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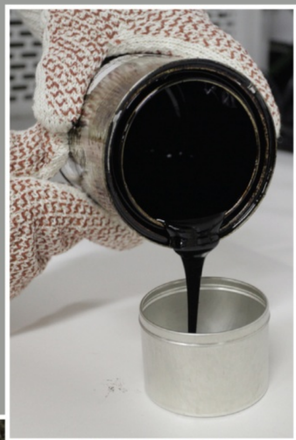

REFINEMENT OF THE BOND STRENGTH PROCEDURE AND INVESTIGATION OF A SPECIFICATION

By

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Background

Pavement structures consisting of several asphalt concrete (AC) layers or AC overlays over Portland cement concrete (PCC) require a certain degree of bond at the layer interfaces. Research has proven that the degree of bond between pavement layers, whether it is within an AC or composite structure, 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 and therefore induce pavement distresses and failures (*2*, *3*). Problems commonly associated with debonding are premature slippage cracking, top-down cracking, and fatigue cracking (*1*, *4*, *5*). These distresses can reduce pavement life from 20 years to 7 or 8 years. A 10% decrease in bond strength may cause 50% reduction in fatigue life (*5*). Studies have shown that the reduction in fatigue life of a debonded pavement can be drastic, prompting the need for extensive repairs such as full-depth patches or complete reconstruction (*6*, *7*).

When bonded AC pavement layers lose adhesion and separate (FIGURE 1), the overall stiffness of the pavement decreases, inciting the development of pavement distresses (*6*, *7*, *8*). The pavement structure can be extensively damaged as cracking courses its way through multiple layers of the structure (FIGURE 2) (*11*).

FIGURE 1 Delamination in HMA Pavement (*11*).

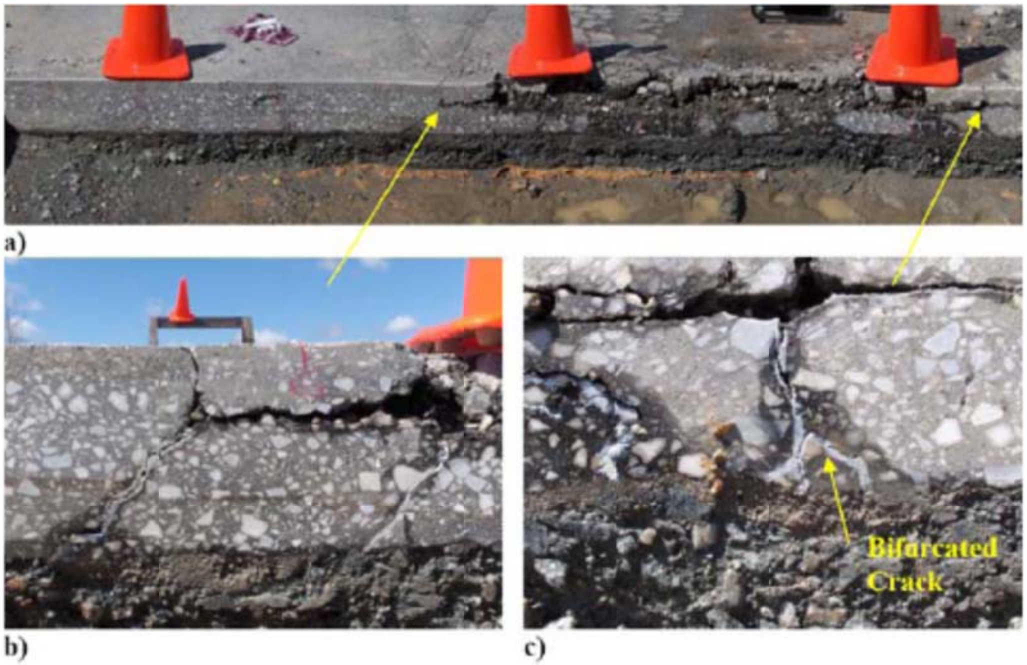


FIGURE 2 Severe Distress Due to Poor Bond between Pavement Layers (*11*).

Another form of distress associated with the lack of bond is slippage cracking (FIGURE 3). Slippage cracking typically indicates an inadequate bond 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 AC structure (*5*, *6*). Slippage cracks are typically half-moon shaped cracks with two ends pointing at the direction of traffic (FIGURE 4).

FIGURE 3 Slippage Failure Due to Inadequate Bond.

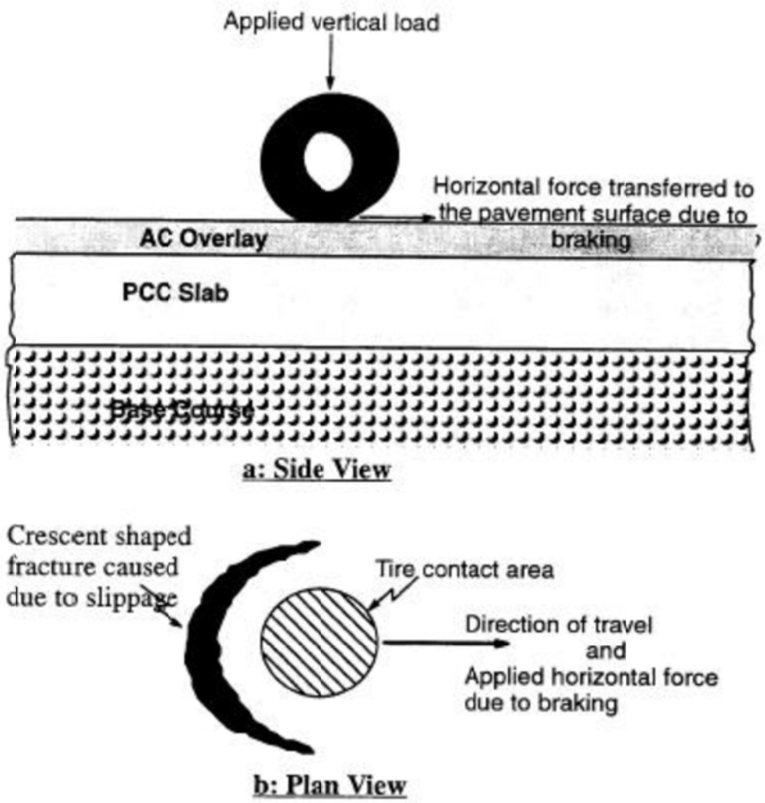


FIGURE 4 Typical Slippage Failure (*10*).

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*).

1.2 Objective

The objective of this research project was twofold:

- Develop a bond strength criterion for evaluating bond strength through a structural pavement analysis and a field study; and
- Evaluate the effect of tack coat material, application rate, underlying surface preparation, traffic, and aging on bond strength through laboratory and field studies to recommend effective tack coat materials and optimum application rates on different receiving surfaces.

1.3 Scope of Work

This research project consisted of six tasks. Task 1 was to conduct a literature review to examine specifications and research in the area of bond strength. Task 2 was to evaluate bond strength for seven sites constructed in Phase I and other pavements exhibiting slippage failures. In Task 3, the BISAR pavement modeling program was used to evaluate the effect of subgrade stiffness, total AC thickness, thickness of wearing course, and seasonal variation of AC stiffness on shear stresses in the top two inches of asphalt pavements. These shear stresses were compared to bond strengths determined from field cores in Task 2 to establish minimum bond strength criteria for different applications.

The laboratory study in Task 4 concentrated on evaluating the effect of tack coat type, tack application rate, and underlying surface preparation. The field study in Task 5 focused on evaluating the effect of tack application rate, aging, and trafficking on bond strength, and developing correlations between laboratory test results and expected field performance of the tack coat materials evaluated in the laboratory study. Task 6 was to prepare a final report of the findings from Tasks 1 through 5.

1.4 Organization of this Report

This report is divided into five chapters. Chapter 1 is the introduction. Chapter 2 summarizes the literature review conducted in Task 1. Chapter 3 presents results of Tasks 2 and 3. Results of Tasks 4 and 5 are summarized in Chapter 4. Conclusions and recommendations based on the results of this study are presented in Chapter 5. Detailed test results are presented in the appendices.

CHAPTER 2 LITERATURE REVIEW

Debonding can occur in three locations in an asphalt or composite structure: 1) between two AC layers, 2) between an AC overlay and its PCC slab, and 3) between the AC and its aggregate base. The first two locations are most critical for asphalt and composite pavements due to their negative effect on the pavement's structural integrity (*14*).

A lack of bond is typically the result of poor construction practices and/or water damage. Construction miscues such as mixture segregation and thermal (density) segregation are discontinuities that have been linked to delamination. Other construction related issues, such as paving thin lifts, improper cleaning of surfaces, excessive or inadequate tack coat, presence of water on the receiving surface, and improper compaction of the upper lifts, have all been shown to reduce the bond strength between pavement layers. In addition, use of mixtures with water-sensitive aggregate or those containing large percentages of sand with rounded particles on an old pavement surface also contributes to the loss of bond between pavement layers (*4*, *14*, *15*).

2.1 Delamination and Slippage

It has been shown that interface bond strength substantially affects the performance and stress-strain distribution of asphalt pavements (*15*). Hachiya and Sato used computer modeling techniques to analyze debonding. They concluded that the separation of asphalt layers occurs if the shear stresses at the layer interface exceed the shear strength (or bond strength). This failure can occur in tension or flexure. When the maximum tensile strength of the pavement is exceeded, a slip plane will develop, and distresses will ensue (*16*). When a pavement structure loses its bond strength, the pavement layers no longer act as a monolithic structure, but they begin to act as independent pavement layers stacked on top of each other (*11*, *15*). Layered elastic analysis shows that when this occurs, the critical strain location within the pavement structure changes from the bottom of the asphalt structure to the debonded location (*6*, *11*).

Delamination is difficult to spot before surface distresses occur. The following are six typical indicators of debonding or loss of bond strength (*14*). While the following five signs can indicate a pavement is debonding, it is difficult to notice them without using non-destructive testing equipment or extracting cores from the pavement for inspections.

- There would be an increase in the amount of voids at the delaminated locations.
- A higher level of moisture is often present in the delaminated areas.
- Stiffness of the pavement material at the delaminated locations is significantly reduced.
- The measured surface deflection is higher in the delaminated areas.
- The horizontal movement of the surface layer that was delaminated from the underlying layer would be higher under heavy loads.

2.2 Bond Strength

Not only is it hard to determine if a pavement has debonded, but it is also difficult to evaluate the bond strength of a pavement. Many factors (i.e. temperature, water infiltration, traffic, and cleanliness) influence the potential bond strength of two pavement layers (*15*).

Studies have shown that peak shear stress is the best fundamental parameter for quantifying bond strength between HMA layers (*18*). Shear stress testing has shown that building a pavement in layers, as is typically done during construction, reduces the shear strength of a pavement. A comparison study conducted by Mohammad et al. (*16*) showed that, at best, a pavement built in layers would have 83% of the shear strength that a monolithic structure would have. However, while building a pavement structure in lifts does decrease the shear strength of structure, it is impractical to build a complete monolithic structure, as it would be impossible to achieve proper compaction.

Although building a pavement in layers reduces the shear resistance capacity of an HMA pavement, one must also realize that temperature, mix design, and pavement thickness affect a pavement structure's bond strength. Shear strength has been shown to decrease as temperature increases due to the visco-thermal properties of asphalt binder. This affect is seen with and without tack coats (*15*).

Two studies have been conducted that were designed to determine the effect of aggregate gradation on bond strength. While Sholar et al. (*18*) found that fine-graded mixes had lower initial bond strength values, West et al. (*5*) saw an increase in bond strength in fine-graded mixes.

When Willis and Timm were conducting their forensic investigation on a debonded pavement at the NCAT Pavement Test Track, they performed bond strength testing using a Marshall press load frame. Bond strengths were determined at two separate interfaces on cores cut from two test sections at the NCAT Pavement Test Track. One section failed due to debonding, and the other section did not encounter this distress. Both sections showed that the bond strength deeper in the pavement was greater than the bond strength near the surface of the pavement (FIGURE 6). Therefore, debonding would be more apt to occur at layer interfaces closer to the surface (*11*).

2.3 Tack Coats

Tack coats (FIGURE 7), have often been used to bond the interfaces of pavement layers together (*15*). Five factors affect the bond characteristics of tack coats (*4*):

- Tack coat type,
- Application rate,
- Curing time,
- Surface conditions, and
- Pavement temperature.

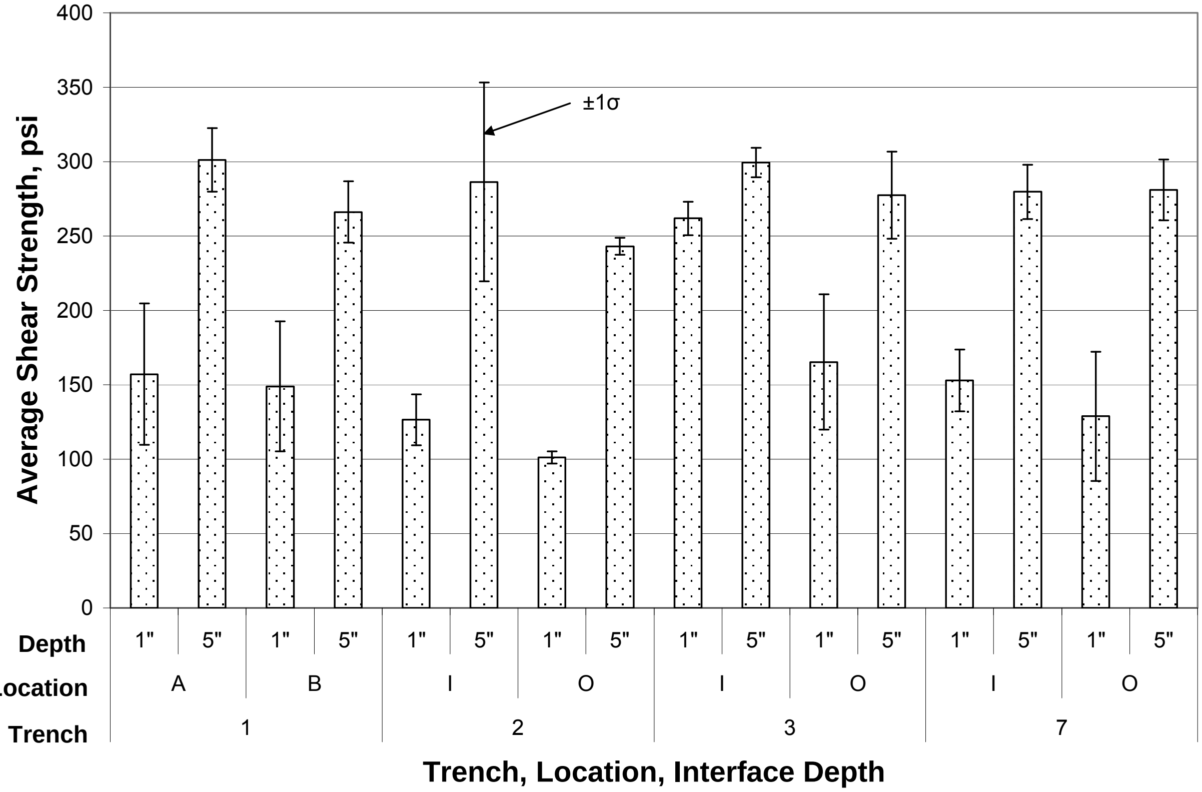


FIGURE 6 Bond Strength Analysis (*11*).

FIGURE 7 Tack Coat Application.

Some states believe that strong tack coats are vital for transferring tensile and shear stresses throughout the entire pavement structure because debonding decreases the bearing capacity of a pavement and accelerates fatigue cracking (*16*). The Florida Department of Transportation (FDOT) requires the use of a tack coat so this stress transfer can take place (*18*). Other states, such as Washington, have noticed one-third of its top-down cracking comes from debonding. It sees tack coats as simple, inexpensive, and essential for preventing this distress; however, the lack of guidelines for using tack coats has hindered the ability to achieve adequate bond strength (*4*).

Three materials (asphalt cement, cutback asphalts, and emulsified asphalts) have typically been used as tack coats (*20*). A recent survey was conducted in conjunction with NCHRP Project 9-40 to determine the current tack coat practices of state agencies and foreign countries. Of the agencies that responded, 100% of them used asphalt emulsions as tack coats. Asphalt cement was used by 26%, and cutbacks were used by 21% of the respondents (*20*).

While these three materials are used, asphalt cement and cutbacks both have disadvantages associated with their use. Asphalt cement requires excessive heating in order to achieve proper viscosity for spraying purposes. Asphalt cement also provides poor coverage and rapidly cools once placed in the field (*1*). Cutback asphalts are not typically used due to their environmental concerns (*1*, *20*).

A 1999 survey by the International Bitumen Emulsion Federation showed that catatonic emulsion was the most commonly used tack coat material worldwide (*21*). Emulsions are practical applications for tack coats because they flow easily and provide a uniform application when sprayed (*1*). The most common slow setting emulsions used for tack coats in the United States are SS-1, SS-1h, CSS-1, and CSS-1h. Some states use rapid-setting grades of emulsions such as RS-1, RS-2, CRS-1, CRS-2, CRS-2P, and CRS-2L (*20*).

One concern when using emulsions is determining if the application rate is based on total emulsion or asphalt residue. The minimum percent asphalt residue differs for emulsion grades. Generally, the "-1" grades have a minimum residue of 55 to 57% , and the "-2" grades have a minimum residue of about 65% . Confounding the matter further, some references recommend diluting emulsions before applications (*22*, *23*); however, this is prohibited by the Alabama Department of Transportation.

Not only is it important to use the correct material when selecting a tack coat, but it is also important to use it at the correct application rate. Excessive use of tack coats (i.e., too heavy an application) has been known to create a slip plane that is detrimental to bond strength (*4*). Also, at low temperatures, the application rate of tack coats should be decreased in order to achieve proper bond strength (*16*).

One of the most significant determinants of the correct application rate of tack coats is the condition of the pavement surface. A higher tack coat application rate is required on old HMA or PCC than is needed to achieve proper bond on a new asphalt pavement (*5*). Surfaces that are open and oxidized need higher applications of tack coat material to achieve proper bond (*22*).

The final concern for tack coats is the surface of the pavement onto which they are placed. Dust and dirt have been shown to increase the probability of debonding. The effects of tack coats being exposed to water were recently evaluated by the FDOT. In this study, when two HMA lifts were bonded together by a tack coat that had been exposed to water, a reduction in shear strength occurred. Over time, the shear strength gradually increased; however, the shear strength never fully recovered to that of a structure whose tack coat had not been contaminated with water. In the end, FDOT determined that rain was detrimental to bond strength due to the water interface introduced to the tack coat (*18*).

While many states tout the successes of tack coats for achieving adequate bond between asphalt layers, one must realize that not all states require tack coats. Mrawira and Damude (*24*) conducted a study that compared the interface shear strength of fresh overlays with and without tack coats to determine the effectiveness of tack coats in increasing interface bond strength. The results of this study showed that non-tacked surfaces showed higher bond strength than those surfaces that had received a tack coat. The authors hypothesized that the tack coat introduced a slip plane into the specimen that was not previously there. Therefore, tack coats would be detrimental to the life of the pavement instead of increasing the shear resistance of the structure.

2.4 Application of Tack Coats

Choosing the correct application rate for tack coats is vital to achieve full bond. Different surfaces (i.e., milled, new, granular) require different application rates of the tack material to achieve adequate bonding. It has been suggested that tack coats only need to cover 90 to 95% of the existing pavement surface; however, it is important to prevent excessive tacking, as it might introduce a shear slippage plane at the layer interface (*20*).

Multiple surveys on tacking patterns in the HMA industry have been conducted. Currently, most contractors tack at rates between 0.02 and 0.09 gal/yd^2 depending on the type of tack being used and the condition of the surface of the pavement (*21*). According to a recent survey, most emulsions and cutbacks are placed at a residual rate between 0.03 and 0.05 gal/yd^2. This rate increases when using asphalt cement to between 0.04 and 0.1 gal/yd^2 (*20*).

When a pavement surface becomes more oxidized and open, it requires more tack material to achieve adequate bond strength. Open, dry, aged, or milled surfaces require more residual asphalt due to the high specific surface area (*22*). TABLE 1 provides the recommended tack coat application rates for slow-setting emulsions on different surfaces in Ohio.

TABLE 1 Typical Tack Coat Application Rates (*25*)

Existing Pavement Condition	Application Rate (gal/yd^2)		
	Residual	Undiluted	Diluted (1:1)
New HMA	0.03~0.04	0.05~0.07	0.10~0.13
Oxidized HMA	0.04~0.06	0.07~0.10	0.13~0.20
Milled Surface (HMA)	0.06~0.08	0.10~0.13	0.20~0.27
Milled Surface (PCC)	0.06~0.08	0.10~0.13	0.20~0.27
Portland Cement Concrete	0.04~0.06	0.07~0.10	0.13~0.20

Tack coats are typically applied by one of two methods: tack coat distributors or pavers with tanks and spray bars. "Double-lap" and "triple-lap" coverage is generally considered ideal for achieving adequate tack. This method provides adequate coverage of the pavement surface without gaps in the tack application (*20*).

2.5 Laboratory Bond Strength Testing

Most pavement interface failures are resultant of shear and tension forces; therefore, most interface bond strength tests characterize bond strength using these two distress modes.

A study was conducted by Sangiorgi et al. (*26*) that compared three simulated bond conditions: (1) with tack coat emulsion, (2) contaminated by dirt and without a tack coat emulsion, and (3) with tack coat emulsion and a thin film of dirt. The Leutner Shear Test (LST) (FIGURE 8) was the method chosen for analysis. The LST applies a vertical shear load at a layer interface in a controlled strain mode (50 mm/min) to determine the maximum shear load and maximum displacement of the specimens. The results showed the strongest bond strengths occurred when tack coat emulsions were used.

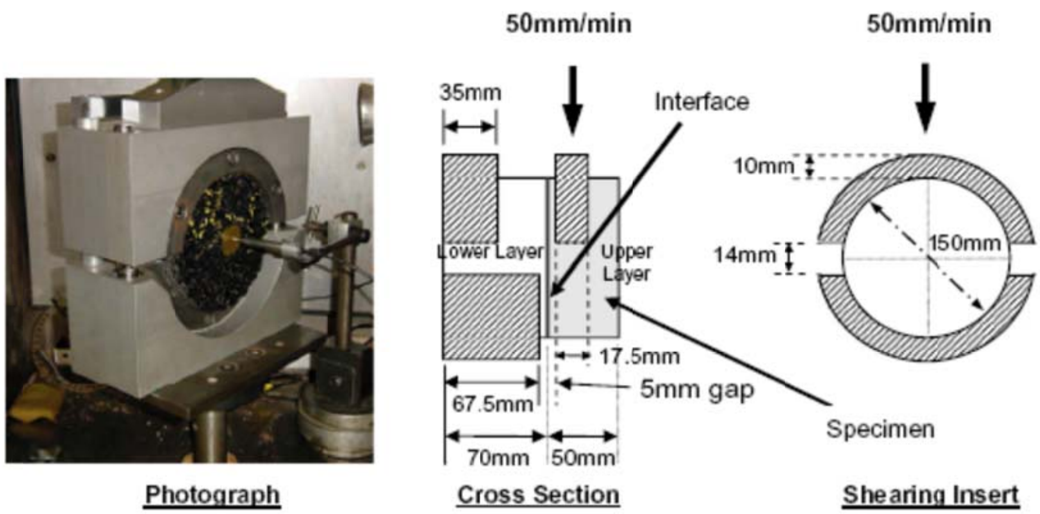


FIGURE 8 Leutner Shear Test (*27*).

Uzan et al. (*8*) also used a laboratory shear test to assess changes in bond strength based on variable temperatures, tack coat application rates, vertical pressures, and asphalt binders. This study showed that increasing vertical pressure and decreasing temperature will positively influence interface bond strength. The study also concluded that an optimum tack application rate is influenced by both the binder and temperature of testing.

Hachiya and Sato (*16*) compared bond strengths of laboratory-compacted asphalt specimens using both simple shear and simple tension tests for catatonic asphalt emulsions and three rubber-modified asphalt emulsions. At low temperatures, the rubber-modified asphalt emulsions mobilized more strength at layer interfaces than the catatonic asphalt emulsions. At higher temperatures, the tack coats provided similar bond strengths.

The Ancona Shear Testing Research and Analysis (ASTRA) testing device **(**FIGURE 9**)** was used by Canestrari and Santagata (*28*) to analyze the effects of variables on shear behavior. The ASTRA applies a constant-rate horizontal load at layer interfaces until failure occurs. The shear stress at failure is calculated from the maximum load and specimen size. The conclusions of this study were as follows:

- An increase in normal stress or decrease in temperature decreases dilatancy.
- An increase in normal stress increased the peak shear stress.
- Emulsified tack coats increased specimen bond strength versus non-tacked specimens.
- Shear resistance is inversely proportional to testing temperature.

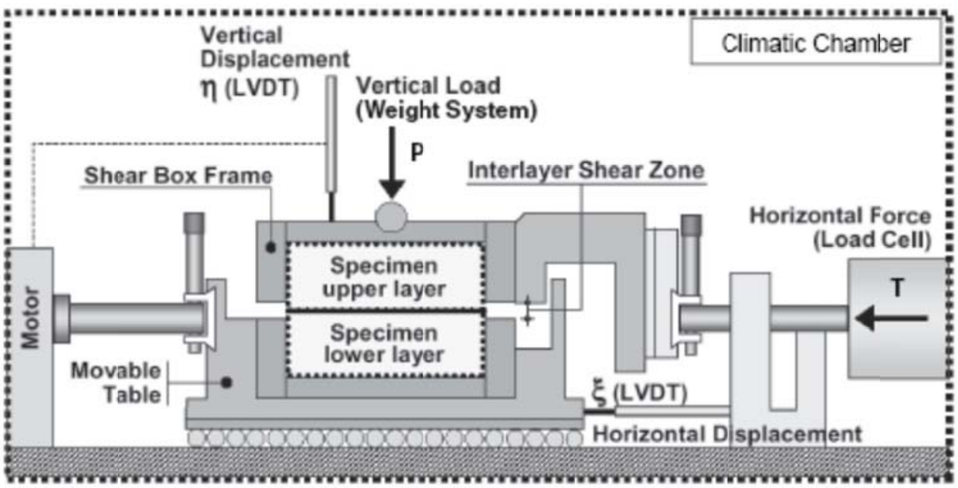


FIGURE 9 Ancona Shear Testing Research and Analysis (*29*).

The Layer-Parallel Direct Shear (LPDS) (FIGURE 10) determines the tensile strength of a cylindrical composite specimen by applying a vertical shear load with a strain control mode at a constant rate. Raab et al. (*30*) used 20 different types of tack coats in a study using the LPDS to determine the influence of tack coat on interlayer bond strength for varying surface conditions (smooth and rough) and compaction efforts (40 and 50 gyrations). The effects of moisture, water, and heat were also included in this study.

Raab et al. (*30*) reported that smooth surfaces were able to sustain higher shear forces because of the larger contact area. When considering the tack coats, the type of application (i.e., tack coat material) did not substantially influence the bond strength of the specimens; however, the use of tack coats in conjunction with moisture and a wet surface did result in better adhesion (*30*).

