EVALUATION OF THE INFLUENCE OF TACK COAT CONSTRUCTION FACTORS ON THE BOND STRENGTH BETWEEN PAVEMENT LAYERS

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Washington State Department of Transportation

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16. ABSTRACT

This study investigated the influence of several factors on the adhesive bond provided by the tack coat at the interface between pavement layers. These factors included the surface treatment, curing time, residual application rate, and coring location. Three tests were performed for measuring the bond strength between an existing hot mix asphalt (HMA) and a new HMA overlay, namely the Florida DOT Shear Tester, the UTEP Pull Off Test, and the Torque Bond Test. Testing involved a CSS-1 type emulsion as the tack coat.

The results from the three tests were statistically analyzed. Generally, milling provided a significantly better bond at the interface between the existing surface and the new overlay. Curing time had a minimal effect on the bond strength. The results indicated that the absence of tack coat did not significantly affect the bond strength at the interface for the milled sections, whereas it severely decreased the strength for the non-milled sections. The results also showed that increasing the residual rate of tack coat did not significantly change the bond strength at the interface. Lastly, the coring location was found to be an insignificant factor.

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Tack coat, interface, bond strength, shear strength, test for tack coat, statistical analysis, performance.

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EXECUTIVE SUMMARY

This study investigated the influence of several factors on the adhesive bond provided by the tack coat at the interface between pavement layers. These factors included the surface treatment, curing time, residual application rate, and coring location. Three tests were performed for measuring the bond strength between an existing hot mix asphalt (HMA) and a new HMA overlay, namely the Florida DOT Shear Tester, the UTEP Pull Off Test, and the Torque Bond Test. Testing involved a CSS-1 type emulsion as the tack coat.

The results from the three tests were statistically analyzed. Generally, milling provided a significantly better bond at the interface between the existing surface and the new overlay. Curing time had a minimal effect on the bond strength. The results indicated that the absence of tack coat did not significantly affect the bond strength at the interface for the milled sections, whereas it severely decreased the strength for the non-milled sections. The results also showed that increasing the residual rate of tack coat did not significantly change the bond strength at the interface. Lastly, the coring location was found to be an insignificant factor.

It should be noted that the aforementioned statements were based on the results from one type of tack coat, one HMA mixture for the existing surface, and one HMA mixture for the overlay. In addition, this study did not include long-term performance analyses, which may affect the overall conclusions.

Keywords: tack coat, interface, bond strength, shear strength, test for tack coat, statistical analysis, performance.

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CHAPTER I

INTRODUCTION

PROBLEM STATEMENT

A tack coat is a light application of an asphaltic emulsion between pavement lifts, most commonly used between an existing surface and a newly constructed overlay. Figure 1.1 shows a tack coat sprayed on an hot mix asphalt (HMA) surface. The role of a tack coat is to provide adequate adhesive bond between pavement lifts so that they behave as a monolithic structure. The inadequacy or failure of this bond causes slippage between the pavement layers, which results in a significant reduction in the shear strength of the pavement structure, thus making it more susceptible to a variety of distresses, such as cracking, rutting, and potholes (*1*).

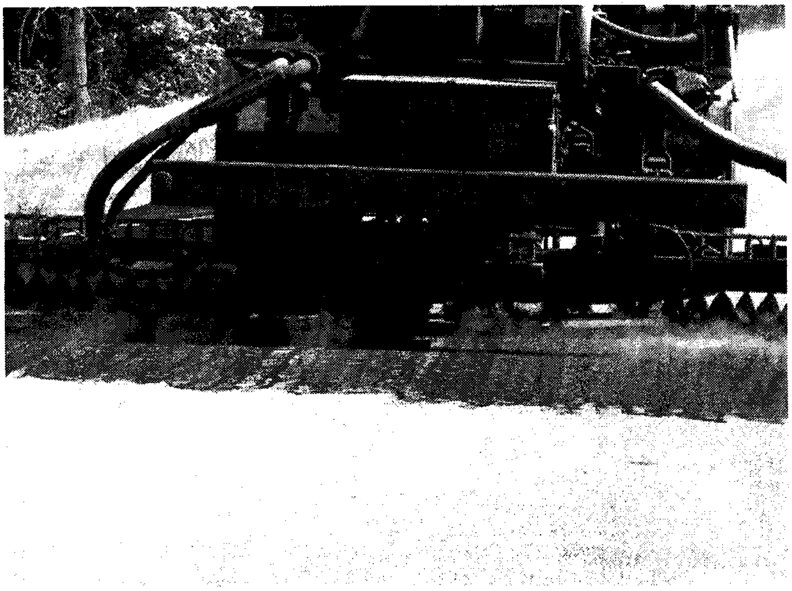


Figure 1.1: A truck spraying tack coat on an HMA surface.

A tack coat is considered as a simple, relatively inexpensive, yet essential step in the pavement construction process. However, there is currently a lack of unified guidelines on the construction practices and quality control/acceptance (QC/QA) of tack coats. In a recent study conducted by Washington State Department of Transportation (WSDOT), field cores were extracted to analyze the mode of cracking failure. Despite the fact that WSDOT requires tack coat on all HMA paving surfaces, approximately one third of the cores that exhibited "top-down cracking" debonded at the interface between the existing pavement and the subsequent overlay during extraction. These bond failures raise concerns about the adequacy of the adhesive bond achieved under current pavement construction practices.

It is therefore in the interest of state DOTs to develop a field test for both tack coat quality control (as performed by the contractor) and quality acceptance (performed by DOT). A protocol for tack coat application is also crucial. It is anticipated that this will contribute to improving the performance of the entire pavement structure by assuring that a minimum adhesive bond is achieved between the pavement lifts. This will yield significant benefits in resisting early failure due to top-down cracking and other pavement stresses, both load and environmentally induced.

RESEARCH OBJECTIVE

The objective of this study was to investigate the factors that influence the adhesive bond provided by the tack coat at the interface between pavement lifts. These factors included the surface condition, tack coat curing time, tack coat residual rate, and coring location (middle of the lane vs. wheel path). This study also aimed at evaluating potential quality tests for tack coat application.

ORGANIZATION OF THE REPORT

This report consists of five chapters. Chapter I is the introduction. Chapter II summarizes the literature review on tack coat. Chapter III provides a description of the experiment. Chapter IV discusses the results and analyses. Chapter V provides a summary of findings and recommendations.

CHAPTER II

LITERATURE REVIEW

This chapter presents a literature review on the current state of the practice for tack coat operations. It also provides a background on test methods used to evaluate the bond strength at the interface between pavement lifts.

FACTORS THAT INFLUENCE THE BOND STRENGTH AT THE INTERFACE

It is generally accepted that the bond characteristics at the interface between an existing pavement and an overlay are affected by several factors. These factors include the tack coat type, application rate, curing time, and surface condition. The subsequent sections present a summary of the literature review pertinent to each one of these factors.

Tack Coat Type

Insufficient bond between layers of HMA can cause many pavement problems such as fatigue cracking, top down cracking, delamination, and slippage failure. Existing literature reveals various kinds of materials used as tack coats between HMA layers. These include asphalt emulsions, paving grade asphalt binders, and cutback asphalts. In general, however, local experience and engineering judgment have dictated the tack coat type to be used.

Emulsions are recognized as the most commonly used types of tack coat material. Emulsified asphalts are graded according to their setting rate, which is controlled by the type and amount of the emulsifying agent. The anionic emulsions include rapid setting (RS), medium setting (MS), and slow setting (SS). The anionic grades are: RS-1, HFRS-2, RS-2, MS-1, HFMS-

2, MS-2, MS-2h, SS-1, and SS-1h. The other types of emulsions are the cationic emulsions, which also include rapid-setting (CRS), medium-setting (CMS), and slow-setting (CSS) grades. The cationic grades include, but are not limited to, CRS-1, CRS-2, CMS-2, CMS-2h, CSS-1, and CSS-1h.

Among the materials mentioned above, slow-setting emulsions are most commonly used for the following reasons: 1) they provide the additional volume needed for the distributor to function at normal speed where lower application rates are used, and 2) they flow easily from the distributor at ambient temperatures allowing for a more uniform application (*2, 3*). However, they take longer to break than rapid-setting emulsions. For this reason, they are not recommended for use as a tack coat in relatively cool weather, at night, or when there is a narrow construction window. The rate of breaking is dependent on the type of emulsion, the amount of water added, the type and concentration of the emulsifying agent, and the atmospheric conditions.

Cationic emulsions are usually used in areas with damp pavement (e.g., coastal areas) because they are less sensitive to moisture and temperature. Rapid-setting emulsions are commonly used at night or in cooler weather since their breaking time is shorter than slow-setting emulsions (*4*). Paving grade asphalt is used for night work or work in cool weather because paving grade asphalt does not require any time to break before it can be overlaid. Paving grade asphalt is commonly used as a tack coat material for new rubberized HMA overlays (*4*). Paving grade asphalt is heated and applied at a much higher temperature than an emulsion, but it tends to cool quickly, which requires immediate application in front of the paver (*5*). Difficulty in controlling flushing of the HMA, and therefore the application rates, hinders the use of paving grade asphalts in tack coat applications. Cutback asphalt is occasionally used as tack coat and can be used in colder climate than emulsions (*6*). However, environmental concerns limit their use in some locations (*7, 8*). It should be noted that the State of Washington is one of the states that does not allow the use of cutbacks for this reason.

An international survey, conducted by the International Bitumen Emulsion Federation in 1999, reported that cationic emulsions are the most commonly used tack coat material (*9*). A U.S. survey, conducted by Paul and Scherocman (*10*), indicated that most states have adopted the use of slow-setting type of emulsions. The most common among them are SS-1, SS-1h, CSS-1, and CSS-1h. Some states like California, Florida, and Vermont use the rapid-setting type of emulsions such as RS-1 and RS-2. Florida and Georgia are the only states that use paving grade asphalts (AC-5, AC-20, and AC-30) as tack coats at the time of the survey. Some states specify the materials used according to the construction situations. For example, Florida DOT Standard Specifications allow the use of one of three types of tack coat materials. For daytime construction, either of two rapid-setting emulsions (RS-1 or RS-2) can be used, whereas a viscosity-grade asphalt binder (AC-5) is specified for nighttime construction.

Cross and Shrestha (*2*) conducted a recent survey in 2004 to determine the most common practices for tack coat applications. In their survey, 13 DOTs reported using tack coats on a routine basis. Twelve of them reported using slow-setting emulsions as the primary material for tack coat, mainly an SS-1, SS-1h, a CSS-1, or CSS-1h. Caltrans reported that paving grade asphalt (AR-4000) was the most common tack coat material followed by either SS-1 or CSS-1 emulsions. New Mexico and Texas reported that PG binders were occasionally used as tack coat. Kansas DOT was the only agency that occasionally uses cutback asphalts as tack coat (*2*). It should be noted that the findings of the aforementioned surveys do not totally agree because of the more recent trend of allowing a wider range of materials in tack coat applications.

Several comprehensive field and laboratory studies were conducted to determine the effectiveness of tack coat materials. The results of these studies were not totally consistent, especially when comparing between emulsions and asphalt binders. Mohammad et al. (*11*) investigated the effect of tack coat materials on the interface shear strength. They examined different types of emulsions and asphalt binders. Four emulsions (CRS-2P, SS-1, CSS-1, and SS-1h) and two paving asphalt binders (PG 64-22 and PG 76-22) were evaluated as tack coat materials. A simple shear test using the Superpave Shear Tester (SST) was performed to determine the shear strength at the interface. Based on their statistical analyses, there was no significant difference in simple shear strength between the tack coat materials evaluated at a test temperature of 131°F. However, at a test temperature of 77°F, CRS-2P was identified as the best tack coat type having significantly higher shear strength than the other types of tack coat.

A similar study was conducted by West et al. (*12*), evaluating two types of emulsions (CRS-2 and CSS-1) and one paving grade binder (PG 64-22). Bond strength at the interface was measured using a shear-testing device, which was a modified version of the Florida DOT shear tester. The researchers reported that the paving grade binder (PG 64-22) had a higher bond strength than the two emulsions, which seems to contradict with the previous study by Mohammad et al. (*11*). However, it is noteworthy that the CRS-2P used by Mohammad et al. (*11*) had the highest viscosity as measured by a rotational viscometer at 275°F. Thus with the limited results from these studies, it can be suggested that the viscosity of the tack coat can play a significant role in influencing the bond strength at the interface between the layers. Indeed, the U.S. military agencies adopted the viscosity as a criterion to determine the proper application of tack coat (Saybolt Furol viscosity between 10 and 60 seconds) (*6*).

Tack Coat Application Rate

An excessive amount of tack coat can cause slippage, whereas too little may result in de-bonding problems. Therefore, it is important to estimate the amount of tack coat that will produce the optimum outcome. The tack coat application rate should vary with the condition of the existing surface to which it is applied. In general, a tight or dense surface requires less tack coat than an open textured, raveled, or milled surface; and a flushed or bleeding surface requires less tack coat than a dry or aged surface. The proper application rate also varies with the product being applied as well as the HMA mixture that will be placed as an overlay. Generally, slow-setting grade emulsions require higher application rates than rapid-setting grade emulsions, and rapid-setting grade emulsions require higher application rates than paving grade asphalt binders. Furthermore, dense and gap-graded HMA overlays require less tack coat than open-graded overlays (*4*).

It is sometimes not clear in the literature whether the application rate includes the water added for dilution or the residual asphalt contents. To avoid confusion, *The Hot-Mix Asphalt Paving Handbook 2000* recommends that application rates should be based on residual asphalt content. The application rate to achieve a specified residual asphalt content can be determined using the following equation:

$$AR = (RAR / RAC) / (D / 100) \qquad (2\text{-}1)$$

Where:

AR = Application or shot rate of undiluted tack;

RAR = Specified residual application rate;

RAC = Residual asphalt content of tack;

D = Percent dilution.

Internationally, the tack coat application rates are based on residual binder content and range between 0.12 and 0.40 L/m^2 (0.0265 and 0.089 gal/yd^2, respectively) (*9*). In the U.S., almost all states typically use residual application rates between 0.06 and 0.26 L/m^2 (0.013 and 0.058 gal/yd^2, respectively) when slow-setting emulsions are used (*10*).

Attempts were made to find the optimum application rate by several researchers in the past. Uzan et al. (*13*) reported interface adhesion properties of asphalt layers based on laboratory shear test results. They conducted direct shear tests on one type of HMA pavement to measure the shear strength considering various application rates of 0.0, 0.49, 0.97, 1.46, and 1.94 L/m^2 (0.0, 0.11, 0.21, 0.32, and 0.43 gal/yd^2, respectively). Their conclusions was that the use of tack coat increased the interface bond strength and that there was an optimum tack coat application rate at which the shear resistance reached a maximum value. According to their study, the optimum application rates were found to be 0.49 and 0.97 L/m^2 (0.11 and 0.21 gal/yd^2, respectively) at 55°C and 25°C, respectively.

Mohammad et al. (*11*) also investigated the influence of asphalt tack coat rate on the interface shear strength using the Simple Shear Test on one type of HMA pavement. The residual rates considered in their study were 0.00, 0.09, 0.23, 0.45, and 0.90 L/m^2 (0.0, 0.02, 0.05, 0.1, and 0.2 gal/yd^2, respectively). For the best performing tack coat material (CRS-2P), which had the highest shear strength, the optimum residual rate was found to be 0.09 L/m^2 (0.02 gal/yd^2).

Lavin (*14*) recommended application rates of 0.2 to 1.0 L/m^2 (0.044 and 0.22 gal/yd^2, respectively) and that tack coat be diluted to a final asphalt binder content of 30% to improve uniformity of spray. He further suggested that milled pavements may require application rates of 1.0 L/m^2 (0.22 gal/yd^2) or more due to a larger surface area caused by grooving.

Sholar et al. (*15*) developed a shear testing device to evaluate shear strength of HMA overlays. Their study also involved the construction of three field projects and the evaluation of several variables that could affect the bonding strength between HMA layers. These variables included the application rate, surface condition, surface texture, and mixture type. The residual application rates examined were 0.00, 0.091, 0.226, and 0.362 L/m^2 (0.0, 0.02, 0.05, 0.08 gal/yd^2, respectively). Their study showed that there was a slight effect of the application rates on the shear strength. They recommended a residual application rates of 0.091 L/m^2 (0.02 gal/yd^2) as a minimum and 0.266 L/m^2 (0.05 gal/yd^2) as an optimum.

For design purposes, there are guidelines and specifications on tack coat application rates available in some handbooks. *The Aggregate Handbook* (*16*) states that the application rate should be within limits (0.05 to 0.15 gal/yd^2) to prevent puddling of material that may result in potential slippage between layers. The USACE's Unified Facilities Criteria (UFC) indicates that lighter application rates of tack coat are generally preferred since heavy application can cause serious pavement slippage and bleeding problems (*6*). USACE's UFC recommends residual application rates of 0.23 to 0.68 L/m^2 (0.05 to 0.15 gal/yd^2, respectively). *The Hot-Mix Asphalt Paving Handbook 2000* (*5*) also recommends application rates based on residual asphalt content between 0.18 and 0.27 L/m^2 (0.04 and 0.06 gal/yd^2, respectively). Table 2.1 and Table 2.2 are examples of recommended application rates used in Ohio and California. Table 2.3 shows recommended application temperatures for typical tack coat materials from the Asphalt Institute (*17*).

Table 2.1: Recommended tack coat application rates in Ohio (*7*).

Existing Pavement Condition	Application Rate		
	Undiluted	**Diluted (1:1 with Water)**	**Residual**
	(gal/yd^2)	(gal/yd^2)	(gal/yd^2)
New Asphalt	0.05 - 0.07	0.10 - 0.13	0.03 - 0.04
Oxidized Asphalt	0.07 - 0.10	0.13 - 0.20	0.04 - 0.06
Milled Surface (HMA)	0.10 - 0.13	0.20 - 0.27	0.06 - 0.08
Milled Surface (PCC)	0.10 - 0.13	0.20 - 0.27	0.06 - 0.08
PCC	0.07 - 0.10	0.13 - 0.20	0.04 - 0.06

Table 2.2: Recommended tack coat application rates in California (*4*).

	Type of Surface	**Slow-Setting** [A]	**Rapid-Setting** [B]	**Paving Asphalt** [C]
HMA Overlay (gal/yd^2)	Dense, Tight Surface (e.g., between lifts)	0.044 - 0.077	0.022 - 0.044	0.011 - 0.022
	Open Textured or Dry, Aged Surface (e.g., milled surface)	0.077 - 0.199	0.044 - 0.088	0.022 - 0.055
Open-Graded HMA Overlay (gal/yd^2)	Dense, Tight Surface (e.g., between lifts)	0.055 - 0.11	0.022 - 0.055	0.011 - 0.033
	Open Textured or Dry, Aged Surface (e.g., milled surface)	0.11 – 0.243	0.055 - 0.121	0.033 - 0.066

[A] Asphalt emulsion diluted with additional water.

[B] Undiluted asphalt emulsion.

[C] Any grade of paving asphalt is acceptable as tack coat material. However, it would be best to use the same grade of paving asphalt that is used in the HMA.

Table 2.3: Recommended spraying temperatures for tack coat (*17*).

