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Missouri's Bond Strength Investigation

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16. Abstract

Delamination or debonding between asphalt layers is a persistent problem often encountered when analyzing pavement cores taken from Missouri's roadways. Delaminated asphalt layers are suspected to be the primary cause of premature pavement deterioration that dramatically decreases the pavement's service life. After a thorough review, the Missouri Department of Transportation (MoDOT) increased their minimum tack coat application rates to more closely follow national recommendations and guidelines in order to mitigate the issues with delaminated asphalt lifts. This report presents the findings of a tack coat investigation conducted by MoDOT to evaluate and verify the effects of the tack coat specification change. The source of the data and information presented in the report is from a laboratory study and field studies that evaluated the bond strength of asphalt overlays between different surface types, tack coat products, varied application rates, and environmental conditions. The laboratory study evaluated different tack coat products for bond strength between two lifts of new asphalt and between new asphalt and concrete. The laboratory study subjected a set of each tack product to freezing temperatures to monitor the effects of cold temperature. Also, the application rates were varied to determine the most optimal rate for adequate bond strength.

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- Calumet Specialty Products Partners – Supplier for the Trackless Tack product who applied the product using their distributor truck for the US 36 field investigation.
- Vance Brothers – Supplier of conventional tack coat products used in the laboratory investigation.
- Blacklidge Co. – Supplier of Trackless Tack products used in the laboratory investigation.

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EXECUTIVE SUMMARY

Delamination or debonding between asphalt layers is a persistent problem often encountered when analyzing pavement cores taken from Missouri's roadways. Delaminated asphalt layers are suspected to be the primary cause of premature pavement deterioration that dramatically decreases the pavement's service life.

After a thorough review, the Missouri Department of Transportation (MoDOT) increased their minimum tack coat application rates to more closely follow national recommendations and guidelines in order to mitigate the issues with delaminated asphalt lifts. This report presents the findings of a tack coat investigation conducted by MoDOT to evaluate and verify the effects of the tack coat specification change. The source of the data and information presented in the report is from a laboratory study and field studies that evaluated the bond strength of asphalt overlays between different surface types, tack coat products, varied application rates, and environmental conditions.

The laboratory study evaluated different tack coat products for bond strength between two lifts of new asphalt and between new asphalt and concrete. The laboratory study subjected a set of each tack product to freezing temperatures to monitor the effects of cold temperature. Also, the application rates were varied to determine the most optimal rate for adequate bond strength. The following conclusions were made based on this investigation.

- As the application rate increased, the bond strength increased up to an application rate of 0.1 gal/yd^2. When the application rate increased over the 0.1 gal/yd^2 rate, the bond strength appeared to level off or even slightly decrease.
- When overlaying new Hot Mix Asphalt (HMA) layer to an existing Portland Cement Concrete Pavement (PCCP) surface, a 0.08 to 0.10 gal/yd^2 application rate of a typical asphalt emulsion (AASHTO M 140) appeared to optimize and yield the highest bond strength for the control (non-frozen) test specimens.
- When overlaying a new HMA to a new HMA surface, a 0.10 gal/yd^2 yielded the highest bond strength. However, as little as 0.03 gal/yd^2 application rate (0.018 gal/yd^2 residual) seemed adequate for acceptable bonding strengths for both the control (non-frozen) and the frozen test specimens.
- There was no significant difference in bond strength between hard penetration asphalt emulsions and conventional (soft penetration) asphalt tack coat products after subjecting the specimens to freezing temperatures.
- Overall, the bond strength results show an approximate 30% reduction when subjected to freezing conditions for all tack products that do not contain polymer.
- Tack coat products that contained polymer showed less bond strength reductions when subjected to freezing temperatures compared to non-polymer tack coat products. Polymers may provide a benefit to bond strength subjected to freezing, but further research is needed to verify the benefits.

A field study was conducted on US 36 in Buchanan County that investigated the bond strength between HMA/PCCP interface and HMA/HMA interface using three different tack coat products: SS1H, SS1HP, and a Calumet Trackless Tack. Bond strength testing was conducted on field sampled cores to determine the bond strength after construction and after the first winter to determine any low temperature effects on Trackless Tack compared to conventional tack. The following conclusions were made from this field study.

- All test sections with variable tack coat projects that consisted of SS1H, SS1H @ 20% dilution, SS1HP, and Trackless Tack achieved adequate bond strengths. The average bond strength of conventional tack coat was consistently higher compared to the Calumet Trackless Tack.
- Overall, there was a decrease in bond strength between layers after the first winter in both the Trackless Tack and conventional tack coat. Trackless Tack had similar bond strengths to conventional tack when subjected to low temperatures.
- After the first winter, the undiluted polymer tack resulted in the lowest reduction in bond strengths after the first winter; however. the constructability of applying the undiluted polymer tack was not practical due to excessive stringing and build-up on tires. Nevertheless, polymers may provide a benefit of maintaining bond strength between asphalt lifts when subjected to freezing temperatures.

A number of asphalt overlay construction projects were visited to help evaluate the constructability of the increased tack application rate. As part of the field visit, the product type, application rate, existing pavement surface type, and weather conditions were documented. Based upon the field construction projects, the following construction issues were typically encountered.

- The minimum 0.08 gal/yd^2 tack application rate was not an optimum rate for some surface types. The rate was too high for existing surface types (such as chip seals) that contained higher residual asphalt binder, while the rate on existing coldmilled surfaces proved to be inadequate for uniform coverage.
- Significant tack rate variability was encountered on the roadway during the application of the tack coat. On some projects proper nozzle type, configurations, and/or clogged nozzles remain an issue for achieving proper uniform tack coat coverage.
- For two-lane routes, trucks backing on the tacked surface immediately or within minutes are common occurrences, causing severe tack coat tracking off issues.
- Tack products containing polymers are more difficult to place due to build up on equipment tires and polymer strings blowing onto nearby areas.
- Tack coat tracking off the roadway prior to the paver is a primary issue in Missouri. It is considered the leading cause of inadequate tack and delaminated asphalt layers.

Based upon laboratory and field test results along with information collected from numerous site visits, the Construction and Materials Pavement Section makes the following recommendations:

- The required tack coat application rate needs to be varied from the 0.08 gal/yd^2 minimum rate depending on the existing surface type. It is recommended that the specification be revised to include a target application rate with +/- tolerances, along with adding higher target rates for coldmilled surface types.
- Trackless Tack products or tack coat products manufactured from hard penetration asphalt binders compared very similarly to conventional tack coat products when subjected to freezing temperatures. MoDOT should proceed with using Trackless Tack

products to help mitigate tracking off in the field. MoDOT also recognizes the limited number of suppliers of the Trackless Tack type products and will allow the use of conventional rapid setting tack coats applied with a spray paver as a contractor option.

- The constructability issues with polymers in tack outweigh the added bond strength performance. Therefore, tack coats containing polymers should be applied using a spray paver.

CHAPTER 1: INTRODUCTION

Delamination or debonding between asphalt layers causes performance issues of asphalt overlays on MoDOT's roadway system. Debonded asphalt layers do not act as one monolithic pavement structure. Surface or intermediate layers not bonded to underlying lifts can cause early surface cracking and deterioration in the pavement. Also, debonded layers create a plane of weakness, where water can infiltrate between the lifts that causes accelerated stripping and raveling.

Pavement cores taken from MoDOT's roadway system often show debonded lifts of asphalt that had caused premature failures within the overlay. The Construction and Materials Division's Pavement Section started researching the debonding issues to determine the cause of this phenomenon and developing solutions to help improve the bond between asphalt lifts and asphalt overlays of PCC pavements.

A literature search was conducted on tack coat optimization to compare MoDOT's tack coat specifications with other state agencies. National Cooperative Highway Research Program (NCHRP) Report 712, *Optimization of Tack Coat for HMA Placement*, recommended the following residual application rates for different surface types:

Table 1-1 NCHRP's Recommended Tack Coat Residual Application Rate [1]

Surface Type	Residual Application Rate (gal/yd^2)
New asphalt mixture	0.035
Old asphalt mixture	0.055
Milled asphalt surface	0.055
Portland cement concrete	0.045

The Asphalt Institute and other industry representatives were consulted to determine their recommended tack coat application rates and construction practices. The Asphalt Institute construction guidelines state the following: "You want to accomplish a very uniform application of about 0.03 to 0.05 gal/yd^2 of residual asphalt on the layer to be tacked (a paint job, so to speak)." [2] Another industry reference was the *Hot-Mix Asphalt Paving Handbook 2000*, which stated "Proper tack coat application will leave a residual asphalt cement content of approximately 0.18 to 0.27 l/m^2 (0.04 to 0.06 gal/yd^2) on the roadway." [3]

Based upon the literature search, MoDOT revised their tack coat application rate to better reflect the industry standard. MoDOT's prior specification allowed a range from 0.02 to 0.1 gal/yd^2. This minimum rate allowed the residual rate to be only 0.012 gal/yd^2, which is well below the recommendations obtained from the literature search. MoDOT increased the minimum tack coat application rates as listed in Table 1-2 for an interim solution based upon national recommendations.

