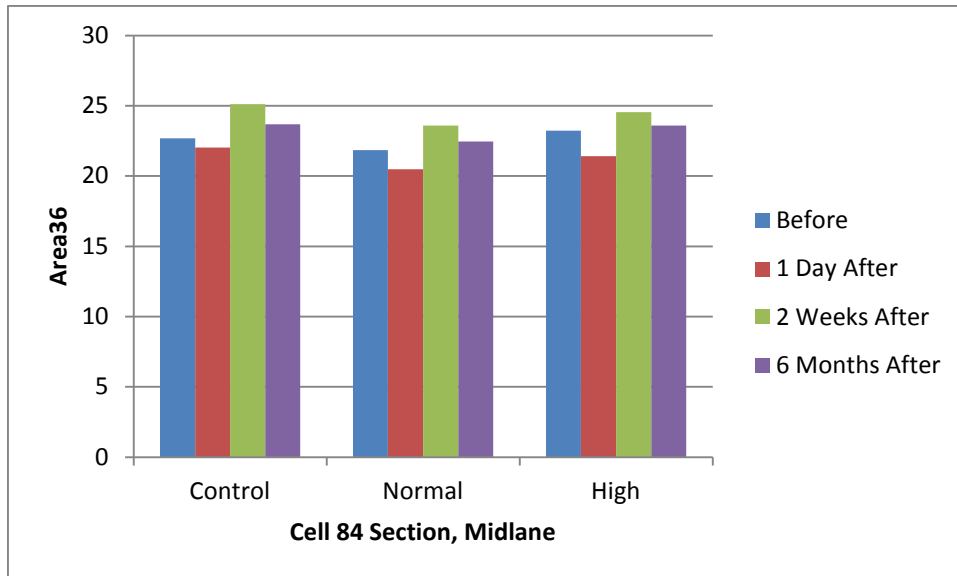


Figure 11 FWD statistics for different tack treatments at Midlane.

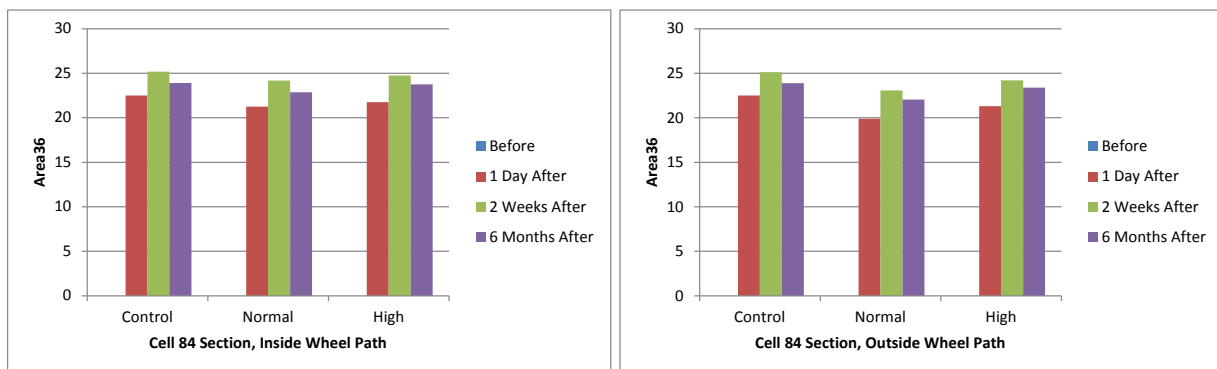


Figure 12 FWD statistics for different tack treatments in both wheel paths.

Comments

The conclusion was that there was very low bond strength in this construction experiment, even though complete tack coverage was achieved. One potential reason for unsuccessful initial coring may be there was insufficient material for bonding to a non-milled surface. Possible causes for this are:

- Application rate set too low
- Highly diluted tack product
- Surface dirt, dust, and other contaminants not sufficiently removed
- Tack emulsion insufficiently broken prior to paving

During the second round of coring it was observed that “cure” time was a factor contributing to improving the tack bond quality of pavement cores. It was also observed that uncontaminated, clean surface conditions improved the tack bond. The presence of tack increased the rate of successful bonding between the new HMA layer and the non-milled HMA surface.

Falling weight deflectometer (FWD) tests showed the deflections increased and the area factor actually declined immediately after overlay construction. The relative percent reduction related to the amount of tack applied; more tack meant lower basin area factors, suggesting poor bonding from inactive tack material or other reasons. Follow up FWD testing collected more encouraging data showing that during the time interval the basin area factor had increased and deflection magnitude had decreased.

Chapter 4: Tack Bond Test Results

[17, 18] During and after the 2013 construction season, MnDOT researchers measured the interfacial tack bond strength using the Florida Bond Tester. Tests were performed on 6-in. diameter field cores obtained from old and new construction projects around Minnesota. The cores were allowed to come to room temperature in the laboratory. The testing setup included a Marshall load frame fitted with a Florida bond test apparatus for evaluating shear along the tack interface. The equipment also recorded slip deformation between the tacked surfaces.

The project cored specimens from existing pavements and new construction and collected information on the date, road and location, and tack application rate. Gyratory mixtures were also collected and tested. Over 100 tests were performed, producing a data set of project statistics, specimen dimension, lift thickness, specimen test temperature, load history, and interfacial shear displacement. A brief summary and analysis follows.

Testing Summary

- Ten cores were taken in failure and non-failure areas of existing pavement on MNTH 95 that was paved the prior year. Dirt was detected between paved layers. Only three cores were survived the coring process to be tested in shear. Results showed that interface shear strength of 46 psi occurred within the pavement slip area. Other results were 69 and 107 psi.
- Two core sets were taken on nine year old pavement on US 10; near RP's 170 and 162. The district notes that the area near RP 162 has developed more cracking and has received more maintenance than the area near RP 170 since the completion of the current asphalt wearing course. Bond strength measured higher than expected for both core sets. Both sets developed relatively higher stresses at lower deformations compared to test results from other roads in the study. Specimens showed little mixture damage during failure, but failure was rapid and brittle-type. Typical values for the sets were approximately 150 psi at RP 162 and 300 psi at RP 170, and corresponding interface slip deformations were 0.07 and 0.18 inches, respectively. Low tack strength was not observed on the sample cores therefore distress does not appear to be the result of low tack strength. These results produced questions about the precise as-built tack rates in the two areas, which are unknown, and whether tack had any influence on the amount of cracking and maintenance activities in the areas.
- Cores were taken during construction at US 10 at Round Lake Boulevard. The project utilized spray-paving equipment and constructed sections from various tack emulsions that did and did not contain polymers. Application rates varied from 0.07 to 0.24 gal/yd². Test results showed that strengths for all of the emulsion types averaged above 100 psi, but the CSS1-h at 0.09 gal/yd² produced the greatest strength (160 psi) that corresponded to relatively large deformation (0.2 in.) at the tacked interface. Undiluted CSS-1h is a common tack material in Minnesota, and the results indicate there are benefits when emulsion coverage is near 0.1 gsy.
- Cores were sent from a "Texas Underseal" project in Beltrami County using FA 2 1/2 chip seal. Test results showed the underseal developed bond strengths between 93 and 135 psi, along with interface slip of 0.110 to 0.137 in.

- Cores were obtained on four construction projects in OtterTail County (CR11, 21, 31, and 73). The projects were overlay construction over tight-blade levelling, and tack was applied to the tight blade course. Bond strengths of the tack layer were near or above average (116 psi) for three of the sites. Lower values were obtained for CR 21 even though construction practices were similar, and there was some variability in shear data tests from CR 11 and CR 31 sites. This was unexpected since each core set was typically cut from a longitudinal path of less than 25 ft. No single explanation is possible for this finding, but factors could include: properly locating the loading location on each tight blade core, quality of tack material, control of application rate, or possibly variable absorption by the tight blade layer.
- Cores and gyratory mixture specimens were obtained for a project on MN 3. District inspectors documented tack application rates between the first and second lift paving of 0.031 and 0.045 gal/yd² and having corresponding average interface shear strengths of 148 and 134 psi. The average strength for all of the cores was approximately 140 psi. All results were above the interfacial strength average in MnDOT’s current data set. Mixture shear strength was also measured by using the Florida bond tester setup. The gyratory specimens were tested across the body in direct shears. Mixture shear strength of 6-in. gyratory specimens across their diameter, values ranged from 270 to 281 psi.
- Cores were obtained during construction of MnDOT’s Materials and Road Research Parking Lot. Intentional Tack / No-Tack areas were constructed. Results showed that the “No-Tack” section had little interface shear strength (4 psi), while the tacked areas developed 175 psi. Areas where tack was applied by wand developed only 48 psi.
- Cores were obtained after construction of Chisago CR 63, a “No-Tack” project that was built using the hot-on-hot paving technique of two lifts of hot mix asphalt. Both lifts were placed in a single day. Bond strength was 186.3 psi, with a corresponding bond interface shear deformation of 0.233 in. The test sheared through the mix of the two-lift, Hot-on-Hot paving specimen.