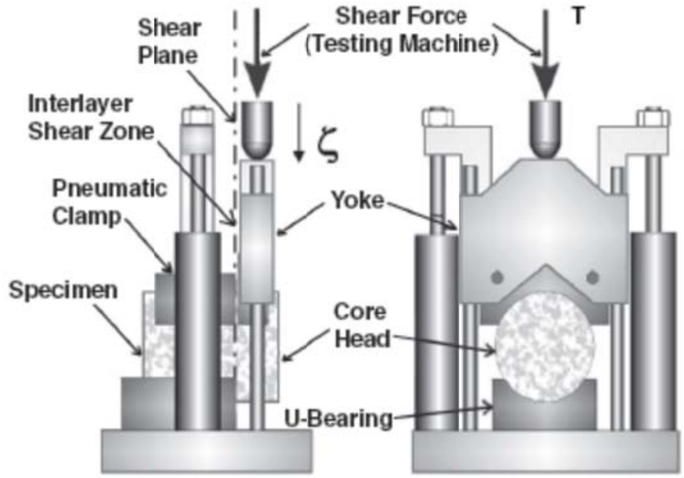


FIGURE 10 Layer-Parallel Direct Shear (*29*).

Mohammad et al. (*62*) used the Superpave Shear Tester (SST) (FIGURE 11) and a direct shear device to assess the effects of tack coat material types and application rates on bond strength. This device was similar to the ASTRA testing device. This direct shear test applies a horizontal load at a rate of 50 lbs/min until the layers separate at controlled temperatures to determine the shear stress at failure. This study suggested applying tack coats between two asphalt concrete layers will improve the bond strength when compared to two non-tacked layers. When compared to other tack coats used in the study, a CRS-2P emulsion tack coat provided the most improvement in interlayer bond strength.

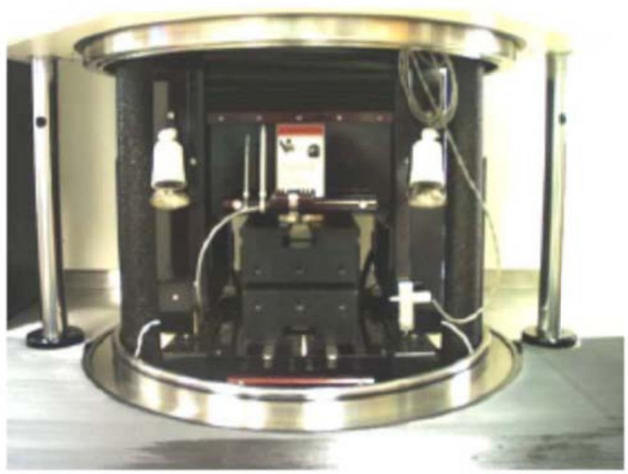


FIGURE 11 Superpave Shear Tester (*62*).

Sholar et al. (*18*) used a direct shear bond test (FIGURE 12) to determine the effects of moisture, application rate, and aggregate interaction on interlayer bond strength. Roadway cores were taken from three field projects using different application rates ranging from no tack to 0.362 L/m^2. Water was applied to two application rates to determine the effects of moisture on bond strength. The results were as follows:

- Water significantly decreased bond strength.
- Changes in tack rates between 0.09 and 0.362 L/m^2 has little influence on bond strength.
- Tack coats influence the bond strength of fine-graded mixes more than coarse-graded mixes.
- Coarse-graded mixes achieve higher bond strengths than fine-graded mixes.
- Milled surfaces achieved the highest bond strengths from the field projects.

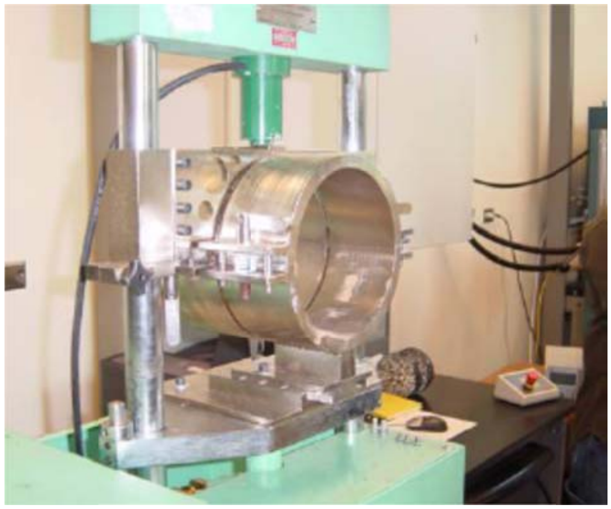


FIGURE 12 FDOT Bond Strength Tester (5).

While many researchers have used shear to study bond strength, Buchannan and Woods (*31*) developed a new method, ATacker™ (FIGURE 13), to characterize the tensile and torque-shear strength of popular tack coat materials at different application temperatures, rates, dilutions, and set times. This device used a pull or torque force to detach tack-coated plates or detach the contact plate from the tack-coated pavement. The results of this study showed that application rate and tack coat type both influence the tensile and torsional-shear properties of the mixes. Like previous studies, the specimens using a CRS-2 emulsion had the greatest bond strengths.

West et al. (*5*) developed a bond strength test procedure during a project to determine the best tack coat material and application rate. Phase 1 of the project was a laboratory exercise comparing emulsions and asphalt cement tack coats at three residual application rates, three test temperatures, and three normal pressures for coarse- and fine-graded mixes. The results of this study were similar to previously mentioned projects; however, the PG 64-22 tack coat had higher bond strengths than the emulsions. This study also showed that fine-graded mixes should have lower application rates. The bond strength of coarse-graded mixes was not influenced by the application rate.

FIGURE 13 ATacker^{TM} (*5*).

The test procedure developed by West et al. (*5*) was adopted and included in the ALDOT Testing Manual as ALDOT Procedure 430 (ALDOT-430). This test method was refined and used in this study to evaluate bond strength of lab and field cores. The test method requires conditioning a dry specimen at 77°F (25°C) for a minimum of two hours prior to testing. The specimen is then loaded into the bond strength device with the direction of traffic vertical, and the marked layer interface centered between the edge of the shearing frame and the edge of the reaction frame. Only the shearing frame is allowed to move while the reaction frame is stationary. The specimen and the bond strength device are then placed in the Marshall Stability test apparatus with the loading head on top of the bonded interface. The Marshall Stability test applies a vertical shear load in a controlled displacement mode (2 in./min.) to determine the maximum shear load and maximum displacement of the interface. The interface bond strength is calculated by dividing the maximum shear load by the cross-sectional area of the test specimen. The test setup is shown in FIGURE 14. The Marshall Stability test apparatus was chosen in the test procedure so that the test procedure could be immediately implemented without requiring a new loading frame and training for ALDOT technicians.

Other tests have been used to evaluate interlayer bond strength of asphalt specimens, including the Virginia Shear Fatigue Test, Switzerland Pull-Off Test, Wedge-Splitting Test, Dynamic Interaction Test, Traction Test, UTEP Pull-Off Test, and the Impulsive Hammer Test. Details regarding these tests have been documented elsewhere (*20*).

FIGURE 14 Bond Strength Testing Apparatus.

2.6 Computer Modeling of Bond Strength

Several computer modeling methods have been employed to evaluate bond strength and stresses at an interface. An analysis of shear stresses was conducted by DeBondt and Scarpas in 1994 to evaluate the conditions generated by a newly developed shear tester (*32*). A constitutive model was used to evaluate the conditions at the interface of extracted cores at varying temperatures and normal stress levels (*6*). Another study developed several finite element models to better understand the stress distribution at the interface (*33*).

When conducting a forensic investigation of a debonded pavement at the National Center for Asphalt Technology (NCAT) Pavement Test Track, Willis and Timm used WESLEA to predict strains profiles of a 7-in. pavement that contained 1 in. of stone matrix asphalt (SMA), 4 in. of densely-graded HMA, and a 2-in. rich-bottom layer. Three strain profiles were developed, representing a fully-bonded pavement, a pavement where the SMA debonded from the HMA, and a pavement where both the SMA and the rich-bottom layers had debonded. The results of this analysis (FIGURE 15) show that the critical strain locations indeed change depending where the loss of bond occurred. The increased strains also present evidence as to why cracking rapidly propagates in a debonded pavement (*11*).

While layered elastic analyses have been used to predict pavement responses to debonding, Maina and Matsui (*34*) developed another program titled GAMES to predict the effects of horizontal and vertical forces on pavement structures. One analysis included a slippage plane between two pavement layers in the structure. When the slippage plane was introduced, horizontal and vertical displacements increased above the debonded layer. The horizontal displacement below the debonded layer decreased, showing the lack of transfer occurring in a debonded structure. The more slippage that occurred, the more the vertical displacement increased.

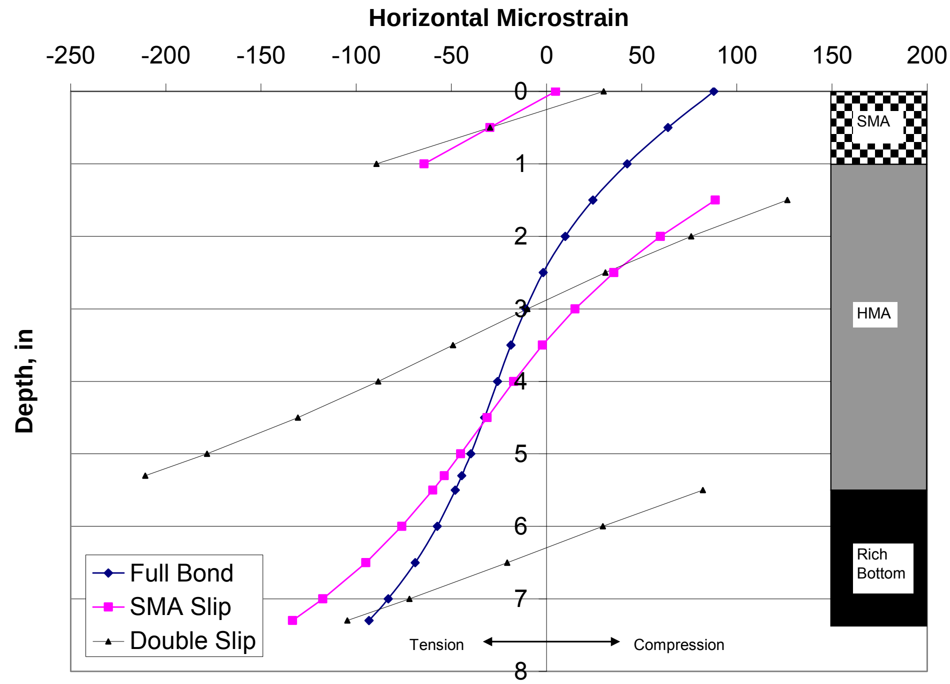


FIGURE 15 Theoretical Strain Profile of Debonded Pavement (*11*).

In 2004, King and May presented an analysis of the effect of bond between HMA layers using the program BISAR (*37*). The pavement structure analyzed consisted of two 4-in. (100 mm) HMA layers over a 6-in. (150 mm) aggregate base and two subgrade stiffnesses. Two load levels were used, 9 kip (40 kN) dual tire and 12 kip (53.4 kN) dual tire. The interface between HMA layers was modeled in separate runs from a no-slip condition to full slip between (no bond) layers. Analyzed program outputs included maximum stress and strain at various locations and numbers of load repetitions to failure. All the outputs show a dramatic increase in stresses and strains or a decrease in pavement life when the interface drops from full bond to about 90 percent bond.

Roffe and Chaignon (*38*) conducted a similar analysis using the French pavement design program ALIZE. The pavement structure evaluated consisted of a 2.4-in. (60 mm) surface layer, a 5.1-in. (130 mm) HMA intermediate layer, and a 7.9-in. (200 mm) aggregate base. The program was run with full bond and no bond between the HMA layers. Their analysis showed that the service life of the pavement was reduced from 20 years to between 7 and 8 years due to the lack of bond between the HMA layers.

CHAPTER 3 DEVELOPMENT OF PRELIMINARY BOND STRENGTH CRITERION

The purpose of this research effort was to investigate the shear stress and bond strength at the interface of the wearing and binder courses to establish a preliminary bond strength requirement that can provide a good bond between pavement layers. This research included both a structural pavement analysis and field studies. The structural pavement analysis was conducted to estimate the horizontal shear stresses at the interface between the wearing and binder courses caused by the horizontal forces applied to pavement surfaces during moving traffic. The field study evaluated bond strengths of cores extracted from five sites with no sign of debonding and nine pavement sections exhibiting slippage cracks. The shear stresses calculated in the structural pavement analysis were then compared to the bond strengths determined from field cores in the field studies to establish a minimum bond strength requirement for different applications.

3.1 Structural Pavement Analysis

Computer modeling efforts have been employed to evaluate bond strength and stresses at pavement layer interfaces in several studies. These modeling efforts range from use of layered elastic programs, such as Waterways Engineering Station Elastic Layer Analysis (WESLEA) (*11*) and Bituminous Structures Analysis in Roads (BISAR) (*37*), to development of constitutive and finite element models (*6*, *32*, *33*) to better understand the stress distribution at the interface.

After reviewing the previous modeling efforts, a multi-layer analysis technique using the BISAR software developed by Shell Oil Company was chosen and conducted in this study. BISAR analysis in this study was done by varying the factors influencing the interface bond strength. Modeling of AC pavements allowed for a more in-depth analysis of stress failures at layer interfaces without performing time-consuming and expensive field studies. Understanding the effects of layer properties (i.e., thickness and stiffness) as well as material limitations aided in establishing a minimum requirement for interface bonding.

3.1.1 BISAR Program

BISAR is an elastic multi-layer analysis program that allows the evaluation of deformation, stresses, and strains within a pavement and between pavement layers. Within BISAR, the depth (z-direction) is an input layer while the length and width (y- and x- axis) are infinite (*36*). BISAR can be used to calculate the effect of vertical and horizontal stresses (shear forces at the surface) and includes an option to account for the effect of (partial) slip between the layers using a shear spring compliance at the interface.

To model the slip between the asphalt layers, BISAR assumes that the shear stresses at the interface cause a relative horizontal displacement of the two layers, which is proportional to the stresses acting at the interface. The physical definition of the standard shear spring compliance, AK (m^3/N), is given by

$$AK = \frac{\text{relative horizontal displacement of layers}}{\text{stresses acting at the interface}} \quad (1)$$

The relationship is treated mathematically through the parameter α, defined as

$$\alpha = \frac{AK}{AK + \frac{1+\nu}{E} \cdot a} \tag{2}$$

in which:

a = radius of the load, m
E = modulus of the layer above the interface, Pa
ν = Poisson's Ratio of that layer
α = friction parameter, with $0 \leq \alpha \leq 1$
($\alpha = 0$ means full friction, $\alpha = 1$ means complete slip).

The reduced shear spring compliance, ALK expressed in unit length (meters), is defined as

$$ALK = \frac{\alpha}{1-\alpha} \cdot a \tag{3}$$

Either AK or ALK must be used as a primary input in BISAR. The value of α, called interface friction, used in all computations is derived from the input (either AK or ALK).

The friction parameter α should not be considered as a classic friction coefficient. The interface friction parameter depends on the diameter of the applied load and is therefore not a pure material property. Within calculations with loads of different diameters, different values for α apply for one ALK or AK value as a physical characteristic for a specific layer interface. It is therefore not formally correct to express a percentage of slip as a proportion of the spring compliance for full slip. On the other hand, it remains difficult to assign or justify a specific value for AK (ALK). Therefore, it is recommended to always perform a series of calculations with different values for ALK as a kind of sensitivity analysis. A numerical variation in ALK from zero to, say, 100 times the radius of the loaded area covers the range from full friction to (practically) full slip ($\alpha = 0.99$). The physical meaning (see above definition of AK) of such input values should be considered in connection with the moduli of the layers in the structure and with the corresponding shear spring compliance (AK) values, with aid of the relation:

$$AK = ALK \cdot \frac{1+\nu}{E} \tag{4}$$

The application of a spring compliance in BISAR to define interlayer friction is best illustrated using an example. Consider a two-layered pavement structure loaded by a single tire that is braking so that horizontal forces are applied to the surface, as shown in FIGURE 16. Assuming the friction coefficient between the tire and the road surface is 0.8, the horizontal force applied at the surface can be calculated as 0.8 x 20 = 16 kN.

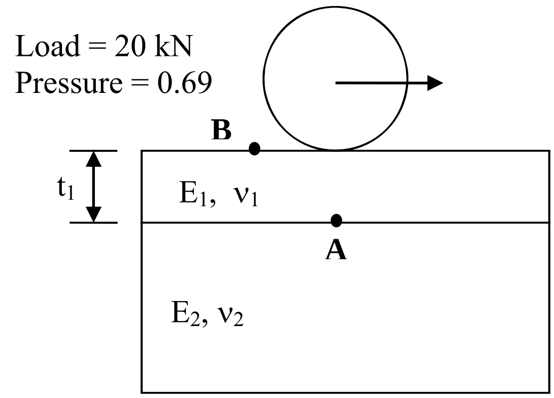


FIGURE 16 Two-Layered Pavement Structure Loaded by a Single Tire.

In an ideal situation with full-friction between the two layers, all horizontal or shear stresses that develop at the bottom of the top layer will be transferred to the top of the bottom layer. In reality, however, one cannot always assume full friction at the interface as the strength of the bond will be influenced by a number of factors (aggregate interlock, use of tack coat, the type of tack coat, the application rate of the tack coat, etc). If the shear stresses at the interface overcome the inherent strength of the bond between the layers, the bond will weaken and eventually fail. If the interface bond weakens or deteriorates (as a result of repeated excessive shear forces at the interface due to braking or acceleration forces on the road surface, for example) then horizontal shear stresses are not fully transferred across the interface, and the upper layer will slide relative to the bottom layer. This scenario is detrimental and can result in significant shear stresses at the surface of the pavement. If these shear stresses exceed the tensile strength of the material in the upper layer then the layer may tear and debond from the underlying layer as typified by slippage failures. Using shear stress data generated by BISAR based on the use of different materials, a minimum bond strength requirement at a pavement interface could be determined.

3.1.2 BISAR Analysis

A structural pavement analysis was conducted using BISAR to determine the effects of subgrade stiffness (5,000 and 15,000 psi), total AC thickness (5, 7 and 9 in.), thickness of wearing course (0.5 to 2 in.), and seasonal variation of AC stiffness on shear stresses in the top two inches of asphalt pavements. As shown in FIGURE 17, a legal 20-kip single axle configuration with a tire pressure of 100 psi was used to load the theoretical pavement structure. To determine the horizontal load acting on the pavement surface, a coefficient of friction between the rubber tire and dry asphalt pavement surface that ranges between 0.5 and 0.8 was used (*39*). A coefficient of friction of 0.8 represents the most detrimental lateral loading scenario in which 80% of the vertical load is mobilized in the horizontal direction when a vehicle brakes.

To determine how the stiffnesses of the wearing course and underlying AC layers should be varied in this analysis, the stiffness and temperature variation of the asphalt layers of Section S11 in the 2006 research cycle at the NCAT Pavement Test Track were analyzed. Section S11 was a typical ALDOT 7-in. pavement design cross-section. In order to determine appropriate dynamic moduli to incorporate in the analysis, dynamic modulus testing was conducted on the AC material used in the surface layer of Section S11 in accordance with AASHTO TP 79-09. The average dynamic modulus for three replicates at 10 Hz was determined for each test temperature. A regression analysis was then conducted on these average moduli to develop a relationship between temperature and stiffness for this material (Equation 5).

$$E = 5{,}000{,}000 \times e^{(-0.031T)} \qquad (5)$$

where:

E = dynamic modulus, psi
T = temperature, °F

Temperature readings were taken at the surface and mid-depth of the AC layer every minute at the Test Track. These values were then conglomerated into an hourly temperature average. Using the temperature-stiffness relationship (Equation 5), an estimated hourly stiffness was calculated at the surface and mid-depth of the pavement.

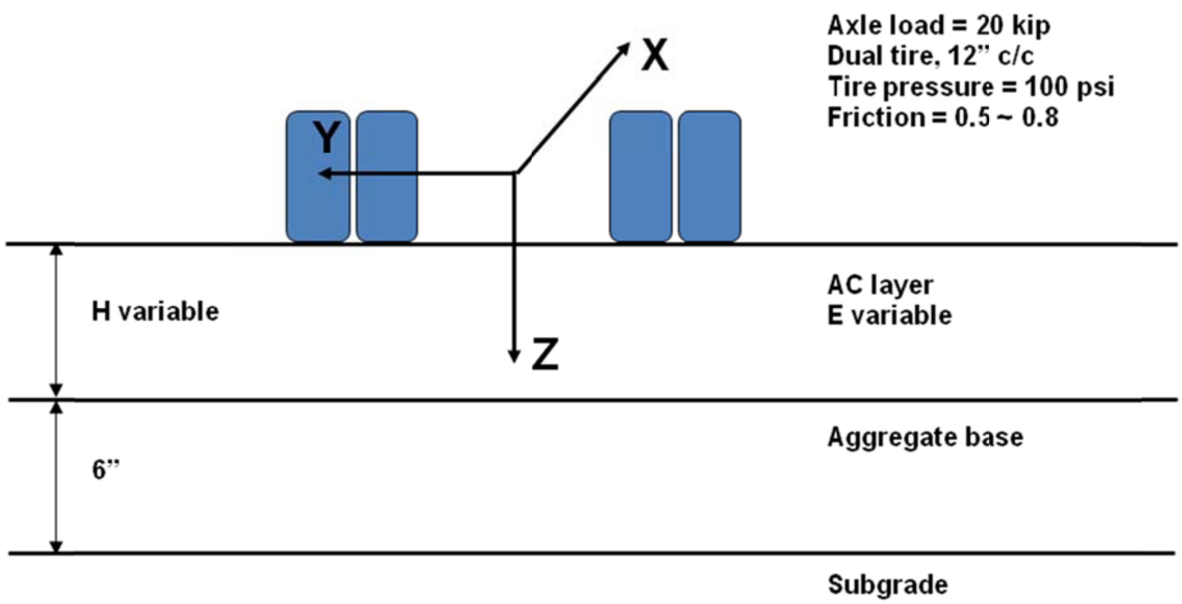


FIGURE 17 Pavement Structure for BISAR Analysis.

Effect of Subgrade Stiffness. A simulated pavement cross-section (FIGURE 18) was created in BISAR to investigate the effects of subgrade stiffness on shear stresses in the top 2 in. of an asphalt pavement structure. The AC was assumed to have a thickness of 7 in. and stiffness of 500,000 psi. Six inches of 30,000 psi of granular base materials were placed below the AC. Two subgrade stiffnesses, including 5,000 psi and 15,000 psi, were investigated in the analysis. Shear stresses were determined in BISAR at the surface of the pavement and at depths of 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, and 2.0 in. under the center and edge of the tire.

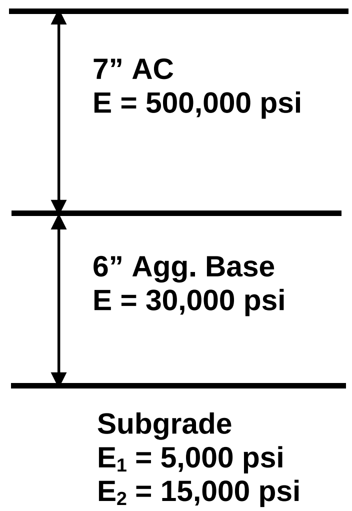
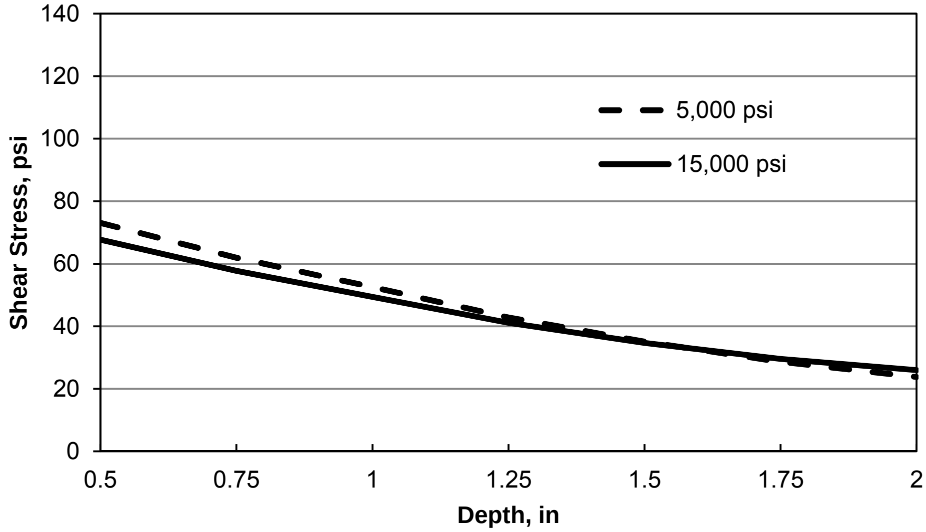


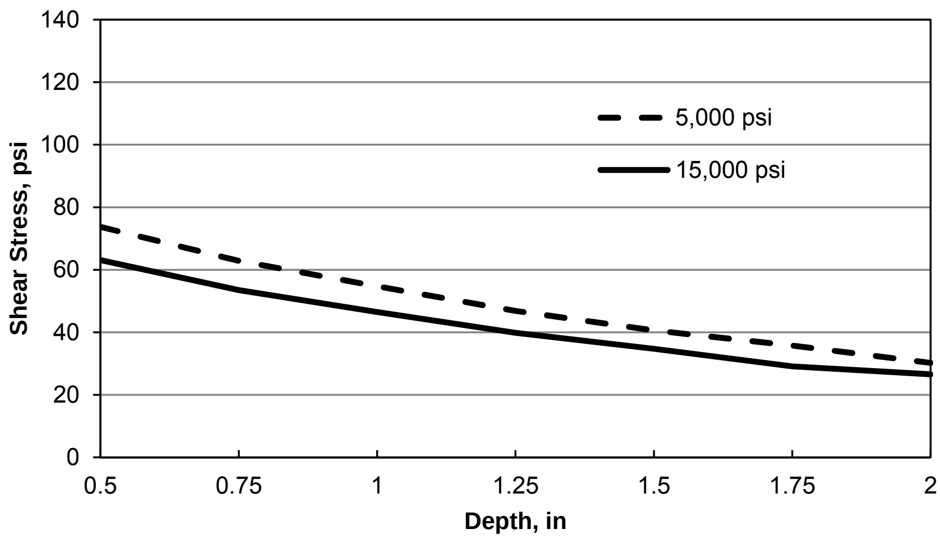
FIGURE 18 Pavement Cross-Section for Evaluating Effect of Subgrade Stiffness.

FIGURE 19 shows how shear stress was affected by the stiffness of the subgrade. Under the center of the tire (FIGURE 19 (a)), the softer subgrade increased the shear stress by 10 psi at the surface; however, at a depth of 0.5 in., the difference had been reduced to 5.5 psi. Most Alabama asphalt pavements have wearing courses no thinner than 0.5 in.; therefore, even with a subgrade stiffness of 5,000 psi, the maximum shear stress at a pavement interface in this scenario was 73 psi.

FIGURE 19 (b) illustrates the pavement responses under the edge of the tire. The subgrade did not affect the shear stresses at the surface of the pavement. For both subgrades, the surface shear stresses were approximately 140 psi. However, the shear stresses were then reduced to 89 and 78 psi for the 5,000 and 15,000 psi subgrades, respectively, at a depth of 0.25 in. The difference in shear stress then ranged from 5 to 9 psi until a depth of 2 in., where the stress differentiation was only 2.5 psi. Since most state agencies do not build wearing courses thinner than 0.5 in., the maximum simulated shear stress at a layer interface under the edge of the tire was 74 psi.



(a) Under the Center of the Tire.



(b) Under the Edge of the Tire.

FIGURE 19 Shear Stress Varying with Subgrade Stiffness.