Table 1-2 MoDOT's Revised Tack Application Rates

Surface Type	Application Rate (gal/yd^2)	Est. Residual Rate (gal/yd^2)
New asphalt mixture	0.05	0.030
Other existing surfaces	0.08	0.048

This report presents the research findings from a laboratory and field investigation that was conducted during the 2013 construction season by MoDOT. The data collected and conclusions drawn from this research should enable MoDOT to implement a better tack coat specification to provide asphalt overlays with adequate bonds and improve the service life of asphalt overlays.

CHAPTER 2: LABORATORY STUDY

A laboratory study was conducted that evaluated a variety of tack coat products. This study tested the bond strength between two lifts of new HMA and between new HMA and PCCP. The laboratory study also subjected a set of each tack product to freezing temperatures along with the room temperature (control) set to monitor the effects of cold temperature on bond strength. Bond strength evaluation was based upon achieving a minimum of 100 psi using a direct pull off testing device borrowed from Road Science. At this bond strength value, the tacked interface appears to be well bonded based upon the comparison of test specimens in which the bond strength result of 100 psi compared favorably to the "well bonded" determination when manually splitting the asphalt lifts with a press. At the present time, MoDOT has not correlated this value with roadway performance. The objectives of this study were to determine the optimum application rate of tack, the effects of cold temperatures, the benefits of polymers in tack products, and the evaluation of hard pen asphalt emulsions on achieving adequate bond strength.

2.1 Products Tested

Eight tack coat products were evaluated in this study. Three of the tack coat products were standard tack products that are commonly used by MoDOT. The remaining tack coat products evaluated are commonly used in spray paving applications, chip seal applications, or hard pen asphalts that are considered low or non-tracking tack coat products. The tack coat products evaluated in this study, along with their residual rates are listed below in Table 2-1.

Table 2-1 Laboratory Study Tack Coat Products and Application Rates

Tack Coat Products		**Surface Type – HMA to PCCP**				**Surface Type – HMA to HMA**		
Emulsion	**% AC**	**Conventional Application Rates (gal/yd^2)**				**Conventional Application Rates (gal/yd^2)**		
		.03	**.05**	**.08**	**.10**	**.03**	**.05**	**.08**
		Final Residual Rate (gal/yd^2)				**Final Residual Rate (gal/yd^2)**		
SS-1	60.4%	0.018	0.030	0.048	0.060	0.018	0.030	0.048
SS-1H	60.4%	0.018	0.030	0.048	0.060	0.018	0.030	0.048
SS-1HP	63.2%	0.019	0.032	0.051	0.063	0.018	0.032	0.048
CRS-1H	65.0%	0.020	0.033	0.052	0.065	0.020	0.033	0.052
CRS-2P	71.0%	0.018	0.030	0.048	0.060	0.018	0.030	0.048
CPEM-1	65.2%	-	-	0.052	0.065	-	-	0.052
Blacklidge Trackless	54.1%	-	0.030	0.048	0.060	0.018	0.030	0.048
Tack Coat Products		**Surface Type – HMA to PCCP**				**Surface Type – HMA to HMA**		
Emulsion	**% AC**	**Higher Residual Rates (gal/yd^2)**				**Higher Residual Rates (gal/yd^2)**		
CPEM-1	65.2%	0.078	0.098	-		0.078	-	
Blacklidge Ultrafuse	100%	-	-	0.12		-	0.12	

2.2 Sample Preparation

Standard concrete cylinders (6-inch x 12-inch) were used to mold concrete specimens for the test surface between HMA and PCCP on this project. Each cylinder was sawed into three equal parts for the test specimens. The sawed face side of the concrete cylinders was used as the test surface for surface consistency in the laboratory study.

Asphalt specimens were molded in the gyratory compactor using a conventional SP125C mixture for the test surface between HMA and HMA. The faces of each 6-inch gyratory specimens were also sawed for surface consistency and would be used as the test surface in the laboratory study.

2.3 Tack Coat Application

After each specimen was sawed, dried, and cleaned, a predetermined amount of tack coat product was applied evenly to the surface area of the test specimen to represent the residual rate. There was variability in the tack coat application as shown in the final residual rates listed in Table 2-1. The surface with the applied tack was placed in an oven at 126° F (52.22° C) for two hours to evaporate the water in the emulsified tack material.

2.4 Fabricating Specimens

A conventional SP125C mixture was used to bond to the test specimen surface using the different tack coat products. Each specimen of the test surfaces with the applied tack coat product was placed in the gyratory compactor mold. Approximately 2,500 grams of the SP125C mixture was placed on top of the tack product and ran through the gyratory compactor for 35 gyrations.

Two test samples were made for each product type and for each residual rate as listed in Table 1-1. One sample was used as a control for routine bond strength testing. The second sample was vacuum saturated and subjected to 50 freeze/thaw cycles to represent a typical Missouri winter.

2.5 Bond Strength Testing

A direct tension pull off device was provided by Road Science and used for bond strength testing for this study. Three 2-inch diameter bond strength samples are extracted from each 6-inch diameter test specimen. The test temperature selected for bond strength testing was 40° F (4.44° C).

2.6 Results and Discussion

The results from the bond strength testing were highly variable. On the one hand, there were only limited data points from each test specimens to draw conclusions. On the other hand, the limited data made a statistical analysis impractical to conduct and remove possible outliers. Table 2-2 below lists the average bond strength of the three specimens tested, regardless of its variability in the data set, at each application rate. The complete individual bond strength data can be found in Appendix A.

Table 2-2 Laboratory Average Bond Strength Data

Bond Strength Data

Control NonFrozen Specimens (HMA to PCCP)						
Application Rate	**0.03**	**0.05**	**0.08**	**0.1**	**0.12**	**0.15**
Product Type	**Bond Strength (psi)**					
SS1	115	105	108	108	-	-
SS1H	90	114	115	113	-	-
SS1HP	90	89	131	117	-	-
CRS1H	97	123	113	160	-	-
CRS2P	97	102	98	-	-	-
Blacklidge Trackless	-	77	148	117	-	-
CPEM1	-	-	114	123	85	114
Blacklidge Ultrafuse	-	-	-	-	137	-

Frozen Specimens - (HMA to PCCP)						
Application Rate	**0.03**	**0.05**	**0.08**	**0.1**	**0.12**	**0.15**
Product Type	**Bond Strength (psi)**					
SS1	75	62	72	74	-	-
SS1H	26	77	46	74	-	-
SS1HP	69	107	63	91	-	-
CRS1H	77	115	70	79	-	-
CRS2P	94	102	118	-	-	-
Blacklidge Trackless	-	85	102	103	-	-
CPEM1	-	-	68	79	89	65
Blacklidge Ultrafuse	-	-	-	-	71	

Control NonFrozen Specimens (HMA to HMA)						
Application Rate	**0.03**	**0.05**	**0.08**	**0.1**	**0.12**	**0.15**
Product Type	**Bond Strength (psi)**					
SS1	167	139	150	-	-	-
SS1H	153	124	178	-	-	-
SS1HP	182	131	155	-	-	-
CRS1H	151	169	171	-	-	-
CRS2P	118	120	122	-	-	-
Blacklidge Trackless	135	144	170	-	-	-
CPEM1	-	-	159	207	183	-
Blacklidge Ultrafuse	-	-	-	-	188	-

Frozen Specimens - (HMA to HMA)						
Application Rate	**0.03**	**0.05**	**0.08**	**0.1**	**0.12**	**0.15**
Product Type	**Bond Strength (psi)**					
SS1	79	123	111	-	-	-
SS1H	127	111	115	-	-	-
SS1HP	126	167	113	-	-	-
CRS1H	97	108	107	-	-	-
CRS2P	105	100	159	-	-	-
Blacklidge Trackless	122	95	119	-	-	-
CPEM1	-	-	123	115	137	-
Blacklidge Ultrafuse	-	-	-	-	159	-

Although there was significant variability in the bond strength data, a few conclusions were made and are listed below. Figure 2.1 and Figure 2.2 below also illustrate the conclusions.

- For new HMA/PCCP surfaces, at least a 0.08 gal/yd^2 application rate (0.048 gal/yd^2 residual) was needed to achieve the desired 100 psi bond strength for the control (non-frozen) test specimens.
- For new HMA/HMA surfaces, a 0.03 gal/yd^2 application rate (0.018 gal/yd^2 residual) was enough to adequately bond the surface together that yielded over 100 psi bond strength for both the control (non-frozen) and the frozen test specimens.
- As the application rate increased, the bond strength increased until an optimum application rate of 0.1 gal/yd^2. After 0.1 gal/yd^2, the bond strength appeared to level off or decrease.
- Most tack coat products did not pass the minimum 100 psi bond strength requirement for bonding between HMA to PCCP after being subjected to freezing temperatures regardless of the application rate. More research is required to compare the bond strength between laboratory vacuum saturating and freezing test specimens compared to field results.