Type and Grade of Asphalt	Temperature Range	
	°C	°F
SS-1, SS-1h, CSS-1, CSS-1h	20 - 70	70 - 160
MS-1, MS-2, MS-2h, CMS-2, CMS-2h	20 - 70	70 - 160
MC-30	≥ 30	≥ 85
MC-70	≥ 50	≥ 120
MC-250	≥ 75	≥ 165

Tack Coat Curing Time

There is not a unanimous agreement in the literature on the curing time of tack coats. Some research studies and guidelines suggest that the tack coat be cured before laying the new pavement layer (*3, 7, 8, 17, 18, 19*). The Asphalt Institute reports that tack coats placed too far ahead of the paver can lose their adhesive characteristics and that any tack that is not covered in one day should be re-tacked prior to paving (*3*). Sholar et al. (*15*) evaluated the importance of curing tack coats. They measured direct shear strength of tack coats from field cores. They concluded that the shear strength slightly increased with curing time.

On the other hand, multiple studies have reported the opposite. The U.S. Army Corps of Engineers indicated that although under most circumstances, an emulsion will set in 1 to 2 hours, HMA can usually be placed on top of an unbroken tack coat without detrimental effect on pavement performance. The idea is that the emulsion will break immediately upon contact with the new HMA. The water will typically evaporate and escape as steam through the loose HMA (*5*). Lavin (*14*) reported that an overlay could be placed either directly after the tack coat has been applied or after it has broken. The bond between the layers will still be created regardless of whether the asphalt emulsion has broken prior to paving the subsequent layer or not.

Paul and Scherocman (*10*) reported the results of a nationwide survey in the U.S. Three states had a maximum time that a tack coat can be left before placement of the HMA overlay and four states indicated that paving was required on the same day the tack coat was applied. While only some states specified maximum curing periods (Alaska – 2 hours, Arkansas – 72 hours, Hawaii – 4 hours, and Texas – 45 minutes), many states specified a minimum time between tack coat application and the placement of the HMA overlay to provide adequate time for the emulsion to break. The minimum required time ranges from 15 minutes to 1 hour or until the emulsion breaks.

Surface Condition

The surface conditions of an existing pavement including texture, cleanliness, and wetness, are very important factors that influence the bond strength at the interface. There is a general agreement in the guidelines concerning the required surface conditions of an existing pavement. It is recommended that tack coat be applied to a clean, dry surface. The recommended cleaning method is to sweep the surface with a power broom (*3, 5, 7, 8, 18*).

Regarding the cleanliness of an existing pavement surface, there are two guideline manuals published by the Asphalt Institute. MS-22 (*3*) suggests that a tack coat be applied under the same weather conditions as HMA paving and that the surface should be clean and dry prior to application. The other manual, MS-19 (*17*), reports that the best bond can be obtained when a tack coat is applied on a dry pavement surface with a temperature above 77 °F. However, Hachiya and Sato's limited lab test results (*20*) indicated that for a certain type of emulsion, the influence of dirt on tack coat strength is minimal. The researchers reported that dirt did not influence the strength of the interface bond if curing was fully achieved (*20*). It should be noted that Hachiya and Sato (*20*) used a laboratory experiment in their study. Cylindrical 4-inch diameter by 4-inch height specimens were cut from large HMA blocks (12-inch wide, 12-inch long, and 4-inch thick), which were prepared in two lifts. Each lift was compacted using a roller compactor.

Sholar et al. (*15*) evaluated the effect of rain falling on a cured tack coat prior to the application of the HMA overlay. The presence of moisture significantly reduced the shear strength at the interface when compared to equivalent sections that did not have moisture. Regarding the surface texture, Sholar et al. (*15*) found that coarse graded HMA mixes had higher shear strength compared to fine grade mixes and that as the surface roughness increased, the influence of the tack coat application rate diminished. Milling increased the shear strength at the interface and reduced the effect of the application rate. For milled sections, it was noticed that using tack coat was not effective in increasing the shear strength at the interface.

West et al. (*12*) also compared bond strengths between fine-graded and coarse-graded mixtures. They found that the fine-graded mixtures generally had higher bond strengths than the coarse-graded mixture when tested at 77 ° F. However, they also reported that there were significant interactions of mix type (texture) with other variables (application rate, materials used, and testing temperature), which would reverse this trend in some cases. It should be noted that West et al. (*12*) used laboratory fabricated specimens in addition to field experiments. Normal Superpave mix design sized samples (4.6-in height by 6-in diameter) were fabricated at optimum asphalt content using a Superpave Gyratory Compactor (SGC). The specimens were cut into two halves and volumetric properties of each half were measured. Tack coat materials were evenly applied to the uncut side of each half using a wooden spatula at each of the desired application rates. The SGC half specimen with tack coat was then put into a SGC mold (tack surfacing upward) and loose mix of the same mix type was placed on top of the tack surface and compacted to 50 gyrations. This compaction effort was selected to provide a density of the upper layer that would be representative of the first few years of the pavement life and to avoid over compacting the mix, which may result in excessive breakdown or disturbance of the tacked interface. The study evaluated the effect of several variables including application rate, mix type, tack coat type, normal pressure, and test temperature.

The literature seems to agree that a milled asphalt pavement requires higher application rates (*3, 6, 17, 18*). However, Cooley (*21*) reported on the results of an experiment involving a milled surface without a tack coat, which had a good bond. In his field study, the existing pavement was milled approximately 2-inches with the majority of the milled materials being used as recycled asphalt pavement (RAP). The contractor lightly swept the milled surface, leaving a small amount of millings primarily in the bottom of the grooves. The new HMA mixture was then placed directly onto the milled surface with no tack coat. The premise of this methodology was that the milled pavement in conjunction with the melting of the asphalt within the lose millings by the heat of the placed mixture would result in a bond between the two layers.

According to WSDOT Standard Specification 5-04.3(5)A, the entire surface of the pavement shall be thoroughly cleaned of dust, soil, pavement grindings, and other foreign matters (*1*). A proper bond cannot be achieved if the surface is not thoroughly cleaned. The tack coat will bond to the excess debris left behind and not to the existing surface as shown in Figure 2.1. When the paving equipment are allowed onto the tack coat, “tracking” or “pick up” can occur, which is the term used to describe when the tires of the paving and delivery equipment pick up the tack coat. Tracking typically occurs in both wheel paths, which is the most critical location for the new surface to bond to the existing surface. This problem happens more often with a milled surface because of the large amount of debris created during the milling process. Brooming the surface typically does not remove the debris adequately. A broom and vacuum system may be necessary to completely clean the roadway prior to the application of the tack coat (*1*).

Figure 2.1: Tracking due to the presence of debris.

TESTING METHODS FOR TACK COAT

Parallel to the importance of the construction practices of tack coat is the need to evaluate the quality of the adhesive bond provided by the tack coat. There are currently several tests available for evaluating the quality of tack coat bond including the following:

☐ Texas DOT UTEP Pull-Off test, which is conducted on the tack coat before the construction of the overlay;

☐ "Attacker", developed by *Instrotek Inc* to evaluate the torque and tensile strength of the tack coat;

☐ NCAT shear test performed on cores;

☐ Leutner test, originally developed in Germany;

☐ Torque Bond test, which was developed in the United Kingdom and can be used in the lab or in the field after paving;

☐ Superpave Shear Tester (SST), which has been recently modified by the Louisiana Transportation Research Center by building a shear mold assembly;

☐ FDOT Shear Tester.

The FDOT Shear Tester, Torque Bond test, and UTEP Pull-Off test were used and investigated for the purpose of this study. Details on these tests are presented in Appendix A, B, and C, respectively. An overview of these test procedures is provided in the subsequent sections.

FDOT Shear Tester

The Florida DOT identified the need for the development of a tack coat test set-up after premature failures in pavements overlaid on wetted tack coats. In 2003, the test set-up and procedure was developed after an extensive literature review and laboratory testing, as well as field investigation (*15*). This simple direct shear device can be used in a universal testing machine (e.g., MTS) as shown in Figure 2.2, or a Marshall Stability apparatus. The developed shear test attachment is shown in Figure 2.3.

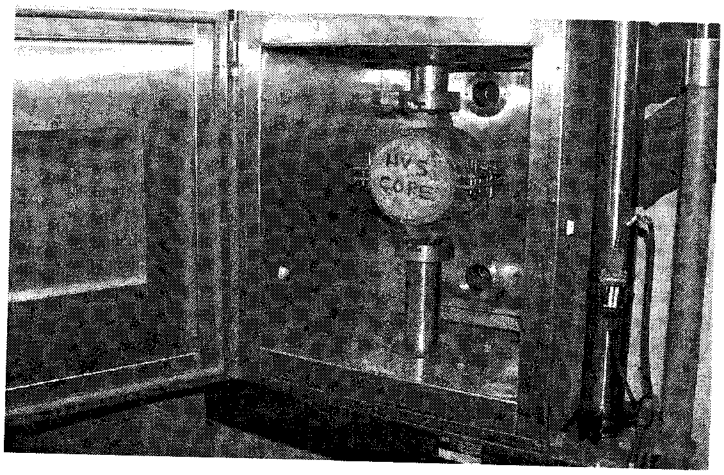


Figure 2.2: FDOT Shear Tester device inside an MTS (Courtesy of FDOT).

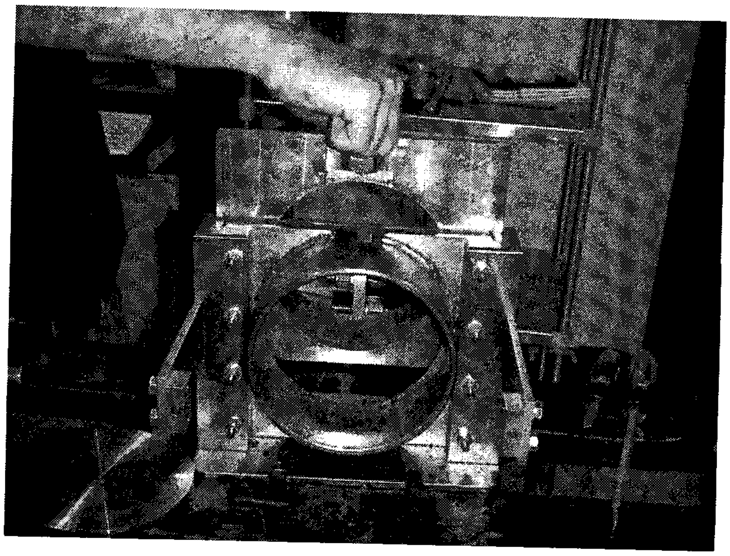


Figure 2.3: Shear test attachments used in FDOT Shear Tester.

Specimens should be 6-inches in diameter in order to reduce testing variability (larger shear surface area). The gap between the two rings is 3/16 inch. This gap is not adjustable and was chosen to account for skewness, bending stresses of the cored mix samples, and/or the irregular surface of the cored specimens. This is to account for the irregular surface of the cored specimens. The load application is strain controlled at a rate of 2-in/min (50.8-mm/min), which can be easily achieved in the Marshall Stability test apparatus or MTS. Before performing the test, the field core is conditioned at a temperature of $25\pm1\,^{\circ}\mathrm{C}$ (77 °F) for a minimum of 2 hours. The core is then placed between the shear plates so that the direction of traffic marked on the core is parallel to the shear direction. The core is then deformed at a constant rate of 2-in/min until failure occurs. The shear strength is then calculated using the following equation.

$$S_B = \frac{4P_{Max}}{\pi D^2} \tag{2-2}$$

where S_B is the shear strength (psi); P_{Max} is the maximum load applied to specimen (lb.f); and D is the specimen diameter (inch).

Torque Bond Test

The Torque Bond test was originally developed in Sweden for the in-situ assessment of bond conditions and has been adopted in the UK as part of the approval system for thin surfacing systems (*22*). In this test, the pavement is cored deeper than the interface of interest and is left in place (*9*). Torque is then applied manually to the top of the core inducing a twisting shear failure at the interface. The maximum torque measured at failure is indicative of the shear strength of the tack coat. For practical reasons, this test is generally limited to the interface between the thin surfacing and the layer underneath and is typically performed in-situ.

Recently, a laboratory-based torque test was developed allowing the test to be conducted in a more controlled environment (*23*). The first step in conducting the Torque Bond test in the laboratory is to take a core through the pavement. The field core is then clamped below the interface using a gripping unit as shown in Figure 2.4a. A steel plate is glued to the top surface of the specimen prior to the test, which acts as an adapter between the specimen and the torque wrench (Figure 2.4b). A torque wrench is then attached to the plate and a torque is applied until the specimen fails. The force required for failure is recorded as well as the location of the failure (Figure 2.4c). The bond strength for the specimen is then calculated using the following equation:

$$\tau = \frac{12M \times 10^6}{\pi D^3} \tag{2-3}$$

Where τ is the inter-layer bond strength (kPa); M is the peak torque at failure (N.m); and D is the diameter of the core (mm). The laboratory Torque Bond test is conducted at 20±2°C (68±4°F) unless otherwise specified. Torque is applied to the plate until failure of the bond occurs or a torque of 300-N.m is exceeded. For a well-bonded material, the failure occurs in the underlying material, and not at the bonded interface. Figure 2.5 show the laboratory test set-up that was used in this study.

a. Torque Grip b. Specimen Set-up c. Laboratory test

Figure 2.4: Laboratory Torque Bond test (*24*).

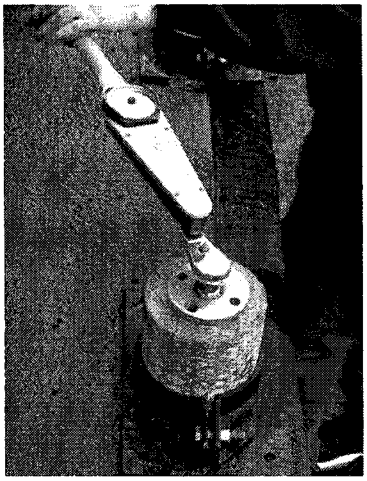


Figure 2.5: WSDOT personnel performing the Torque Bond test.

UTEP Pull-Off Test

The Pull-Off test was developed at the University of Texas at El Paso (UTEP). It measures the tensile strength of the tack coat before a new overlay is paved (*25*). The UTEP Pull-Off device measures the strength of the tack coat in tension mode rather than in shear mode. The instrument weighs about 23 pounds and it is leveled through pivoting feet as shown in Figure 2.6. A torque wrench, which is attached to the device, pulls the plate up from the tacked surface.

The UTEP Pull-Off test procedure is simple. After the tack coat is applied on the pavement, it is allowed to set (typically less than 30 minutes). Thereafter, the device is placed on the tack-coated surface. The torque wrench is rotated clockwise until the contact plate is firmly set on the tack-coated pavement. A 40-pound load is placed on the weight key (at the top of the device) for ten minutes prior to testing in order to set the contact plate. The load is then removed and the torque wrench is rotated in the counter clockwise direction to detach the contact plate from the tack-coated pavement. The torque required to detach the contact plate from the tacked pavement is recorded in inch-lb, and then is converted to the strength using a calibration factor. The calibration factor is obtained by placing loads in uniform increments on the contact plate and recording the torque required to pull the plate for each load increment. The relationship between the torque and load is established by fitting a straight line through the data points. Figure 2.7 shows one of the two UTEP Pull-Off devices used in this study.

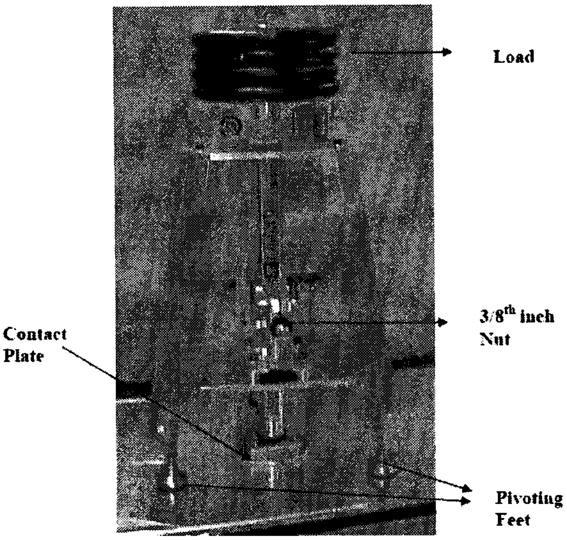
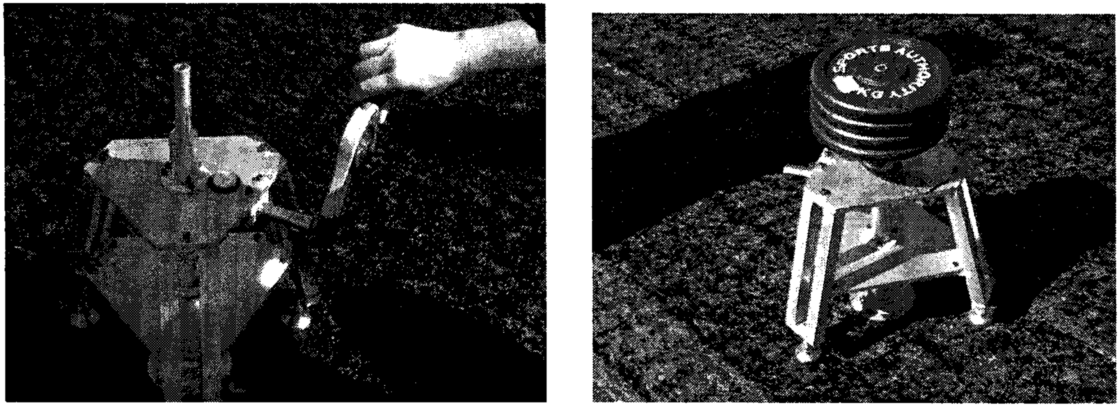


Figure 2.6: UTEP Pull-Off Test device.



a. Torque Wrench

b. 40-pound load

Figure 2.7: UTEP Pull-Off device used in this study.

Summary Comparison of Test Methods

Table 2.4 shows a comparison between the three aforementioned test methods. These tests were performed in order to evaluate their potential in quantifying the adhesive bond provided by the tack coat at the interface between pavement lifts.

Table 2.4: Comparison of the test methods used in this study.

	FDOT Shear Tester	**Torque Bond Test**	**UTEP Pull-Off Test**
Load Type	Direct Shear	Torsion	Tension
Loading Rate	2 inches/min.	Wrench sweeps 90 ° within 30±15 sec.	N/A
Specimen Diameter	5.91 inches	5.91 inches[1]	5 inches[2]
Conditions[3] prior to test	77 ± 1.8 ° F for a minimum of 2 hours	68 ± 3.6 ° F for 4-16 hours	40 pound load for 10 minutes

[1] 3.94 inches diameter is preferred to limit the magnitude of the moment to break the bond.

[2] Diameter of the contact plate.

[3] For laboratory tests.

CHAPTER III

EXPERIMENT

The experiment began on September 13, 2005 under the supervision of WSDOT and in cooperation with the Washington Asphalt Pavement Association (WAPA), Woodworth & Company Inc, and Lakeside Industries. It consisted of building 14 test sections in order to investigate the influence of several factors on the bond strength at the interface between the existing surface and the newly constructed overlay. These factors included the following:

- Surface treatment: milled vs. non-milled;
- Curing time: broken vs. unbroken;
- Approximate target residual rate: 0.00, 0.018, 0.048, and 0.072 gal/yd^2;
- Location: wheel path (WP) vs. middle of lane (ML).