Effect of Total AC Thickness. In addition to the analysis of subgrade stiffness that showed only slight effects on the shear stress in the top two inches of an asphalt pavement, another analysis was conducted to determine the influence of total AC thickness on shear stresses in the wearing course of a pavement. As shown in FIGURE 20, 6 inches of a 30,000 psi granular base was constructed over a 15,000 psi subgrade. The modulus of the HMA material was kept constant (500,000 psi); however, three different total AC thicknesses, including 5, 7, and 9 in., were investigated. The shear stresses under the center of the tire (FIGURE 21 (a)) and at the edge of the tire (FIGURE 21 (b)) were determined in BISAR.

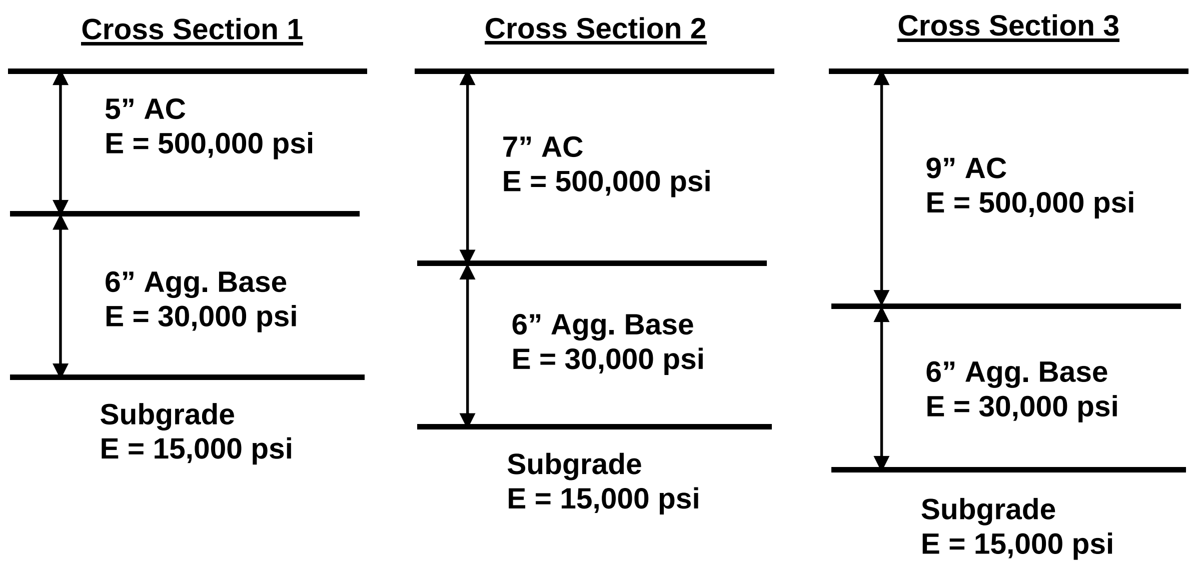
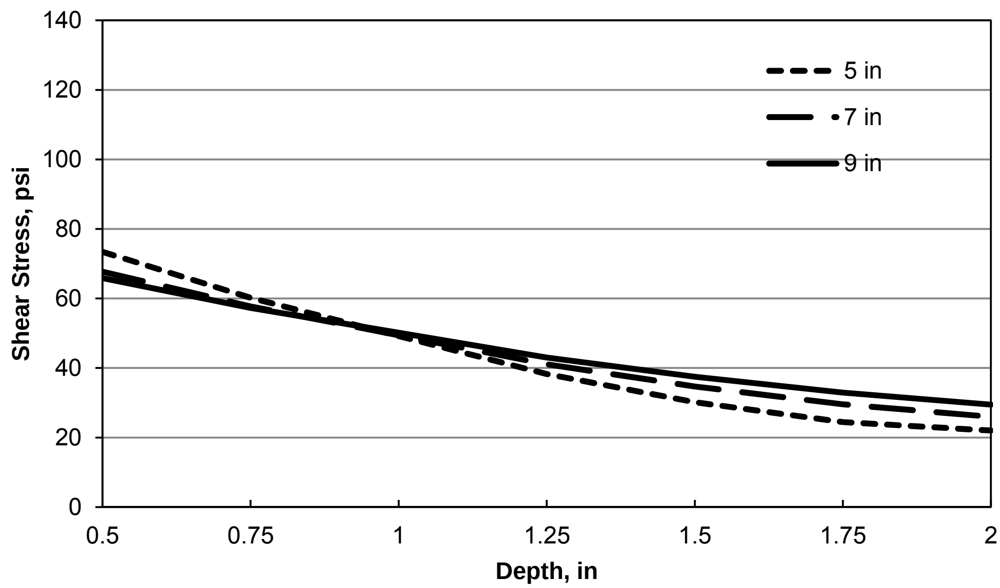


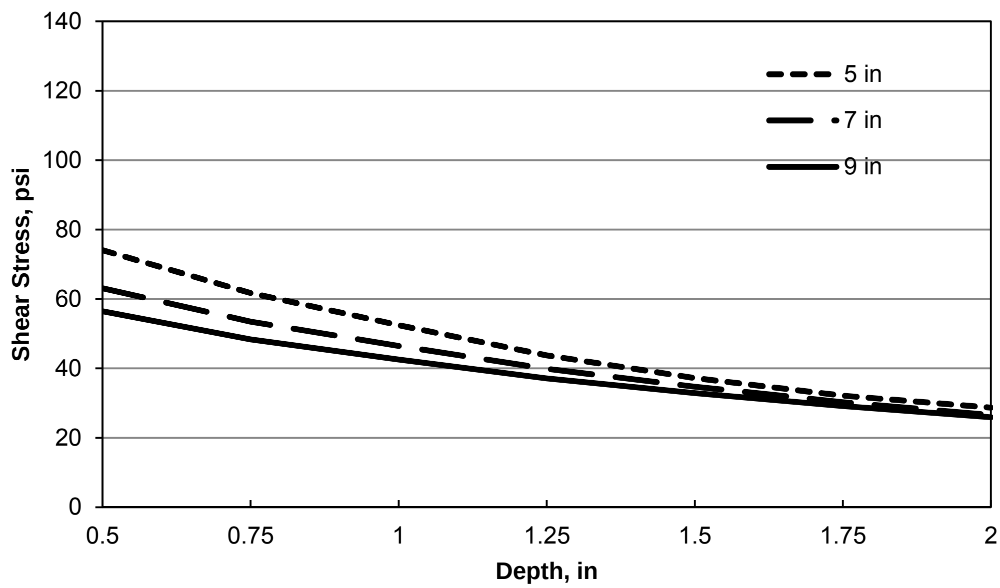
FIGURE 20 Pavement Cross-Sections for Evaluating Effect of AC Total Thickness.

As shown in FIGURE 21 (a), the thinner sections carried higher shear stresses in the top 1 inch of the pavement under the center of the tire; however, all three graphical representations converged at a depth of 1 inch at approximately 50 psi. Below this depth, the thicker pavements exhibited the higher shear stresses. The greatest shear stress (74 psi) at a depth of 0.5 in. occurred in the 5-in. pavement structure.

When considering pavement responses under the edge of the tire (FIGURE 21 (b)), the pavement thickness did not influence the shear stress at the surface of the pavement (140 psi). Similar to the subgrade stiffness analysis, a significant drop in shear stress occurred between the surface and 0.25 in. for all three total AC thicknesses. The thinnest pavement always had the greatest shear stresses. The stress differentiation between the 5- and 9-inch sections decreased from 22.3 psi at 0.25 in. to 2.76 psi at 2 in. depth. The greatest shear stress occurring in the 5-in.-thick section was 74 psi at a depth of 0.5 in.



(a) Under the Center of the Tire.

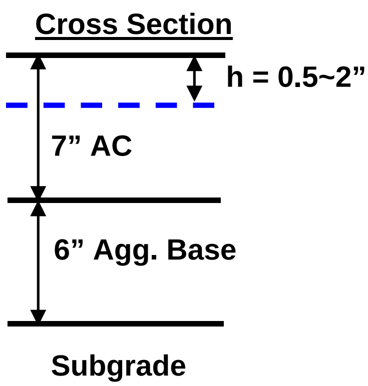


(b) Under the Edge of the Tire.

FIGURE 21 Shear Stress Varying with HMA Total Thickness under the Center of the Tire.

Effect of Variation of Asphalt Stiffness. While the previous analyses have been conducted using the constant AC stiffness of 500,000 psi, it is impractical to assume that the pavement structure's stiffness would not vary with temperature. Therefore, the final analysis was conducted to determine the effects of variation of asphalt stiffness (due to variation of temperature with season and depth) on the shear stress at layer interfaces in the top 2 inches of the pavement.

A 7-in. asphalt pavement on top of the previously described subgrade and base materials (FIGURE 22) was modeled in BISAR. While the subgrade and base materials as well as the total AC thickness remained constant, the stiffness and thickness of both the wearing course and underlying AC layers were varied.



Stiffness (x 1,000psi)	
Surface AC	Underlying AC
100	100
100	250
250	100
250	250
250	500
500	250
500	500
500	750

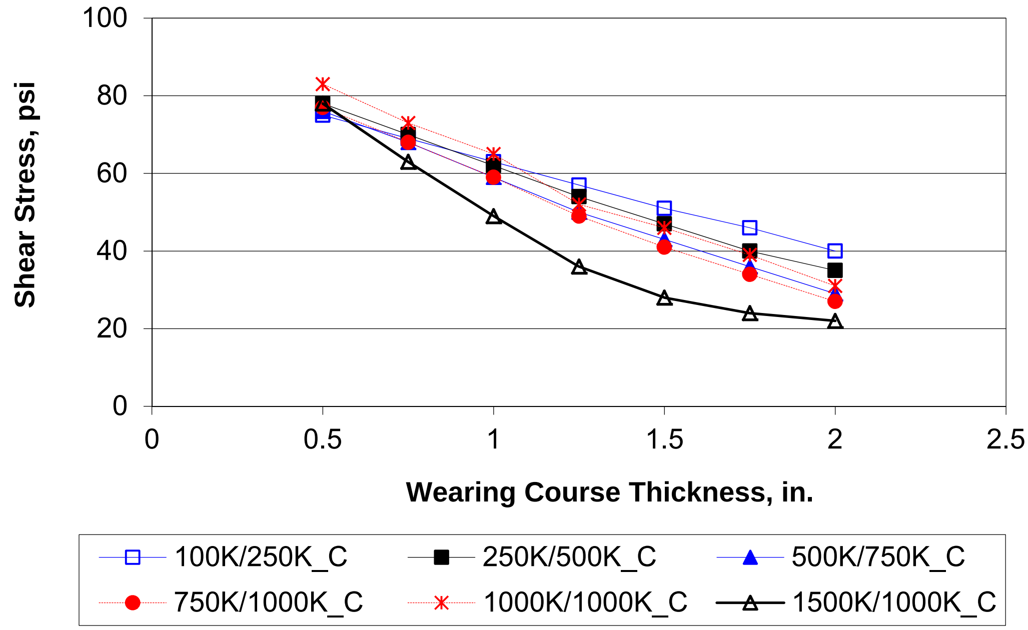
Stiffness (x 1,000psi)	
Surface AC	Underlying AC
750	500
750	750
750	1000
1,000	750
1,000	1,000
1,000	1,500
1,500	1,000
1,500	1,500

FIGURE 22 Cross Section and Stiffness Variation of Surface and Underlying AC Layers.

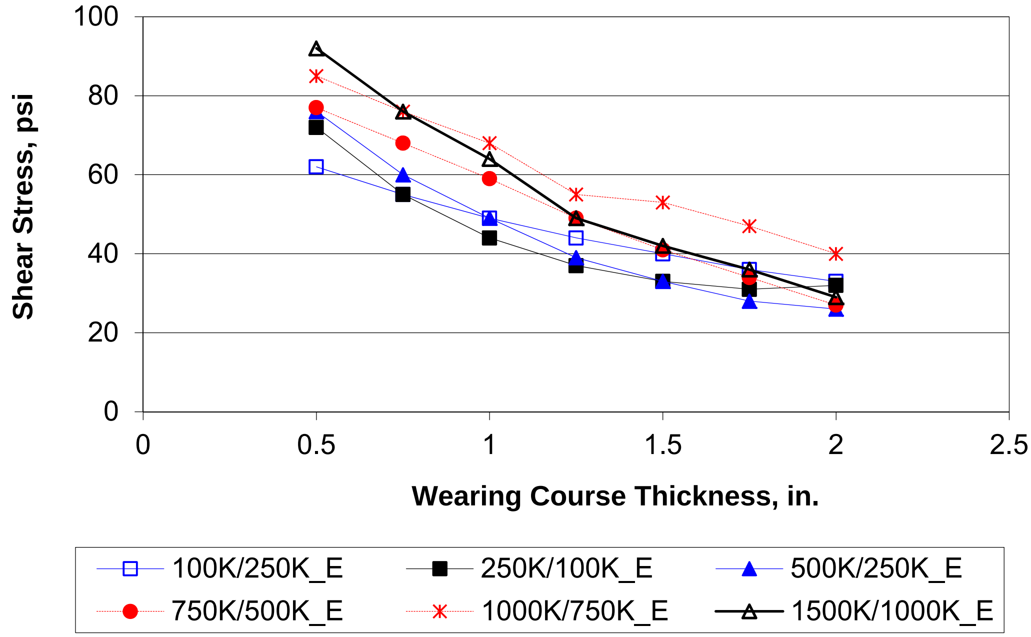
February is typically the coldest month in Opelika, Alabama. In order to quantify stiffness variability during low-temperature conditions at the Test Track, temperature data collected in February were analyzed. Using this temperature data, pavement stiffnesses were calculated at the surface and mid-depth of the pavement. The maximum percent difference between the surface and mid-depth stiffnesses was 18% when the stiffness of the surface layer was 1,462 ksi. A similar analysis was conducted for August, when the pavement stiffness would be the softest due to high temperatures. The maximum difference between the surface and mid-depth stiffnesses was 45%. At this point, the stiffness at the mid-depth of the pavement was only 180 ksi.

Wearing courses are typically placed between 0.5 and 2.0 inches thick in Alabama; therefore, interface depths of 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, and 2.0 inches were chosen for this analysis. The stiffnesses (100, 250, 500, 750, 1000, and 1500 ksi) chosen for this analysis were selected based on the minimum and maximum moduli of the mix, as previously described. FIGURE 22 (shown above) shows the AC moduli of the surface and underlying layers used in this analysis.

FIGURE 23 illustrates critical shear stresses under the center and edge of the tire due to seasonal variation of stiffnesses of asphalt layers. A further analysis of modeling results showed that when the stiffness of the wearing course was different from that of the underlying layer, the shear stress at the interface increased. This was the case whether the underlying materials were softer or stiffer than the wearing course. Reducing the underlying AC stiffness increased the shear stresses in the top 1 inch of the pavement. Below a depth of 1 inch, a shear stress reduction was typically seen when compared to a pavement of constant stiffness. In all cases, increasing the underlying AC stiffness increased the shear stresses at the layer interfaces.



(a) Under the Center of the Tire



(b) Under the Edge of the Tire

FIGURE 23 Shear Stress Varying with Seasonal AC Stiffness (Temperature) Variation.

As shown in FIGURE 23, the maximum shear stress at an interface between 0.5 and 2 in. was 92 psi. This occurred under the edge of the tire when a stiff surface (1500 ksi) was on top of a slightly softer binder layer (1000 ksi). This probably occurs during the winter in Alabama.

In summary, the structural pavement analysis showed that the thickness and stiffness of wearing course as well as the variation of stiffnesses of asphalt layers due to temperature variation had more effects on the interface shear stress than the stiffness of subgrade and total AC thickness. The maximum interface shear stress determined using BISAR was 92 psi at a depth of 0.5 in. The interface shear stress decreased for thicker surface layers, and it was approximately 40 psi at a depth of 2 in. Based on the structural pavement analysis results, it appeared that a bond strength requirement of at least 92 psi would be reasonable.

3.2 Field Study

The field study was conducted to determine the bond strength at the interface of the wearing and binder courses using cores extracted from pavement sections with and without slippage failures. A total of twelve sites, which were divided in two groups, were visited. The first group included five test sites that were constructed to evaluate the interface bond strength for the previous ALDOT study (*5*). These sites have been in service for more than four years and showed no sign of failure relating to debonding. The second group included nine test sections exhibiting slippage failures.

3.2.1 Test Sections with No Sign of Debonding

TABLE 2 lists the information of the five sites constructed in the previous ALDOT study. Site No. 5 had two test sections. In the first section, a regular distributor was used to apply the tack coat. For the second section, a Novachip spreader was employed to apply the tack coat and surface mix. The five test sites had different thicknesses of the surface layer constructed on three types of receiving surfaces (new AC, milled AC, and old portland cement concrete). For each of the test sections, four cores were extracted. All the cores were then brought to the NCAT laboratory and tested according to ALDOT-430.

TABLE 2 Information of Five Sites Constructed in Previous ALDOT Study

Site No.	Location	City	Surface Layer		Receiving Surface
			Mix	Thickness	
1	CR 32	Lafayette	Dense	0.7~0.9 in.	New AC
2	AL 22 W	Roanoke	Dense	1.5~1.9 in.	Milled AC
3	CR 19	Montgomery	Dense	1.7~2.1 in.	New AC
4	US 31	Prattville	Dense	1.4~1.9 in.	Milled AC
5 (1)	US 280	Birmingham	OGFC	0.9~1.1 in.	Old PCC
5 (2)	US 280	Birmingham	OGFC	0.8~1.0 in.	Old PCC

Notes: OGFC = Open graded friction course; PCC = Portland cement concrete; AC = Asphalt concrete

FIGURE 24 shows the average interface bond strengths determined from the cores extracted in this study and four years ago (shortly after construction) from the five test sites constructed in the previous ALDOT study. The interface bond strength for the cores from Site No. 1, where a neat asphalt (PG 64-22) was used as the tack coat, did not increase over time. However, the bond strengths for the cores from other test sections appeared to increase over time. The most significant bond strength increase occurred in the two test sections in Site No. 5, where the high application rates of asphalt emulsion CQS-1HP were applied. However, the results from this study did not allow for determining the rate of bond strength development. Based on the bond strengths determined in this study, shown in FIGURE 24, and the performance of these test sections, it appeared that a bond strength requirement of at least 100 psi would be necessary.

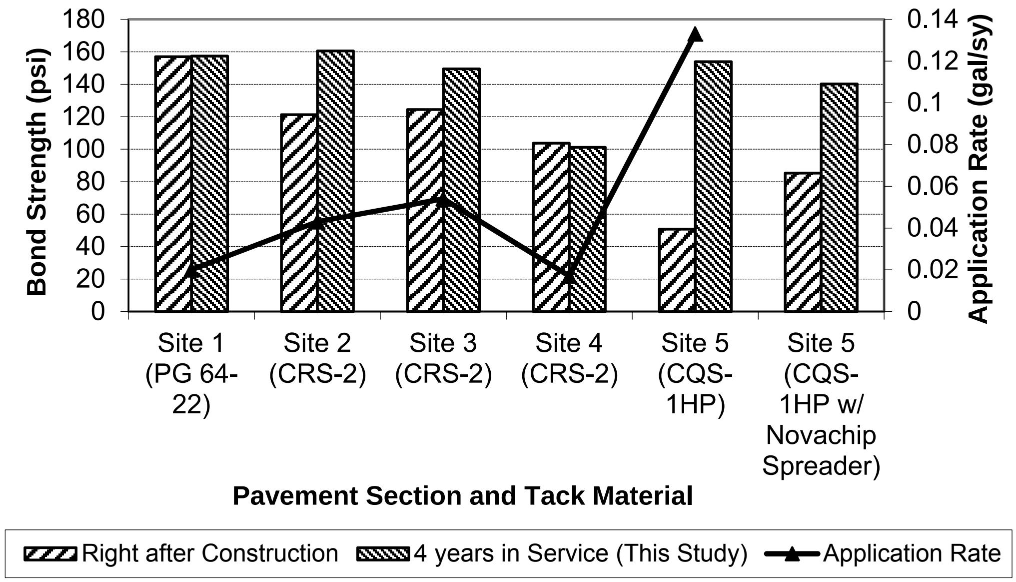


FIGURE 24 Interface Bond Strength for Five Sites Constructed in Previous Study.

3.2.2 Test Sections Exhibiting Slippage Failures

The information from the nine in-service pavement sections that exhibited slippage failures is presented in TABLE 3. FIGURE 25 includes pictures of some pavement sections showing slippage failures evaluated in this study. For each of the nine sections, the research team tried to cut four cores close to the failed areas and four cores in other areas that were in the same section but did not show slippage failures. These shoulder sections were opened for traffic during the rehabilitation of I-59, and they failed quickly due to severe slippage cracking. All the cores were then tested in the NCAT laboratory according to ALDOT-430.

The average interface bond strengths for the cores from inside and outside of the failed areas are shown in FIGURE 26. The average bond strengths of the cores extracted outside of the failed areas for all the sites (except for sites No. 6 and No. 7) were greater than 87 psi. For the cores cut inside the failed areas, the interface bond broke during coring, or the average bond strengths were much lower than 87 psi. Based on the bond strengths shown in FIGURE 26, it appears that a minimum bond strength requirement of at least 87 psi is needed.

TABLE 3 Information of Nine Sections Exhibiting Slippage Failures

Site No.	Location	City/County	Surface Layer		Notes
			Mix	Thickness	
1	US 82	Autauga	Dense	1.7~1.9 in.	*
2	SR 126	Montgomery	Dense	1.0~1.3 in.	
3	SR 22 (MP 96.5)	Rockford	Dense	1.2~1.4 in.	*
4	SR 22 (MP 93.2)	Rockford	Dense	0.7~0.9 in.	*
5	SR 22 (MP 90.6)	Rockford	Dense	1.2~1.4 in.	
6	Outside Shoulder of I-59	Etowah	Dense	1.3~2.0 in.	**
7	Inside Shoulder of I-59	Etowah	Dense	1.3~2.4 in.	**
8	AL 5 (Southbound)	Wilcox	Dense	1.1~1.6 in.	*
9	AL 5 (Northbound)	Wilcox	Dense	1.2~1.3 in.	

Notes: * All cores in the slippage areas broke during coring.
** No intact area was available at these sites. All cores extracted from failed areas. There may be other causes of failure in these sections, such as structural capacity deficiency.

FIGURE 25 Some Pavement Sections Showing Slippage Failures Evaluated in this Study.

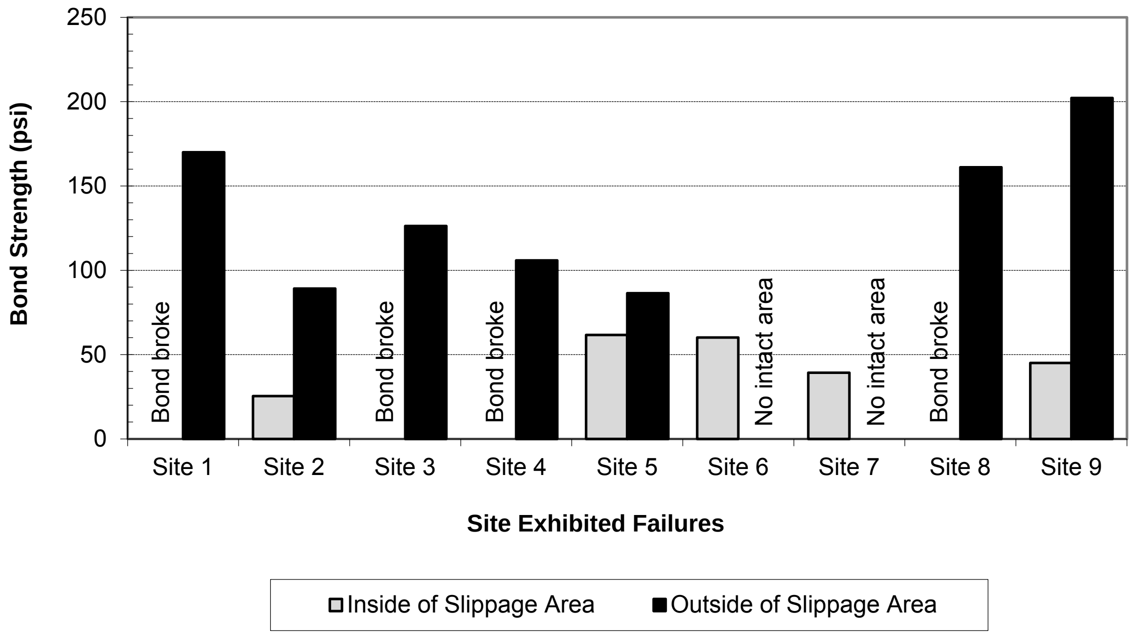


FIGURE 26 Interface Bond Strength for Nine Sites Showing Slippage Failures.

3.3 Discussion

Even though BISAR modeled static loads instead of moving loads as seen in the field, the analysis helped better understand the shear stress distribution within the AC structure. The results of the structural pavement analysis suggested that a bond strength of at least 92 psi would be necessary to maintain a good bond between the surface and binder layers when the thickness of the surface layer was 0.5 in. This interface bond strength requirement could be lower for thicker surface layers.

The evaluation of the bond strengths for the cores from the five test sites with no sign of debonding showed that the test sections had the average bond strengths greater than 100 psi. This suggested a bond strength requirement of at least100 psi for providing a good interface bond.

Based on the analysis of the bond strengths of the cores extracted inside and outside of the failed areas, the bond strengths of the cores from the intact areas were greater than 87 psi. All the cores cut inside the failed areas broke during coring or have the bonds strengths lower than 87 psi. This suggested that an interface bond strength of at least 87 psi is necessary.

The results from the above analyses showed that a minimum bond strength requirement between 87 psi and 100 psi would be necessary. Hence, a preliminary minimum bond strength requirement of 100 psi tested according to ALDOT-430 was proposed for further evaluation and use in evaluating the interface bond between the wearing and underlying layers. Even though a set of preliminary minimum bond strength requirements varied with depth may be more accurate, further evaluation and implementation would require more efforts due to the variation of the surface layer thickness.

3.4 Summary

This research conducted a structural pavement analysis and field evaluation to understand the shear stress distribution and bond strength at the interface between the wearing and binder layers with the goal of establishing a preliminary bond strength requirement. Based on the results from this research effort, the following key findings and recommendations can be offered.

- Based on the structural pavement analysis, the thickness and stiffness of wearing course as well as the variation of stiffnesses of asphalt layers due to temperature variation with depth and season, had more effects on the interface shear stress than the stiffness of the subgrade and total AC thickness.
- The maximum shear stress determined using BISAR was 92 psi for the interface at a depth of 0.5 in. The interface shear stress decreased for thicker surface layers, and it was approximately 40 psi at a depth of 2 in.
- The bond strength did not increase over time for the section in which a straight asphalt binder was used as the tack coat, but it increased over time when asphalt emulsions were used. The increase was more significant for the higher emulsion application rates.
- The lowest bond strength of approximately 100 psi was determined for the cores extracted from the test sections with no sign of delamination.
- For the test sections exhibiting slippage failures, the bond strengths of the cores from the intact areas were greater than 87 psi, and those of the cores from the failed areas were much lower than 87 psi.
- Based on the results of this research effort, a minimum bond strength requirement between 87 psi and 100 psi would be necessary. Thus, a preliminary minimum bond strength requirement of 100 psi tested according to ALDOT-430 was proposed for evaluating the interface bond between the wearing and underlying layers.
- Further evaluation of the preliminary minimum bond strength requirement may be done by continuing to assess the interface bond strength of new pavements and other in-service pavement sections that show slippage failures in the future.