Analysis

All of the data acquired during the laboratory phase of the project is plotted in Figure 13. The plot shows peak interfacial bond shear stress of 6-in. cores and the deformation at peak stress. Data includes shear strengths of distributor- and spray-paver-applied tack coats as well as the shear strength of several asphalt mixtures used in the study. Boundaries for outlying peak shear and deformation data points were included on the plot. Outliers were defined as:

$$\text{Low Outliers} < (\text{MEDIAN} \pm 1.5 \times \text{IQR}) < \text{High Outliers} \quad \text{Equation 2}$$

Where:

IQR is the Interquartile Range; the difference between the dataset’s 3rd quartile and 1st quartile.

The outlier boundary for the full data set was determined to be located between shear values of 36.8 and 197.0 psi and between deformation values of 0.0087 and 0.2813 in. Outlier limits are plotted as a box within Figure 13. Tests of spray paver (in squares) construction resulted in no outliers with respect to deformation or interfacial shear strength. Mixture shear tests (in circles) typically resulted in strengths beyond, or close to the maximum outlier limit.

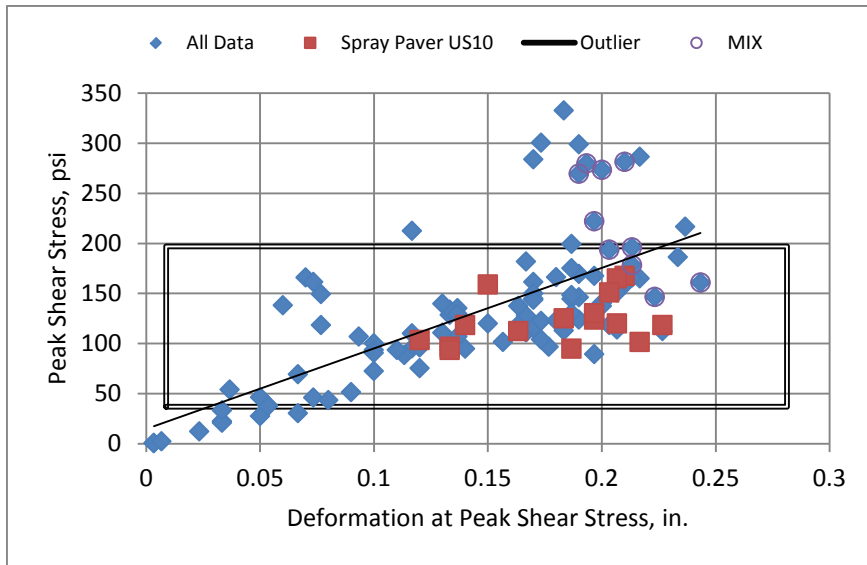


Figure 13 Interfacial bond shear strength versus deformation.

Cores taken from eight-year-old construction produced values that plotted above the main data group for Peak Shear Stress versus Deformation at Peak Shear Stress (Figure 14).

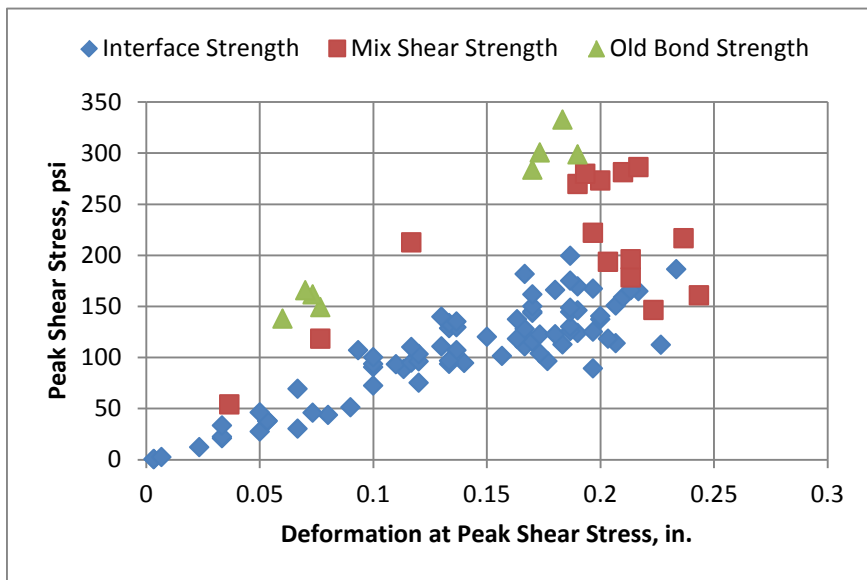


Figure 14 Interfacial bond shear strength versus deformation by specimen type and age.

Figure 14 also shows the relative location of Mixture Shear Strengths with respect to Old Bond Strength (8-yr old) and the Interface Strength of new construction. From inspection of the data, it was decided that both the eight-year old bond data and the mix shear strength situations should be considered separately from the interfacial bond strength of new construction.

A linear fit using all of the gyratory mixture specimen shear data for shear strength versus deformation produced an R-squared value of 0.33. This indicated a relatively weak relationship, and that perhaps more experimental data would be needed to strengthen the relationship. As an alternative, a sampling of the gyratory mixture specimens were evaluated for air voids and then

in shear. Figure 15 shows shear strength and displacement results for gyratory mixture specimens after testing in the Florida shear device. The figure illustrates the idea that relatively greater displacement occurs as air voids increase. Additionally, greater shear strength and can be associated with air voids near design value.

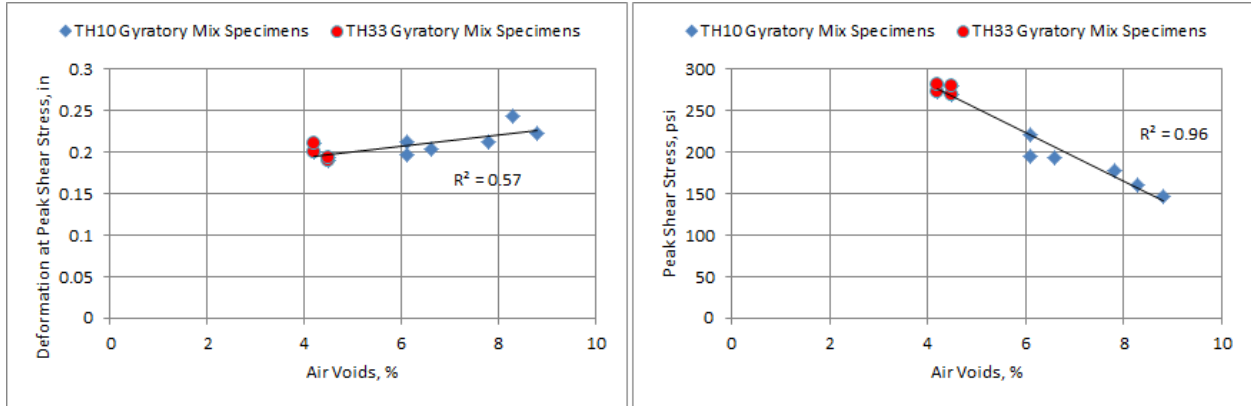


Figure 15 Behavior of gyratory mixture specimens tested in shear.

Figure 16 shows the interfacial bond strength of specimens cored from projects on an older roadway (US 10). The behavior in the Florida test apparatus indicated higher strength at lower deformation levels. Failure was less ductile than with any of the other specimens from new construction. The clustered data groups produce a best fit line that plots above the bond test data from new construction (Figure 16, Table 4). The fit shows likelihood that the intercept was approximately 58 psi, and not equal to zero, meaning that adhesive strength may have developed since the time of construction.