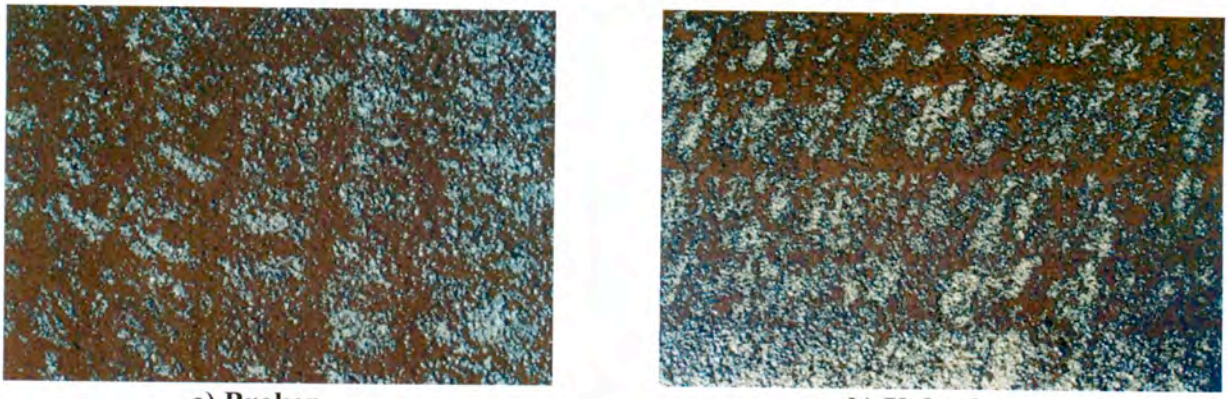
The experiment took place at the Nisqually weigh station near exit 116 of northbound Interstate I-5 in Olympia, WA. The weather conditions during the experiment were sunny and clear with an average high temperature of 73 °F and a wind speed of 3 mph. Figure 3.1 shows a layout of the test sections. The first 7 sections were milled and cleaned using a broom, whereas sections 8 through 14 were not milled but cleaned (non-milled sections). Figure 3.2 shows the milled and non-milled sections after cleaning. A non-diluted CSS-1 tack coat emulsion was applied to the test sections at four different target residual rates of 0.00, 0.018, 0.048, 0.072 gal/yd^2. These target rates are hence referred to as No-Tack, 0.02, 0.05, and 0.07, respectively, throughout the report for simplicity. A new 2-inch overlay was placed using a Superpave ½ inch nominal maximum aggregate size HMA mixture. The odd sections (except section 7) were paved after the tack coat had broken, i.e., the tack coat had enough time to cure and set (approximately 2.5 hours). The placement of HMA on the even sections (except section 8) began approximately 3 minutes after the tack coat was applied (Unbroken sections). Test sections number 7 and 8 had no tack coat (No Tack sections). Figure 3.3 shows a picture taken during paving and compaction of the milled and broken sections number 1 and 3, respectively. Figure 3.4 shows two pictures, one taken for a broken tack coat and the other for an unbroken one. Figure 3.5 shows pictures representing the three residual rates for the milled and non-milled sections.

Non-milled	**13**	0.07	**14**	0.07	48’
	11	0.05	**12**	0.05	48’
	9	0.02	**10**	0.02	48’
	8	No tack coat			48’
Milled	**7**	No tack coat			55’
	5	0.07	**6**	0.07	50’
	3	0.05	**4**	0.05	50’
	1	0.02	**2**	0.02	50’
	Broken		**Unbroken**		
	14’		14’		

Figure 3.1: Layout of the test sections. Approximate target residual rates are listed in gal/yd^2.

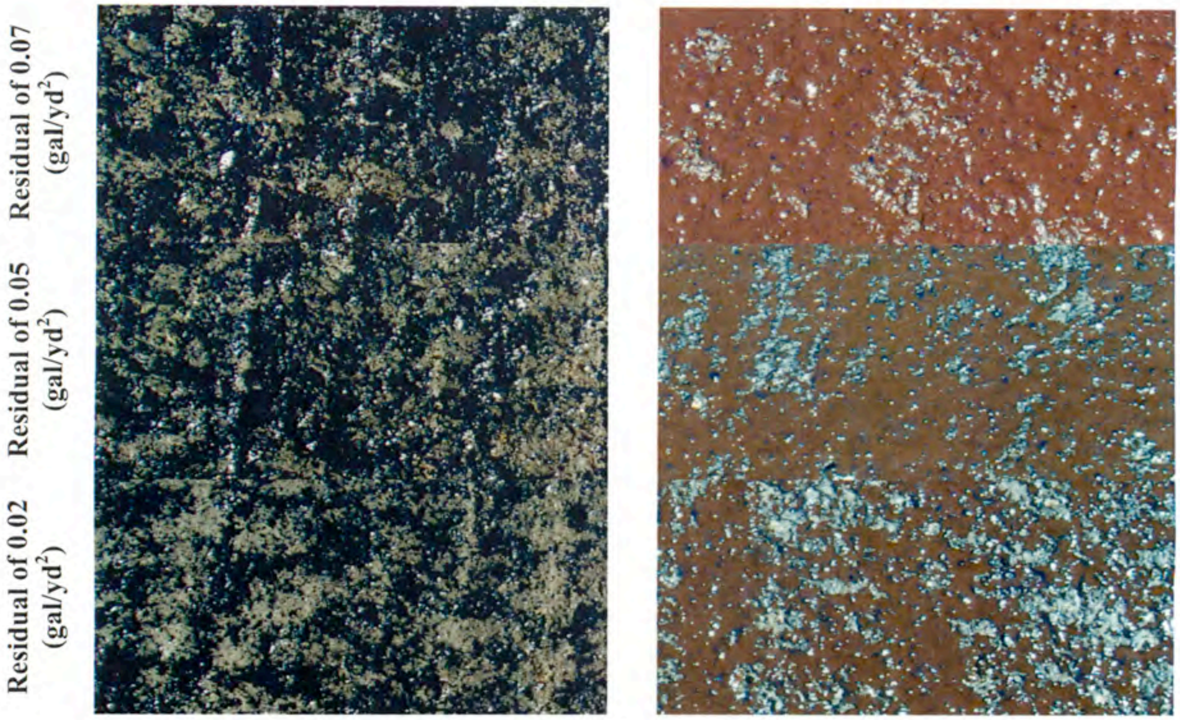
Figure 3.2: Milled and non-milled sections after cleaning.

Figure 3.3: Compaction and paving of sections number 1 and 3, respectively.



a) Broken b) Unbroken

Figure 3.4: Pictures showing a broken and an unbroken section, on a non-milled surface with 0.02 gal/yd^2 residual rate.



a) Milled Sections b) Non-milled Sections

Figure 3.5. Varying residual tack coat rates (approximate) on milled and non-milled sections.

The residual tack coat rates were measured by WSDOT according to ASTM D2995 as shown in Figure 3.6. One measurement was taken for each section (except the No Tack sections number 7 and 8). It should be noted that WSDOT has modified the ASTM D2995 test to measure the residual rate instead of the application rate. Table 3.1 shows the target and measured residual rates. The correlation between them was 0.62 indicating that, in general, high values of target residual rates corresponded to high values of measured residual rates and low values of target residual rates corresponded to low values of measured residual rates. Nonetheless, the test over-predicted the target residual rates at lower rates and under-predicted them at higher rates as shown in Figure 3.7 (measured rates varied by only 0.019 gal/yd2). This could be attributed to an inaccuracy in measuring the target residual rates, lack of samples, an inaccuracy in applying the target rates by the truck, or any combination of these factors. However, it was noticed during the placement of the tack coat that the variations in the residual rates among the test sections were larger than the predicted values by the ASTM test as visually shown in Figure 3.5. Based on this visual observation, it was decided to use the target residual rates in the subsequent statistical analyses.

Figure 3.6: Measuring the residual rate of tack coat on a test section.

Table 3.1: Target and measured residual tack coat rates (gal/yd^2).

Test Section	Target Residual Rate	Measured Residual Rate	Average Measured Residual Rate
1	0.018	0.033	0.037
2	0.018	0.046	
9	0.018	0.034	
10	0.018	0.033	
3	0.048	0.038	0.041
4	0.048	0.043	
11	0.048	0.035	
12	0.048	0.046	
5	0.072	0.042	0.046
6	0.072	0.052	
13	0.072	0.044	
14	0.072	0.044	
Correlation	0.62		

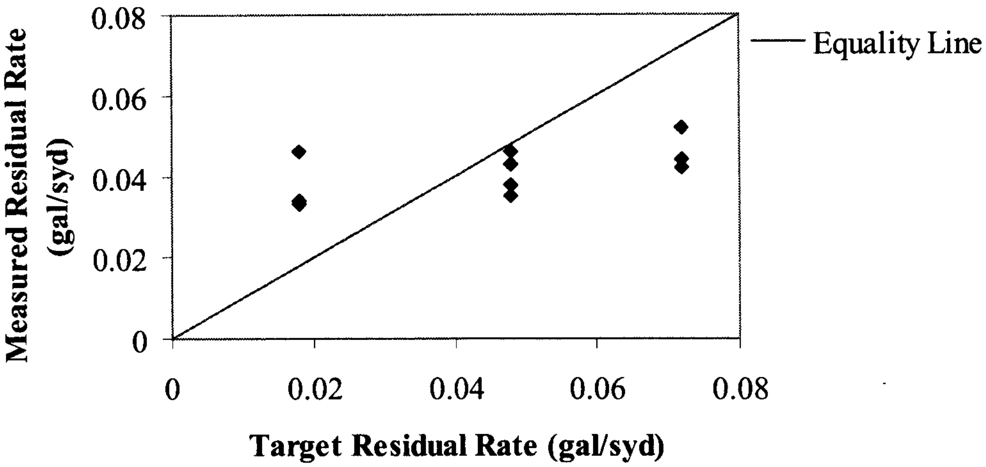


Figure 3.7: Target residual rates vs. measured residual rates.

The experiment consisted of performing three tests, namely the UTEP Pull-Off test, the Torque Bond test, and the FDOT Shear Tester. The UTEP Pull-Off test was performed on the broken sections before paving. Two devices were used simultaneously, one on the milled sections and the other on the non-milled sections. Figure 3.8 shows the approximate location and sequence of the UTEP Pull-Off tests. The P_B tests (numbers 4, 5, and 6) were performed approximately 45 minutes after the P_A tests (numbers 1, 2, and 3) on the same test section. Test number P_A7 was an additional one taken approximately one hour after test number P_A3 at approximately the same location.

The day following paving and compaction, five nuclear density tests were taken for each section. The density measurements are presented in Appendix D. The average density for each test section is tabulated in Table 3.2. The coefficient of variation for all the density measurements was 2.1% on average, and did not exceed 5% on any test section. This was an indication of the uniformity in the density within each test section and among the test sections, thus it was anticipated that the density would not be a factor that would significantly affect the analyses. It should be noted that these density measurements compared well to typical WSDOT values. WSDOT long-term average density is approximately 93.6% with a standard deviation of 1.6, and the minimum average density for a lot is 91%.

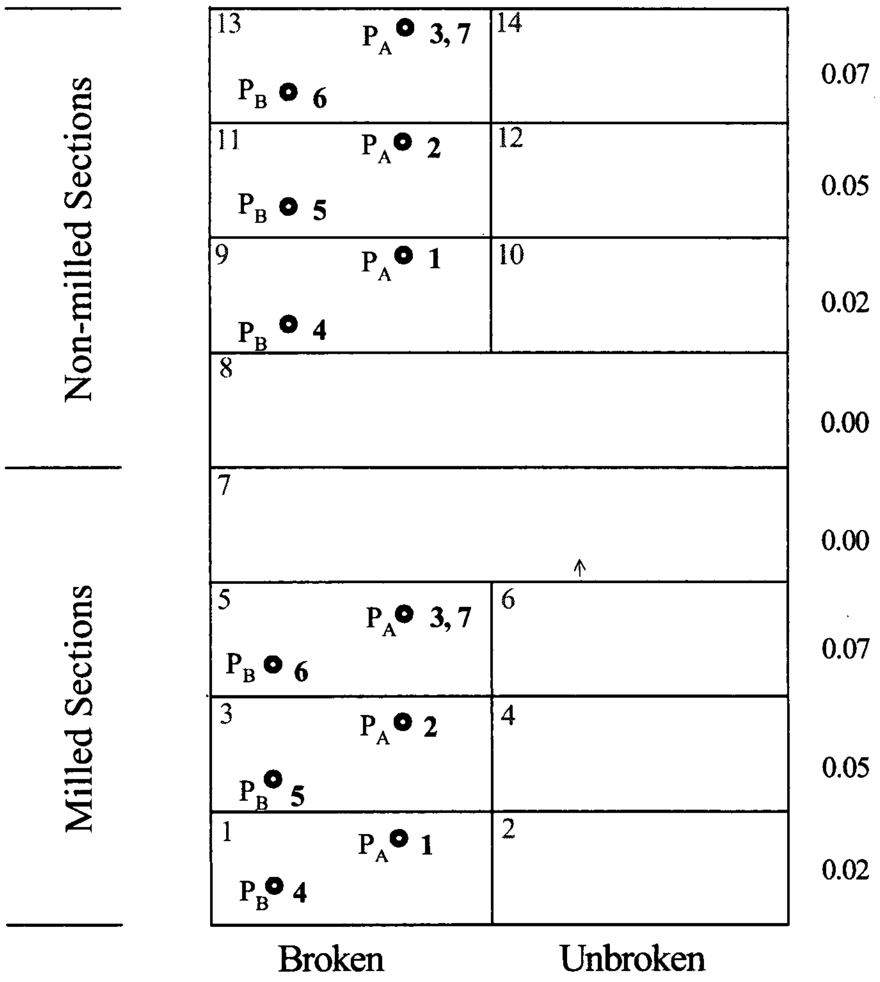


Figure 3.8: A schematic diagram showing the approximate location and sequence of the UTEP Pull-Off tests.

Table 3.2: In-place density measurements using a nuclear gauge.

Test Section	In-Place Average Density (%Gmm)	Coefficient of Variation (%)
1	92.5	2.95
2	92.3	1.84
3	92.5	1.38
4	92.7	0.89
5	94.1	1.48
6	93.4	1.63
7	92.4	2.76
8	93.1	4.11
9	93.4	1.29
10	94.5	0.64
11	94.4	1.31
12	91.3	1.69
13	91.6	1.72
14	91.9	1.97
***Overall Average**	**92.9**	
***Overall Standard Deviation**	**1.95**	
***Overall Coefficient of Variation**	**2.10**	

* Based on all nuclear gauge density measurements, not the averages per sections.

Twelve six-inch cores were taken from each test section, of which six were taken in the wheel path and six were taken in the middle of the lane as shown in Figure 3.9. This was to assess the potential loss of tack coat as it adheres to the tires of the paving and delivery equipment as shown in Figure 10. Figure 3.11 is an image taken during HMA placement during this experiment. The figure shows that the tack coat was not removed from the roadway during this experiment, hence tack coat pick up did not occur.

A total of 168 cores were planned to be obtained and tested. However, all the cores taken from test section number 8 de-bonded at the interface during sampling. In addition, two cores from test section number 9, two from test section number 14, and one from test section number 1, broke during sampling, shipping, or testing. Thus, a total of 151 cores were tested. Of these, 74 cores were tested using the FDOT Shear Tester, and 77 were tested using the Torque Bond test at the WSDOT Materials Lab in Tumwater, Washington. The cores that were excluded and the ones that were not tested but included in the analyses are listed in Appendix E and Appendix F.

Each core was labeled with a number followed by a letter followed by a number (0X0). The first number represents the section number. The letter represents the location; letter A indicates a core taken from the middle of the lane, whereas letter B indicates it was taken from the wheel path as shown in Figure 3.9. The second number represents the replicate; odd numbers (1, 3, 5) were tested for the torque bond test and even numbers (2, 4, 6) were tested for the FDOT shear tester. Thus, a total number of three replicates were tested for each combination of test section and coring location.

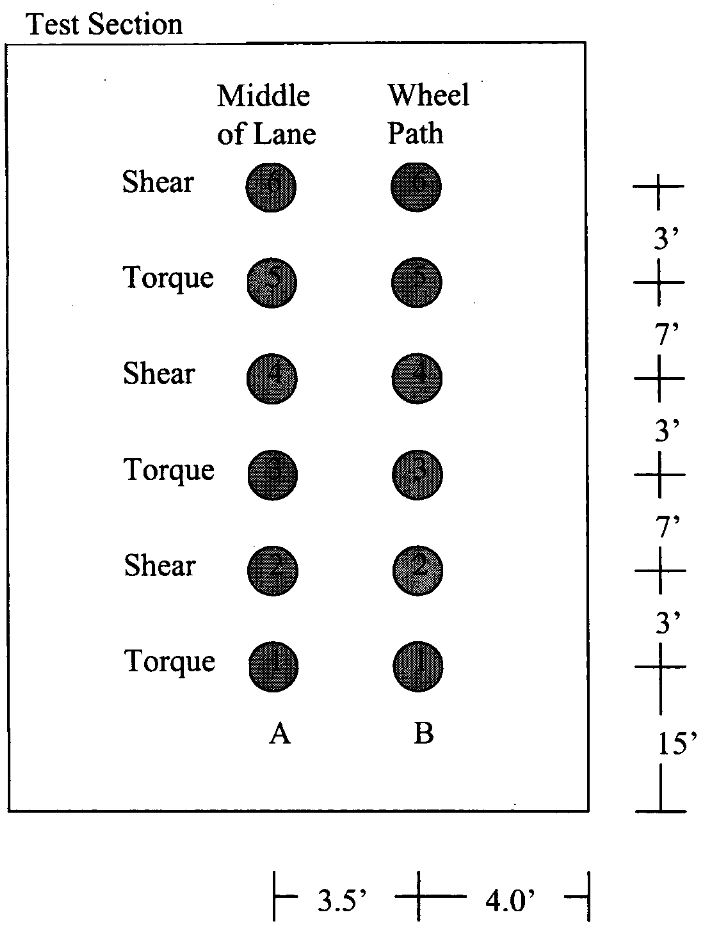


Figure 3.9: Labeling system and location of the field cores measured from the right corner of a test section (Not to scale).

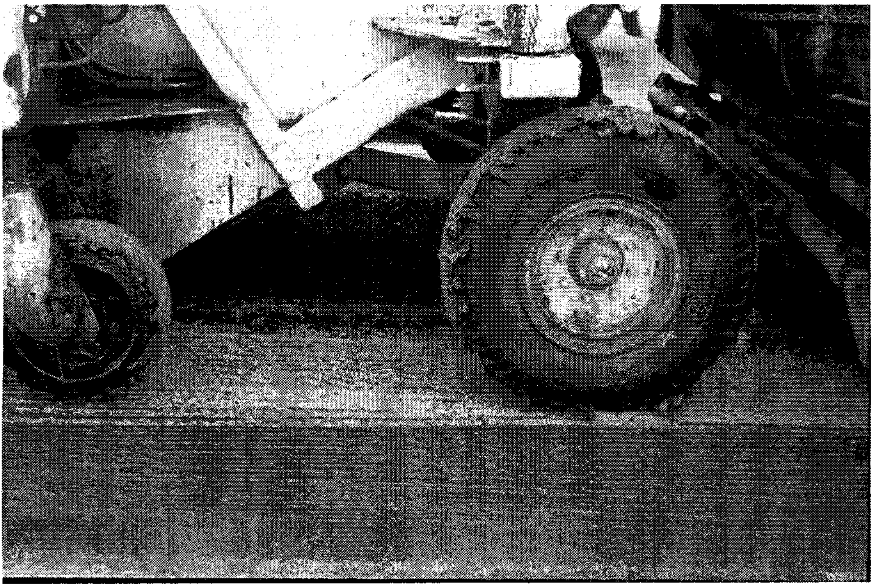


Figure 10: Tracking as seen on separate WSDOT HMA paving projects.

