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Midwest States Accelerated Testing Program: Well Bonded Superpave Overlays on Hot Mix Asphalt

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This study compares the bond strength of these materials by compacting a fresh HMA layer in the laboratory on top of cores taken from milled and non-milled highway sections. These cores were treated with different tack materials and application rates in order to find the optimal bond strength. The samples were tested in direct tension at two days, similar to KDOT's construction quality assurance tests for the in-situ interface bond strength. Preliminary results indicate that SS-1HP does not improve bond strength at rates below 0.05 gal/yd2 (0.23 liter/m2) while EBL performs well at a rate that is 50% of the manufacturer's recommendation. Trackless tack achieved acceptable bond strength as well. Surface texture was significant in achieving acceptable bond strength in some cases. A full-scale accelerated pavement testing (APT) was also performed, and the results showed that EBL had better bond strength and slightly less permanent deformation, but showed no difference in cracking.

Further APT testing with variable application rates of SS-1HP indicated that the KDOT-recommended rate of 0.05 gal/yd2 (0.23 liter/m2) showed good performance as a tack coat material based on the in-situ strain, in-situ bond strength, laboratory bond strength, and bond energy. Strain at the overlay interface and the existing HMA pavement was lowest for this rate. Although very heavy application of SS-1HP showed somewhat good performance, such high rate tends to decrease the interface bond strength as when evaluated in-situ as well as in the laboratory. Comparison of the SS-1HP test sections in the two APT experiments of this study indicates that the cleanliness of the milled surface is a big contributor to interface bonding.

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Final Report

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Abstract

The construction of hot-mix asphalt (HMA) overlay or multiple lifts involves spraying tack coat onto the existing surface to obtain a good bond and to ensure that the multiple pavement layers behave monolithically. Insufficient tack coat application has been linked to premature cracking failure. The Kansas Department of Transportation (KDOT) regularly uses a slow setting anionic polymer-modified emulsion (SS-1HP) as a tack material in both new construction and rehabilitation. Recently, KDOT has allowed the use of Emulsion Bonding Liquid (EBL, applied with spray pavers) and trackless tack, both of which avoid the problem of truck/paver tires picking up the tack material.

This study compares the bond strength of these materials by compacting a fresh HMA layer in the laboratory on top of cores taken from milled and non-milled highway sections. These cores were treated with different tack materials and application rates in order to find the optimal bond strength. The samples were tested in direct tension at two days, similar to KDOT's construction quality assurance tests for the in-situ interface bond strength. Preliminary results indicate that SS-1HP does not improve bond strength at rates below 0.05 gal/yd^2 (0.23 liter/m^2) while EBL performs well at a rate that is 50% of the manufacturer's recommendation. Trackless tack achieved acceptable bond strength as well. Surface texture was significant in achieving acceptable bond strength in some cases. A full-scale accelerated pavement testing (APT) was also performed, and the results showed that EBL had better bond strength and slightly less permanent deformation, but showed no difference in cracking.

Further APT testing with variable application rates of SS-1HP indicated that the KDOT-recommended rate of 0.05 gal/yd^2 (0.23 liter/m^2) showed good performance as a tack coat material based on the in-situ strain, in-situ bond strength, laboratory bond strength, and bond energy. Strain at the overlay interface and the existing HMA pavement was lowest for this rate. Although very heavy application of SS-1HP showed somewhat good performance, such high rate tends to decrease the interface bond strength as when evaluated in-situ as well as in the laboratory. Comparison of the SS-1HP test sections in the two APT experiments of this study indicates that the cleanliness of the milled surface is a big contributor to interface bonding.

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Chapter 1: Introduction

1.1 Introduction

Lifts of Hot-Mix Asphalt (HMA), compacted days or even years apart from each other, are designed to unite into a monolithic structure and carry the applied traffic loads. A reliable bond between the lifts of a new pavement or between the overlay and the existing HMA pavement can be obtained by placing a tack coat before paving. A tack coat is a light application of an asphaltic emulsion or asphalt binder between the pavement lifts in new construction or most commonly used in between an existing surface and a newly constructed overlay. Typically, tack coats are emulsions consisting of asphalt binder particles, which have been dispersed in water with an emulsifying agent (Brown et al., 2009). A colloid mill and an emulsifying agent suspend the neutral asphalt particles with a charge that prevents them from clumping back together, reducing asphalt consistency at ambient temperature from a semi-solid to a liquid form. The most common types of emulsions used for tack coats include slow-setting (SS) grades such as SS-1, SS-1H, CSS-1, and CSS-1H and the rapid-setting (RS) grades of emulsion such as RS-1, RS-2, CRS-1, CRS-2, CRS-2P (polymer-modified), and CRS-2L (latex-modified). Here "C" stands for cationic types, others being "anionic." This emulsified asphalt is easier to apply at ambient temperatures. When this liquid emulsion is applied on a clean surface, water evaporates from the emulsion, leaving behind a thin layer of residual asphalt on the pavement surface. The tack coat promotes bonding between the layers or lifts that result in mobilizing maximum structural capacity of the pavement structure. It also prevents delamination, thus ensuring long-term performance of the pavement. Lack of bond can lead to premature failure in the form of debonding, mat slippage, and potentially fatigue cracking, which may lead to reduced pavement life. Determining the optimal amount of tack for pavement performance is a concern for many in the HMA industry today (Mohammad et al., 2012).

As mentioned earlier, most tack coats are produced from an asphaltic material which is emulsified to allow for spray application. The supplied materials are diluted with a maximum of 35–43% water. Once an emulsion is sprayed on a surface and is exposed to the air, water evaporates in a process known as "breaking" (Brown et al., 2009). What begins as a rich brown layer turns into a sticky black layer as shown in Figure 1.1.

Figure 1.1: Tack Coat Application

1.2 Problem Statement

The Kansas Department of Transportation (KDOT) regularly uses a slow setting anionic polymer-modified emulsion (SS-1HP) as a tack material. Their recommended application rate is 0.05 gal/yd^2 (0.226 liter/m^2 [lpm^2]). Another tack often promoted is Emulsion Bonding Liquid (EBL). "EBL is a polymerized emulsion used primarily undiluted at rates that depend on the existing pavement macro-texture" (KDOT, 2015). This material is applied at much higher quantities, often at 0.14 gal/yd^2 (0.63 lpm^2), nearly three times as much as SS-1HP. EBL is applied with special spray pavers, in contrast to the traditional methods where a distributor truck with nozzles sprays tack on the road in advance of the paver, which can lead to trucks and other construction equipment compromising the tack by driving over it. Figure 1.2 shows a truck picking up tack as it passes over a surface where tack has been placed. A third type of tack material being promoted is trackless, which is applied like traditional tack, but will lose its stickiness within minutes. It is not susceptible to tire pick up and yet still bonds the layers together (Clark, Rorrer, & McGhee, 2010).

Figure 1.2: Tack Pick Up by Truck Tire

Sometimes roads are overlaid on existing surfaces, and sometimes they are milled first, often to recycle the surface layer. This is an expensive process. All KDOT mill and inlay projects from January 2013 to February 2014 were studied. Two major rehabilitation mill and inlay projects, worth over $10 million each, were excluded. The rest of the projects can be seen in Figure 1.3 to have an understandably increasing cost for each mile. While very short projects can be done rather inexpensively, the average cost is about $1 million for any mill and inlay project, with an additional $95,000 per mile paved.

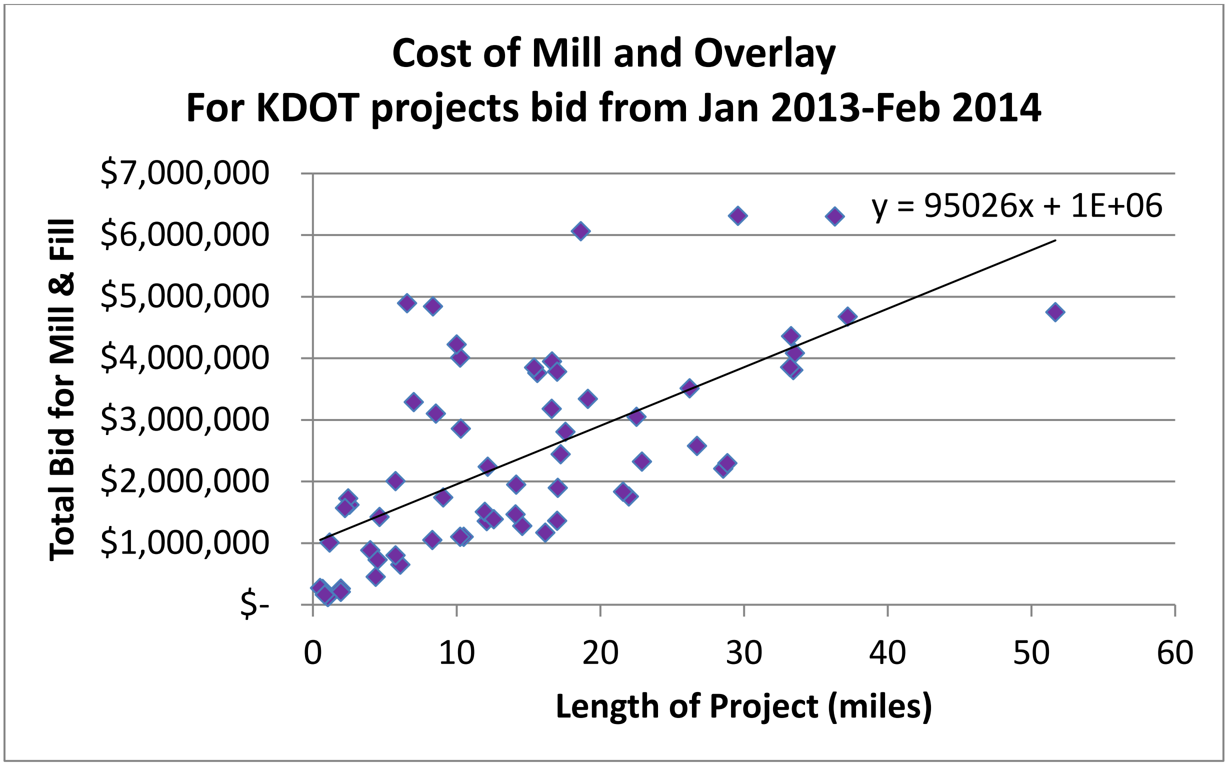

Figure 1.3: Cost of Mill and Overlay in KDOT

Figure 1.3 shows that anything that can extend the life of a roadway for a year or two will save millions of dollars in construction over time. Recent experiences in Kansas have shown some premature cracking on newly overlaid pavements and one of the contributing factors may have been a lack of proper tack coat. Thus, an optimal tack rate needs to be found in order to help mitigate this problem.

1.3 Study Objective and Approach

This study focused on SS-1HP, EBL, and Trackless tacks. The objective was to find the optimum application rate for each of these materials, as determined by the interface bond strength. KDOT uses a direct tension pull-off test (KT-78) to validate in-situ bond strength. To compare laboratory results with those from the field tests, a method similar to KT-78 was used in this study. Varying rates of tack were applied to the existing (cored) asphalt surface and a fresh HMA layer was compacted on top to simulate the overlay. A laboratory pull-off test examined the bond strength at two days, while a full-scale test looked at various tack performance under accelerated pavement testing (APT).

1.4 Report Outline

This report has five chapters. Chapter 1 provides the introduction, problem statement, objectives, etc. Chapter 2 is the literature review regarding the use of tack coats for HMA pavements. Chapter 3 presents details of the laboratory tests. Chapter 4 describes the full-scale tests conducted at Kansas State University. Chapters 5 and Chapter 6 discuss the results of the lab and full-scale tests. Conclusions and recommendations from this study are presented in Chapter 7.

Chapter 2: Literature Review

2.1 Bond Strength Evaluation Tests

Various HMA interlayer bond strength evaluation tests have been developed over the last two decades. West, Zhang, and Moore (2005) and Rahman (2010) described the notable ones.

Romanoschi (1999) proposed a direct shear test with the normal load. The test schematic has been illustrated in Figure 2.1. A cylindrical sample is placed between two metal cups such that the interface is positioned in the middle of two cups. A constant normal stress is applied at the interface while it is sheared at a constant rate of shear displacement. The test is repeated at several normal stress levels. A relationship between the interface shear strength or reaction modulus and the normal stress is obtained by regression analysis (Romanoschi, 1999). This test presents an improvement over Iowa Test Method No. 406 (Grove, Harris, & Skinner, 1993), which is a direct shear test without the normal load.

Canestrari, Ferrotti, Partl, and Santagata (2005) developed a device and criteria for evaluating bond strength of HMA layers. The device, known as an LPDS tester, uses 6-inch (150-mm) diameter cores (Figure 2.2a). The test is a simple shear test with a loading rate of 2 in./min (50 mm/min). The minimum shear force criterion is 3.4 kip (15 kN) for the bond between the thin surface layer and the binder course, and 2.7 kip (12 kN) for the bond between the asphalt binder course and the base layer.

The Superpave shear tester (SST) developed through the Strategic Highway Research Program, can be used to evaluate interface bond strength (Figure 2.2b). The shear test set up has two chambers to hold the specimen during testing in the SST. The shear load is applied at a constant rate of 45 lb./min (0.2 kN/min) until failure. Since the SST has a temperature controlled chamber, the specimen can be tested at different temperatures.

In the UK, an in-situ torque test is used to assess interface bond strength. During testing, the pavement is cored below the interface in question and left in place. A plate is then attached to the surface of the core and the torque is applied until failure. The core diameter is limited to 4 in. (100 mm) to reduce the magnitude of the moment necessary to fail the sample. Another Austrian test, Luetner test, has also been adopted in UK. Tests using the Luetner device are performed with shear load at 68°F (20 °C) with a loading rate of 2 in./min (50 mm/min).

The Florida Department of Transportation (FDOT) also developed a simple bond shear device that can be used in the universal testing machine (UTM) or a Marshall Stability tester (Figure 2.2c). The test is performed at a temperature of 77°F (25°C) with a loading rate of 2 in./min (50 mm/min).

The ASTRA device, shown in Figure 2.2d, is used in Italy to evaluate shear behavior of bonded interfaces (Canestrari, Ferrotti, Graziani, & Baglieri, 2009). The device applies a normal load to the sample during shear with a shear displacement rate of 0.1 in./min (2.5 mm/min).

InstroTek, Inc., markets a device named ATTACKER™ for testing bond strength. In the test procedure with this device, the tack material is applied to a metal plate, or HMA sample, or to a pavement surface. A metal dice is then placed on the tack material to make contact with the tacked surface, and bond strength can be measured in tensile or torsion mode.

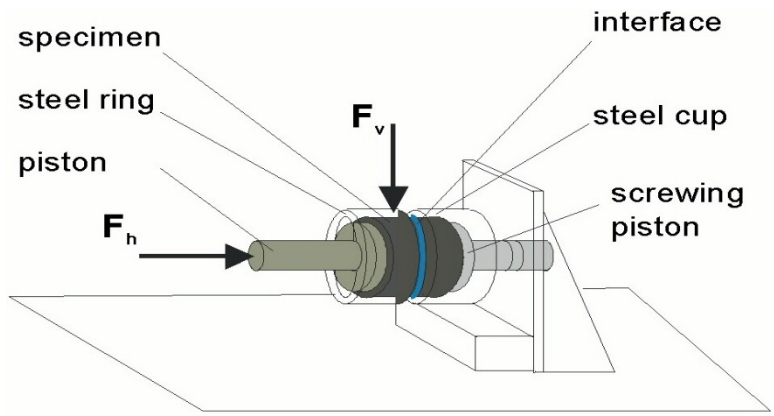

Figure 2.1: Interface Shear Test with Normal Load
Source: Romanoschi (1999)

Tschegg, Kroyer, Tan, Stanzl-Tschegg, and Litzka (1995) developed a wedge-splitting test to evaluate bond at the HMA interface. The specimens are prepared with a groove at the interface and then are split with a wedge at a specified angle (Figure 2.2e). The specimens are failed in tension at the interface. Vertical and horizontal displacements and vertical loads are measured during testing. Those loads are then converted to horizontal loads based on a specified wedge angle. The load-displacement curves are obtained by plotting the horizontal force versus horizontal displacement, and the fracture energy of the specimen is calculated from the area under the load-displacement curve. Their study suggested that the fracture energy is more appropriate to describe fracture power of the specimen at the interface rather than the maximum load.

InstroTek, Inc. also markets a tack coat evaluation device (TCED; Figure 2.2f) to assess adhesive strength of tack coat materials. The TCED determines the tensile and torque or shear strength by compressing a smooth circular aluminum plate onto a prepared tack material. The device applies a normal force to detach the aluminum plate from the testing surface, either by tension or by torque or shear force. Woods (2004) showed that TCED can distinguish between the tack coat application rates.

A pull-off test was developed at the University of Texas at El Paso (UTEP; Deysarkar, 2004). It measures the tensile strength of the tack coat before a new overlay is placed. The test procedure is fairly simple. After the tack coat is applied on the pavement, it is allowed to set which takes typically less than 30 minutes. Then 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 preload is placed on the weight key located at the top of the device for 10 minutes prior to testing in order to set the contact plate. The load is then removed and the torque required to detach the contact plate from the tacked pavement is recorded in in.-lb., and then is converted to the strength using a calibration factor. The relationship between the torque and load is established by fitting a straight line through the data points.

The ASTM D4541 (2009) standard, “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers,” has been modified by KDOT to evaluate in-situ bond strength in the field (Rahman, 2010). The test measures the tensile force required to remove two bonded surfaces. The test result can be reported either in pass/fail system or by recording tensile force to split the bonded layers. No specifications are available regarding the initial normal force or pre-compression time required to perform the test (Rahman, 2010). This test method has been adopted to test the in-situ bond strength of tack coat materials as KT-78 (2014), “Method for Determining the Tensile Adhesive Strength of Asphalt Pavement Tack Coat.”