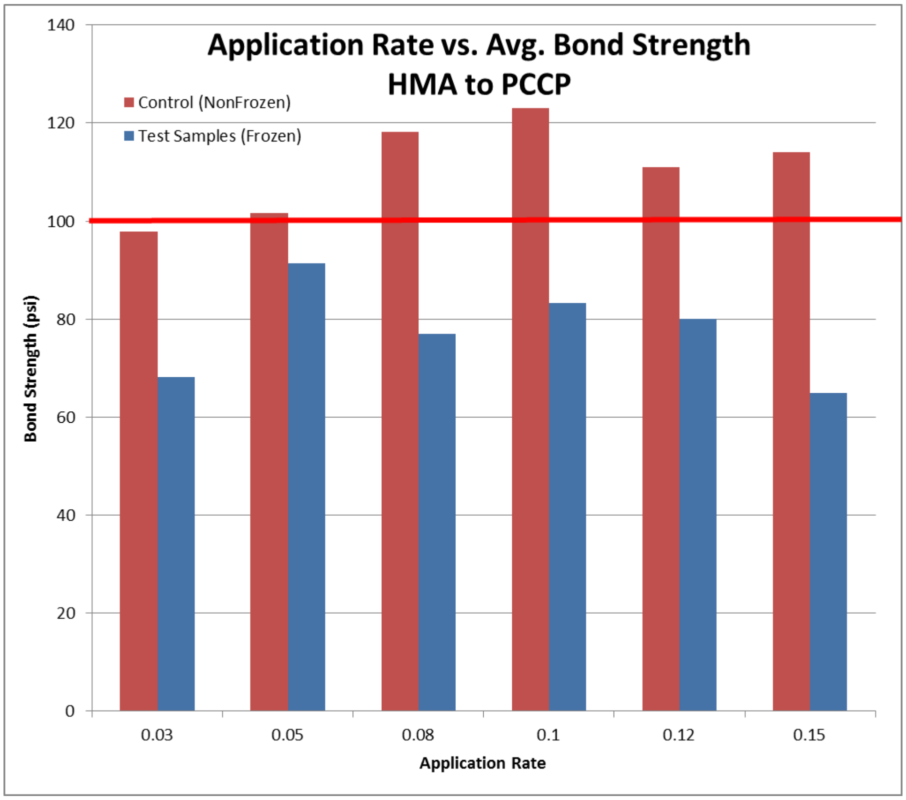

Figure 2.1 Laboratory HMA to PCCP Bond Strength Results

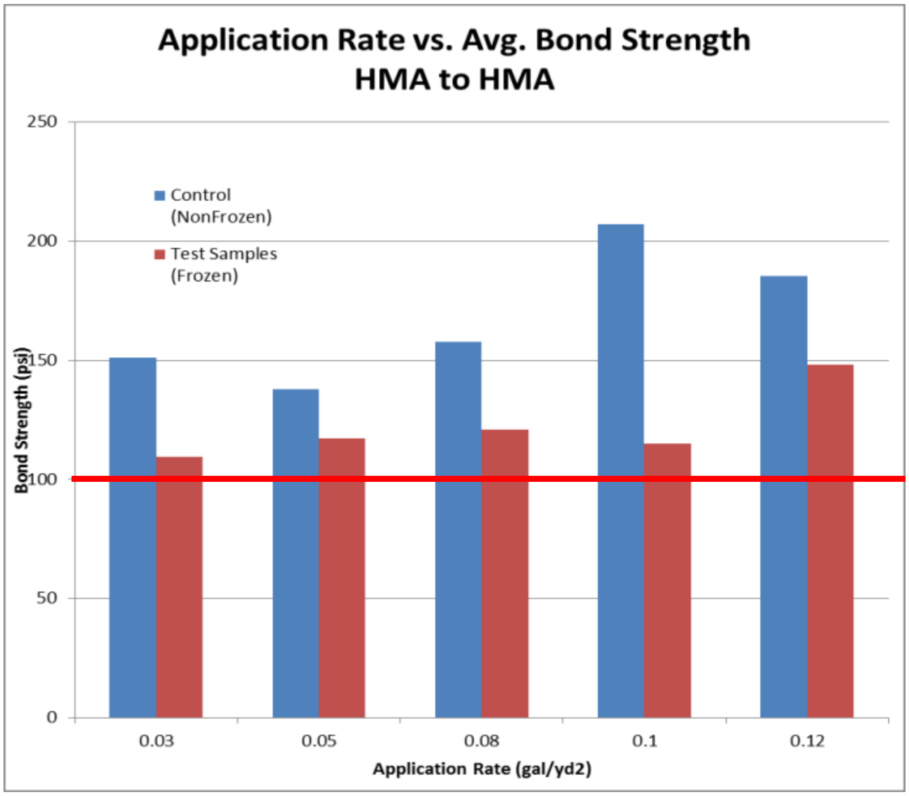

Figure 2.2 Laboratory Study HMA to HMA Bond Strength Results

The effects of freezing temperatures to hard penetration asphalt and emulsions were a concern for MoDOT due to Missouri's wet/freeze climate. Table 2-3 below lists the average percent decrease in bond strength of all tack coat products after subjecting the test specimens to freezing temperatures. Although the laboratory freeze tests on vacuum saturated test specimens proved to be harsher compared to field performance, some conclusions could be drawn from the analysis and are stated below.

- There was no significant difference in bond strength between hard penetration asphalt emulsions and conventional asphalt tack coat products after subjecting the specimens to freezing temperatures.
- CRS2P appeared to have no reduction in bond strength due to freezing temperatures and SS1HP showed lower reductions in bond strength. Polymers may provide a benefit to bond strength subjected to freezing, but further research is needed.

Table 2-3 Laboratory Bond Strength Freeze vs. Control Comparison

Control Specimens vs Freezing Specimens						
	HMA to PCCP			HMA to HMA		
Tack Coat Product	Avg Bond Stength Control	Avg Bond Stength Frozen	% Decease	Avg Bond Stength Control	Avg Bond Stength Frozen	% Decease
SS1	109	71	35.1%	152	104	31.4%
SS1H	108	56	48.4%	152	118	22.4%
CRS1H	123	85	30.8%	164	104	36.5%
Average of Control Products	**113**	**71**	**38.1%**	**156**	**109**	**30.1%**
SS1HP	107	83	22.7%	156	135	13.2%
CRS2P	99	105	-5.7%	120	121	-1.1%
CPEM	109	80	26.8%	183	125	31.7%
Average of Polymer Tack	**105**	**89**	**14.6%**	**153**	**127**	**14.6%**
Blacklidge Trackless	114	97	15.2%	150	112	25.2%
Blacklidge Ultrafuse	137	71	48.2%	188	159	15.4%

CHAPTER 3: FIELD STUDY

A field study was also conducted that evaluated the bond strength results between conventional tack, conventional tack with polymer, and trackless tack type products in between two lifts of asphalt and between asphalt and concrete. The bond strength was measured between the layers of each tack product approximately one month after construction and also after the first winter that subjected each tack product to freezing temperatures. The objectives of this field study were to determine the effects of cold temperatures on bond strength between different tack products, the benefits of polymers in tack products, and the evaluation of a trackless tack type product.

3.1 Project Set-Up

The field study took place on the eastbound lanes of US 36 in the Northwest District, near St. Joseph, Missouri. The project is located 0.8 miles east of Rte AC in Buchanan County to 0.7 miles east of Rte 31 in DeKalb County. This project was constructed by Herzog Inc. under project number J1P2195 in 2013. The project consisted of placing an HMA overlay that consisted of three lifts of asphalt on top of original PCC pavement. The project was divided into test sections where different tack coat products were applied and evaluated for bond strength. Figure 3.1 and Figure 3.2 below show the areas by stationing where the different tack coat products were applied along with a block diagram showing the tack coat that was applied between each lift.