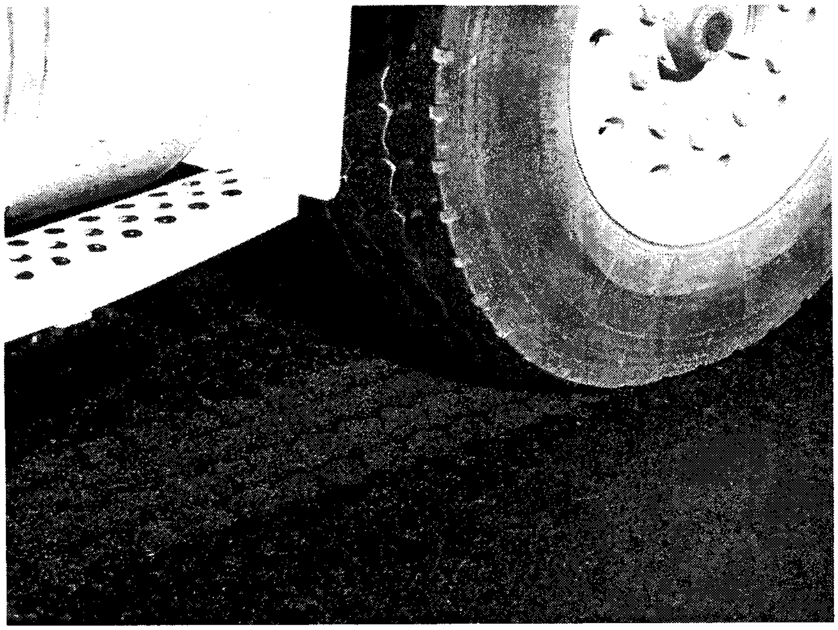


Figure 3.11: Equipment tracking during this experiment.

CHAPTER IV

RESULTS AND ANALYSES

STATISTICAL ANALYSES

Appendix E, Appendix F, and Appendix G present the experimental data for the FDOT Shear Tester, Torque Bond test, and UTEP Pull-Off test, respectively. Analysis of variance (ANOVA) was used to determine the factors that significantly influenced the bond strength at the interface between the existing surface and the newly constructed overlay. ANOVA refers broadly to a collection of statistical procedures suited to quantitatively determine whether particular treatments and their combinations affect a particular outcome, which is the bond strength at the interface in this study. MINITAB statistical software (MINITAB Release 14.20) was used to perform the statistical analyses. The ANOVA table consists of a value called the P-value. The P-value is the smallest level of significance at which the factor is considered significant in affecting the response. A level of significance equal to 0.05 is considered for the purpose of this study, i.e., 95% confidence level. A P-value of 0.05 or less indicates the factor is significant, whereas a P-value greater than 0.05 indicates the factor is not.

FDOT Shear Tester

The randomization scheme of the experiment dictated the analysis of variance (ANOVA). The randomization was done at various levels. At first, the road was divided into two Surface Condition categories: “Milled” and “Non-milled” sections. Hence, Surface Condition was considered a main effect factor. Thereafter, within each category, the Surface Condition was divided into three Curing Time categories: No-Tack, Broken, and Unbroken.

Hence, the Curing Time was considered as "nested" within the Surface Condition. Target residual rates of 0.02, 0.05, and 0.07 gal/yd^2 were applied within the Broken and Unbroken sections. As a result the Residual Rate was nested within the Curing Time. The coring Location (ML vs. WP) effect was over the entire road and hence was considered as a crossed main effect factor. The statistical model used for the FDOT Shear Tester results was as follows:

> *FDOT Shear Strength = overall mean + effect due to Surface Condition + effect due to Curing Time within the Surface Condition + effect of Residual Rate within the Curing Time + effect due to the Location + random errors.* (4-1)

Table 4.1 shows the results from the ANOVA on the FDOT Shear Tester. Except for the Location factor, all other listed factors in the table are statistically significant. Figure 4.1 shows the effect of the Surface Condition on the FDOT shear strength. There is a significant difference in the mean shear strength between the Milled and Non-milled sections: the Milled sections had significantly higher shear strength than the Non-milled sections.

Figure 4.2 shows the effect of the Curing Time within the Surface Condition. When comparing more than two means, the ANOVA *F*-test determines whether the means are significantly different from each other, however it does not determine which means are significantly different from others. Tukey Test provides more detailed information about the differences among them. It is a test designed to perform a pair-wise comparison of the means to determine when the difference among them is significant.

The Tukey test was conducted in order to obtain the pair-wise comparisons and it is presented in Appendix H. The pair-wise comparisons show that for the Milled sections, there was no significant difference in the mean shear strength between the three Curing Time categories (No-Tack, Broken, Unbroken). For the Non-milled sections, there was a significant difference between the No-Tack and the Broken sections as well as between the No Tack and the Unbroken sections. There was no significant difference between the Broken and the Unbroken sections for the two surface conditions. Furthermore, the Unbroken sections had a *slightly higher* shear strength than the Broken ones. Thus, according to the Tukey comparisons for the FDOT Shear Tester results, curing time was an insignificant factor.

Table 4.1: General Linear Model for FDOT Shear Tester (Response: Shear Strength).

Factor	**Type**	**Levels**	**Values**
Surface Condition	Fixed	2	Milled, Non-milled
- Curing Time	Fixed	6	Broken, No-Tack, Unbroken, Broken, No-Tack, Unbroken
- Residual Rate	Fixed	14	0.02, 0.05, 0.07, 0.00, 0.02, 0.05, 0.07, 0.02, 0.05, 0.07, 0.00, 0.02, 0.05, 0.07
Location	Fixed	2	ML, WP

ANOVA for FDOT Shear Tester

Factor	**DF**[a]	**SS**[b]	**MS**[c]	**F**[d]	**P-value**
Surface Condition	1	280358	280358	507.10	0.000*
- Curing Time	4	21847	5462	9.88	0.000*
- Residual Rate	8	20642	2580	4.67	0.000*
Location	1	1714	1714	3.10	0.083
Error	65	35936	553		
Total	79				

- Tabbing indicates a nested factor.

a. Degrees of Freedom.

b. Sum of Squares.

c. Mean square, which is the SS divided by DF.

d. Ratio of mean squares. It is used to determine the P-value.

* Factor is significant (P-value < 0.05).

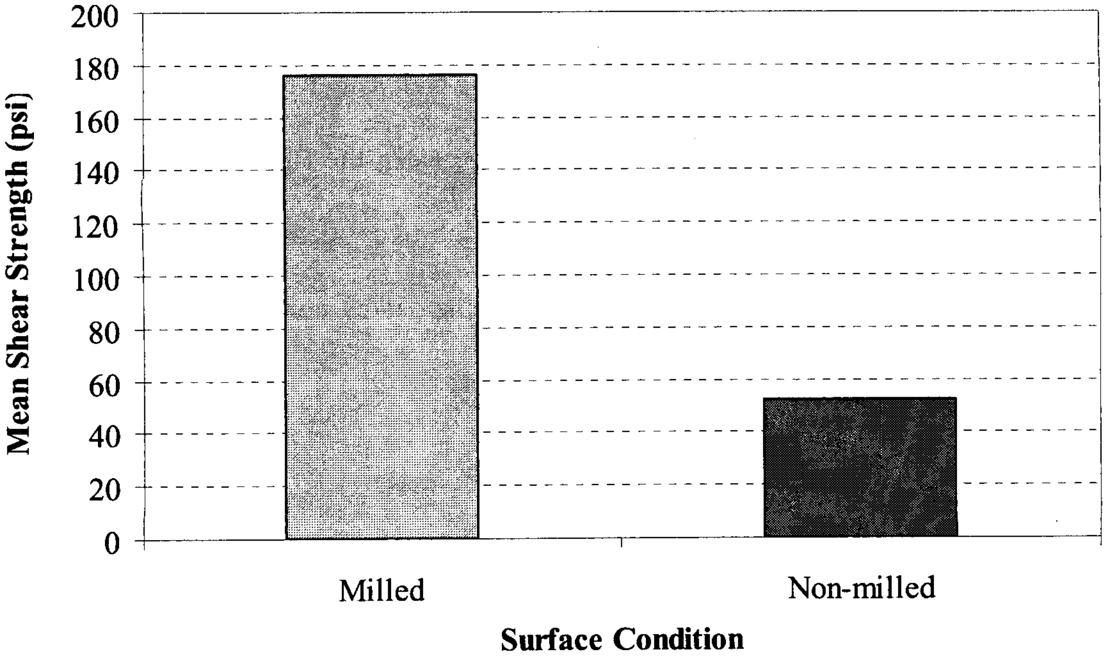


Figure 4.1: Effect of Surface Condition on the FDOT shear strength.

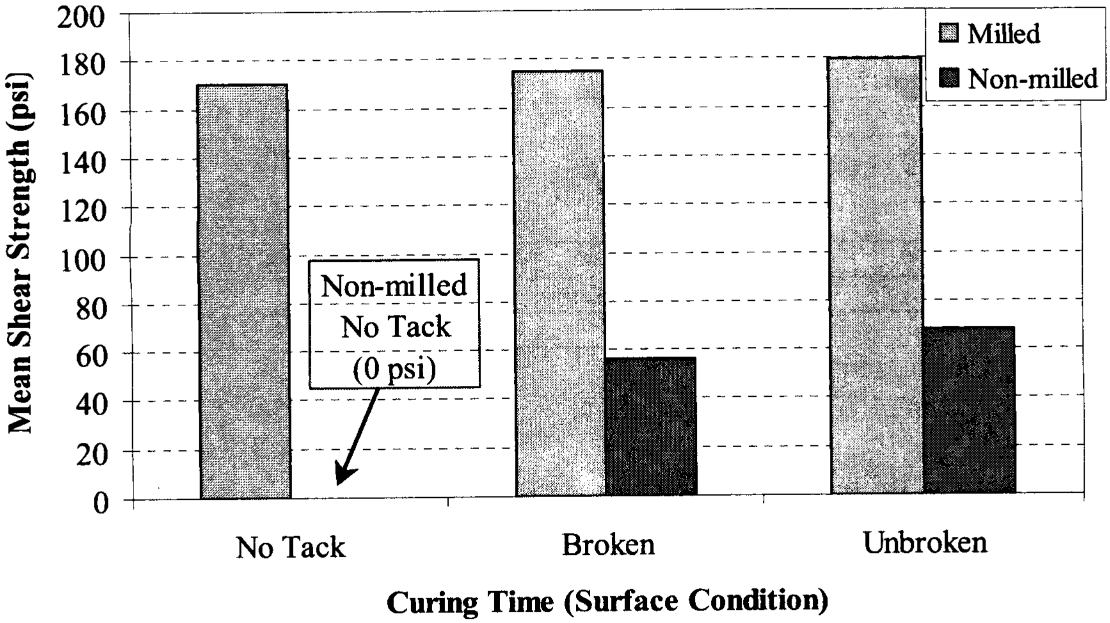


Figure 4.2: Effect of Curing Time nested within Surface Condition on the FDOT shear strength.

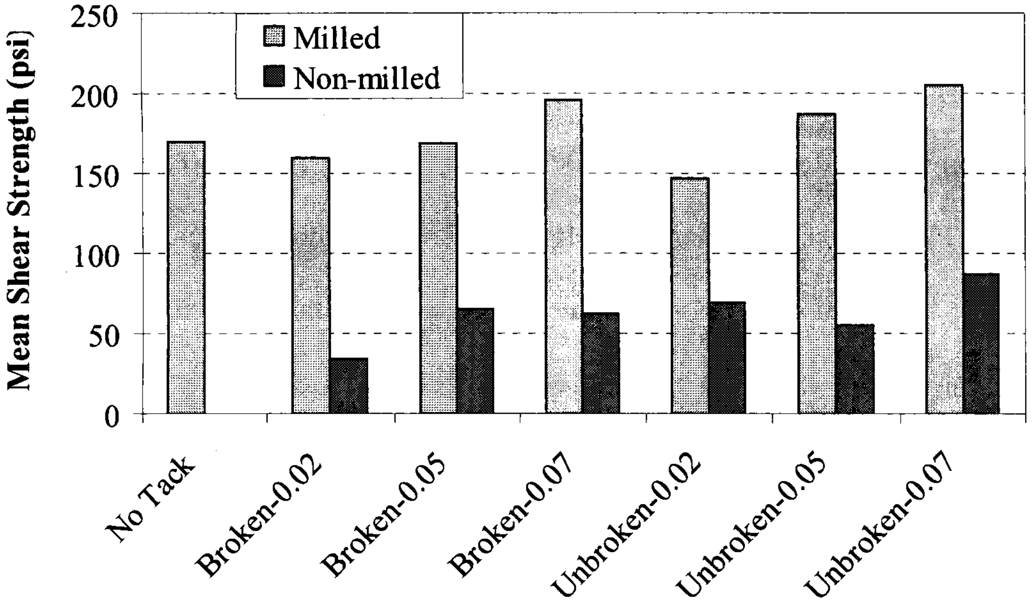


Figure 4.3: Effect of Residual Rate nested within Curing Time on the FDOT shear strength.

Figure 4.3 shows the effect of the Residual Rate nested within the Curing Time. The Tukey test was conducted in order to obtain the pair-wise comparisons and it is presented in Appendix I. The pair-wise comparisons show that for the Milled sections, the only significant difference was between 0.02-Unbroken and the 0.07-Unbroken. For the Non-milled sections, the significant difference was between the No-Tack and all other combinations except for the 0.02-Broken. Thus, according to the FDOT Shear test results, the absence of tack coat did not significantly affect the shear strength of the milled sections, where as it significantly did so for the Non-milled sections. Furthermore, increasing the application rate did not significantly improve the shear strength either for the Milled sections or for the Non-milled ones. There was one exception to that, which was between the 0.02-Unbroken and the 0.07-Unbroken Milled sections.

Figure 4.4 shows the effect of the coring location on the shear strength. Field cores taken in the wheel path (WP) had slightly higher mean shear strength than the ones cored in the middle of the lane (ML). Although this was opposite to the general wisdom, the difference was found to be statistically insignificant (P-value > 0.05), and hence can be neglected.

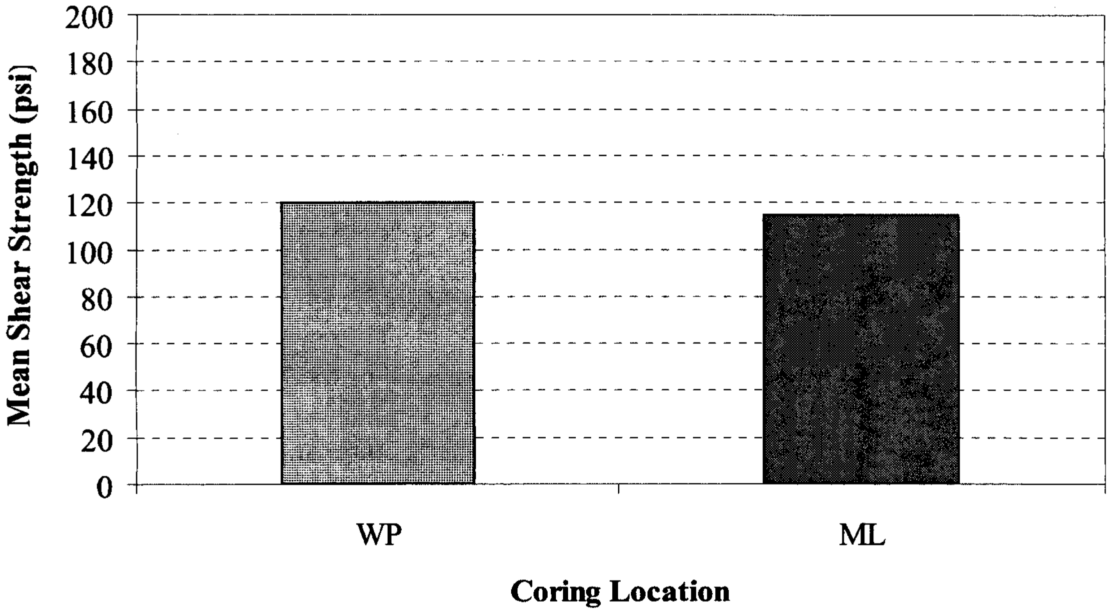


Figure 4.4: Effect of coring Location on the FDOT shear strength (factor insignificant).

Torque Bond Test

Although the Torque Bond Test was performed according to the British Board of Agrément (BBA), which requires a torque wrench of 300-N.m capacity (400-N.m was used in this study), only 28% of the tested cores failed at a torque value lower than 400-N.m (23 cores out of a total of 83 including the ones from test section number 8). This could be an indication that most of the sections are acceptable and will perform well (according to the BBA standards). However, this will require performance data that will not be available until another few years. Another possibility is that 400-N.m torque is not sufficient and that there is a need to increase the shear stress induced by the test either by increasing the capacity of the torque wrench or coring 4-inch diameter cores instead of 6-inch. The latter will significantly increase the shear stress, as it is inversely proportional to the diameter cubed as shown in Eq. (2-3).

In order to take into account the high-censored nature of the Torque Bond data, the "Regression with Life Data" analysis was used. Censored observations are those for which an exact failure time or value is unknown. Cores that did not fail before reaching the 400-N.m torque value were considered right-censored, whereas cores that failed before reaching the 400-N.m torque value were considered left-censored. It should be noted that the torque was used in the statistical analyses instead of the shear strength because the torque was the censoring criterion. Also, given that the coefficient of variation (C.V.) of the cores' diameter was small (2.4%), it was evident that the torque and shear strength were highly correlated (0.98 correlation).

The response variable (Torque) was regressed using the Surface Condition, Curing Time, Location, and Residual Rate as explanatory variables. The results from regression are presented in Table 4.2. Table 4.2 gives the Maximum Likelihood estimates of the slope parameters

(Coefficient), the standard error of the slopes (SE), the Z-statistic, which tests if the slope is different from zero, and the P-value for the corresponding test. The aforementioned factors were categorical predictors, thus the Z-tests indicate the difference between the levels of the factors.

Table 4.2 indicates that there is a significant difference between the Milled and the Non-milled sections. Milled sections yielded a higher torque than the Non-milled sections as shown in Figure 4.5. In fact, only one of the cores taken from the milled sections failed before reaching the 400-N.m torque. The rest of the cores that failed at torque values less than 400-N.m belonged to the non-milled sections. Table 4.2 also indicates that for the Curing Time factor, there was a significant difference between the No-Tack sections (zero torque bond) and the Broken ones as well as between the No-Tack sections and the Unbroken ones. This was particularly true for the Non-milled sections as shown in Figure 4.6. However, the latter could not be verified statistically due to the high level of censoring for the Torque Bond data, which made the nesting impossible (i.e., Curing Time analysis was treated independent of the Surface Condition). No other factors were found to be significant.

It should be noted that test section number 8, which recorded zero torque with the Torque Bond test and zero shear stress with the FDOT Shear Tester (due to delamination of the cores during removal), experienced minor shoving and cracking problems during construction as shown in Figure 4.7. This could be an indication that the lack of bond at the interface manifests itself in a poor pavement performance.