Mohammad et al. (2012) developed two new test methods and associated criteria for characterizing the quality and performance of tack coat materials: the Louisiana Tack Coat Quality Tester (LTCQT) and the Louisiana Interlayer Shear Strength Test (LISST) in NCHRP

Project 9-40: “Optimization of Tack Coat for HMA Placement.” The LTCQT is intended for measuring the bond strength of a tack coat in the field. The LISST is a laboratory test fixture that can be fitted into a universal testing machine to measure the interface shear strength of a tack coat in a field or laboratory specimen. The effects of existing pavement surface types and conditions, tack coat material types, and tack coat application rates and methods on tack coat performance can be assessed by LISST.

A summary of bond strength test methods, originally prepared by Woods (2004) and updated in this study, is provided in Table 2.1.

Table 2.1: Current Bond Strength Measuring Devices

Shear Strength Test	**Tensile Strength Test**	**Torsion Strength Test**
ASTRA (Italy) FDOT method (Florida) LPDS method (Swiss) Japan method Superpave shear tester (SST) TCED (InstroTek, Inc.) Wedge-Splitting test Romanoschi LISST (NCHRP)	ATACKER (Austrian method) MTQ method (Quebec) TCED (InstroTek, Inc.) UTEP Pull-off test Pull-off test (KDOT) LTCQT (NCHRP)	ATACKER (InstroTek, Inc.) TCED (InstroTek, Inc.)

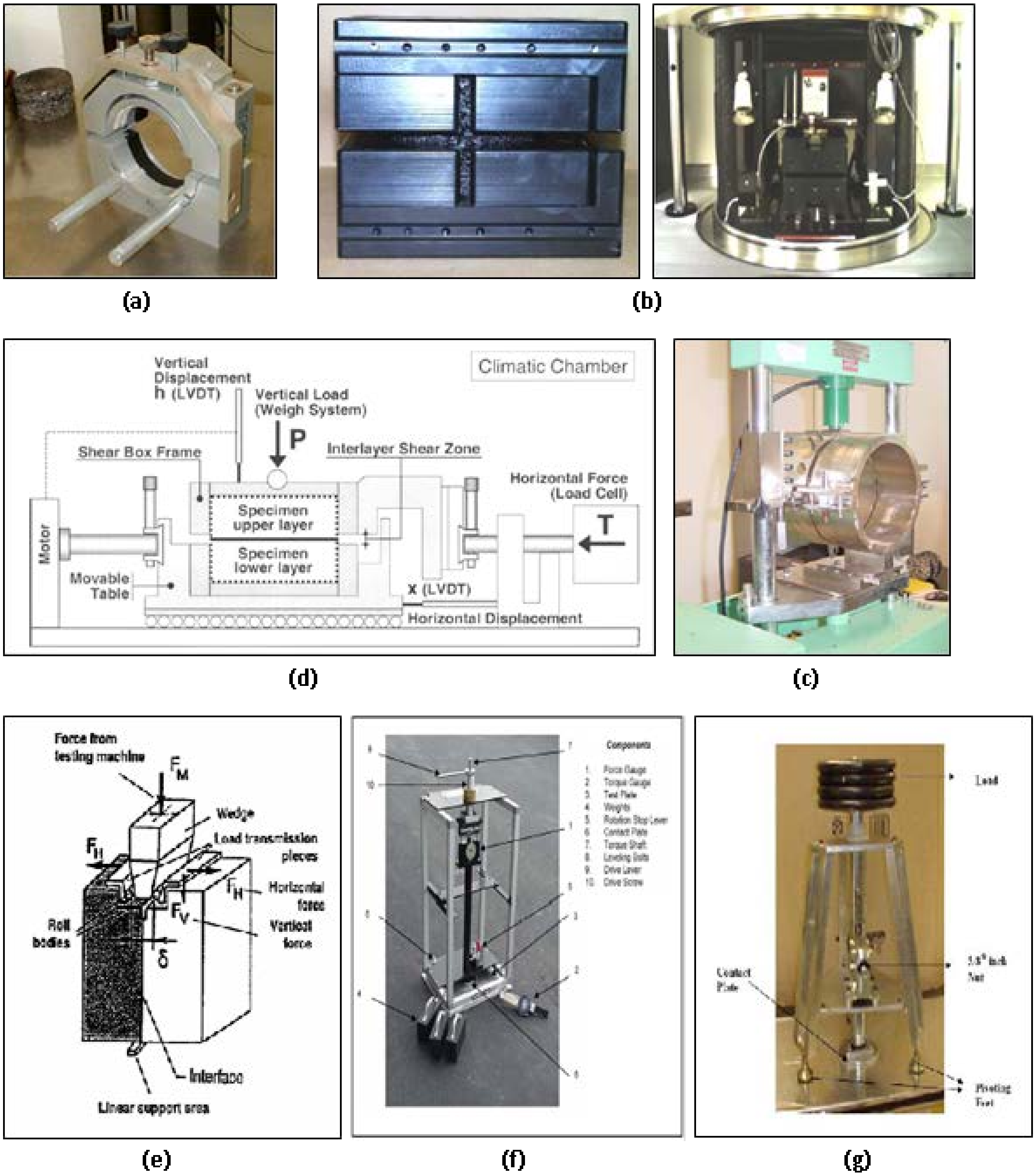

Figure 2.2: Bond Strength Testing Set Up: (a) LPDS Tester, (b) SST, (c) FDOT Shear Tester, (d) ASTRA, (e) Wedge-Split Device, (f) TCED, (g) Pull-Off Test Device
Source: West et al. (2005); Rahman (2010)

2.2 Study on Tack Coat Materials

In 1999, the International Bitumen Emulsion Federation (IBEF) conducted a worldwide survey to collect information on tack material types, their application rates, curing time, test methods, and inspection methods (West et al., 2005). Survey results showed that cationic emulsions are most commonly followed by anionic emulsions. Only the United States mentioned using the paving grade asphalt cement as a tack coat. The application rate generally ranged from 0.026 to 0.088 gal/yd^2 (0.12 to 0.4 lpm^2). No other countries except Austria and Switzerland have bond strength evaluation methods and applicable criteria regarding bond strength. An earlier U.S. survey, conducted by Paul and Scherocman (1998) revealed that most states have adopted the use of slow-setting emulsions, most common being SS-1, SS-1H, CSS-1, and CSS-1H. However, 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. Some states specify the materials according to the construction situation.

Uzan, Livneh, and Eshed (1978) studied HMA interface bond properties based on laboratory shear tests. They conducted direct shear tests to measure the shear strength considering various tack application rates of 0.0, 0.11, 0.21, 0.32, and 0.43 gal/yd^2 (0.0, 0.49, 0.97, 1.46, and 1.94 lpm^2), respectively. They found that the use of tack coat increased the interface bond strength and that there was an optimum tack coat application rate for maximum shear resistance. The optimum application rates were found to be 0.11 and 0.21 gal/yd^2 (0.49 and 0.97 lpm^2) at 131°F and 77°F (55°C and 25°C), respectively.

Sholar, Page, Musselman, Upshaw, and Moseley (2004) evaluated the effect of a rain event on a cured tack coat before an HMA overlay. Moisture significantly reduced the shear strength at the interface when compared to equivalent dry sections. Coarse-graded HMA mixes had higher shear strength compared to fine grade mixes. Milling increased the shear strength at the interface and reduced the effect of the application rate. For milled sections, tack coat was not effective in increasing the shear strength at the interface.

Woods (2004) conducted a study to develop a tack coat evaluation device (TCED) and to perform laboratory testing on different tack coat application rates. Another aim was to develop a laboratory bond interface strength device (LBISD) for evaluation of interface bond strength. The experimental test plan included a series of tests to investigate the effects of application rate, tack coat set time, tack material, and other variables on tack coat tensile and torque-shear strength. The application temperature varied from 75°F (24°C) to 325°F (163°C) and the allowed set time from 5 minutes to an hour. The tack application rate was selected from 0.04 to 0.13 gal/yd^2 (0.18 to 0.6 lpm^2) and dilution rate was either none (0% dilution) or diluted 1 to 1 (emulsions only). Four types of tack coat materials were selected: SS-1, CSS-1 and CRS-2 emulsions, and PG 67-22 asphalt binder. Laboratory TCED and LBISD tests were performed at different combinations of the factors. Results showed that the CRS-2 consistently yielded the highest mean strength while SS-1 was the lowest. Increasing set time and decreasing application rate significantly increased the tensile and torque shear strength. Evaporation of water from emulsions with time and low application rates significantly increased tack coat performance at the interface.

Yildirim, Smit, and Korkmaz (2005) evaluated the performance of tack coats in the laboratory setting to examine the best combination of tack coat materials, mixture type, and application rate. Six-inch (150-mm) gyratory compactor-compacted HMA specimens were bonded onto portland cement concrete (PCC) specimens. Four factors, such as mix type (Type D and CMBH in Texas), tack coat type (SS-1 and CSS-1H), tack coat application rate 0.024 gal/yd^2 (0.11 lpm^2) and 0.05 gal/yd^2 (0.23 lpm^2), and trafficking (Hamburg wheel tracking device [HWTD] cycles 0 and 5,000) were used in the experimental design. The HWTD tests were done at 122°F (50°C) and shear tests were conducted at 68°F (20°C). The shear was applied at the interface at a constant rate of 2 in./min (50 mm/min). Results of this study indicated the test to be feasible to investigate the interface shear strength of the tack coat between the HMA and the PCC. Statistical analysis showed that factors (mix type, tack coat type and rate, and trafficking) considered during the experimental design significantly influenced the tack coat performance. Tack coat performance, in general, was better at higher application rate.

Mrawira and Yin (2006) did a field study of tack coats on a two-lane highway for the New Brunswick Department of Transportation in Canada. The main objective was to evaluate the structural effectiveness of tack coat in an overlay project using Dynaflect and FWD deflection testing and by laboratory testing of core samples. During testing, a baseline structural survey and pre-overlay deflection testing were performed. Three 656-ft. (200-m) homogeneous sections were subdivided into "experimental lane" and "control lane." The "experimental lane" was constructed using three different tack coat application rates, which consist of 0.033, 0.045, and 0.055 gal/yd^2 (0.15, 0.20, and 0.25 lpm^2). The "control lane" section had no tack coat at the interface layer. Dynaflect and FWD deflection tests were performed after overlay application. Laboratory resilient modulus and splitting strength tests were also performed on the cores taken from the field. The study failed to reach any specific conclusions based on their objectives.

West et al. (2005) performed a study at NCAT to develop a test to evaluate the bond strength between pavement layers. The study was done in two phases. In Phase One, a laboratory experiment was conducted to refine the bond test strength device and then, to establish a method to assess the factors, including tack coat material type (CRS-2, CSS-1 and PG 64-22), application rate (0.04, 0.08 and 0.12 gal/yd^2), applied normal pressure (0, 10, and 20 psi), and average test temperature (500, 770, and 1400 °F), affecting bond strength of the interface between two HMA layers. Laboratory fabricated samples were prepared and tested. In the second phase, field validation of the proposed method from phase one was performed. This phase involved setting up of tack coat application sections on seven project locations in Alabama and obtaining cores from each test section.

Results from the laboratory experiments indicated that a bond strength test at a low temperature (50°F) was not practical. The research suggested performing bond strength test at an intermediate temperature (77°F) and under a 20 psi (140 kPa) normal pressure. Mixture type was a potential factor affecting bond strength; a fine-graded mixture with smaller Nominal Maximum Aggregate Size (NMAS) had higher bond strength compared to the coarse-graded mixture with larger NMAS. In general, PG 64-22 showed higher bond strength compared to the emulsions. Higher tack coat application rate resulted in lower bond strength. Results from the field study indicate that ASTM D2995 (2014), "Standard Practice for Estimating Application Rate and Residual Application Rate of Bituminous Distributors," is an effective method for assessing the tack application rate. A milled HMA surface yielded higher bond strength with the overlaying HMA layer. Paving grade asphalt performed better than the asphalt emulsion as a tack material.

The marginal bond strength in field conditions appeared to be between 50 to 100 psi (345 to 690 kPa). Bond strengths below 50 psi (345 kPa) were concluded to be poor.

Tashman, Nam, and Papagiannakis (2006) and Tashman et al. (2008) performed a research study to establish the guidelines for tack coat construction practices in the state of Washington. Several factors that are known to influence the interface such as surface condition, tack coat curing time, tack coat residual rate, and coring location (middle lane and wheel path) were studied. The experimental design included surface treatment (milled vs. non-milled), curing time (broken vs. unbroken), approximate target residual rate (0, 0.018, 0.048, and 0.072 gal/yd^2), and core location (wheel path vs. middle lane). A new 2-inch (50-mm) overlay was placed using a 0.5-inch (12.5-mm) NMAS Superpave mixture. A total of 14 sections were constructed incorporating the abovementioned factors. Field cores were collected from selected locations to perform the FDOT shear tester, torque bond strength, and UTEP pull-off test. The results show that FDOT shear test and torque bond strength showed significantly higher shear strengths for the milled sections compared to the non-milled sections. However, the UTEP pull-off test provided higher pull-off strength for non-milled sections. Curing time was an insignificant factor for all test types. Absence of tack coat did not have a major impact on the shear strength for the milled sections but that was not the case for the non-milled sections. In general, the increasing tack rate did not potentially improve the shear strength for either the milled or non-milled sections. However, milled sections were more sensitive to the tack coat application rate.

Wheat (2007) did a study on bond strength at the HMA pavement interface layer at the Civil Infrastructure Systems Laboratory (CISL) of Kansas State University. The study objective was to evaluate the shear behavior of three asphalt-to-asphalt mix interfaces with different tack coat application rates. The experimental design included construction of three asphalt interfaces: (1) a coarse-coarse mix interface, (2) a coarse-fine mix interface, and (3) fine-fine mix interface. Each of these mix combination section was subdivided into four equal parts with different tack coat application rates (0, 11, 21, and 32 g/ft^2) resulting in 12 different combinations. The BM-1 coarse mix and a 12.5-mm NMAS fine mix were laid during construction. Cores of 3.94-inch (100-mm) diameter were collected and dynamic shear reaction modulus and shear strength tests were performed in a UTM-25 machine. Shear test attachments were fabricated to allow testing of specimen at angles from 0 to 45 degrees. The test was performed at two different angles (20 and 30 degree) and at a rate of deformation of 0.002 in./sec (0.05 mm/sec). Results show that the interface shear strength was about the same at different normalized pressures 15 and 16 psi (105 and 109 kPa) for all interface types and tack coat application rates. No tack coat performed the best for the coarse-coarse interface. The study concluded that current KDOT specifications for tack coat application rates (0.05 gal/yd^2 or 0.23 lpm^2) are sufficient to produce higher strength for all three mixture type combinations.

Mohammad, Raqib, and Huang (2002) evaluated tack coat application rate using a Superpave simple shear tester (SST). The influence of tack coat material, application rate, and test temperature was examined. The tack coat materials included two performance-graded asphalt cement (PG 64-22 and PG 76-22) and four emulsions (CRS-2P, SS-1, CSS-1, and SS-1H). Application rates studied were 0.00, 0.02, 0.05, 0.1, and 0.2 gal/yd^2 (0.00, 0.09, 0.23, 0.45, and 0.9 lpm^2). Shear tests were conducted at 77°F (25°C) and 131°F (55°C). The statistical analysis of the results showed that CRS-2P provided significantly higher interface shear strength. The optimum application rate for this emulsion was 0.02 gal/yd^2 (0.09 lpm^2).

NCHRP Project 9-40, "Optimization of Tack Coat for HMA Placement," was conducted by the Louisiana Transportation Research Center (Mohammad et al., 2012). The objectives of this research were to determine optimum application methods, equipment type and calibration procedures, application rates, and asphalt binder materials for the various uses of tack coats and to propose new or revised AASHTO methods and practices related to tack coats. As mentioned earlier, in this study, two new test methods and associated criteria for characterizing the quality and performance of tack coat materials are discussed: LTCQT for assessing bond strength in the field and LISST for assessing interface shear strength in the laboratory. The research demonstrated a strong relationship between the interface shear strength and the residual application rate of a wide range of tack coat materials, including a PG 64-22 asphalt binder, and trackless, CRS-1, SS-1, and SS-1H emulsions. LISST test results showed that for a given tack coat material, the interfacial shear strength is a function of pavement surface roughness. The study also proposed minimum laboratory-measured interfacial shear strength to provide acceptable tack coat performance in the field as well as optimal tack coat residual application rates for different pavement surface types.

2.3 Field Evaluation of Tack Coat Performance

The Florida Department of Transportation (FDOT) conducted a study to document the performances of bonded open-graded friction courses (OGFC) from Florida. The OGFC layers were laid on a thick polymer modified tack coat. Performances of bonded OGFC were compared to OGFC laid with a regular tack material as well as a Novachip layer with a thick polymer-modified tack coat. Results showed that the newly introduced polymer-modified tack material significantly improved the rutting and cracking resistance (Birgisson, Roque, Varadhan, Thai, & Jaiswal, 2006).

The effect of contact surface roughness on interface bond strength was studied by Partl, Canestrari, Ferrotti, and Santagata (2006). A laser profilometer and a profile combo were used to determine roughness of the test sections before paving. In addition, lower-layer roughness was also evaluated with the traditional sand patch method. ASTRA and LPDS devices were used to evaluate the relationship between the interlayer shear resistance and surface roughness. Results showed that the interlayer shear resistance increased when the adjacent layer was rougher (Partl et al., 2006).

Interlayer bonding was studied for a porous asphalt course interface in Italy. The ASTRA test method was used in the study. The tack coat was applied at the interface of an existing porous asphalt layer and a newly laid open-graded course. Results showed that different tack coat application rates had achieved the acceptable interlayer bonding, while higher application rates might generate some scatter of the results (Canestrari et al., 2009).

The Virginia Department of Transportation (VDOT) studied a new tack coat material called “Trackless” tack. This new material uses a very hard performance-graded binder and has a positive charge with break time less than a minute. The VDOT special provision for this trackless tack material is 40 psi (279 kPa) in terms of bond strength (Clark et al., 2010). The VDOT research lab compared the performance of “trackless” tack with two conventional tack materials, CRS-1 and CRS-2, which are commonly used in Virginia (Figure 2.3). Results of this study showed that trackless tack materials performed better than the CRS-1 tack coat material in the laboratory and oven-dried conditions. The materials provided better shear and tensile strength compared to CRS-1 and CRS-2 materials (Clark et al., 2010).

