

NCAT Report 12-02

**EFFECTS OF NANOTAC  
ADDITIVE ON BOND  
STRENGTH AND  
MOISTURE RESISTANCE  
OF TACK COATS**

*Final Report*

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**May 2012**



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Sponsored by

Zydex Industries, India

November 2011

## **ACKNOWLEDGEMENTS**

This project was sponsored by Zydex Industries, India. The project team appreciates and thanks Zydex Industries, India for their sponsorship of this project. Particularly, thanks are owed to Dr. Ajay Ranka and Dr. Prakash Mehta for their guidance.

## **DISCLAIMER**

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## **1. INTRODUCTION**

### **1.1 Background**

#### *1.1.1 Importance of Pavement Interface Bond Strength*

Pavement structures consisting of several hot-mix asphalt (HMA) layers require a certain degree of bond at the layer interfaces. Research has proven that the degree of bond between pavement layers can significantly affect the overall performance of the pavement structure or overlay (1).

Poor bond has been known to decrease the structural bearing capacity of a pavement inducing pavement distresses and failures (2, 3). Problems commonly associated with debonding are premature slippage cracking, top-down cracking, and fatigue cracking (1, 4, 5). Past research shows debonding can reduce the pavement's fatigue life by more than 50 percent, prompting the need for extensive repairs such as full-depth patches or complete reconstruction (6, 7).

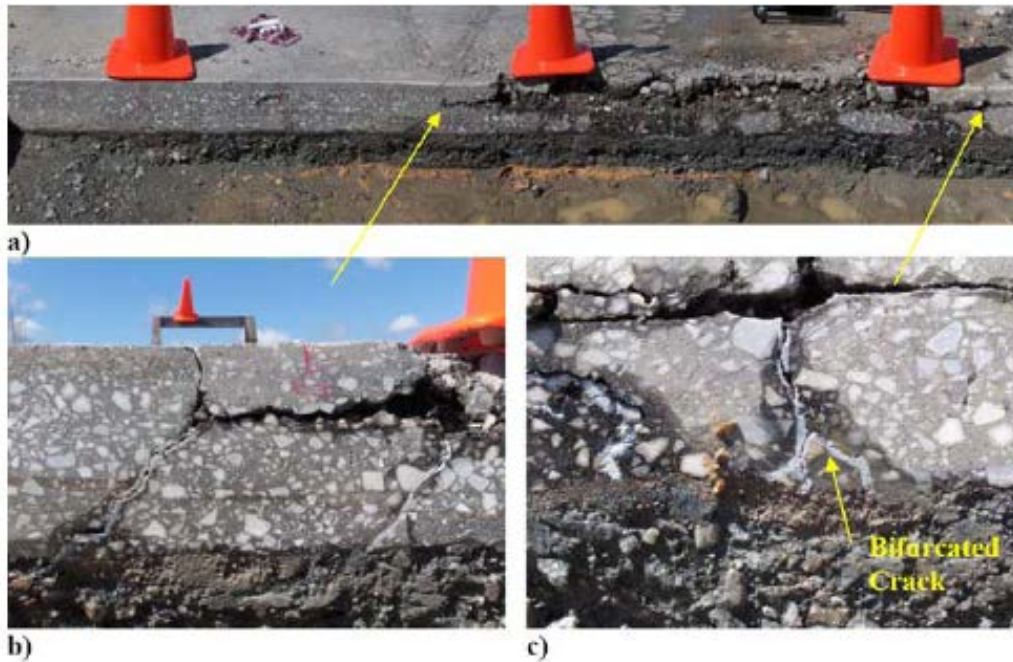
When bonded HMA pavement layers lose adhesion and separate (Figure 1), the overall stiffness of the pavement decreases, inciting the development the aforementioned pavement distresses (6, 7, 8). While these distresses might start at the debonded location, the pavement structure will eventually show extensive damage as cracking courses its way through multiple layers of the structure (Figure 2) (11).

Another form of distress associated with the lack of bond is slippage cracking (Figure 3). Slippage cracking typically indicates inadequate bonding between an asphalt wearing course and its underlying layer. This distress is developed in areas where braking, accelerating, or turning wheels move and deform the surface of the HMA structure (5, 6). Slippage cracks are typically in the form of half-moon shaped cracks with two ends pointing into the direction of traffic (Figure 4).

The best way to prevent debonding is through good construction practices. First of all, the surface to be paved over should be swept clean of dirt and debris and should not be excessively wet. A quality tack coat material that provides sufficient bond strength should be used, and it should be uniformly applied to the pavement surface. Common issues with tack coat application include non-uniform spray (often due to clogged nozzles on the spray truck) and tire pickup (tires from construction traffic removing the tack and rendering it ineffective). Quality construction practices are critical to achieving a quality tack coat interface in the field.



**Figure 1 Delamination in HMA Pavement (II)**

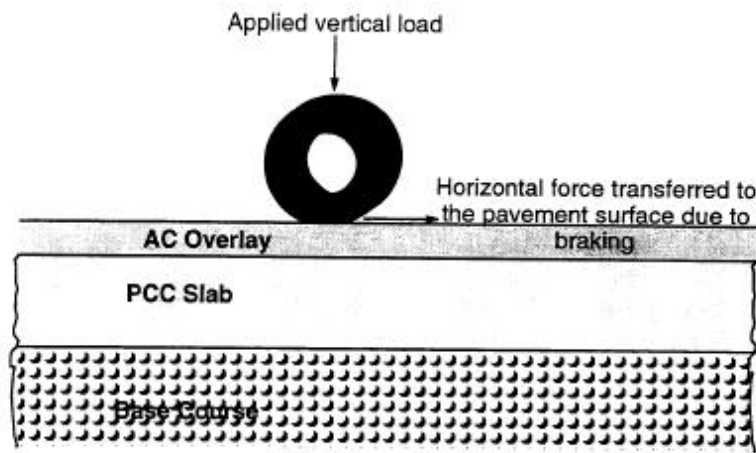


**Figure 2 Severe Distress due to Poor Bond between Pavement Layers (II)**

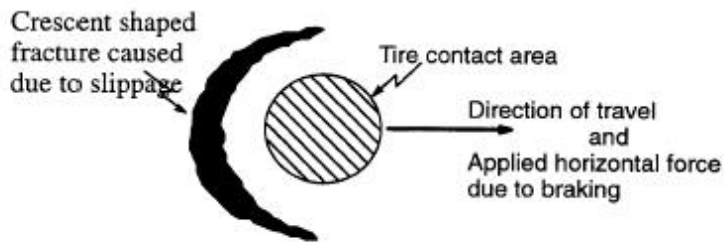




**Figure 3 Slippage Failure due to Inadequate Bonding**



**a: Side View**



**b: Plan View**

**Figure 4 Typical Slippage Failure (10)**

Debonding can be especially rapid if water is forced along the lift boundary (Figure 5) by hydrostatic pressure induced by trafficking (12).



**Figure 5 Moisture Present at Delaminated Interface between HMA Layers (12)**

### *1.1.2 Description of the Nanotac Additive*

The Nanotac additive is derived from organosilane nanotechnology. Nanotac is designed to convert the surface of the treated material (untreated aggregate, soil, or HMA) from a water loving (hydrophilic) surface to a water repelling (hydrophobic) surface. The Nanotac additive is added to a diluted tack coat material by blending a small quantity of the additive with the water used to dilute the emulsion. This is designed to improve the water resistance and bonding of the tack coat interface. The Nanotac additive is also designed to lower the surface tension of a cationic emulsion with which it is blended, reducing droplet size and improving spray coverage. Nanotac is also intended to wet, penetrate, and set quickly to reduce the problem of tire pickup, which is common with construction traffic driving over newly placed tack coats and removing the tack, rendering it ineffective.

In addition to the benefits mentioned above, the use of the Nanotac additive is designed to reduce the amount of asphalt residual required to provide adequate interlayer bond strength. According to the manufacturer, production of the additive does not produce any waste products requiring treatment. Given this fact, in conjunction with a lower asphalt requirement in emulsions blended with Nanotac, the manufacturer is looking to evaluate Nanotac as a potential “green” technology.

## **1.2 Objective**

The purpose of this project was to evaluate the quality of a tack coat emulsion modified with the Nanotac additive versus the quality of an unmodified emulsion tack coat.

## **1.3 Scope**

For this study, a diluted cationic slow setting (CSS) emulsion using the Nanotac additive was evaluated in comparison with a diluted CSS emulsion with no other additive (control). This

study was performed to evaluate the effect of the Nanotac additive on tack coat bond strength, spreadability, time to dry, tire pickup, and moisture susceptibility. Plant-produced HMA was sampled to produce the two-layer slabs for this study. The tack coat was evaluated on samples with both milled and unmilled surfaces. Multiple application rates and the effect of curing time on the bond strength were evaluated as well. The critical variables impacting bond strength were determined using statistical analyses. Visual inspection was used to determine the impact of the Nanotac on emulsion spreadability and tire pickup. Additionally, the moisture resistance of the tack coat was tested by applying freeze-thaw cycles and testing the bond strength of samples using both a control emulsion and emulsion blended with the Nanotac additive.

## **2. EXPERIMENTAL SETUP**

The experimental plan was developed to compare the effect of Nanotac on the bond strength of HMA layer interfaces. Additionally, the spreadability, resistance to tire pickup, and resistance to moisture damage were assessed.

### **2.1 Mix Design**

Ninety 5-gallon (18.9 L) buckets of plant-produced hot mix asphalt were sampled for the following experimental plan. The mix collected was a 3/8" (9.5 mm) nominal maximum aggregate size (NMAS) mixture compacted to 60 gyrations using the Alabama Department of Transportation (ALDOT) mix design requirements. The mix consisted of a PG 67-22 asphalt binder and contained 20% RAP by weight of the mixture. The complete mix design is given in Appendix A.

### **2.2 Sample Fabrication**

To test the bond strength between pavement layers using laboratory mixes, two HMA slabs approximately 2 inches (50.8 mm) thick each were compacted using a rolling slab compactor. This produced a final two-layer slab approximately 4 inches (101.6 mm) thick. The same mix was used in both lifts of the asphalt slab to ensure the air voids of the core could be calculated for the moisture susceptibility experiment, which will be explained in detail later in this report.

To create the bottom slabs, four pans of asphalt were mixed and placed in a 300°F (148.9°C) oven for two hours. Upon completing the short-term aging cycle according to AASHTO R30, a heated mold was removed from the oven and assembled with a base plate (Figure 6). Wax paper was then placed on top of the base plate followed by a metal partition that divided the slab into four quadrants (Figure 7). One pan of mix was poured into each quadrant using a material transfer funnel to prevent segregation (Figure 8). Once all four quadrants had been filled, the metal partition was removed, and a large trowel was used to ensure all four quadrants had an approximately uniform depth (Figure 9) before a second piece of wax paper was placed on top of the mix.



**Figure 6 Slab compaction mold**



**Figure 7 Slab Compaction Mold with Quadrant Dividers**



**Figure 8 Filling Quadrants with Mix**



**Figure 9 Leveling Mix in Mold**

Forty-nine vertical kneading plates were then placed on top of the wax paper simultaneously from each side perpendicular to the front of the mold before it was moved to the rolling compactor (Figure 10). The roller operated at a minimum pressure of 1,200 psi (8.274 MPa) until compaction was achieved (Figure 11). The slabs were then removed from the mold and were allowed to cool for at least one hour.



**Figure 10 Adding Kneading Plates**

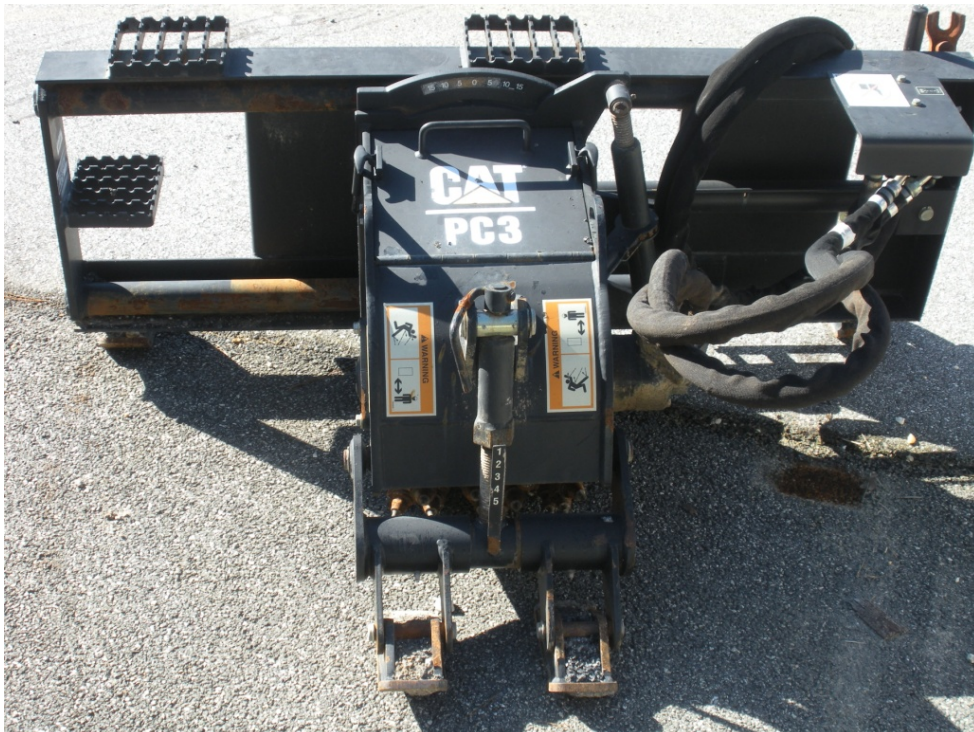


**Figure 11 Compacting Slab**

Two different surfaces were created for the bottom slabs upon cooling: new and milled. In order to create a milled surface, a standard milling head (Figure 12) was attached to a CAT PC3 (Figure 13). The drum and head combination (Figure 13) were then lowered onto the bottom slabs to create a milled surface (Figure 14).



**Figure 12 Milling Head**



**Figure 13 CAT PC3**





**Figure 14 Milling Process**

### **2.3 Spray Application Methodology**

A diluted cationic slow setting (CSS) emulsion with a 60% residual AC (asphalt cement) content was used for this work as requested by the project sponsor. For the control tack coat, the emulsion was diluted by half to a 30% residual AC content. For the Nanotac application, the emulsion was diluted to a 10% residual AC content, per the sponsor's request. This was done to see if the addition of the Nanotac would provide equivalent bond strength for a tack coat with a lower residual AC content. More information about the application rates can be found later in this report. The tack coat material was applied with a hand-pump operated garden sprayer (Figure 15), available from a local hardware store. The model sprayer used for this project was acquired for around \$10. Experiments using more costly mechanical sprayers were attempted with little success. The sprayer was primed by hand after every ten spray passes to maintain consistency of operation.



**Figure 15 Sprayer used for Applying Tack Coat in Laboratory**

Figure 16 shows the spray application process used to apply the tack coat material to the base layer slabs. A couple of things are notable from this figure. First, a flexible metal collar was fitted around the base of each slab and attached with caulk so as to prevent the diluted tack coat material from excessively running off the sides of the slab. Secondly, the tack was sprayed in the direction of traffic to ensure simulation of field application. For the milled slabs, the tack coat material was sprayed in the direction of the milling operation, as shown in Figure 16. It was also apparent that not all of the tack was sprayed on the surface of the slab. The spray could have been forced to remain in the slab area, but this would have created a non-uniform distribution of tack coat with very large concentrations of residual tack around the edges of the slab. A spraying motion that did not stop at the edges of the slab was the best way to prevent this. The biggest challenge for this project was to determine a method with which the material could be sprayed in a uniform fashion but still be able to accurately quantify the amount of tack coat being placed on the slab.