CHAPTER 4 EVALUATION OF TACK COAT TYPE AND APPLICATION RATE

The purpose of this research effort was to investigate how tack coat material, application rate, surface of underlying layer, aging and traffic affect interface bond strength. This research included both laboratory testing and field work. The laboratory study included a thorough evaluation of the effect of tack coat material, application rate, receiving surface, curing time, and traffic loading on bond strength. To evaluate the effect of traffic loading on bond strength in the laboratory, specimens were loaded in an Asphalt Pavement Analyzer (APA) before they were tested for interface bond strength. The field work was conducted on a limited number of construction projects to validate results of the laboratory study. Results of the laboratory testing and field study were then analyzed to recommend tack coat materials and their appropriate application rates for future field applications.

4.1 Laboratory Study

4.1.1 Testing Plan

As previously discussed, the purpose of the laboratory study was to evaluate the effect of tack coat material, application rate, receiving surface, curing time, and traffic loading on interface bond strength. A testing plan for this study is shown in TABLE 4. The plan included five tack coats, four application rates, and three underlying layer surfaces. The five most frequently used tack coats chosen by ALDOT for this study were CRS-2, CRS-2L, CQS-1h, NTSS-1HM, and a neat asphalt binder (PG 67-22). The three underlying layer surfaces evaluated included a milled, a micro-milled, and a new HMA surface. The three undiluted spray application rates (low, medium, and high) for each tack coat are described below. The low and high undiluted application rates were selected based on the minimum and maximum application rates specified in the ALDOT specification for the three types of receiving surface. In addition, the bond strength of non-tack interface was also evaluated.

- 0.05, 0.075 and 0.1 gal/yd^2 for CRS-2, CRS-2L and CQS-1h;
- 0.04, 0.06 and 0.08 gal/yd^2 for NTSS-1HM;
- 0.03, 0.05, and 0.07 gal/yd^2 for PG 67-22; and
- No tack on the milled, micro-milled and new HMA surfaces.

TABLE 4 Experimental Plan for Laboratory Study

Tack		CRS-2			CRS-2L			CQS-1h			NTSS-1HM			PG 67-22		
Underlying Surface		Mill	Micro Mill	New HMA	Mill	Micro Mill	New HMA	Mill	Micro Mill	New HMA	Mill	Micro Mill	New HMA	Mill	Micro Mill	New HMA
Rate	Low	2		2	2		2	2		2	2		2	2		2
	Medium	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	High	2		2	2		2	2		2	2		2	2		2
	No Tack	2	2	2												
Slabs/Tack		20			14			14			14			14		
Total (Slabs)		76														
Total (Cores)		76 slabs x 6 cores/slabs = 456 cores														

For each cell in TABLE 4, two 20 in. by 20 in. slabs were each made of two HMA layers: one with no tack and one with a tack coat between the layers. Six cores were extracted from each slab, and a total of 12 cores were prepared for each cell. After extracted from the slab, three cores each were tested immediately, and three were tested after being cured for 1 and 6 months respectively. The other three cores were loaded in an Asphalt Pavement Analyzer (APA) to simulate traffic loading and then tested after being cured for 6 months.

4.1.2 Specimen Preparation and Testing

As previously discussed, each HMA slab was made of two HMA layers. The HMA in the underlying layer was a 25-mm (maximum aggregate size) mix, and the HMA in the surface layer was a 12.5-mm (maximum aggregate size) mix. It should be noted that ALDOT uses a maximum aggregate size instead of a nominal maximum aggregate size in the mix design. The 12.5-mm and 25-mm mixtures were ALDOT-approved production mixes sampled in 5-gallon buckets at the APAC Southeast, Inc. plants in Mount Meigs, Alabama, and in Tocwah, Alabama, respectively. The emulsified tack coat materials were obtained from Blacklidge Emulsions, Inc. The residual content of each emulsion was determined in accordance with ASTM D 6934-08. TABLE 5 shows the residual application rates of each tack coat material calculated based on the corresponding undiluted application rates required in the ALDOT specification and residual contents.

TABLE 5 Residual Application Rates

Tack Coat		CRS-2 (gal/yd2)		CRS-2L (gal/yd2)		CQS-1h (gal/yd2)		NTSS-1HM (gal/yd2)		PG 67-22 (gal/yd2)
		Undiluted	Residual	Undiluted	Residual	Undiluted	Residual	Undiluted	Residual	
Rate	Low	0.05	0.03	0.05	0.03	0.05	0.03	0.04	0.02	0.03
	Medium	0.075	0.05	0.075	0.05	0.075	0.05	0.06	0.03	0.05
	High	0.10	0.07	0.10	0.07	0.10	0.07	0.08	0.04	0.07

To compact a slab, three basic steps were followed. First, the 25-mm mix was reheated to the compaction temperature (approximately 300^{o}F) and used to compact the bottom layer to the target air voids of 7±1% in a kneading compactor (FIGURE 27). For the “milled” or “micro-milled” surface slabs, the receiving surface was then milled or micro-milled using a skid steer with a milling or micro-milling attachment (FIGURE 28) at the NCAT Pavement Test Track facility. Second, a tack coat was applied on the receiving surface following the tack coat supplier’s recommended temperature and setting time. Finally, the 12.5-mm mix was reheated and used to compact the surface layer on top of the non-tacked (FIGURE 29) or tack-coated receiving surface as soon as the tack coat material set. The target air voids for the surface layer were 7±1%.

Six cores 150 mm in diameter were then cut from each slab (FIGURE 30), and 12 cores were prepared for each testing combination in TABLE 4. Three sets of three cores were each tested immediately and after being cured for three and six months. The last set of three cores was loaded in an APA in accordance with AASHTO TP 63-07, except that a steel plate was placed on top of each specimen to avoid rutting, to simulate traffic loading and then was tested after being cured for 6 months. Bond strength testing was conducted in accordance with ALDOT-430, which was developed in the previous NCAT study by West et al. (*5*). A brief description of ALDOT-430 was included in Section 2.5.

FIGURE 27 Kneading Compactor for Compacting Lab Slabs.

FIGURE 28 Attachment with Two Milling Drums for Milling and Micro-Milling Slabs.

FIGURE 29 Compacting Top Layer on Non-Tacked Milled Underlying Layer Surface.

FIGURE 30 Cutting Cores from Slab.

FIGURE 31 150-mm Steel Plates Placed on Specimens to Avoid Rutting in APA Testing.

4.1.3 Results and Analysis

Detailed results of the laboratory study are presented in Appendix A. The analysis of the test results was conducted in two steps. First, a series of statistical tests was conducted across the tack coat materials tested in the laboratory study to determine the general effect of tack coat material, application rate, receiving surface, curing time, and APA loading on bond strength for all the tack coat materials evaluated in this laboratory study. Second, a graphical comparison and a statistical analysis were conducted for each tack coat material to determine the impact of application rate and receiving surface on bond strength.

Statistical Analyses Conducted across Tack Coat Materials. FIGURE 32 summarizes results of an Analysis of Variance (ANOVA) and Tukey's tests conducted across the tack coat materials to determine the general effect of four factors—tack coat material, application rate, receiving surface, and curing time—on interface bond strength at the 95% confidence level for all the tack coat materials evaluated in this laboratory study. Based on the ANOVA results, all four factors significantly affected the bond strength results.

Based on the Tukey method for grouping (or ranking) tack coat materials shown in FIGURE 32, the five tack coat materials evaluated in the laboratory study could be divided into three groups. The first group of tack coat materials that yielded higher interface bond strengths included PG 67-22, CRS-2L, and NTSS-1HM. The second group of tack coats that yielded lower bond strengths consisted of CRS-2L, NTSS-1HM, and CRS-2. The last group that yielded the lowest bond strength included only CQS-1H.

General Linear Model: Bond_Strength versus Tack, App_Rate, Surface, Curing

Factor	Type	Levels	Values
Tack	fixed	5	CQS-1H, CRS-2, CRS-2L, NTSS-1HM, PG 67-22
App_Rate	fixed	3	High, Low, Medium
Surface	fixed	2	Milled, New
Curing_Time	fixed	3	0, 1, 6

Analysis of Variance for Bond_Strength, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack	4	48956.7	48956.7	12239.2	14.22	0.000
App_Rate	2	29140.9	29140.9	14570.5	16.93	0.000
Surface	1	6525.3	6525.3	6525.3	7.58	0.007
Curing_Time	2	158572.7	158572.7	79286.4	92.11	0.000
Tack*App_Rate	8	70600.6	70600.6	8825.1	10.25	0.000
Tack*Surface	4	23242.3	23242.3	5810.6	6.75	0.000
Tack*Curing_ Time	8	167784.8	167784.8	20973.1	24.36	0.000
App_Rate*Surface	2	42169.8	42169.8	21084.9	24.49	0.000
App_Rate*Curing_ Time	4	19026.0	19026.0	4756.5	5.53	0.000
Surface*Curing_ Time	2	56916.2	56916.2	28458.1	33.06	0.000
Tack*App_Rate*Surface	8	38919.9	38919.9	4865.0	5.65	0.000
Tack*App_Rate*Curing_ Time	16	48259.4	48259.4	3016.2	3.50	0.000
Tack*Surface*Curing_ Time	8	81925.0	81925.0	10240.6	11.90	0.000
App_Rate*Surface*Curing_ Time	4	9463.4	9463.4	2365.8	2.75	0.003
Tack*App_Rate*Surface*Curing_ Time	16	40750.6	40750.6	2546.9	2.96	0.000
Error	180	154941.9	154941.9	860.8		
Total	269	997195.3				

S = 29.3392   R-Sq = 84.46%   R-Sq(adj) = 76.78%

Grouping Information Using Tukey Method and 95.0% Confidence

Tack	N	Mean	Grouping
PG 67-22	54	215.9	A
CRS-2L	54	206.4	A B
NTSS-1HM	54	202.8	A B
CRS-2	54	195.2	B
CQS-1H	54	175.8	C

Curing_Time	N	Mean	Grouping
6	90	230.2	A
1	90	196.4	B
0	90	171.0	C

App_Rate	N	Mean	Grouping
Medium	90	213.8	A
Low	90	193.1	B
High	90	190.6	B

Surface	N	Mean	Grouping
Milled	135	204.1	A
New	135	194.3	B

App_Rate	Surface	N	Mean	Grouping
Medium	Milled	45	221.6	A
High	Milled	45	209.2	A
Medium	New	45	206.0	A
Low	New	45	204.8	A
Low	Milled	45	181.5	B
High	New	45	172.0	B

Means that do not share a letter are significantly different.

FIGURE 32 Effect of Tack, Application Rate, Surface, and Curing Time on Bond Strength.

In terms of the application rate, the medium application rates generally yielded statistically higher bond strengths, as shown in FIGURE 32. The low and high application rates were in the second group that yielded lower bond strengths. With respect to the receiving surface, the milled surface yielded statistically higher bond strengths than the new surface. In addition, on the milled surface, the medium and high application rates yielded higher bond strengths than the low application rate. However, on the new surface, the medium and low application rates yielded higher bond strengths than the high application rate. This suggested that the application rate should be higher on a milled surface than on a new surface.

As shown in FIGURE 32, the curing time also significantly affected bond strength—the longer the curing time, the higher bond strength. However, a further investigation of this effect for each tack coat showed that the curing time significantly affected bond strength for the four emulsions—CRS-2, CRS-2L, CQS-1H, and NTSS-1HM—but did not significantly affect bond strength for PG 67-22 and non-tack surfaces.

Since APA-loaded specimens were tested after they had been cured for 6 months and the micro-milled surface was tested at the medium application rate only, separate statistical analyses were conducted to determine the effect of APA loading and micro-milled surface on bond strength. FIGURE 33 summarizes a statistical analysis to determine the effect of APA loading. It should be noted that the effect of three factors—tack coat material, application rate, receiving surface—have been discussed earlier; thus, only the grouping information for APA loading is shown in FIGURE 33. Based on the Tukey grouping method at the 95% confidence level, the bond strengths of APA-loaded specimens were statistically lower than those of specimens that had not been loaded in APA.

General Linear Model: Bond_Strength versus Tack, App_Rate, Surface, APA_Loading

Factor	Type	Levels	Values
Tack	fixed	5	CQS-1H, CRS-2, CRS-2L, NTSS-1HM, PG67-22
App_Rate	fixed	3	High, Low, Medium
Surface	fixed	2	Milled, New
APA_Loading	fixed	2	N, Y

Grouping Information Using Tukey Method and 95.0% Confidence

APA_Loading	N	Mean	Grouping	
N	90	230.2	A	
Y	90	218.3		B

Means that do not share a letter are significantly different.

FIGURE 33 Effect of APA Loading on Bond Strength.

FIGURE 34 shows a summary of a statistical analysis to evaluate the effect of three receiving surface types (new, milled and micro-milled) at the medium application rate. Based on the Tukey grouping method at the 95% confidence level, the micro-milled surface yielded statistically higher bond strengths, followed by the milled surface and, finally, the new surface.

General Linear Model: Bond_Strength versus Tack, Surface, Curing Time

Factor	Type	Levels	Values
Tack	fixed	5	CQS-1H, CRS-2, CRS-2L, NTSS-1HM, PG67-22
Surface	fixed	3	Micromilled, Milled, New
Curing_Time	fixed	2	0, 6

Analysis of Variance for Bond_Strength_2, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tack	4	90148	90148	22537	21.67	0.000
Surface	2	43201	43201	21600	20.77	0.000
Curing_Time	1	92126	92126	92126	88.59	0.000
Tack_2*Surface	8	24083	24083	3010	2.89	0.009
Tack_2*Curing_Time	4	28047	28047	7012	6.74	0.000
Surface_2*Curing_Time	2	7369	7369	3685	3.54	0.035
Tack_2*Surface_2*Curing_Time	8	64358	64358	8045	7.74	0.000
Error	60	62395	62395	1040		
Total	89	411727				

S = 32.2477   R-Sq = 84.85%   R-Sq(adj) = 77.52%

Grouping Information Using Tukey Method and 95.0% Confidence

Surface	N	Mean	Grouping
Micromilled	30	269.5	A
Milled	30	241.4	B
New	30	215.8	C

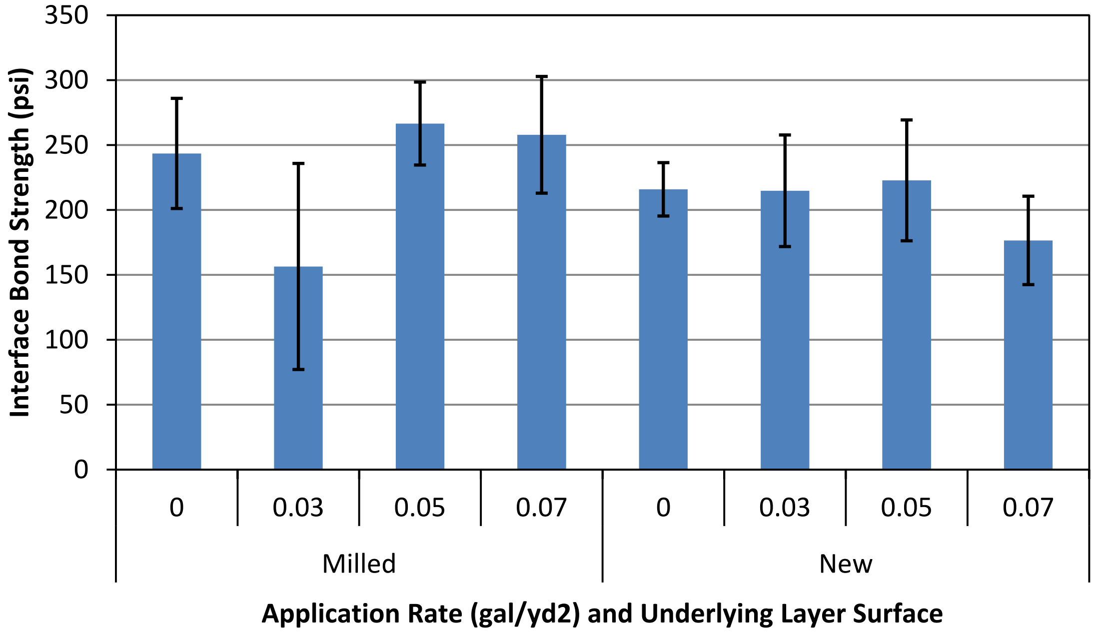
Means that do not share a letter are significantly different.

FIGURE 34 Effect of Milled and Micro-Milled Surfaces on Bond Strength.

Graphical Comparison and Statistical Analysis Conducted for Each Tack Coat. In the second series of analyses, a graphical comparison and a statistical analysis were conducted for each tack coat material to determine the impact of application rate and receiving surface on bond strength. FIGURE 35 through FIGURE 39 show the graphical comparisons of average bond strength results and standard deviations, and the results of statistical analyses. Based on the analysis results, the following observations can be made.

- The non-tack surfaces appeared to yield the highest or second-highest bond strengths for all the tack coats tested in this study. However, these results should be viewed with caution because the receiving surfaces were well-cleaned in the laboratory study; these results should be validated with results from the field study presented later in this report.
- The medium application rates yielded statistically higher bond strengths than the low and high application rates for PG 67-22, NTSS-1HM, and CQS-1H. For other tack coats (CRS-2 and CRS-2L), the medium application rates yielded higher average (but not statistically higher) bond strengths.
- Based on the Tukey grouping method at the 95% confidence level, the milled receiving surface yielded statistically higher bond strengths for PG 67-22, CRS-2L, and CRS-2 when compared with the new receiving surface. For other tack coat materials (NTSS-1HM and CQS-1H), the two surfaces did not yield statistically different bond strengths.

- As discussed in the first series of analyses, for the milled receiving surfaces, the medium and high application rates generally yielded higher bond strengths than the low application rate. However, for the new receiving surfaces, the medium and low application rates generally yielded higher bond strengths than the high application rate.



General Linear Model: Bond_Strength versus App_Rate, Surface, Curing

Factor	Type	Levels	Values
App_Rate	fixed	4	0.00, 0.03, 0.05, 0.07
Surface	fixed	2	Milled, New
Curing	fixed	3	0, 1, 6

Grouping Information Using Tukey Method and 95.0% Confidence

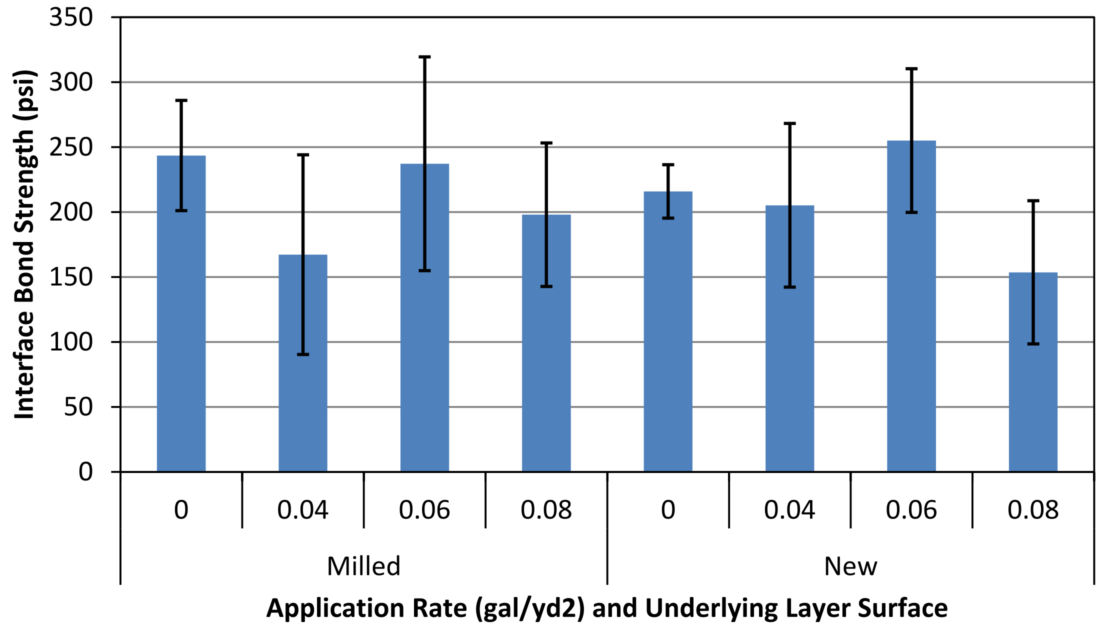
App_Rate	N	Mean	Grouping
0.05	18	244.7	A
0.00	18	229.7	A B
0.07	18	217.2	B
0.03	18	185.7	C

Surface	N	Mean	Grouping
Milled	36	231.1	A
New	36	207.5	B

Surface	App_Rate	N	Mean	Grouping
Milled	0.05	9	266.6	A
Milled	0.07	9	257.9	A B
Milled	0.00	9	243.6	A B
New	0.05	9	222.8	A B
New	0.00	9	215.9	B C
New	0.03	9	214.8	B C
New	0.07	9	176.5	C D
Milled	0.03	9	156.5	D

Means that do not share a letter are significantly different.

FIGURE 35 Effect of Application Rate and Surface Condition on PG 67-22 Bond Strength.



General Linear Model: Bond_Strength versus App_Rate, Surface, Curing

Factor	Type	Levels	Values
Surface	fixed	2	Milled, New
App_Rate	fixed	4	0.00, 0.04, 0.06, 0.08
Curing	fixed	3	0, 1, 6

Grouping Information Using Tukey Method and 95.0% Confidence

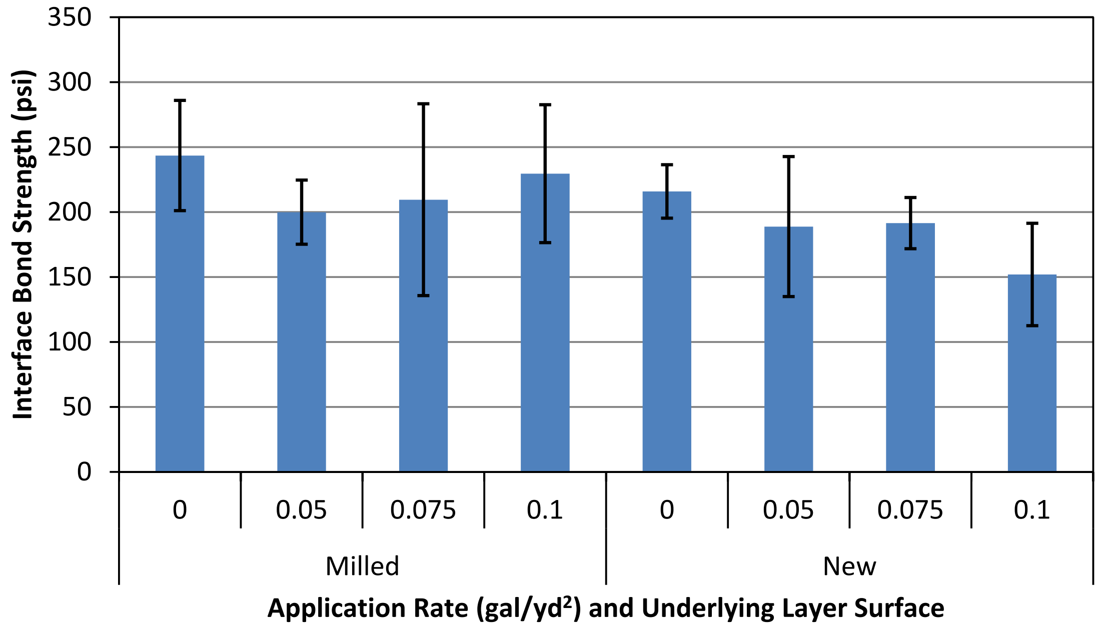
App_Rate	N	Mean	Grouping
0.06	18	246.2	A
0.00	18	229.7	A
0.04	18	186.3	B
0.08	18	175.8	B

Surface	N	Mean	Grouping
Milled	36	211.5	A
New	36	207.5	A

Surface	App_Rate	N	Mean	Grouping
New	0.06	9	255.1	A
Milled	0.00	9	243.6	A B
Milled	0.06	9	237.2	A B
New	0.00	9	215.9	A B C
New	0.04	9	205.2	A B C D
Milled	0.08	9	198.0	B C D
Milled	0.04	9	167.3	C D
New	0.08	9	153.7	D

Means that do not share a letter are significantly different.

FIGURE 36 Effect of Application Rate and Surface on NTSS-1HM Bond Strength.



General Linear Model: Bond_Strength versus App_Rate, Surface, Curing

Factor	Type	Levels	Values
Surface	fixed	2	Milled, New
App_Rate	fixed	4	0.00, 0.050, 0.075, 0.100
Curing	fixed	3	0, 1, 6

Grouping Information Using Tukey Method and 95.0% Confidence

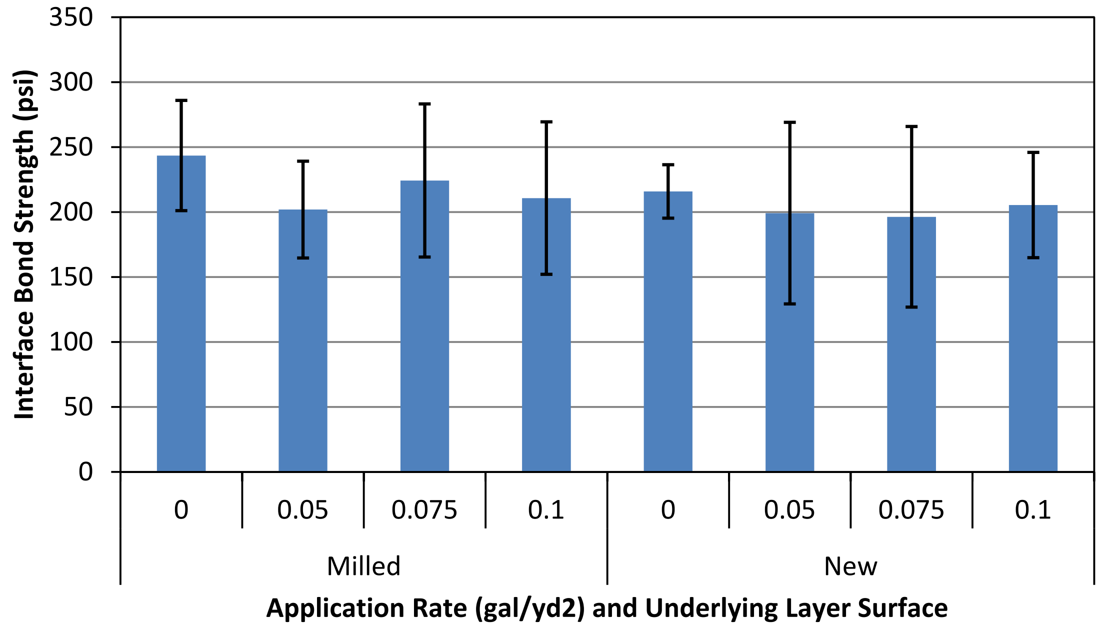
App_Rate	N	Mean	Grouping
0.000	18	229.7	A
0.075	18	200.5	B
0.050	18	194.4	B
0.100	18	190.8	B

Surface	N	Mean	Grouping
Milled	36	220.7	A
New	36	187.1	B

Surface	App_Rate	N	Mean	Grouping
Milled	0.000	9	243.6	A
Milled	0.100	9	229.6	A B
New	0.000	9	215.9	A B
Milled	0.075	9	209.5	A B
Milled	0.050	9	200.0	B
New	0.075	9	191.5	B C
New	0.050	9	188.9	B C
New	0.100	9	152.0	C

Means that do not share a letter are significantly different.

FIGURE 37 Effect of Application Rate and Surface on CRS-2L Bond Strength.