Figure 2.3: Trackless Tack Performance Testing in Virginia
Source: Clark et al. (2010)

The Illinois Center for Transportation studied the interface bonding between HMA overlays and portland cement concrete (PCC) pavement. Laboratory testing, numerical modeling, and accelerated pavement testing were conducted to address the factors that affect interface bond strength. These factors include HMA materials (SM-9.5 surface mix and IM-19.5A binder mixture), tack coat materials (SS-1H, SS-1HP emulsions, and RC-70 cutback asphalt), tack coat application rate, PCC surface texture (smooth, longitudinal and transverse tined, and milled), temperature, and moisture condition. A direct shear strength device at a constant loading rate of 0.5 in./min (12 mm/min) was used to investigate the interface shear strength of HMA overlay. Test results showed that SS-1H and SS-1HP had higher interface bond strength compared to RC-70 cutback asphalt. The SM-9.5 surface mixture had better interface strength compared to the IM-19.5A mix. The 0.05 gal/yd^2 (0.23 lpm^2) rate provided the maximum interface shear strength. The direction of tining on the PCC surface did not have any significant effect on interface shear strength. The milled PCC surface provided higher shear strength than a smooth and tined surface. Smoother PCC surface produced higher interface shear strength compared to a tined surface at the optimum tack coat application rate. Bond strength decreased with increasing temperature and moisture conditions (Leng, Al-Qadi, Carpenter, & Ozer, 2009).

Accelerated pavement testing (APT) sections were built on the PCC surfaces mentioned above (Figure 2.4). The HMA overlay was placed on the PCC surface. A zebra section was introduced to evaluate the non-uniform tack coat application rate.

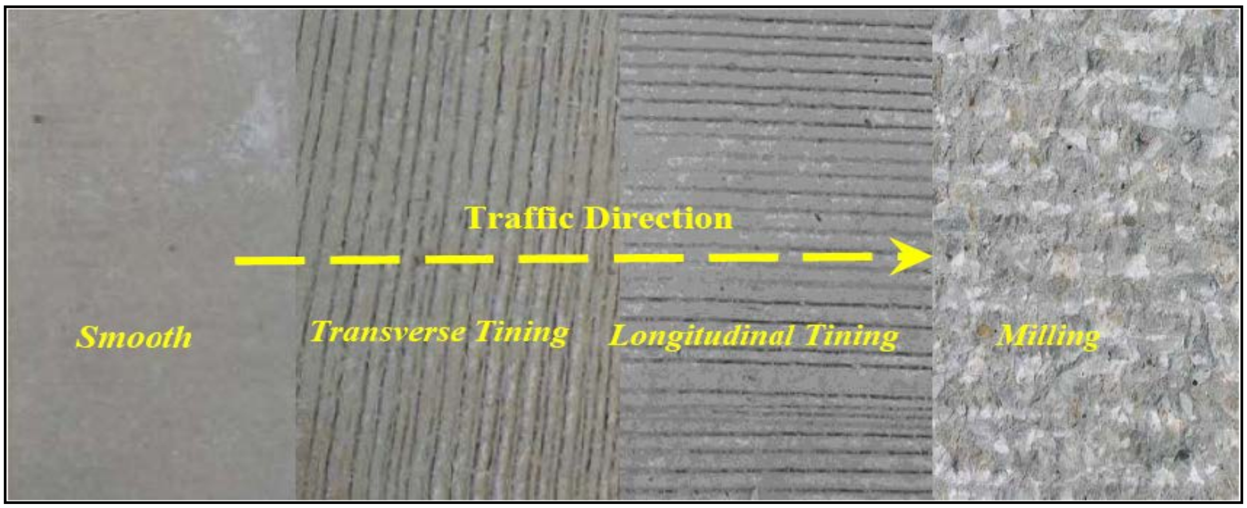

Figure 2.4: PCC Surface Textures in Illinois Study
Source: Leng et al. (2009)

The emulsified asphalt SS-1HP and RC-70 cutback asphalt were applied at 0.02, 0.04, and 0.09 gal/yd^2 (0.09, 0.18, and 0.41 lpm^2) and a binder, PG 64-22, was applied at 0.04 gal/yd^2 (0.18 lpm^2). Tensile strains at the bottom of HMA layer were measured for 25 selective sections to quantify the slippage, if any. Rut measurements were taken and analyzed for all sections (Figure 2.5). SS-1HP and PG 64-22 binder offered better rut resistance when compared to the cutback asphalt. The milled surface performed better in rutting compared to a transverse tined and smooth PCC surface. Cleanliness of the PCC surface cleaning methods significantly affects the interface bond strength as does a uniform tack coat application rate (Leng et al., 2009; Al-Qadi, Carpenter, Leng, Ozer, & Trepanier, 2009).

Figure 2.5: Surface Profile Measurements after APT Loading
Source: Leng et al. (2009)

2.4 Summary

This chapter reviews the bond strength evaluation tests and recent laboratory and field studies on evaluation of tack coat materials and rates. A variety of tests for bond strength evaluation have been developed over the last two decades in three categories: shear test, tension test, and torque test. There is no consensus among the researchers about the best type of test for tack evaluation or best tack coat materials and optimum application rates. The field studies and corresponding tack coat performance also seemed to be location specific.

Chapter 3: Laboratory Testing

3.1 Introduction

This chapter discusses the field sampling, trimming samples, and simulated overlay with tack for laboratory testing, as well as the test procedures.

3.2 Field Sampling

For the laboratory tests, 6-inch (150-mm) diameter cores were taken from the wheel paths of selected highways of the Kansas Department of Transportation (KDOT) as shown in Table 3.1. Half of the cores were taken from a milled surface, and the other half from a non-milled, weathered surface. These cores were then used as the existing surface while overlaying with a new hot-mix asphalt (HMA) layer in the laboratory. Different tack materials at various rates were placed on the existing core surface before overlaying.

Table 3.1: Cores Collected for Lab Tests

Designation	Location	Texture	Surface Material	Date	Quantity
A	WB K-9, just east of Barnes, KS	Milled	BM-2A	6/6/12	18
B	WB K-9, just east of Barnes, KS	Milled	BM-2A	6/6/12	18
C	WB K-16, 4 miles W of Holton, KS	No-mill	SM-9.5A	8/22/12	18
D	WB K-16, W of K-99	No-mill	SM-12.5A	9/23/13	15
E	WB K-16, W of K-99	Milled	SRECYL of BM-2A	9/23/13	15
F	EB US-50, 2 miles West of Burrton, KS	Milled	SM-9.5T	6/24/14	15
G	EB US-50, 2 miles W of Burrton, KS	No-mill	SM-9.5T	6/24/14	15
W	EB K-68 between Ottawa and I-35	No-mill	BM-1T	7/31/12	18

Note: BM2A: Bituminous Mat Grading 2, Coarse; SRECYCL: Surface Recycle Pavement (Heater Scarifier); SM-9.5A: Superpave Recycle Mix, 9.5 mm Nominal Aggregate Size, Friction Coarse Mix; SM-9.5T: Superpave Mix, 9.5 mm Nominal Aggregate Size, Friction Coarse Mix; BM-1T: Bituminous Mix with Combined Aggregates, 30% Crushed Material, 15% Natural Sand.

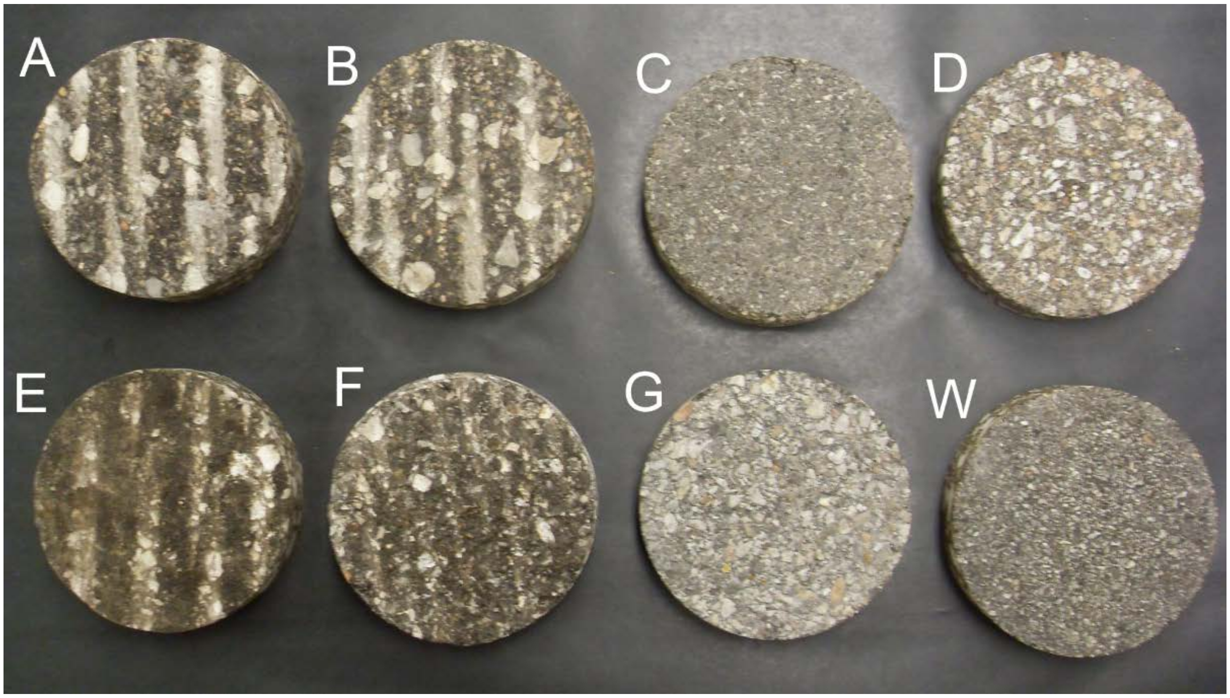

Figure 3.1: Core Sample Surface

Figure 3.1 illustrates the diverse appearances and textures of the core types. Cores A and B are identical, but from separate wheel paths. Cores C and W have little texture when compared with the cores G and D.

3.3 Laboratory Sample Preparation

To prepare the cores for use in the Superpave Gyratory Compactor (SGC), all but the top 1.5 in. (38 mm) were cut off using a large water-cooled table-saw. Many of the cores were too wide to fit inside of the 6-inch (150-mm) diameter SGC mold, and had to be shaved down on the edges. Attempts to reduce the diameter involved a belt sander and grating with an abrasive bridge deck material, but what proved most efficient was lightly gluing cores to a board and re-coring with a 6-in. bit slightly off center. The cores were labeled with grease chalk on the bottom, and the top was gently scrubbed under running water with a wire brush, to remove any sediment that had caked on during coring and sawing.

Figure 3.2: Coring, Cutting, Resizing, and Cleaning Cores

Nearly 400 lb. (181 kg) of plant-produced HMA was collected from Shilling Construction Company in Manhattan. This material was 12.5-mm NMAS Superpave mixture (SR-12.5A) with 30% reclaimed asphalt pavement (RAP), and a PG 58-28 binder. Superpave mixture properties are listed in Table 3.2 and met all the requirements of KDOT for an SR-12.5A mixture. The loose HMA was stored in medium burlap sacks of 30 to 50 lb. (14 to 23 kg) each. Care was taken not to reheat the material multiple times to limit the effect of reheating on the asphalt binder.

Table 3.2: Superpave Properties of HMA Used in Lab Testing

Mix Properties	
% AC by Mass of Mix	5.71
% Aggr. by Mass of Mix	94.29
Sp. Gr. of AC	1.0339
Bulk Sp. Gr. of Aggr.	2.588
Theoretical Max. Sp. Gr.	2.429
Bulk Sp. Gr. of Mix	2.326
Eff. Sp. Gr. of Aggr.	2.645
Absorbed % AC	0.86
Eff. Asphalt Content (%)	4.90
% VMA	15.3
% Air Voids	4.24
% VFA	72
Eff. Film Thickness	8.86
Dust/Binder Ratio	1.1

The SGC, shown in Figure 3.3, is designed to use hot "charged" molds that shape the compacted HMA samples without sucking the heat out of it. The influence of the hot mold on the binder of cores was a concern though, and so cold molds were used following the examples of KDOT and the Illinois Department of Transportation. The goal of compaction was 1.5 in. (38 mm) of HMA on top of 1.5 in. of a cored and trimmed highway sample. Several test batches of HMA were compacted, varying the number of gyrations to find what compactive effort would yield 7% air voids, as this is the desired air void in the field. The test for percent of bulk specific gravity (G_{mb}), which compares the weight of the core underwater and in air to the maximum possible density of the loose mix, showed that 35 gyrations yielded 7% air.

Initially, more convoluted methods were attempted to achieve 3 in. (76 mm) high samples. Attempts were made to correlate weight of the bottom section with volume and height, since they had the same diameter. This proved unsuccessful, as too much variability occurred from shaving down the sides of the cores so they would fit in the molds. Another method involved measuring the height at several places with a micrometer and averaging it out; 1.5 in. (38 mm) was added on top of that to get the final height the SGC would compact to. This method was also problematic, especially with the milled samples, whose varied surface height was estimated at best. Samples were either over or under compacted until it was decided to compact by number of gyrations.

The tack materials of interest have recommended application rates, which were varied as seen in Table 3.3. The rates varied anywhere from 25% to 150% of the recommended application rate. Trackless was tested only at the manufacturer's recommended rate of 0.08 gal/yd^2 (0.362 lpm^2).

Table 3.3: Tack Application Rates

	SS-1HP			EBL			Trackless
Percent of recommended rate	25%	50%	100%	50%	100%	150%	100%
Gallon/yd^2	0.0125	0.025	0.05	0.07	0.14	0.21	0.08
Liter/m^2	0.057	0.113	0.226	0.317	0.634	0.951	0.362
Gram/6-inch sample	1.05	2.10	4.20	5.85	11.70	17.54	6.65

In the field, tack is applied and paid for by weight, since thermal expansion makes volumetric measurements unreliable. An example calculation of 100% SS-1HP on a 6-inch (150-mm) diameter sample is shown in the equation below.

$$0.05\,\frac{gal}{yd^2} * (3^2\pi)in^2 * \frac{yd^2}{1296\ in^2} * \frac{8.486\ lb\ SS-1HP}{gal} * \frac{453.6\ g}{lb} = 4.2\ grams/sample$$

Tack was spread by weight using a rag or brush on a precise scale. SS-1HP was applied at room temperature, while EBL and Trackless were first heated to 140°F (60°C) in a metal tin. Tack was spread quickly as it immediately began to break (Figure 3.4) and change the weight on the scale. EBL at higher rates required a duct tape rim to prevent the tack material from running off. It was allowed to break and then 3.27 lb. (1.48 kg) of loose HMA were compacted on top in the SGC with 35 gyrations. Samples were compacted in sets of three, with no identical treatments in each batch to minimize the effect of any differences in procedure.

Figure 3.3: Superpave Gyratory Compactor with Compacted Sample Extruded from Mold

Figure 3.4: Core with Tack that is Breaking and Core with Compacted Overlay

After the compacted samples had cooled overnight, they were weighed again and placed in a freezer for an hour before coring. A 2-inch coring bit was used to cut three 2-inch (50-mm) diameter cores out of each 6-inch (150-mm) diameter plug. A wooden brace was assembled which allowed the samples to be wedged in place and leveled before coring. Each core was marked with an identifying number and allowed to dry. They were glued to steel plates 3 in. × 2.75 in. × 0.5 in. (7.62 cm × 6.99 cm × 1.27 cm), using a two-part fast curing epoxy anchoring gel as shown in Figure 3.5a. Wooden molds kept the plates centered and leveled. The epoxy was allowed to set for 12 hours before testing. At 48 hours after compaction, the samples were tested in a Universal Testing Machine (UTM). This machine has a hydraulically-driven load-frame in an environmentally controlled chamber and is capable of applying 5.6-kip (25-kN) load (Figure 3.5b). The load-deformation curve was obtained from each test. The outputs include peak load and strain at test termination. From these results, fracture energy was estimated for each sample.

Figure 3.5: (a) Epoxying to Steel Plates, (b) Sample Loaded in the UTM

The KT-78 test method for field testing of interface bond calls for pulling in tension at 0.8 ± 0.1 in./min (2.03 ± 0.25 cm/min). Initial testing found that a rate of 0.7 in./min (1.78 cm/min) produced more consistent results, and so all tests were done at this rate. The samples were loaded into the UTM and the assembly was hand tightened to apply pretension. A computer recorded the loading at 100 Hz. Testing occurred at 70–75 °F (21–24 °C) temperature. After the samples had been broken, the metal plates were secured in a vice and the epoxy was removed using an air hammer. Results were exported into an Excel spreadsheet for further analysis. All compaction and testing stages were recorded on paper initially as a confirmation and backup of the digital files.

Chapter 4: Accelerated Pavement Testing (APT)

4.1 Accelerated Pavement Testing at Kansas State University

Accelerated Pavement Testing (APT) at the Civil Infrastructure Systems Laboratory (CISL) of Kansas State University (KSU) was the second phase of the project. The test attempted to replicate a realistic pavement loading environment to examine interface bond performance. CISL is an indoor 7,000 ft^2 (650 m^2) KSU off-campus lab that has two 16 ft. × 20 ft. (4.88 m × 6.10 m) rectangular pits and one 14 ft. × 20 ft. (4.27 m × 6.10 m) rectangular pit. They are 6 ft. (1.83 m) deep and encased in concrete to prevent interference from external water or soils. One of these pits had an existing asphalt pavement which was milled and had a 2-inch (50-mm) HMA overlay applied, with varying tack materials and rates at the interlayer.