**Figure 16 Spray Application of Tack Coat in Laboratory**

A small experiment was developed to determine the most appropriate method of applying the tack coat materials. For the spray application, the easiest and best method of determining the amount of tack coat on the slab was to weigh the sprayer before and after application. This data would give the amount of tack coat sprayed. However, a certain percentage of this was the aforementioned “overspray.” To determine the approximate percentage of overspray, an experiment was performed where the slab was surrounded with a tight-fitting cardboard during the application process, as shown in Figure 17. The cardboard cut-out was weighed before and after the spray application to determine the amount of emulsion that was ‘overspray’. This experiment was performed in triplicate and the data from this experiment are shown as Table 1. The results show the overspray fell between 30 and 35% with a single operator. This gave the research team confidence that a consistent percent overspray could be achieved with a single operator.

A single operator was used to apply the tack coat to all of the slabs fabricated and tested in this project to ensure consistency of operation. A value of 30% overspray was used throughout this project, meaning 70% of the amount of sprayed emulsion (by weight) was assumed to have been placed on the surface of the slab.

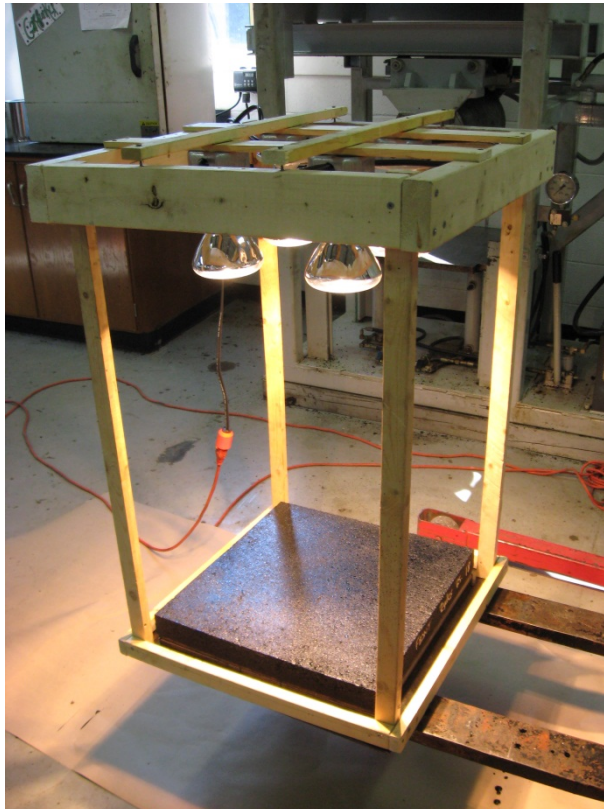


**Figure 17 Device Used to Calibrate Application Overspray**

**Table 1 Data from Overspray Experiment**

<b>Quantity</b>	<b>Trial 1</b>	<b>Trial 2</b>	<b>Trial 3</b>
Weight of Cardboard Initial (grams)	877.3	880.9	905.7
Weight of Cardboard Final (grams)	942.5	938	959
Weight of Sprayer Initial (grams)	1271.7	1606.5	1404.2
Weight of Sprayer Final (grams)	1055.7	1424.3	1255.1
Weight of Spray on Cardboard (grams)	65.2	57.1	53.3
Weight Lost From Sprayer (grams)	216	182.2	149.1
Weight of Spray on Slab (grams)	150.8	125.1	95.8
Percent Overspray	30	31	35
Number of Passes	21	16	11
Weight per Spray	10.3	11.3	123.6
Weight on Slab per Spray	7.2	7.8	8.8

Since the laboratory evaluation was taking place indoors with room temperature emulsion, the research team wanted to better simulate the outdoor curing conditions of the emulsion. For this, a cradle was fabricated that placed an array of heat lamps a distance above the surface of the slab (Figure 18). The device provided a surface temperature of the slab between 90-100°F (32.2-37.8°C), as measured by an infrared temperature gun. These pavement temperatures are very common in Alabama and aided in providing a faster breaking emulsion for laboratory testing purposes. After the emulsion on the base slab had broken, the surface slab was then compacted above it.



**Figure 18 Emulsion Curing Environment in Laboratory**

## 2.4 Emulsion Proportions

For this project, two emulsion tack applications were compared: a control and a Nanotac modified application. For both emulsions, the base emulsion was a cationic slow-setting emulsion (CSS). The CSS emulsion had a residual AC content of 60% as determined by the ASTM 6934-04 test for determining the residue of emulsified asphalt by evaporation. The viscosity of this emulsion at 25°C was 85.8 SFS, and the penetration and ductility of the asphalt residue were 182.5 dmm and 44.5 cm, respectively. For the control application, the CSS emulsion was diluted by half to have an emulsion application with 30% residual AC. The Nanotac application was blended according to the proportions listed in Table 2, per the sponsor’s request. The emulsion using the Nanotac additive contained a 10% residual AC content. The experiment was designed in this manner to test whether adding the Nanotac additive to emulsion would allow the use of a lower residual AC content to provide equivalent bond strength to an unmodified emulsion. The correct amount of water was weighed out and blended with the correct amount of Nanotac (1% of the added water) drop wise with a syringe while the water/Nanotac blend was being stirred. The water/Nanotac blend was then added to the correct amount of CSS emulsion (Table 2) for the application. The blended Nanotac emulsion was used within 4-6 hours of blending, per the manufacturer’s instructions. All emulsion applications were performed at room temperature.

**Table 2 Applied Emulsion Proportions**

Emulsion ID	Parts CSS Emulsion (60% Residual)	Parts Water	Parts Nanotac	Total Parts	Residual AC Content (%)
Control	100	100	0	200	30
Nanotac	33	167	1.67	201.7	10

## 2.5 Top Slab Fabrication

After the appropriate tack coat application had been applied to the bottom slab and the emulsion had broken, the quadrant dividers were again placed into the slab molds on top of the bottom slab, and mix was placed in each quadrant (Figure 19). Once the mix was in the mold, the previously described compaction methodology was completed to ensure the top slab reached the target air voids.

Once the completed two-lift slab had cooled, six 6-inch (152.4 mm) diameter cores were marked and cut using NCAT’s coring rig (Figure 20 and Figure 21). The six cores were then randomly divided into test groups. Three cores from each slab were tested for bond strength after three days, and the other three cores were cured for 45 days before they would be tested for bond strength (Note: The photo in Figure 21 was taken from a previous study in which nine cores were taken from each slab).



**Figure 19 Creating Top Slab**



**Figure 20 NCAT Coring Rig**



**Figure 21 Coring of Slabs**

## **2.6 Testing Procedure**

The interlayer bond strength of each core was determined using ALDOT-430 *Standard Test Method for Determining the Bond Strength Between Layers of an Asphalt Pavement*. NCAT uses a Marshall Press (Figure 22) to conduct its bond strength tests. Each core was then placed in a 6-inch (152.4 mm) diameter collar (Figure 23) and loaded, as shown in Figure 24, by the press at a rate of 2 inches (50.8 mm) per minute.





Figure 22 Marshall Press Testing Apparatus

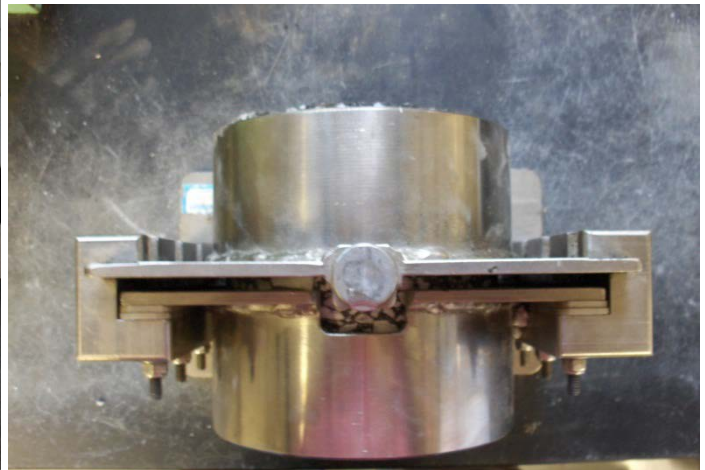
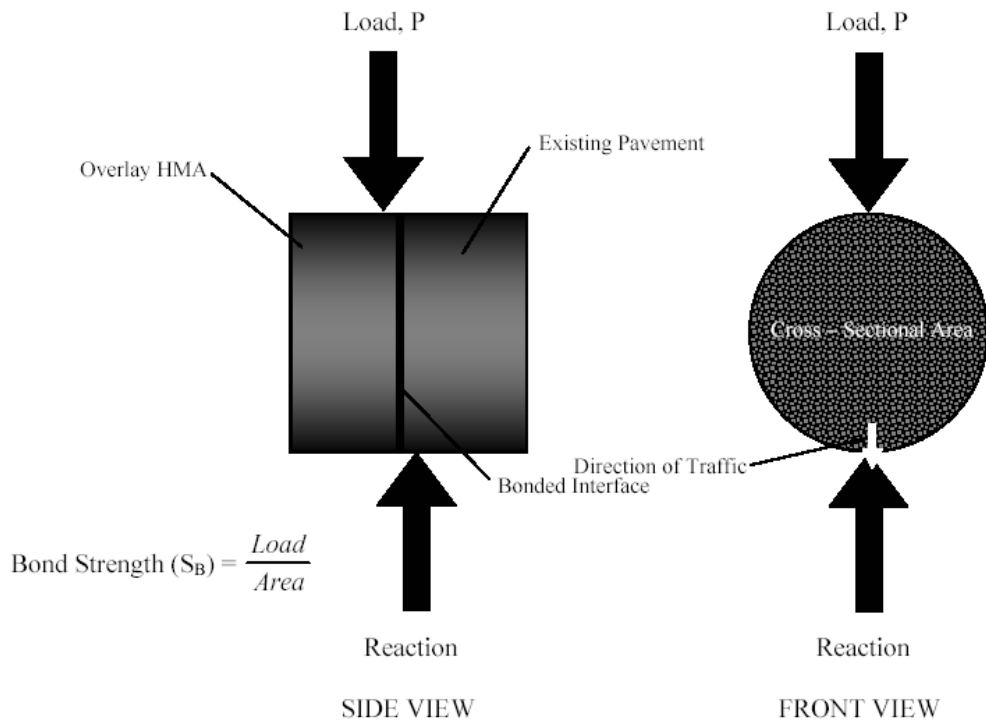


Figure 23 Bond Strength Testing Collar



**Figure 24 Loading scheme Used for Bond Strength Test (5)**

As the core is loaded at its interface, the force applied to the specimen is recorded using the Marshall press (Figure 25). The force typically increases gradually until the point where the bond breaks between the two layers. At this point, the force applied by the Marshall Press decreases dramatically (Figure 26). The maximum force applied to the specimen is then rounded off to the nearest 50 pounds (22.6 kg), recorded, and divided by the cross-sectional area of the specimen to calculate the bond strength of the core.

Past research has indicated that a bond strength of 100 psi (0.69 MPa) is appropriate for enduring the levels of stress typically generated near the surface of the pavement (13).



Figure 25 Conducting the Bond Strength Test

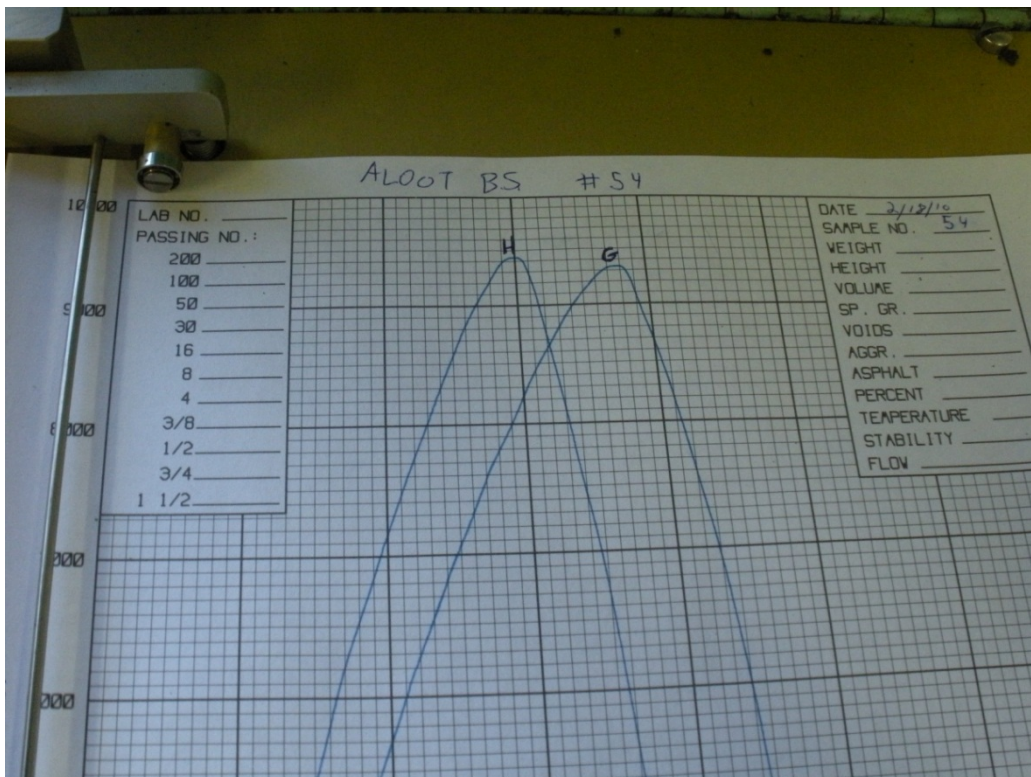


Figure 26 Bond Strength Test Data Collection

### 3. BOND STRENGTH TESTING PLAN

An experiment was designed to determine the optimal tack coat application rate for both the control emulsion and the Nanotac modified emulsion on both a milled and an unmilled (new HMA) surface. The samples for this testing were fabricated in the manner described in the Experimental Setup section of this report. The target application rate for the asphalt residual and spray application are given in Table 3 and Table 4, respectively. The target residual application rates were derived from past experience.

Three application rates were used for each combination of emulsion and treated surface. For the milled surface, the target application rate of the new HMA surface was doubled to account for the increase in surface area generated by the milling process. Note that the spray application rate (Table 4) was identical for both emulsion applications on a given surface. However, the residual contents (Table 3) were different since the control application and Nanotac application had different residual AC contents. As mentioned previously, the control emulsion application had a 30% AC residual while the Nanotac modified application had only a 10% AC residual.

For each cell in the testing matrix, a multi-layered slab was prepared and six – 6 inch (152.4 mm) diameter cores obtained, as described previously. The first subset of three cores was tested for bond strength 3 days after fabrication, and the second subset of three cores was tested for bond strength 45 days after fabrication. The 3-day cores were used to determine the optimum tack coat application rate for each combination of pavement surface and emulsion type. The data from the 3-day and 45-day cores were used to determine the effect of curing time on the interface bond strength.

**Table 3 Target Residual Application Rates**

Surface	Application Option	Residual Application Rate - gal/sy (L/m <sup>2</sup> )		
		Low	Medium	High
HMA	Control	0.020 (0.091)	0.040 (0.181)	0.060 (0.272)
	Nanotac	0.007 (0.032)	0.013 (0.059)	0.020 (0.091)
Milled Surface	Control	0.040 (0.181)	0.080 (0.362)	0.120 (0.543)
	Nanotac	0.013 (0.059)	0.027 (0.122)	0.040 (0.181)

**Table 4 Target Spray Application Rates**

Surface	Application Option	Residual Mass (%)	Spray Application Rate - gal/sy (L/m <sup>2</sup> )		
			Low	Medium	High
HMA	Control	30	0.067 (0.303)	0.133 (0.602)	0.200 (0.906)
	Nanotac	10	0.067 (0.303)	0.133 (0.602)	0.200 (0.906)
Milled Surface	Control	30	0.133 (0.602)	0.267 (1.209)	0.400 (1.811)
	Nanotac	10	0.133 (0.602)	0.267 (1.209)	0.400 (1.811)

## 4. BOND STRENGTH EVALUATION

### 4.1 Analysis Approach

The first step in the analysis process was to perform statistical analysis using a general linear model (GLM) ( $\alpha = 0.05$ ) in Minitab® on the complete bond strength database to see which factors were significant. The analysis looked at statistical differences in bond strength based on four factors: curing time (3-day or 45-day), surface type (milled or unmilled), emulsion treatment (control or Nanotac modified), and application rate (low, medium, or high). A summary of this analysis can be found in Table 5 and the complete analysis results can be found in APPENDIX B. The results showed all four of these variables to be statistically significant in the context of the overall dataset.