Table 4.2: Generalized linear model for the Torque Bond test (Response: Torque).

Censoring Information Count	23 uncensored value, 60 right censored value
Estimation Method	Maximum Likelihood
Distribution	Normal

Regression Table

Predictor	**Coefficient**	**Standard Error**	**Z**	**P-Value**
Surface Condition (Milled vs. Non-milled)	-430.988	86.700	-4.97	0.000*
Curing Time (Broken vs. No Tack)	-280.832	94.550	-2.97	0.003*
Curing Time (No Tack vs. Unbroken)	324.839	97.194	3.34	0.001*
Curing Time (Broken vs. Unbroken)	44.007	56.544	0.78	0.436
Location (WP vs. ML)	-46.516	49.997	-0.93	0.352
Residual Rate (0.02 vs. 0.05, 0.02 vs. 0.07, and 0.05 vs. 0.07)	430.234	1397.58	0.31	0.758
Scale	155.395	25.833		

* Factor is significant (P-value < 0.05).

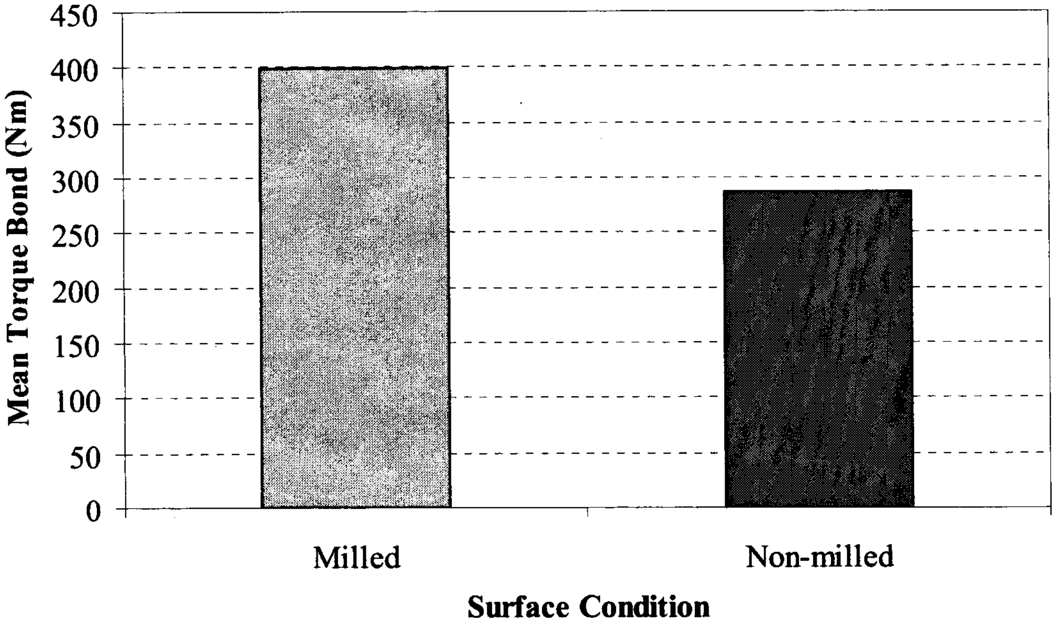


Figure 4.5: Effect of Surface Condition on the Torque Bond strength.

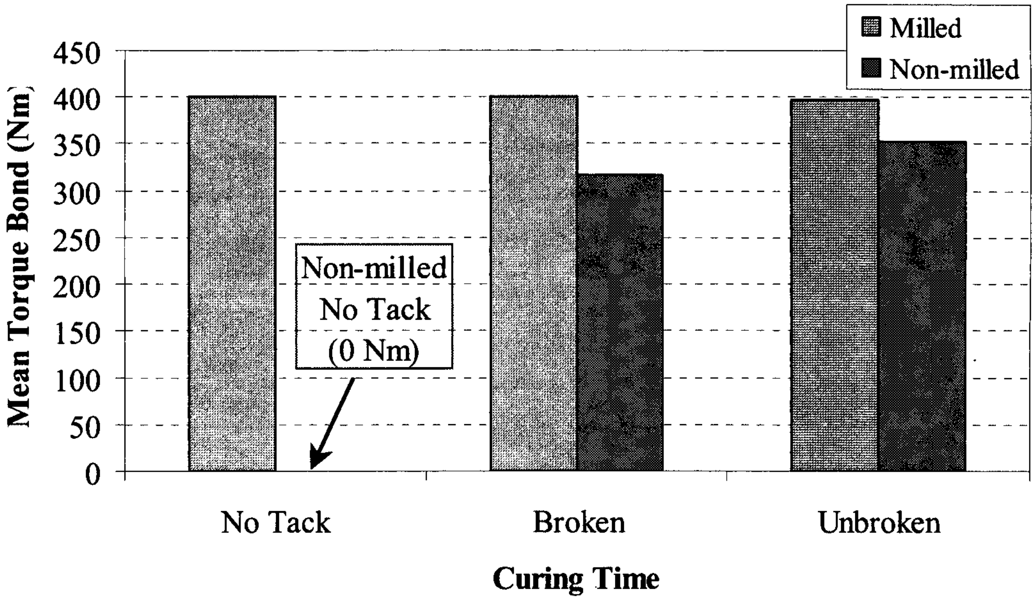


Figure 4.6: Effect of Curing Time on the Torque Bond strength.

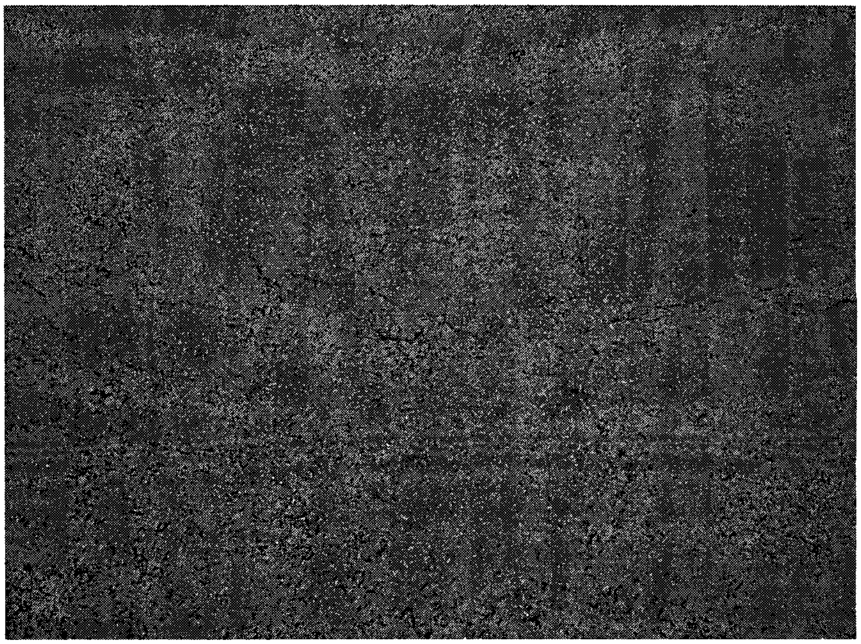


Figure 4.7: Cracking problems in test section number 8.

UTEP Pull-Off Test

The randomization scheme of the experiment also suggested that the ANOVA approach is suitable for analyzing the UTEP Pull-Off test results. The randomization was done at various levels. At first, the road was divided into two Surface Condition categories: Milled and Non-milled sections. Hence, Surface Condition was considered a main effect factor. Thereafter, within each category, the Surface Condition was divided into three Residual Rates: 0.02, 0.05, and 0.07 gal/yd^2. As a result, Residual Rate was nested within the Surface Condition. The Testing Time (A vs. B, where test B was performed 45 minutes after test A) effect was over the entire road and hence, was considered as a crossed factor. The statistical model used for the UTEP Pull-Off test was as follows:

UTEP Pull-Off Strength = overall mean + effect due to Surface Condition + effect of Residual Rate within the Surface Condition + effect due to Testing Time + random errors. (4-2)

Table 4.3 shows the ANOVA table for the UTEP Pull-Off test. The table shows that the Surface Condition was the only significant factor. Figure 4.8 shows that the Non-milled sections had a higher Pull-Off strength than the Milled sections. The UTEP Pull-Off contact plate had a smaller contact area on the milled surface compared to the non-milled surface because of the nature of the milling. Figure 4.9 shows the UTEP Pull-Off contact plate has partially adhered to the tack coat due to the irregularities of a milled surface. Hence, the UTEP Pull-Off test results indicated that the Non-milled sections had higher tensile strength than the milled ones.

Figure 4.10 shows the effect of the Residual Rates within the Surface Condition. In general, the Pull-Off strength decreases with the residual rate. It should be noted that the UTEP Pull-Off test was performed in chronological order starting from the lowest rate (0.02 gal/yd^2)

and moving to higher rates (0.05, then 0.07 gal/yd^2). The period between two successive tests was approximately 12 minutes. This might have influenced the results of the Residual Rates.

Figure 4.11 shows the effect of the Testing Time. The UTEP Pull-Off strength decreased with time. This was also supported by the result from test number P_A7, which was taken approximately one hour after test number P_A3 at approximately the same location. P_A7 had a tensile strength of approximately 2.4 psi; a decrease of 25% from test number P_A3. It should be noted that the Residual Rate within the Surface Condition and the Testing Time factors were found to be insignificant. Figures 4.9 and 4.10 are only presented to illustrate the trends.

Table 4.3: General Linear Model for UTEP Pull-Off Test (Response: Tensile strength).

Factor	**Type**	**Levels**	**Values**
Surface Condition	Fixed	2	Milled, Non-milled
- Residual Rate	Fixed	6	0.02, 0.05, 0.07, 0.02, 0.05, 0.07
Testing Time	Fixed	2	A, B (B is performed 45 minutes after A)

ANOVA for UTEP Pull-Off Test.

Factor	**DF**[a]	**SS**[b]	**MS**[c]	**F**[d]	**P-value**
Surface Condition	1	3.7297	3.7297	15.96	0.010*
- Residual Rate	4	0.7323	0.1831	0.78	0.582
Testing Time	1	0.8060	0.8060	3.45	0.122
Error	5	1.1685	0.2337		
Total	11				

- Tabbing indicates a nested factor.

a. Degrees of Freedom.
b. Sum of Squares.
c. Mean square, which is the SS divided by DF.
d. Ratio of mean squares. It is used to determine the P-value.
* Factor is significant (P-value < 0.05).

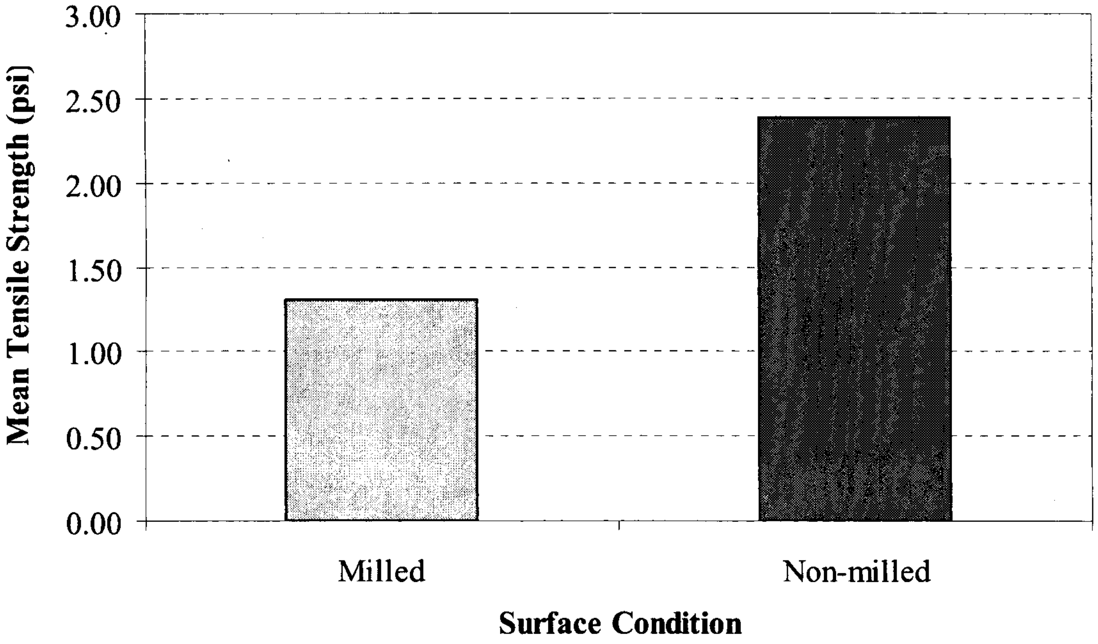


Figure 4.8: Effect of Surface Condition on the UTEP Pull-Off tensile strength.

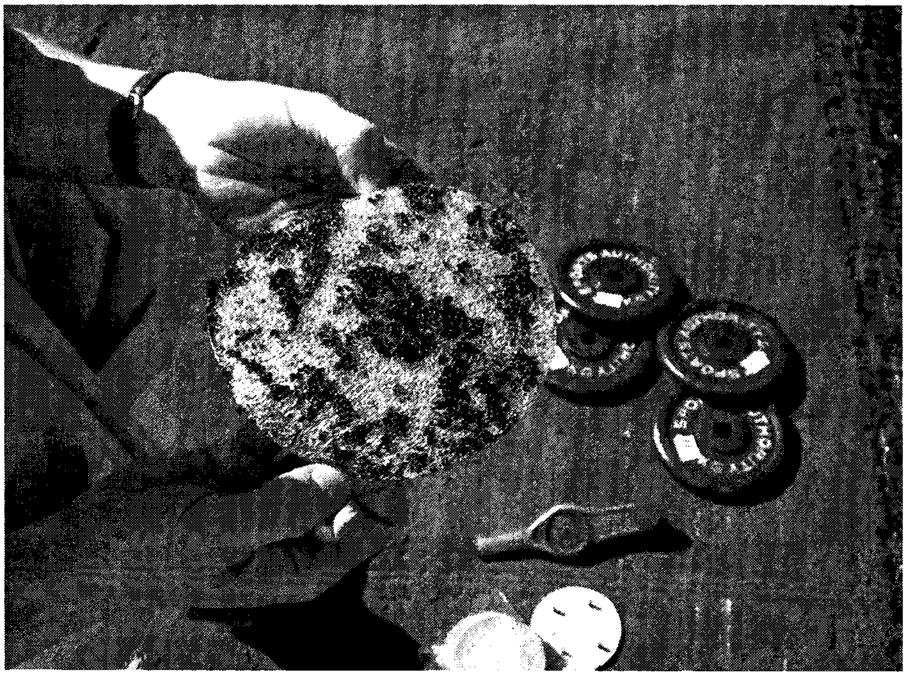


Figure 4.9: UTEP Pull-Off contact plate after the test completion.

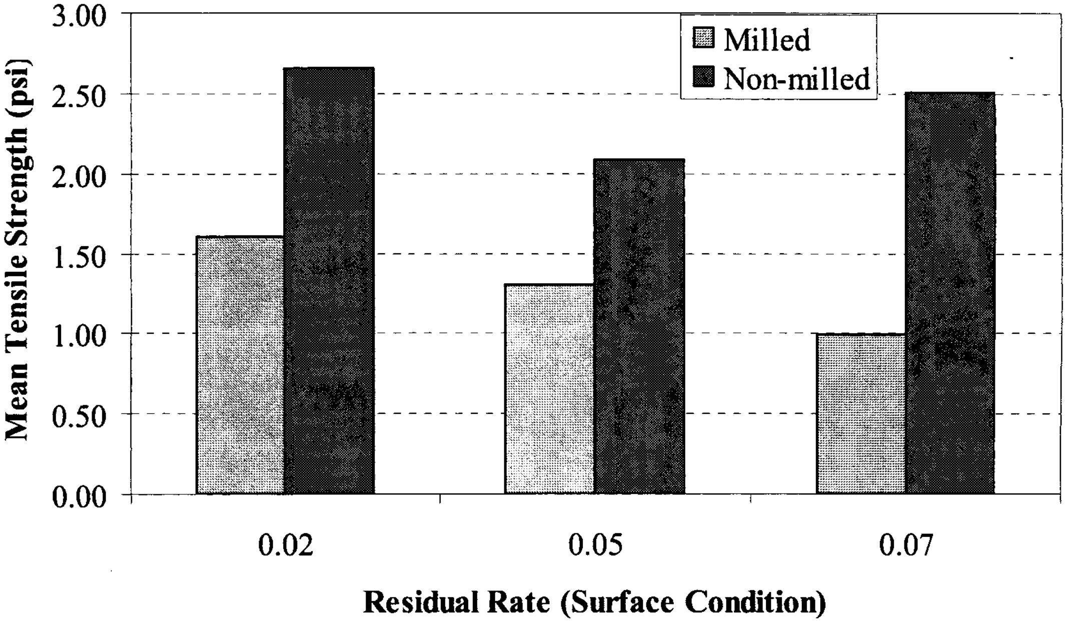


Figure 4.10: Effect of Residual Rate nested within Surface Condition on the UTEP Pull-Off tensile strength (factor insignificant).

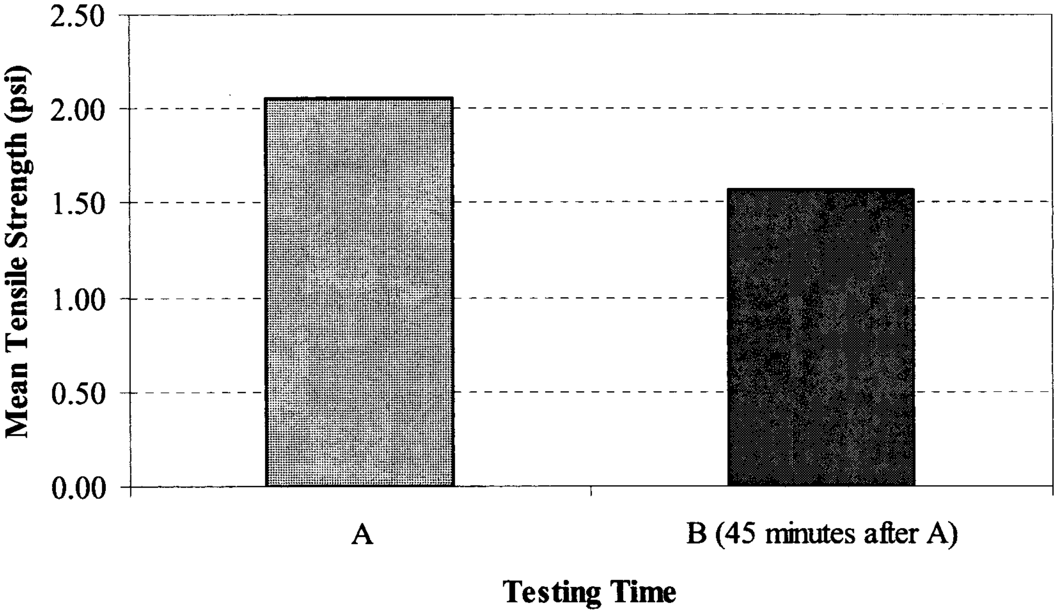


Figure 4.11: Effect of Testing Time on the UTEP Pull-Off tensile strength (factor insignificant).

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Three tack coat construction quality tests were evaluated. These tests were the FDOT Shear Tester, Torque Bond test, and UTEP Pull-Off test. These tests were used to study the influence of several factors on the bond strength provided by the tack coat at the interface between pavement lifts. These factors included the surface condition, curing time, application rate, and location. The results from each test are summarized subsequently.