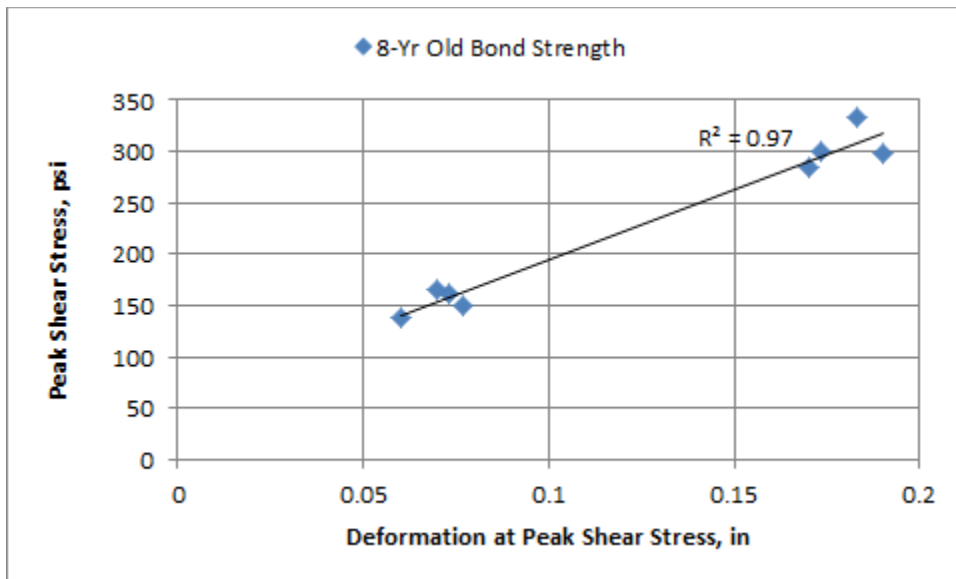


Figure 16 Interfacial bond strength of old construction.

Table 4 Linear Fit of 8-Yr Old Bond Shear Strength

Data set = Book1, Name of Fit = L1					
Normal Regression					
Kernel mean function = Identity					
Response = PSI-shear					
Terms = (In.-def)					
Coefficient Estimates					
Label	Estimate	Std. Error	t-value	p-value	
Constant	58.0852	13.1186	4.428	0.0044	
In.-def	1370.46	96.3159	14.229	0.0000	
R Squared:	0.971217				
Sigma hat:	14.9966				
Number of cases:	8				
Degrees of freedom:	6				
Summary Analysis of Variance Table					
Source	df	SS	MS	F	p-value
Regression	1	45532.5	45532.5	202.46	0.0000
Residual	6	1349.38	224.897		

Finally, a linear regression was performed on the specimens from new construction. The data was conditioned by removing the mixture shear results, interfacial bond results from old construction, and also low strength outliers below 36.8 psi. The conditioned data set had mean values of 117.1 psi shear strength and 0.1517 in. deformation. Corresponding standard deviations were 37.47 psi and 0.0465 in.

Table 5 presents the regression on the conditioned data. Figure 17 uses dashed lines to show the regression and standard deviation. The calculated intercept using this set of new construction data was approximately 20 psi. A Lowess function was also plotted for comparison. Note that the standard deviation from the linear fit is of constant value while that from the Lowess function increases with shear strength.

Table 5 Linear Fit of Bond Shear Strength with Outliers Removed

```

Data set = Book1, Name of Fit = L2
9 cases are missing at least one value.
Normal Regression
Kernel mean function = Identity
Response      = PSI-shear
Terms        = (In.-def)
Cases not used and missing at least one value are:
(70 71 72 73 74 75 76 77 78)
Coefficient Estimates
Label      Estimate      Std. Error    t-value    p-value
Constant   19.7492      9.36671      2.108     0.0387
In.-def    641.742     59.0639     10.865    0.0000

R Squared:      0.634512
Sigma hat:      22.8189
Number of cases: 79
Number of cases used: 70
Degrees of freedom: 68

Summary Analysis of Variance Table
Source      df      SS      MS      F      p-value
Regression  1      61470.5  61470.5  118.05  0.0000
Residual    68     35407.8  520.703
Lack of fit  37     21259.7  574.587  1.26   0.2576
Pure Error  31     14148.1  456.39
    
```

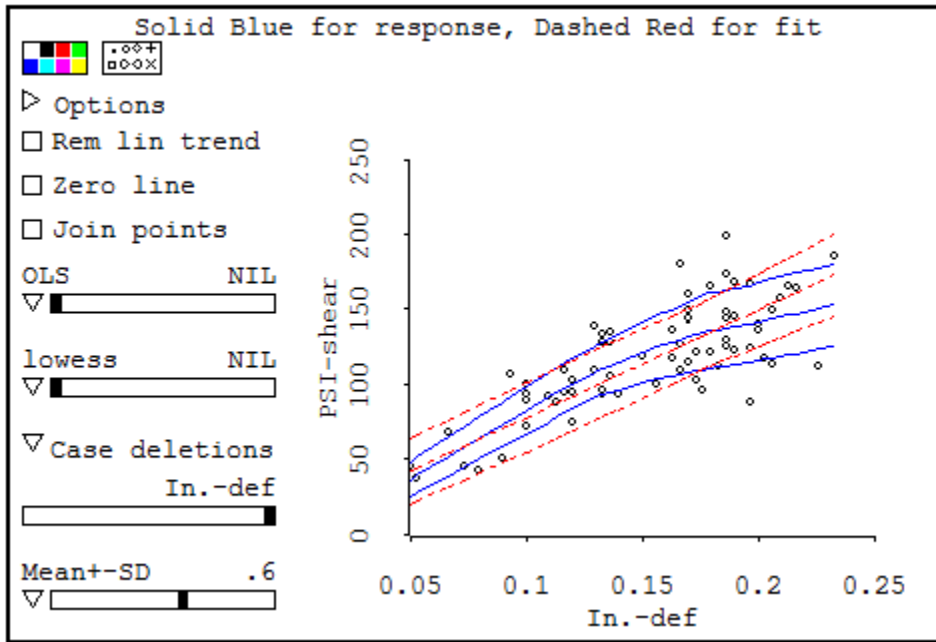


Figure 17 Interfacial bond shear strength versus deformation with outliers removed [19].

Chapter 5: Discussion and Recommendations

Minnesota Bond Strength Data

In the previous chapters it was shown that testing was performed on three general types of specimens: specimens made from cores taken from new construction projects, old construction projects, and specimens made from gyratory mixture design cores. Interfacial Bond Shear Strengths on newer construction ranged from:

- 1) minimums of 0 psi on cores cut in contaminated situations, to
- 2) low strengths of 37 psi when free of contaminants, and a
- 3) maximum of 200 psi.

Tack Coat Test Criteria Established by Others

- Tack coat application rates discussed by other researchers generally matched well with in-place Minnesota specifications.
- Average tack coat strength observations by NCHRP [5] between 35 and 80 psi provide a guide in screening poor strength performers.
- Use of Florida Shear test by others (Washington DOT [11]) supports the usefulness for Minnesota evaluations and potential tech-transfer situations.
- NCAT's findings [13] support MnDOT's decision to conduct bond testing at ambient laboratory temperatures and recommended a minimum bond shear of 100 psi.

Comments on Contamination

During this study several cases of contamination by dusty and/or fine aggregate were documented. In those cases core specimens either did not maintain sufficient bond adhesion to survive coring, or survived to produce weak bond shear strength results. The common practice of limiting tack coat application lengths to reasonable distances is due to the expected length of paving, requirements of crossing traffic, weather, and other related influences. The practice minimizes exposure to contaminants and tracking, and also fits well with an overall goal of efficiently providing tack and then paving over it as soon as practical. It also seems reasonable that tack coats should be able to withstand minor amounts of contamination. Regarding the Minnesota specification for tack coat, residual asphalt application rates range from 0.03 to 0.06 gal/yd². The rates would theoretically convert to residual asphalt film deposits of nearly 130 to 280 microns if applied evenly.

Recommendations for Test Implementation

Minnesota test data was grouped by project and averages were then calculated for peak shear stress of the interfacial bond and for mixture shear stress when possible. Figure 18 shows that standard deviations were near the value of 20 psi despite a somewhat increasing trend. The plot shows that most of the data is grouped below 40 psi with the exception of the two points (circled) with standard deviations near 80 psi. Records indicated that all of the higher standard deviations came from test sections on US 10 where materials and application rates were intentionally varied in a tack material study.