**Table 5 Summary of Statistical Analysis – Tukey-Kramer Groupings ( $\alpha= 0.05$ ) - Bond Strength – Full Dataset**

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	36	189.9	A
Nanotac Option 2	36	168.2	B

Surface	N	Mean	Grouping
Milled	36	191.0	A
HMA	36	167.1	B

Application Rate	N	Mean	Grouping
Low	24	203.2	A
High	24	171.9	B
Medium	24	162.0	B

Curing Time (days)	N	Mean	Grouping
3	36	188.3	A
45	36	169.8	B

Means that do not share a letter are significantly different.

Since the spray rates used for milled and new HMA surfaces were different, the research team decided to analyze the bond strength data from the milled and unmilled surfaces separately. The first phase of the analysis was to look at the 3-day bond strength values as a function of emulsion type and application rate. A separate evaluation was then conducted using the 3-day and 45-day bond strength values to determine the effect of curing time on the interface bond strength. If curing time proved to be a significant variable, the 45-day bond strength values would be analyzed separately. If curing time proved insignificant, then the 3-day and 45-day bond strength values would be pooled to develop overall conclusions about which emulsion and application rate combinations provided the best interface bond strength. The complete data set of all bond strength results used for this evaluation can be found in APPENDIX C.

## 4.2 Bond Strength after Three-Day Curing Period

The first samples tested were the bond strength samples tested after three days of curing. These samples will be referred to as 3-day samples for the purposes of this report. These samples were used to determine the optimum application rate for each combination of additive and surface type. For project expedience, the 3-day samples were also used to determine the optimum application rate that would be later used in the moisture susceptibility evaluation.

### 4.2.1 New HMA Surface

Figure 27 shows the average bond strengths of the 3-day cure samples for both the control and Nanotac emulsions on a new HMA surface. The data shows similar trends for both products, with the low application rate having the highest bond strength and the medium application rate having the lowest bond strength.

A general linear model ( $\alpha = 0.05$ ) statistical analysis was performed on this dataset to determine the relevant statistical factors. A summary of the Tukey-Kramer portion of this analysis can be found in Table 6 while the complete statistical analysis can be found in APPENDIX B. This analysis shows that the control and Nanotac emulsions provided equivalent bond strength values when viewed in the context of the entire dataset. When looking at the interaction between the emulsion type and the application rate, it showed that all six combinations in this dataset were statistically equivalent. However, it also showed the low and high application rate to have the highest bond strength. Therefore, since the low application rate had the highest mean bond strength values for both the control and Nanotac emulsions, it was chosen as the optimum application rate for those applications on the new HMA surface.

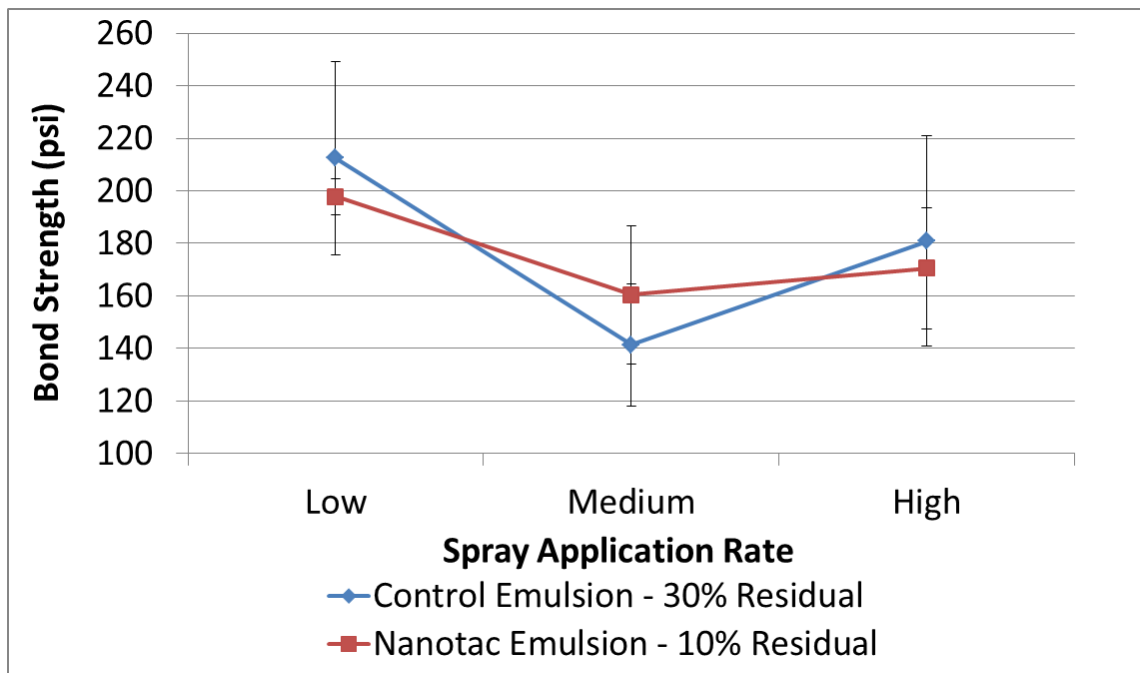


Figure 27 Bond Strength Comparison – 3 day cure - New HMA Surface

**Table 6 Summary of Statistical Analysis – Tukey-Kramer Groupings - Bond Strength - 3 Day Cure - New HMA Surface**

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	9	178.2	A
Nanotac Option 2	9	176.2	A

Application	Rate	N	Mean	Grouping
Application	Low	6	205.1	A
	High	6	175.7	A B
	Medium	6	150.9	B

Tack ID	Application	Rate	N	Mean	Grouping
Control	Low	Low	3	212.4	A
Nanotac Option 2		Low	3	197.8	A
Control	High	High	3	180.9	A
Nanotac Option 2		High	3	170.6	A
Nanotac Option 2	Medium	Medium	3	160.4	A
Control		Medium	3	141.4	A

Means that do not share a letter are significantly different.

#### 4.2.2 Milled Surface

Figure 28 shows the average bond strengths of the 3-day cure samples for both the control and Nanotac emulsions on a milled HMA surface. The data shows the control and Nanotac samples have equivalent bond strengths at the medium and high application rates, but at the low application rate the control samples have a bond strength about 90 psi (0.62 MPa) higher than the Nanotac samples. It is possible that the low application rate for the Nanotac emulsion did not have enough AC residual to provide bond strength equivalent to the higher application rates. This is likely due to the increased slab surface area generated by the milling process.

A general linear model ( $\alpha = 0.05$ ) statistical analysis was performed on this dataset to determine the relevant statistical factors. A summary of the Tukey-Kramer portion of this analysis can be found in Table 7 while the complete statistical analysis can be found in APPENDIX B. The analysis shows the control bond strength was statistically higher than the Nanotac bond strength in the context of the overall data set. This is likely driven by the low bond strength for the low application rate using the Nanotac emulsion. According to the overall analysis, the application rate did not have a statistical impact on the bond strength, with all three application rates falling in the same statistical grouping. However, based on inspection of the results, this is likely due to the average bond strength of the Nanotac and control emulsions at the low application rate being similar to the average bond strengths of both applications at the medium and high application rates. When the interaction between the emulsion and application rates were analyzed, it showed the control with a low application rate and the Nanotac with a medium application rate had the highest average bond strength and fell within the same statistical grouping. Therefore, these application rates were selected as the optimum rates for the control and Nanotac applications.

It should also be noted that even though a higher spray application rate of Nanotac emulsion was required to get equivalent bond strength to the control emulsion, the Nanotac still had a lower total AC residual than the control emulsion due how much the Nanotac emulsion was diluted. The residual application rate for the control emulsion was 0.040 gal/sy (0.181 L/m<sup>2</sup>) at the low application rate while the residual application rate for the Nanotac emulsion was 0.027 gal/sy (0.122 L/m<sup>2</sup>) at the medium application rate.

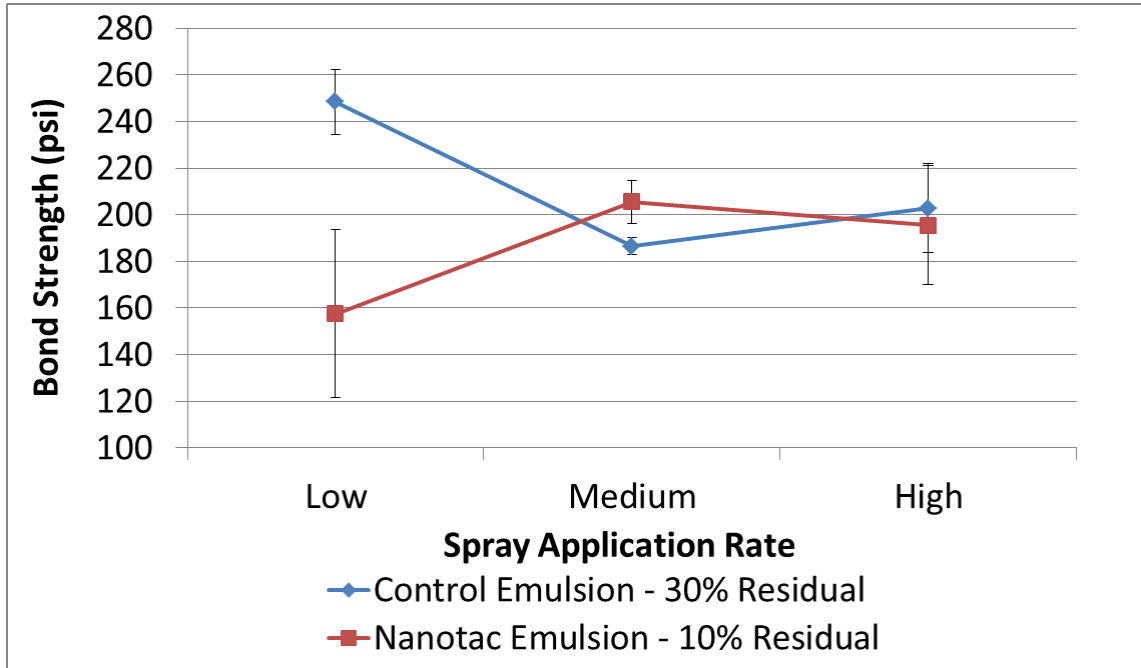


Figure 28 Bond Strength Comparison – 3 day cure - Milled Pavement Surface

Table 7 Summary of Statistical Analysis – Tukey-Kramer Groupings - Bond Strength - 3 Day Cure - Milled Surface

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	9	212.6	A
Nanotac Option 2	9	186.2	B

Application Rate	N	Mean	Grouping
Low	6	203.0	A
High	6	199.2	A
Medium	6	196.0	A

Tack ID	Application Rate	N	Mean	Grouping
Control	Low	3	248.5	A
Nanotac Option 2	Medium	3	205.5	A B
Control	High	3	202.8	A B
Nanotac Option 2	High	3	195.6	A B
Control	Medium	3	186.5	B
Nanotac Option 2	Low	3	157.5	B

Means that do not share a letter are significantly different.



### 4.3 Effect of Curing

With data collected for each combination of application rate, emulsion application, and surface type (12 sets total) at both a 3-day and 45-day curing period, an evaluation of how the curing time effects bond strength could be performed. The initial statistical evaluation performed on the entire database (Table 5) showed that curing time had a significant statistical impact on the bond strength. The analysis showed the average bond strength was reduced by about 10% over the 6-week curing period. To confirm this trend, an additional evaluation was performed.

Figure 29 shows the average and standard deviations of the bond strength at both curing periods for each of the 12 sample sets tested. Figure 30 shows the percent change in the bond strength between the 3 day samples and the 45 day samples. From this plot, it is evident that the majority of the sample sets saw a reduction in bond strength over the additional six weeks of curing. The typical reduction was between 10 and 20%. Interestingly, the only sample sets to increase in bond strength over the curing period were the control applications using the low application rate on both the milled and HMA surface (optimum application rate for both surfaces). This increase in strength was between 5 and 10% for both sets.

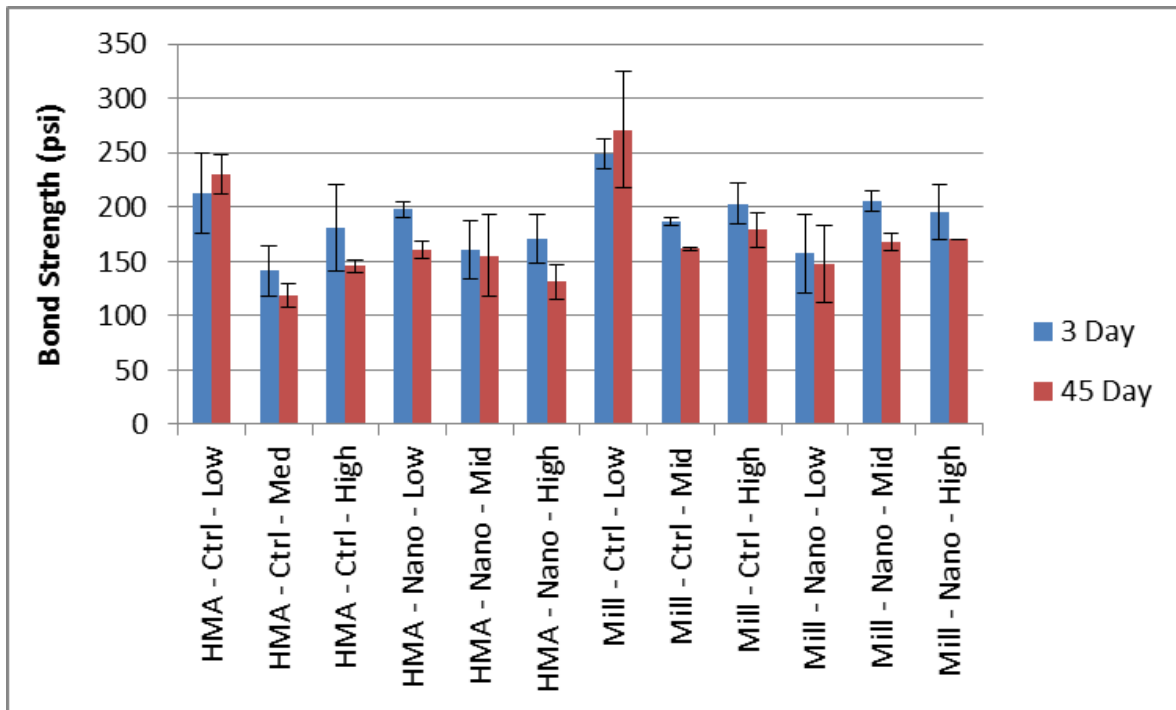
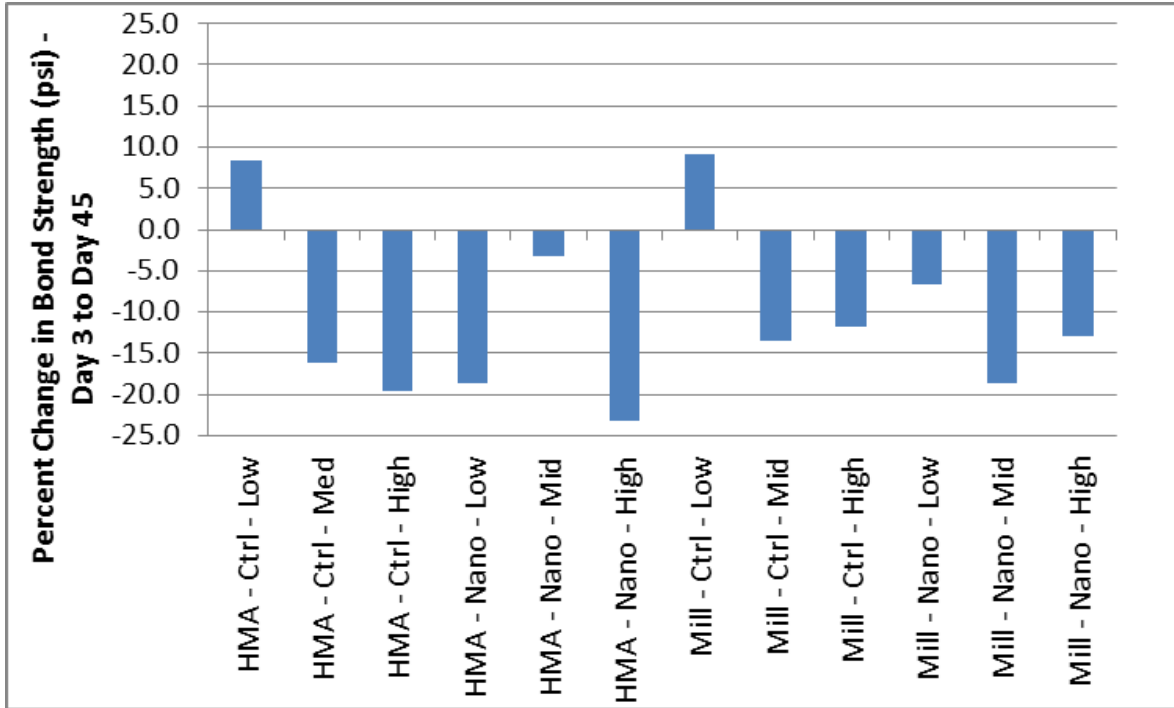