FDOT Shear Tester

- The milled sections had significantly higher shear strength than the non-milled sections.
- Curing time was an insignificant factor.
- The absence of tack coat did not affect the shear strength for the milled sections, where as it significantly did so for the non-milled sections.
- Generally, increasing the residual rate did not significantly improve the shear strength for either the milled sections or the non-milled ones. However, the milled sections were more sensitive to increasing the residual rate compared to the non-milled sections.
- The shear strength at the interface was not affected by the location (wheel path vs. middle of lane).

Torque Bond Test

- The milled sections had significantly higher strength than the non-milled ones.

- Curing time had no effect on the strength at the interface.
- The absence of tack coat significantly decreased the strength at the interface for the non-milled sections.

UTEP Pull-Off Test

- The non-milled sections had a higher Pull-Off strength than the milled sections. This was the only significant factor.

Generally, the results from the FDOT Shear Tester were consistent with those in the literature. The experimental data from the Torque Bond test were highly censored, and thus provided limited observations. This was despite the fact that the test was performed according to the BBA standards. As a result, only a regression based Expected Life type of analysis could be conducted. Nonetheless, the limited observations from the Torque Bond test were consistent with those from the FDOT Shear Tester. The results from the UTEP Pull-Off test were generally the opposite of the other two tests. This was attributed to two factors that might have affected the test results: 1) lack of adhesion between the contact plate and the tack coat on milled sections, and 2) performing the test in a chronological order starting with the lowest residual rate.

The three tests have different testing mechanisms. The FDOT Shear Tester measures the bond strength of the interface between the two lifts in shear, the Torque Bond test measures it in torsional shear, whereas the UTEP Pull-Off test measures the tensile strength of the tack coat. The FDOT Shear Tester seems to better simulate the state of stress encountered in the field (shear stress) that causes the de-bonding at the interface between pavement layers.

Overall, milling provided a significantly better bond at the interface between the existing surface and the new overlay. For milled sections, the absence of tack coat did not significantly affect the bond strength at the interface. This was not true for the non-milled sections, where the absence of tack coat severely decreased the bond strength (there was no bond at all). Curing time had minimal effect on the bond strength at the interface. Residual rates in the range of 0.02 - 0.07 gal/yd^2 did not significantly change the bond strength at the interface. Equipment tracking did not occur to the extent expected during the experiment, hence the coring location did not significantly affect the bond strength at the interface.

It should be noted that these conclusions were drawn based on the initial results from this study, which only used one type of tack coat and one HMA mixture for the existing surface as well as the new overlay. These results could be different if other types of tack coat and HMA mixtures were used. Also, this study was conducted in one day where the weather condition remained almost unchanged. The results could differ if the experiment was conducted under different weather conditions (effect of moisture and/or temperature). Furthermore, long-term performance data have not been collected at this time.

RECOMMENDATIONS AND FUTURE WORK

Based on the observations from this study, the following are recommended as part of a future work (second phase). It is envisioned that these will assist in a better evaluation of future data. In addition, some of these will complement the results from this study.

- It is recommended to take field cores from the experimental site twice a year for several years and measure the bond strength using the FDOT Shear Tester and the Torque Bond test. This will complement the results from this study with performance data, which will assist in pinpointing the factors that significantly affect the bond strength at the interface from a long-term performance perspective. This might change some of the aforementioned conclusions as some factors that were found to be insignificant might become significant in the long run and vice versa. Furthermore, this will assist in determining a minimum shear strength criterion that should be achieved using either test to ensure that the pavement will have adequate adhesive bond at the interface of the layers.

- The test method used to measure the tack coat residual rates did not accurately predict the target rates. This could be attributed to one or a combination of the following factors:
    a) inaccuracy in the test method to measure the residual rates,
    b) lack of samples (only one per test section), and
    c) inaccuracy in applying the target rates by the tack coat truck.

  This discrepancy between the target and measured residual rates could be an important issue to WSDOT that needs to be addressed.

- None of the tests evaluated in this study was promising as an in-situ test to assess the bond strength at the interface. The FDOT Shear Tester seems to be a fundamental laboratory test that could be recommended as a laboratory test but not as an in-situ. The Torque Bond test requires a 28-day waiting period. Besides, it applies a torsional shear stress, which is not fundamentally similar to the shear stress encountered in the field. The UTEP Pull-Off test applies a tensile strength (not shear) and suffered from the lack of adhesion on the contact plate. Thus, it might be of interest to WSDOT to evaluate other devices (e.g. the Attacker) or develop their own.

ACKNOWLEDGEMENT

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Special thanks go to John Grisham of *Woodworth & Company Inc.* (Tacoma, WA), Dave Bell *of Lakeside Industries* (Tacoma, WA), and Tom Gaetz of Washington Asphalt Pavement Association for their contributions to this study. *Woodworth & Company Inc.* contributed to the building of the test sections by grinding the existing surface, placing, and compacting the HMA for the cost of materials. *Lakeside Industries* provided and sprayed the tack coat.

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APPENDICES

APPENDIX A: FDOT Shear Tester

Sample Preparation

1. Cores should be 6" in diameter. Cores with a diameter less than this can be accommodated with shims.
2. Measure the diameter of the core at three equally spaced locations around the circumference of the core. Take the average of the three readings.
3. Cores do not need to be trimmed with a saw. The machine can accommodate any length core.
4. The core should be conditioned at 77 °F for three hours. This can be accomplished in an air chamber or water bath. If a water bath is used, the core should be placed in a sealed bag so that it does not get wet.

Machine and Sample Setup

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

Testing the Sample

1. The loading rate is 2"/min.
2. Set the load range to 10,000 lbs. as an initial starting point. If the cores are shearing at loads lower than 5,000 lbs, the load range can be changed to 5,000 lbs for better resolution.
3. Start the test and plot the load versus displacement curve. From the plot, obtain the maximum load.
4. Divide the load by the cross-sectional area to obtain the shear stress.

APPENDIX B: Torque Bond Test

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FOR HIGHWAYS

July 2004
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Transport Research Laboratory (TRL)

TORQUE BOND TEST

(Draft for development)

1 Scope

The following protocol describes methods for determining the Bond Strength between a thin surfacing system and its substrate, which may be bituminous or cementitious, by measuring the peak shearing torque, at a known temperature.

Two methods of test are described for tests carried out on site and on cores taken from site and tested in the laboratory.

The test shall only be carried out on thin surfacing systems which have been installed for a period of between 28 and 56 days(1).

The protocol describes a test procedure that has been developed specifically for the assessment of thin surfacing systems under HAPAS Certification procedures. The method is currently at the draft for development stage and should not be used for specifying purposes.

2 Definitions

τ : inter-layer bond strength in kiloPascals (kPa),
M : peak value of applied shearing torque in Newton metres (N m),
D : diameter of core in millimetres (mm)

3 Apparatus

3.1 Equipment

3.1.1 *Core cutting apparatus*: suitable for cutting 100mm(1) diameter cores in bituminous and cementitious materials;
3.1.2 *Torque meter*: fitted with a fiducial reading gauge. The device shall be calibrated over a range of 0-350 N m with a scale readable to at least 10 N m. The device shall be fitted with a socket-fitting allowing steel plates to be fitted and removed.
3.1.3 *Metal Plate*: of mild steel having a diameter of (95±5), and a thickness of (14±2) mm. The plate shall incorporate a fitting enabling it to be coupled to the torque meter.(2)
3.1.4 *Thermometer*: readable to 0.1°C and accurate to 0.5°C.
3.1.5 *Steel Rule*
3.1.6 *Callipers:* for measurement of core diameters;
3.1.7 Mould or other means of confining laboratory test samples for testing.
3.1.8 *Watch or Timer*: readable and accurate to 1 second.
3.1.9 *Mould*: for confining laboratory test specimens, (e.g. 150 mm concrete cube mould).
3.1.10 *Spirit Level*: for checking laboratory test specimens;
3.1.11 *Oven or refrigerated incubator (optional)*

Note:

1. **Cores may be cut prior to the 28 days post-installation period and stored at 5 ± 2°C prior to testing.**
2. **Fittings of 12.7 mm and 19.05 mm have been found to be suitable.**

3.2 Materials

3.2.1 *Adhesive*: (a stiff adhesive, such as rapid setting epoxy resin, with sufficient strength to avoid failure within the adhesive or at the adhesive/thin surfacing interface).
3.2.2 *Mounting material (for laboratory tests)*: e.g. rapid hardening mortar, concrete or grout.

4 Test methods

4.1 Site test method

4.1.1 Core the location to be tested using a 100 mm (±5mm) diameter core barrel to a depth of 20 mm below the thin surfacing layer to be tested. The method for sampling shall be to cut six cores at nominally even spacing along a diagonal line across the lane width. Cores shall be taken from a 100m length of the installation or the total installation where this is less than 100m.

4.1.2 Ensure that all debris is removed from the rebate formed by the core barrel. Clean and dry the surface to be tested.

4.1.3 Use the bonding agent to secure the metal plate to the surface of the core, taking care to ensure that the plate is parallel to the surface.

4.1.4 When the bonding agent has developed sufficient strength, (i.e. failure should not occur within the adhesive), fit the torque meter to the metal plate, using adapters and extension rods as appropriate.

4.1.5 Apply torque to the core at a steady rate so that the torque wrench sweeps an angle of 90° within (30±15) s. Care must be taken to ensure that the torque is applied parallel to the core surface (within ± 10°). Torque is applied to the plate until failure of the bond occurs or a torque of 300 N m is exceeded.

4.1.6 Record the value of torque at failure, M, in Newton metres. Measure and record the bond interface temperature immediately after failure.

4.1.7 Examine the core and substrate and record the condition of the bond interface (e.g. smooth, planer, rough or irregular). Record the substrate type (e.g. bituminous or cementitious surface). Where known record details of the substrate condition prior to surfacing, (i.e. planed, untreated or regulated).

4.1.8 Measure and record the core diameter at two locations approximately 90° apart using callipers and record the mean value, D, to an accuracy of 1 mm.

4.1.9 Measure and record the depth of the surfacing to the substrate interface to an accuracy of 1mm.

4.1.10 Calculate the bond strength in accordance with section 5.

4.2 Laboratory test method

4.2.1 Cut a 100mm (or 150mm) diameter core to a minimum depth of 80mm below the bottom of the surface layer. Extract the core taking care not to damage the surface layer of the core or the bond interface with the substrate. Six such cores shall be taken along a 100m length of the installation at nominally even spacing along a diagonal line across the lane width.

4.2.2 Trim the core to a length suitable for mounting if appropriate.

4.2.3 Place the core in the mould, using mortar or grout as a bedding layer if appropriate, so that the upper layer and the bond interface to be tested is (20±10) mm above the rim of the mould. Fill the mould with the mortar/grout and trim flush with the mould rim, ensuring that the core is perpendicular to, and the upper surface parallel with, the mould surface. Check using the spirit level.

4.2.4 Fix the metal plate to the core using the adhesive and allow to set.

4.2.5 Unless otherwise specified(1), condition the mounted cores by storing at a temperature of (20±2)°C for a minimum of 4 hours and for not more than 16 hours before testing. Record the times and temperatures employed.

4.2.6 Unless otherwise specified, test the core at a temperature of (20±2)°C: where other temperatures are used the test shall be completed within 5 minutes of removal from the conditioning environment.

4.2.7 Fix or clamp the mould containing the mounted core to a suitably rigid surface. Carry out the test as described in 4.1.5.

4.2.8 Examine the core and record all the relevant information as described in 4.1.6 to 4.1.9.

5 Calculation of Bond Strength and expression of results

Calculate the bond strength for each specimen using the following formula:

$$\tau = \frac{12M \times 10^6}{\pi D^3}$$

Calculate the arithmetic mean of the inter-layer bond strength, τ, for the six specimens

6 Test report

6.1 The test report shall include the following information:

i) Name of organisation carrying out the test
ii) Method of test used
iii) Description of materials (system and substrate)
iv) Date of test
v) Peak torque at failure (N m)
vi) Inter-layer bond strength (kPa), (individual and mean values)
vii) Time to failure (seconds)
viii) Diameter of core (mm)
ix) Depth of Bond interface (mm)
x) Temperature of the Bond interface at test (°C)
xi) Conditioning details (duration and temperature)
xii) Site or Laboratory test
xiii) Identification of Site or Scheme
xiv) Core location
xv) Age of the installation / specimen at the time of test
xvi) Nature of the Bond interface
xvii) Mode of Failure

7 Precision

The precision for this test method has not been determined.

Note:

1 Temperatures outside this range may be specified, e.g. in order to compare data obtained from site tests carried out at temperatures other than (20±2)°C. In this case additional laboratory apparatus (i.e. ovens or refrigerated incubators) may be required. Conditioning of specimens in a soaked condition may also be undertaken. Details of the conditioning used prior to testing shall be recorded.

APPENDIX C: Tex-243-F, Tack Coat Adhesion Test (UTEP Pull-Off Test)

Overview

Effective Date: May 2006
Use this test method to evaluate the adhesive properties of tack coat for roadway use at the project site.

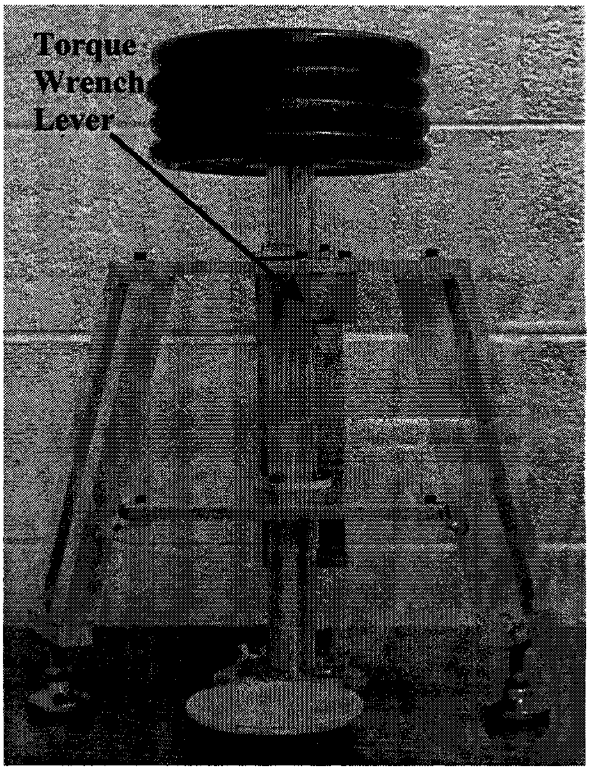
Units of Measurement

The values given in parentheses (if provided) are not standard. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

Apparatus

Use the following apparatus:

- Tack Coat Pull Off Device (as shown in figure below)
- Torque wrench, 150 lb-in capacity
- Handheld non-contact infrared thermometer capable of measuring from 40°F (4°C) to 350°F (177°C) with an accuracy of ± 2°F (± 1°C), with a LCD display capable of displaying the maximum temperature, adjustable emissivity in increments of 0.01 or a fixed emissivity equal to or greater than 0.95 and a minimum 6:1 distance to spot ratio.
- Pocket weather meter capable of measuring wind speed (0.7 to 89 mph) and ambient temperature (5°F [-15°C] to 122°F [50°C]).



Tack Coat Pull Off Device

Materials

- Utility cutting knife
- Moisture bearing foam
- Double sided tape

Procedure

Follow these steps to prepare the testing apparatus for use and to perform the tack coat adhesion test.

Preparing Tack Coat Pull Off Device for Use	
Preparing Apparatus	
Step	**Action**
1	Cut a circular piece of double-sided tape approximately 5 in. (127 mm) in diameter.
2	Attach the double-sided tape from Step 1 to the contact plate of the testing apparatus. Remove any excess double-sided tape with a utility cutting knife.
3	Cut a circular piece of the moisture bearing foam approximately 5 in. (127mm) in diameter.
4	Attach the smooth and slick textured side of the moisture bearing foam from step 3 to the double-sided tape. Remove any excess moisture bearing foam
5	Fasten the contact plate with the double-sided tape and moisture bearing foam to the bottom of the testing device using wing nuts (placed diagonally of each other).
Performing Field Test	
6	Select a test section of pavement coated with tack coat. NOTE: Select an area of approximately 2 ft^2 (0.2 m^2) in size.
7	a. Record relevant information as suggested in the Data Sheet:
8	Allow tack coat to cure for approximately 30 minutes.
9	Position the testing device onto the test section selected in Step 6.
10	Let the contact plate (prepared according to Steps 1-5) fall into the test area by rotating torque wrench lever in counter-clockwise direction.
11	Place 40 lb. (18 kg) load on top of the testing device and hold in place for approximately 10 min.
12	Remove the load from the testing device after approximately 10 min.
13	Connect the torque wrench to the testing device.
14	Apply torque until the contact plate completely separates from the pavement surface.
15	Record the maximum torque required to completely separate the contact plate from the pavement surface.

Calculations

- Calculate the adhesive strength of the applied tack coat material by multiplying the Toque with the appropriate calibration Factor.

UPOD No.	Calibration Factor, psi
1	**0.079**
2	**0.072**
3	**0.085**
4	**0.085**
5	**0.081**
6	**0.075**

Acceptance Criterion

Compare the measured adhesive strength with the provided nomographs. If the measured strength is lower than strength estimated from nomograph, the tack is rejected otherwise the tack coat is acceptable.