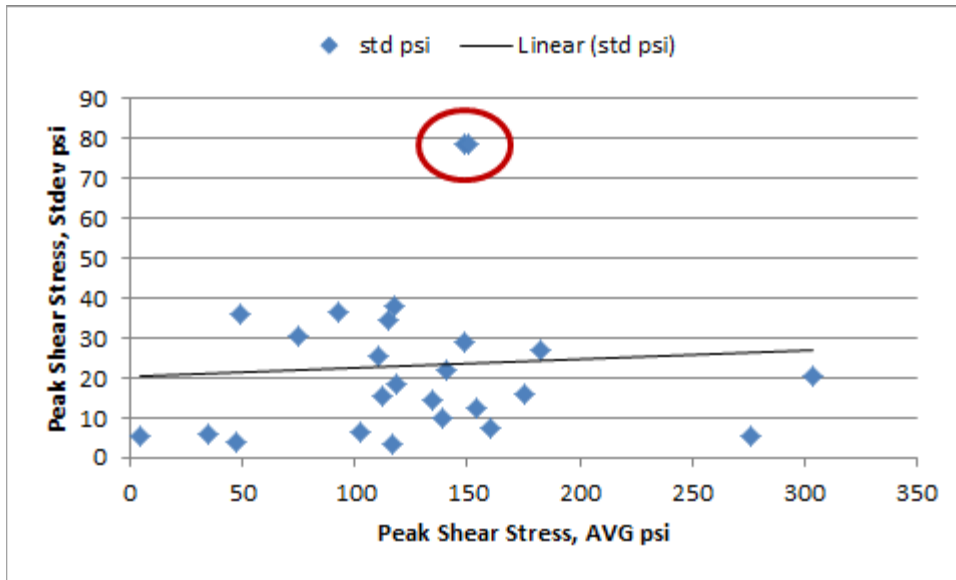


Figure 18 Standard deviation from Minnesota test data.

However, the US 10 averages were not easily identified from a plot of the coefficient of variation (Figure 19).

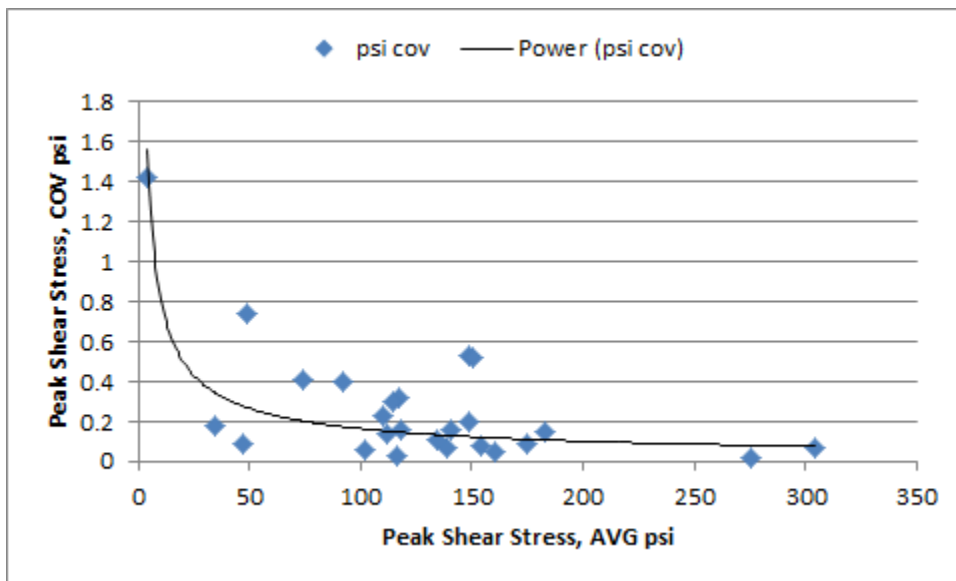


Figure 19 Coefficient of variation from Minnesota test data.

Conclusions from Florida's work (15) and comparisons of Minnesota test statistics (Figure 18, Figure 19) support the use of standard deviation and peak shear stress as a screening tool for interfacial bond strength. One proposed version of a screening tool is shown in Figure 20.

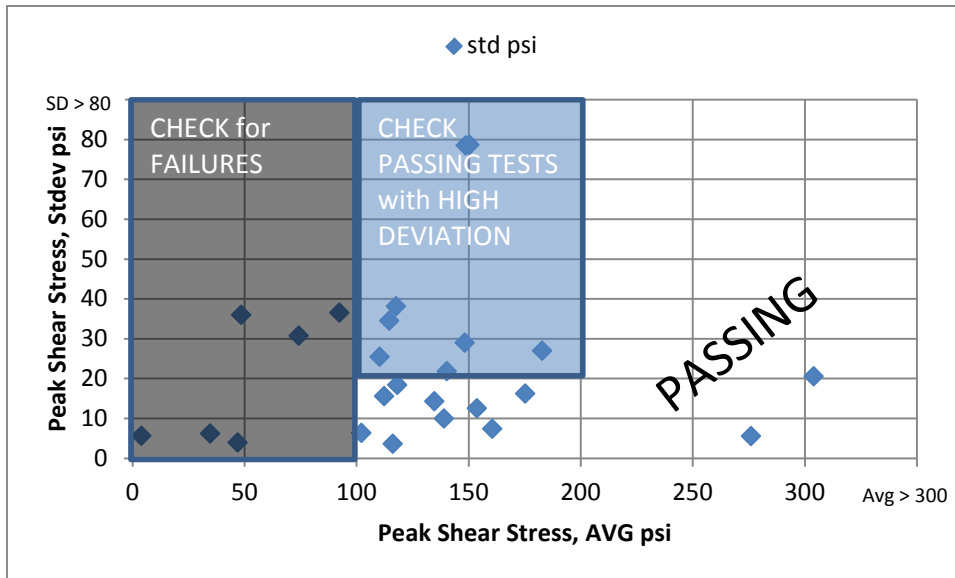


Figure 20 Example guideline proposed for evaluating shear stress results.

Note that the proposed criteria are based solely on laboratory results. It is unknown if the limiting values qualify as conservative with respect to actual field performance. Also note that the example screening tool currently lacks data in the region where the peak shear stress average exceeds 200 psi and the sample standard deviation is greater than 20 psi. It is expected that future testing will encounter such cases and allow the opportunity to compare test statistics with the current data set.

It is expected that refinements to failure criteria and frequency of testing will naturally occur as testing experience increases, test data is accumulated, and more field performance is observed.

Recommendations for Pilot Testing Program

This section contains options for equipment, data collection, test protocol, and performance criteria for a pilot tack bond strength testing program.

Equipment options:

- Recommendations for a Minnesota Tack Bond testing program include the use of a Marshall-style load frame. Rationale is that load frames of this type have been used in asphalt laboratories for many years, and should be readily available at no cost.
 - Load frame with maximum of 10,000 lb or more, capable of loading at a rate of 2 in/min.
 - Displacement measurement is desired for research level work, not necessary for production type work.

Data collection options:

- Digital readout of individual test maximum load, or
 - Marshall stability and flow testing software (Humboldt HMTS or similar)
- Capable of fitting a Florida Bond Test apparatus

Testing protocol:

- Follow Minnesota modifications of Florida Bond Test protocol (Appendix A)
- Cores should be marked to show the direction of milling, or traffic

Tack bond test performance criteria for Minnesota mixtures:

- Compute the average and standard deviation of peak shear stress from specimen sets made of three or more testable cores
 - Cores exhibiting layer separation during coring, or during removal from the core hole will be included in the specimen statistical values, and assigned a peak shear stress of 0 psi
- Core sampling location
 - Test core sets may be obtained from any location within an overlay project when cores are obtained within one month of construction
 - Test cores sets should be obtained in pairs so that one set is located between wheel paths and the other set is located outside of wheel paths when overlay projects are older than one month
- Test criteria
 - Average peak shear stress will be 100 psi or greater
 - The standard deviation of peak shear stress will be 25 psi or less

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Appendix A Florida Bond Test Procedure Used by MnDOT

Florida Bond Test Procedure used by MnDOT

FDOT Shear Test (8/21/06)

Sample Preparation

1. Cores should be 6" in diameter (**CHANGE: MnDOT add "and marked with traffic and milling direction"**). Cores with a diameter less than this can be accommodated with shims.
2. Measure the diameter of the core at three equally spaced locations around the circumference of the core. Take the average of the three readings.
3. Cores do not need to be trimmed with a saw. The machine can accommodate any length core.
4. The core should be (**CHANGE: MnDOT change to "acclimated to room temperature for three hours", and delete the rest.**) conditioned at 77 °F for three hours. ~~This can be accomplished in an air chamber or water bath. If a water bath is used, the core should be placed in a sealed bag so that it does not get wet.~~

Machine and Sample Setup

1. The gap width between the shearing platens should be set at 3/16".
2. Without a specimen in place, snugly clamp the upper and lower halves of each shearing platen. Use a straightedge to align the platens.
3. Unclamp the upper and lower halves of each shearing platen.
4. Insert shims at this time if needed.
5. Place the sample into the shearing platens, aligning the layer interface with the center of the gap between the platens.
6. Cores are typically sheared in the direction of traffic. FDOT routinely inserts the cores so the direction of traffic faces up.
7. If the core was obtained at a slight skew, then the core should be rotated so that the skew will not affect the test results, i.e. the failure plane is vertical.