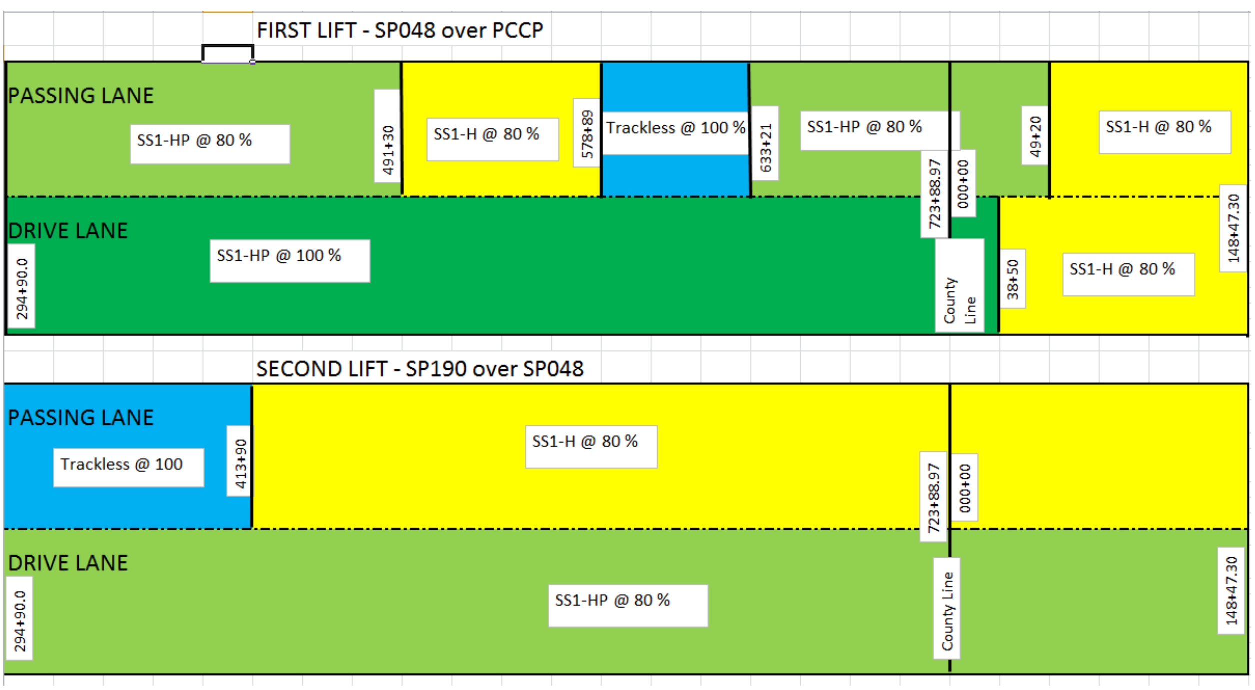

Figure 3.1 US 36 Field Study Asphalt Lift vs. Tack Product Plan View

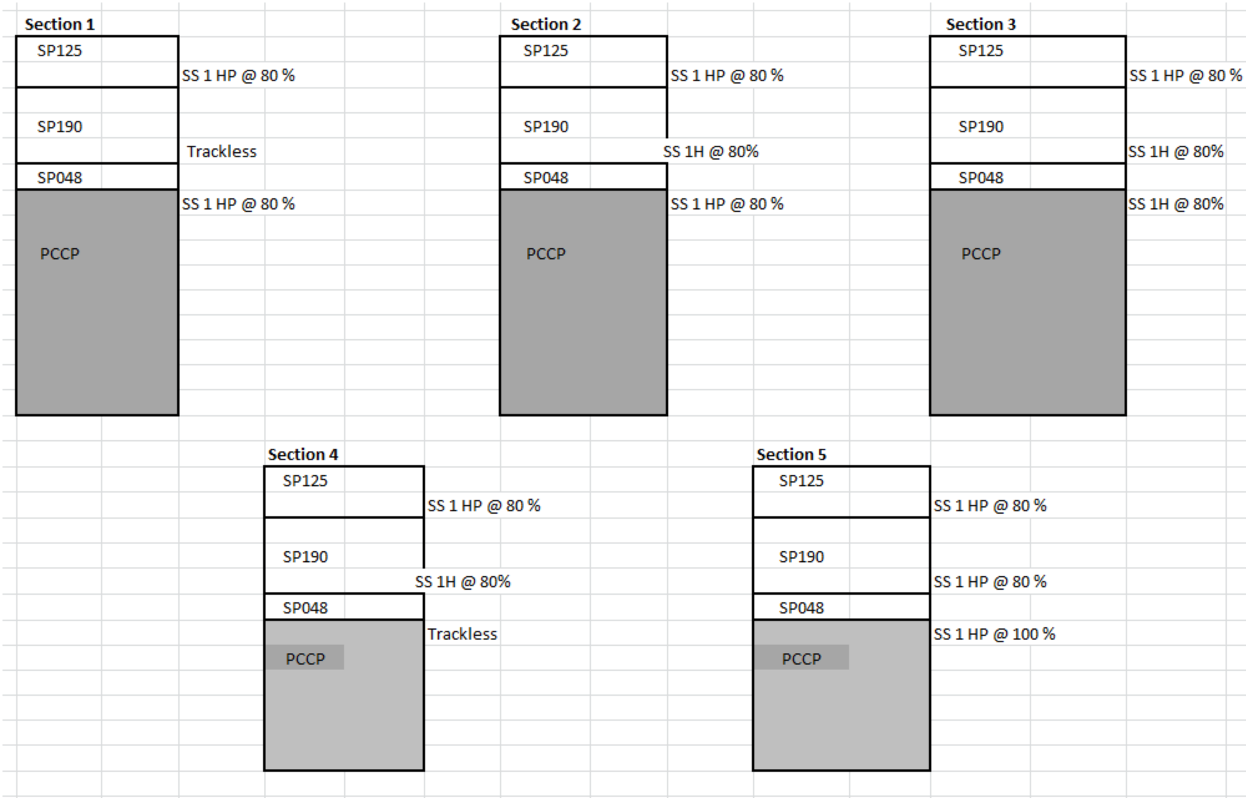

Figure 3.2 US 36 Field Study Pavement Cross Sections

3.2 Testing

The direct tension pull off device provided by Road Science was also used for bond strength testing for this study, along with the determination that 100 psi was considered an acceptable bond strength. Cores with a 6-inch diameter were extracted both 30 days after construction and after the first winter. Three 2-inch diameter bond strength samples are extracted from each 6-inch diameter core. The test temperature selected for bond strength testing was 40° F (4.44° C). The bond strength result of each test specimen in the field study can be found in Appendix B.

3.3 Results and Discussion

The primary lifts to be tested for bond strength were the HMA/PCCP interface and the next lift between the HMA/HMA interfaces. The third lift of HMA/HMA interface was also tested, but the results were erroneous and are not shown. It is believed that this lift may have been damaged during the coring and testing of the bond strength of the other lifts. Table 3-1 lists the average bond strength from the roadway before and after the 2013/2014 winter months, while Figure 3.3 and Figure 3.4 graphically show the results. Based upon the field results, the following conclusions can be made.

- The Calumet Trackless Tack product had lower bond strengths compared to conventional tack products. However, the bond strengths obtained were well above the minimum bond strength requirement of 100 psi.

- The decrease in bond strength on conventional tack coat before and after winter was a little more than 25 percent on HMA/PCCP interface and almost 50 percent decrease on HMA/HMA interface. The decrease in bond strength before and after winter for the Calumet Trackless Tack product was favorable compared to the control tack products with significantly less bond strength reductions.

Table 3-1 US 36 Field Study Bond Strength Results

US 36_Buchanan County_Bond Strength Results				
Surface Type	**Product**	**Avg. Strength Before Winter**	**Avg. Strength after Winter**	**% Decrease in Strength**
PCCP to SP048	SS1HP @ 80 %	237	163	-31.2%
	SS1HP @ 100 %	263	214	-18.6%
	SS1H @ 80 %	269	199	-26.0%
	Average of Control	256	192	-25.3%
	Calumet Trackless	171	148	-13.5%
SP048 to SP190	SS1H @ 80 %	311	158	-49.2%
	Calumet Trackless	258	179	-30.6%

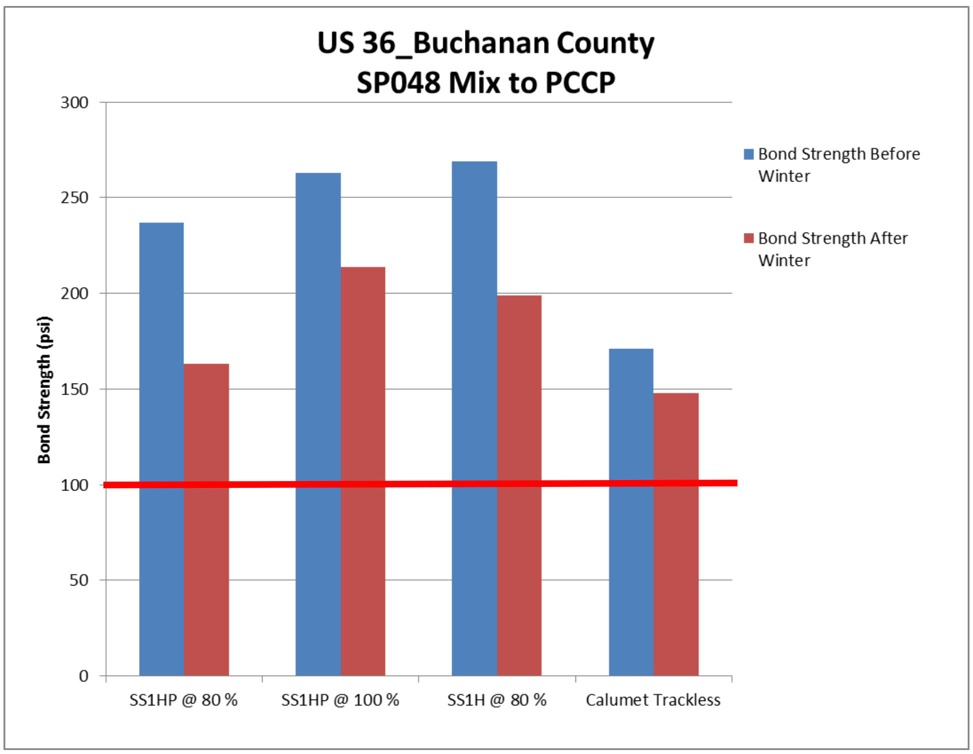

Figure 3.3 US 36 Bond Strength Results (HMA to PCCP)