Figure 29 Three-Day versus 45-Day Bond Strengths for All Sample Sets



**Figure 30% Change in Bond Strength (3-Day versus 45-Day)**

To determine if the changes in bond strength for each set were statistically significant, a two-tailed t-test ( $\alpha = 0.05$ ) was performed comparing the 3-day and 45-day bond strengths for each set of samples. The  $p$ -values of this testing are shown in Figure 31 with the significance level highlighted. This plot shows no clear trends in the statistical significance of curing versus surface type, emulsion type, or application rate. Furthermore, only 25% of the sample sets (3 out of 12) showed the curing to be statistically significant. Thus, while the overall data set showed the curing time to be statistically significant, a closer analysis of the data shows this is not the case. Therefore, the effect of sample curing does not outweigh the effect of spatial variability due to sample fabrication of the cores within each slab.

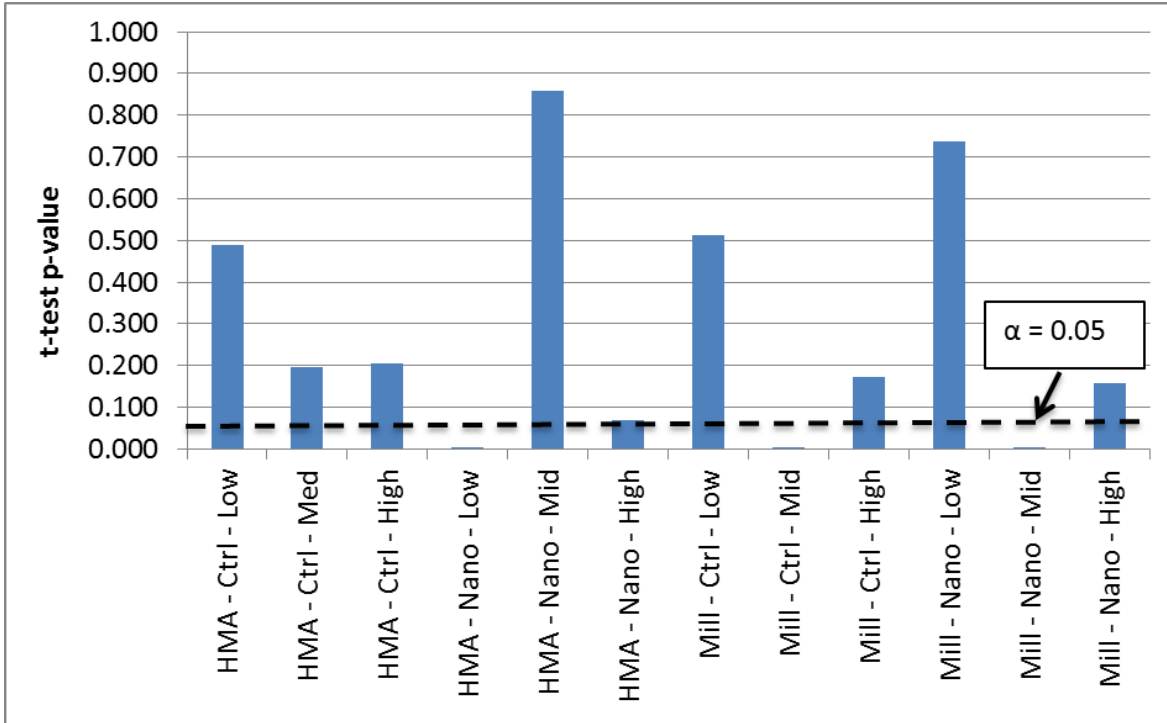


Figure 31 *t*-test *p*-values for Curing Evaluation

#### 4.4 Pooled Analysis

With no definitive evidence on the effect of bond strength change due to curing, a final analysis was performed on the bond strength database without using curing time as a variable. This allowed for a more robust dataset for analysis (6 samples per set instead of 3). The analysis technique previously used on the 3-day strength samples was repeated for this investigation.

##### 4.4.1 New HMA Surface

Figure 32 shows the average bond strengths of all of the bond strength samples (both 3-day and 45-day cure) for both the control and Nanotac emulsions on a new HMA surface. For the control emulsion, the low application rate had the highest average bond strength and the medium application rate had the lowest average bond strength. For the Nanotac emulsion, the average bond strength decreased as the application rate increased.

A general linear model ( $\alpha = 0.05$ ) statistical analysis was performed on this dataset to determine the relevant statistical factors. A summary of the Tukey-Kramer portion of this analysis can be found in Table 8 while the complete statistical analysis can be found in APPENDIX B. The analysis of the entire dataset showed that the control and Nanotac emulsions provided equivalent bond strengths, and the low application rate provided the highest bond strength on the new HMA surface. These observations were confirmed when looking at the interaction between the emulsion type and application rate.

Therefore, when applied to a new HMA surface, a highly diluted CSS emulsion (10% AC residual) treated with Nanotac can provide equivalent bond strength to a diluted CSS emulsion (30% AC residual). It should be noted that all of the bond strengths collected in this investigation fall above the desired threshold values of 100 psi (0.69 MPa) (13).

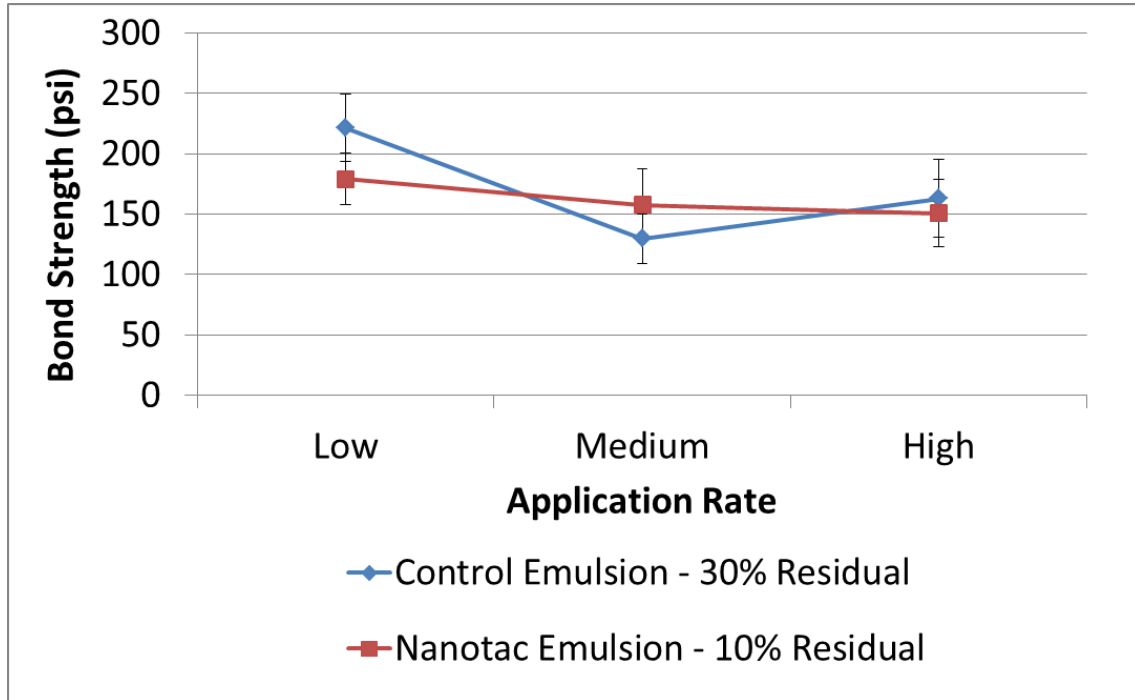


Figure 32 Bond Strength Comparison - All Samples - New HMA Surface

Table 8 Summary of Statistical Analysis – Tukey-Kramer Groupings - Bond Strength – All Samples - New HMA Surface

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	18	171.5	A
Nanotac Option 2	18	162.7	A

Application Rate	N	Mean	Grouping
Low	12	200.3	A
High	12	157.0	B
Medium	12	143.9	B

Tack ID	Application Rate	N	Mean	Grouping
Control	Low	6	221.4	A
Nanotac Option 2	Low	6	179.3	A B
Control	High	6	163.2	B C
Nanotac Option 2	Medium	6	157.9	B C
Nanotac Option 2	High	6	150.8	B C
Control	Medium	6	129.9	C

Means that do not share a letter are significantly different.

4.4.2 Milled Surface

Figure 33 shows the average bond strengths of all of the bond strength samples (both 3-day and 45-day cure) for both the control and Nanotac emulsions on a milled surface. For the control emulsion, the low application rate had the highest average bond strength, and the medium application rate had the lowest average bond strength. For the Nanotac emulsion, the low application rate had the lowest average bond strength, with the medium and high application rates having the highest average bond strengths. As with the 3-day and 45-day evaluation, the biggest disparity between the two emulsions can be seen at the low application rate.

A general linear model ( $\alpha = 0.05$ ) statistical analysis was performed on this dataset to determine the relevant statistical factors. A summary of the Tukey-Kramer portion of this analysis can be found in Table 9 while the complete statistical analysis can be found in APPENDIX B. The individual factor analysis showed the control emulsion had a statistically higher bond strength than the Nanotac emulsion on the complete dataset. The application rate was not statistically significant in the context of the full dataset. The interaction comparisons between emulsion type and application rate confirmed the control emulsion at the low application rate had the highest bond strength by a wide margin (approximately 70 psi (0.48 MPa)). The remaining 5 subsets were statistically equivalent. However, even the poorest performing application did not have a bond strength below 150 psi (1.03 MPa), well above the desired threshold value of 100 psi (0.69 MPa) (13).

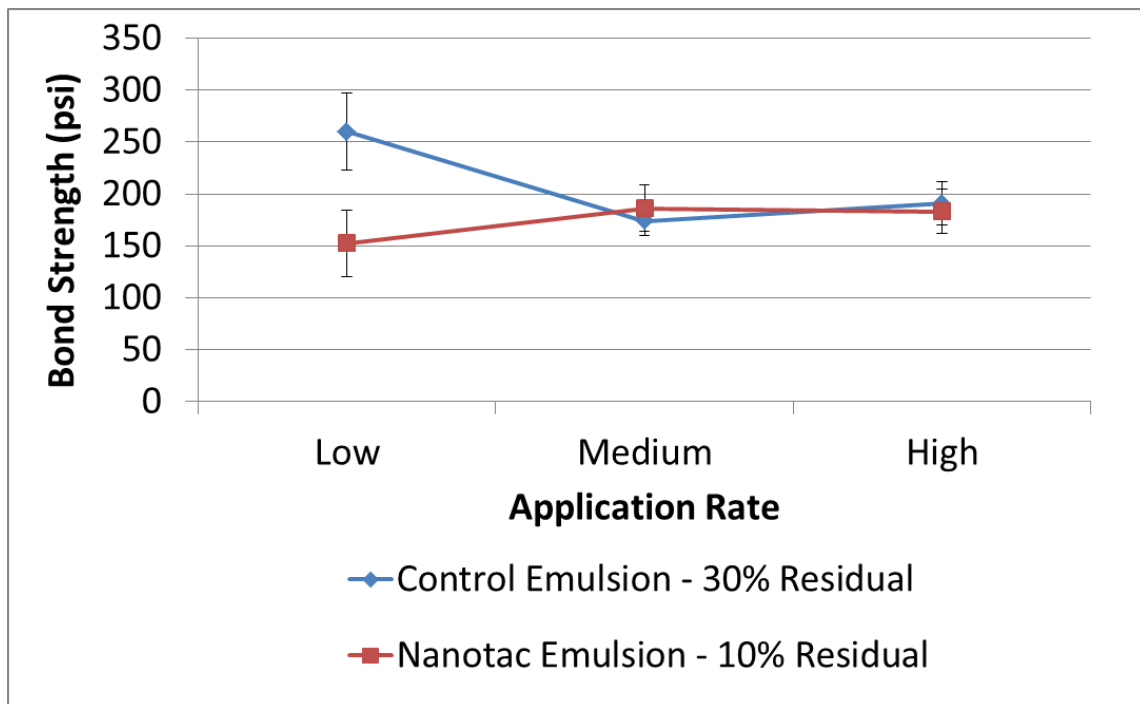


Figure 33 Bond Strength Comparison - All Samples - Milled Surface

**Table 9 Summary of Statistical Analysis – Tukey-Kramer Groupings - Bond Strength – All Samples - Milled Surface**

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	18	208.2	A
Nanotac Option 2	18	173.8	B

Application	Rate	N	Mean	Grouping
Low		12	206.1	A
High		12	186.9	A
Medium		12	180.1	A

Tack ID	Application	Rate	N	Mean	Grouping
Control	Low		6	259.9	A
Control	High		6	190.9	B
Nanotac Option 2	Medium		6	186.3	B
Nanotac Option 2	High		6	182.8	B
Control	Medium		6	174.0	B
Nanotac Option 2	Low		6	152.3	B

Means that do not share a letter are significantly different.

In summary, the bond strength evaluation showed both the control and Nanotac emulsion applications provided adequate bond strength (greater than 150 psi (1.03 MPa)) at their optimum application levels. For the new HMA surface, the Nanotac application (10% AC residual) provided equivalent bond strength to a control emulsion application (30% AC residual). For the milled surfaces, the optimum control application outperformed the optimum Nanotac application. An additional six week curing period did not significantly impact the bond strength of the majority of tested specimens.

## 5. MOISTURE SUSCEPTIBILITY EVALUATION

An experimental evaluation was conducted to induce moisture damage into the tack coat and determine the effects of the moisture damage on the interface bond strength. The method used to induce moisture damage into the tack coat was derived from the method used to determine a tensile strength ratio (TSR) for a Superpave mix design (AASHTO T283-07). It was desired to look at how applying freeze-thaw cycles to the cored specimens impacted the bond strength.