Testing the Sample

1. The loading rate is 2"/min.
2. Set the load range to 10,000 lbs. as an initial starting point. If the cores are shearing at loads lower than 5,000 lbs, the load range can be changed to 5,000 lbs for better resolution.
3. Start the test and plot the load versus displacement curve. From the plot, obtain the maximum load. (**CHANGE: MnDOT add "Cores having interfaces that failed during coring or removal from the hole will be assigned a maximum load of 0 lb and included in the sample mean."**)

5. Divide the load by the cross-sectional area to obtain the shear stress.
6. **(CHANGE: MnDOT add “Calculate mean and standard deviation from a minimum of three test results obtained from #3 above.”)**

Appendix B Minnesota Tack Strength Case Studies

Minnesota Tack Strength Case Studies

Case No.	Agency	Highway	Location	Cores	Gyratory	Remark
1	MnDOT	MNTH 95	Metro	x		Bituminous slide
2	MnDOT	USTH 10	D3	x		2 RAP+shingles sections
3	Beltrami County	CSAH 22	Beltrami	x		Texas underseal
4	Chisago County	CR 63	Chisago	x		Hot to Hot HMA
5	MnDOT	I-35 and CR 61	Carlton Co.	x		Dirty/clean conditions
6	MnDOT	Parking lot	Metro	x		Tack/no-tack
7	Otter Tail County	CR 11, 21, 31, 73	Otter Tail	x		Tightblade level course
8	MnDOT	MNTH 33	D1	x	x	Tack rates
9	MnDOT	USTH 10	Metro	x	x	Tack rates/methods

Case Study No. 1

Project Location: TH95 RP55+ at CR14

Project Inclusion Criteria: HMA wear coarse slide condition

Roadway Owner: MnDOT Metro

Roadway Information: 2012 Bit. Overlay

Project Specifics:

Coring Plan: Core in slide area, Control Section -180ft. from affected area

Tack Rates, Product Used, Specification Notes:

Results: Seven of the 10 failed at the tack interface during the drilling process. No area consistently produced solid cores, including the "control". Strengths on the surviving cores were low to moderate.

Conclusions: Distress and no/low bond strength are both present. Presence of fines between paving lifts contributed to low bond strength.



Above: Roadway after coring – Core 6 was the only core in slide area to remain intact for testing (Circled in red).

Left: Inside faces After Bond Testing.

Control Core (Left) and Core 6 from Slide area (Right)

Notice Dirt present inside Core 6

Table Tack Interface Shear Results

Core Label	Max Load, lb	Max PSI	Deformation at failure, in.	Notes
T095E001	Failed at Drilling	0.0	FAD	1 st core from control section, 180ft. west of slide condition. Layers separated, no base mix retained – No Test
T095E002	2760.0	107.0	0.0933	Solid control core retained and tested
T095E003	1793.6	69.4	0.0667	Solid control core retained and tested
T095E004	Failed at Drilling	0.0	FAD	Control core 004 Taken <u>between</u> cores 002 and 003. Core Split @ layers – No Test
T095E005	Failed at Drilling	0.0	FAD	Control core, layers separated, base mix stripped – No Test
T095E006	1197.4	46.2	0.05	1st Core east of slide condition, Base mix stripped and poor, was tested
T095E007	Failed at Drilling	0.0	FAD	Limestone base materials encountered, Layers separated – No Test
T095E008	Failed at Drilling	0.0	FAD	Limestone base materials encountered, Layer separated in pickup after drilling – No Test
T095E009	Failed at Drilling	0.0	FAD	Limestone base materials encountered, Layers separated – No Test
T095E010	Failed at Drilling	0.0	FAD	Drilled in RWP alongside acceptance cores from construction, No Limestone base, Layers separated – No Test

The data set obtained in 2013 testing from multiple locations had mean and median values of 114 psi for interface shear strength.



Figure - Google Map of area. Blue Arrow is the approximate “Control Section” location, Red Arrow the 2013 slide area, Green arrow is the previous patch area.

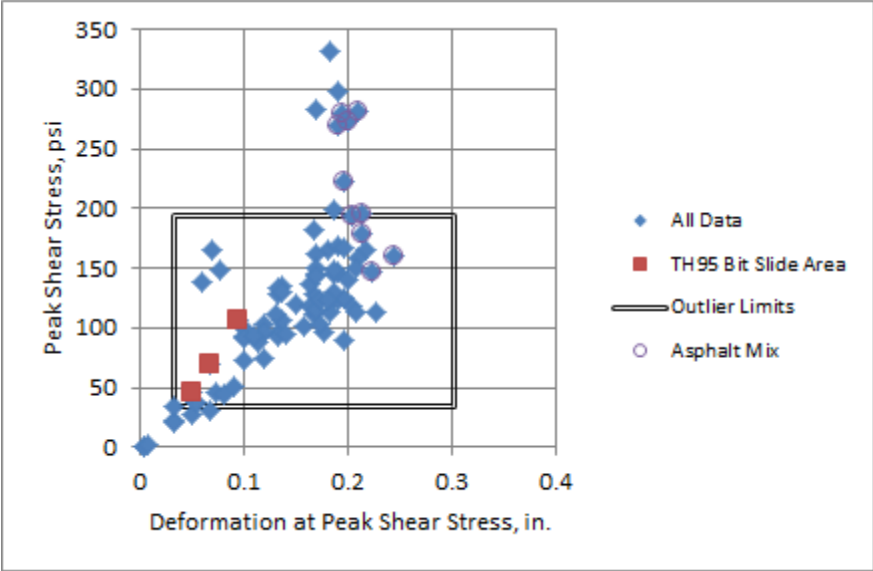


Figure - Bond strength data.

Case Study No. 2

Project Location: D3 US10 RP170 and RP162

Project Inclusion Criteria: Shingle Mix Sections, Heavy maintenance on northern section

Roadway Owner: MnDOT D3

Roadway Information: Shingle mix used as HMA wear course. Patching and crack sealing densely required north of Rice, MN. Cored for possible poor tack as cause of distress.

Project Specifics: See Tom Wood

Coring Plan: Core South (RP170) and North (RP162) of Rice, MN

Tack Rates, Product Used, Specification Notes:

Cores at RP170 required tools to break bond from original concrete surface. No Tools required on north section at RP162.

Results: Bond strength was measured higher than expected at both locations. Typical values for US 10 near Rice were approximately 150 psi at RP162 and 300 psi at RP170, with corresponding deformations of 0.07 and 0.18 inches.

At the time of testing the US 10 shingle mix samples developed relatively higher stresses at lower deformations compared to others in the data set. Specimens showed little damage during failure, and failure appeared to be rapid and nearly brittle-type.

The data set obtained in 2013 testing from multiple locations had median and mean values of 116 and 117 psi for interface shear strength.

Conclusions: Low tack strength was not observed on the sample cores. Distress does not appear to be the result of low tack strength. These results produce questions about the difference in distress rates and as-built tack rates in the two areas of core sampling.



Figure - Cores @ RP162 after testing



Figure - Cores @ RP170 after testing

Table - Tack Interface Shear Results

Roadway	Core No.	Max Load, lbs	Max PSI	Deformation at failure, in.
US10 D3 Shingle Mix Sections	U010W170001	3523.3	138.1	0.06
US10 D3 Shingle Mix Sections	U010W170002	3814.9	149.4	0.0767
US10 D3 Shingle Mix Sections	U010W170003	4237.5	165.8	0.07
US10 D3 Shingle Mix Sections	U010W170004	4132.7	161.6	0.0733
US10 D3 Shingle Mix Sections	U010W162005	7290.7	283.9	0.17
US10 D3 Shingle Mix Sections	U010W162006	7641.3	298.8	0.19
US10 D3 Shingle Mix Sections	U010W162007	8507.8	332.6	0.1833
US10 D3 Shingle Mix Sections	U010W162008	7687.1	300.5	0.1733