Tex-243-F Tack Coat Adhesion Test Data Sheet

District: ________________ Existing Mix Type or Surface: _____________

County: ________________ Overlay Mix Type: ______________________

Highway:________________ Contractor: __________________________

Lot Number: _____________ Date Tested: ________________________

Location Mark: _______________________________________

____

Comments: _______________________________________

Tack Coat Type: _________

Estimated Application Rate:_______ gal/yd^2 Measured Application Rate:____ gal/yd^2

Break Time:_______________

Circle- Field Lab

Trials	Application Quality*	Ambient Temperature, °F	Wind Velocity, mph	Pavement Temperature, °F	Tested Time, min.	(Measured Torque-3), in-lbs
1						
2						
3						
4						
5						
6						

Application Quality*

A. Proper Coverage on Existing Surface

B. Proper Coverage on Milled Surface

C. Delivery Vehicle Tracking

D. Material Transfer Device Tracking

E. Small Nozzle Opening

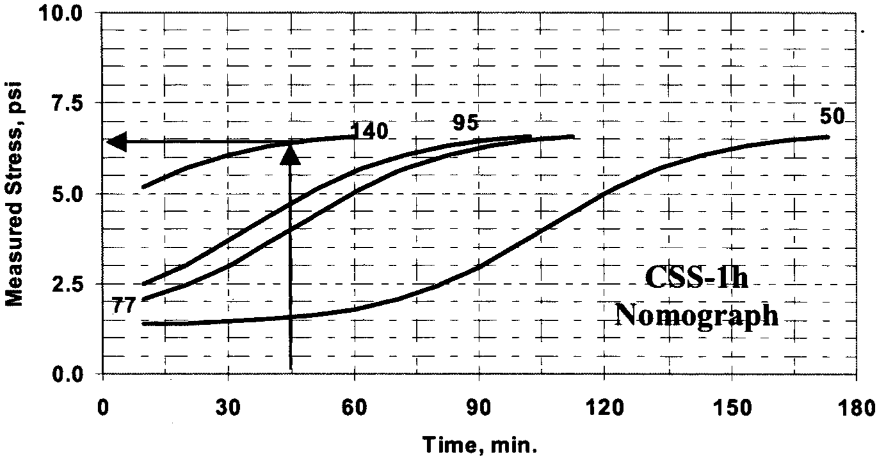
F. Application on Oxidized Asphalt

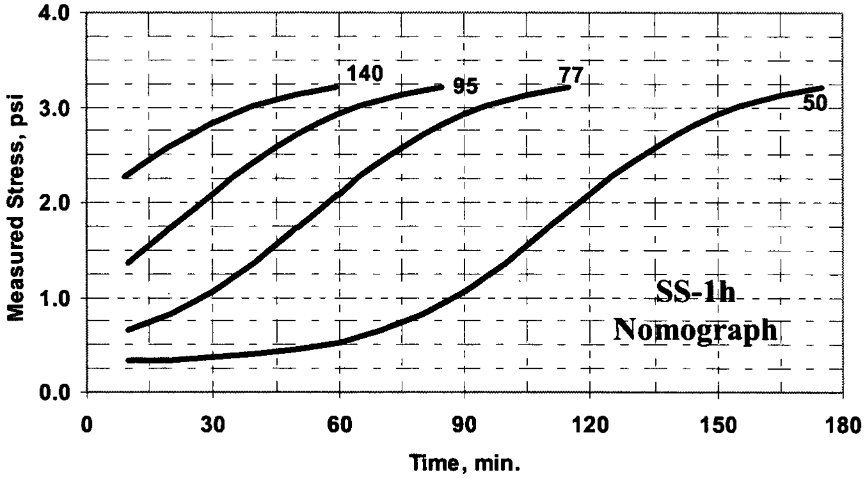
G. Excessive Unbroken Tack

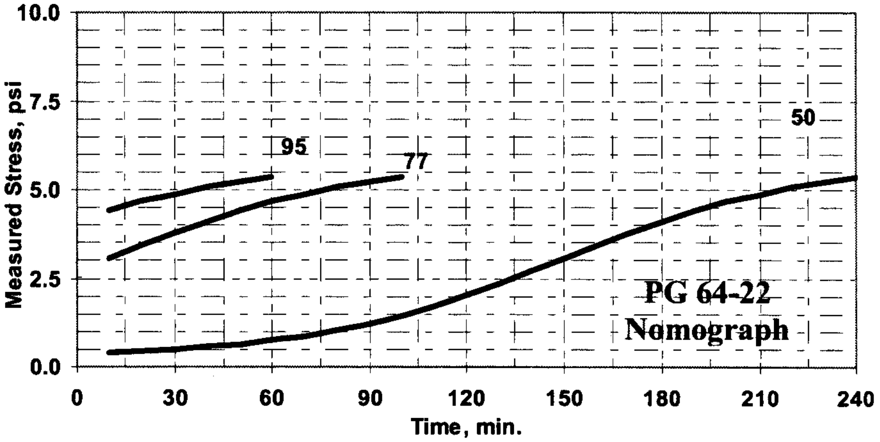
H. Uneven Distribution

Boot Heel Evaluation

Adhesive Quality: ___ Good ___ Fair ____Poor


10.0
7.5
5.0
2.5
0.0
Measured Stress, psi
0
30
60
90
120
150
180
Time, min.
140
95
50
77
CSS-1h
Nomograph


4.0
3.0
2.0
1.0
0.0
Measured Stress, psi
0
30
60
90
120
150
180
Time, min.
140
95
77
50
SS-1h
Nomograph


10.0
7.5
5.0
2.5
0.0
Measured Stress, psi
0
30
60
90
120
150
180
210
240
Time, min.
95
77
50
PG 64-22
Nomograph

APPENDIX D: In-Place Field Density Measurements

Section		Offset (ft)		Gauge Readings (lbs/cu ft)		Average (lb/cu ft)	Corrected Density (lb/cu ft)	Percent of Rice (%)	Lot Average (%)	Lot Standard Deviation	Lot C.V.
1	milled broken 0.018	3.0	Left	133.2	134.4	133.8	138.3	89.5	92.5	2.73	2.95
		8.5	Left	135.1	137.0	136.1	140.7	91.1			
		5.0	Left	143.4	145.4	144.4	149.3	96.6			
		1.5	Left	136.0	138.1	137.1	141.7	91.7			
		7.0	Left	140.3	139.5	139.9	144.7	93.6			
2	milled unbroken 0.018	3.0	Left	139.4	140.7	140.1	144.8	93.7	92.3	1.69	1.84
		8.5	Left	133.9	133.9	133.9	138.5	89.6			
		5.0	Left	136.3	137.9	137.1	141.8	91.8			
		1.5	Left	139.8	139.3	139.6	144.3	93.4			
		7.0	Left	139.5	138.9	139.2	143.9	93.2			
3	milled broken 0.048	3.0	Left	139.9	141.0	140.5	145.2	94.0	92.5	1.27	1.38
		8.5	Left	136.5	139.5	138.0	142.7	92.4			
		5.0	Left	135.7	136.2	136.0	140.6	91.0			
		1.5	Left	138.0	136.0	137.0	141.7	91.7			
		7.0	Left	139.0	140.8	139.9	144.7	93.6			
4	milled unbroken 0.048	3.0	Left	135.8	140.6	138.2	142.9	92.5	92.7	0.83	0.89
		8.5	Left	137.7	137.9	137.8	142.5	92.2			
		5.0	Left	138.1	136.2	137.2	141.8	91.8			
		1.5	Left	140.0	140.8	140.4	145.2	94.0			
		7.0	Left	138.3	139.4	138.9	143.6	92.9			
5	milled broken 0.072	3.0	Left	141.9	141.0	141.5	146.3	94.7	94.1	1.39	1.48
		8.5	Left	137.2	137.9	137.6	142.2	92.1			
		5.0	Left	141.4	142.5	142.0	146.8	95.0			
		1.5	Left	139.1	139.8	139.5	144.2	93.3			
		7.0	Left	144.1	141.2	142.7	147.5	95.5			
6	milled unbroken 0.072	3.0	Left	140.9	142.0	141.5	146.3	94.7	93.4	1.53	1.63
		8.5	Left	137.7	138.1	137.9	142.6	92.3			
		5.0	Left	139.3	139.0	139.2	143.9	93.1			
		1.5	Left	137.5	136.1	136.8	141.5	91.6			
		7.0	Left	141.6	142.7	142.2	147.0	95.1			
7	milled no-tack	6.0	Left	141.2	141.0	141.1	145.9	94.4	92.4	2.55	2.76
		17.0	Left	139.7	140.3	140.0	144.8	93.7			
		10.0	Left	135.6	137.5	136.6	141.2	91.4			
		3.0	Left	140.8	140.5	140.7	145.4	94.1			
		14.0	Left	133.5	130.6	132.1	136.5	88.4			
8	non-milled no-tack	6.0	Left	143.7	142.9	143.3	148.2	95.9	93.1	3.82	4.11
		17.0	Left	141.6	141.7	141.7	146.5	94.8			
		10.0	Left	142.2	142.9	142.6	147.4	95.4			
		3.0	Left	139.2	137.7	138.5	143.2	92.7			
		14.0	Left	126.9	131.9	129.4	133.8	86.6			

Section		Offset (ft)		Gauge Readings (lbs/cu ft)		Average (lb/cu ft)	Corrected Density (lb/cu ft)	Percent of Rice (%)	Lot Average (%)	Lot Standard Deviation	Lot C.V.
9	non-milled broken 0.018	3.0	Left	136.9	137.6	137.3	141.9	91.9	93.4	1.20	1.29
		8.5	Left	139.4	139.8	139.6	144.3	93.4			
		5.0	Left	142.3	139.7	141.0	145.8	94.4			
		1.5	Left	139.0	138.2	138.6	143.3	92.8			
		7.0	Left	142.6	140.8	141.7	146.5	94.8			
10	non-milled unbroken 0.018	3.0	Left	139.6	139.9	139.8	144.5	93.5	94.5	0.61	0.64
		8.5	Left	141.3	140.9	141.1	145.9	94.4			
		5.0	Left	142.5	141.7	142.1	146.9	95.1			
		1.5	Left	140.8	142.8	141.8	146.6	94.9			
		7.0	Left	140.8	141.5	141.2	145.9	94.5			
11	non-milled broken 0.048	3.0	Left	142.0	140.7	141.4	146.2	94.6	94.4	1.24	1.31
		8.5	Left	142.5	140.9	141.7	146.5	94.8			
		5.0	Left	143.6	142.6	143.1	148.0	95.8			
		1.5	Left	136.8	139.3	138.1	142.7	92.4			
		7.0	Left	140.7	141.8	141.3	146.1	94.5			
12	non-milled unbroken 0.048	3.0	Left	137.9	137.0	137.5	142.1	92.0	91.3	1.54	1.69
		8.5	Left	138.0	138.9	138.5	143.2	92.7			
		5.0	Left	133.2	132.4	132.8	137.3	88.9			
		1.5	Left	135.3	135.8	135.6	140.2	90.7			
		7.0	Left	136.7	139.1	137.9	142.6	92.3			
13	non-milled broken 0.072	3.0	Left	137.6	137.7	137.7	142.3	92.1	91.6	1.57	1.72
		8.5	Left	138.2	139.5	138.9	143.6	92.9			
		5.0	Left	136.3	138.7	137.5	142.2	92.0			
		1.5	Left	132.9	132.6	132.8	137.3	88.8			
		7.0	Left	136.2	138.4	137.3	142.0	91.9			
14	non-milled unbroken 0.072	3.0	Left	134.8	134.7	134.8	139.3	90.2	91.9	1.81	1.97
		8.5	Left	139.8	139.6	139.7	144.4	93.5			
		5.0	Left	138.1	137.5	137.8	142.5	92.2			
		1.5	Left	132.7	135.9	134.3	138.9	89.9			
		7.0	Left	139.6	140.6	140.1	144.9	93.8			
							Overall Average	92.9			
							Overall Standard Deviaton	1.95			

APPENDIX E: FDOT Shear Tester Results

Surface Condition	Curing Time	Location	[a]Residual Rate (gal/syd)	Core ID	Average Diameter (inch)	Average Thickness (inch)	Load (lb.)	Shear Stength (psi)
Milled	Broken	ML	0.02	1A2	5.94	2.51	4400	159
Milled	Broken	ML	0.02	1A4	5.95	2.32	4500	162
Milled	Broken	ML	0.02	1A6	5.95	2.13	4720	170
Milled	Broken	WP	0.02	1B2	5.95	2.43	4260	153
Milled	Broken	WP	0.02	1B4	5.96	2.49	4340	156
Milled	Broken	WP	0.02	1B6	5.95	2.36	4400	158
Milled	Unbroken	ML	0.02	2A2	5.64	2.55	3280	131
Milled	Unbroken	ML	0.02	2A4	5.64	2.57	4050	162
Milled	Unbroken	ML	0.02	2A6	5.65	2.55	3640	145
Milled	Unbroken	WP	0.02	2B2	5.66	2.59	4000	159
Milled	Unbroken	WP	0.02	2B4	5.67	2.86	2480	98
Milled	Unbroken	WP	0.02	2B6	5.67	2.89	4680	185
Milled	Broken	ML	0.05	3A2	5.95	2.38	4160	150
Milled	Broken	ML	0.05	3A4	5.95	2.23	5120	184
Milled	Broken	ML	0.05	3A6	5.95	2.13	5000	180
Milled	Broken	WP	0.05	3B2	5.95	1.71	5380	193
Milled	Broken	WP	0.05	3B4	5.95	1.81	4640	167
Milled	Broken	WP	0.05	3B6	5.95	1.77	3940	142
Milled	Unbroken	ML	0.05	4A2	5.65	1.96	4500	180
Milled	Unbroken	ML	0.05	4A4	5.64	2.03	3900	156
Milled	Unbroken	ML	0.05	4A6	5.65	2.38	3600	144
Milled	Unbroken	WP	0.05	4B2	5.67	1.82	5120	203
Milled	Unbroken	WP	0.05	4B4	5.67	1.90	4720	187
Milled	Unbroken	WP	0.05	4B6	5.67	1.89	6300	250
Milled	Broken	ML	0.07	5A2	5.95	1.89	5500	198
Milled	Broken	ML	0.07	5A4	5.95	2.19	5100	183
Milled	Broken	ML	0.07	5A6	5.95	1.90	5900	212
Milled	Broken	WP	0.07	5B2	5.94	1.84	4800	173
Milled	Broken	WP	0.07	5B4	5.95	1.93	5580	201
Milled	Broken	WP	0.07	5B6	5.96	1.67	5860	210

Milled	Unbroken	ML	0.07	6A2	5.64	2.40	3500	140
Milled	Unbroken	ML	0.07	6A4	5.65	2.39	4680	187
Milled	Unbroken	ML	0.07	6A6	5.66	2.60	4180	166
Milled	Unbroken	WP	0.07	6B2	5.67	1.81	6150	244
Milled	Unbroken	WP	0.07	6B4	5.68	1.64	5750	227
Milled	Unbroken	WP	0.07	6B6	5.67	1.50	6740	267
Milled	No Tack	ML	0	7A2	5.96	2.03	4740	170
Milled	No Tack	ML	0	7A4	5.94	1.84	5080	183
Milled	No Tack	ML	0	7A6	5.95	1.65	5680	204
Milled	No Tack	WP	0	7B2	5.95	1.77	4740	170
Milled	No Tack	WP	0	7B4	5.96	1.78	3550	127
Milled	No Tack	WP	0	7B6	5.96	1.81	4660	167
Overlay	No Tack	ML	0	8A2				0
Overlay	No Tack	ML	0	8A4				0
Overlay	No Tack	ML	0	8A6				0
Overlay	No Tack	WP	0	8B2				0
Overlay	No Tack	WP	0	8B4				0
Overlay	No Tack	WP	0	8B6				0
Overlay	Broken	ML	0.02	9A2	N/A	N/A	[b]	[b]
Overlay	Broken	ML	0.02	9A4	N/A	N/A	[b]	[b]
Overlay	Broken	ML	0.02	9A6	5.95	1.89	1280	46
Overlay	Broken	WP	0.02	9B2	5.97	1.88	1130	40
Overlay	Broken	WP	0.02	9B4	5.95	1.84	490	18
Overlay	Broken	WP	0.02	9B6	5.96	1.94	890	32
Overlay	Unbroken	ML	0.02	10A2	5.65	1.76	1950	78
Overlay	Unbroken	ML	0.02	10A4	5.66	1.84	1390	55
Overlay	Unbroken	ML	0.02	10A6	5.66	1.89	1350	54
Overlay	Unbroken	WP	0.02	10B2	5.72	1.76	2010	78
Overlay	Unbroken	WP	0.02	10B4	5.71	1.72	1850	72
Overlay	Unbroken	WP	0.02	10B6	5.72	1.76	1950	76
Overlay	Broken	ML	0.05	11A2	5.95	1.78	2540	91
Overlay	Broken	ML	0.05	11A4	5.95	1.88	1940	70
Overlay	Broken	ML	0.05	11A6	5.94	1.98	1040	38
Overlay	Broken	WP	0.05	11B2	5.96	1.78	1840	66
Overlay	Broken	WP	0.05	11B4	5.96	1.84	2510	90
Overlay	Broken	WP	0.05	11B6	5.97	2.11	1020	36
Overlay	Unbroken	ML	0.05	12A2	5.66	1.76	1275	51
Overlay	Unbroken	ML	0.05	12A4	5.67	1.71	1040	41
Overlay	Unbroken	ML	0.05	12A6	5.66	1.98	1800	72
Overlay	Unbroken	WP	0.05	12B2	5.71	1.75	1950	76
Overlay	Unbroken	WP	0.05	12B4	5.71	1.69	1360	53
Overlay	Unbroken	WP	0.05	12B6	5.71	1.77	930	36

Overlay	Broken	ML	0.07	13A2	5.95	2.01	1650	59
Overlay	Broken	ML	0.07	13A4	5.95	2.06	1200	43
Overlay	Broken	ML	0.07	13A6	5.97	1.98	1850	66
Overlay	Broken	WP	0.07	13B2	5.97	2.05	1700	61
Overlay	Broken	WP	0.07	13B4	5.98	1.99	1900	68
Overlay	Broken	WP	0.07	13B6	5.97	1.98	2180	78
Overlay	Unbroken	ML	0.07	14A2	5.66	1.97	2260	90
Overlay	Unbroken	ML	0.07	14A4	5.66	1.97	[b]	[b]
Overlay	Unbroken	ML	0.07	14A6	5.66	1.92	1520	60
Overlay	Unbroken	WP	0.07	14B2	5.72	1.84	[b]	[b]
Overlay	Unbroken	WP	0.07	14B4	5.72	1.82	3010	117
Overlay	Unbroken	WP	0.07	14B6	5.72	1.68	2110	82
Average					5.82	2.01	3382	117.4
Standard Deviation					0.14	0.30	1683	69.3
Coefficient of Variation (%)					2.4	15.0	49.8	59.0

Notes

a- Cores number 8A2, 8A4, 8A6, 8B2, 8B4, and 8B6 de-bonded during coring, thus were assumed to have no shear strength (zero). These cores were not tested but their results (zero shear strength) were included in the analyses.

b- The results from the following cores were excluded from the analyses:

1. Core number 9A2. It was damaged (delaminated) during shipping.
2. Core number 9A4. It was damaged (delaminated) during coring.
3. Core number 14A4. It was damaged (delaminated) during shipping.
4. Core number 14B2. It was damaged during testing.

c- No outliers were found among the data, i.e., for each group of Surface Condition, Curing Time, Location, and Target Residual Rate, the tests results were within the Average±2SD.