The APT load assembly hydraulically applies loading to a single axle with dual tires as it moves across the test pit, traveling at about 7 mph (11.3 km/hr; Figure 4.1). A protective housing insulates the system and enables air conditioners to maintain steady temperatures. This custom-built machine also introduces wander to deviate up to 6 in. (150 mm) either way with a truncated normal distribution to simulate more realistic load application (Figure 4.2). When operating without any interruption, 100,000 passes are possible per week.

Figure 4.1: APT Load Assembly

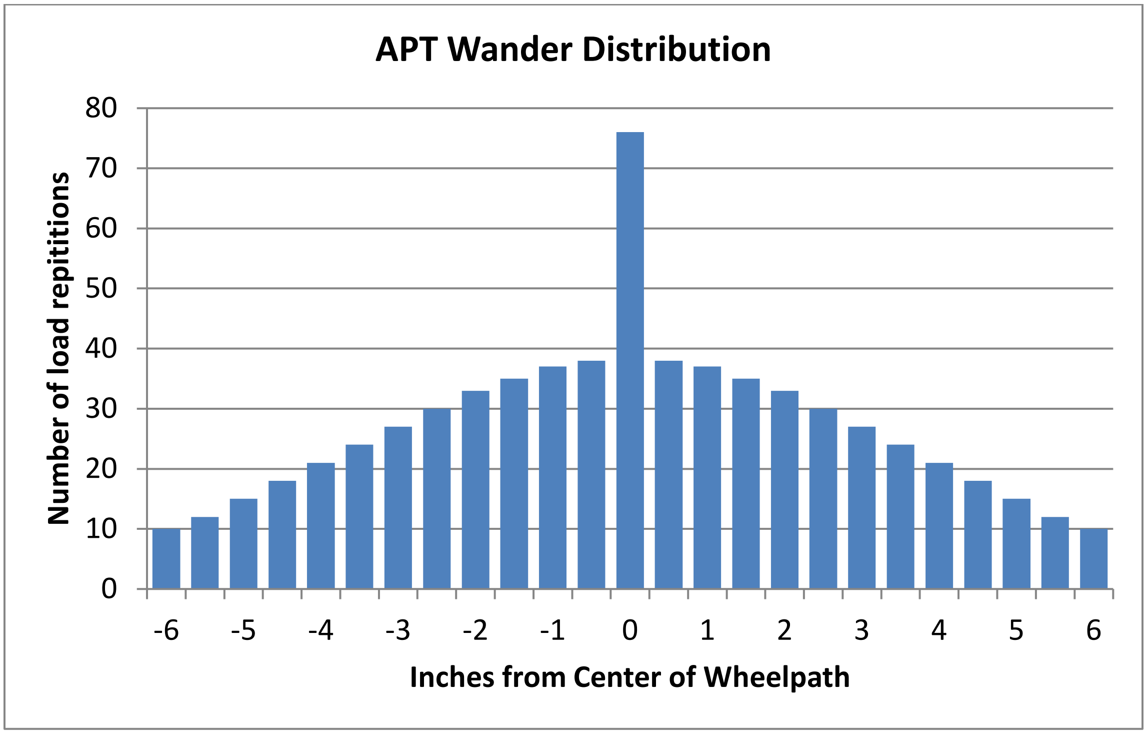

Figure 4.2: Distribution of the 676 Load Paths per Wander Cycle

4.2 Construction

This APT project, designated as CISL 17, was conducted on the 14 ft. × 20 ft. (4.27 m × 6.10 m) north pit at CISL. The pit was paved from a previous experiment, CISL 14, which sought to verify the mechanistic-empirical design models for flexible pavements. The existing pavement consisted of 4 in. (100 mm) of 12.5-mm NMAS Superpave mixture tested for fatigue. This was on top of 6 in. (150 mm) of AB-3 stone base that was placed on top of 5 ft. (1.52 m) of A-7-6 clay subgrade. The HMA mix contained mostly APAC Sugar Creek rock from Kansas City, Missouri, and 25% Humble S&G flint chat. The north lane had 5.3% AC with PG 70-22. The south lane had 5.4% AC with PG 64-22. After application of over 2.2 million Equivalent Single Axle Loads (ESALs), it did not show any signs of failure.

This existing pavement had 1.5 in. (38 mm) milled off and was cleaned by broom and compressed air (Figure 4.3a). The pit was divided into six test sections, as shown in Table 4.1, to compare the interface bond of various tack materials. Tack was applied evenly using a hand-pumped pressure sprayer (Figure 4.3b). Spray rate was verified by measuring the weight difference of a hand-held pressure sprayer before and after application on each test section.

Table 4.1: Setup of Test Pit

North West **EBL at 50%** 0.07 gal/yd^2	North Middle **EBL at 150%** 0.22 gal/yd^2 (target was 0.21)	North East **EBL at 100%** 0.16 gal/yd^2 (target was 0.14)
South West **SS-1HP at 25%** 0.013 gal/yd^2	South Middle **SS-1HP at 100%** 0.05 gal/yd^2	South East **SS-1HP at 50%** 0.025 gal/yd^2

The pit measures 20 ft. × 14 ft. (6.10 m × 4.27 m), with each test section being 6.66 ft. × 7 ft. (2.03 m × 2.13 m). The NM and NE sections were found to be slightly over sprayed, and pictures reveal the SM section had uneven coverage.

Figure 4.3: (a) Cleaning Surface with Compressed Air, (b) Applying Tack with Hand Sprayer

Twelve H-Bar strain gages from Tokyo Sokki Kenkyujo Co., Ltd., were used to measure the strain at the interface between the two layers. Previous experience has shown the stock lead wires perform poorly in the extreme conditions of hot HMA, so they were replaced with high quality shielded wiring (Figure 4.4a). The soldered connection at the base of the strain gage was covered by heat shielding. The strain gage was epoxied to two notched aluminum bars and attached to the milled surface using metal staples after the tack had been sprayed. Two strain gages were allotted for each test section, for a total of 12 gages installed, all in the longitudinal direction as shown in Figure 4.4b. The gage length was 2.4 in. (60 mm), with a gage factor of 2.09 ± 1%. Resistance was 120 ± 0.5 Ω. Before paving, the gages and wires were covered with a shovelful of HMA and hand compacted in an effort to protect them from the paver.

Figure 4.4: (a) Soldering New Lead Wires onto Strain Gages, (b) Installing Strain Gages after Tack is Applied

HMA was placed in a 2-inch (50-mm) thick lift. The mixture was an SR-12.5A with PG 58-28 binder. Superpave properties of the mix can be seen in Table 4.2. The pad was compacted with a vibratory roller several times in an effort to reach 7% in-situ air voids. A Troxler 3440 surface moisture-density gage was used to check the density (Figure 4.5d).

Table 4.2: HMA Properties

Mix Properties	
% AC by Mass of Mix	5.63
% Agg. by Mass of Mix	94.37
Sp. Gr. of AC	1.0315
Bulk Sp. Gr. of Agg.	2.555
Theoretical Max. Sp. Gr.	2.430
Bulk Sp. Gr. of Mix	2.340
Eff. Sp. Gr. of Agg.	2.644
Absorbed % AC	1.36
Eff. Asphalt Content	4.35
% VMA	13.6
% Air Voids	3.70
% VFA	73
Eff. Film Thickness	8.44
Dust/Binder Ratio	1.1

Figure 4.5: (a) Paver Backing In, Instrumentation is Protected by HMA, (b) Paving, (c) Roller Compacting the Fresh HMA, (d) Using Nuclear Density Gage to Check Compaction

It was discovered that on the day of construction, the nuclear density gage had not been properly calibrated to correct for natural decay of its radioactive elements. When calibrated and used a week later, much higher density results were found (Table 4.3). This instrument operates by using a backscatter of neutrons to determine the density of a surface, and cannot focus solely on the top 2 in. (50 mm). Therefore, the existing well-compacted underlying asphalt contributed to the high-density readings. But the new material was compacted more than was hoped.

Table 4.3: In-Situ Post Construction Density as Found by Nuclear Gage

Section	Coating	Density (pcf)	Average Density (pcf)	% Air
NW	50% EBL	145.5	144.35	4.80
		143.2		
SW	25% SS-1HP	143.2	143.6	5.30
		144		
NM	150% EBL	149.6	149.8	1.21
		150		
SM	100% SS-1HP	146.7	148.65	1.97
		150.6		
NE	100% EBL	144.1	143.05	5.66
		142		
SE	50% SS-1HP	142.3	141.9	6.42
		141.5		

After construction, a falling weight deflectometer (FWD) test was performed on each test section to verify that the subbase was uniform for the test sections. A weight is dropped and the surface deflection is recorded by seven sensors that are offset at certain radial distances in a straight line. This process is automated and can be seen in Figure 4.6. Figure 4.7 displays the eastbound and westbound test points and the direction in which the sensors were aligned.

Figure 4.6: FWD with APT in Background

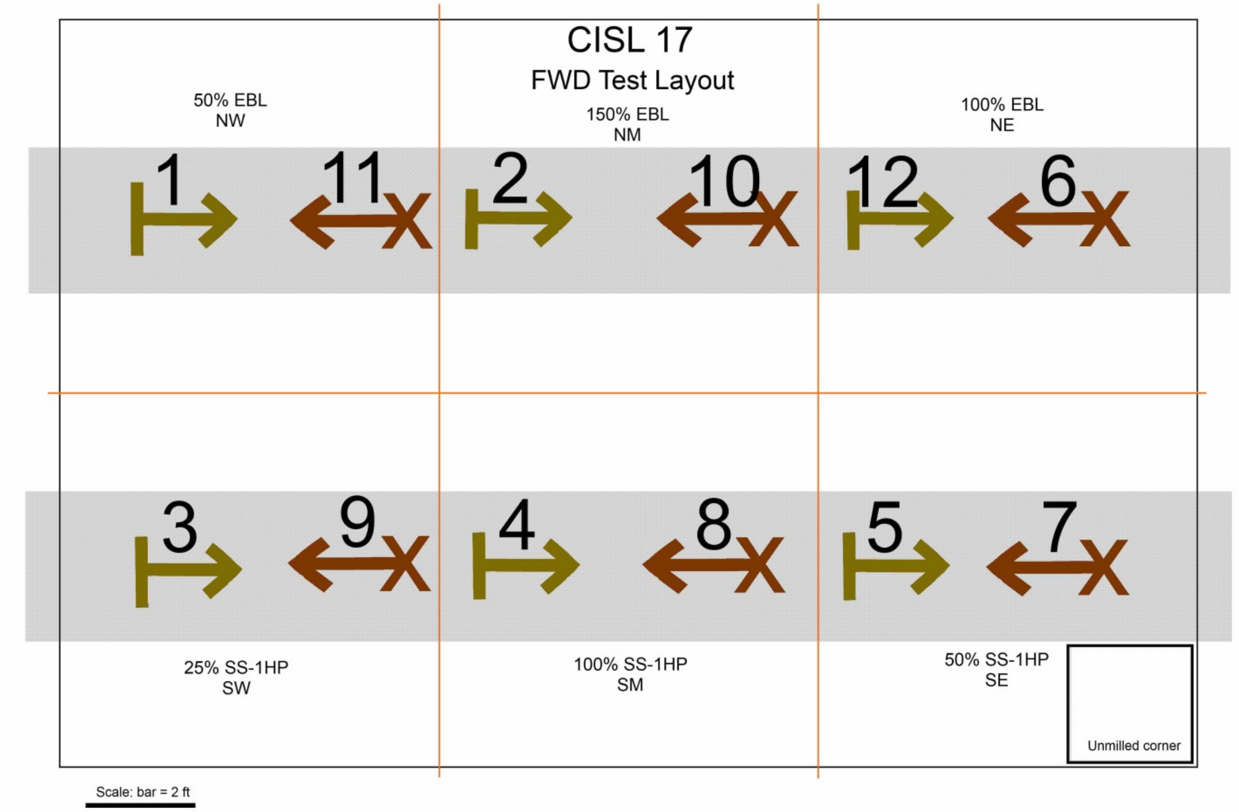

Figure 4.7: Station Locations for FWD Testing

The data from the FWD test was input into the Evercalc 5.0 software package and used to back calculate the elastic moduli of the underlying layers (Table 4.4). These results indicate the variable stiffness of the materials in the layers. The wide range of values is a reminder that it is difficult to assess what is underneath the surface. This data found is being used in other related studies.

Table 4.4: FWD Data

	Layer	E_1 (ksi) 4.5" HMA	E_2 (ksi) 6" base	E_3 (ksi) 5' subgrade	E_4 (ksi) Concrete
NW	Station 1	1000.0	100.0	10.0	10000
	Station 11	1000.0	36.0	7.9	10000
	Average	**1000.0**	**68.0**	**9.0**	**10000**
NM	Station 2	686.6	43.6	9.5	10000
	Station 10	560.1	41.5	9.4	10000
	Average	**623.4**	**42.6**	**9.5**	**10000**
NE	Station 6	561.9	83.5	10.0	10000
	Station 12	997.2	13.5	9.3	10000
	Average	**779.6**	**48.5**	**9.7**	**10000**
SW	Station 3	997.5	200.0	10.0	10000
	Station 9	574.0	12.9	10.0	10000
	Average	**785.8**	**106.5**	**10.0**	**10000**
SM	Station 4	300.0	50.2	9.6	10000
	Station 8	651.6	11.2	9.1	10000
	Average	**475.8**	**30.7**	**9.4**	**10000**
SE	Station 5	306.8	65.7	10.0	10000
	Station 7	580.1	39.0	10.0	10000
	Average	**443.5**	**52.4**	**10.0**	**10000**

4.3 Accelerated Testing and Data Collection

The APT applied 20-kip (89-kN) bi-directional loading as it rolled back and forth. This load was maintained though hydraulic load cells on each wheel. The rig was propelled by an electric motor attached to a wide belt pulley. An air suspension system assisted in braking and reversing directions. Two window unit air conditioners were activated while the machine operated, as it produced a significant amount of heat. The privilege of using this unique machine also brought unique challenges, as mechanical difficulties resulted in multiple delays in testing.

Transverse profiles were taken intermittently using a Chicago dial indicator, a digital Linear Variable Differential Transformer (LVDT) with a roller on the end that can be mounted on a leveled beam (Figure 4.8). Two profiles were taken for each test section, with benchmarks epoxied to the concrete floor outside the pit to ensure a consistent location unaffected by loading.

Elevation at every 0.5 inch (12.7 mm) was measured across the 14-ft (4.6-m) section. A laptop was attached to the set up to expedite the profiling process.

Figure 4.8: Transverse Profile Being Taken Using a Chicago Dial Indicator

Longitudinal profiling was done with a conventional surveying rod and level. Both wheel paths were surveyed at 0.5-ft. (0.152-m) increments. During survey, the pavement was visually inspected for cracks or deformations. After 400,000 repetitions, several core samples outside the wheel paths were taken to determine the bond strength in the laboratory.

Chapter 5: Results and Analysis

5.1 Laboratory Test Results

As mentioned earlier, the 1.97-inch (50-mm) diameter samples consisting of HMA overlay and existing surface were tested in the UTM machine in direct tension. The loading rate was at 0.7 in./min (18 mm/min). Under this uniaxial tension, the samples consistently broke apart at the interface. Stress was calculated by dividing the peak load by the area of the samples. Some came apart with an audible pop, while others simply pulled apart, but loading plots were similar for all: a steady increase in stress and a quick decrease after the peak, as seen in Figure 5.1.

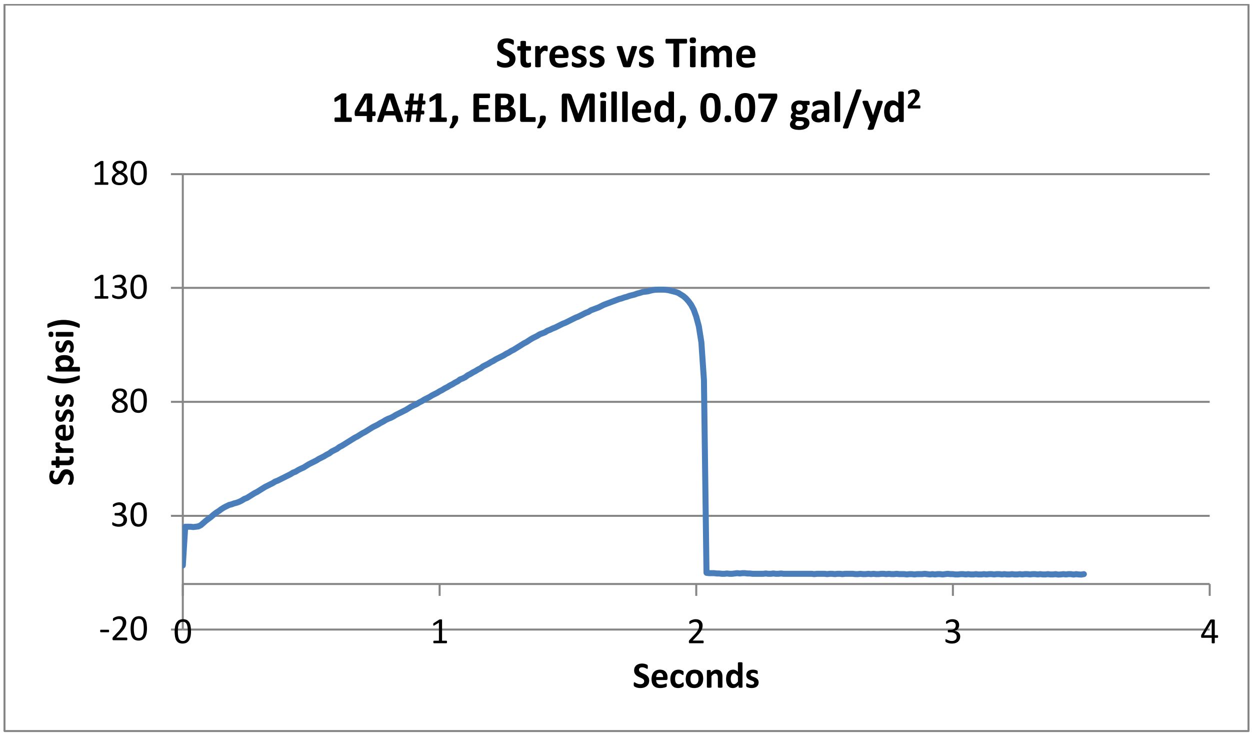

Figure 5.1: Stress vs. Time for Typical Sample Break

Table 5.1 is included again as a reminder of the materials and tack quantities that were tested.