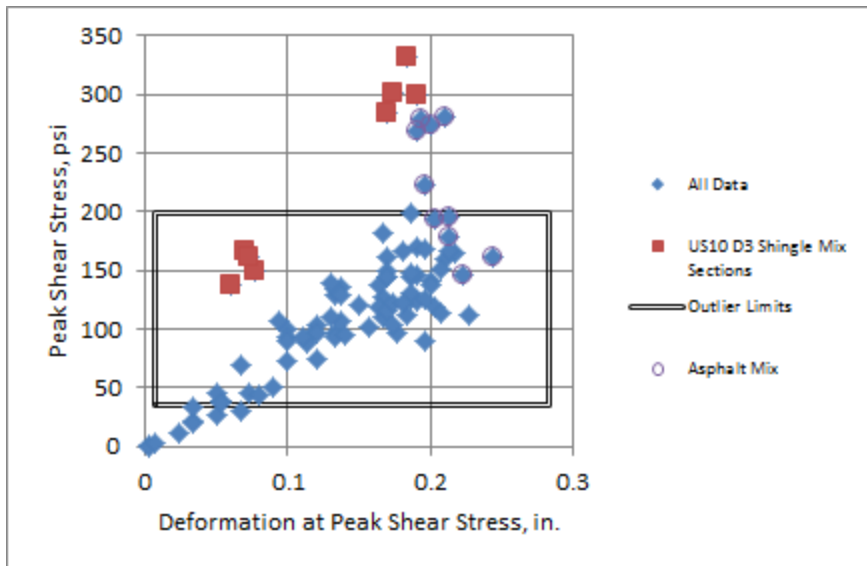
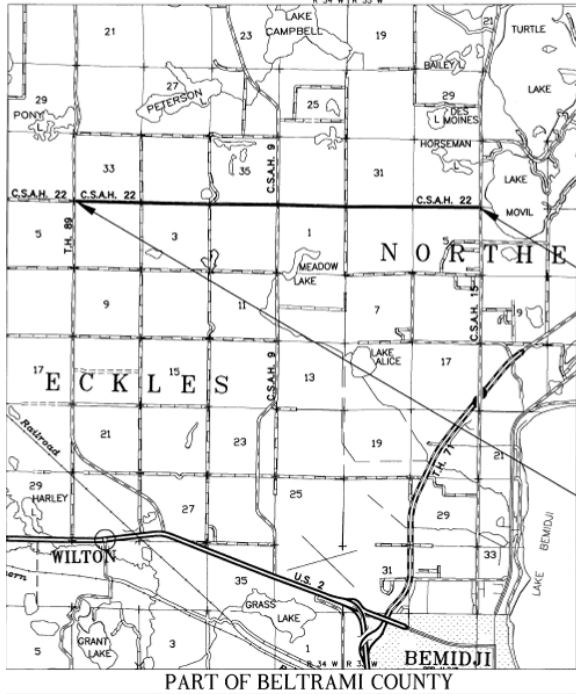


Figure - Bond strength data.

Case Study No. 3

Project Location: Beltrami County



Project Inclusion Criteria: Texas Underseal Project

Roadway Owner: Beltrami County

Roadway Info:



Figure - Preconstruction view of Beltrami CSAH 22 at RP 9.3, looking east. Image from PM video file.

Project Specifics: Beltrami utilized a Texas Underseal method, which is to construct a chip seal before placing new HMA overlay without milling in-place materials.

Coring Plan: Core Barrel was shipped to County staff for coring with local equipment. Direction of travel was marked well. No coring issues.

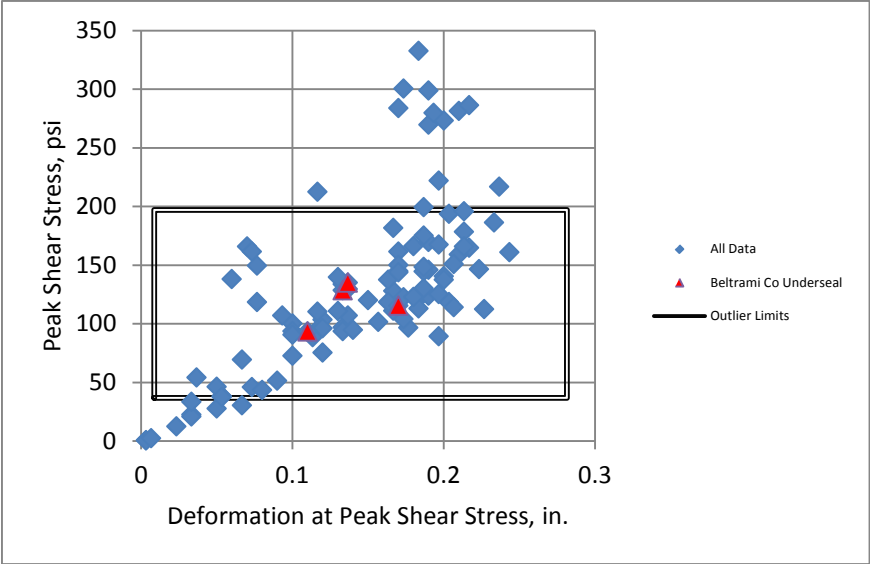


Figure - Underseal sample after testing.

Tack Rates, Product Used, Specification Notes: The project plan filed by Beltrami County (SAP 004-600-020) for bituminous resurfacing and aggregate shouldering on CSAH 22 specified the use of CSS-1h and FA-2 1/2 for underseal materials. The underseal was applied 24 ft wide across the existing surface, and was placed within 24 hours prior to paving. The plan quantity of emulsion was 23,680 gallons for 84,570 square yards of seal coat; approximately 0.28 gsy.

Tack was also specified at 0.05 gsy between the two layers of new pavement.

Results: The underseal cores developed strengths between 93 and 135 psi, along with interface slippage deformations of 0.110 to 0.137 in.



Case Study No. 4

Project Location: Chisago County Road 63 in Fish Lake Township, MN. Chisago 63 runs northwest from intersection with CSAH 8.

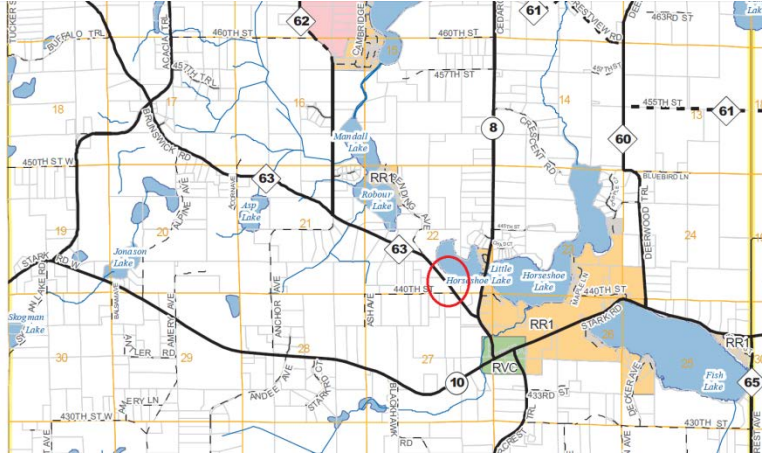


Figure - Coring location on Chisago CR63.

Project Inclusion Criteria: Hot-to-Hot HMA paving

Roadway Owner: Chisago County Highway Department.

Roadway Information: CR63

Project Specifics: Two lifts of hot mix asphalt. The surface lift was paved hot on hot without tack. Both lifts were placed in a single day.

Tack Rates, Product Used, Specification

Notes: County reported 0% tack between HMA layers.

Coring Plan: Core CR63 as a newly constructed county project. Cores were obtained in the northbound lane in an area south of Little Horseshoe Lake.

Results:

Bond strength was 186.3 psi, with a corresponding bond interface shear deformation of 0.2333 in. The test sheared through the mix of the Hot-on-Hot paving specimen.



Figure - RP 0.283 CR63 facing northwest. Image from PM videolog.

Case Study No. 5

Project Location: D1 Duluth

Project Inclusion Criteria: Researcher noticed hauling of concrete/aggregate materials overtop of well-placed tack.

Results:

Roadway Owner: Carlton CR via MnDOT D1 Duluth Concrete Overlay project

Roadway Info: Carlton CR61 under I35N @ CR61 exit, west side of exit/bridge, left wheel path in EB lane. Inspector suggests shoulder construction on I35 @ RP 245

Project Specifics: Research note dirty condition of tack on project. Tack was placed at 100% coverage using “Black sheet of paper” specification.

Coring Plan: Core in LWP of CR61 at approximate station 265+00 and 247+00, Local Control on shoulder of RP245 used. Note, different HMA was required between study and control area.

Tack Rates, Product Used, Specification Notes:



Figure – Top and Center: Haul Trucks dropping dirt
Below: Coring LWP of area



Left: Backhoe Operations at soft spot (notice dirt pile)



Right: Coring at location

Case Study No. 6

Project Location: MnDOT
Materials and Road Research
Parking Lot

Project Inclusion Criteria:
Parking Lot reconstruction and
ramp removal created an
opportunity to construct an
intentional Tack / No-Tack area.

Roadway Owner: MnDOT –
MRR Lab Lot



Figure - Ramp area with wand-applied tack.