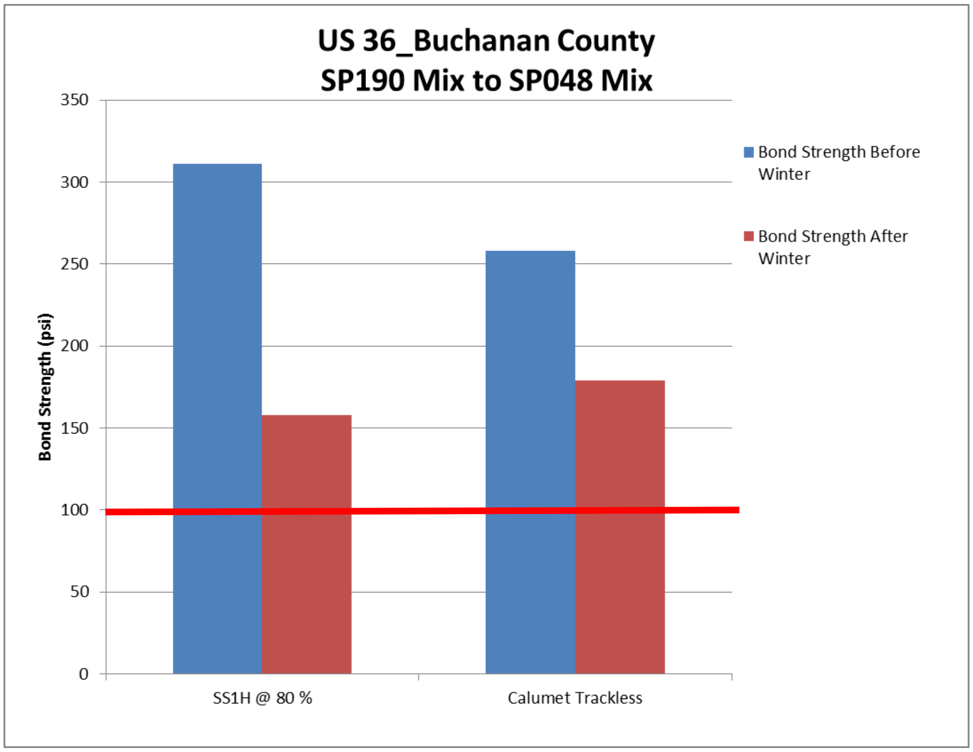

Figure 3.4 US 36 Bond Strength Results (HMA to HMA)

CHAPTER 4: PROJECT SITE VISITS AND FIELD INVESTIGATIONS

Asphalt overlay construction projects were visited during the 2013 construction season to evaluate constructability of the increased tack application rate required by specifications and to observe any construction issues that remained regarding proper tack application. Some of the issues encountered are addressed in the following excerpts.

4.1 Rte 129_Linn County_J1L1300E

The scope of this project consisted of placing a 1-inch surface level course on the roadway. The existing surface was composed of a chip seal surface with multiple cold mix patches. This project required a minimum of 0.08 gal/yd^2 for the tack coat application rate. A couple of issues were encountered during this project. One issue is that the existing chip seal surface already had some residual asphalt available, which made the 0.08 gal/yd^2 application rate excessive. The contractor reported having issues with the paver sliding and difficulty in pulling up grades. MoDOT agreed to reduce the rate to 0.06 gal/yd^2 to alleviate this issue and this rate appeared to uniformly cover the existing surface as illustrated in Figure 4.1. The second issue with this project is that the tack coat was tracking off the roadway. Due to the two-lane route with sharp curves, the contractor was unable to apply tack for a long distance. Also, the trucks were driving on the tacked surface within minutes after the tack was applied. Figure 4.2 illustrates the tacked surface just prior to the paver.

Figure 4.1 0.06 gal/yd^2 Tack Coverage

Figure 4.2 Tack Tracking Off Roadway

A core was taken and tested for bond strength for this project that resulted in inadequate bond strength. Figure 4.3 illustrates the interface of the test cores in which only an average of 20 psi bond strength was achieved.

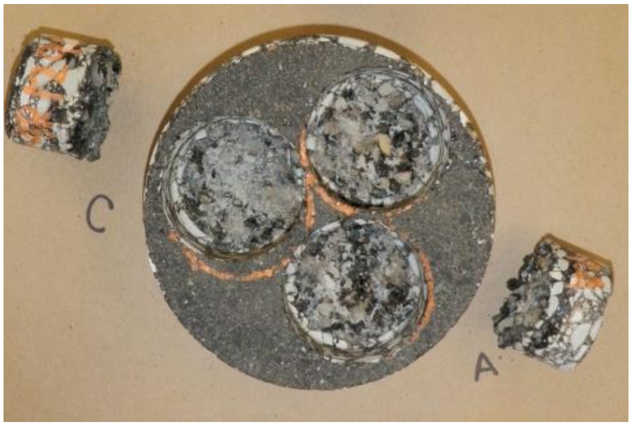

Figure 4.3 Test Cores with Inadequate Strength

4.2 Rte 47_Warren County_J3P2194

The scope of this project consisted of coldmilling ½-inch of the existing pavement and placing 1 ¾-inch bituminous plant mixture over the coldmilled surface. This project also required a minimum tack application rate of 0.08 gal/yd^2. Two issues documented on this project were that the amount of tack was inadequate and did not uniformly cover the coldmilled surface, and that the undiluted tack was not spraying uniformly across the surface of the roadway. These two issues, depicted below in Figure 4.4 and Figure 4.5, show the inadequate coverage and the inconsistent spray on the cardboard pieces. The inconsistency of the tack application was also reflected in the bond strength results which ranged from 93 psi to 255 psi.

Figure 4.4 Inadequate Tack

Figure 4.5 Inconsistent Spray

4.3 I-70 SOR_Warren County_J2S3063

The scope of this project consisted of a two lift asphalt overlay consisting of SuperPave mixtures that was intended to add structure to a deficient roadway. This project required a polymer tack coat to be used in which a SS1HP was selected at the 0.08 gal/yd^2 application rate. The pictures below (Figure 4.6 and Figure 4.7) illustrate the constructability issues with the use of polymers that sometimes occurs.

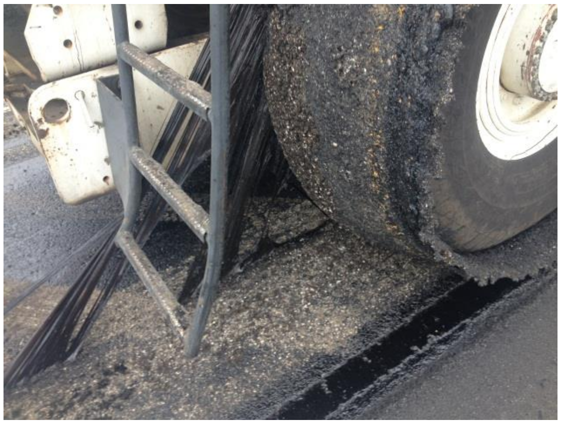

Figure 4.6 Polymer Tack Build Up (1)

Figure 4.7 Polymer Tack Build Up (2)

All tack coat application procedures were determined to be acceptable. The exact cause of the extraordinary build up on tires and the paver was not determined, other than the roadway was paved early in the spring during cooler temperatures.

4.4 Results and Discussion

Other site visits appeared to have few tack application issues; however, the tack tracking off the roadway seemed to be the most predominant issue with asphalt overlays on two-lane routes. Interstates and 4-lane divided highways had minimal tack tracking off due to the contractor's ability to distribute the tack well in advance of the paving operation and having adequate time for the tacked surface to cure prior allowing construction traffic to drive on it.

Based upon the site visits, the following conclusions were made.

- The application rate of 0.08 gal/yd^2 is not a catchall for all existing surface types. Some surfaces that have more asphalt residuals at the surface such as chip seals that require less tack while coldmilled surfaces require a higher rate of tack.
- Tack coat products containing polymers are more difficult to apply on the roadway without the side effects of stringers flying in the air and an excessive amount of tack building up on the equipment tires.
- When dilution is not allowed, some contractors have difficulty in achieving uniform coverage. This is suspected to be related to nozzle size and the set-up of the distributor.