General Linear Model: Bond_Strength versus App_Rate, Surface, Curing

Factor	Type	Levels	Values
Surface	fixed	2	Milled, New
App_Rate	fixed	4	0.00, 0.050, 0.075, 0.100
Curing	fixed	3	0, 1, 6

Grouping Information Using Tukey Method and 95.0% Confidence

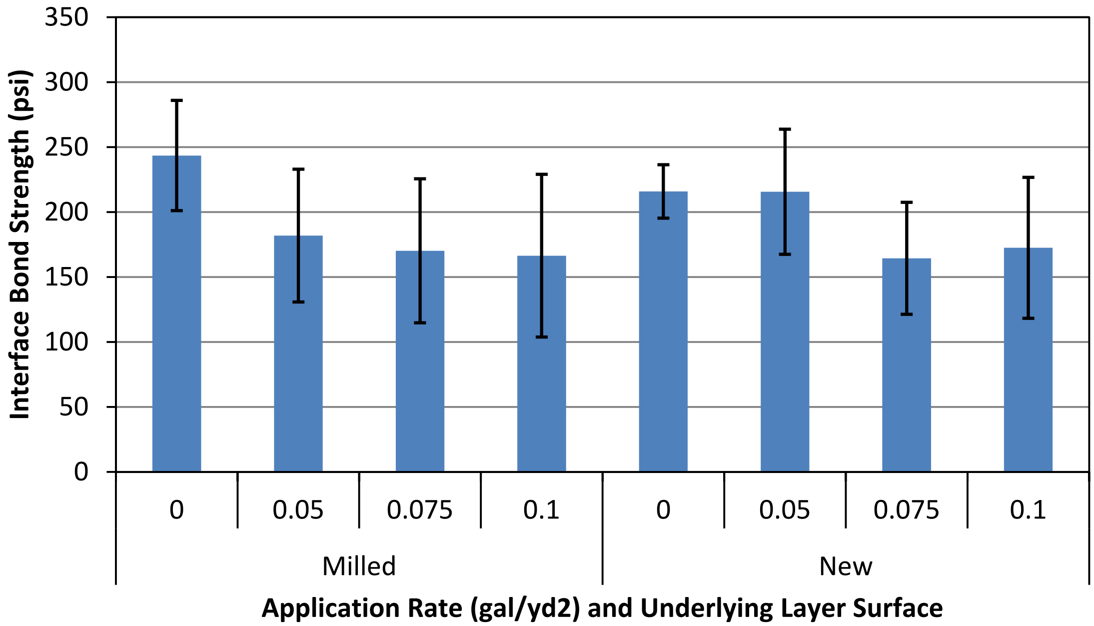
App_Rate	N	Mean	Grouping
0.000	18	229.7	A
0.075	18	210.4	A B
0.100	18	208.1	A B
0.050	18	200.6	B

Surface	N	Mean	Grouping
Milled	36	220.2	A
New	36	204.2	B

Surface	App_Rate	N	Mean	Grouping
Milled	0.000	9	243.6	A
Milled	0.075	9	224.3	A B
New	0.000	9	215.9	A B
Milled	0.100	9	210.8	A B
New	0.100	9	205.4	A B
Milled	0.050	9	202.0	A B
New	0.050	9	199.2	A B
New	0.075	9	196.4	B

Means that do not share a letter are significantly different.

FIGURE 38 Effect of Application Rate and Surface on CRS-2 Bond Strength.



General Linear Model: Bond_Strength versus App_Rate, Surface, Curing

Factor	Type	Levels	Values
Surface	fixed	2	Milled, New
App_Rate	fixed	4	0.00, 0.050, 0.075, 0.100
Curing	fixed	3	0, 1, 6

Grouping Information Using Tukey Method and 95.0% Confidence

App_Rate	N	Mean	Grouping
0.000	18	229.7	A
0.050	18	198.8	B
0.100	18	169.5	C
0.075	18	167.3	C

Surface	N	Mean	Grouping
New	36	192.1	A
Milled	36	190.5	A

Surface	App_Rate	N	Mean	Grouping
Milled	0.000	9	243.6	A
New	0.000	9	215.9	A B
New	0.050	9	215.7	A B
Milled	0.050	9	181.9	B C
New	0.100	9	172.5	C
Milled	0.075	9	170.2	C
Milled	0.100	9	166.5	C
New	0.075	9	164.4	C

Means that do not share a letter are significantly different.

FIGURE 39 Effect of Application Rate and Surface on CQS-1H Bond Strength.

4.2 Field Study

4.2.1 Testing Plan

The field work was conducted on a limited number of construction sites to validate the results of the laboratory study presented earlier. The proposed testing plan consisted of 12 test sites. Ten sites would be used to test the five tack coat materials evaluated in the laboratory study on new and milled surfaces, and two sites would be used to evaluate one or two tack coat materials on micro-milled surfaces.

With the assistance from ALDOT, the research team was able to find good project candidates for this study. However, most of these projects used either NTSS-1HM or CQS-1H, and no contractor in Alabama had access to a micro-milling drum or used CRS-2L as a tack coat during the course of this study. Therefore, the final experimental plan for this project, as shown in TABLE 6, consisted of more construction projects using NTSS-1HM and CQS-1H and no projects for evaluating CRS-2L and micro-milling. In addition, two test sections without tack coat on a new receiving surface [S9(T)] and on a milled surface [S9(B)] were constructed in the inside lane of the test track.

TABLE 6 Test Sites for Field Study

Site No.	Tack	City	Road*	Surface	Northing		Westing	
					Deg.	Min.	Deg.	Min.
1	PG 67-22	Midway	US 82(T)	New	N 32	04.714'	W 85	31.285'
2	PG 67-22	Opelika	Track/S6(B) Inside	Milled	N 32	35.703'	W 85	18.211'
3	NTSS-1HM	Opelika	Track/S9(T) Inside	New	N 32	35.705'	W 85	18.097'
4	NTSS-1HM	Mobile	SR 193(T)	New	N 30	33.864'	W 88	07.735'
5	NTSS-1HM	Montgomery	US 80(T)	Milled	N 32	22.082'	W 86	04.720'
6	NTSS-1HM	Opelika	Track/S9(B) Inside	Milled	N 32	35.705'	W 85	18.097'
7	CQS-1H	Opp	US 331(T)	New	N 31	22.745'	W 86	16.313'
8	CQS-1H	Seale	US 431(T)	New	N 32	16.199'	W 85	09.935'
9	CQS-1H	Selma	US 80(T)	Milled	N 32	22.394'	W 87	00.466'
10	CRS-2	Montgomery	US 80(T)	New	N 32	21.930'	W 86	02.596'

*(B) = Interface between leveling course and milled receiving surface; (T) = interface between surface course and new/milled receiving surface.

For each test site shown in TABLE 6, only one tack coat material was used for the paving job, and three test sections were constructed for three target application rates corresponding to the tack coat material used (TABLE 7). The application rate used in each test section was measured in accordance with ASTM D 2995. Three cores were then cut from each test section right after construction, and three more cores each were extracted after 3 and 6 months in service for testing in accordance with ALDOT Procedure 430 (ALDOT-430), developed in the previous NCAT study by West et al. (*5*).

TABLE 7 Target Application Rates for Each Tack Coat Material

Level	Target Application Rate (gal/yd^2)				
	PG 67-22	CRS-2	CRS-2L	CQS-1H	NTSS-1HM
No Tack*	0	0	0	0	0
Low Rate	0.03	0.05	0.05	0.05	0.04
Medium Rate	0.05	0.075	0.075	0.075	0.06
High Rate	0.07	0.10	0.10	0.10	0.08

* Non-tack sections were constructed in the inside lane of the test track.

4.2.2 Field Work

With assistance from the ALDOT field engineers and the NCAT Pavement Test Track staff, the research team was able to construct three test sections in each test site. Two test sections without tack coat on new and milled surfaces were constructed in the inside lane of the test track.

For each test site, the field work consisted of several steps. First, after discussing with the paving crew, the research team marked the locations of three 500-ft test sections (FIGURE 40). Geotextile pads, which had been numbered and weighed in the laboratory, were setup in each test section (FIGURE 41) to measure the application rate in accordance with ASTM D 2995. Third, after the tack coat had been applied (FIGURE 42), the pads were removed and were later dried out and weighed in the laboratory to measure the application rate in each section. The research team also obtained a sample of the tack material used in each paving project to determine the residue in accordance with ASTM D 6934-04. Based on the results of ASTM D 2995 and ASTM D 6934-04, the spraying and residual application rates for each section were determined. Finally, after the paving mat was cooled down and before the test site was opened to the traffic, three 6-in. cores were extracted from each test section. Three more cores were later extracted from each test section after 3 and 6 months in service. All the core locations were chosen close to the centerline of the paving lane. The cores were then tested in the laboratory in accordance with ALDOT-430.

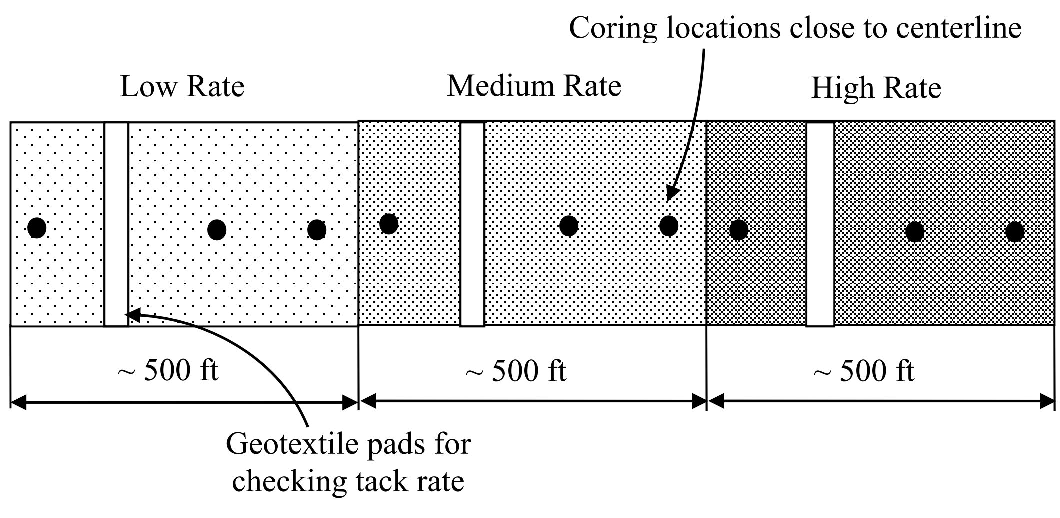


FIGURE 40 Layout of Three Test Sections for Each Test Site.

FIGURE 41 Installing Geotextile Pads for Measuring Application Rate.

FIGURE 42 Installing Geotextile Pads for Measuring Application Rate.

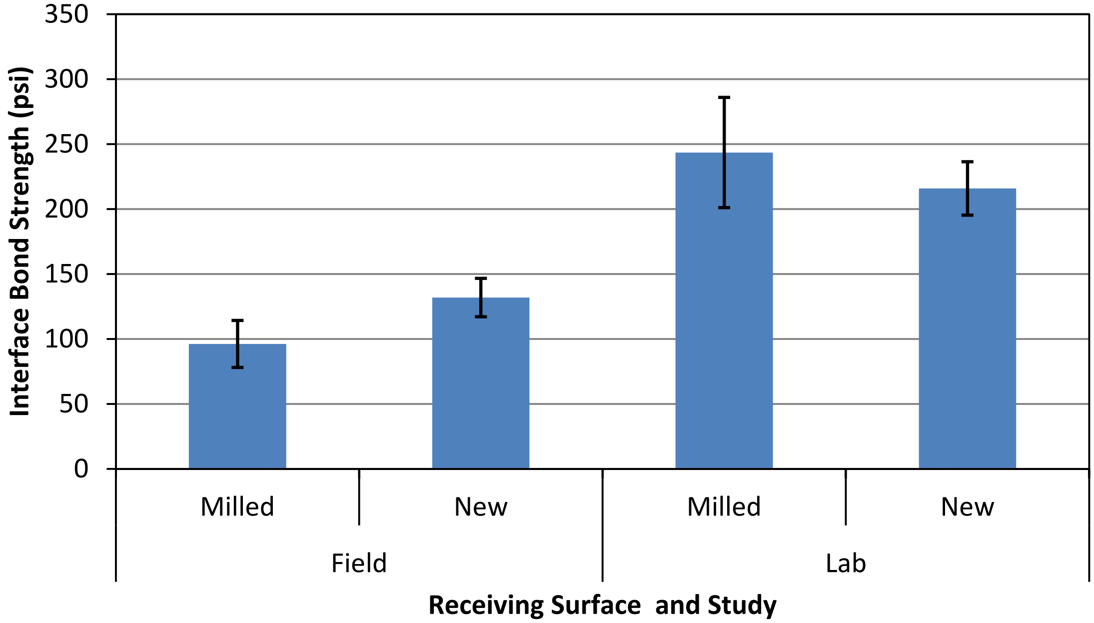
4.2.3 Results and Analysis

Detailed results of the field evaluation are presented in Appendix B. The analysis of field study results was conducted for each tack coat material tested in the field study (TABLE 6). Then, the field study results for each tack coat were compared with the laboratory study results. As discussed earlier, the CRS-2L tack coat material and the micro-milling surface were not evaluated in the field study.

Non-Tack Receiving Surfaces. FIGURE 43 compares the lab and field test results for non-tack receiving surfaces. The two non-tack test sections [S9(T) and S9(B)] were constructed in the inside lane of the test track. Based on the statistical analysis at the 95% confidence level, the bond strengths determined from the field cores were statistically lower than those determined from the lab cores. The receiving surface did not significantly affect the lab results. However, it significantly affected the field results; the new surface yielded statistically higher bond strengths. It should be noted that while the field results were lower than the lab results, they were equal or higher than the bond strength criterion of 100 psi recommended in the previous chapter. However, it is not known if the bond strength can be maintained at this level if water is present at the interface, as shown in FIGURE 5. The curing time was not a significant factor when no tack coat was used for both the laboratory and field study results.

PG 67-22 Tack Coat. FIGURE 44 compares the field study results of PG 67-22 tack coat on the new and milled surfaces. For the milled surface, the four application rates yielded significantly different bond strengths. The highest bond strength was obtained at the highest application rate (0.064 gal/yd^2) tested, and the lowest bond strength was obtained when no tack was applied on the milled surface. For the new receiving surface, the results could be divided into three groups. The first group that yielded higher test results included those obtained at the highest (0.063 gal/yd^2) and second-highest (0.047 gal/yd^2) application rates tested. The second group that yielded lower bond strengths included those obtained at the second-highest and the lowest tack application rate (0.025 gal/yd^2). The last group that had the lowest bond strength was obtained from the non-tack interfaces.

FIGURE 45 compares the bond strength results determined from the laboratory and field studies for the PG 67-22 tack coat. It should be noted that the field application rates did not match those used in the laboratory study exactly. However, there was a good agreement between the laboratory and field study results. The minimum and maximum application rates (0.03 and 0.07 gal/yd^2) specified in the ALDOT specification appear to be reasonable for the new surface. However, the application rates for the milled surface should be higher; based on the test results, it is recommended that the minimum and maximum application rates be 0.05 and 0.09 gal/yd^2, respectively.



General Linear Model: Bond_Strength versus Study, Surface, Curing_Time

Factor	Type	Levels	Values
Study	fixed	2	Field, Lab
Surface	fixed	2	Milled, New
Curing_Time	fixed	3	0, 3, 6

Analysis of Variance for Bond_Strength, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Study	1	120423	120423	120423	173.43	0.000
Surface	1	146	146	146	0.21	0.651
Curing_Time	2	1385	1385	693	1.00	0.384
Study*Surface	1	9034	9034	9034	13.01	0.001
Study*Curing_Time	2	2131	2131	1066	1.53	0.236
Surface*Curing_Time	2	465	465	233	0.34	0.719
Study*Surface*Curing_Time	2	1502	1502	751	1.08	0.355
Error	24	16665	16665	694		
Total	35	151750				

S = 26.3508   R-Sq = 89.02%   R-Sq(adj) = 83.99%

Grouping Information Using Tukey Method and 95.0% Confidence

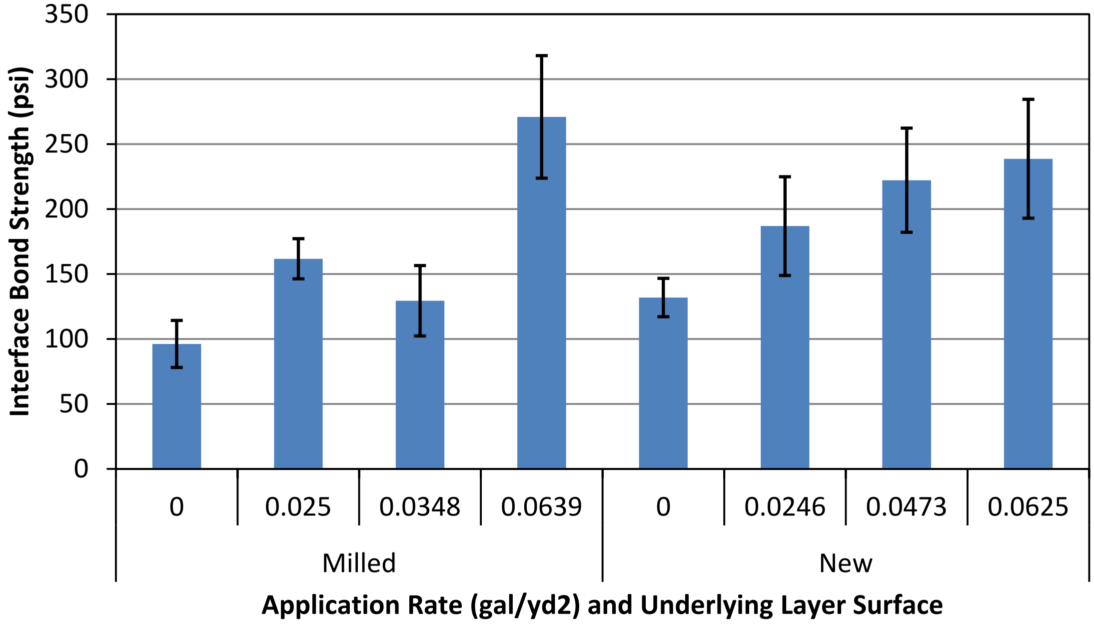
Study	N	Mean	Grouping
Lab	18	229.7	A
Field	18	114.1	B

Study	Surface	N	Mean	Grouping
Lab	Milled	9	243.6	A
Lab	New	9	215.9	A
Field	New	9	131.9	B
Field	Milled	9	96.2	C

Study	Curing_Time	N	Mean	Grouping
Lab	3	6	243.9	A
Lab	6	6	225.2	A
Lab	0	6	220.2	A
Field	6	6	127.5	B
Field	3	6	108.6	B
Field	0	6	106.1	B

Means that do not share a letter are significantly different.

FIGURE 43 Comparing Lab and Field Results for Non-Tack Surfaces.



General Linear Model: Milled Receiving Surface

```
Factor        Type   Levels  Values
App_Rate      fixed       4  0.0000, 0.0250, 0.0348, 0.0639
Curing_Time   fixed       3  0, 3, 6

Grouping Information Using Tukey Method and 95.0% Confidence

App_Rate  N   Mean  Grouping
0.0639    9  271.0  A
0.0250    9  161.8    B
0.0348    9  129.5      C
0.0000    9   96.2        D

Means that do not share a letter are significantly different.
```

General Linear Model: New Receiving Surface

```
Factor        Type   Levels  Values
App_Rate      fixed       4  0.0000, 0.0246, 0.0473, 0.0625
Curing_Time   fixed       3  0, 3, 6

Grouping Information Using Tukey Method and 95.0% Confidence

App_Rate  N   Mean  Grouping
0.0625    9  238.7  A
0.0473    9  222.2  A B
0.0246    9  186.9    B
0.0000    9  131.9      C

Means that do not share a letter are significantly different.
```

FIGURE 44 Analysis of Field Results for PG 67-22 Tack Coat.

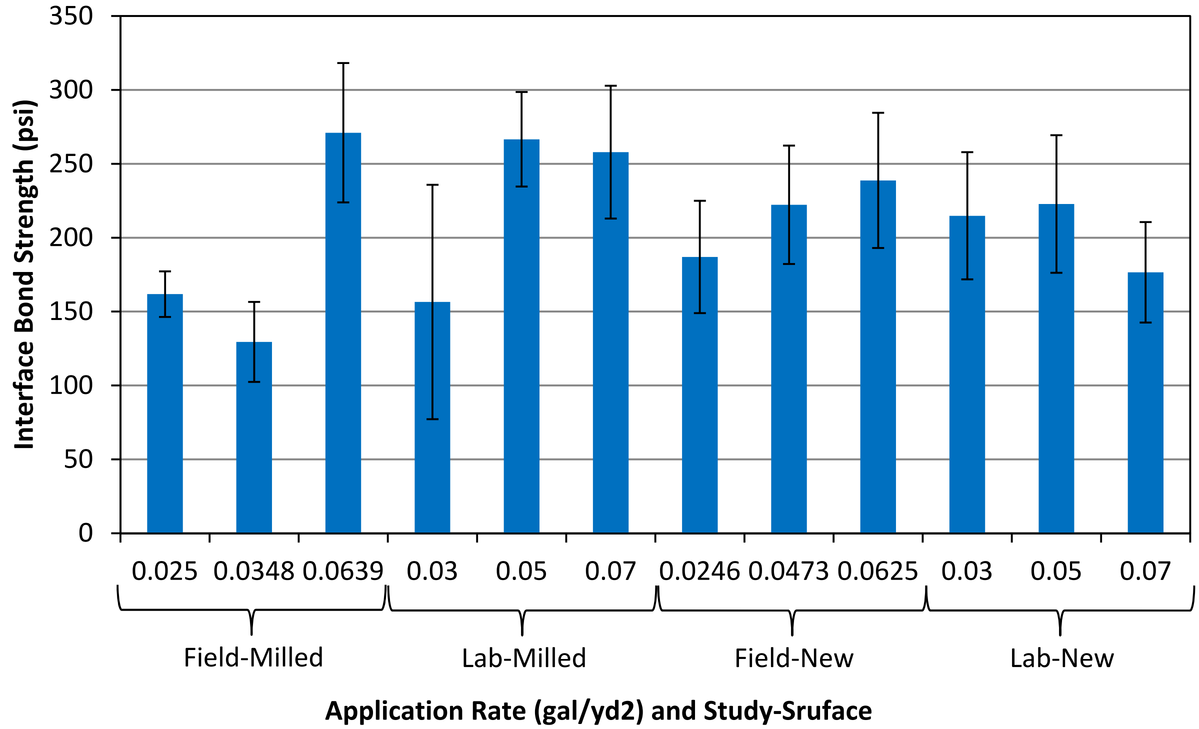
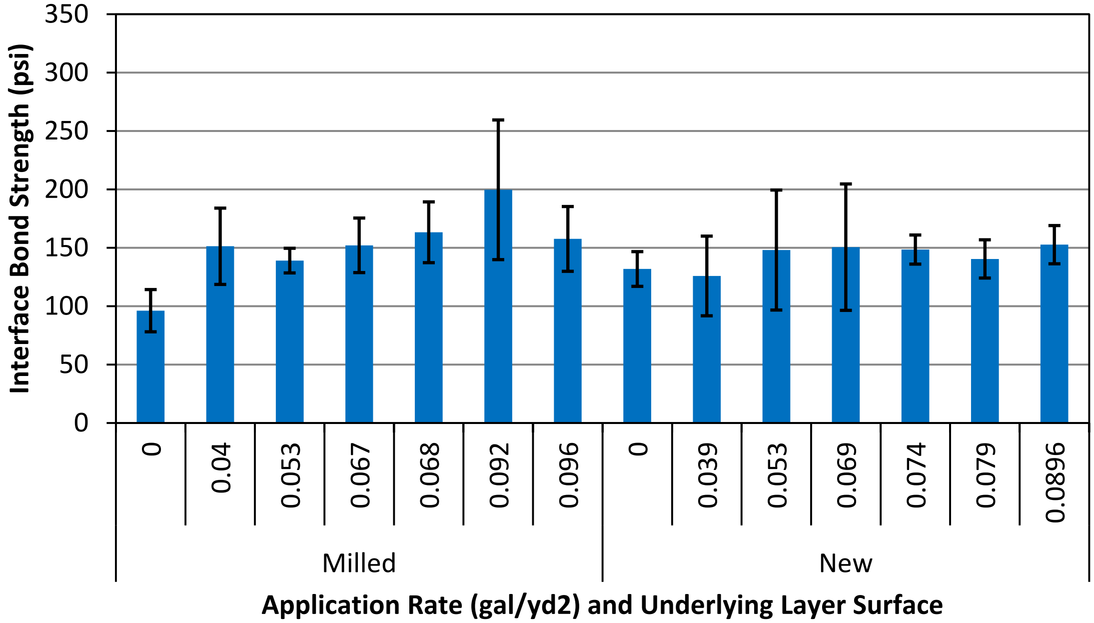


FIGURE 45 Comparing Lab and Field Results for PG 67-22 Tack Coat.

NTSS-1HM Tack Coat. FIGURE 46 compares the field study results of NTSS-1HMA tack coat on the new and milled surfaces. As for the PG 67-22 tack coat, the statistical analyses were conducted separately for the milled and new surfaces. For the milled surface, the bond strengths at 0.092 gal/sy^2 and for the non-tack surface were significantly higher and lower than the results obtained at the other application rates. For the new receiving surface, the bond strengths at different application rates were not significantly different. As seen in the laboratory study results, the curing time significantly affected bond strength. However, the difference in the bond strengths measured after 3 and 6 months was not statistically significant.

FIGURE 47 compares the bond strength results determined from the laboratory and field studies for the NTSS-1HM tack coat. As for the PG 67-22 tack coat, there was a good agreement between the laboratory and field study results for the milled surface. However, for the new surface, the laboratory study results appeared to be higher than the field study results. The minimum and maximum application rates (0.04 and 0.08 gal/sy^2) specified in the ALDOT specification seem to be reasonable for the new surface. However, for the milled surface, the higher application rates appeared to yield higher bond strengths. Thus, it is recommended that the minimum and maximum application rates be increased to 0.06 and 0.1 gal/sy^2, respectively.



General Linear Model: Milled Receiving Surface

Factor	Type	Levels	Values
App_Rate	fixed	7	0.000, 0.040, 0.053, 0.067, 0.068, 0.092, 0.096
Curing_Time	fixed	3	0, 3, 6

Grouping Information Using Tukey Method and 95.0% Confidence

App_Rate	N	Mean	Grouping
0.092	9	199.7	A
0.068	9	163.3	B
0.096	9	157.7	B
0.067	9	152.1	B
0.040	9	151.4	B
0.053	9	139.1	B
0.000	9	96.2	C

Curing_Time	N	Mean	Grouping
6	21	170.0	A
3	21	159.5	A
0	21	138.6	B

General Linear Model: New Receiving Surface

Factor	Type	Levels	Values
App_Rate	fixed	7	0.0000, 0.0390, 0.0530, 0.0690, 0.0740, 0.0790, 0.0896
Curing_Time	fixed	3	0, 3, 6

Grouping Information Using Tukey Method and 95.0% Confidence

App_Rate	N	Mean	Grouping
0.0896	9	152.7	A
0.0690	9	150.6	A
0.0740	9	148.6	A
0.0530	9	148.1	A
0.0790	9	140.5	A
0.0000	9	131.9	A
0.0390	9	125.9	A

Curing_Time	**N**	**Mean**	**Grouping**
6	21	159.8	A
3	21	145.2	A B
0	21	127.8	B

Means that do not share a letter are significantly different.

FIGURE 46 Analysis of Field Results for NTSS-1HM Tack Coat.