Table 5.1: Tack Application Rates

	SS-1HP			EBL			Trackless
Percent of recommended rate	25%	50%	100%	50%	100%	150%	100%
gal/yd^2	0.0125	0.025	0.05	0.07	0.14	0.21	0.08
lpm^2	0.057	0.113	0.226	0.317	0.634	0.951	0.362
gram/6-inch sample	1.05	2.10	4.20	5.85	11.70	17.54	6.65

5.1.1 Two-Day Bond Strength

The distribution of breaking stresses for SS-1HP after 48 hours is illustrated in Figure 5.2. The solid lines indicate the average values. Higher variability exists at lower application rates. In all cases, the milled surface performed better than the unmilled surface. This is believed to be because of the extra surface area. KDOT used to specify acceptable and failing strengths, with a break below 35 psi (241 kPa) to be a failure, but now leaves that to the discretion of the engineer. A 70 psi (483 kPa) break is considered a sign that test frequency can be minimal. Most samples in this laboratory study were above the 70 psi (483 kPa) mark, even those at the 50% tack application rate.

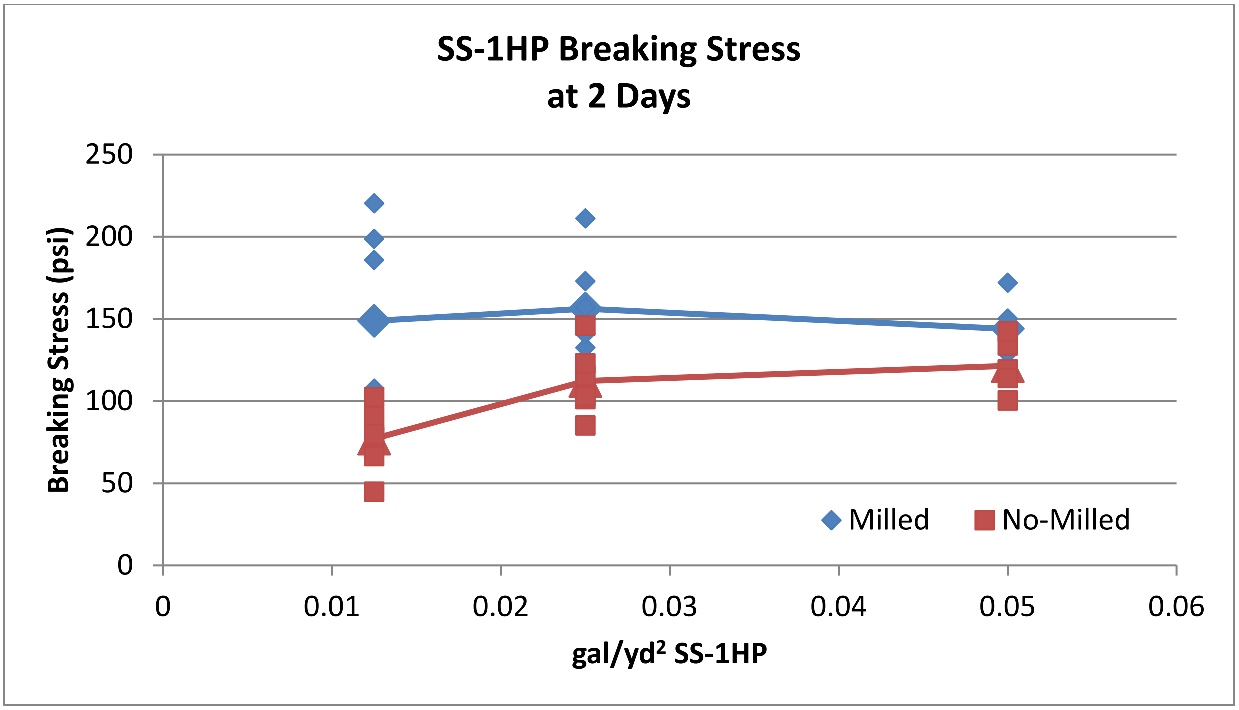

Figure 5.2: SS-1HP Breaking Stress

In EBL on the non-milled surfaces, less tack yielded higher strength values as shown in Figure 5.3. It is believed that at these high quantities, the tack acted as a slip plane. In the field, EBL is applied inside of a spray paver, seconds before the HMA is placed. However, in the lab it was allowed to break first. KDOT's manual states, "the EBL's performance may be reduced if it is allowed to break prior to the placement and compaction of the HMA overlay" (Appendix A of KDOT, 2015). Thus, results may be even higher without breaking. Milled surfaces showed the best strength at the recommended dosage of 0.14 gal/yd^2 (0.634 lpm^2).

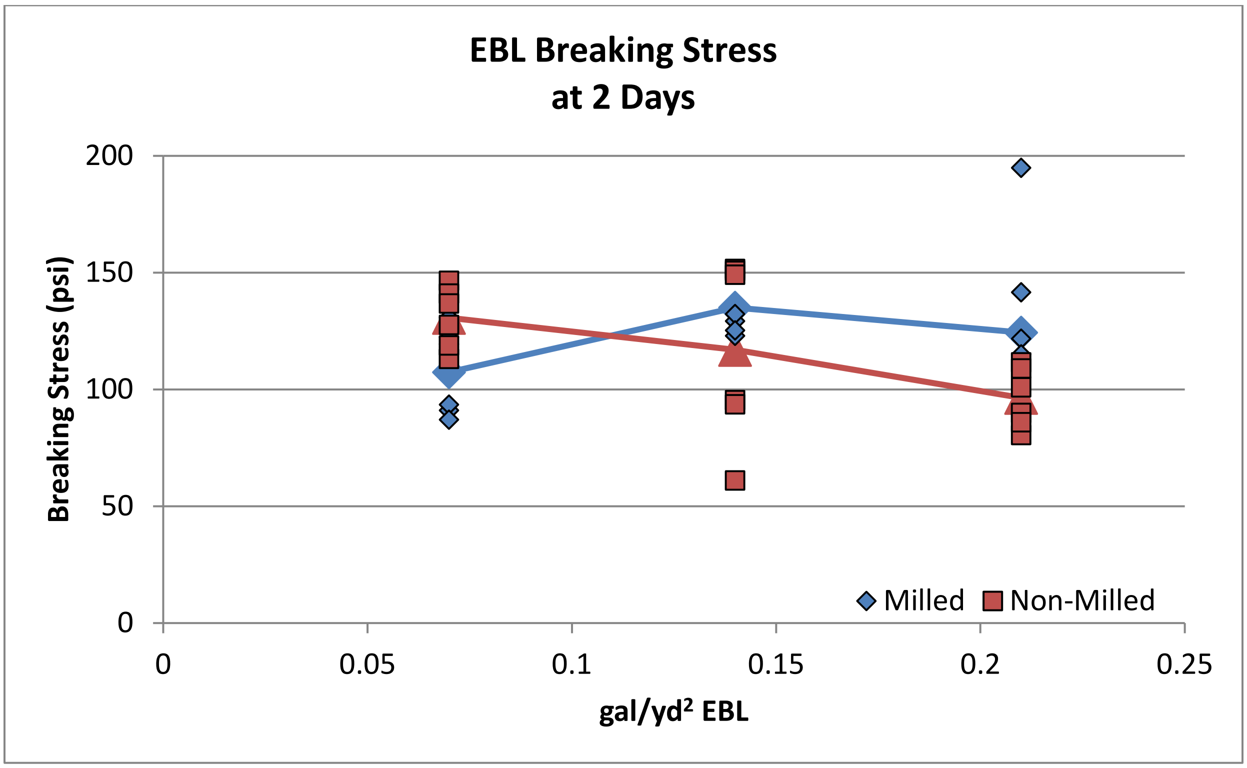

Figure 5.3: EBL Breaking Stress

As mentioned earlier, the application rate was not variable for the trackless tack; only the manufacturer's recommended 0.08 gal/yd^2 (0.362 lpm^2) was used. Despite some high outliers, it showed no significant difference in bond strength between the milled and the non-milled surface. Trackless breaking strength has been compared with the other tack rates in Figure 5.4. All three tack materials appear to have acceptable bond strength from these lab tests, mostly falling in the 100 to 150 psi (690 to 1035 kPa) range.

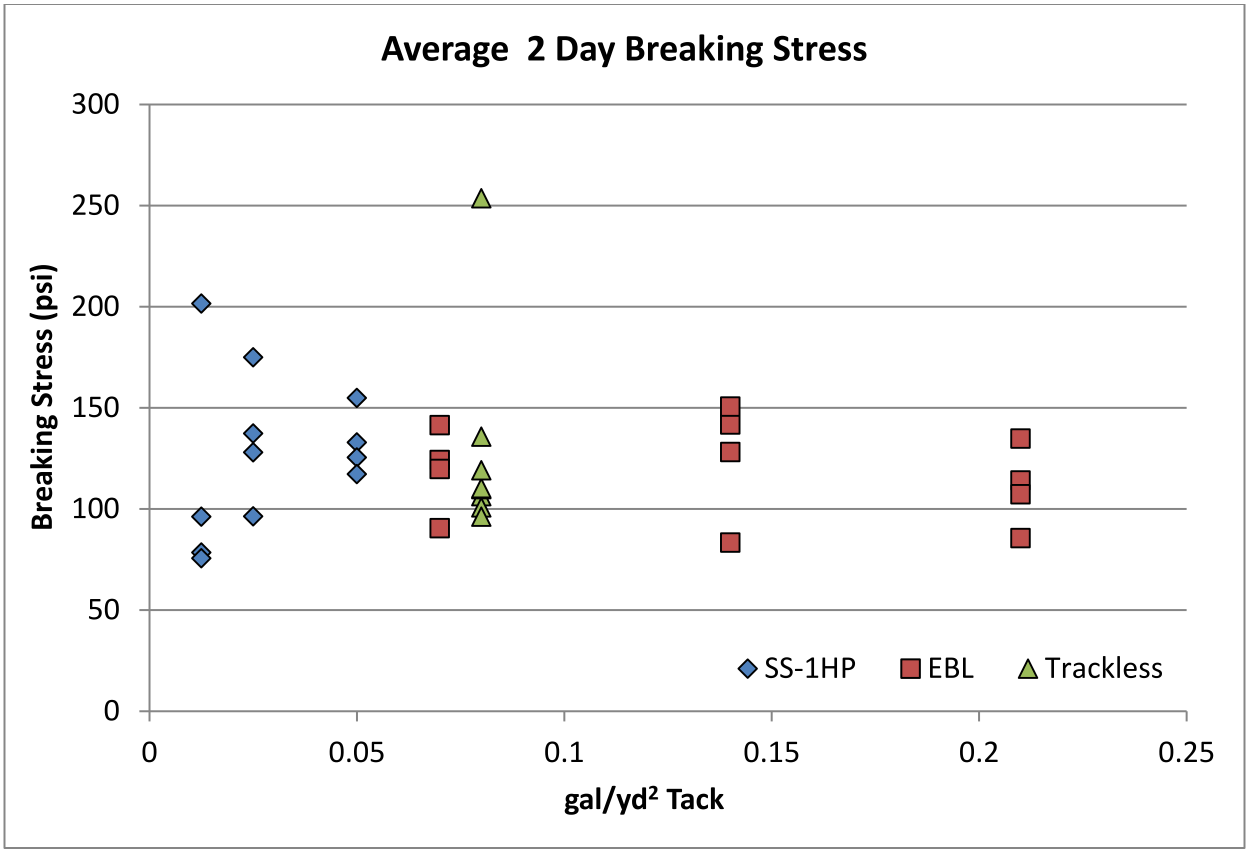

Figure 5.4: Breaking Stress for All Track Materials

An Analysis of Variance (ANOVA) was performed using the computer software SAS. The bond strength was taken as the response variable, and texture, tack application rate, and their interaction as the treatments. The ANOVA analysis results have been tabulated in Tables 5.2, 5.3, and 5.4. With a level of significance of 5%, texture with SS-1HP is statistically significant, but the application rate is not. The interaction between the texture and the rate is not significant. Thus, while the milled surface gets better results, the tack rate used does not matter. For EBL, the tack rate was significant when a Type III analysis was used, but not when Type I was. The interaction was significant, showing there is a difference between the treatments. Trackless tack showed no significant difference between the surface textures (milled vs. non-milled).

Table 5.2: SS-1HP ANOVA Results

Source	DF	Type I SS	Mean Square	F Value	Pr > F
texture	1	909070.0752	909070.0752	19.86	<.0001
gsy	1	88702.3666	88702.3666	1.94	0.1735
gsy*texture	1	174157.5904	174157.5904	3.80	0.0599

Source	DF	Type III SS	Mean Square	F Value	Pr > F
texture	1	668314.0482	668314.0482	14.60	0.0006
gsy	1	88702.3666	88702.3666	1.94	0.1735
gsy*texture	1	174157.5904	174157.5904	3.80	0.0599

Table 5.3: EBL ANOVA Results

Source	DF	Type I SS	Mean Square	F Value	Pr > F
texture	1	51211.69	51211.69	1.95	0.1725
gsy	1	3757.50	3757.50	0.14	0.7079
gsy*texture	1	267907.27	267907.27	10.19	0.0032

Source	DF	Type III SS	Mean Square	F Value	Pr > F
texture	1	154975.20	154975.20	5.89	0.0210
gsy	1	3757.50	3757.50	0.14	0.7079
gsy*texture	1	267907.27	267907.27	10.19	0.0032

Table 5.4: Trackless ANOVA Results

Source	DF	Type I SS	Mean Square	F Value	Pr > F
texture	1	258923.96	258923.96	2.71	0.1144

Source	DF	Type III SS	Mean Square	F Value	Pr > F
texture	1	258923.96	258923.96	2.71	0.1144

5.1.2 Two-Day Bond Energy

Another variable examined was the bond energy of the tack. This was calculated by finding the area under the load-displacement graph, an example of which is shown in Figure 5.5. The area was found by using a middle Riemann sum method, which approximates the area as thousands of narrow rectangles. An example calculation is as below:

$$\left(\frac{(1.228+1.231)kN}{2} * (.463 - .468)mm + previous\ total\right) * \frac{1000\ N}{kN} * \frac{m}{1000\ mm} = 0.322\ J\ (Nm = J)$$

This was divided by the cross-sectional area of the sample (which had a 1.97-inch [50-mm] diameter) to find the bond energy in terms of J/m^2. The average bond energy for each section has been listed in Table 5.5.

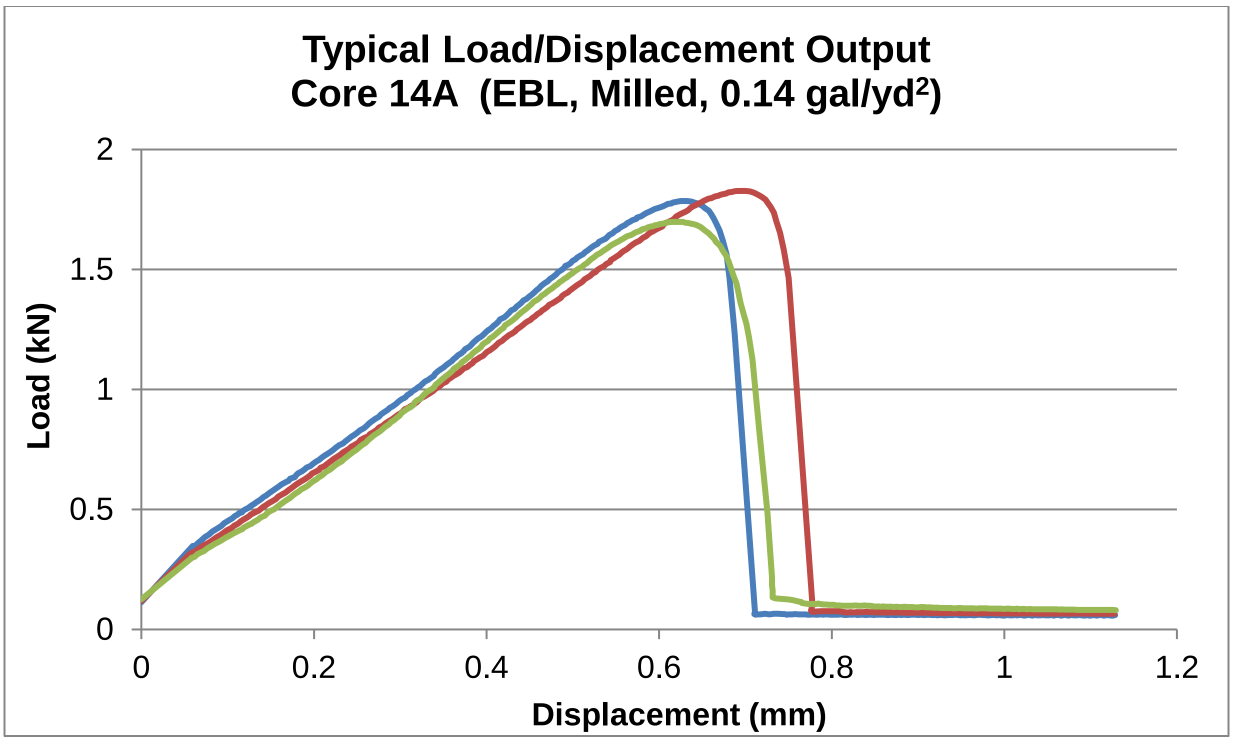

Figure 5.5: Typical Load/Displacement Graph for the Three Cores from a Compacted Sample

One advantage of the bond energy value over a peak stress is that it allows for comparison against the samples tested at varying loading rates. Future testing by others may make use of this data to more deeply understand the significance of the bond energy. For this study, only 0.7 in./min (18 mm/min) was used, and so with that loading, the bond energy values correlate with the bond strength values well, as seen in Figure 5.6. Figure 5.6 reveals a linear relationship between the bond strength and the bond energy. A statistical analysis for the bond energy results confirmed the findings from the bond strength analysis.