CHAPTER 5: RECOMMENDATIONS

Based upon a MoDOT laboratory study, the US 36 field investigation, and numerous site visits and data collection, the Construction and Materials Pavement Section presents the following recommendations.

1) The minimum tack coat application rate is recommended to be revised as follows.

Table 5-1 MoDOT's Proposed Tack Rate Application

Surface Type	Current Rate	Proposed Target Rate
New Asphalt Surface	0.05	0.05
Existing Asphalt or PCCP Surfaces	0.08	0.08
Coldmilled Asphalt or PCCP Surfaces	0.08	0.10

The tack rate on several projects needed to be reduced from the minimum required tack application rate due to higher residual/richer asphalt at the surface of the existing pavement. It is therefore recommended that a target rate be specified instead of a minimum required rate with the flexibility to adjust the target rate by +/- 0.02 gal/yd^2 to account for the different pavement surface types encountered in the field.

2) The application rate for a coldmilled surface was increased by 0.02 gal/yd^2 to a proposed target rate of 0.10 gal/yd^2. This application rate yielded the highest bond strength results during the laboratory study and the current 0.08 gal/yd^2 did not appear to uniformly cover the surface of a coldmilled surface on a couple of site projects.
3) A contractor's request to dilute the tack coat emulsion may be allowed for easier spraying and a more uniform coverage. Although dilution is not ideal to obtain the final residual amount needed for bond strength, MoDOT should allow the contractor the flexibility in diluting the tack coat up to 20% with the caveat that a) the application rate would be increased to account for the addition of water and b) the contractor's tack coat supplier would dilute, monitor, and document the dilution prior to shipping the tack coat material to the contractor.
4) Trackless Tack coat products can achieve adequate bond strength and acceptable performance in a wet/freeze climate in Missouri. Therefore, it is recommended that Trackless Tack products be allowed and specified in contracts where needed.
5) Tack coat products containing polymers are very difficult to apply and maintain on the roadway during construction. Therefore, it is recommended that if polymer tacks are needed, then a spray paver should be required to place the tack coat material.
6) Tracking off the tack coat during construction is the predominant issue that MoDOT is experiencing. In certain situations such as two-lane roadways with numerous entrances or urban areas where getting on the tacked surface is inevitable, then the use of trackless tack coat products or a spray paver option should be considered to provide the contractor with two practical solutions.

CHAPTER 6: BIBLIOGRAPHY

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Appendix A. Laboratory Bond Strength Testing Data

SS-1 Bond Strength Results

SS1													
	Manufacturer	Vance		A/C Content		60%		0.03	0.05	0.08	0.1		
		Control						After Freeze/Thaw					
Surface Type	Application Rate	Core ID	Test Temp °F	Force (lbs)	PSI	Energy (J/m²)	Failure Type	Core ID	Test Temp °F	Force (lbs)	PSI	Energy (J/m²)	Failure Type
SP 125 to PCCP	0.03	A	41	375	119	250	interface	A	42.8	257	82	273	interface
		B	41	345	110	184	interface	B	42.8	211	67	108	interface
		C	42.8	361	115	240	interface	C	-	-	-	-	debonded during coring
		Avg		**360**	**115**	**225**	4.2%	**Avg**		**234**	**75**	**191**	13.9%
	0.05	A	39.2	335	107	234	interface	A	41	243	77	196	mix
		B	41	317	101	161	interface	B	41	113	36	52	interface
		C	42.8	340	108	205	interface	C	42.8	226	72	123	interface
		Avg		**331**	**105**	**200**	3.7%	**Avg**		**235**	**62**	**124**	6.2%
	0.08	A	41	303	96	137	interface	A	42.8	161	51	96	interface
		B	41	248	79	108	interface	B	42.8	234	75	149	mix
		C	41	463	147	341	interface	C	44.6	284	90	183	interface
		Avg		**338**	**108**	**195**	33.0%	**Avg**		**259**	**72**	**143**	15.6%
	0.1	A	42.8	327	104	204	interface	A	42.8	248	79	157	1/2 interface 1/2 mix @ interface
		B	42.8	351	112	166	interface	B	42.8	241	77	152	mix
		C	42.8	337	107	197	interface	C	44.6	205	65	97	3/4 interface 1/4 mix @ interface
		Avg		**338**	**108**	**189**	3.6%	**Avg**		**231**	**74**	**135**	10.0%
SP125 to SP125	0.03	A	42.8	547	174	464	interface	A	42.8	231	74	284	interface
		B	46.4	539	172	450	mix	B	42.8	239	76	185	interface
		C	42.8	486	155	496	mix	C	37.4	274	87	198	surface area
		Avg		**524**	**167**	**470**	6.3%	**Avg**		**248**	**79**	**222**	9.2%
	0.05	A	42.8	387	123	378	mix	A	41	421	134	376	1/2 mix @ interface
		B	42.8	431	137	361	interface	B	-	370	118	252	mix @ surface
		C	48.2	488	155	422	mix	C	-	367	117	329	mix @ surface
		Avg		**435**	**139**	**387**	11.6%	**Avg**		**386**	**123**	**319**	7.9%
	0.08	A	41	452	144	363	mix	A	42.8	248	79	188	interface
		B	46.4	478	152	493	mix	B	-	393	125	350	mix @ surface
		C	42.8	486	155	433	3/4 interface 1/4 mix	C	42.8	402	128	386	mix
		Avg		**472**	**150**	**430**	3.8%	**Avg**		**348**	**111**	**308**	24.9%

SS-1H Bond Strength Results

SS1H														
Manufacturer		Vance		**A/C Content**		60%								
Surface Type	**Application Rate**	Control						After Freeze/Thaw						
		Core ID	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**
SP 125 to PCCP	0.03	A	42.8	322	103	268	interface	A	37.4	139	44	239	interface
		B	41	376	120	190	interface	B	41	51	16	103	interface
		C	42.8	152	48	152	interface	C	41	54	17	133	interface
		Avg		**283**	**90**	**203**	41.3%	**Avg**		**81**	**26**	**158**	61.4%
	0.05	A	41	300	96	516	interface	A	42.8	255	81	140	interface
		B	41	394	125	367	interface	B	42.8	285	91	166	interface
		C	42.8	378	120	300	interface	C	42.8	190	61	98	interface
		Avg		**357**	**114**	**394**	14.1%	**Avg**		**243**	**77**	**135**	20.0%
	0.08	A	42.8	374	119	239	interface	A	42.8	269	86	146	interface
		B	42.8	342	109	216	interface	B	42.8	75	24	55	mix
		C	48.2	368	117	293	mix	C	42.8	89	28	34	1/2 interface 1/2 mix @ interface
		Avg		**361**	**115**	**249**	4.7%	**Avg**		**269**	**46**	**146**	75.0%
	0.1	A	39.2	400	127	276	interface	A	41	223	71	103	interface
		B	41	309	98	167	interface	B	41	256	82	167	interface
		C	-	-		-	broke at interface*	C	42.8	215	68	93	interface
		Avg		**355**	**113**	**222**	18.2%	**Avg**		**231**	**74**	**121**	9.4%
SP125 to SP125	0.03	A	42.8	566	180	568	mix	A	39.2	365	116	406	interface
		B	44.6	386	123	307	mix	B	42.8	410	131	327	interface
		C	42.8	485	154	411	mix	C	37.4	418	133	307	interface
		Avg		**479**	**153**	**429**	18.8%	**Avg**		**398**	**127**	**347**	1.4%
	0.05	A	42.8	420	134	498	interface	A	39.2	361	115	247	mix/surface area
		B	42.8	363	116	290	interface	B	41	370	118	348	interface
		C	44.6	381	121	253	interface	C	41	310	99	254	interface
		Avg		**388**	**124**	**347**	7.5%	**Avg**		**347**	**111**	**283**	9.3%
	0.08	A	41	611	195	619	interface	A	42.8	380	121	373	interface
		B	42.8	467	149	433	mix	B- redo	44.6	375	119	327	mix @ interface
		C	44.6	602	192	625	mix	C	42.8	325	104	245	interface
		Avg		**560**	**178**	**559**	14.4%	**Avg**		**360**	**115**	**315**	8.4%