APPENDIX F: Torque Bond Test Results

Surface Condition	Curing Time	Location	[a]Residual Rate (gal/syd)	Core ID	Average Thickness (inch)	Average Diameter (inch)	Torque (Nm)	Bond Strength (Pa)
Milled	Broken	ML	0.02	1A1	60	150.7	[b]	[b]
Milled	Broken	ML	0.02	1A3	59.7	151.0	400	444
Milled	Broken	ML	0.02	1A5	54.7	151.0	400	444
Milled	Broken	WP	0.02	1B1	53.7	150.4	400	450
Milled	Broken	WP	0.02	1B3	61.3	150.3	400	450
Milled	Broken	WP	0.02	1B5	47.0	150.5	400	449
Milled	Unbroken	ML	0.02	2A1	45.0	142.6	400	527
Milled	Unbroken	ML	0.02	2A3	43.3	142.7	400	526
Milled	Unbroken	ML	0.02	2A5	49.3	142.7	400	526
Milled	Unbroken	WP	0.02	2B1	36.0	143.3	400	520
Milled	Unbroken	WP	0.02	2B3	53.7	143.4	400	519
Milled	Unbroken	WP	0.02	2B5	48.3	143.3	400	519
Milled	Broken	ML	0.05	3A1	44.0	150.6	400	448
Milled	Broken	ML	0.05	3A3	44.0	150.5	400	448
Milled	Broken	ML	0.05	3A5	50.0	150.7	400	447
Milled	Broken	WP	0.05	3B1	47.7	150.3	400	450
Milled	Broken	WP	0.05	3B3	47.3	150.5	400	449
Milled	Broken	WP	0.05	3B5	47.7	150.4	400	449
Milled	Unbroken	ML	0.05	4A1	47.0	142.8	400	525
Milled	Unbroken	ML	0.05	4A3	50.0	142.7	400	526
Milled	Unbroken	ML	0.05	4A5	50.0	142.8	400	525
Milled	Unbroken	WP	0.05	4B1	70.3	143.5	400	518
Milled	Unbroken	WP	0.05	4B3	48.0	143.4	400	518
Milled	Unbroken	WP	0.05	4B5	49.7	143.6	350	452
Milled	Broken	ML	0.07	5A1	46.3	150.4	400	449
Milled	Broken	ML	0.07	5A3	50.0	150.4	400	450
Milled	Broken	ML	0.07	5A5	51.0	150.4	400	449
Milled	Broken	WP	0.07	5B1	50.3	150.5	400	448
Milled	Broken	WP	0.07	5B3	45.7	150.5	400	449
Milled	Broken	WP	0.07	5B5	42.3	150.5	400	448

Milled	Unbroken	ML	0.07	6A1	61.7	143.0	400	522
Milled	Unbroken	ML	0.07	6A3	46.0	143.0	400	523
Milled	Unbroken	ML	0.07	6A5	47.7	142.8	400	525
Milled	Unbroken	WP	0.07	6B1	42.7	143.6	400	517
Milled	Unbroken	WP	0.07	6B3	42.3	143.5	400	518
Milled	Unbroken	WP	0.07	6B5	47.0	143.5	400	518
Milled	No Tack	ML	0	7A1	55.3	150.5	400	449
Milled	No Tack	ML	0	7A3	47.3	150.4	400	449
Milled	No Tack	ML	0	7A5	43.3	150.6	400	447
Milled	No Tack	WP	0	7B1	45.3	150.5	400	449
Milled	No Tack	WP	0	7B3	45.0	150.8	400	446
Milled	No Tack	WP	0	7B5	44.7	150.9	400	445
Overlay	No Tack	ML	0	8A1			0	0
Overlay	No Tack	ML	0	8A3			0	0
Overlay	No Tack	ML	0	8A5			0	0
Overlay	No Tack	WP	0	8B1			0	0
Overlay	No Tack	WP	0	8B3			0	0
Overlay	No Tack	WP	0	8B5			0	0
Overlay	Broken	ML	0.02	9A1	45.0	150.7	400	447
Overlay	Broken	ML	0.02	9A3	44.0	150.3	400	450
Overlay	Broken	ML	0.02	9A5	47.0	150.2	350	395
Overlay	Broken	WP	0.02	9B1	49.7	151.0	140	155
Overlay	Broken	WP	0.02	9B3	49.0	150.9	110	122
Overlay	Broken	WP	0.02	9B5	49.0	150.7	175	195
Overlay	Unbroken	ML	0.02	10A1	45.0	143.0	400	522
Overlay	Unbroken	ML	0.02	10A3	45.3	143.0	400	522
Overlay	Unbroken	ML	0.02	10A5	47.0	143.2	400	520
Overlay	Unbroken	WP	0.02	10B1	45.0	143.4	400	518
Overlay	Unbroken	WP	0.02	10B3	43.7	144.7	400	504
Overlay	Unbroken	WP	0.02	10B5	44.0	144.8	280	352
Overlay	Broken	ML	0.05	11A1	45.3	150.5	280	314
Overlay	Broken	ML	0.05	11A3	46.7	150.5	295	331
Overlay	Broken	ML	0.05	11A5	50.0	150.5	295	331
Overlay	Broken	WP	0.05	11B1	45.3	151.0	400	444
Overlay	Broken	WP	0.05	11B3	46.0	150.9	400	445
Overlay	Broken	WP	0.05	11B5	50.3	150.8	290	323

Overlay	Unbroken	ML	0.05	12A1	44.7	143.2	400	521
Overlay	Unbroken	ML	0.05	12A3	43.0	143.8	180	231
Overlay	Unbroken	ML	0.05	12A5	48.7	143.4	250	324
Overlay	Unbroken	WP	0.05	12B1	44.7	144.6	400	505
Overlay	Unbroken	WP	0.05	12B3	43.7	144.9	400	503
Overlay	Unbroken	WP	0.05	12B5	43.0	144.7	400	504
Overlay	Broken	ML	0.07	13A1	52.7	150.4	285	320
Overlay	Broken	ML	0.07	13A3	52.7	150.4	290	326
Overlay	Broken	ML	0.07	13A5	50.3	150.3	400	450
Overlay	Broken	WP	0.07	13B1	52.3	151.1	400	443
Overlay	Broken	WP	0.07	13B3	50.3	151.1	400	443
Overlay	Broken	WP	0.07	13B5	50.0	151.3	400	441
Overlay	Unbroken	ML	0.07	14A1	50.0	143.4	400	518
Overlay	Unbroken	ML	0.07	14A3	49.3	143.5	400	518
Overlay	Unbroken	ML	0.07	14A5	48.3	143.3	400	519
Overlay	Unbroken	WP	0.07	14B1	46.3	144.7	290	366
Overlay	Unbroken	WP	0.07	14B3	46.0	144.8	235	296
Overlay	Unbroken	WP	0.07	14B5	42.7	144.8	300	378
Average					48.0	147.3	342.1	411.1
Standard Deviation					5.0	3.6	115.0	142.9
Coefficient of Variation (%)					10.3	2.4	33.6	34.8

Notes

a- Cores number 8A1, 8A3, 8A5, 8B1, 8B3, and 8B5 de-bonded during coring, thus were assumed to have no bond strength (zero). These cores were not tested but their results (zero torque) were included in the analyses.

b- Core number 1A1 was damaged during testing. The results from this core were excluded from the analyses.

c- No outliers were found among the data, i.e., for each group of Surface Condition, Curing Time, Location, and Target Residual Rate, the test results were within the Average±2SD.

APPENDIX G: UTEP Pull-Off Test Results

			Tensile Strength (psi)	
			Testing Time	
Test Section	**Surface Condition**	**Target residual Rate (gal/syd)**	A	B (45 minutes after A)
1	Milled	0.02	1.38	1.84
3	Milled	0.05	1.38	1.22
5	Milled	0.07	1.07	0.92
9	Non-milled	0.02	3.19	2.13
11	Non-milled	0.05	2.50	1.67
13	Non-milled	0.07	3.19	1.82
Average			2.12	1.60
Standard Deviation			0.88	0.88
Coefficient of Variation (%)			41.5	25.5
Overall Average			1.86	
Standard Deviation			0.73	
Overall Coefficient of Variation (%)			39.4	

APPENDIX H: Tukey Simultaneous Tests for FDOT Shear Tester. All Pair-wise Comparisons among Levels of Curing Time (Surface Condition)

```
Tukey Simultaneous Tests
Response Variable Shear Strength (psi)
All Pairwise Comparisons among Levels of Curing Time_1(Surface Condition)
Surface Condition = Milled
Curing Time_1 = Broken  subtracted from:

Surface    Curing    Difference       SE of            Adjusted
Condition  Time_1      of Means  Difference  T-Value    P-Value
Milled     No Tack         -4.9      11.084    -0.44     0.9978
Milled     Unbroken         4.4       7.838     0.57     0.9928
Non-milled    Broken        -121.9       8.170    -14.93    0.0000
Non-milled    No Tack       -175.1      11.084    -15.79    0.0000
Non-milled    Unbroken      -104.7       8.158    -12.84    0.0000


Surface Condition = Milled
Curing Time_1 = No Tack  subtracted from:

Surface    Curing    Difference       SE of            Adjusted
Condition  Time_1      of Means  Difference  T-Value    P-Value
Milled     Unbroken         9.3      11.08      0.84     0.9584
Non-milled    Broken        -117.1       11.32    -10.34    0.0000
Non-milled    No Tack       -170.2       13.58    -12.54    0.0000
Non-milled    Unbroken       -99.9       11.31     -8.83    0.0000


Surface Condition = Milled
Curing Time_1 = Unbroken  subtracted from:

Surface    Curing    Difference       SE of            Adjusted
Condition  Time_1      of Means  Difference  T-Value    P-Value
Non-milled    Broken        -126.4       8.170    -15.47    0.0000
Non-milled    No Tack       -179.5      11.084    -16.19    0.0000
Non-milled    Unbroken      -109.2       8.158    -13.39    0.0000


Surface Condition = Non-milled
Curing Time_1 = Broken  subtracted from:

Surface    Curing    Difference       SE of            Adjusted
Condition  Time_1      of Means  Difference  T-Value    P-Value
Non-milled    No Tack       -53.11      11.321    -4.691    0.0002
Non-milled    Unbroken       17.19       8.477     2.028    0.3381


Surface Condition = Non-milled
Curing Time_1 = No Tack  subtracted from:

Surface    Curing    Difference       SE of            Adjusted
Condition  Time_1      of Means  Difference  T-Value    P-Value
Non-milled    Unbroken       70.31       11.31     6.215    0.0000


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

Surface    Difference       SE of            Adjusted
Condition    of Means  Difference   T-Value   P-Value
Non-milled        -133.8       5.940   -22.52     0.0000
```

APPENDIX I: Tukey Simultaneous Tests for FDOT Shear Tester. All Pair-wise Comparisons among Levels of Target Residual Rate (Curing Time (Surface Condition))

```
Tukey Simultaneous Tests
Response Variable Shear Strength (psi)
All Pairwise Comparisons among Levels of Target Residual Rate(Surface Condition
     Curing Time_1)
Surface Condition = Milled
Curing Time_1 = Broken
Target Residual Rate = 0.02  subtracted from:

                     Target
Surface    Curing    Residual  Difference       SE of           Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value   P-Value
Milled     Broken    0.05             9.7       13.58     0.71    1.0000
Milled     Broken    0.07            36.5       13.58     2.69    0.3089
Milled     No Tack   0.00            10.5       13.58     0.77    0.9999
Milled     Unbroken  0.02           -13.0       13.58    -0.96    0.9994
Milled     Unbroken  0.05            27.0       13.58     1.99    0.7685
Milled     Unbroken  0.07            45.5       13.58     3.35    0.0710
Non-milled    Broken    0.02          -128.0       15.24    -8.40    0.0000
Non-milled    Broken    0.05           -94.5       13.58    -6.96    0.0000
Non-milled    Broken    0.07           -97.2       13.58    -7.16    0.0000
Non-milled    No Tack   0.00          -159.7       13.58   -11.76    0.0000
Non-milled    Unbroken  0.02           -90.8       13.58    -6.69    0.0000
Non-milled    Unbroken  0.05          -104.8       13.58    -7.72    0.0000
Non-milled    Unbroken  0.07           -72.4       15.18    -4.77    0.0009


Surface Condition = Milled
Curing Time_1 = Broken
Target Residual Rate = 0.05  subtracted from:

                     Target
Surface    Curing    Residual  Difference       SE of           Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value   P-Value
Milled     Broken    0.07            26.8       13.58     1.98    0.7758
Milled     No Tack   0.00             0.8       13.58     0.06    1.0000
Milled     Unbroken  0.02           -22.7       13.58    -1.67    0.9189
Milled     Unbroken  0.05            17.3       13.58     1.28    0.9903
Milled     Unbroken  0.07            35.8       13.58     2.64    0.3371
Non-milled    Broken    0.02          -137.7       15.24    -9.04    0.0000
Non-milled    Broken    0.05          -104.2       13.58    -7.67    0.0000
Non-milled    Broken    0.07          -106.8       13.58    -7.87    0.0000
Non-milled    No Tack   0.00          -169.3       13.58   -12.47    0.0000
Non-milled    Unbroken  0.02          -100.5       13.58    -7.40    0.0000
Non-milled    Unbroken  0.05          -114.5       13.58    -8.43    0.0000
Non-milled    Unbroken  0.07           -82.1       15.18    -5.41    0.0001


Surface Condition = Milled
Curing Time_1 = Broken
Target Residual Rate = 0.07  subtracted from:

                     Target
Surface    Curing    Residual  Difference       SE of           Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value   P-Value
Milled     No Tack   0.00           -26.0       13.58    -1.92    0.8107
Milled     Unbroken  0.02           -49.5       13.58    -3.65    0.0318
Milled     Unbroken  0.05            -9.5       13.58    -0.70    1.0000
Milled     Unbroken  0.07             9.0       13.58     0.66    1.0000
Non-milled    Broken    0.02          -164.5       15.24   -10.80    0.0000
Non-milled    Broken    0.05          -131.0       13.58    -9.65    0.0000
Non-milled    Broken    0.07          -133.7       13.58    -9.85    0.0000
Non-milled    No Tack   0.00          -196.2       13.58   -14.45    0.0000
```

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Non-milled    Unbroken  0.02          -127.3       13.58     -9.38     0.0000
Non-milled    Unbroken  0.05          -141.3       13.58    -10.41     0.0000
Non-milled    Unbroken  0.07          -108.9       15.18     -7.18     0.0000


Surface Condition = Milled
Curing Time_1 = No Tack
Target Residual Rate = 0.00  subtracted from:

                     Target
Surface    Curing    Residual  Difference       SE of            Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value    P-Value
Milled     Unbroken  0.02           -23.5       13.58    -1.73     0.8969
Milled     Unbroken  0.05            16.5       13.58     1.22     0.9938
Milled     Unbroken  0.07            35.0       13.58     2.58     0.3742
Non-milled    Broken    0.02          -138.5       15.24     -9.09     0.0000
Non-milled    Broken    0.05          -105.0       13.58     -7.73     0.0000
Non-milled    Broken    0.07          -107.7       13.58     -7.93     0.0000
Non-milled    No Tack   0.00          -170.2       13.58    -12.54     0.0000
Non-milled    Unbroken  0.02          -101.3       13.58     -7.46     0.0000
Non-milled    Unbroken  0.05          -115.3       13.58     -8.50     0.0000
Non-milled    Unbroken  0.07           -82.9       15.18     -5.46     0.0001


Surface Condition = Milled
Curing Time_1 = Unbroken
Target Residual Rate = 0.02  subtracted from:

                     Target
Surface    Curing    Residual  Difference       SE of            Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value    P-Value
Milled     Unbroken  0.05            40.0       13.58     2.95     0.1854
Milled     Unbroken  0.07            58.5       13.58     4.31     0.0041
Non-milled    Broken    0.02          -115.0       15.24     -7.55     0.0000
Non-milled    Broken    0.05           -81.5       13.58     -6.00     0.0000
Non-milled    Broken    0.07           -84.2       13.58     -6.20     0.0000
Non-milled    No Tack   0.00          -146.7       13.58    -10.80     0.0000
Non-milled    Unbroken  0.02           -77.8       13.58     -5.73     0.0001
Non-milled    Unbroken  0.05           -91.8       13.58     -6.76     0.0000
Non-milled    Unbroken  0.07           -59.4       15.18     -3.91     0.0144


Surface Condition = Milled
Curing Time_1 = Unbroken
Target Residual Rate = 0.05  subtracted from:

                     Target
Surface    Curing    Residual  Difference       SE of            Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value    P-Value
Milled     Unbroken  0.07            18.5       13.58     1.36     0.9830
Non-milled    Broken    0.02          -155.0       15.24    -10.17     0.0000
Non-milled    Broken    0.05          -121.5       13.58     -8.95     0.0000
Non-milled    Broken    0.07          -124.2       13.58     -9.15     0.0000
Non-milled    No Tack   0.00          -186.7       13.58    -13.75     0.0000
Non-milled    Unbroken  0.02          -117.8       13.58     -8.68     0.0000
Non-milled    Unbroken  0.05          -131.8       13.58     -9.71     0.0000
Non-milled    Unbroken  0.07           -99.4       15.18     -6.55     0.0000


Surface Condition = Milled
Curing Time_1 = Unbroken
Target Residual Rate = 0.07  subtracted from:

                     Target
Surface    Curing    Residual  Difference       SE of            Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value    P-Value
Non-milled    Broken    0.02          -173.5       15.24    -11.39     0.0000
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Non-milled    Broken    0.05          -140.0        13.58   -10.31     0.0000
Non-milled    Broken    0.07          -142.7        13.58   -10.51     0.0000
Non-milled    No Tack   0.00          -205.2        13.58   -15.11     0.0000
Non-milled    Unbroken  0.02          -136.3        13.58   -10.04     0.0000
Non-milled    Unbroken  0.05          -150.3        13.58   -11.07     0.0000
Non-milled    Unbroken  0.07          -117.9        15.18    -7.77     0.0000


Surface Condition = Non-milled
Curing Time_1 = Broken
Target Residual Rate = 0.02  subtracted from:

                      Target
Surface     Curing    Residual  Difference        SE of            Adjusted
Condition   Time_1    Rate         of Means  Difference  T-Value    P-Value
Non-milled    Broken     0.05          33.50        15.24    2.199     0.6317
Non-milled    Broken     0.07          30.83        15.24    2.024     0.7474
Non-milled    No Tack    0.00         -31.67        15.24   -2.079     0.7123
Non-milled    Unbroken  0.02          37.16        15.24    2.439     0.4647
Non-milled    Unbroken  0.05          23.16        15.24    1.520     0.9588
Non-milled    Unbroken  0.07          55.58        16.68    3.332     0.0746


Surface Condition = Non-milled
Curing Time_1 = Broken
Target Residual Rate = 0.05  subtracted from:

                      Target
Surface     Curing    Residual  Difference        SE of            Adjusted
Condition   Time_1    Rate         of Means  Difference  T-Value    P-Value
Non-milled    Broken     0.07          -2.67        13.58   -0.196     1.0000
Non-milled    No Tack    0.00         -65.17        13.58   -4.800     0.0008
Non-milled    Unbroken  0.02           3.67        13.58    0.270     1.0000
Non-milled    Unbroken  0.05         -10.33        13.58   -0.761     1.0000
Non-milled    Unbroken  0.07          22.08        15.18    1.455     0.9708


Surface Condition = Non-milled
Curing Time_1 = Broken
Target Residual Rate = 0.07  subtracted from:

                      Target
Surface     Curing    Residual  Difference        SE of            Adjusted
Condition   Time_1    Rate         of Means  Difference  T-Value    P-Value
Non-milled    No Tack   0.00          -62.50        13.58   -4.604     0.0015
Non-milled    Unbroken  0.02            6.33        13.58    0.467     1.0000
Non-milled    Unbroken  0.05           -7.67        13.58   -0.565     1.0000
Non-milled    Unbroken  0.07           24.75        15.18    1.631     0.9311


Surface Condition = Non-milled
Curing Time_1 = No Tack
Target Residual Rate = 0.00  subtracted from:

                      Target
Surface     Curing    Residual  Difference        SE of            Adjusted
Condition   Time_1    Rate         of Means  Difference  T-Value    P-Value
Non-milled    Unbroken  0.02           68.83        13.58    5.070     0.0003
Non-milled    Unbroken  0.05           54.83        13.58    4.039     0.0098
Non-milled    Unbroken  0.07           87.25        15.18    5.749     0.0001


Surface Condition = Non-milled
Curing Time_1 = Unbroken
Target Residual Rate = 0.02  subtracted from:
```

```
                    Target
Surface    Curing    Residual  Difference       SE of            Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value    P-Value
Non-milled    Unbroken  0.05          -14.00       13.58   -1.031     0.9988
Non-milled    Unbroken  0.07           18.42       15.18    1.213     0.9939


Surface Condition = Non-milled
Curing Time_1 = Unbroken
Target Residual Rate = 0.05  subtracted from:

                    Target
Surface    Curing    Residual  Difference       SE of            Adjusted
Condition  Time_1    Rate        of Means  Difference  T-Value    P-Value
Non-milled    Unbroken  0.07           32.42       15.18    2.136     0.6746
```