Table 5.5: Average Bond Energy and Bond Strength for Sample Groups

		SS-1HP			EBL			Trackless
	Percent of recommended rate	25%	50%	100%	50%	100%	150%	100%
	gal/yd^2	0.0125	0.025	0.05	0.07	0.14	0.21	0.08
Milled	Ave. Breaking Stress (psi)	149	156	144	107	135	134	140
	Ave. Bond Energy (J/m^2)	369	424	354	335	277	204	322
Non-Milled	Ave. Breaking Stress (psi)	77	111	123	131	117	96	109
	Ave. Bond Energy (J/m^2)	103	220	245	228	338	366	210

A complete list of bond strength and energy values can be found in Appendix A.

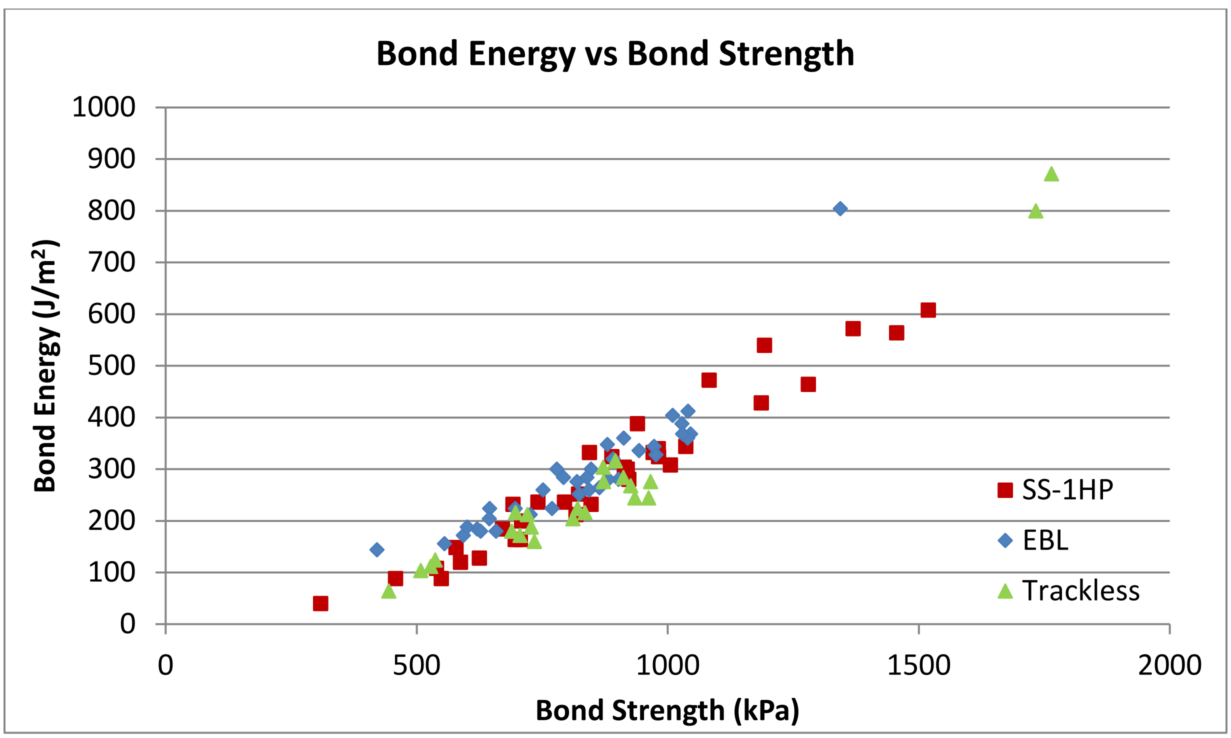

Figure 5.6: Bond Energy Plotted Against Bond Strength at 2 Days

5.1.3 Bond Strength Over Time

Although it was not part of the initial parameters, time of testing was also a variable. This began from the equipment delays and continued out of curiosity. Samples that were tested at times greater than two days had on average higher strength. The small number of samples tested at later times does not allow for the outliers to be counterbalanced, but trends are clearly evident in Figures 5.7 through 5.11.

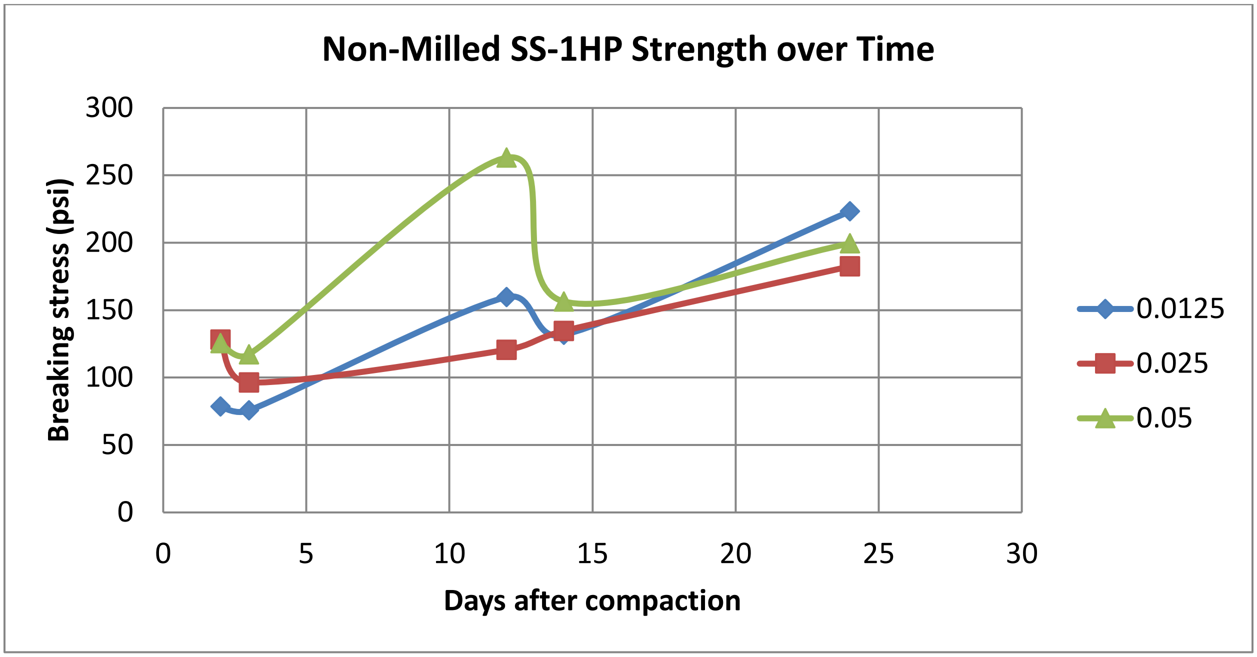

Figure 5.7: Bond Strength Increases Over Time for Non-Milled SS-1HP

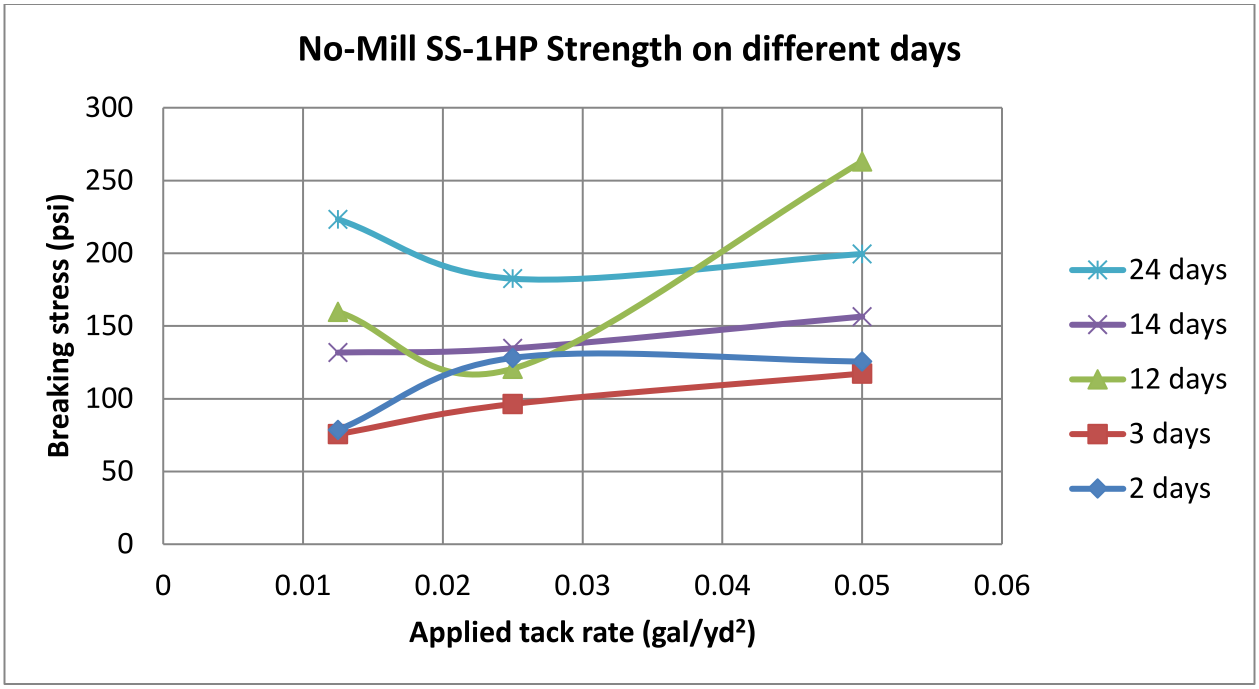

Figure 5.8: SS-1HP Tack Rates Compared on Different Days (Same Data as Figure 5.5)

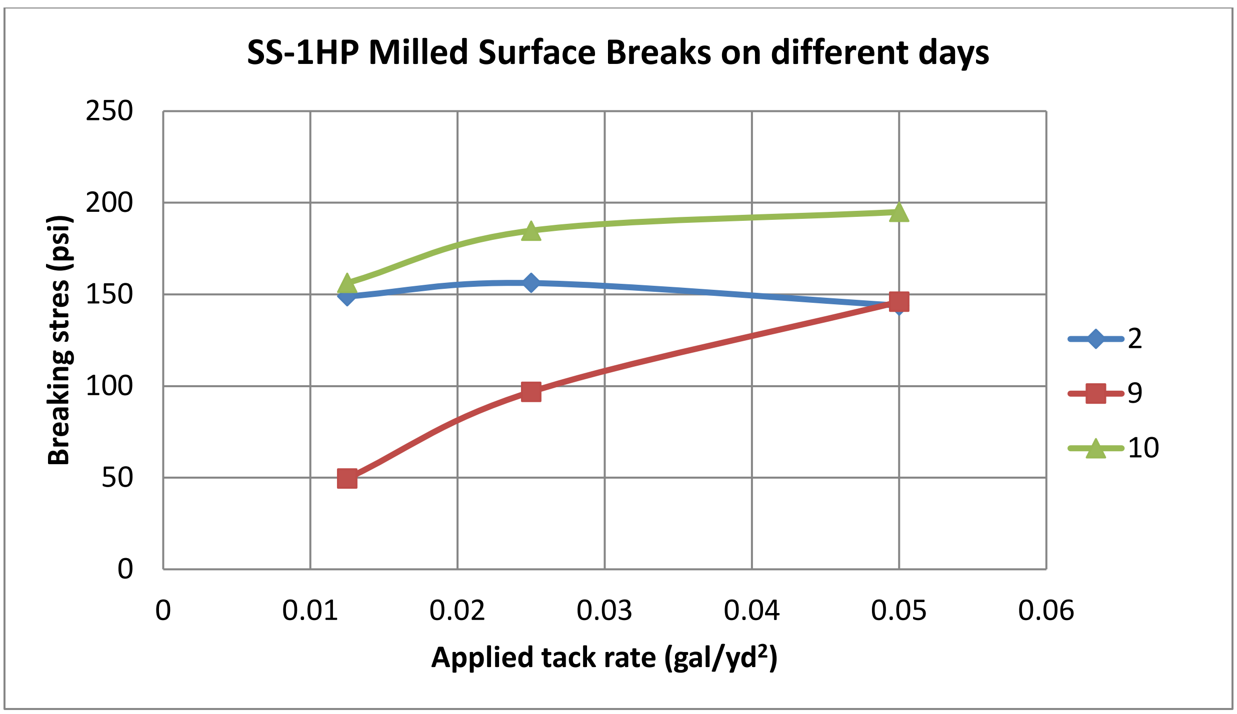

Figure 5.9: SS-1HP Milled Surface on Different Days

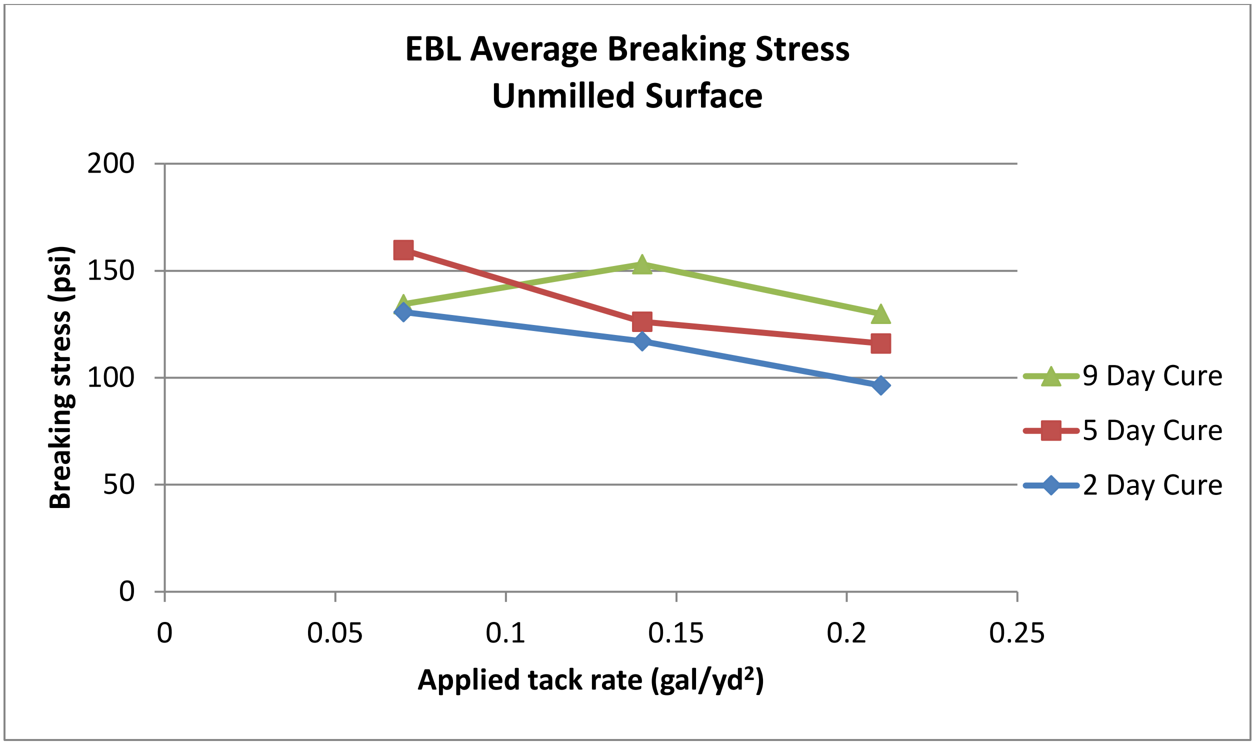

Figure 5.10: EBL Tack Rates Compared on Different Days

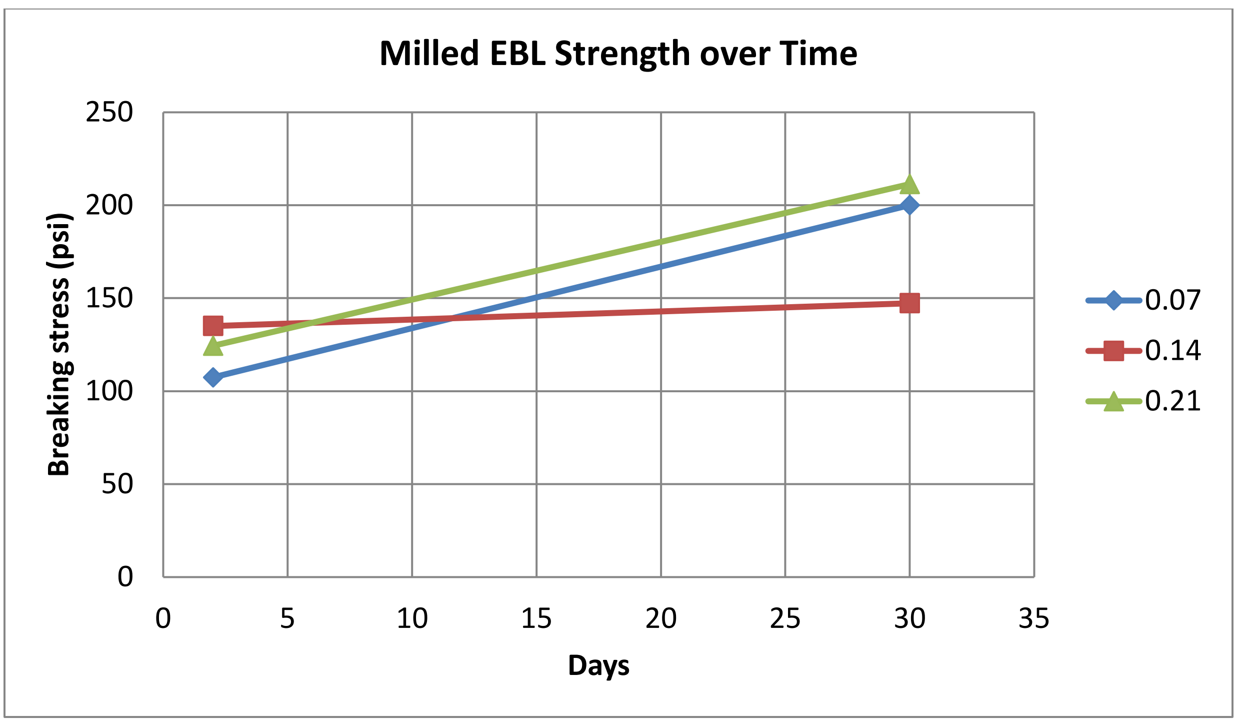

Figure 5.11: EBL Strength Over Time on Milled Surface

These figures illustrate the importance of having a consistent time of testing, as the bond grows stronger over time, sometimes doubling in the course of a month as seen in Figure 5.11. It also provides reassurance that if a pavement does not debond immediately after construction, it will not likely debond in the near future.