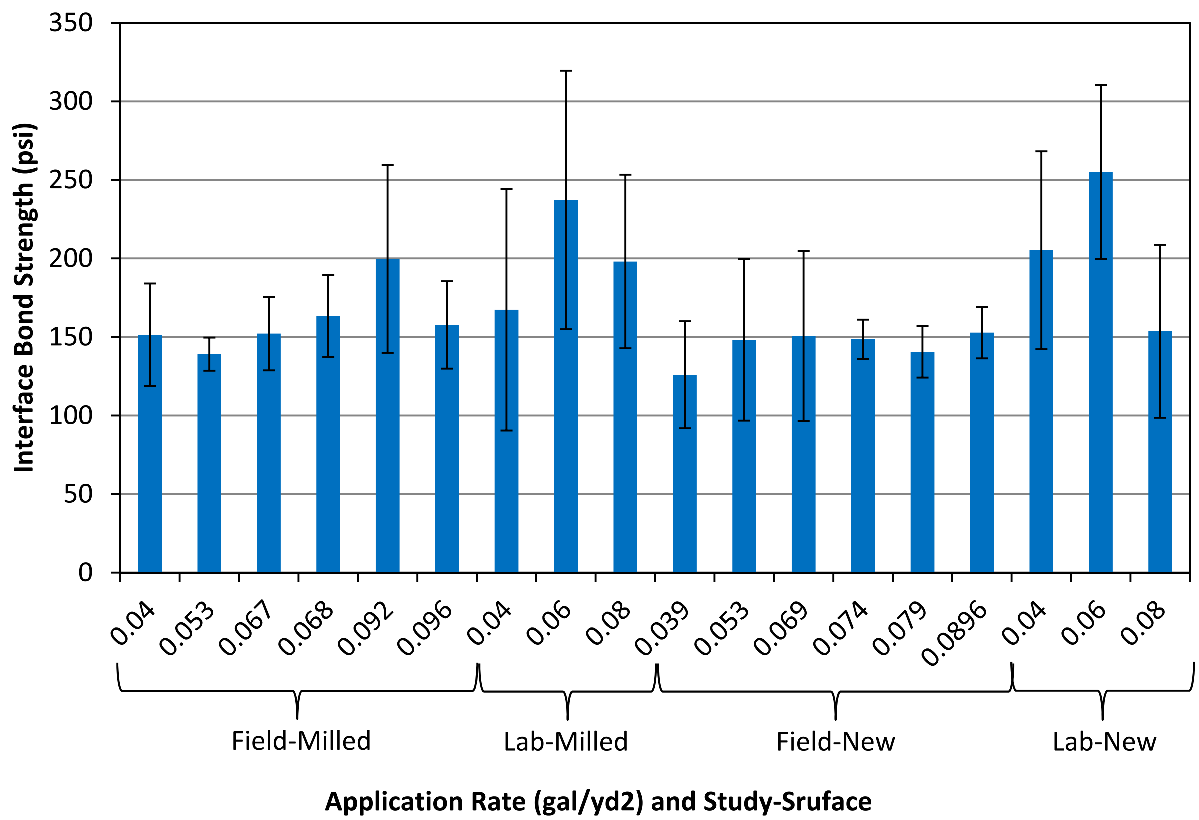
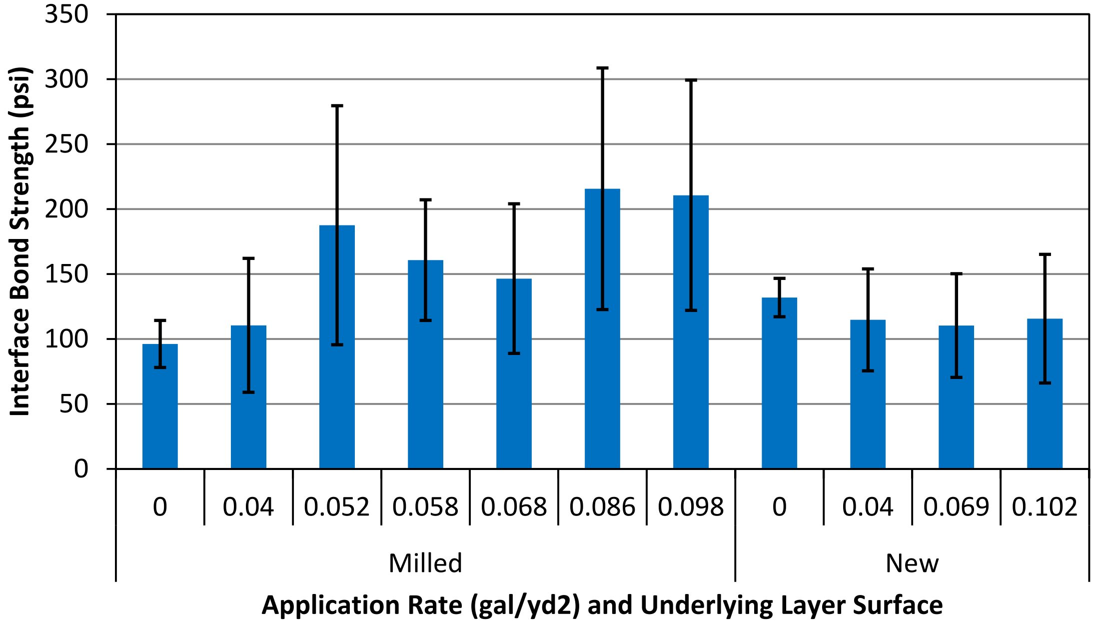


FIGURE 47 Comparing Lab and Field Results for NTSS-1HM Tack Coat.

CQS-1H Tack Coat. FIGURE 48 compares the field study results of CQS-1H tack coat on the new and milled surfaces. For the milled surface, use of the CQS-1H tack coat appeared to increase the bond strength. However, for the new surface, use of the CQS-1H tack coat did not make a significant difference in the bond strength. The bond strength increased significantly in the first 3 months in service but did not increase significantly after that time.

FIGURE 49 compares the bond strength results determined from the laboratory and field studies for the CQS-1H tack coat. There was a good agreement between the laboratory and field study results for the milled surfaces. However, for the new surfaces, the laboratory study results appeared to be higher than the field study results. The minimum and maximum application rates (0.05 and 0.1 gal/yd^2) specified in the ALDOT specification seem to be reasonable for both the new and milled surfaces.



General Linear Model: Milled Receiving Surface

Factor	Type	Levels	Values
App_Rate	fixed	7	0.000, 0.040, 0.052, 0.058, 0.068, 0.086, 0.098
Curing_Time	fixed	3	0, 3, 6

Grouping Information Using Tukey Method and 95.0% Confidence

App_Rate	N	Mean	Grouping
0.086	9	215.7	A
0.098	9	210.7	A B
0.052	9	187.6	A B C
0.058	9	160.8	B C D
0.068	9	146.5	C D E
0.040	9	110.5	D E
0.000	9	96.2	E

Curing_Time	N	Mean	Grouping
6	21	199.4	A
3	21	191.7	A
0	21	92.3	B

Means that do not share a letter are significantly different.

General Linear Model: New Receiving Surface

Factor	Type	Levels	Values
App_Rate_1	fixed	4	0.000, 0.040, 0.069, 0.102
Curing_Time_1	fixed	3	0, 3, 6

Grouping Information Using Tukey Method and 95.0% Confidence

App_Rate_1	N	Mean	Grouping
0.000	9	131.9	A
0.102	9	115.7	A
0.040	9	114.8	A
0.069	9	110.4	A

Curing_Time_1	N	Mean	Grouping
6	12	134.2	A
3	12	132.0	A
0	12	88.4	B

Means that do not share a letter are significantly different.

FIGURE 48 Analysis of Field Results for CQS-1H Tack Coat.

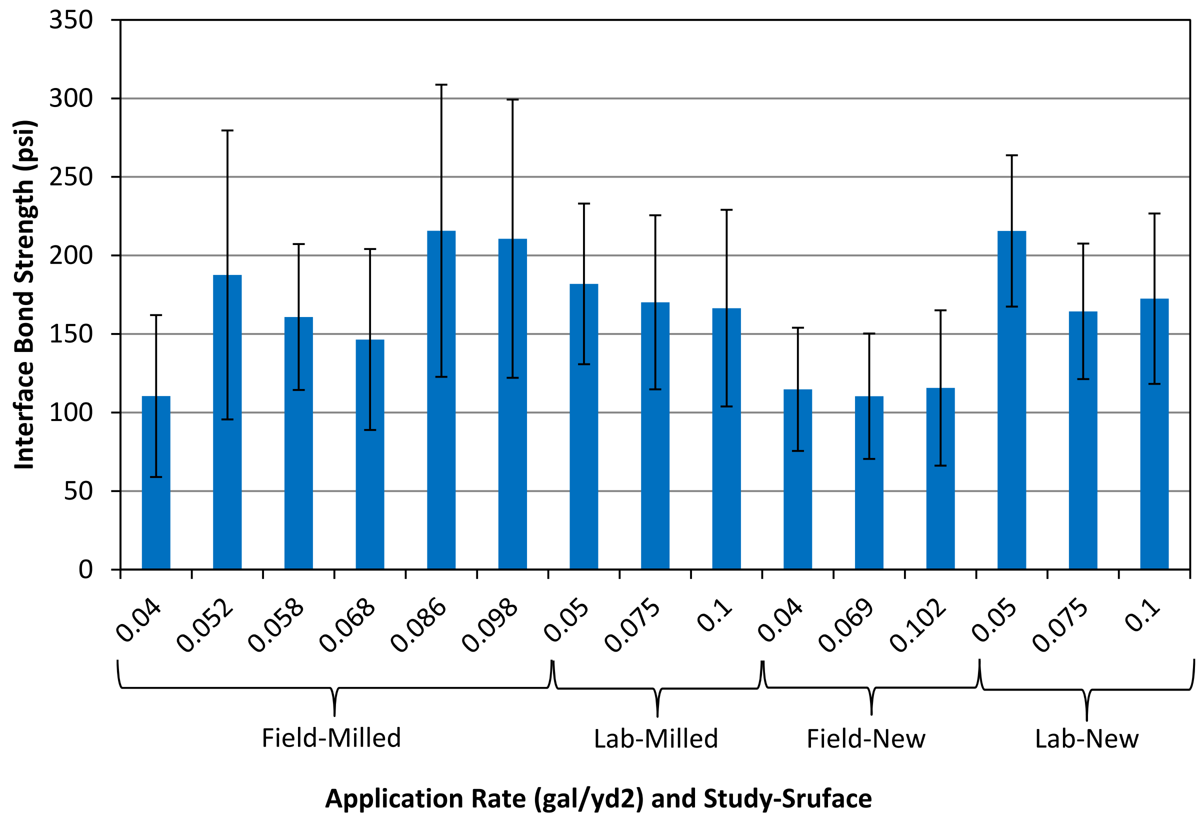
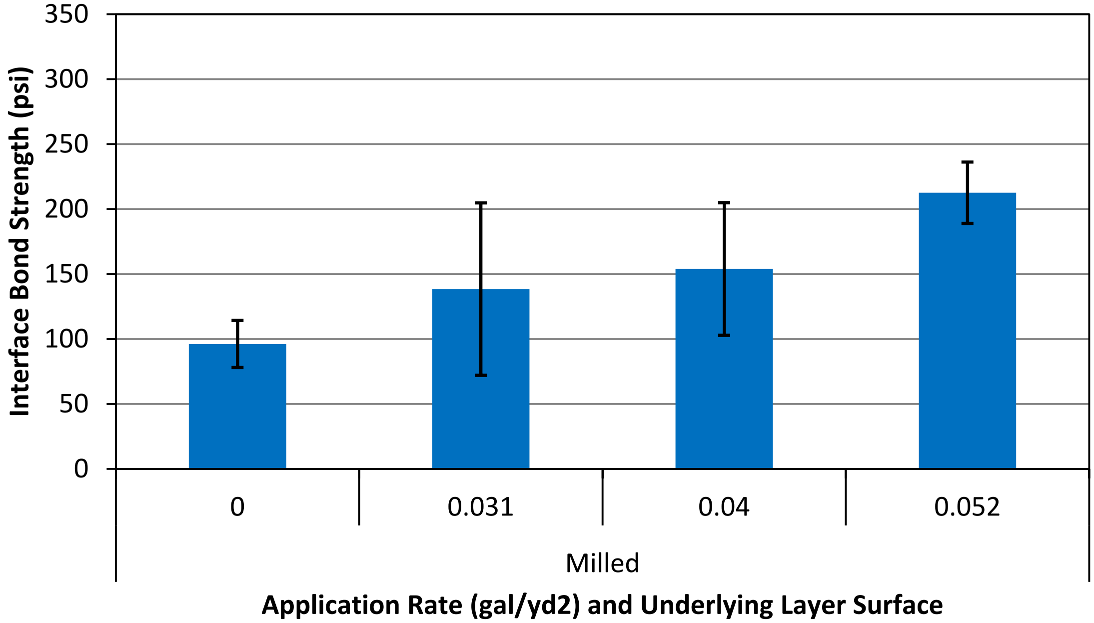


FIGURE 49 Comparing Lab and Field Results for CQS-1H Tack Coat.

CRS-2 Tack Coat. FIGURE 50 compares the field study results of CRS-2 tack coat on the milled surface only. As previously mentioned, the research was able to evaluat only one project in which the CRS-2 tack coat was used. For the milled surface, use of the CRS-2 tack coat appeared to increase the bond strength. As for the CQS-1H tack coat, the bond strength of the CRS-2 increased significantly in the first 3 months in service but did not increase significantly after that time.

FIGURE 51 compares the bond strength results determined from the laboratory and field studies for the CRS-2 tack coat. The field bond strength obtained at 0.052 gal/yd^2 appeared to agree with the laboratory study results. Based on the limited field results, the minimum and maximum application rates (0.05 and 0.1 gal/yd^2) specified in the ALDOT specification seem to be reasonable for both the new and milled surfaces.



General Linear Model: Bond_Strength versus App_Rate, Curing_Time

```
Factor        Type   Levels  Values
App_Rate      fixed       4  0.000, 0.031, 0.040, 0.052
Curing_Time   fixed       3  0, 3, 6

Grouping Information Using Tukey Method and 95.0% Confidence

App_Rate   N   Mean  Grouping
0.052      9  177.4  A
0.040      9  169.6  A
0.031      9  138.5    B
0.000      9   96.2      C

Curing_Time   N   Mean  Grouping
6            12  175.3  A
3            12  172.4  A
0            12   88.6    B

Means that do not share a letter are significantly different.
```

FIGURE 50 Analysis of Field Results for CRS-2 Tack Coat.

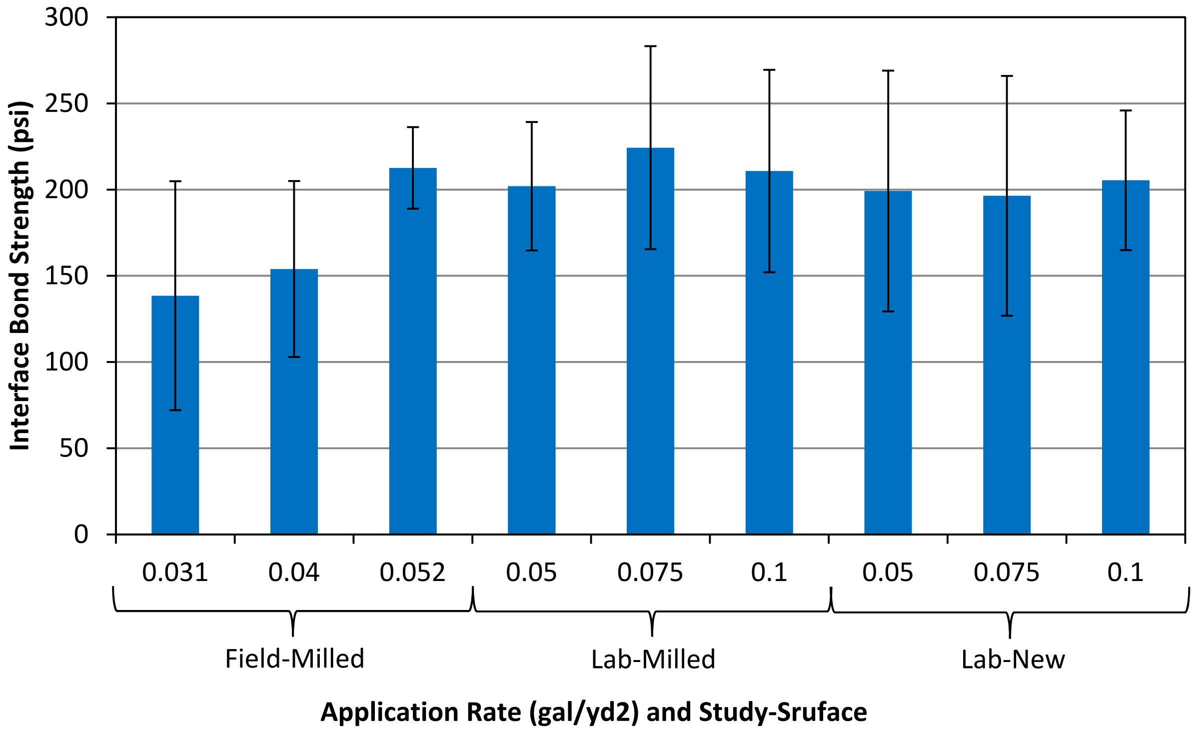


FIGURE 51 Comparing Lab and Field Results for CRS-2 Tack Coat.

4.3 Summary

The purpose of the laboratory and field studies was to investigate how tack coat material, application rate, surface of underlying layer, aging, and traffic affect interface bond strength. Based on the results of this research effort, the following key findings and recommendations can be offered.

- Based on the laboratory study results, the five tack coat materials evaluated in the laboratory study could be divided into three groups. The first group of tack coat materials that yielded higher interface bond strengths included PG 67-22, CRS-2L, and NTSS-1HM. The second group of tack coats that yielded lower bond strengths consisted of CRS-2L, NTSS-1HM, and CRS-2. CRS-2L and NTSS-1HM yielded interface bond strengths that were on the borderline between the two groups. The last group that yielded the lowest bond strength included only CQS-1H.
- The curing time also significantly affected bond strength—the longer the curing time, the higher bond strength. However, a further investigation of this effect for each tack coat showed that the curing time significantly affected bond strength for the four emulsions—CRS-2, CRS-2L, CQS-1H, and NTSS-1HM—but did not significantly affect bond strength for PG 67-22 and non-tack surfaces.
- Based on the laboratory study results, the micro-milled surface generally yielded statistically higher bond strengths, followed by the milled surface, finally, the new surface.

- For the non-tacked new and milled receiving surfaces, the bond strengths determined from the field cores were statistically lower than those determined from the lab cores. The receiving surface did not significantly affect the lab results. However, it significantly affected the field results; the new surface yielded statistically higher bond strengths. It should be noted that while the field results were lower that the lab results, they were equal or higher than the bond strength criterion of 100 psi recommended in the previous chapter. However, it is not known if the bond strength can be maintained at this level if water is present at the interface, as shown in FIGURE 5.
- For the PG 67-22 tack coat, there was a good agreement between the laboratory and field study results. The minimum and maximum application rates (0.03 and 0.07 gal/yd^2) specified in the ALDOT specification appear to be reasonable for the new surface. However, the application rates for the milled surface should be higher; based on the test results, it is recommended that the minimum and maximum application rates be 0.05 and 0.09 gal/sy^2, respectively. In the field study, the PG 67-22 tacked surfaces yielded higher bond strengths than the non-tack new and milled surfaces.
- For the NTSS-1HM tack coat, there was a good agreement between the laboratory and field study results for the milled surface. However, for the new surface, the laboratory study results appeared to be higher than the field study results. The minimum and maximum application rates (0.04 and 0.08 gal/yd^2) specified in the ALDOT specification seem to be reasonable for the new surface. However, for the milled surface, the higher application rates appeared to yield higher bond strengths. Thus, it is recommended that the minimum and maximum application rates for the milled surface be increased to 0.06 and 0.1 gal/yd^2, respectively. In the field study, the tacked milled surfaces yielded higher bond strengths than the non-tacked milled surfaces, but the tacked and non-tacked new surfaces yielded similar bond strengths.
- For the CQS-1H tack coat, the laboratory study results appeared to be similar to the field study results for the milled surfaces but significantly higher than the field study results for the new surfaces. The minimum and maximum application rates (0.05 and 0.1 gal/yd^2) specified in the ALDOT specification seem to be reasonable for both the new and milled surfaces. In the field study, the bond strengths of the tacked milled surfaces were higher than those of the non-tacked milled surfaces, and the bond strengths of the tacked and non-tacked new surfaces were similar.
- The CRS-2 tack coat was evaluated only on the milled surfaces in the field study. The bond strengths of the tacked milled surfaces were higher than those of the non-tacked milled surfaces. Based on the limited field results, the minimum and maximum application rates (0.05 and 0.1 gal/yd^2) specified in the ALDOT specification seem to be reasonable for both the new and milled surfaces.
- It is not clear why the laboratory study results were higher than the field study results for the non-tack surfaces and for the NTSS-1HM and CQS-1H emulsions applied on the new surfaces.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this research project was to (1) develop a bond strength criterion for evaluating bond strength through the structural pavement analysis and the field study of well-performed and prematurely failed pavement sections; and (2) evaluate the effect of tack coat material, application rate, underlying surface preparation, traffic, and aging on bond strength through laboratory and field studies to recommend the effective tack coat materials and optimum application rates on different receiving surfaces. Based on the study results, the following key findings and recommendations can be offered.

5.1 Development of the bond strength requirement

- Based on the structural pavement analysis, the thickness, stiffness of wearing course, and pavement temperature had more effects on the interface shear stress than the stiffness of subgrade and total AC thickness. The interface shear stress determined using BISAR decreased with depth. The maximum shear stress was approximately 92 psi at a depth of 0.5 in., and it was approximately 40 psi at a depth of 2 in.
- Based on the bond strength evaluation of the test sections built in the previous bond strength study for ALDOT, the bond strength did not increase over time for the section in which a straight asphalt binder was used as the tack coat, but it increased over time when asphalt emulsions were used. The increase was more significant for the higher emulsion application rates. The lowest bond strength of approximately 100 psi was determined for the cores extracted from the test sections with no sign of delamination.
- Based on the evaluation of pavement sections exhibiting slippage failures, the bond strengths of the cores from the intact areas were greater than 87 psi, and those of the cores from the failed areas were much lower than 87 psi.
- Based on the results of the structural pavement analysis and the field study of well-performed and prematurely failed pavement sections, a minimum bond strength requirement between 87 psi and 100 psi would be necessary. Thus, a preliminary minimum bond strength requirement of 100 psi tested according to ALDOT-430 was proposed for evaluating the interface bond between the wearing and underlying layers.

5.2 Laboratory and Field Evaluations of Factors Affecting Bond Strength

- Based on the laboratory study results, the five tack coat materials evaluated in the laboratory study could be divided into three groups that yielded statistically different bond strengths, with the first group yielding the highest bond strengths. The first group included PG 67-22, CRS-2L, and NTSS-1HM. The second group consisted of CRS-2L, NTSS-1HM, and CRS-2, and the last group included only CQS-1H.
- The curing time significantly affected the bond strength of the four emulsions—CRS-2, CRS-2L, CQS-1H, and NTSS-1HM—but did not significantly influence the bond strength of PG 67-22.
- Based on the laboratory study results, the micro-milled surface generally yielded statistically higher bond strengths, followed by the milled surface and, finally, the new surface.

- For the non-tacked new and milled receiving surfaces, the bond strengths determined from the field cores were statistically lower than those determined from the lab cores. In the field study, the non-tacked new surface yielded statistically higher bond strength than the non-tacked milled surface. It should be noted that while the field results were lower that the lab results, they were close to the recommended bond strength criterion of 100 psi. However, it is not known if the bond strength can be maintained at this level if water is present at the interface, as shown in FIGURE 5. Thus, it is recommended that receiving surfaces be tacked.
- For the PG 67-22 tack coat, there was a good agreement between the laboratory and field study results. The minimum and maximum application rates (0.03 and 0.07 gal/yd^2) specified in the ALDOT specification appear to be reasonable for the new surface. However, based on the test results, it is recommended that the minimum and maximum application rates be 0.05 and 0.09 gal/yd^2, respectively.
- For the NTSS-1HM tack coat, there was a good agreement between the laboratory and field study results for the milled surface but not for the new surface. The minimum and maximum application rates (0.04 and 0.08 gal/yd^2) specified in the ALDOT specification seem to be reasonable for the new surface. However, for the milled surface, the higher application rates appeared to yield higher bond strengths. Thus, it is recommended that the minimum and maximum application rates for the milled surface be increased to 0.06 and 0.1 gal/yd^2, respectively.
- For the CQS-1H tack coat, the laboratory study results appeared to be similar to the field study results for the milled surfaces but significantly higher than the field study results for the new surfaces. The minimum and maximum application rates (0.05 and 0.1 gal/yd^2) specified in the ALDOT specification seem to be reasonable for both the new and milled surfaces.
- The CRS-2 tack coat was evaluated only on the milled surfaces in the field study. The bond strengths of the tacked milled surfaces were higher than those of the non-tacked milled surfaces. Based on the limited field results, the minimum and maximum application rates (0.05 and 0.1 gal/yd^2) specified in the ALDOT specification seem to be reasonable for both the new and milled surfaces.
- Based on the field study results, the PG 67-22 tacked surfaces yielded higher bond strengths than the non-tack new and milled surfaces. However, for the NTSS-1HM and CQS-1H tack coats, the tacked milled surfaces yielded higher bond strengths than the non-tacked milled surfaces, but the tacked and non-tacked new surfaces yielded similar bond strengths.
- It is not clear why the laboratory study results were higher than the field study results for the non-tack surfaces and for the NTSS-1HM and CQS-1H emulsions applied on the new surfaces.

In summary, further evaluation of the preliminary minimum bond strength requirement should be done by assessing the interface bond strength of new pavements in the future and other in-service pavement sections that show slippage failures. It is also recommended that higher application rates be used for milled surfaces.

REFERENCES

1. Leng, Z., H. Ozar, I.L. Al-Qadi, and S.H. Carpenter. Interface Bonding between Hot-Mix Asphalt and Various Portland Cement Concrete Surfaces: Laboratory Assessment, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2057, 2008, pp. 46-53.
2. Van Dam, T., K. Kirchner, M. Shahin, and E. Blackmon. *Consequence of Layer Separation of Pavement Performance*, Report DOT/FAA/PM-86/48. U.S. Department of Transportation, Federal Aviation Administration, Washington, D.C., April 1987.
3. Ziari, H. and M. Khabiri. Interface Condition on Prediction of Flexible Pavement Life, *Journal of Civil Engineering and Management*, Vol. 13, No. 1, 2007, pp. 71-76.
4. Tashman, L., K. Nam, T. Papagiannakas, K. Willoughby, L. Pierre, and T. Baker. Evaluation of Construction Practices that Influence the Bond Strength at the Interface between Pavement Layers, *Journal of Performance of Constructed Facilities*, Vol. 22, No. 3, 2008, pp. 154-161.
5. West, R.C., J. Zhang, and J. Moore. *Evaluation of Bond Strength between Pavement Layers*. NCAT Report 05-08, National Center for Asphalt Technology, Auburn University, 2005.
6. Romanoschi, S. and J. Metcalf. Characterization of Asphalt Concrete Layer Interfaces, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1778, 2001, pp. 132-139.
7. Romanoschi, S. and J. Metcalf. Effects of Interface Condition and Heavy Wheel Loads on Life of Flexible Pavement Structures, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1778, 2001, pp. 123-131.
8. Uzan, J., M. Livneh, and Y. Eshed. Investigation of Adhesion Properties Between Asphaltic Concrete Layers, *Journal of the Association of Asphalt Paving Technologists*, Vol. 47, 1978, pp. 495-521.
9. Bognacki, C., A. Frisvold, and T. Bennert. Investigation of Asphalt Pavement Slippage Failures on Runway 4R-22L, Newark International Airport, *Proceedings of the FAA Worldwide Airport Technology Transfer Conference*, Atlantic City, New Jersey, 2007.
10. Kullkarni, M. *Effect of Track and Prime Coats and Baghouse Fines on Composite Asphalt Pavements*, Ph.D. Dissertation, North Carolina State University, 2004.
11. Willis, J. and D. Timm. Forensic Investigation of Debonding in Rich-bottom Pavement, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2040, 2007, pp. 107-114.
12. Khandal, P. and I. Rickards. *Premature Failure of Asphalt Overlays from Stripping: Case Histories*, NCAT Report 01-01, 2001.
13. Tsubokawa, Y., J. Mizukami, T. Esaki, and K. Hayano. Study on Infared Thermographic Inspection of Debonded Layer of Airport Flexible Pavement, *Proceedings of the FAA Worldwide Airport Technology Transfer Conference*, Atlantic City, New Jersey, 2007.
14. Mejia, D., M. Celaya, S. Iyer, C. Rao, P. Shokeuhi, and S. Nazarian. *A Work Plan toward Evaluation of Technologies to Assess Presence and Extent of Delamination of HMA Airfield Pavements*, AAPTP, Project 06-04, Center for Transportation Infrastructure Systems, El Paso, TX, 2008.