Roadway Informaton: Parking Lot, 2
lifts over aggregate base/

Project Specifics:

Coring Plan: Core Tack / No-Tack
sections for testing

**Tack Rates, Product Used,
Specification Notes:** CSS-1h with
“Black sheet of paper” spec.



Figure - Distributor applying tack.



Figure - No-Tack Core (left) with clean layer separation. Tacked Core (right) was semi-bound after shear testing.

Results:

The greatest shear loading was The “Ramp Set Tack” shear tests

Table - Interface Bond Shear Data from Laboratory Lot Cores

Test Area	No. Cores Taken	Max Shear (stdev), psi	Deformation at Max Shear (stdev), in.
Lab Lot - Intended NoTack	4	4.0 (5.6)	0.0092 (0.0096)
Lab Lot - Intended Tack	4	175.2 (16.2)	0.1925 (0.0145)
Lab Lot - RampsetTack/Wand	6	48.4 (36.0)	0.0722 (0.0534)

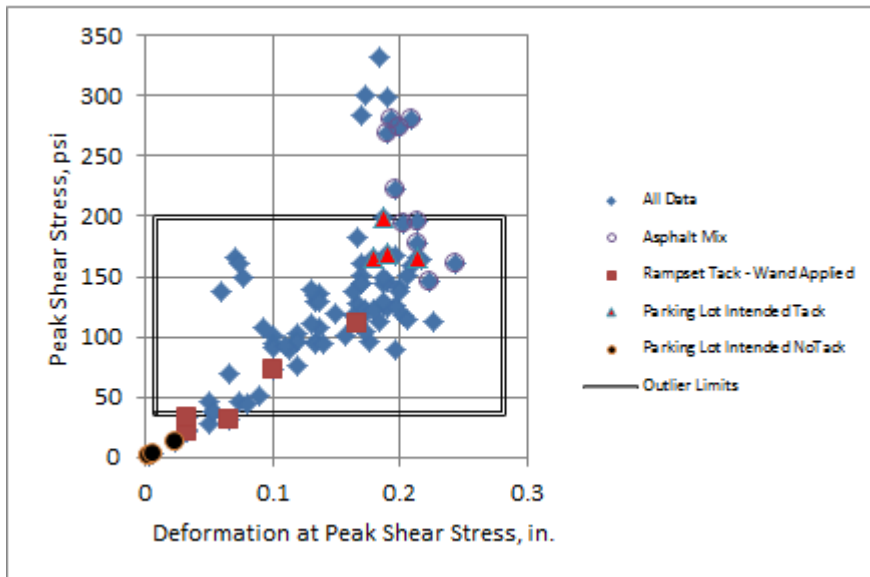


Figure - Bond strength data.

Case Study No. 7

Project Location: Otter Tail County

Project Inclusion Criteria: Tight blade to HMA wear course

Roadway Owner: Otter Tail Co. Hwy. Dept.

Roadway Information: CR11, CR21, CR31, CR73

Project Specifics: Local Inspectors recorded and documented tack and paving for research staff to review. Coring Field log described core adhesion to the primed base layer as stronger in some areas than was the newly constructed layers. Historically, primed base was standard practice in county sections at original construction.



Figure - CSAH 21 STA 46+00 Left Lane on Existing Pavement.

Coring Plan: Core newly constructed misc. county projects

Tack Rates, Product Used, Specification Notes:

Results:

Bond strengths of the tack layer in full depth cores were near or above average (116 psi) for three of the four sites that were investigated. Note the lower values obtained for CR 21 even though construction practices were similar. Figure shows conditions of the CR 21 coring location prior to paving.

Table - Average Bond Strength, OtterTail County, 2013

Road	Strength, PSI	Deformation at failure, in.	Field Notes
CR 11	101.8	0.111	East/West Sections, Rubber tired roller used in finish see pics, all samples seem primed when built? Tightblade-HMA layer const.
CR 21	46.9	0.081	Sections, Tightblade-HMA layer const.
CR 31	114.5	0.162	Sections, Tightblade-HMA layer const.
CR 73	139.0	0.190	Sections, Tightblade-HMA layer const. was being paved day of coring - some pics of tack from drive by, last cored for day

There was some variability in shear data from cores obtained on CR 11 and CR 31 sites. This was unexpected since each core set was typically cut from a longitudinal path of less than 25 ft. No single explanation is possible for this finding, but factors could include: properly locating the loading location on each tight blade core, quality of tack material, control of application rate, or possibly variable absorption by the tight blade layer.

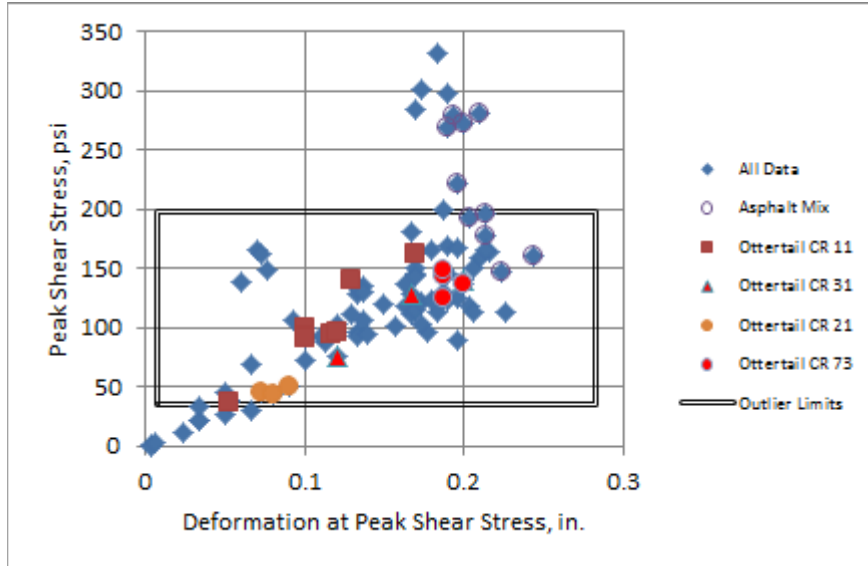


Figure - Bond strength results.



Figure - CSAH 11 STA 47+50 Left Lane on Tight Blade.



Figure - Core Bond to Base exceeds tight blade layer bond.



Figure - CR73 Paving Train.



Figure - CR73 Distributor finishing application.

Case Study No. 8

Project Location: D1 TH33

Project Inclusion Criteria: Tack Rates measured and verified in field

Roadway Owner: MnDOT D1

Roadway Information: Mill and overlay for 2013

Project Specifics: Gyrotory pucks and coring reports provided. See coring reports MDR and Tack Sample Tests

Coring Plan: Core barrel shipped to the District for coring the tacked roadway. Cored specimens were returned without direction of travel marked on cores so wear-to-non-wear tack bond was tested, and specimen orientation was determined in the lab.

Tack Rates, Product Used, and Specification Notes: Rates and materials were documented by district staff.

Table - TH33 CSS-1h Tack Application

Site – Tacked Surface	% Water	Wet Appl. Rate, gsy	Max. Load, PSI	Deformation at Failure, in.
Site 1 – Milled to 1st Paved Layer	50%	0.086	No Test	No Test
Site 2 – Milled to 1st Paved Layer	50%	0.072	No Test	No Test
Site 1 – 1st to 2nd Paved Layer	50%	0.045	133.7	0.1333
			181.7	0.1667
			129.5	0.1367
			No Test	Damaged core
Site 2 – 1st to 2nd Paved Layer	50%	0.031	150.1	0.1700
			143.7	0.1700
			122.5	0.1733
			122.8	0.1800

Results: Tack rates between the first and second lift paving were measured at 0.031 to 0.045 gsy and the corresponding average interface shear strengths were 148 and 134 psi. The average strength for all of the cores was approximately 140 psi. All results were above the interfacial strength average in MnDOT's current data set.

When testing the mixture shear strength of 6-in. gyrotory specimens across their diameter, values ranged from 270 to 281 psi. These values were nearly 75 psi higher than the upper outlier criterion from MnDOT's data set of bond shear strength along the paved layer interface.