5.1.4 Unusable Results and Possible Sources of Error

The D and E cores were tested a year later than A, B, C, and W. Tack was stirred and appeared to still be in good condition, but after most of them had been tested it was discovered that the bottom of the buckets contained a weighty residue of tack that had settled out of suspension. This resulted in applying a diluted tack. Figures 5.12 and 5.13 compare the bond strength results of the D and E (with diluted tack) cores to the original ones.

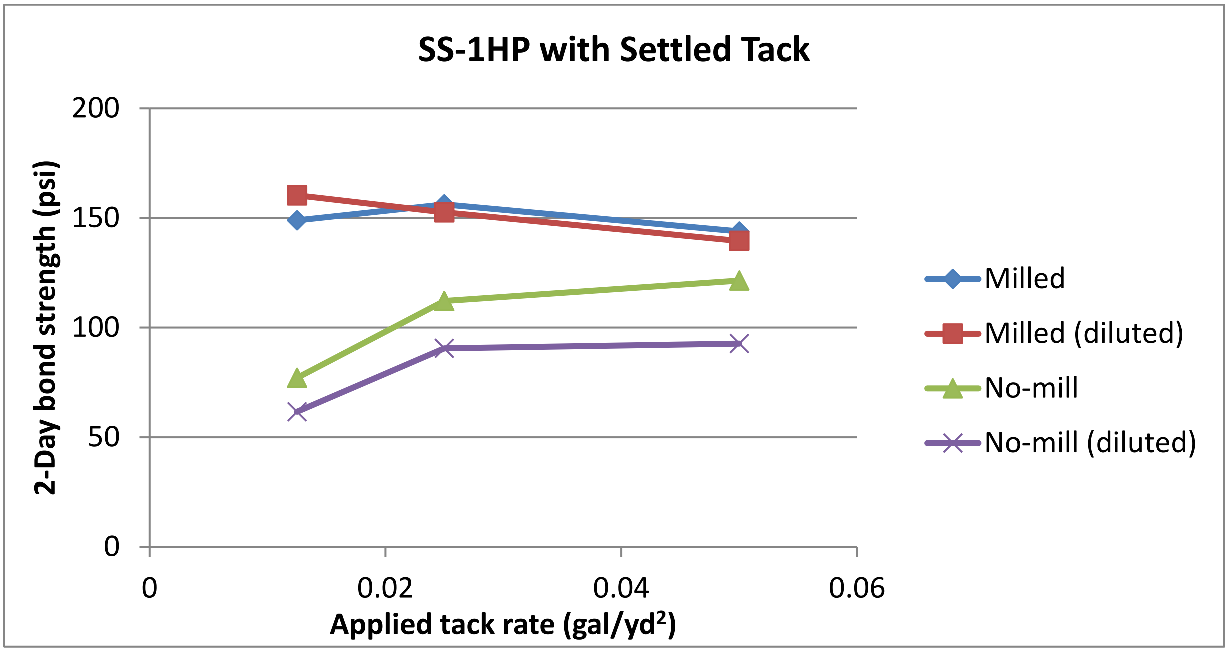

Figure 5.12: Comparing Original 2 Day Tests with 2 Day Tests that used Settled Tack (SS-1HP)

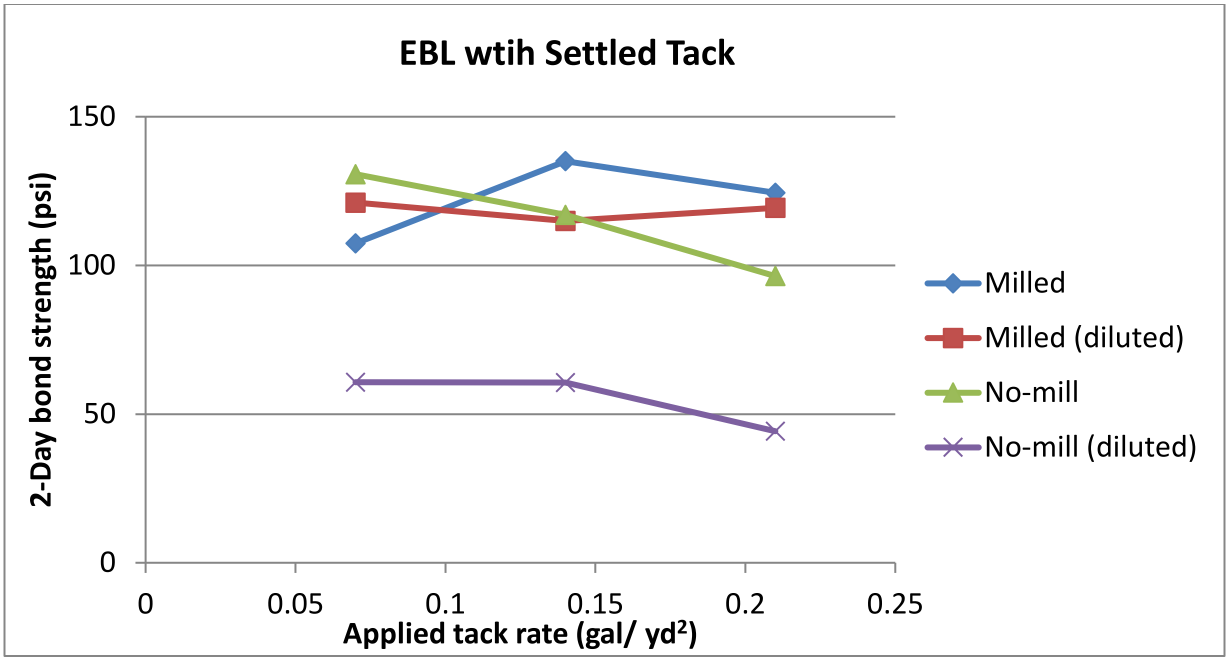

Figure 5.13: Comparing Original 2 Day Tests with 2 Day Tests that Used Settled Tack (EBL)

While the milled surfaces do not show a significant difference with the diluted tack, the non-milled samples are drastically lower in strength. It is possible that the surface texture of the D cores contributed to a poor bond. It was observed to have a greater macrotexture and to contain dribbles of tack that were likely from the road construction where it was cored. But being unable to ascertain the equivalent rate with this diluted tack, it was decided to not include these values in the data analysis.

5.2 APT Results

5.2.1 Rutting

The APT was run at 20 kip (89 kN) load in increasingly large time increments, periodically taking strain measurements and also moving the machine off of the pit to survey the permanent surface deformation and distresses. Permanent deformation is the difference between the same points at different times. The largest difference is the reported value, as seen in Figure 5.14.

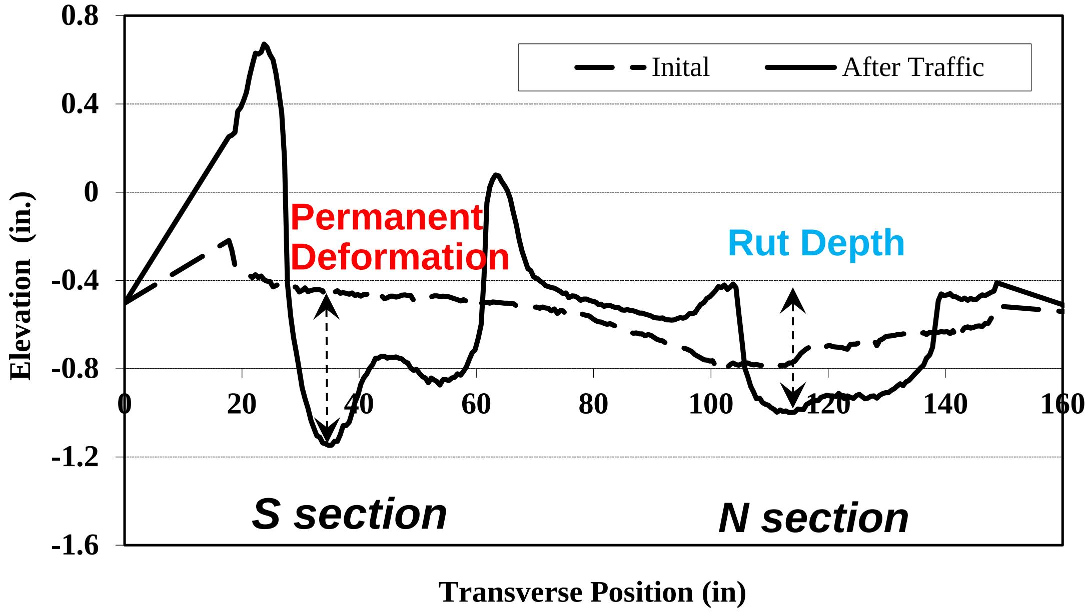

Figure 5.14: Definition of Permanent Deformation and Rut Depth
Source: Romanoschi, Lewis, Gedafa, and Hossain (2014)

A Chicago dial gage indicator on a level beam was used to take two transverse profiles per section at every 0.5-inch (12.5 mm). The SS-1HP sections in Figure 5.15 all appear to have deformed over time, with the middle section only deforming 0.08 in. (2 mm) before leveling off. This is possibly because it was over compacted and had less room to consolidate. The sections with lesser amounts of tack continued to deform permanently over time.

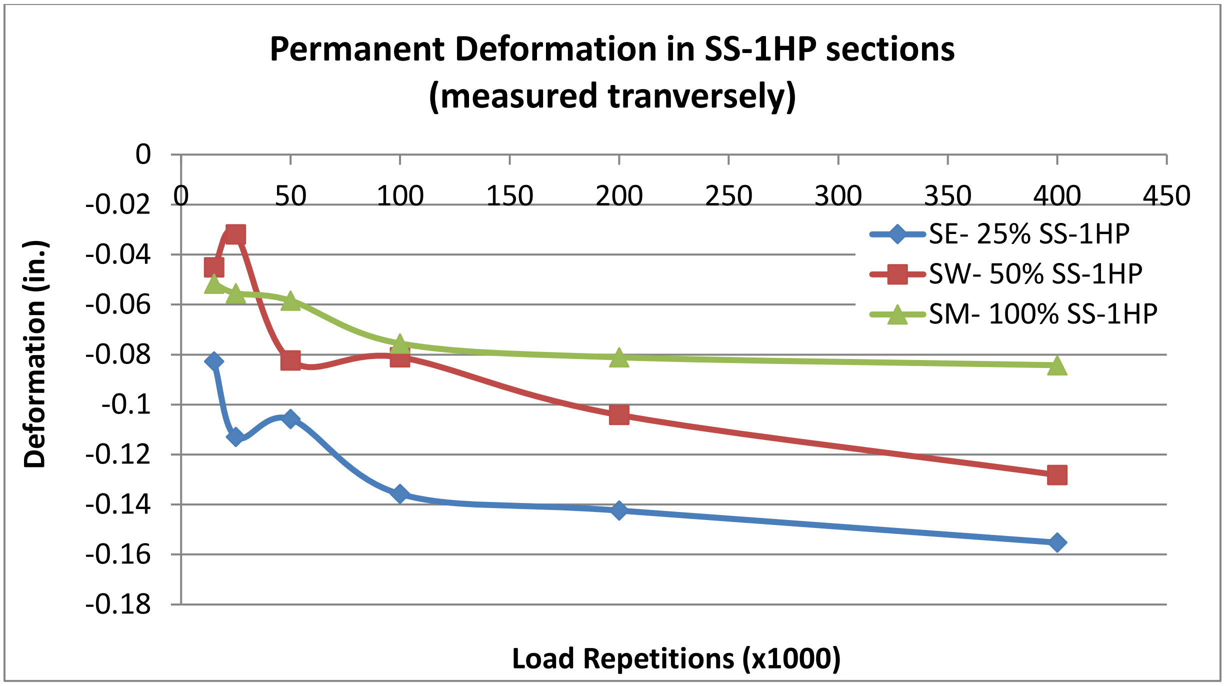

Figure 5.15: Permanent Deformation in SS-1HP Sections

The rut depth was also found, subtracting the lowest point from the highest near the wheel path. The section used to determine rut depth was from 10 in. (254 mm) south to 10 in. (254 mm) north of each wheel path. Figure 5.16 shows a similar rut depth of around 0.3 in. (7.5 mm) for the three SS-1HP sections. It should be noted that the unloaded pavement already had a rut depth of a quarter inch or so, and it did not dramatically increase from there.

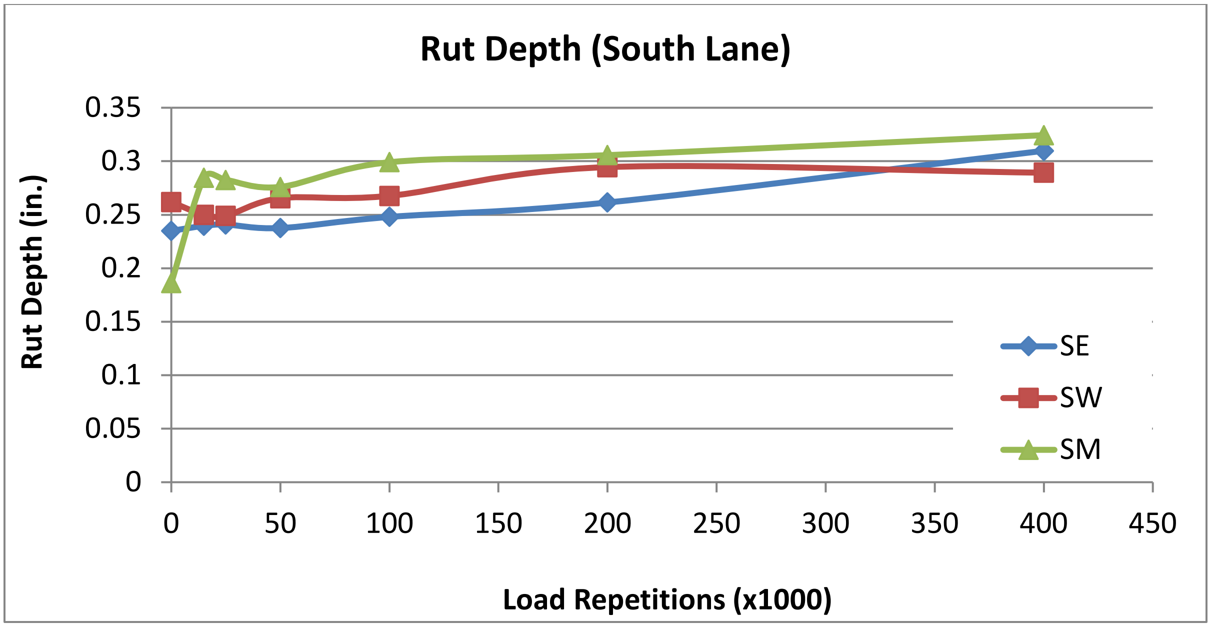

Figure 5.16: SS-1HP Rut Depth (Highest Minus Lowest Point)

A longitudinal survey was also conducted periodically using a traditional rod and level survey to plot the wheel path at every 6 in. (150 mm). The deformation for each section was averaged and plotted in Figure 5.17. This confirms that the SM section deformed less than the others, though it does not show the SE section deforming as much. The longitudinal survey is less accurate than the transverse, but more representative of the entire section.

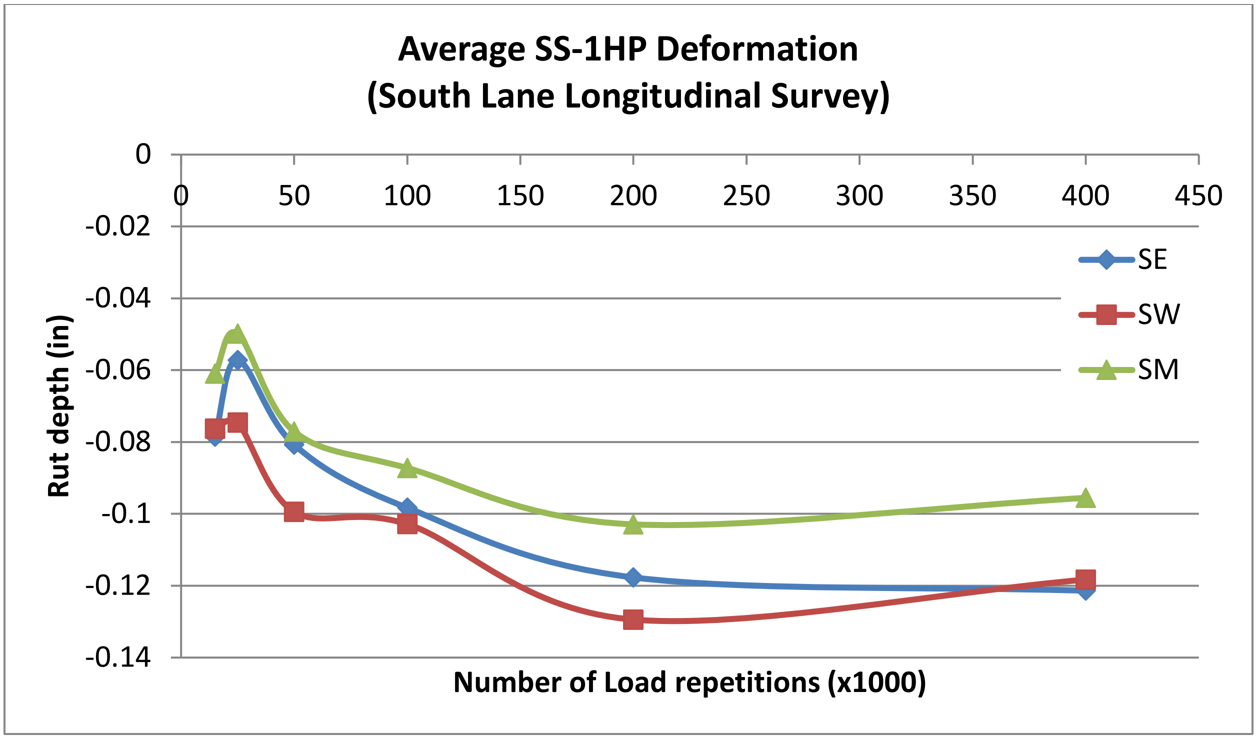

Figure 5.17: Longitudinal Survey of South Lane

EBL provided more interesting results. The NM section initially appears to have negative deformation according to the transverse profile data in Figure 5.18. After an initial spike, the pavement continues to deform. This is possibly due to an error in the data collection process. Although the NM section was well compacted, several months passed between construction and the first profile and loading, thus reactionary expansion seems unlikely.