15. Canestrari, F., G. Gerrotti, M. Portl, and E. Santagata. Advanced Testing and Characterization of Interface Shear Resistance, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1929, 2005, pp. 69-78.
16. Hachiya, Y. and K. Sato. "Effect of Tack Coat on Bonding Characteristics at Interface between Asphalt Concrete Layers," Proceeding of the 8th International Conference on Asphalt Pavemetns, 1997, pp. 349-362.
17. Mohammad, L., M.A. Raqib, and B. Huang. Influence of Asphaltic Tack Coat Materials on Interface Shear Strength, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1789, 2002, pp. 56-65.
18. Sholar, G.A., G.C. Page, J.A. Musselman, P.B. Upshaw, and J.L. Moreley. Preliminary Investigation of a Test Method to Evaluate Bond Strength of Bituminous Tack Coats, *Journal of the Association of Asphalt Paving Technologists*, Vol. 72, 2004.
19. "ASTM D8-02 Standard Terminology Relating to Materials for Roads and Pavements." *Annual Book of ASTM Standards 2003*, Section 4: Construction, Volume 04.03, American Society for Testing and Materials, West Conshohocken, PA, 2003.
20. Mohammad, L. and J. Button. *NCHRP Project 9-40: Optimization of Tack Coat for HMA Placement*, Draft Phase 1 Report, Transportation Research Board, Washington, D.C., 2005.
21. Chaignon, F. and J. Roffe. Characterization Test on Bond Coats: Worldwide Study, Impact, Tests, Recommendations," Canadian Technical Asphalt Association, Toronto, Canada, November, 2001.
22. The Asphalt Handbook, MS-4, 1989 Edition, The Asphalt Institute.
23. Construction of Hot Mix Asphalt Pavements, MS-22, Second Edition, The Asphalt Institute.
24. Mrawira, D. and D.J. Damude. Revisiting the Effectiveness of Tack Coats in HMA Overlays: The Shear Strength of Tack Coats in Young Overlays, *Proceedings of the 14th Annual Conference, Canadian Technical Asphalt Association Proceedings*, 1999, pp. 116-129.
25. "Proper Tack Coat Application." *Technical Bulletin*, Flexible Pavement of Ohio, Columbus, OH, 2001.
26. Sangiorgi, C., A.C. Collop, and N.H. Thom. "Laboratory Assessment of Bond Condition using the Leutner Shear Test," 3rd International Conference on Bituminous Mixtures and Pavements, Thessalonkiki, Greece, 2002, pp. 315-324.
27. Collop, A., M. Sutanto, G. Airey, and R. Elliot. Shear bond strength between asphalt layers for laboratory prepared samples and field cores, *Journal of Construction and Materials*, No. 23, 2009, pp. 2251-2258.
28. Canestrari, F. and E. Santagata. "Temperature Effects on the Shear Behavior of Tack Coat Emulsions Used in Flexible Pavements," International Journal of Pavement Engineering, Vol. 6, No. 1, pp. 39-46, March 2005.
29. Canestrari, F., G. Ferrotti, M. Partl, and E. Santagata. Advanced Testing and Characterization of Interlayer Shear Resistance, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1929, 2005, 69-78.
30. Raab, C. and M.N. Partl. "Effect of Tack Coats on Interlayer Shear Bond of Pavements," 8th Conference on Asphalt Pavements for Southern Africa.
31. Buchanan, S. and M. Woods. "Field Tack Coat Evaluator (ATACKer™)," Final Report, FHWA/MS-DOT-RD-04-168, December 2004.

32. DeBondt, A. and A. Scarpas. “Theoretical analysis of shear interface setups,” Report 7-93-203-9, Road and Railway Research Laboratory, Delft University of Technology, Delft, Netherlands, 1994.
33. Kruntcheva, M., A. Collop, and N. Thom. “Properties of Asphalt Concrete Layer Interfaces,” *Journal of Materials in Civil Engineering*, ASCE, May/June 2006.
34. Maina, J.W. and K. Matsui. Developing Software for Elastic Analysis of Pavement Structure Responses to Vertical and Horizontal Surface Loading, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1896, 2004, pp. 107-118.
35. Hansen, K. Avoid Slippage by Using Good Tack Coat Practices, Hot Mix Asphalt Technology, Vol. 9, pp. 33-37, November 2004.
36. Ksaibati, Khaled. "Pavement Design for Highways." University of Wyoming. Laramie, WY, 11 March 1996.
37. King, G, and R. May, “New Approaches to Tack Application”, presentation made to the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.
38. Roffe J.C., and Chaignon, F., “Chatacterisation Tests on Bond Coats: Worldwide Study, Impact, Tests, and Recommendations”, 3rd International Conference Bituminous Mixtures and Pavements, Thessaloniki, 2002.
39. http://www.engineershandbook.com/Tables/frictioncoefficients.htm

APPENDIX A RESULTS OF LABORATORY STUDY

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
PG 67-22	0.03	N	Milled	4	251.53	100
PG 67-22	0.03	N	Milled	4	245.90	100
PG 67-22	0.03	N	Milled	4	229.73	100
PG 67-22	0.03	N	Milled	57	86.47	100
PG 67-22	0.03	N	Milled	57	66.12	100
PG 67-22	0.03	N	Milled	57	46.78	100
PG 67-22	0.03	N	Milled	183	172.71	100
PG 67-22	0.03	N	Milled	183	190.53	100
PG 67-22	0.03	N	Milled	183	118.70	100
PG 67-22	0.03	Y	Milled	183	156.03	100
PG 67-22	0.03	Y	Milled	183	127.33	100
PG 67-22	0.03	Y	Milled	183	129.53	100
PG 67-22	0.03	N	New	2	248.81	100
PG 67-22	0.03	N	New	2	200.83	100
PG 67-22	0.03	N	New	2	178.00	100
PG 67-22	0.03	N	New	29	182.55	100
PG 67-22	0.03	N	New	29	182.51	100
PG 67-22	0.03	N	New	29	157.46	100
PG 67-22	0.03	N	New	192	259.61	100
PG 67-22	0.03	N	New	192	249.96	100
PG 67-22	0.03	N	New	192	273.81	100
PG 67-22	0.03	Y	New	191	217.13	100
PG 67-22	0.03	Y	New	191	229.01	100
PG 67-22	0.03	Y	New	191	224.26	100
PG 67-22	0.05	N	Micromilled	2	309.47	100
PG 67-22	0.05	N	Micromilled	2	344.90	100
PG 67-22	0.05	N	Micromilled	2	249.57	100
PG 67-22	0.05	N	Micromilled	150	354.02	80
PG 67-22	0.05	N	Micromilled	150	339.98	100
PG 67-22	0.05	N	Micromilled	150	343.51	80
PG 67-22	0.05	Y	Micromilled	150	335.59	100
PG 67-22	0.05	Y	Micromilled	150	304.10	100
PG 67-22	0.05	Y	Micromilled	150	350.39	100
PG 67-22	0.05	N	Milled	2	274.90	100
PG 67-22	0.05	N	Milled	2	310.55	100
PG 67-22	0.05	N	Milled	2	296.47	100
PG 67-22	0.05	N	Milled	38	266.29	100
PG 67-22	0.05	N	Milled	38	240.78	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
PG 67-22	0.05	N	Milled	38	237.34	100
PG 67-22	0.05	N	Milled	185	265.87	100
PG 67-22	0.05	N	Milled	185	294.94	100
PG 67-22	0.05	N	Milled	185	212.21	100
PG 67-22	0.05	Y	Milled	184	237.45	100
PG 67-22	0.05	Y	Milled	184	276.93	100
PG 67-22	0.05	Y	Milled	184	307.72	100
PG 67-22	0.05	N	New	2	214.06	100
PG 67-22	0.05	N	New	2	219.98	100
PG 67-22	0.05	N	New	2	121.91	100
PG 67-22	0.05	N	New	41	221.80	100
PG 67-22	0.05	N	New	41	226.10	100
PG 67-22	0.05	N	New	41	210.81	100
PG 67-22	0.05	Y	New	181	218.83	100
PG 67-22	0.05	Y	New	181	261.79	100
PG 67-22	0.05	Y	New	181	279.91	100
PG 67-22	0.07	N	Milled	2	294.11	100
PG 67-22	0.07	N	Milled	2	267.46	100
PG 67-22	0.07	N	Milled	2	195.18	50
PG 67-22	0.07	N	Milled	36	204.65	100
PG 67-22	0.07	N	Milled	36	230.04	100
PG 67-22	0.07	N	Milled	36	223.15	100
PG 67-22	0.07	N	Milled	183	301.73	100
PG 67-22	0.07	N	Milled	183	295.28	100
PG 67-22	0.07	N	Milled	183	309.47	100
PG 67-22	0.07	Y	Milled	182	330.69	100
PG 67-22	0.07	Y	Milled	182	313.75	100
PG 67-22	0.07	Y	Milled	182	305.77	100
PG 67-22	0.07	N	New	2	152.79	100
PG 67-22	0.07	N	New	2	160.31	100
PG 67-22	0.07	N	New	2	117.56	100
PG 67-22	0.07	N	New	36	168.85	100
PG 67-22	0.07	N	New	36	162.31	100
PG 67-22	0.07	N	New	36	184.04	100
PG 67-22	0.07	N	New	194	207.78	100
PG 67-22	0.07	N	New	194	205.60	100
PG 67-22	0.07	N	New	194	229.65	100
PG 67-22	0.07	Y	New	195	175.34	100
PG 67-22	0.07	Y	New	195	174.21	100
PG 67-22	0.07	Y	New	195	199.21	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
NTSS-1HM	0.04	N	Milled	2	244.53	100
NTSS-1HM	0.04	N	Milled	2	220.66	100
NTSS-1HM	0.04	N	Milled	2	294.85	100
NTSS-1HM	0.04	N	Milled	8	144.34	100
NTSS-1HM	0.04	N	Milled	8	93.96	100
NTSS-1HM	0.04	N	Milled	8	79.71	100
NTSS-1HM	0.04	N	Milled	190	199.55	100
NTSS-1HM	0.04	N	Milled	190	144.72	100
NTSS-1HM	0.04	N	Milled	190	83.36	90
NTSS-1HM	0.04	Y	Milled	190	207.08	100
NTSS-1HM	0.04	Y	Milled	190	195.96	95
NTSS-1HM	0.04	Y	Milled	190	156.50	100
NTSS-1HM	0.04	N	New	2	249.62	100
NTSS-1HM	0.04	N	New	2	270.48	100
NTSS-1HM	0.04	N	New	2	304.62	100
NTSS-1HM	0.04	N	New	26	148.12	100
NTSS-1HM	0.04	N	New	26	150.00	100
NTSS-1HM	0.04	N	New	26	132.94	100
NTSS-1HM	0.04	N	New	193	187.65	90
NTSS-1HM	0.04	N	New	193	245.14	100
NTSS-1HM	0.04	N	New	193	158.42	100
NTSS-1HM	0.04	Y	New	192	208.67	90
NTSS-1HM	0.04	Y	New	192	223.23	95
NTSS-1HM	0.04	Y	New	192	172.42	100
NTSS-1HM	0.06	N	Micromilled	2	254.48	100
NTSS-1HM	0.06	N	Micromilled	2	178.92	100
NTSS-1HM	0.06	N	Micromilled	2	194.85	100
NTSS-1HM	0.06	N	Micromilled	162	338.57	90
NTSS-1HM	0.06	N	Micromilled	162	323.16	90
NTSS-1HM	0.06	N	Micromilled	162	329.86	70
NTSS-1HM	0.06	Y	Micromilled	162	353.77	100
NTSS-1HM	0.06	Y	Micromilled	162	324.06	100
NTSS-1HM	0.06	Y	Micromilled	162	359.30	90
NTSS-1HM	0.06	N	Milled	2	254.96	100
NTSS-1HM	0.06	N	Milled	2	183.77	100
NTSS-1HM	0.06	N	Milled	2	299.05	100
NTSS-1HM	0.06	N	Milled	8	152.01	100
NTSS-1HM	0.06	N	Milled	8	173.40	100
NTSS-1HM	0.06	N	Milled	8	115.76	100
NTSS-1HM	0.06	N	Milled	190	332.10	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
NTSS-1HM	0.06	N	Milled	190	332.89	100
NTSS-1HM	0.06	N	Milled	190	291.25	100
NTSS-1HM	0.06	Y	Milled	189	322.50	100
NTSS-1HM	0.06	Y	Milled	189	159.69	100
NTSS-1HM	0.06	Y	Milled	189	213.00	90
NTSS-1HM	0.06	N	New	2	277.04	100
NTSS-1HM	0.06	N	New	2	283.85	100
NTSS-1HM	0.06	N	New	2	320.17	100
NTSS-1HM	0.07	N	New	49	155.82	100
NTSS-1HM	0.07	N	New	49	197.97	100
NTSS-1HM	0.07	N	New	49	202.43	100
NTSS-1HM	0.07	N	New	195	277.78	100
NTSS-1HM	0.07	N	New	195	295.36	100
NTSS-1HM	0.07	Y	New	195	259.21	100
NTSS-1HM	0.07	Y	New	195	287.38	100
NTSS-1HM	0.07	Y	New	195	284.07	100
NTSS-1HM	0.08	N	Milled	4	187.27	100
NTSS-1HM	0.08	N	Milled	4	222.83	100
NTSS-1HM	0.08	N	Milled	4	268.88	100
NTSS-1HM	0.08	N	Milled	14	112.51	100
NTSS-1HM	0.08	N	Milled	14	123.31	100
NTSS-1HM	0.08	N	Milled	14	164.99	100
NTSS-1HM	0.08	N	Milled	188	254.28	50
NTSS-1HM	0.08	N	Milled	188	214.88	50
NTSS-1HM	0.08	N	Milled	188	233.20	100
NTSS-1HM	0.08	Y	Milled	188	234.61	50
NTSS-1HM	0.08	Y	Milled	188	185.03	50
NTSS-1HM	0.08	Y	Milled	188	231.94	50
NTSS-1HM	0.08	N	New	2	138.62	100
NTSS-1HM	0.08	N	New	2	203.14	100
NTSS-1HM	0.08	N	New	2	237.37	100
NTSS-1HM	0.08	N	New	26	111.74	100
NTSS-1HM	0.08	N	New	26	90.33	100
NTSS-1HM	0.08	N	New	26	90.27	100
NTSS-1HM	0.08	N	New	193	119.73	85
NTSS-1HM	0.08	N	New	193	188.90	90
NTSS-1HM	0.08	N	New	193	202.81	90
NTSS-1HM	0.08	Y	New	189	166.46	85
NTSS-1HM	0.08	Y	New	189	190.85	90
NTSS-1HM	0.08	Y	New	189	238.62	80

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
NTSS-1HM	0.11	N	New	47	115.36	100
NTSS-1HM	0.11	N	New	47	165.58	100
NTSS-1HM	0.11	N	New	47	180.59	100
NTSS-1HM	0.11	N	New	193	284.46	100
NTSS-1HM	0.11	N	New	193	299.92	100
NTSS-1HM	0.11	Y	New	193	230.99	100
NTSS-1HM	0.11	Y	New	193	82.47	100
NTSS-1HM	0.11	Y	New	193	237.30	100
NTSS-1HM	0.15	N	New	43	156.83	100
NTSS-1HM	0.15	N	New	43	146.61	100
NTSS-1HM	0.15	N	New	43	193.41	100
NTSS-1HM	0.15	N	New	189	268.17	100
NTSS-1HM	0.15	Y	New	189	226.82	100
NTSS-1HM	0.15	Y	New	189	221.50	100
NTSS-1HM	0.15	Y	New	189	233.73	100
CRS-2	0.05	N	Milled	4	190.52	100
CRS-2	0.05	N	Milled	4	208.56	100
CRS-2	0.05	N	Milled	4	221.24	100
CRS-2	0.05	N	Milled	6	188.90	100
CRS-2	0.05	N	Milled	6	162.64	100
CRS-2	0.05	N	Milled	6	152.83	100
CRS-2	0.05	N	Milled	189	275.74	90
CRS-2	0.05	N	Milled	189	187.65	100
CRS-2	0.05	N	Milled	189	229.66	100
CRS-2	0.05	Y	Milled	189	196.07	95
CRS-2	0.05	Y	Milled	189	246.13	100
CRS-2	0.05	Y	Milled	189	217.49	100
CRS-2	0.05	N	New	2	91.10	100
CRS-2	0.05	N	New	2	123.27	100
CRS-2	0.05	N	New	2	147.36	100
CRS-2	0.05	N	New	13	220.57	100
CRS-2	0.05	N	New	13	205.45	100
CRS-2	0.05	N	New	13	179.45	100
CRS-2	0.05	N	New	13	289.83	100
CRS-2	0.05	N	New	13	253.56	100
CRS-2	0.05	N	New	13	282.11	100
CRS-2	0.05	Y	New	13	288.69	100
CRS-2	0.05	Y	New	13	289.01	100
CRS-2	0.05	Y	New	13	267.67	100
CRS-2	0.075	N	Micromilled	4	264.70	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
CRS-2	0.075	N	Micromilled	4	163.93	100
CRS-2	0.075	N	Micromilled	4	168.13	100
CRS-2	0.075	N	Micromilled	146	348.84	100
CRS-2	0.075	N	Micromilled	146	327.81	100
CRS-2	0.075	N	Micromilled	146	330.22	100
CRS-2	0.075	Y	Micromilled	146	227.45	100
CRS-2	0.075	Y	Micromilled	146	344.90	100
CRS-2	0.075	Y	Micromilled	146	313.09	100
CRS-2	0.075	N	Milled	4	190.20	100
CRS-2	0.075	N	Milled	4	273.35	100
CRS-2	0.075	N	Milled	4	260.43	100
CRS-2	0.075	N	Milled	6	278.14	100
CRS-2	0.075	N	Milled	6	192.01	100
CRS-2	0.075	N	Milled	6	203.50	100
CRS-2	0.075	N	Milled	189	216.03	90
CRS-2	0.075	N	Milled	189	316.67	100
CRS-2	0.075	N	Milled	189	299.34	100
CRS-2	0.075	Y	Milled	189	233.72	95
CRS-2	0.075	Y	Milled	189	223.96	100
CRS-2	0.075	Y	Milled	189	216.49	100
CRS-2	0.075	N	New	42	149.99	100
CRS-2	0.075	N	New	42	190.56	100
CRS-2	0.075	N	New	42	206.16	100
CRS-2	0.075	N	New	188	242.74	100
CRS-2	0.075	N	New	188	306.58	100
CRS-2	0.075	Y	New	188	249.61	100
CRS-2	0.075	Y	New	188	233.34	100
CRS-2	0.075	Y	New	188	265.53	100
CRS-2	0.1	N	Milled	2	172.96	100
CRS-2	0.1	N	Milled	2	216.01	100
CRS-2	0.1	N	Milled	2	184.13	100
CRS-2	0.1	N	Milled	4	229.34	100
CRS-2	0.1	N	Milled	4	242.18	100
CRS-2	0.1	N	Milled	4	235.03	100
CRS-2	0.1	N	Milled	12	130.30	100
CRS-2	0.1	N	Milled	12	166.01	100
CRS-2	0.1	N	Milled	12	199.71	100
CRS-2	0.1	N	Milled	188	226.98	80
CRS-2	0.1	N	Milled	188	286.30	100
CRS-2	0.1	N	Milled	188	314.79	35

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
CRS-2	0.1	Y	Milled	188	256.47	100
CRS-2	0.1	Y	Milled	188	259.41	100
CRS-2	0.1	Y	Milled	188	249.56	95
CRS-2	0.1	N	New	2	144.07	100
CRS-2	0.1	N	New	2	188.01	100
CRS-2	0.1	N	New	2	172.61	100
CRS-2	0.1	N	New	12	165.51	100
CRS-2	0.1	N	New	12	217.79	100
CRS-2	0.1	N	New	12	212.67	100
CRS-2	0.1	N	New	186	259.53	100
CRS-2	0.1	N	New	186	233.38	100
CRS-2	0.1	N	New	186	255.15	75
CRS-2	0.1	Y	New	186	231.08	100
CRS-2	0.1	Y	New	186	259.47	100
CRS-2	0.1	Y	New	186	259.44	100
CRS-2	0.75	N	Milled	4	158.36	100
CRS-2	0.75	N	Milled	4	162.70	100
CRS-2	0.75	N	Milled	4	192.21	100
CRS-2	0.75	N	New	2	122.36	100
CRS-2	0.75	N	New	2	135.47	100
CRS-2	0.75	N	New	2	127.20	100
CRS-2L	0.05	N	Milled	4	207.50	100
CRS-2L	0.05	N	Milled	4	205.71	100
CRS-2L	0.05	N	Milled	4	188.52	100
CRS-2L	0.05	N	Milled	11	161.50	100
CRS-2L	0.05	N	Milled	11	172.92	100
CRS-2L	0.05	N	Milled	11	183.32	100
CRS-2L	0.05	N	Milled	187	230.49	100
CRS-2L	0.05	N	Milled	187	225.73	100
CRS-2L	0.05	N	Milled	187	224.01	90
CRS-2L	0.05	Y	Milled	187	252.49	100
CRS-2L	0.05	Y	Milled	187	225.95	95
CRS-2L	0.05	Y	Milled	187	223.63	100
CRS-2L	0.05	N	New	4	105.22	100
CRS-2L	0.05	N	New	4	152.84	100
CRS-2L	0.05	N	New	4	168.42	100
CRS-2L	0.05	N	New	14	234.22	100
CRS-2L	0.05	N	New	14	146.83	100
CRS-2L	0.05	N	New	14	203.76	100
CRS-2L	0.05	N	New	188	168.94	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
CRS-2L	0.05	N	New	188	260.08	100
CRS-2L	0.05	N	New	188	259.70	100
CRS-2L	0.05	Y	New	188	259.44	100
CRS-2L	0.05	Y	New	188	225.42	100
CRS-2L	0.05	Y	New	188	219.66	100
CRS-2L	0.075	N	Micromilled	4	255.78	100
CRS-2L	0.075	N	Micromilled	4	262.55	100
CRS-2L	0.075	N	Micromilled	4	211.93	100
CRS-2L	0.075	N	Micromilled	153	298.31	100
CRS-2L	0.075	N	Micromilled	153	280.51	100
CRS-2L	0.075	N	Micromilled	153	228.53	100
CRS-2L	0.075	Y	Micromilled	153	356.89	100
CRS-2L	0.075	Y	Micromilled	153	291.58	90
CRS-2L	0.075	Y	Micromilled	153	289.64	100
CRS-2L	0.075	N	Milled	11	132.31	100
CRS-2L	0.075	N	Milled	11	159.03	100
CRS-2L	0.075	N	Milled	11	195.46	100
CRS-2L	0.075	N	Milled	186	249.16	90
CRS-2L	0.075	N	Milled	186	324.63	90
CRS-2L	0.075	N	Milled	186	328.46	100
CRS-2L	0.075	Y	Milled	185	252.71	100
CRS-2L	0.075	Y	Milled	185	303.12	100
CRS-2L	0.075	Y	Milled	185	360.05	100
CRS-2L	0.075	N	New	2	198.60	100
CRS-2L	0.075	N	New	2	191.43	100
CRS-2L	0.075	N	New	2	226.55	100
CRS-2L	0.077	N	New	36	172.98	100
CRS-2L	0.077	N	New	36	154.26	100
CRS-2L	0.077	N	New	36	190.67	100
CRS-2L	0.077	N	New	182	197.89	100
CRS-2L	0.077	N	New	182	198.84	100
CRS-2L	0.077	N	New	182	192.37	100
CRS-2L	0.077	Y	New	182	185.10	100
CRS-2L	0.077	Y	New	182	138.60	100
CRS-2L	0.077	Y	New	182	128.09	100
CRS-2L	0.1	N	Milled	10	234.22	100
CRS-2L	0.1	N	Milled	10	226.68	100
CRS-2L	0.1	N	Milled	10	162.40	100
CRS-2L	0.1	N	Milled	185	295.93	100
CRS-2L	0.1	N	Milled	185	299.58	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
CRS-2L	0.1	N	Milled	185	274.11	100
CRS-2L	0.1	Y	Milled	185	342.90	100
CRS-2L	0.1	Y	Milled	185	314.05	100
CRS-2L	0.1	Y	Milled	185	263.81	100
CRS-2L	0.1	N	New	2	97.80	100
CRS-2L	0.1	N	New	2	104.07	100
CRS-2L	0.1	N	New	2	111.11	100
CRS-2L	0.115	N	New	34	162.52	100
CRS-2L	0.115	N	New	34	161.12	100
CRS-2L	0.115	N	New	34	152.58	100
CRS-2L	0.115	N	New	180	183.83	100
CRS-2L	0.115	N	New	180	189.01	100
CRS-2L	0.115	N	New	180	206.04	100
CRS-2L	0.115	Y	New	180	214.35	100
CRS-2L	0.115	Y	New	180	162.23	100
CRS-2L	0.115	Y	New	180	153.63	100
CRS-2L	0.154	N	New	32	169.76	100
CRS-2L	0.154	N	New	32	166.86	100
CRS-2L	0.154	N	New	32	182.58	100
CRS-2L	0.154	N	New	178	234.60	100
CRS-2L	0.154	N	New	178	238.03	100
CRS-2L	0.154	N	New	178	194.12	100
CRS-2L	0.154	Y	New	178	219.58	100
CRS-2L	0.154	Y	New	178	166.20	100
CRS-2L	0.154	Y	New	178	165.86	100
CQS-1H	0.05	N	Milled	4	243.82	100
CQS-1H	0.05	N	Milled	4	242.92	100
CQS-1H	0.05	N	Milled	4	236.73	100
CQS-1H	0.05	N	Milled	14	122.23	100
CQS-1H	0.05	N	Milled	14	172.76	100
CQS-1H	0.05	N	Milled	14	104.22	100
CQS-1H	0.05	N	Milled	182	158.37	100
CQS-1H	0.05	N	Milled	182	172.61	100
CQS-1H	0.05	N	Milled	182	183.50	100
CQS-1H	0.05	Y	Milled	182	158.40	100
CQS-1H	0.05	Y	Milled	182	151.12	100
CQS-1H	0.05	Y	Milled	182	115.19	100
CQS-1H	0.05	N	New	2	138.66	100
CQS-1H	0.05	N	New	2	201.58	100
CQS-1H	0.05	N	New	2	230.90	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
CQS-1H	0.05	N	New	70	310.93	75
CQS-1H	0.05	N	New	70	258.69	100
CQS-1H	0.05	N	New	70	202.59	100
CQS-1H	0.05	N	New	184	203.19	100
CQS-1H	0.05	N	New	184	185.87	100
CQS-1H	0.05	N	New	184	208.47	100
CQS-1H	0.05	Y	New	184	239.03	100
CQS-1H	0.05	Y	New	184	274.82	100
CQS-1H	0.05	Y	New	184	131.24	100
CQS-1H	0.074	N	New	29	174.10	100
CQS-1H	0.074	N	New	29	153.60	100
CQS-1H	0.074	N	New	29	189.83	100
CQS-1H	0.074	N	New	192	191.49	100
CQS-1H	0.074	N	New	192	214.20	100
CQS-1H	0.074	N	New	192	208.50	100
CQS-1H	0.074	Y	New	191	189.24	100
CQS-1H	0.074	Y	New	191	195.84	100
CQS-1H	0.074	Y	New	191	148.01	100
CQS-1H	0.075	N	Micromilled	2	159.27	100
CQS-1H	0.075	N	Micromilled	2	180.51	95
CQS-1H	0.075	N	Micromilled	2	184.41	100
CQS-1H	0.075	N	Micromilled	157	289.58	100
CQS-1H	0.075	N	Micromilled	157	308.49	100
CQS-1H	0.075	N	Micromilled	157	259.62	100
CQS-1H	0.075	Y	Micromilled	157	341.07	100
CQS-1H	0.075	Y	Micromilled	157	346.47	100
CQS-1H	0.075	Y	Micromilled	157	294.64	100
CQS-1H	0.075	N	Milled	2	233.77	100
CQS-1H	0.075	N	Milled	2	193.88	100
CQS-1H	0.075	N	Milled	2	258.99	100
CQS-1H	0.075	N	Milled	53	79.75	100
CQS-1H	0.075	N	Milled	53	142.65	100
CQS-1H	0.075	N	Milled	53	134.55	100
CQS-1H	0.075	N	Milled	182	159.26	100
CQS-1H	0.075	N	Milled	182	135.33	100
CQS-1H	0.075	N	Milled	182	193.68	100
CQS-1H	0.075	Y	Milled	182	106.19	100
CQS-1H	0.075	Y	Milled	182	106.43	100
CQS-1H	0.075	Y	Milled	182	139.46	100
CQS-1H	0.075	N	New	2	81.54	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
CQS-1H	0.075	N	New	2	138.01	100
CQS-1H	0.075	N	New	2	128.58	100
CQS-1H	0.1	N	Milled	2	233.61	100
CQS-1H	0.1	N	Milled	2	261.40	100
CQS-1H	0.1	N	Milled	2	252.12	100
CQS-1H	0.1	N	Milled	52	77.60	100
CQS-1H	0.1	N	Milled	52	95.42	100
CQS-1H	0.1	N	Milled	52	95.10	100
CQS-1H	0.1	N	Milled	181	103.11	100
CQS-1H	0.1	N	Milled	181	116.52	100
CQS-1H	0.1	N	Milled	181	113.39	100
CQS-1H	0.1	Y	Milled	181	98.87	100
CQS-1H	0.1	Y	Milled	181	91.75	100
CQS-1H	0.1	Y	Milled	181	120.70	100
CQS-1H	0.1	N	New	2	89.37	100
CQS-1H	0.1	N	New	2	116.81	100
CQS-1H	0.1	N	New	2	106.51	100
CQS-1H	0.111	N	New	34	183.72	100
CQS-1H	0.111	N	New	34	191.68	100
CQS-1H	0.111	N	New	34	193.76	100
CQS-1H	0.111	N	New	192	212.15	100
CQS-1H	0.111	N	New	192	238.72	100
CQS-1H	0.111	N	New	192	220.06	100
CQS-1H	0.111	Y	New	193	253.88	100
CQS-1H	0.111	Y	New	193	190.09	100
CQS-1H	0.111	Y	New	193	167.02	100
CQS-1H	0.148	N	New	39	165.10	100
CQS-1H	0.148	N	New	39	169.76	100
CQS-1H	0.148	N	New	39	122.71	100
CQS-1H	0.148	Y	New	183	252.91	100
CQS-1H	0.148	Y	New	183	294.81	100
CQS-1H	0.148	Y	New	183	155.69	100
None	0	N	Micromilled	2	323.19	100
None	0	N	Micromilled	2	243.24	100
None	0	N	Micromilled	2	261.49	100
None	0	N	Micromilled	4	265.15	100
None	0	N	Micromilled	4	217.27	100
None	0	N	Micromilled	4	233.85	100
None	0	N	Micromilled	153	149.91	100
None	0	N	Micromilled	153	173.88	100