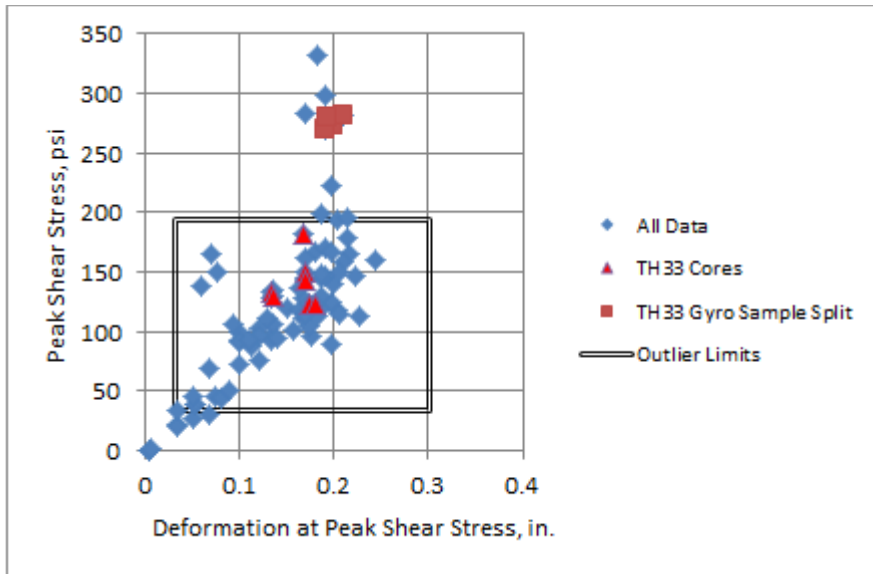


Figure - Bond strength data.



Figure - Site 1 - first tack on milled surface, NB Passing Lane.



Figure - Site 1 - after 2nd tack, NB Passing Lane.



Figure - Site 2 - after 2nd tack, NB Passing Lane.



Figure - Gyratory mix specimens broken in shear device - notice apparent layer separation without a layer interface.

Case Study No. 9

Project Location: EB US10 at Round Lake Blvd.

Project Inclusion Criteria:
Project featuring varied tack rates using polymer modified asphalt emulsion (PMAE). Road Science Spray Paver Study.

Roadway Owner: MnDOT Metro

Roadway Information:
US10 Milled, paved with HMA below Ultra Thin Bonded Wear Course as surface course

Project Specifics: All bond tests conducted at Milled/HMA layer. UTBWC was too thin for successful testing.

Coring Plan: Core each Tack Rate section by station. Nighttime paving operations for Metro Construction, lack of construction photos because of poor light.

Tack Rates, Product Used, Specification Notes:
PMAE: 0.144, 0.207, 0.24 gsy
CSS-1h: 0.094 gsy

Results:
The Road Science sections developed bond strengths averaging between 115 and 160 psi. The average for other spray paving was 102 psi, which was just in the lower half of all 2013 test results.

Conclusion:
Based on average to above average test results, tack coats on these sections should have good performance.



Figure - Typical Core after bond testing - Layers would require tools to separate. 0.24 g/sy PMAE pictured



Figure - Samples from 0.144 g/sy PMAE

Table - US 10 Spray-Paver Sections

Date	Station	Material	Application Rate, gsy*	Max Load, lbs	Max PSI	Deformation at failure, in.
9/16/2013	EB Passing US 10	MnDOT 2357	0.07-0.11	2498.0	96.8	0.133
9/16/2013	EB Passing US 10	MnDOT 2357	0.07-0.11	2414.4	93.6	0.133
9/16/2013	EB Passing US 10	MnDOT 2357	0.07-0.11	2663.4	103.3	0.120
9/16/2013	EB Passing US 10	MnDOT 2357	0.07-0.11	2627.4	101.5	0.157
9/16/2013	EB Passing US 10	MnDOT 2357	0.07-0.11	2763.3	106.9	0.137
9/16/2013	EB Passing US 10	MnDOT 2357	0.07-0.11	2873.1	110.8	0.130
10/1/2013	306+00 to 311+00	PMAE	0.144	3244.9	125.2	0.197
10/1/2013	306+00 to 311+00	PMAE	0.144	3371.0	130.0	0.187
10/1/2013	306+00 to 311+00	PMAE	0.144	2912.4	112.8	0.183
10/1/2013	306+00 to 311+00	PMAE	0.144	2317.8	89.3	0.197
10/1/2013	311+00 to 316+00	PMAE	0.207	Failed at Drill		
10/1/2013	311+00 to 316+00	PMAE	0.207	3079.4	118.3	0.163
10/1/2013	311+00 to 316+00	PMAE	0.207	3220.3	123.9	0.190
10/1/2013	311+00 to 316+00	PMAE	0.207	2348.9	94.6	0.140
10/1/2013	316+00 to 321+00	PMAE	0.24	3079.4	120.0	0.150
10/1/2013	316+00 to 321+00	PMAE	0.24	3054.9	118.4	0.203
10/1/2013	316+00 to 321+00	PMAE	0.24	2928.7	113.9	0.207
10/1/2013	316+00 to 321+00	PMAE	0.24	2917.3	112.4	0.227
10/1/2013	321+00 to 326+00	CSS-1h	0.094	4340.7	167.5	0.197
10/1/2013	321+00 to 326+00	CSS-1h	0.094	4268.6	164.8	0.217
10/1/2013	321+00 to 326+00	CSS-1h	0.094	4136.0	159.0	0.210
10/1/2013	321+00 to 326+00	CSS-1h	0.094	3921.4	150.9	0.207
(*) Undiluted tack residual normally 57% of applied rate for CSS-1 and CSS-1h (MnDOT 2357)						

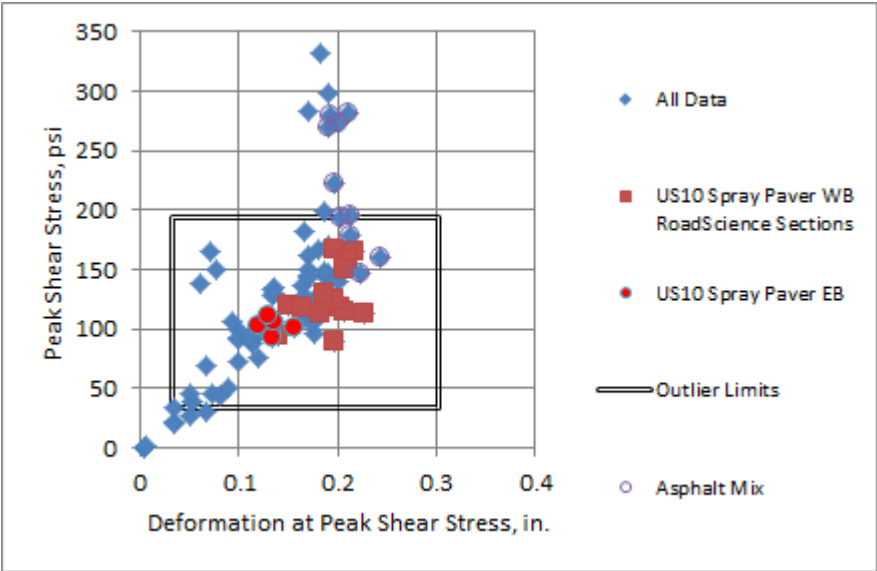


Figure - Bond strength data.

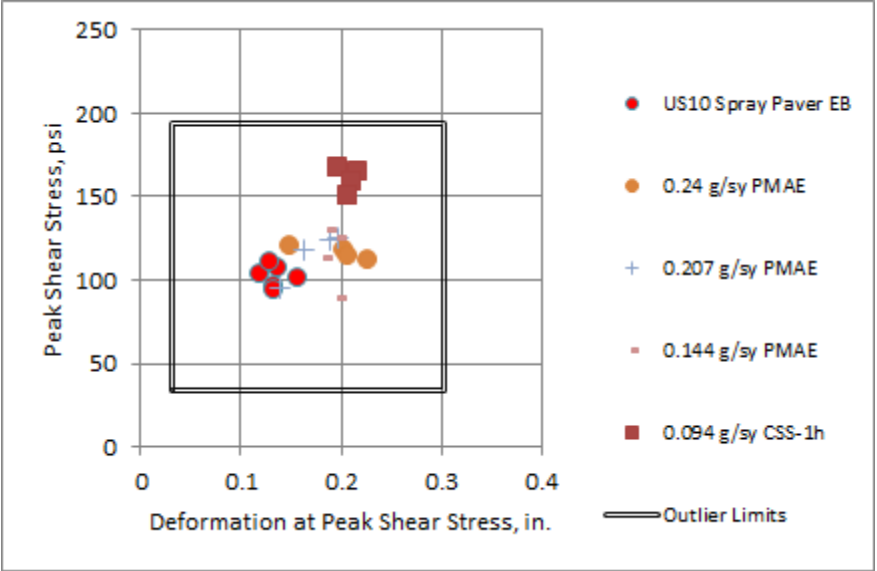


Figure - Bond strength for various spray paver application rates.