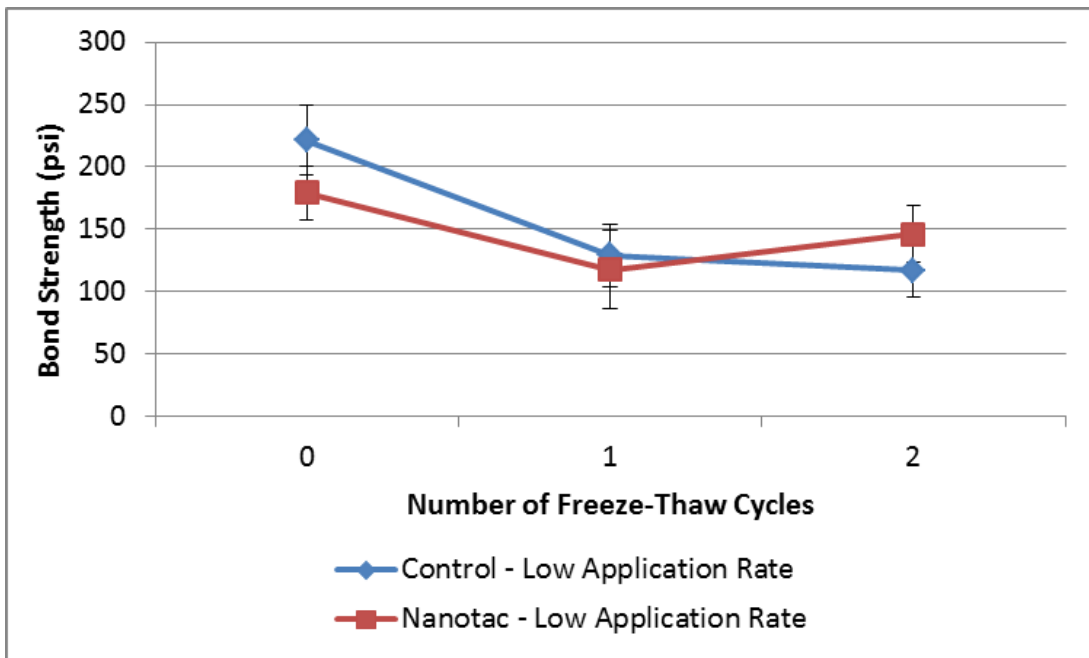
To perform this evaluation, four additional two-layer slabs were fabricated. A slab was fabricated for each optimum combination of surface type, emulsion type, and application rate determined during the bond strength evaluation. A summary of these optimum values is presented in Table 10. A single two-layer slab was fabricated for each row in Table 10. From each slab, six 6-inch (152.4 mm) cores were obtained as previously described. For the moisture evaluation, a subset of three cores was tested with one freeze-thaw cycles, and the other subset of three cores were tested with two freeze-thaw cycles. The freeze-thaw cycles were applied to the cores in the same way they are applied for AASHTO T283 testing. The cores are vacuum saturated underwater until 70-80% of the internal voids are filled with water. The samples are then frozen for a minimum of 16 hours prior to being placed in a 140°F (60°C) water bath for 24

± 1 hours. The samples were then placed in a 77 ± 2°F (25 ± 1°C) water bath for two hours prior to being tested for bond strength. The bond strength of the samples undergoing a freeze-thaw cycle were then compared with the bond strength of the samples tested during the bond strength evaluation that had undergone no moisture conditioning.

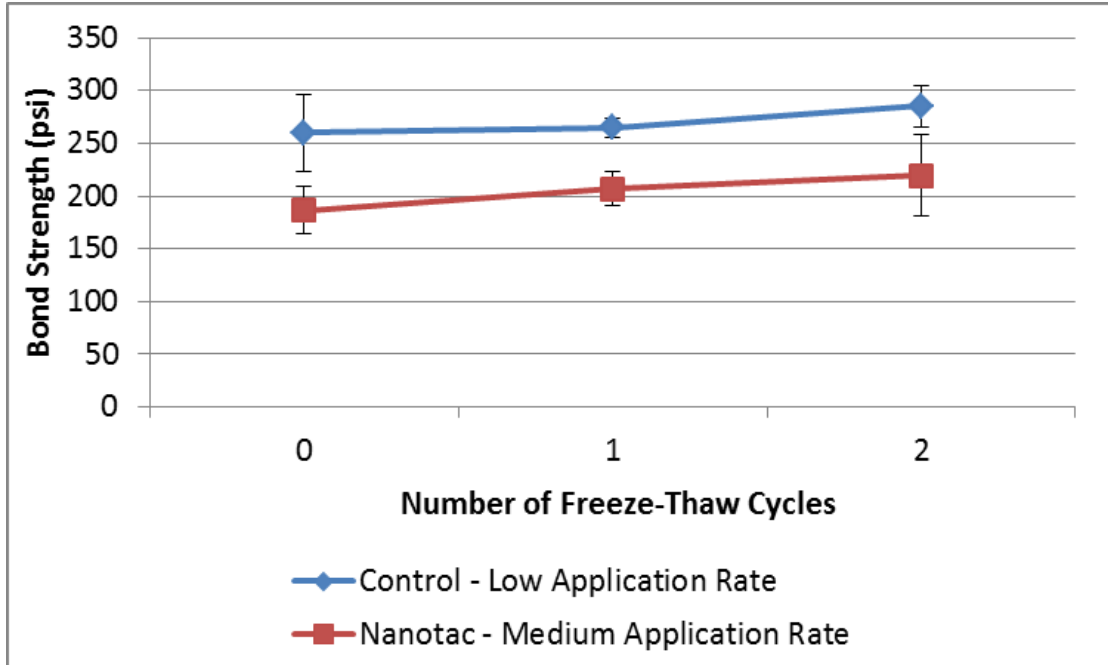
**Table 10 Summary of Optimum Tack Coat Rates**

Surface Type	Emulsion Type	Application Rate	Residual Application Rate- gal/sy (L/m <sup>2</sup> )	Spray Application Rate - gal/sy (L/m <sup>2</sup> )
New HMA	Control	Low	0.020 (0.091)	0.067 (0.303)
New HMA	Nanotac	Low	0.007 (0.032)	0.067 (0.303)
Milled	Control	Low	0.040 (0.181)	0.133 (0.602)
Milled	Nanotac	Medium	0.027 (0.122)	0.267 (1.209)

Figure 34 and Figure 35 show the average and standard deviation of the sample bond strength versus the number of freeze-thaw cycles to which it was exposed for the new HMA and milled surfaces, respectively. The freeze-thaw cycles caused a reduction in bond strength (as expected) for the samples taken with a new HMA surface as the bottom layer. However, the bond strength increased for the milled surface with additional freeze-thaw cycles. This seems to suggest the additional moisture conditioning increased the bond strength of these samples, which was opposite of the expected trend. This also suggests the method of moisture conditioning was sufficient to induce moisture damage in the new HMA samples but not sufficient to induce said damage in the milled samples. More extreme moisture conditioning may be needed to generate moisture damage in the milled slab tack coats.



**Figure 34 Bond Strength versus Number of Freeze-Thaw Cycles - New HMA Surface**



**Figure 35 Bond Strength versus Number of Freeze-Thaw Cycles - Milled Surface**

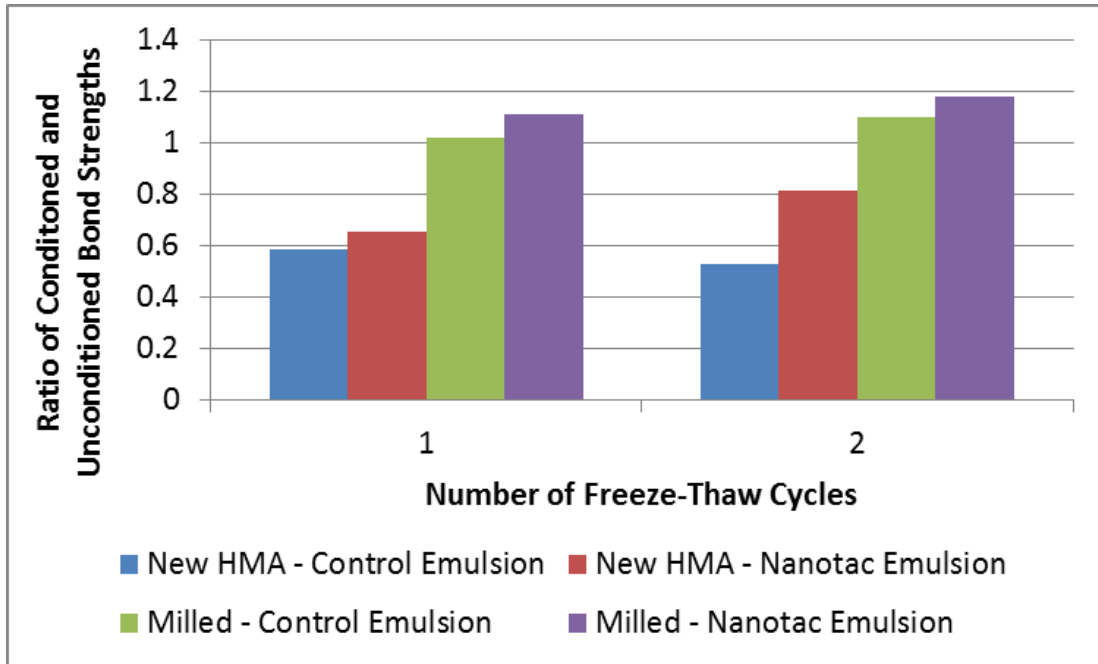
Figure 36 shows the ratio of the average bond strengths after moisture conditioning to the average unconditioned bond strength for each data point tested. A ratio lower than one means the conditioned samples had a lower bond strength than the unconditioned samples while a ratio higher than one means the conditioned samples had a higher bond strength than the unconditioned samples. For the purposes of this report, this will be referred to as the bond strength ratio. Figure 36 shows the bond strength ratio of the new HMA surface samples fell between 0.5 and 0.6 for the control emulsion and between 0.6 and 0.8 for the Nanotac emulsion. For the milled slabs, all of the bond strength ratios fell between 1.0 and 1.2. In all cases, the Nanotac emulsion had a slightly higher bond strength ratio than the control emulsion for comparable data sets. The only set for which the bond strength ratio seemed significantly improved over the control was for the new HMA surface and 2 freeze-thaw cycles.

To verify this finding statistically, a general linear model ( $\alpha = 0.05$ ) was performed on the moisture study dataset for both the milled and new HMA slabs. A summary of the Tukey-Kramer portion of this analysis can be found in Table 11 for the new HMA surface and Table 12 for the milled HMA surface. The complete statistical analysis for the moisture evaluation can be found in APPENDIX B. These statistics confirm that the new HMA with 2 freeze-thaw cycles is the only data point where the bond strength of the Nanotac emulsion is statistically superior to the bond strength of the control emulsion. For all other conditioned samples, the control and new HMA had statistically equivalent performance.

In summary, the results seem to indicate the experimental moisture study successfully created moisture damage in the samples fabricated on a new HMA surface but not on a milled surface. For the new HMA surface, the bond strength of the Nanotac emulsion was less affected by increasing levels of moisture damage than the control emulsion. Additional testing should



likely be done both in the lab and in the field to assess the viability of this experimental methodology.



**Figure 36 Ratio of Conditioned and Unconditioned Bond Strengths**

**Table 11 Summary of Statistical Analysis - Moisture Evaluation - New HMA Surface**

Grouping Information Using Tukey Method and 95.0% Confidence

Additive	N	Mean	Grouping
Control	12	155.8	A
Nanotac	12	147.6	A

Number of Freeze-Thaw Cycles	N	Mean	Grouping
0	12	200.3	A
2	6	131.4	B
1	6	123.3	B

Additive	Number of Freeze-Thaw Cycles	N	Mean	Grouping
Control	0	6	221.4	A
Nanotac	0	6	179.3	A B
Nanotac	2	3	146.0	B C
Control	1	3	129.2	B C
Nanotac	1	3	117.4	C
Control	2	3	116.7	C

Means that do not share a letter are significantly different.

**Table 12 Summary of Statistical Analysis - Moisture Evaluation - Milled Surface**

Grouping Information Using Tukey Method and 95.0% Confidence

Additive	N	Mean	Grouping
Control	12	269.9	A
Nanotac	12	204.3	B

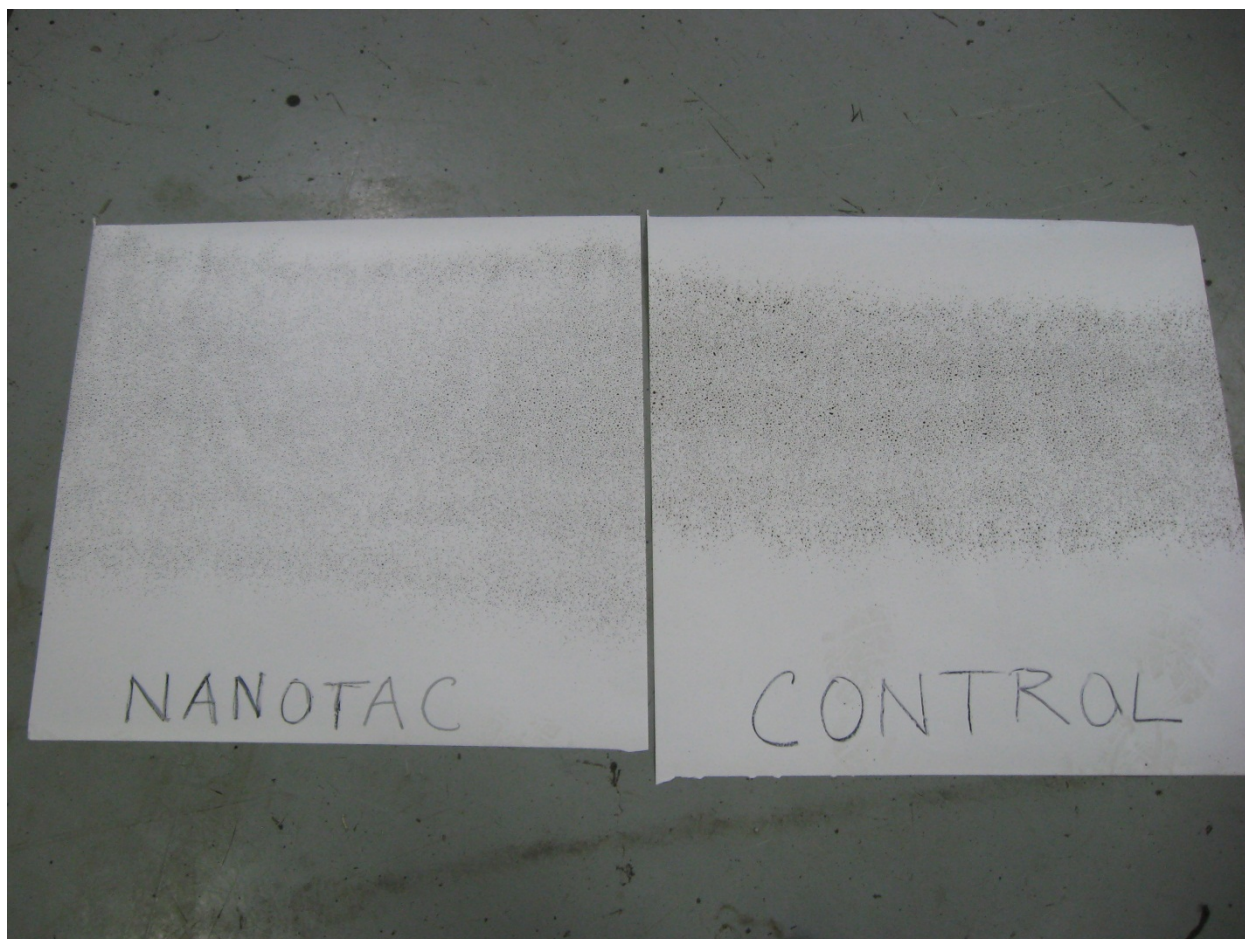
Number of Freeze-Thaw Cycles	N	Mean	Grouping
2	6	252.4	A
1	6	235.8	A
0	12	223.1	A

Additive	Number of Freeze-Thaw Cycles	N	Mean	Grouping
Control	2	3	285.1	A
Control	1	3	264.8	A B
Control	0	6	259.9	A B
Nanotac	2	3	219.7	A B C
Nanotac	1	3	206.8	B C
Nanotac	0	6	186.3	C

Means that do not share a letter are significantly different.