Tack	App_Rate (gal/yd^2)	APA	Surface	Curing (days)	Bond_Strength (psi)	%Interface
None	0	N	Micromilled	153	210.60	100
None	0	N	Micromilled	196	240.43	100
None	0	N	Micromilled	196	240.68	100
None	0	N	Micromilled	196	202.63	100
None	0	Y	Micromilled	153	166.71	100
None	0	Y	Micromilled	153	114.13	100
None	0	Y	Micromilled	153	191.96	100
None	0	Y	Micromilled	196	224.11	100
None	0	Y	Micromilled	196	243.17	100
None	0	Y	Micromilled	196	257.26	100
None	0	N	Milled	2	193.45	100
None	0	N	Milled	2	280.42	100
None	0	N	Milled	2	204.14	100
None	0	N	Milled	4	234.49	100
None	0	N	Milled	4	278.68	100
None	0	N	Milled	4	302.03	100
None	0	N	Milled	181	65.26	100
None	0	N	Milled	181	172.40	100
None	0	N	Milled	181	180.43	100
None	0	N	Milled	194	191.77	100
None	0	N	Milled	194	279.55	100
None	0	N	Milled	194	227.49	100
None	0	Y	Milled	181	50.61	100
None	0	Y	Milled	181	54.09	100
None	0	Y	Milled	181	112.59	100
None	0	Y	Milled	194	240.56	100
None	0	Y	Milled	194	230.72	100
None	0	Y	Milled	194	218.05	100
None	0	N	New	2	212.53	100
None	0	N	New	2	227.37	100
None	0	N	New	2	203.11	100
None	0	N	New	195	249.91	100
None	0	N	New	195	217.10	100
None	0	N	New	195	175.09	100
None	0	Y	New	195	162.33	100
None	0	Y	New	195	185.03	100
None	0	Y	New	195	185.47	100

APPENDIX B RESULTS OF FIELD STUDY

Location	Tack	App_Rate (gal/yd^2)	Traffic	Surface	Curing (days)	Bond_ Strength (psi)	%Interface
US82_Midway	PG 67-22	0.0246	Y	Existing	98	229.65	100
US82_Midway	PG 67-22	0.0246	Y	Existing	98	191.25	100
US82_Midway	PG 67-22	0.0246	Y	Existing	98	251.70	100
US82_Midway	PG 67-22	0.0246	Y	Existing	181	135.84	100
US82_Midway	PG 67-22	0.0246	Y	Existing	181	164.04	100
US82_Midway	PG 67-22	0.0246	Y	Existing	181	203.14	100
US82_Midway	PG 67-22	0.0473	Y	Existing	2	169.47	100
US82_Midway	PG 67-22	0.0473	Y	Existing	2	228.01	100
US82_Midway	PG 67-22	0.0473	Y	Existing	2	169.00	100
US82_Midway	PG 67-22	0.0473	Y	Existing	98	221.54	100
US82_Midway	PG 67-22	0.0473	Y	Existing	98	248.64	100
US82_Midway	PG 67-22	0.0473	Y	Existing	98	256.21	100
US82_Midway	PG 67-22	0.0473	Y	Existing	181	186.23	100
US82_Midway	PG 67-22	0.0473	Y	Existing	181	236.71	100
US82_Midway	PG 67-22	0.0473	Y	Existing	181	284.24	100
US82_Midway	PG 67-22	0.0625	Y	Existing	2	216.56	100
US82_Midway	PG 67-22	0.0625	Y	Existing	2	190.63	100
US82_Midway	PG 67-22	0.0625	Y	Existing	2	191.08	100
US82_Midway	PG 67-22	0.0625	Y	Existing	98	229.97	100
US82_Midway	PG 67-22	0.0625	Y	Existing	98	319.08	100
US82_Midway	PG 67-22	0.0625	Y	Existing	98	288.37	100
US82_Midway	PG 67-22	0.0625	Y	Existing	181	197.18	100
US82_Midway	PG 67-22	0.0625	Y	Existing	181	248.05	100
US82_Midway	PG 67-22	0.0625	Y	Existing	181	267.83	100
US82_Midway	PG 67-22	0.246	Y	Existing	2	188.43	100
US82_Midway	PG 67-22	0.246	Y	Existing	2	142.30	100
US82_Midway	PG 67-22	0.246	Y	Existing	2	176.09	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	7	112.32	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	7	126.36	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	7	119.08	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	102	155.52	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	102	156.53	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	102	57.81	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	190	150.75	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	190	158.91	100
SR193_Mobile	NTSS-1HM	0.039	Y	Existing	190	96.08	100
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	7	111.64	100

Location	Tack	App_Rate (gal/yd^2)	Traffic	Surface	Curing (days)	Bond_ Strength (psi)	%Interface
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	7	140.50	100
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	7	151.31	100
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	102	54.27	100
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	102	112.20	100
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	102	201.70	100
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	190	173.99	100
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	190	162.60	100
SR193_Mobile	NTSS-1HM	0.053	Y	Existing	190	224.89	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	7	154.96	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	7	111.79	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	7	93.85	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	102	72.24	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	102	166.09	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	102	148.23	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	190	166.17	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	190	253.97	100
SR193_Mobile	NTSS-1HM	0.069	Y	Existing	190	187.76	100
US80_Montgomery	CRS-2	0.031	Y	Milled	26	27.51	100
US80_Montgomery	CRS-2	0.031	Y	Milled	26	73.94	100
US80_Montgomery	CRS-2	0.031	Y	Milled	141	183.79	100
US80_Montgomery	CRS-2	0.031	Y	Milled	141	161.81	100
US80_Montgomery	CRS-2	0.031	Y	Milled	141	198.17	100
US80_Montgomery	CRS-2	0.031	Y	Milled	222	198.13	100
US80_Montgomery	CRS-2	0.031	Y	Milled	222	165.45	100
US80_Montgomery	CRS-2	0.031	Y	Milled	222	180.22	100
US80_Montgomery	CRS-2	0.04	Y	Milled	26	91.33	100
US80_Montgomery	CRS-2	0.04	Y	Milled	26	124.41	100
US80_Montgomery	CRS-2	0.04	Y	Milled	141	205.24	100
US80_Montgomery	CRS-2	0.04	Y	Milled	141	190.74	100
US80_Montgomery	CRS-2	0.04	Y	Milled	141	216.08	100
US80_Montgomery	CRS-2	0.04	Y	Milled	222	212.21	100
US80_Montgomery	CRS-2	0.04	Y	Milled	222	194.42	100
US80_Montgomery	CRS-2	0.04	Y	Milled	222	191.49	100
US80_Montgomery	CRS-2	0.052	Y	Milled	141	227.00	100
US80_Montgomery	CRS-2	0.052	Y	Milled	141	212.44	100
US80_Montgomery	CRS-2	0.052	Y	Milled	141	248.53	100
US80_Montgomery	CRS-2	0.052	Y	Milled	222	213.03	100
US80_Montgomery	CRS-2	0.052	Y	Milled	222	183.86	100
US80_Montgomery	CRS-2	0.052	Y	Milled	222	190.74	100

Location	Tack	App_Rate (gal/yd^2)	Traffic	Surface	Curing (days)	Bond_ Strength (psi)	%Interface
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	27	149.43	100
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	27	134.88	100
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	27	162.31	100
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	27	163.85	100
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	141	153.44	50
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	141	147.53	50
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	141	148.97	50
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	223	180.17	100
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	223	202.59	100
US80_Montgomery	NTSS-1HM	0.04	Y	Milled	223	83.05	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	27	135.82	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	27	133.95	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	27	138.17	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	27	104.91	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	27	182.70	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	27	138.85	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	141	149.56	50
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	141	143.28	50
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	141	143.88	50
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	223	133.14	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	223	155.26	100
US80_Montgomery	NTSS-1HM	0.053	Y	Milled	223	119.00	100
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	27	141.59	100
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	27	136.07	100
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	27	163.88	100
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	27	190.73	100
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	27	139.67	100
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	141	186.05	50
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	141	187.24	50
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	141	162.14	50
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	223	129.89	100
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	223	132.33	100
US80_Montgomery	NTSS-1HM	0.067	Y	Milled	223	129.94	100
US331_Opp	CQS-1H	0.052	Y	Milled	9	33.25	100
US331_Opp	CQS-1H	0.052	Y	Milled	9	72.44	100
US331_Opp	CQS-1H	0.052	Y	Milled	9	114.12	100
US331_Opp	CQS-1H	0.052	Y	Milled	115	216.33	100
US331_Opp	CQS-1H	0.052	Y	Milled	115	270.33	100
US331_Opp	CQS-1H	0.052	Y	Milled	115	291.90	100

Location	Tack	App_Rate (gal/yd^2)	Traffic	Surface	Curing (days)	Bond_ Strength (psi)	%Interface
US331_Opp	CQS-1H	0.052	Y	Milled	209	202.29	100
US331_Opp	CQS-1H	0.052	Y	Milled	209	237.44	100
US331_Opp	CQS-1H	0.052	Y	Milled	209	250.42	100
US331_Opp	CQS-1H	0.086	Y	Milled	9	80.94	100
US331_Opp	CQS-1H	0.086	Y	Milled	9	97.75	100
US331_Opp	CQS-1H	0.086	Y	Milled	9	100.96	100
US331_Opp	CQS-1H	0.086	Y	Milled	115	266.68	100
US331_Opp	CQS-1H	0.086	Y	Milled	115	298.91	100
US331_Opp	CQS-1H	0.086	Y	Milled	115	294.91	100
US331_Opp	CQS-1H	0.086	Y	Milled	209	276.74	100
US331_Opp	CQS-1H	0.086	Y	Milled	209	254.78	100
US331_Opp	CQS-1H	0.086	Y	Milled	209	269.44	100
US331_Opp	CQS-1H	0.098	Y	Milled	9	116.27	100
US331_Opp	CQS-1H	0.098	Y	Milled	9	105.92	100
US331_Opp	CQS-1H	0.098	Y	Milled	9	80.66	100
US331_Opp	CQS-1H	0.098	Y	Milled	115	230.14	100
US331_Opp	CQS-1H	0.098	Y	Milled	115	316.97	100
US331_Opp	CQS-1H	0.098	Y	Milled	115	262.94	100
US331_Opp	CQS-1H	0.098	Y	Milled	209	271.41	100
US331_Opp	CQS-1H	0.098	Y	Milled	209	299.59	100
US331_Opp	CQS-1H	0.098	Y	Milled	209	212.16	100
US431_Seale	CQS-1H	0.04	N	Existing	3	79.12	100
US431_Seale	CQS-1H	0.04	N	Existing	3	28.82	100
US431_Seale	CQS-1H	0.04	N	Existing	3	118.88	100
US431_Seale	CQS-1H	0.04	N	Existing	126	120.50	100
US431_Seale	CQS-1H	0.04	N	Existing	126	140.34	100
US431_Seale	CQS-1H	0.04	N	Existing	126	164.01	100
US431_Seale	CQS-1H	0.04	N	Existing	197	132.92	100
US431_Seale	CQS-1H	0.04	N	Existing	197	126.14	100
US431_Seale	CQS-1H	0.04	N	Existing	197	122.62	100
US431_Seale	CQS-1H	0.069	N	Existing	3	79.26	100
US431_Seale	CQS-1H	0.069	N	Existing	3	82.86	100
US431_Seale	CQS-1H	0.069	N	Existing	3	86.46	100
US431_Seale	CQS-1H	0.069	N	Existing	126	122.86	100
US431_Seale	CQS-1H	0.069	N	Existing	126	126.56	100
US431_Seale	CQS-1H	0.069	N	Existing	126	147.70	100
US431_Seale	CQS-1H	0.069	N	Existing	197	162.48	100
US431_Seale	CQS-1H	0.069	N	Existing	197	144.04	100
US431_Seale	CQS-1H	0.069	N	Existing	197	41.19	100

Location	**Tack**	**App_Rate (gal/yd^2)**	**Traffic**	**Surface**	**Curing (days)**	**Bond_ Strength (psi)**	**%Interface**
US431_Seale	CQS-1H	0.102	N	Existing	3	35.84	0
US431_Seale	CQS-1H	0.102	N	Existing	3	86.46	100
US431_Seale	CQS-1H	0.102	N	Existing	3	93.67	100
US431_Seale	CQS-1H	0.102	N	Existing	126	156.60	100
US431_Seale	CQS-1H	0.102	N	Existing	126	126.36	100
US431_Seale	CQS-1H	0.102	N	Existing	126	86.74	100
US431_Seale	CQS-1H	0.102	N	Existing	197	206.15	100
US431_Seale	CQS-1H	0.102	N	Existing	197	145.66	100
US431_Seale	CQS-1H	0.102	N	Existing	197	103.67	100
US80_Selma	CQS-1H	0.04	Y	Milled	30	111.92	100
US80_Selma	CQS-1H	0.04	Y	Milled	30	118.45	100
US80_Selma	CQS-1H	0.04	Y	Milled	30	7.38	100
US80_Selma	CQS-1H	0.04	Y	Milled	113	104.44	100
US80_Selma	CQS-1H	0.04	Y	Milled	113	209.33	100
US80_Selma	CQS-1H	0.04	Y	Milled	113	90.21	100
US80_Selma	CQS-1H	0.04	Y	Milled	209	108.32	100
US80_Selma	CQS-1H	0.04	Y	Milled	209	118.88	100
US80_Selma	CQS-1H	0.04	Y	Milled	209	125.94	100
US80_Selma	CQS-1H	0.058	Y	Milled	30	138.48	100
US80_Selma	CQS-1H	0.058	Y	Milled	30	121.77	100
US80_Selma	CQS-1H	0.058	Y	Milled	30	99.20	100
US80_Selma	CQS-1H	0.058	Y	Milled	113	202.22	100
US80_Selma	CQS-1H	0.058	Y	Milled	113	194.83	100
US80_Selma	CQS-1H	0.058	Y	Milled	113	187.33	100
US80_Selma	CQS-1H	0.058	Y	Milled	209	165.54	100
US80_Selma	CQS-1H	0.058	Y	Milled	209	230.97	100
US80_Selma	CQS-1H	0.058	Y	Milled	209	106.89	100
US80_Selma	CQS-1H	0.068	Y	Milled	30	70.21	100
US80_Selma	CQS-1H	0.068	Y	Milled	30	128.74	100
US80_Selma	CQS-1H	0.068	Y	Milled	30	73.30	100
US80_Selma	CQS-1H	0.068	Y	Milled	113	205.24	100
US80_Selma	CQS-1H	0.068	Y	Milled	113	151.13	100
US80_Selma	CQS-1H	0.068	Y	Milled	113	133.36	100
US80_Selma	CQS-1H	0.068	Y	Milled	209	154.29	100
US80_Selma	CQS-1H	0.068	Y	Milled	209	149.46	100
US80_Selma	CQS-1H	0.068	Y	Milled	209	252.84	100
Location10_TTrack	None	0	N	New	22	117.31	95
Location10_TTrack	None	0	N	New	22	124.08	100
Location10_TTrack	None	0	N	New	22	128.06	100

Location	Tack	App_Rate (gal/yd^2)	Traffic	Surface	Curing (days)	Bond_ Strength (psi)	%Interface
Location10_TTrack	None	0	N	New	123	118.48	100
Location10_TTrack	None	0	N	New	123	117.31	100
Location10_TTrack	None	0	N	New	123	156.27	100
Location10_TTrack	None	0	N	New	209	143.72	85
Location10_TTrack	None	0	N	New	209	150.32	100
Location10_TTrack	None	0	N	New	209	131.63	90
Location10_TTrack	NTSS-1HM	0.074	N	New	22	146.95	50
Location10_TTrack	NTSS-1HM	0.074	N	New	22	132.29	45
Location10_TTrack	NTSS-1HM	0.074	N	New	22	135.66	50
Location10_TTrack	NTSS-1HM	0.074	N	New	123	145.57	100
Location10_TTrack	NTSS-1HM	0.074	N	New	123	141.95	50
Location10_TTrack	NTSS-1HM	0.074	N	New	123	166.25	75
Location10_TTrack	NTSS-1HM	0.074	N	New	209	147.81	100
Location10_TTrack	NTSS-1HM	0.074	N	New	209	169.46	85
Location10_TTrack	NTSS-1HM	0.074	N	New	209	151.40	85
Location10_TTrack	NTSS-1HM	0.079	N	New	22	127.58	85
Location10_TTrack	NTSS-1HM	0.079	N	New	22	120.42	95
Location10_TTrack	NTSS-1HM	0.079	N	New	22	124.29	100
Location10_TTrack	NTSS-1HM	0.079	N	New	123	155.28	50
Location10_TTrack	NTSS-1HM	0.079	N	New	123	161.60	50
Location10_TTrack	NTSS-1HM	0.079	N	New	123	148.53	50
Location10_TTrack	NTSS-1HM	0.079	N	New	209	158.46	90
Location10_TTrack	NTSS-1HM	0.079	N	New	209	143.48	80
Location10_TTrack	NTSS-1HM	0.079	N	New	209	125.08	100
Location10_TTrack	NTSS-1HM	0.0896	N	New	22	138.85	50
Location10_TTrack	NTSS-1HM	0.0896	N	New	22	131.96	65
Location10_TTrack	NTSS-1HM	0.0896	N	New	22	135.51	50
Location10_TTrack	NTSS-1HM	0.0896	N	New	123	161.02	50
Location10_TTrack	NTSS-1HM	0.0896	N	New	123	173.91	50
Location10_TTrack	NTSS-1HM	0.0896	N	New	123	173.71	50
Location10_TTrack	NTSS-1HM	0.0896	N	New	209	140.13	70
Location10_TTrack	NTSS-1HM	0.0896	N	New	209	162.15	100
Location10_TTrack	NTSS-1HM	0.0896	N	New	209	157.49	100
Location7_TTrack	PG 67-22	0.025	N	Milled	23	143.39	100
Location7_TTrack	PG 67-22	0.025	N	Milled	23	150.50	100
Location7_TTrack	PG 67-22	0.025	N	Milled	23	158.12	95
Location7_TTrack	PG 67-22	0.025	N	Milled	124	150.19	100
Location7_TTrack	PG 67-22	0.025	N	Milled	124	157.18	100
Location7_TTrack	PG 67-22	0.025	N	Milled	124	166.67	100

Location	Tack	App_Rate (gal/yd^2)	Traffic	Surface	Curing (days)	Bond_ Strength (psi)	%Interface
Location7_TTrack	PG 67-22	0.025	N	Milled	209	188.77	100
Location7_TTrack	PG 67-22	0.025	N	Milled	209	184.01	100
Location7_TTrack	PG 67-22	0.025	N	Milled	209	157.31	100
Location7_TTrack	PG 67-22	0.0348	N	Milled	23	84.39	95
Location7_TTrack	PG 67-22	0.0348	N	Milled	23	103.31	100
Location7_TTrack	PG 67-22	0.0348	N	Milled	23	102.90	100
Location7_TTrack	PG 67-22	0.0348	N	Milled	124	149.72	100
Location7_TTrack	PG 67-22	0.0348	N	Milled	124	138.31	100
Location7_TTrack	PG 67-22	0.0348	N	Milled	124	154.32	100
Location7_TTrack	PG 67-22	0.0348	N	Milled	209	162.70	90
Location7_TTrack	PG 67-22	0.0348	N	Milled	209	144.11	95
Location7_TTrack	PG 67-22	0.0348	N	Milled	209	125.59	90
Location7_TTrack	PG 67-22	0.0639	N	Milled	23	206.83	100
Location7_TTrack	PG 67-22	0.0639	N	Milled	23	324.81	95
Location7_TTrack	PG 67-22	0.0639	N	Milled	23	251.08	100
Location7_TTrack	PG 67-22	0.0639	N	Milled	124	278.19	100
Location7_TTrack	PG 67-22	0.0639	N	Milled	124	354.84	100
Location7_TTrack	PG 67-22	0.0639	N	Milled	124	294.76	90
Location7_TTrack	PG 67-22	0.0639	N	Milled	209	255.32	100
Location7_TTrack	PG 67-22	0.0639	N	Milled	209	228.17	100
Location7_TTrack	PG 67-22	0.0639	N	Milled	209	245.22	100
Location8_TTrack	None	0	N	Milled	23	65.99	100
Location8_TTrack	None	0	N	Milled	23	98.54	100
Location8_TTrack	None	0	N	Milled	23	102.45	100
Location8_TTrack	None	0	N	Milled	123	82.58	100
Location8_TTrack	None	0	N	Milled	123	86.15	100
Location8_TTrack	None	0	N	Milled	123	90.86	100
Location8_TTrack	None	0	N	Milled	209	125.29	100
Location8_TTrack	None	0	N	Milled	209	95.33	100
Location8_TTrack	None	0	N	Milled	209	118.65	100
Location8_TTrack	NTSS-1HM	0.068	N	Milled	23	143.28	85
Location8_TTrack	NTSS-1HM	0.068	N	Milled	23	139.64	85
Location8_TTrack	NTSS-1HM	0.068	N	Milled	23	146.66	90
Location8_TTrack	NTSS-1HM	0.068	N	Milled	123	200.15	75
Location8_TTrack	NTSS-1HM	0.068	N	Milled	123	171.07	30
Location8_TTrack	NTSS-1HM	0.068	N	Milled	123	209.62	30
Location8_TTrack	NTSS-1HM	0.068	N	Milled	209	164.43	95
Location8_TTrack	NTSS-1HM	0.068	N	Milled	209	154.72	90
Location8_TTrack	NTSS-1HM	0.068	N	Milled	209	140.32	95

Location	Tack	App_Rate (gal/yd^2)	Traffic	Surface	Curing (days)	Bond_ Strength (psi)	%Interface
Location8_TTrack	NTSS-1HM	0.092	N	Milled	23	157.12	75
Location8_TTrack	NTSS-1HM	0.092	N	Milled	23	146.62	100
Location8_TTrack	NTSS-1HM	0.092	N	Milled	23	212.43	100
Location8_TTrack	NTSS-1HM	0.092	N	Milled	209	140.13	95
Location8_TTrack	NTSS-1HM	0.092	N	Milled	209	162.15	100
Location8_TTrack	NTSS-1HM	0.092	N	Milled	209	157.49	90
Location8_TTrack	NTSS-1HM	0.096	N	Milled	23	127.58	55
Location8_TTrack	NTSS-1HM	0.096	N	Milled	23	120.42	100
Location8_TTrack	NTSS-1HM	0.096	N	Milled	23	153.53	75
Location8_TTrack	NTSS-1HM	0.096	N	Milled	209	180.57	100
Location8_TTrack	NTSS-1HM	0.096	N	Milled	209	154.51	85
Location8_TTrack	NTSS-1HM	0.096	N	Milled	209	196.82	95
Location8_TTrack	NTSS-1HM	0.92	N	Milled	123	274.99	100
Location8_TTrack	NTSS-1HM	0.92	N	Milled	123	289.86	100
Location8_TTrack	NTSS-1HM	0.92	N	Milled	123	256.94	100
Location8_TTrack	NTSS-1HM	0.96	N	Milled	123	130.01	100
Location8_TTrack	NTSS-1HM	0.96	N	Milled	123	167.05	95
Location8_TTrack	NTSS-1HM	0.96	N	Milled	123	188.38	90