SS-1HP Bond Strength Results

SS1HP

Manufacturer Vance **A/C Content** 63%

Surface Type	Application Rate	Control						After Freeze/Thaw					
		Core ID	Test Temp °F	Force (lbs)	PSI	Energy (J/m²)	Failure Type	Core ID	Test Temp °F	Force (lbs)	PSI	Energy (J/m²)	Failure Type
SP 125 to PCCP	0.03	A	42.8	267	85	139	interface	A	42.8	254	81	150	interface
		B	44.6	321	102	230	interface	B	44.6	114	36	59	interface
		C	44.6	261	83	168	interface	C	44.6	285	91	148	interface
		Avg		**283**	**90**	**179**	11.7%	**Avg**		**218**	**69**	**119**	41.9%
	0.05	A	42.8	303	96	172	interface	A	42.8	375	119	304	interface
		B	44.6	274	87	152	interface	B	42.8	347	111	215	interface
		C-redo	44.6	259	82	115	Surface area	C	42.8	286	91	140	interface
		Avg		**279**	**89**	**146**	8.0%	**Avg**		**336**	**107**	**220**	13.5%
	0.08	A	41	353	112	280	interface	A		267	85	258	interface
		B	42.8	469	149	327	mix	B		193	61	104	mix @ interface
		C	42.8	332	106	189	interface	C		134	43	63	mix @ interface
		Avg		**385**	**131**	**265**	18.0%	**Avg**		**198**	**63**	**142**	33.7%
	0.1	A	42.8	425	135	364	interface	A	42.8	322	103	413	interface
		B	42.8	352	112	217	interface	B	44.6	381	121	303	mix
		C	46.4	322	103	225	interface	C	44.6	156	50	82	3/4 mix @ interface 1/4 interface
		Avg		**366**	**117**	**269**	14.5%	**Avg**		**286**	**91**	**266**	40.7%
SP125 to SP125	0.03	A	42.8	641	204	632	interface	A	44.6	341	109	202	interface
		B	41	588	187	525	interface	B	44.6	469	149	375	interface
		C	42.8	486	155	418	interface	C	50	374	119	237	mix
		Avg		**572**	**182**	**525**	13.8%	**Avg**		**395**	**126**	**271**	16.8%
	0.05	A	46.4	480	153	419	mix	A	41	593	189	542	
		B	50	327	104	288	mix	B	42.8	435	139	325	mix
		C	46.4	344	110	224	3/4 interface 1/4 mix	C	48.2	457	146	408	mix
		Avg		**384**	**131**	**310**	20.4%	**Avg**		**495**	**167**	**425**	16.3%
	0.08	A	41	664	211	672	interface	A	44.6	270	86	273	mix
		B	41	329	105	187	interface	B	42.8	315	100	235	interface
		C	44.6	467	149	305	mix	C	44.6	397	126	454	interface
		Avg		**487**	**155**	**388**	34.6%	**Avg**		**327**	**113**	**321**	18.1%

CRS-2P Bond Strength Results

CRS2P														
	Manufacturer	Vance		**A/C Content**	71%									
		Control						After Freeze/Thaw						
Surface Type	**Application Rate**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**
SP 125 to PCCP	0.03	A	41	332	106	304	interface	A	41	329	105	346	interface
		B	42.8	241	77	182	interface	B	42.8	359	114	264	interface
		C	44.6	338	108	300	interface	C	42.8	193	61	135	interface
		Avg		**304**	**97**	**262**	17.9%	**Avg**		**294**	**94**	**248**	30.1%
	0.05	A	42.8	354	113	377	interface	A	41	328	104	399	interface
		B	42.8	307	98	187	interface	B	41	360	115	252	interface
		C	44.6	296	94	354	interface	C	42.8	270	86	203	interface
		Avg		**319**	**102**	**306**	9.7%	**Avg**		**319**	**102**	**285**	14.3%
	0.08	A	44.6	344	110	248	interface	A	42.8	397	126	305	interface
		B	44.6	287	91	251	interface	B	42.8	269	86	256	interface
		C	46.4	296	94	215	interface	C	42.8	342	109	239	interface
		Avg		**309**	**98**	**238**	9.9%	**Avg**		**336**	**118**	**267**	17.4%
SP125 to SP125	0.03	A	42.8	426	136	322	interface	A	41	389	124	391	interface
		B	42.8	372	118	213	interface	B	42.8	341	109	286	interface
		C	42.8	309	98	161	interface	C	42.8	263	84	201	interface
		Avg		**369**	**118**	**232**	15.9%	**Avg**		**331**	**105**	**293**	19.2%
	0.05	A	39.2	425	135	330	interface	A	42.8	323	103	325	mix @ interface
		B	41	321	102	223	mix	B	41	297	95	229	3/4 interface 1/4 mix @ interface
		C	44.6	388	124	347	mix	C	42.8	325	104	265	interface
		Avg		**378**	**120**	**300**	13.9%	**Avg**		**315**	**100**	**273**	5.0%
	0.08	A	39.2	387	123	259	mix	A	41	357	114	389	below interface
		B	41	406	129	322	mix	B	41	528	168	523	mix @ interface
		C	42.8	359	114	257	mix	C	50	471	150	403	mix
		Avg		**384**	**122**	**279**	6.2%	**Avg**		**452**	**159**	**438**	17.4%

CRS-1H Bond Strength Results

CRS1H														
Manufacturer	Vance		**A/C Content**	65%										
		Control						After Freeze/Thaw						
Surface Type	**Application Rate**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**
SP 125 to PCCP	0.03	A	42.8	332	106	304	interface	A	39.2	251	80	136	interface
		B	42.8	241	77	182	interface	B	41	247	79	156	interface
		C	44.6	338	108	300	interface	C	41	223	71	100	interface
		Avg		**304**	**97**	**262**	17.9%	**Avg**		**240**	**77**	**131**	6.3%
	0.05	A	42.8	472	150	551	mix	A	37.4	431	137	527	interface
		B	42.8	449	143	378	mix	B	41	292	93	157	interface
		C	46.4	238	76	191	interface	C	41	360	115	263	interface
		Avg		**386**	**123**	**373**	33.4%	**Avg**		**361**	**115**	**316**	19.3%
	0.08	A	48.2	507	161	421	mix	A	42.8	208	66	225	mix @ interface
		B	-	253	81	105	epoxy	B	44.6	234	75	207	mix @ interface
		C	48.2	306	97	211	mix	C	-	-	-	-	broke before testing @ interface
		Avg		**507**	**113**	**246**	37.7%	**Avg**		**221**	**70**	**216**	8.3%
	0.1	A	41	489	156	311	interface	A	42.8	290	92	200	interface
		B	48.2	582	185	517	mix	B	42.8	303	96	262	interface
		C	44.6	432	138	274	interface	C	46.4	155	49	100	interface
		Avg		**501**	**160**	**367**	15.1%	**Avg**		**249**	**79**	**187**	32.9%
SP125 to SP125	0.03	A	44.6	422	134	294	interface	A	42.8	272	87	149	interface
		B	42.8	438	139	351	interface	B	42.8	329	105	278	interface
		C	48.2	559	178	499	mix	C	42.8	313	100	212	mix @ interface
		Avg		**473**	**151**	**381**	15.8%	**Avg**		**305**	**97**	**213**	9.6%
	0.05	A	41	512	163	668	interface	A		372	118	354	mix @ interface
		B	46.4	549	175	509	mix	B		364	116	420	below interface
		C	44.6	533	170	452	interface	C		285	91	239	1/2 interface 1/2 mix @ interface
		Avg		**531**	**169**	**543**	3.5%	**Avg**		**340**	**108**	**338**	14.1%
	0.08	A	42.8	505	161	749	mix	A	-	344	110	293	mix/ surface area
		B	41	595	189	770	interface	B	41	324	103	230	mix
		C	41	513	163	546	interface	C	-	339	108	232	mix/ surface area
		Avg		**538**	**171**	**688**	9.3%	**Avg**		**336**	**107**	**252**	3.1%

CPEM-1 Bond Strength Results

CPEM1													
Manufacturer		Vance	**A/C Content**	65%									
		Control						After Freeze/Thaw					
Surface Type	**Application Rate**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**
SP 125 to PCCP	0.08	A	42.8	397	126	519	interface	A	41	219	70	129	1/2 mix 1/2 interface
		B	42.8	377	120	309	interface	B	42.8	202	64	232	mix @ interface
		C	44.6	301	96	281	interface	C	42.8	219	70	151	mix @ interface
		Avg		**358**	**114**	**370**	14.1%	**Avg**		**213**	**68**	**171**	4.6%
	0.1	A	41	365	116	312	interface	A	41	239	76	149	interface
		B	41	418	133	359	interface	B	42.8	236	75	167	mix
		C	42.8	375	119	337	mix	C	46.4	273	87	198	mix
		Avg		**386**	**123**	**336**	7.3%	**Avg**		**249**	**79**	**171**	8.2%
	0.12	A	46.4	324	103	259	last mix connected to interface/interface	A	41	292	93	191	mix
		B	46.4	235	75	232	last mix connected to interface/interface	B	50	285	91	208	mix
		C	46.4	240	76	306	last mix connected to interface/interface	C	51.8	266	85	171	mix
		Avg		**266**	**85**	**266**	18.8%	**Avg**		**281**	**89**	**190**	4.8%
	0.15	A	42.8	340	108	346	interface/ existing	A	44.6	189	60	172	last mix connected to interface/interface
		B	46.4	370	118	401	interface	B	46.4	260	83	253	interface
		C	50	365	116	394	mix	C	48.2	167	53	102	interface
		Avg		**358**	**114**	**380**	4.5%	**Avg**		**205**	**65**	**176**	23.7%
SP125 to SP125	0.08	A	50	468	149	390	mix/contact area	A	41	385	123	534	last mix connected to interface/interface
		B	44.6	549	175	451	mix	B	46.4	422	134	602	mix
		C	51.8	483	154	358	mix	C	50	348	111	336	mix
		Avg		**500**	**159**	**400**	8.6%	**Avg**		**385**	**123**	**491**	9.6%
	0.1	A	44.6	749	239	981	mix	A	44.6	296	94	204	last mix connected to interface/interface
		B	46.4	632	201	590	mix	B	41	354	113	341	mix @ interface
		C	50	567	181	537	mix	C	46.4	430	137	443	mix
		Avg		**649**	**207**	**703**	14.2%	**Avg**		**360**	**115**	**329**	18.7%
	0.12	A	39.2	657	209	657	1/2 mix 1/2 interface	A	42.8	476	152	627	interface
		B	46.4	548	175	602	mix	B	44.6	437	139	550	below interface
		C	46.4	516	164	427	mix	C	46.4	375	119	296	last mix connected to interface/interface
		Avg		**574**	**183**	**562**	12.9%	**Avg**		**429**	**137**	**491**	11.9%