## 6. SPREADABILITY EVALUATION

One of the desired effects of the Nanotac product is to lower the surface tension of a cationic emulsion with which it is blended, reducing droplet size and improving spray coverage. A quick experiment was performed in the laboratory to verify this theory. Both the control and Nanotac emulsion applications were sprayed in one pass over a clean piece of wax paper. As with the rest of the slabs fabricated in this study, the sprayer was primed to the same level by the same operator prior to spraying the wax paper. This was done to see if there was a difference in spreadability and droplet size for the Nanotac versus the control emulsion. This comparison can be seen in Figure 37. The figure shows generally that the Nanotac spray application had a wider spray range. It also shows a smaller droplet size than the control application. This comparison can be better seen when zoomed in on a small section of the individual droplets (Figure 38). While the results of this experiment are encouraging, it should be noted that ultimately the success of the additive is determined by the improvements it makes to the spraying process in the field.



**Figure 37 Emulsion Spreadability Comparison**



**Figure 38 Emulsion Droplet Size – Nanotac Modified (left) and Control (right)**

## **7. TIRE PICKUP**

The Nanotac additive is designed to dramatically improve the issue of “tire pickup” common with unmodified emulsions. Tire pickup refers to the problem of fresh tack coat being removed from the treated surface by construction traffic, rendering it ineffective.

A small laboratory experiment was designed to simulate tire pickup in the lab for a slab treated with both the control and Nanotac emulsions. For this experiment, a three-wheel polishing device (TWPD) equipped with rubber tires was used to simulate five passes with a loaded wheel. The TWPD (Figure 39) is typically used at NCAT for friction studies. A slab is loaded for a preset number of cycles while water is sprayed over it with rubber tires. Friction measurements can then be taken to gauge the relative quality of materials with respect to surface friction. The reason the TWPD was used for this evaluation was simply to see the effect of running a loaded rubber tire over a freshly broken emulsion application. In this way, the amount of emulsion removed by the rubber tire could be visually examined.

For this experiment, the water spray was turned off and the device was used simply to apply five passes of a loaded tire to the pavement surface. A slab with each emulsion type was prepared and tested immediately after the emulsion had broken. Slab, emulsion, and curing procedures were consistent with those previously documented in this report. Each slab was tested with five passes of the loaded wheel in the TWPD and photographs taken before and after testing.

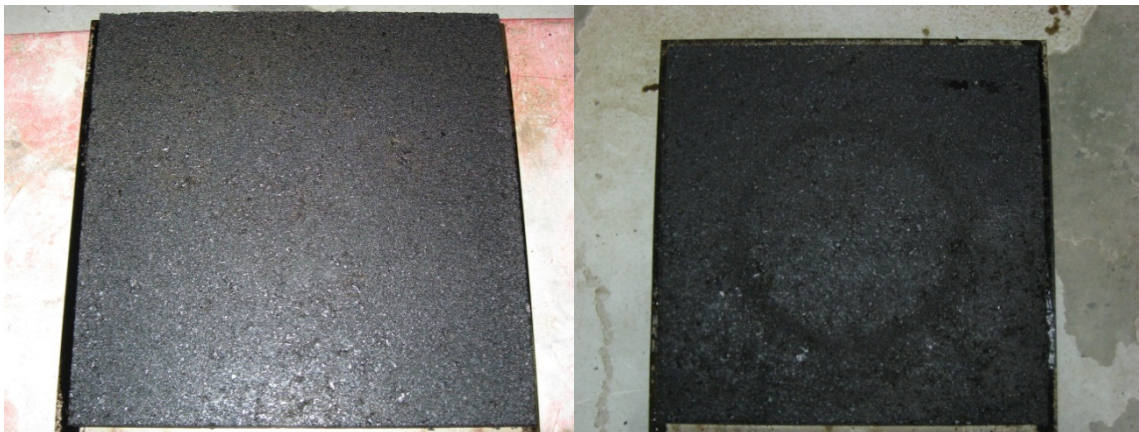


**Figure 39 Three-Wheel Polishing Device (TWPD) used for Tire Pickup Experiment**

Figure 40 shows the results of the tire-pickup experiment for the control emulsion, and Figure 41 shows the results of the tire-pickup experiment for the Nanotac emulsion. While the Nanotac application appeared to be more even than the control application, a wheel path was visible on both slabs. As such, both applications appeared to perform equivalently in this experiment. While the Nanotac offered no apparent improvements in this experiment, it should be noted that the value of the additive in whether it improves tire pickup is best determined by field studies.



**Figure 40 Slab with Control Emulsion both Before (left) and After (right) Tire-Pickup Experiment**



**Figure 41 Slab with Nanotac Emulsion both Before (left) and After (right) Tire-Pickup Experiment**

## 8. COST ANALYSIS

Finally, a cost analysis was performed on the Nanotac modified and unmodified emulsions used for this project. For this analysis, the cost of a 60% AC residual CSS emulsion was assumed to be \$2.04 per gallon. The cost of a gallon of Nanotac additive was assumed to be \$57.60 per gallon. A summary of this analysis is shown in Table 13. This analysis shows the Nanotac modified emulsion with 10% AC residual costs approximately \$0.86 per gallon to blend while an unmodified emulsion with 30% AC residual costs approximately \$1.02 per gallon. Therefore, the Nanotac modified emulsion nets a savings of about 15% over the unmodified emulsion used in this evaluation.

**Table 13 Summary of Cost Analysis**

<b>Tack Coat (% Asphalt)</b>	<b>Asphalt % in Tack Coat</b>	<b>% Water in Tack Coat</b>	<b>Amount of Emulsion, gal</b>	<b>Amount of Nanotac, gal</b>	<b>Cost of Emulsion</b>	<b>Cost of Nanotac</b>	<b>Cost of Tack Coat/Gal</b>
Unmodified (30)	30	70	0.50	0.00	\$ 1.02	\$ -	\$ 1.02
Modified (10)	10	90	0.17	0.009	\$ 0.34	\$ 0.52	\$ 0.86

## 9. CONCLUSIONS

The purpose of this study was to evaluate the properties of a diluted cationic slow setting (CSS) emulsion containing the Nanotac additive versus the properties of a diluted emulsion with no additive. Based on the results of this study, the following conclusions can be made:

1. The Nanotac modified emulsion (10% AC residual) with a lower residual AC content provided equivalent bond strength to that of a control emulsion (30% AC residual) on an unmilled (new HMA) surface.
2. For the milled surface, the optimum control application had a higher bond strength than the optimum Nanotac application. The control and Nanotac applications performed equivalently at the medium and high application rates. However, the control application outperformed the Nanotac application at the lowest application rate.
3. All optimum bond strength values for both the control and Nanotac emulsions were greater than 150 psi (1.03 MPa). Literature recommends a minimum value of 100 psi (0.69 MPa) to have adequate bond strength in the field. Therefore, both the control and Nanotac emulsions provided a quality tack coat interface.
4. The Nanotac technology shows promise as a potential “green” technology given its ability to provide a quality tack coat interface with a lower AC residual.
5. No definitive statistical evidence could be found to show an increase or decrease in bond strength as a function of curing time after an additional six-week curing period.
6. A small experiment was performed to visually compare the spreadability of the Nanotac emulsion versus a control emulsion. Visually, the Nanotac emulsion appeared to have greater spreadability and a smaller droplet size.
7. An experiment was conducted to compare the resistance of both the Nanotac and control emulsions to “tire pickup.” For this evaluation, a loaded wheel tester with rubber tires was used to compare the amount of emulsion removed off freshly broken control and Nanotac emulsions. This evaluation was inconclusive.
8. The moisture susceptibility of the tack coat with and without Nanotac was evaluated with an experimental procedure in which multi-layer cores were subjected to freeze-thaw cycles. These cores were then tested for bond strength to determine the reduction in bond strength as a function of moisture damage. This method of inducing moisture damage seemed to work for the unmilled HMA slabs but not for the milled HMA slabs. For the new HMA slabs, the Nanotac modified emulsion seemed to have greater resistance to moisture damage than the slabs treated with the control emulsion. However, additional testing should be performed to verify the validity of this experimental methodology.
9. The Nanotac modified emulsion with 10% AC residual used in this evaluation costs approximately 15% less to manufacture than the emulsion with 30% AC residual that was used as the control.

## **10. RECOMMENDATIONS**

Given the results of this study, the following actions are recommended:

1. Bolster the laboratory data set obtained in this project using the Nanotac application with additional residual asphalt contents.
2. A field study should be conducted with sections containing the Nanotac and control emulsions used as the tack coat material. Cores should be taken from those sections to verify the conclusions from this study relating to bond strength and curing.
3. A field study would also be useful to take detailed photos and video regarding time to break, tire pickup, and spreadability of both a control and Nanotac modified emulsions.



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## APPENDIX A HMA Mix Design

### Alabama Department of Transportation

Sampled By: Vinson, Jackie	Sample ID: 375274
Project Manager: ALEX MURPHREE	Sample Date: 04/20/2011
County: HOUSTON	Date Tested: 05/03/2011
Producer: GULF COAST DIV OF APAC - DOTHAN	Sample Test Number: 352G-11
Intended Use: SURFACE/PATCH, LEVEL, WIDEN	Division: 07

### GYRATORY COMPACTOR (HMA4302B)

Contractor's Address: APAC MID-SOUTH, INC. P.O. BOX 8888 DOTHAN, AL 36304	Date: 5/3/11 Producer: APAC MID-SOUTH, INC. Plant: DOTHAN
Section/ESAL Category: 424 A/B, C/D	Intended Use: SURFACE/PATCH, LEVEL, WIDEN
Max. Size Aggregate: 1/2" THRU RESTRICTED ZONE	Binder Grade: PG 67-22 BLACKLIDGE
Metric Size Aggregate: 12.5MM THRU RESTRICTED ZONE	Specific Gravity of AC: 1.034

%	Description	I.D.#	Source	BPN
18	#89 LIMESTONE	1405-G	MM-O'NEIL; SAGINAW, AL	-9
12	#8910 LIMESTONE SCRNS	1405-G	MM-O'NEIL; SAGINAW, AL	26
15	#810 GRANITE SCRNS	1723	VMC-NOTASULGA QUARRY; LOACHAPOKA, AL	26
20	SHOT GRAVEL	0261	MM-PINKSTON PIT; SHORTER, AL	
15	SAND	1642-F	COUCH, HILTON, GA	
20	RAP		STOCKPILE #10-7-2	

Job Mix:	Other Information:	Note:
Sieves	% AC Required..... 5.50*	*4.38% PG 67-22 must be added to the mix. The remaining 1.12% comes from the RAP. comes from RAS.
1 1/2" (37.5 mm)	AC Req'd/Ton, lbs/MT, kg... 110.0 55.0	
1" (25.0 mm)	Max. Sp. Gr. Mix..... 2.467	# Gyration: 60 % Gmm: 96.1
3/4" (19.0 mm)	Wt., lbs/Mass, kg/m <sup>3</sup> ..... 147.3 2360.0	<b>Additional Notes:</b> MIXING TEMP 325°F ST-352-G-11  Hot-Mix Asphalt Engineer
1/2" (12.5 mm)	TSR..... 0.84	
3/8" (9.5 mm)	Anti-Strip..... .25	
#4 (4.75 mm)	ADHERE 1500	
#8 (2.36 mm)	Effective AC..... 5.22	
#16 (1.18 mm)	Dust/Asphalt Ratio..... 1.11	
#30 (600 µm)	Coarse Agg. Angularity... 96/92	
#50 (300 µm)	Fine Agg. Angularity..... 46	
#100 (150 µm)	Agg Bulk SG..... 2.683	
#200 (75 µm)	% VMA..... 15.8	

Standard Remarks: This material has been tested in accordance with ALDOT specifications.

Authorized By: cato2437  
Authorized Date: 05/05/2011

Print: \_\_\_\_\_  
Signature: 

## APPENDIX B Statistical Analysis

**Table B1 Minitab Analysis of Complete Bond Strength Database**

**General Linear Model: Bond Strength (psi) versus Tack ID, Surface, ...**

Factor	Type	Levels	Values
Tack ID	fixed	2	Control, Nanotac Option 2
Surface	fixed	2	HMA, Milled
Application Rate	fixed	3	High, Low, Medium
Curing Time (days)	fixed	2	3, 45

Analysis of Variance for Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack ID	1	8426	8426	8426	7.56	0.008
Surface	1	10326	10326	10326	9.26	0.003
Application Rate	2	22184	22184	11092	9.95	0.000
Curing Time (days)	1	6193	6193	6193	5.56	0.021
Error	66	73558	73558	1115		
Total	71	120688				

S = 33.3843    R-Sq = 39.05%    R-Sq(adj) = 34.43%

Unusual Observations for Bond Strength (psi)

Obs	Bond Strength (psi)	Fit	SE Fit	Residual	St Resid
42	319.586	216.720	9.637	102.866	3.22 R
56	126.529	213.633	9.637	-87.103	-2.73 R
57	148.953	213.633	9.637	-64.680	-2.02 R
58	107.640	195.084	9.637	-87.443	-2.74 R

R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	36	189.9	A
Nanotac Option 2	36	168.2	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)

All Pairwise Comparisons among Levels of Tack ID

Tack ID = Control subtracted from:

Tack ID	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	-21.64	7.869	-2.750	0.0077

Grouping Information Using Tukey Method and 95.0% Confidence

Surface	N	Mean	Grouping
Milled	36	191.0	A
HMA	36	167.1	B

*Taylor and Willis*

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests  
 Response Variable Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Surface  
 Surface = HMA subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Milled	23.95	7.869	3.044	0.0034

Grouping Information Using Tukey Method and 95.0% Confidence

Application Rate	N	Mean	Grouping
Low	24	203.2	A
High	24	171.9	B
Medium	24	162.0	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests  
 Response Variable Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Application Rate  
 Application Rate = High subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Low	31.270	9.637	3.245	0.0052
Medium	-9.922	9.637	-1.030	0.5610

Application Rate = Low subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Medium	-41.19	9.637	-4.274	0.0002

Grouping Information Using Tukey Method and 95.0% Confidence

Curing Time (days)	N	Mean	Grouping
3	36	188.3	A
45	36	169.8	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests  
 Response Variable Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Curing Time (days)  
 Curing Time (days) = 3 subtracted from:

Curing Time (days)	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
45	-18.55	7.869	-2.357	0.0214

**Table B2 Statistical Analysis on 3 day cured Bond Strength Data – New HMA Surface**

**General Linear Model: 3 day Bond Stren versus Tack ID, Application Rate**

Factor	Type	Levels	Values
Tack ID	fixed	2	Control, Nanotac Option 2
Application Rate	fixed	3	High, Low, Medium

Analysis of Variance for 3 day Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack ID	1	17.5	17.5	17.5	0.02	0.884
Application Rate	2	8843.2	8843.2	4421.6	5.57	0.019
Tack ID*Application Rate	2	1007.5	1007.5	503.8	0.63	0.547
Error	12	9527.1	9527.1	793.9		
Total	17	19395.4				

S = 28.1766 R-Sq = 50.88% R-Sq(adj) = 30.41%

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	9	178.2	A
Nanotac Option 2	9	176.2	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 3 day Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Tack ID  
 Tack ID = Control subtracted from:

Tack ID	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	-1.972	13.28	-0.1485	0.8844

Grouping Information Using Tukey Method and 95.0% Confidence

Application Rate	N	Mean	Grouping
Low	6	205.1	A
High	6	175.7	A B
Medium	6	150.9	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 3 day Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Application Rate  
 Application Rate = High subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Low	29.40	16.27	1.807	0.2089
Medium	-24.83	16.27	-1.527	0.3137

*Taylor and Willis*

Application Rate = Low subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Medium	-54.23	16.27	-3.334	0.0152

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	Application Rate	N	Mean	Grouping
Control	Low	3	212.4	A
Nanotac Option 2	Low	3	197.8	A
Control	High	3	180.9	A
Nanotac Option 2	High	3	170.6	A
Nanotac Option 2	Medium	3	160.4	A
Control	Medium	3	141.4	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 3 day Bond Strength (psi)

All Pairwise Comparisons among Levels of Tack ID\*Application Rate

Tack ID = Control

Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Low	31.56	23.01	1.372	0.7420
Control	Medium	-39.51	23.01	-1.717	0.5463
Nanotac Option 2	High	-10.31	23.01	-0.448	0.9971
Nanotac Option 2	Low	16.92	23.01	0.735	0.9733
Nanotac Option 2	Medium	-20.47	23.01	-0.890	0.9419

Tack ID = Control

Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Medium	-71.07	23.01	-3.089	0.0783
Nanotac Option 2	High	-41.87	23.01	-1.820	0.4891
Nanotac Option 2	Low	-14.65	23.01	-0.637	0.9857
Nanotac Option 2	Medium	-52.03	23.01	-2.262	0.2801

Tack ID = Control

Application Rate = Medium subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	High	29.20	23.01	1.2691	0.7955
Nanotac Option 2	Low	56.43	23.01	2.4527	0.2129
Nanotac Option 2	Medium	19.04	23.01	0.8276	0.9565

Tack ID = Nanotac Option 2

Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
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*Taylor and Willis*

Nanotac Option 2	Low	27.23	23.01	1.1836	0.8364
Nanotac Option 2	Medium	-10.16	23.01	-0.4415	0.9973

Tack ID = Nanotac Option 2

Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Medium	-37.39	23.01	-1.625	0.5990

**Table B3 Statistical Analysis on 3 day cured Bond Strength Data – Milled Surface**

**General Linear Model: 3 day Bond Stren versus Tack ID, Application Rate**

Factor	Type	Levels	Values
Tack ID	fixed	2	Control, Nanotac Option 2
Application Rate	fixed	3	High, Low, Medium

Analysis of Variance for 3 day Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack ID	1	3133.8	3133.8	3133.8	7.21	0.020
Application Rate	2	146.1	146.1	73.1	0.17	0.847
Tack ID*Application Rate	2	9885.8	9885.8	4942.9	11.37	0.002
Error	12	5214.6	5214.6	434.6		
Total	17	18380.4				

S = 20.8459 R-Sq = 71.63% R-Sq(adj) = 59.81%

Unusual Observations for 3 day Bond Strength (psi)

Obs	3 day Bond Strength (psi)	Fit	SE Fit	Residual	St Resid
10	197.142	157.541	12.035	39.601	2.33 R

R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	9	212.6	A
Nanotac Option 2	9	186.2	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 3 day Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Tack ID  
 Tack ID = Control subtracted from:

Tack ID	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	-26.39	9.827	-2.685	0.0198

Grouping Information Using Tukey Method and 95.0% Confidence

Application Rate	N	Mean	Grouping
Low	6	203.0	A
High	6	199.2	A
Medium	6	196.0	A

Means that do not share a letter are significantly different.



*Taylor and Willis*

Tukey Simultaneous Tests

Response Variable 3 day Bond Strength (psi)

All Pairwise Comparisons among Levels of Application Rate

Application Rate = High subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Low	3.820	12.04	0.3174	0.9462
Medium	-3.148	12.04	-0.2616	0.9631

Application Rate = Low subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Medium	-6.968	12.04	-0.5790	0.8337

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	Application Rate	N	Mean	Grouping
Control	Low	3	248.5	A
Nanotac Option 2	Medium	3	205.5	A B
Control	High	3	202.8	A B
Nanotac Option 2	High	3	195.6	A B
Control	Medium	3	186.5	B
Nanotac Option 2	Low	3	157.5	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 3 day Bond Strength (psi)

All Pairwise Comparisons among Levels of Tack ID\*Application Rate

Tack ID = Control

Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Low	45.66	17.02	2.683	0.1502
Control	Medium	-16.26	17.02	-0.955	0.9236
Nanotac Option 2	High	-7.23	17.02	-0.425	0.9978
Nanotac Option 2	Low	-45.26	17.02	-2.659	0.1558
Nanotac Option 2	Medium	2.73	17.02	0.160	1.0000

Tack ID = Control

Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Medium	-61.92	17.02	-3.638	0.0313
Nanotac Option 2	High	-52.90	17.02	-3.108	0.0759
Nanotac Option 2	Low	-90.92	17.02	-5.342	0.0019
Nanotac Option 2	Medium	-42.94	17.02	-2.523	0.1919

Tack ID = Control

Application Rate = Medium subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
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*Taylor and Willis*

Nanotac Option 2	High	9.03	17.02	0.530	0.9937
Nanotac Option 2	Low	-29.00	17.02	-1.704	0.5540
Nanotac Option 2	Medium	18.99	17.02	1.116	0.8660

Tack ID = Nanotac Option 2  
Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Low	-38.02	17.02	-2.234	0.2910
Nanotac Option 2	Medium	9.96	17.02	0.585	0.9902

Tack ID = Nanotac Option 2  
Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Medium	47.99	17.02	2.819	0.1212

**Table B4 Statistical Analysis on 45 day cured Bond Strength Results – New HMA Surface**

**General Linear Model: 45 day Bond Stre versus Tack ID, Application Rate**

Factor	Type	Levels	Values
Tack ID	fixed	2	Control, Nanotac Option 2
Application Rate	fixed	3	High, Low, Medium

Analysis of Variance for 45 day Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack ID	1	1109.3	1109.3	1109.3	2.97	0.110
Application Rate	2	13465.3	13465.3	6732.7	18.05	0.000
Tack ID*Application Rate	2	8510.5	8510.5	4255.2	11.41	0.002
Error	12	4477.2	4477.2	373.1		
Total	17	27562.3				

S = 19.3158 R-Sq = 83.76% R-Sq(adj) = 76.99%

Unusual Observations for 45 day Bond Strength (psi)

Obs	45 day Bond Strength (psi)	Fit	SE Fit	Residual	St Resid
13	114.585	155.319	11.152	-40.733	-2.58 R
15	189.910	155.319	11.152	34.591	2.19 R

R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	9	164.8	A
Nanotac Option 2	9	149.1	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 45 day Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Tack ID  
 Tack ID = Control subtracted from:

Tack ID	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	-15.70	9.106	-1.724	0.1103

Grouping Information Using Tukey Method and 95.0% Confidence

Application Rate	N	Mean	Grouping
Low	6	195.6	A
High	6	138.3	B
Medium	6	136.9	B

Means that do not share a letter are significantly different.

*Taylor and Willis*

Tukey Simultaneous Tests

Response Variable 45 day Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Application Rate  
 Application Rate = High subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Low	57.297	11.15	5.1379	0.0007
Medium	-1.419	11.15	-0.1273	0.9911

Application Rate = Low subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Medium	-58.72	11.15	-5.265	0.0005

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	Application Rate	N	Mean	Grouping
Control	Low	3	230.4	A
Nanotac Option 2	Low	3	160.8	B
Nanotac Option 2	Medium	3	155.3	B
Control	High	3	145.5	B
Nanotac Option 2	High	3	131.1	B
Control	Medium	3	118.4	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 45 day Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Tack ID\*Application Rate  
 Tack ID = Control  
 Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Low	84.87	15.77	5.382	0.0018
Control	Medium	-27.09	15.77	-1.718	0.5460
Nanotac Option 2	High	-14.43	15.77	-0.915	0.9352
Nanotac Option 2	Low	15.29	15.77	0.969	0.9192
Nanotac Option 2	Medium	9.82	15.77	0.623	0.9870

Tack ID = Control

Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Medium	-112.0	15.77	-7.099	0.0002
Nanotac Option 2	High	-99.3	15.77	-6.297	0.0004
Nanotac Option 2	Low	-69.6	15.77	-4.412	0.0085
Nanotac Option 2	Medium	-75.1	15.77	-4.759	0.0048

Tack ID = Control

Application Rate = Medium subtracted from:

*Taylor and Willis*

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	High	12.66	15.77	0.8028	0.9616
Nanotac Option 2	Low	42.38	15.77	2.6872	0.1492
Nanotac Option 2	Medium	36.92	15.77	2.3407	0.2505

Tack ID = Nanotac Option 2  
Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Low	29.72	15.77	1.884	0.4545
Nanotac Option 2	Medium	24.25	15.77	1.538	0.6491

Tack ID = Nanotac Option 2  
Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Medium	-5.466	15.77	-0.3466	0.9992

**Table B5 Statistical Analysis on 45 day cured Bond Strength Results – Milled Surface**

**General Linear Model: 45 day Bond Stre versus Tack ID, Application Rate**

Factor	Type	Levels	Values
Tack ID	fixed	2	Control, Nanotac Option 2
Application Rate	fixed	3	High, Low, Medium

Analysis of Variance for 45 day Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack ID	1	8121.4	8121.4	8121.4	11.05	0.006
Application Rate	2	6625.3	6625.3	3312.6	4.51	0.035
Tack ID*Application Rate	2	15204.5	15204.5	7602.3	10.34	0.002
Error	12	8822.2	8822.2	735.2		
Total	17	38773.4				

S = 27.1142 R-Sq = 77.25% R-Sq(adj) = 67.77%

Unusual Observations for 45 day Bond Strength (psi)

Obs	45 day Bond Strength (psi)	Fit	SE Fit	Residual	St Resid
1	214.272	271.241	15.654	-56.969	-2.57 R
3	319.586	271.241	15.654	48.345	2.18 R

R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	9	203.9	A
Nanotac Option 2	9	161.4	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 45 day Bond Strength (psi)  
All Pairwise Comparisons among Levels of Tack ID  
Tack ID = Control subtracted from:

Tack ID	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	-42.48	12.78	-3.324	0.0061

Grouping Information Using Tukey Method and 95.0% Confidence

Application Rate	N	Mean	Grouping
Low	6	209.1	A
High	6	174.5	A B
Medium	6	164.3	B

Means that do not share a letter are significantly different.

*Taylor and Willis*

Tukey Simultaneous Tests

Response Variable 45 day Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Application Rate  
 Application Rate = High subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Low	34.57	15.65	2.2082	0.1101
Medium	-10.29	15.65	-0.6571	0.7920

Application Rate = Low subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Medium	-44.85	15.65	-2.865	0.0353

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	Application Rate	N	Mean	Grouping
Control	Low	3	271.2	A
Control	High	3	179.0	B
Nanotac Option 2	High	3	170.1	B
Nanotac Option 2	Medium	3	167.1	B
Control	Medium	3	161.4	B
Nanotac Option 2	Low	3	147.0	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable 45 day Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Tack ID\*Application Rate  
 Tack ID = Control  
 Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Low	92.27	22.14	4.168	0.0128
Control	Medium	-17.55	22.14	-0.793	0.9635
Nanotac Option 2	High	-8.85	22.14	-0.400	0.9983
Nanotac Option 2	Low	-31.99	22.14	-1.445	0.7019
Nanotac Option 2	Medium	-11.88	22.14	-0.537	0.9934

Tack ID = Control

Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Medium	-109.8	22.14	-4.960	0.0035
Nanotac Option 2	High	-101.1	22.14	-4.568	0.0066
Nanotac Option 2	Low	-124.3	22.14	-5.613	0.0012
Nanotac Option 2	Medium	-104.2	22.14	-4.705	0.0052

Tack ID = Control

Application Rate = Medium subtracted from:

*Taylor and Willis*

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	High	8.69	22.14	0.3926	0.9985
Nanotac Option 2	Low	-14.44	22.14	-0.6524	0.9841
Nanotac Option 2	Medium	5.66	22.14	0.2558	0.9998

Tack ID = Nanotac Option 2  
Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Low	-23.14	22.14	-1.045	0.8935
Nanotac Option 2	Medium	-3.03	22.14	-0.137	1.0000

Tack ID = Nanotac Option 2  
Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Medium	20.11	22.14	0.9082	0.9370



**Table B6 Statistical Analysis on All Bond Strength Results – New HMA Surface**

**General Linear Model: Bond Strength (p versus Tack ID, Application Rate**

Factor	Type	Levels	Values
Tack ID	fixed	2	Control, Nanotac Option 2
Application Rate	fixed	3	High, Low, Medium

Analysis of Variance for Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack ID	1	702.7	702.7	702.7	0.98	0.331
Application Rate	2	20961.7	20961.7	10480.9	14.57	0.000
Tack ID*Application Rate	2	7425.9	7425.9	3713.0	5.16	0.012
Error	30	21587.0	21587.0	719.6		
Total	35	50677.3				

S = 26.8247 R-Sq = 57.40% R-Sq(adj) = 50.30%

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	18	171.5	A
Nanotac Option 2	18	162.7	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Tack ID  
 Tack ID = Control subtracted from:

Tack ID	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	-8.836	8.942	-0.9882	0.3310

Grouping Information Using Tukey Method and 95.0% Confidence

Application Rate	N	Mean	Grouping
Low	12	200.3	A
High	12	157.0	B
Medium	12	143.9	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Application Rate  
 Application Rate = High subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Low	43.35	10.95	3.958	0.0012
Medium	-13.13	10.95	-1.199	0.4632

*Taylor and Willis*

Application Rate = Low subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Medium	-56.47	10.95	-5.157	0.0001

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	Application Rate	N	Mean	Grouping
Control	Low	6	221.4	A
Nanotac Option 2	Low	6	179.3	A B
Control	High	6	163.2	B C
Nanotac Option 2	Medium	6	157.9	B C
Nanotac Option 2	High	6	150.8	B C
Control	Medium	6	129.9	C

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)

All Pairwise Comparisons among Levels of Tack ID\*Application Rate

Tack ID = Control

Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Low	58.22	15.49	3.759	0.0088
Control	Medium	-33.30	15.49	-2.150	0.2902
Nanotac Option 2	High	-12.37	15.49	-0.799	0.9655
Nanotac Option 2	Low	16.10	15.49	1.040	0.9006
Nanotac Option 2	Medium	-5.32	15.49	-0.344	0.9993

Tack ID = Control

Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Medium	-91.52	15.49	-5.909	0.0000
Nanotac Option 2	High	-70.59	15.49	-4.558	0.0011
Nanotac Option 2	Low	-42.12	15.49	-2.719	0.1008
Nanotac Option 2	Medium	-63.54	15.49	-4.103	0.0036

Tack ID = Control

Application Rate = Medium subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	High	20.93	15.49	1.351	0.7545
Nanotac Option 2	Low	49.40	15.49	3.190	0.0355
Nanotac Option 2	Medium	27.98	15.49	1.807	0.4769

Tack ID = Nanotac Option 2

Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
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*Taylor and Willis*

Nanotac Option 2	Low	28.475	15.49	1.8386	0.4577
Nanotac Option 2	Medium	7.049	15.49	0.4551	0.9973

Tack ID = Nanotac Option 2

Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Medium	-21.43	15.49	-1.383	0.7363

**Table B7 Statistical Analysis on All Bond Strength Results – Milled Surface**

**General Linear Model: Bond Strength (p versus Tack ID, Application Rate)**

Factor	Type	Levels	Values
Tack ID	fixed	2	Control, Nanotac Option 2
Application Rate	fixed	3	High, Low, Medium

Analysis of Variance for Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack ID	1	10672.6	10672.6	10672.6	16.03	0.000
Application Rate	2	4339.7	4339.7	2169.8	3.26	0.052
Tack ID*Application Rate	2	24704.5	24704.5	12352.2	18.56	0.000
Error	30	19967.7	19967.7	665.6		
Total	35	59684.4				

S = 25.7990 R-Sq = 66.54% R-Sq(adj) = 60.97%

Unusual Observations for Bond Strength (psi)

Obs	Bond Strength (psi)	Fit	SE Fit	Residual	St Resid
6	319.586	259.852	10.532	59.733	2.54 R

R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	N	Mean	Grouping
Control	18	208.2	A
Nanotac Option 2	18	173.8	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)

All Pairwise Comparisons among Levels of Tack ID

Tack ID = Control subtracted from:

Tack ID	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	-34.44	8.600	-4.004	0.0004

Grouping Information Using Tukey Method and 95.0% Confidence

Application

Rate	N	Mean	Grouping
Low	12	206.1	A
High	12	186.9	A
Medium	12	180.1	A

Means that do not share a letter are significantly different.