Blacklidge Trackless Tack

Manufacturer	Blacklidge	A/C Content	54%										
		Control						After Freeze/Thaw					
Surface Type	**Application Rate**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**
SP 125 to PCCP	0.05	A	42.8	258	82	130	interface	A	39.2	309	98	195	interface
		B	41	180	57	84	interface	B	39.2	239	76	107	interface
		C	42.8	287	91	147	interface	C	41	248	79	125	interface
		Avg		**242**	**77**	**120**	22.9%	**Avg**		**265**	**85**	**142**	14.4%
	0.08	A	41	508	162	498	interface	A	41	345	110	230	interface
		B	42.8	561	179	576	interface	B	41	366	117	196	interface
		C	42.8	326	104	156	interface	C	42.8	250	80	137	interface
		Avg		**465**	**148**	**410**	26.5%	**Avg**		**320**	**102**	**188**	19.3%
	0.1	A	41	361	115	260	interface	A	42.8	363	116	340	interface
		B	42.8	376	120	310	interface	B	46.4	288	92	161	interface
		C	-	-	-	-	broke during coring	C	42.8	318	101	238	interface
		Avg		**369**	**117**	**285**	2.9%	**Avg**		**323**	**103**	**246**	11.7%
SP125 to SP125	0.03	A	42.8	356	113	519	interface	A	39.2	465	148	346	interface
		B	42.8	547	174	628	interface	B	41	332	106	272	interface
		C	44.6	368	117	298	interface	C	41	355	113	315	interface
		Avg		**424**	**135**	**482**	25.3%	**Avg**		**384**	**122**	**311**	18.5%
	0.05	A	39.2	360	115	213	interface	A	42.8	312	99	241	interface
		B	41	461	147	343	interface	B	42.8	281	89	184	interface
		C	42.8	532	169	646	interface	C	44.6	298	95	190	interface
		Avg		**451**	**144**	**401**	19.2%	**Avg**		**297**	**95**	**205**	5.2%
	0.08	A	39.2	564	180	438	interface	A	42.8	354	113	344	interface
		B	41	500	159	354	mix	B	42.8	485	154	423	interface
		C	41	536	171	387	mix	C	42.8	284	90	135	interface
		Avg		**533**	**170**	**393**	6.0%	**Avg**		**374**	**119**	**301**	27.3%

Blacklidge Ultrafuse Bond Strength Results

Ultrafuse														
Manufacturer		Blacklidge		**A/C Content**	100%									
Surface Type	**Application Rate**	Control						After Freeze/Thaw						
		Core ID	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**	**Core ID**	**Test Temp °F**	**Force (lbs)**	**PSI**	**Energy (J/m²)**	**Failure Type**
SP 125 to PCCP	0.12	A	37.4	414	132	370	interface	A	42.8	216	69	94	interface
		B	39.2	540	172	383	interface	B	42.8	231	74	104	interface
		C	41	333	106	155	interface	C	-	-		-	
		Avg		**429**	**137**	**303**		**Avg**		**224**	**71**	**99**	
SP125 to SP125	0.12	A	41	656	209	651	mix	A	44.6	472	150	507	mix
		B	42.8	630	201	559	mix	B	42.8	519	165	638	interface
		C	42.8	482	154	408	mix	C	42.8	504	161	413	interface
		Avg		**589**	**188**	**539**		**Avg**		**498**	**159**	**519**	

Appendix B. U.S. 36 Bond Strength Testing Data

Job # J1P2195		Route			36			County		Buchanan			
		Before Freeze/Thaw						After Freeze/Thaw					
Surface Type	Product	Core ID	Test Temp °F	Force (lbs)	PSI	Energy (J/m²)	Failure Type	Core ID	Test Temp °F	Force (lbs)	PSI	Energy (J/m²)	Failure Type
PCCP to SP048	SS1HP @ 80%	3A	39	595	189	441	interface	4A	39.2	600	191	602	interface
		3B	39.5	566	180	449	interface	4B	41	363	116	251	interface
		3C	41.4	580	185	449	interface	4C	42.8	306	97	173	interface
		4A	41.4	1000	318	1469	max load	5A	42.8	627	200	534	interface
		4B	43.2	992	316	1253	max load	5B	42.8	590	188	569	interface
		4C	44.2	937	298	1181	mix	5C	42.8	588	187	527	interface
		6A	39	749	239	667	interface						
		6B	41.7	720	229	620	interface						
		6C	42.8	559	178	424	interface						
		Avg		**744**	**237**	**773**		**Avg**		**512**	**163**	**443**	
	SS1HP @ 100%	11-A	41.4	915	291	1003	interface	13A	41	514	164	426	interface
		11-B	43.5	956	304	1125	interface	13B	42.8	820	261	907	interface
		11-C	44.2	905	288	1029	interface	13C	46.4	743	237	821	interface
		12-A	40.6	744	237	674	interface	14A	42.8	612	195	528	048 mix
		12-B	41	762	243	719	interface	14B	42.8	689	219	642	048 mix
		12-C	41.7	675	215	575	interface	14C	46.4	652	208	551	concrete
		Avg		**826**	**263**	**854**		**Avg**		**672**	**214**	**646**	
	SS1H @ 80%	13-A	77	270	86	284	interface	8A	41	966	308	1113	broke in Concrete
		13-B	77	299	95	347	interface	8B	41	548	175	443	interface
		13-C	39	844	269	820	interface	8C		-	-	-	debonded after coring
								9A	41	520	166	367	interface
								9B	42.8	560	178	444	interface
								9C	42.8	530	169	360	interface
		Avg		**471**	**150**	**484**		**Avg**		**625**	**199**	**545**	
	Trackless	7-A	41.4	640	204	560	interface	10A	42.8	562	179	614	interface
		7-B	41.4	389	124	359	interface	10B	41	499	159	493	interface
		7-C	43.5	423	135	246	interface	10C	42.8	468	149	358	interface
		8-A	40.3	656	209	518	interface	11A	41	554	176	500	interface
		8-B	42	488	155	439	interface	11B	42.8	431	137	414	interface
		8-C	46	631	201	469	interface	11C	44.6	453	144	538	interface
								12A	44.6	415	132	262	interface
								12B	42.8	391	125	220	interface
								12C	41	410	131	296	interface
		Avg		**538**	**171**	**432**		**Avg**		**465**	**148**	**411**	

Job # J1P2195		Route		36				County		Buchanan			
		Before Freeze/Thaw						After Freeze/Thaw					
Surface Type	Product	Core ID	Test Temp °F	Force (lbs)	PSI	Energy (J/m²)	Failure Type	Core ID	Test Temp °F	Force (lbs)	PSI	Energy (J/m²)	Failure Type
SP048 to SP190	SS1H @ 80%	10-A	-	996	317	1791	max load cell	6A	42.8	491	156	457	048 mix
		10-B	42.8	1003	319	1797	mix	6B	42.8	406	129	661	048 mix
		10-C	46	935	298	1675	mix	6C	44.6	373	119	560	048 mix
								7A-redo	44.6	610	194	727	190 mix
								7B- redo	46.4	564	180	622	interface
								7C- redo	46.4	534	170	570	interface
		Avg		978	311	1754		Avg		496	158	600	
	Trackless	1-A	39	871	277	1137	mix	1A	42.8	513	163	580	048 mix
		1-B	39	942	300	1395	epoxy	1B	44.6	438	139	469	048 mix
		1-C	39	661	211	951	mix	1C	46.4	407	130	350	048 mix
		2-A	46.8	808	257	1244	mix	2A	44.6	723	230	886	048 mix
		2-B	43.2	859	274	1308	mix	2B	46.4	607	193	635	190 mix
		2-C	46.8	718	229	970	mix	2C	46.4	435	139	416	048 mix
								3A	-	724	231	791	048 mix
								3B	46.4	714	227	856	190 mix
								3C	46.4	502	160	552	interface
		Avg		810	258	1168		Avg		563	179	615	