*Taylor and Willis*

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)

All Pairwise Comparisons among Levels of Application Rate

Application Rate = High subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Low	19.194	10.53	1.8223	0.1796
Medium	-6.718	10.53	-0.6378	0.8006

Application Rate = Low subtracted from:

Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Medium	-25.91	10.53	-2.460	0.0506

Grouping Information Using Tukey Method and 95.0% Confidence

Tack ID	Application Rate	N	Mean	Grouping
Control	Low	6	259.9	A
Control	High	6	190.9	B
Nanotac Option 2	Medium	6	186.3	B
Nanotac Option 2	High	6	182.8	B
Control	Medium	6	174.0	B
Nanotac Option 2	Low	6	152.3	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)

All Pairwise Comparisons among Levels of Tack ID\*Application Rate

Tack ID = Control

Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Low	68.97	14.90	4.630	0.0009
Control	Medium	-16.90	14.90	-1.135	0.8630
Nanotac Option 2	High	-8.04	14.90	-0.540	0.9940
Nanotac Option 2	Low	-38.62	14.90	-2.593	0.1303
Nanotac Option 2	Medium	-4.58	14.90	-0.307	0.9996

Tack ID = Control

Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	Medium	-85.9	14.90	-5.765	0.0000
Nanotac Option 2	High	-77.0	14.90	-5.170	0.0002
Nanotac Option 2	Low	-107.6	14.90	-7.223	0.0000
Nanotac Option 2	Medium	-73.5	14.90	-4.937	0.0004

Tack ID = Control

Application Rate = Medium subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
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*Taylor and Willis*

Nanotac Option 2	High	8.86	14.90	0.595	0.9906
Nanotac Option 2	Low	-21.72	14.90	-1.458	0.6922
Nanotac Option 2	Medium	12.33	14.90	0.827	0.9600

Tack ID = Nanotac Option 2  
Application Rate = High subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Low	-30.58	14.90	-2.053	0.3380
Nanotac Option 2	Medium	3.47	14.90	0.233	0.9999

Tack ID = Nanotac Option 2  
Application Rate = Low subtracted from:

Tack ID	Application Rate	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac Option 2	Medium	34.05	14.90	2.286	0.2311

**Table B8 Statistical Analysis on Moisture Evaluation Bond Strength Results – New HMA Surface**

**General Linear Model: Bond Strength (p versus Additive, Number of Freeze**

Factor	Type	Levels	Values
Additive	fixed	2	Control, Nanotac
Number of Freeze-Thaw Cycles	fixed	3	0, 1, 2

Analysis of Variance for Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Additive	1	1670.4	363.9	363.9	0.58	0.455
Number of Freeze-Thaw Cycles	2	32187.7	32187.7	16093.9	25.78	0.000
Additive*	2	5147.2	5147.2	2573.6	4.12	0.034
Number of Freeze-Thaw Cycles						
Error	18	11235.7	11235.7	624.2		
Total	23	50241.1				

S = 24.9842 R-Sq = 77.64% R-Sq(adj) = 71.42%

Grouping Information Using Tukey Method and 95.0% Confidence

Additive	N	Mean	Grouping
Control	12	155.8	A
Nanotac	12	147.6	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Additive  
 Additive = Control subtracted from:

Additive	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac	-8.209	10.75	-0.7635	0.4551

Grouping Information Using Tukey Method and 95.0% Confidence

Number of Freeze-Thaw Cycles	N	Mean	Grouping
0	12	200.3	A
2	6	131.4	B
1	6	123.3	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Number of Freeze-Thaw Cycles  
 Number of Freeze-Thaw Cycles = 0 subtracted from:

Number of Freeze-Thaw Cycles	Difference	SE of	Adjusted
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*Taylor and Willis*

Cycles	of Means	Difference	T-Value	P-Value
1	-77.08	12.49	-6.170	0.0000
2	-68.95	12.49	-5.520	0.0001

Number of Freeze-Thaw Cycles = 1 subtracted from:

Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	8.129	14.42	0.5635	0.8409

Grouping Information Using Tukey Method and 95.0% Confidence

Additive	Number of Freeze-Thaw Cycles	N	Mean	Grouping
Control	0	6	221.4	A
Nanotac	0	6	179.3	A B
Nanotac	2	3	146.0	B C
Control	1	3	129.2	B C
Nanotac	1	3	117.4	C
Control	2	3	116.7	C

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)

All Pairwise Comparisons among Levels of Additive\*Number of Freeze-Thaw Cycles

Additive = Control

Number of Freeze-Thaw Cycles = 0 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	1	-92.2	17.67	-5.221	0.0007
Control	2	-104.7	17.67	-5.924	0.0002
Nanotac	0	-42.1	14.42	-2.920	0.0825
Nanotac	1	-104.0	17.67	-5.889	0.0002
Nanotac	2	-75.4	17.67	-4.266	0.0053

Additive = Control

Number of Freeze-Thaw Cycles = 1 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	2	-12.42	20.40	-0.6090	0.9890
Nanotac	0	50.12	17.67	2.8371	0.0963
Nanotac	1	-11.81	20.40	-0.5788	0.9912
Nanotac	2	16.87	20.40	0.8271	0.9585

Additive = Control

Number of Freeze-Thaw Cycles = 2 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac	0	62.5437	17.67	3.54025	0.0241



*Taylor and Willis*

Nanotac	1	0.6159	20.40	0.03019	1.0000
Nanotac	2	29.2959	20.40	1.43611	0.7060

Additive = Nanotac

Number of Freeze-Thaw Cycles = 0 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac	1	-61.93	17.67	-3.505	0.0259
Nanotac	2	-33.25	17.67	-1.882	0.4432

Additive = Nanotac

Number of Freeze-Thaw Cycles = 1 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac	2	28.68	20.40	1.406	0.7233

**Table B9 Statistical Evaluation on Moisture Evaluation Bond Strength Results – Milled Surface**

**General Linear Model: Bond Strength (p versus Additive, Number of Freeze**

Factor	Type	Levels	Values
Additive	fixed	2	Control, Nanotac
Number of Freeze-Thaw Cycles	fixed	3	0, 1, 2

Analysis of Variance for Bond Strength (psi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Additive	1	27443.2	23280.1	23280.1	30.30	0.000
Number of Freeze-Thaw Cycles	2	3476.6	3476.6	1738.3	2.26	0.133
Additive*	2	251.0	251.0	125.5	0.16	0.851
Number of Freeze-Thaw Cycles						
Error	18	13830.5	13830.5	768.4		
Total	23	45001.3				

S = 27.7194 R-Sq = 69.27% R-Sq(adj) = 60.73%

Unusual Observations for Bond Strength (psi)

Obs	Bond Strength (psi)	Fit	SE Fit	Residual	St Resid
18	319.586	259.852	11.316	59.733	2.36 R

R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

Additive	N	Mean	Grouping
Control	12	269.9	A
Nanotac	12	204.3	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)  
 All Pairwise Comparisons among Levels of Additive  
 Additive = Control subtracted from:

Additive	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac	-65.66	11.93	-5.504	0.0000

Grouping Information Using Tukey Method and 95.0% Confidence

Number of Freeze-Thaw Cycles	N	Mean	Grouping
2	6	252.4	A
1	6	235.8	A
0	12	223.1	A

*Taylor and Willis*

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)

All Pairwise Comparisons among Levels of Number of Freeze-Thaw Cycles

Number of Freeze-Thaw Cycles = 0 subtracted from:

Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	12.72	13.86	0.9176	0.6365
2	29.32	13.86	2.1151	0.1148

Number of Freeze-Thaw Cycles = 1 subtracted from:

Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	16.60	16.00	1.037	0.5639

Grouping Information Using Tukey Method and 95.0% Confidence

Additive	Number of Freeze-Thaw Cycles	N	Mean	Grouping
Control	2	3	285.1	A
Control	1	3	264.8	A B
Control	0	6	259.9	A B
Nanotac	2	3	219.7	A B C
Nanotac	1	3	206.8	B C
Nanotac	0	6	186.3	C

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests

Response Variable Bond Strength (psi)

All Pairwise Comparisons among Levels of Additive\*Number of Freeze-Thaw Cycles

Additive = Control

Number of Freeze-Thaw Cycles = 0 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	1	4.95	19.60	0.253	0.9998
Control	2	25.25	19.60	1.288	0.7874
Nanotac	0	-73.54	16.00	-4.595	0.0026
Nanotac	1	-53.06	19.60	-2.707	0.1223
Nanotac	2	-40.17	19.60	-2.049	0.3549

Additive = Control

Number of Freeze-Thaw Cycles = 1 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Control	2	20.30	22.63	0.897	0.9423
Nanotac	0	-78.50	19.60	-4.005	0.0091
Nanotac	1	-58.01	22.63	-2.563	0.1577

*Taylor and Willis*

Nanotac 2 -45.12 22.63 -1.994 0.3831

Additive = Control

Number of Freeze-Thaw Cycles = 2 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac	0	-98.80	19.60	-5.041	0.0010
Nanotac	1	-78.31	22.63	-3.460	0.0284
Nanotac	2	-65.42	22.63	-2.891	0.0871

Additive = Nanotac

Number of Freeze-Thaw Cycles = 0 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac	1	20.48	19.60	1.045	0.8962
Nanotac	2	33.38	19.60	1.703	0.5471

Additive = Nanotac

Number of Freeze-Thaw Cycles = 1 subtracted from:

Additive	Number of Freeze-Thaw Cycles	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Nanotac	2	12.89	22.63	0.5696	0.9919

## APPENDIX C

### Bond Strength Test Results

**Table C1 Bond Strength Test Results – Bond Strength Evaluation**

Tack ID	Surface	Slab ID	Application Rate	Residual Application Rate (gal/sy)	Spray Application Rate (gal/sy)	Test	3 day Bond Strength (psi)	45 day Bond Strength (psi)
Control	HMA	18	Low	0.02	0.067	1	178.02	213.49
Control	HMA	18	Low	0.02	0.067	2	250.97	249.79
Control	HMA	18	Low	0.02	0.067	3	208.31	227.84
Control	HMA	27	Medium	0.04	0.133	1	150.85	125.33
Control	HMA	27	Medium	0.04	0.133	2	158.34	106.10
Control	HMA	27	Medium	0.04	0.133	3	114.89	123.79
Control	HMA	20	High	0.06	0.2	1	196.10	138.58
Control	HMA	20	High	0.06	0.2	2	211.12	147.01
Control	HMA	20	High	0.06	0.2	3	135.40	150.90
Nanotac Option 2	HMA	21	Low	0.0067	0.067	1	201.49	161.51
Nanotac Option 2	HMA	21	Low	0.0067	0.067	2	189.87	152.54
Nanotac Option 2	HMA	21	Low	0.0067	0.067	3	202.01	168.30
Nanotac Option 2	HMA	22	Medium	0.013	0.133	1	155.97	114.59
Nanotac Option 2	HMA	22	Medium	0.013	0.133	2	136.48	161.46
Nanotac Option 2	HMA	22	Medium	0.013	0.133	3	188.75	189.91
Nanotac Option 2	HMA	23	High	0.02	0.2	1	157.77	122.07
Nanotac Option 2	HMA	23	High	0.02	0.2	2	156.80	149.00
Nanotac Option 2	HMA	23	High	0.02	0.2	3	197.11	122.12
Control	Milled	1	Low	0.04	0.133	1	232.39	214.27
Control	Milled	1	Low	0.04	0.133	2	258.01	279.86
Control	Milled	1	Low	0.04	0.133	3	254.98	319.59
Control	Milled	2	Medium	0.08	0.267	1	183.54	162.47
Control	Milled	2	Medium	0.08	0.267	2	185.47	159.45
Control	Milled	2	Medium	0.08	0.267	3	190.61	162.36
Control	Milled	3	High	0.12	0.4	1	184.72	168.52
Control	Milled	3	High	0.12	0.4	2	201.00	170.72
Control	Milled	3	High	0.12	0.4	3	222.68	197.67
Nanotac Option 2	Milled	4	Low	0.013	0.133	1	197.14	107.64
Nanotac Option 2	Milled	4	Low	0.013	0.133	2	126.53	157.08
Nanotac	Milled	4	Low	0.013	0.133	3	148.95	176.23

Tack ID	Surface	Slab ID	Application Rate	Residual Application Rate (gal/sy)	Spray Application Rate (gal/sy)	Test	3 day Bond Strength (psi)	45 day Bond Strength (psi)
Option 2								
Nanotac Option 2	Milled	6	Medium	0.0267	0.267	1	210.11	161.62
Nanotac Option 2	Milled	6	Medium	0.0267	0.267	2	211.69	163.42
Nanotac Option 2	Milled	6	Medium	0.0267	0.267	3	194.78	176.23
Nanotac Option 2	Milled	7	High	0.04	0.4	1	219.31	169.82
Nanotac Option 2	Milled	7	High	0.04	0.4	2	168.75	170.66
Nanotac Option 2	Milled	7	High	0.04	0.4	3	198.64	169.88

**Table C2 Bond Strength Test Results – Moisture Evaluation**

Additive	Slab ID	Surface	Application Rate	Test	Number of Freeze-Thaw Cycles	Saturation Level (%)	Bond Strength (psi)
Control	18	Unmilled	Low	1	0	n/a	178.02
Control	18	Unmilled	Low	2	0	n/a	250.97
Control	18	Unmilled	Low	3	0	n/a	208.31
Control	28	Unmilled	Low	1	1	71.35	145.22
Control	28	Unmilled	Low	2	1	79.82	100.36
Control	28	Unmilled	Low	3	1	78.54	141.92
Control	28	Unmilled	Low	1	2	72.26	96.94
Control	28	Unmilled	Low	2	2	72.83	115.01
Control	28	Unmilled	Low	3	2	71.83	138.28
Nanotac	21	Unmilled	Low	1	0	n/a	201.49
Nanotac	21	Unmilled	Low	2	0	n/a	189.87
Nanotac	21	Unmilled	Low	3	0	n/a	202.01
Nanotac	29	Unmilled	Low	1	1	70.16	82.75
Nanotac	29	Unmilled	Low	2	1	77.59	125.66
Nanotac	29	Unmilled	Low	3	1	77.70	143.67
Nanotac	29	Unmilled	Low	1	2	73.92	134.60
Nanotac	29	Unmilled	Low	2	2	71.35	131.01
Nanotac	29	Unmilled	Low	3	2	71.35	172.51
Nanotac	6	Milled	Medium	1	0	n/a	210.11
Nanotac	6	Milled	Medium	2	0	n/a	211.69
Nanotac	6	Milled	Medium	3	0	n/a	194.78
Nanotac	8	Milled	Medium	1	1	73.42	224.63
Nanotac	8	Milled	Medium	2	1	72.91	194.08
Nanotac	8	Milled	Medium	3	1	71.11	201.67
Nanotac	8	Milled	Medium	1	2	69.95	255.69
Nanotac	8	Milled	Medium	2	2	71.06	225.16
Nanotac	8	Milled	Medium	3	2	71.52	178.20
Control	1	Milled	Low	1	0	n/a	232.39
Control	1	Milled	Low	2	0	n/a	258.01
Control	1	Milled	Low	3	0	n/a	254.98
Control	12	Milled	Low	1	1	70.42	273.79
Control	12	Milled	Low	2	1	Above 80*	265.96
Control	12	Milled	Low	3	1	71.17	254.66
Control	12	Milled	Low	1	2	70.50	262.81
Control	12	Milled	Low	2	2	71.21	295.31
Control	12	Milled	Low	3	2	69.99	297.21

\* = Due to extremely low sample air voids