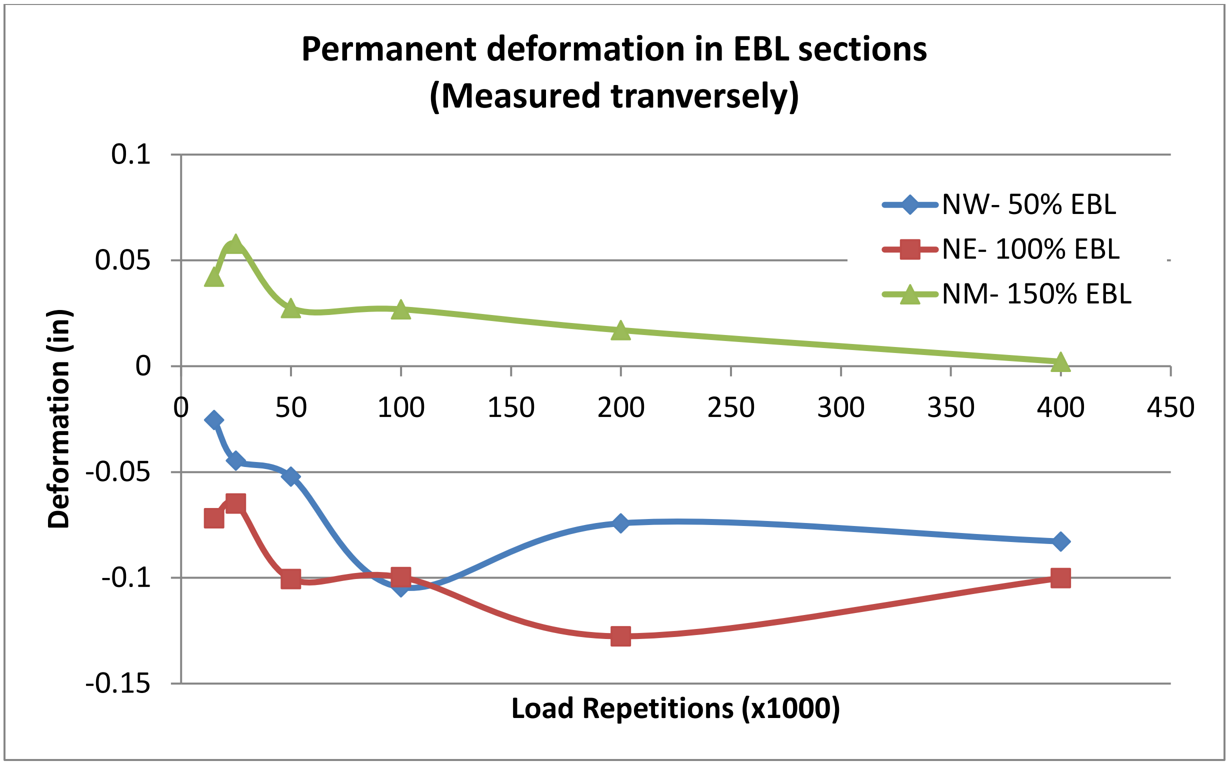

Figure 5.18: Permanent Deformation in EBL Sections

The rut depths for the north lane sections, seen in Figure 5.19, appear consistent over time after 100,000 repetitions. Although the NE section has a rut depth of nearly 0.5 in. (12.5 mm), it is not noticeable. It is noted that the deformation is still less than 0.1 in. (2.5 mm) as shown in Figure 5.18.

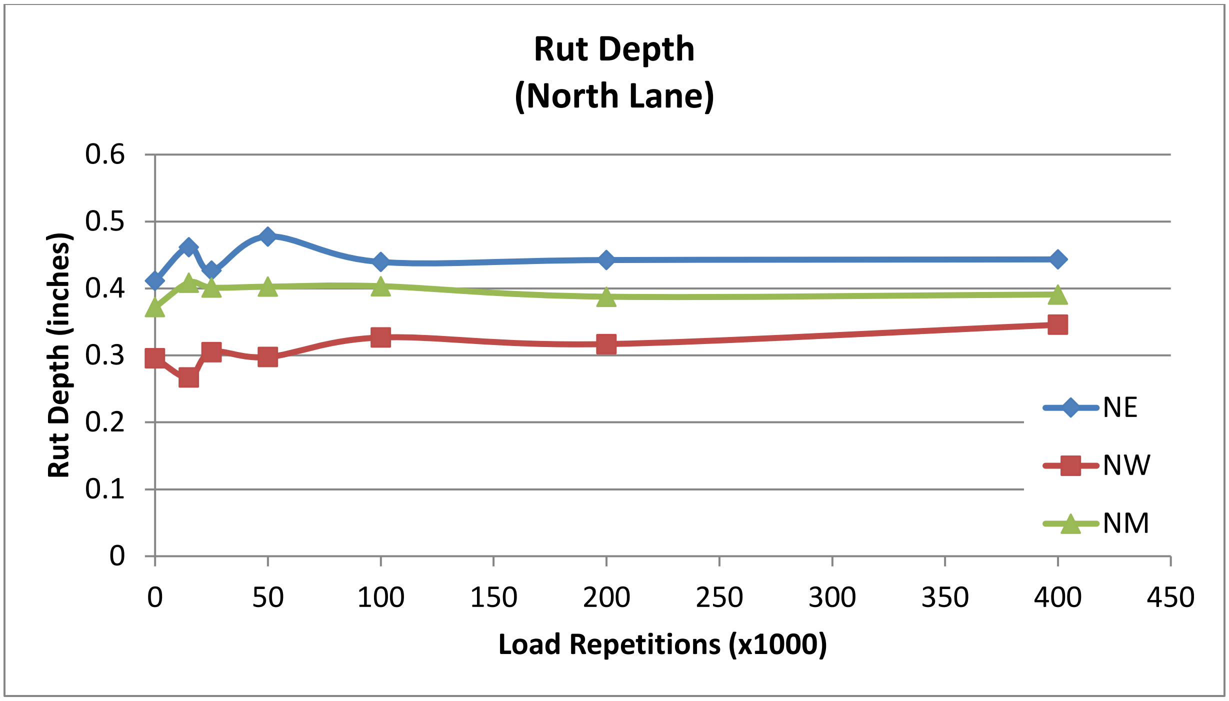

Figure 5.19: EBL Rut Depth (Highest Minus Lowest Point)

The longitudinal survey of the north lane shows an interesting upswing at the end. Since this survey was done two months after loading, it is thought to be caused by the pavement recovering/healing. Otherwise it could be extra sediment in the wheel paths from the samples that had been cored to check the bond strength.

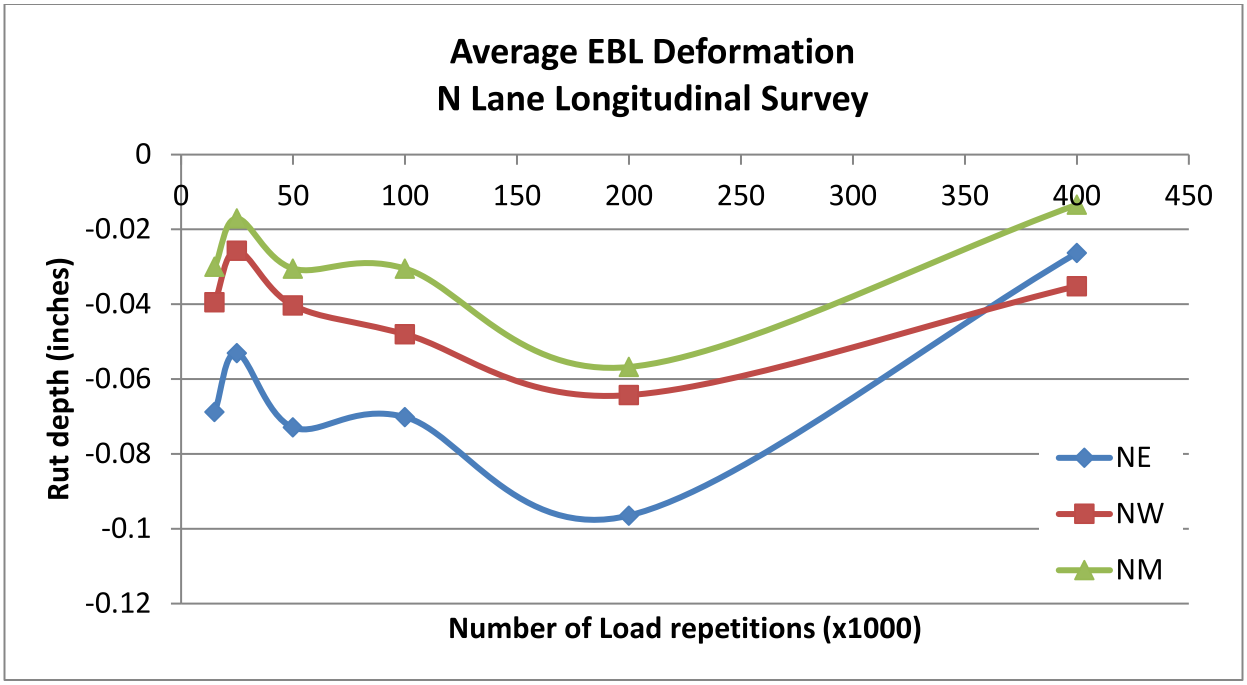

Figure 5.20: Longitudinal Survey of North Lane

No failure criteria were established for the pavement deformation and rut depth, but visually very little rutting occurred.

5.2.2 Strain

Strain gages had a depressingly high failure rate. While 12 were installed, with two longitudinally per section, only six were operational after construction. This is likely due to poor soldering and stress from the construction vehicles. Within minutes after loading began, two of the gages showed signs of failure, with the SW section showing a flat line, and the second SE gage showing extreme variation.

Resilient strain has been calculated as the distance between a baseline and the peak strain value. It was found that the median strain value for a 90-second interval aligned well with the visual baseline for that unit of time (Figure 5.21).

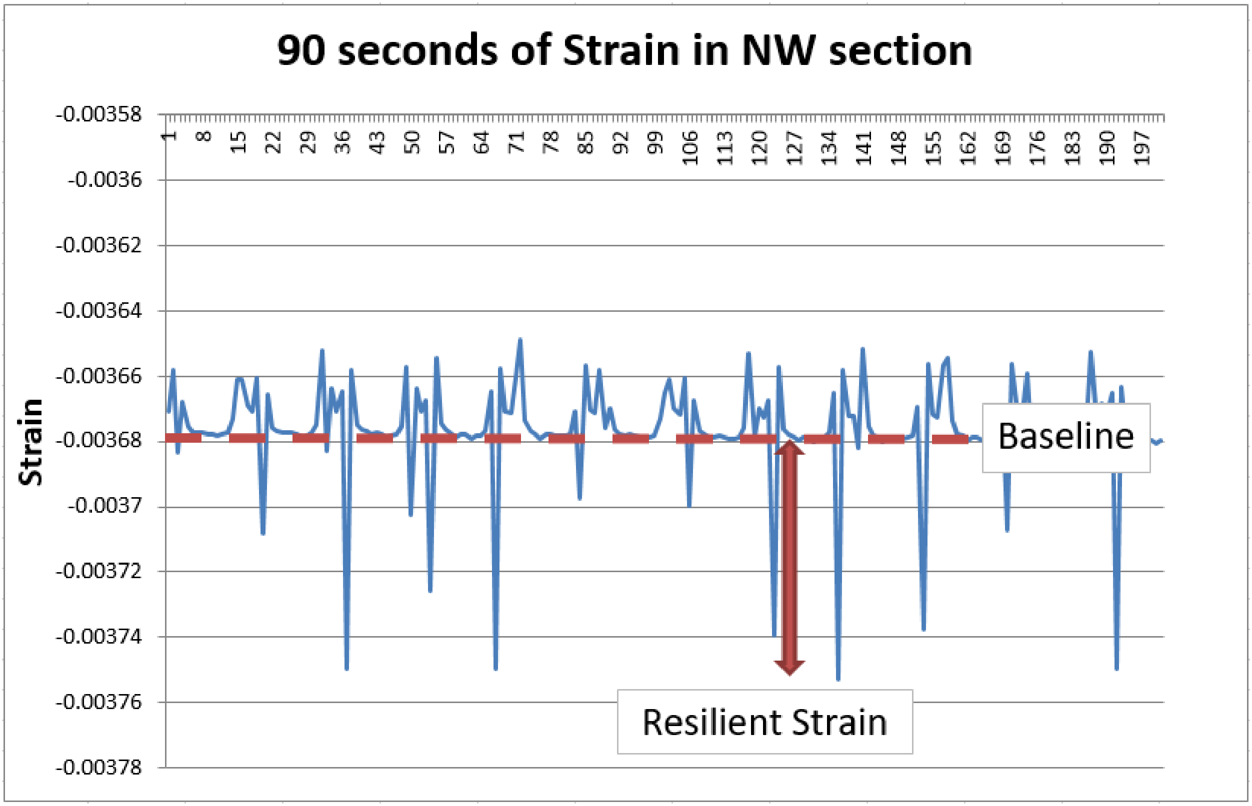

Figure 5.21: Finding Resilient Strain

Strain was measured for an entire wander cycle, or 676 load repetitions. The top 50 resilient strains for a wander cycle were averaged and plotted in Figure 5.22. The gage on the SE section (0.025 gal/yd^2 SS-1HP) began to fail at 50,000 repetitions. The SW and other SE section gages failed within minutes of initial loading. The NE and NW section gages, with 0.07 and 0.14 gal/yd^2 (0.32 and 0.63 lpm^2) EBL, respectively, show very similar strain throughout the whole loading cycle. No temperature correction was used. The SM section (0.05 gal/yd^2 of SS-1HP) gage shows a much higher strain than the others, though it has not completely failed yet.

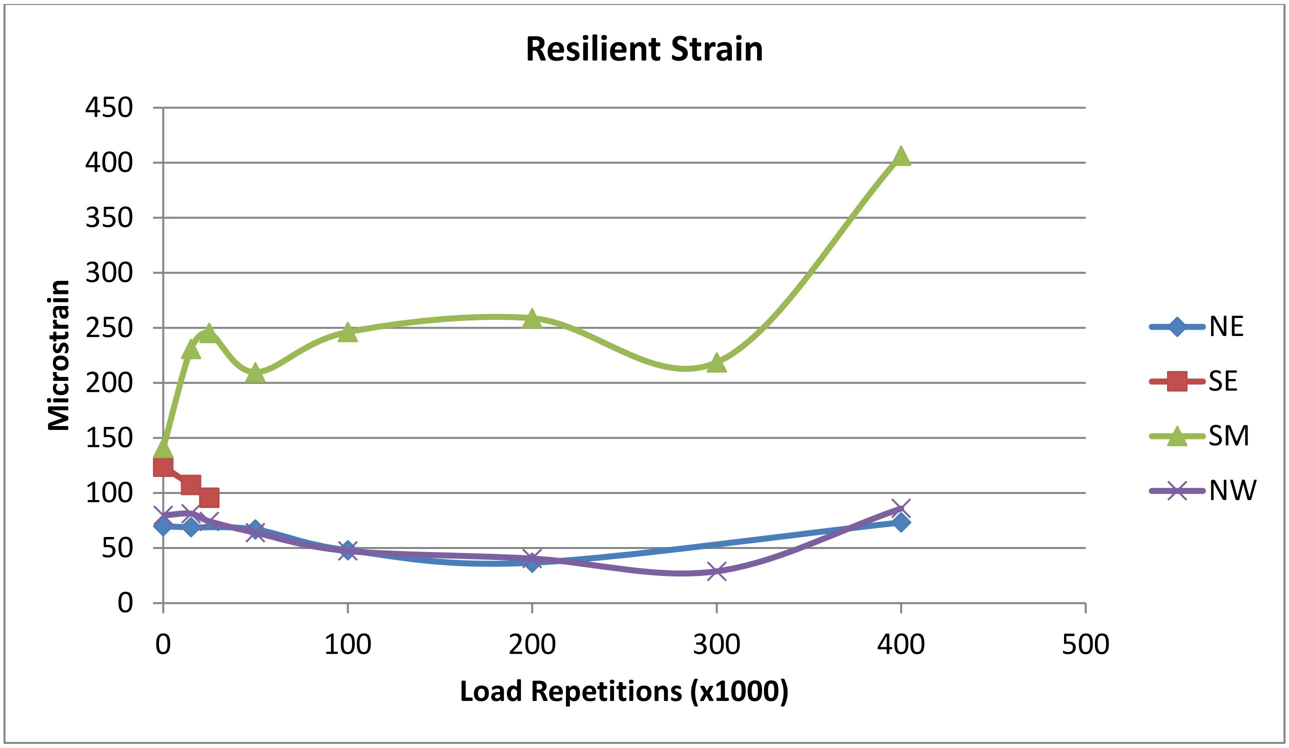

Figure 5.22: Resilient Strain During Loading

This full-scale test was conducted on top of pavement built for the CISL No. 14 project. That project made use of several strain gages at the interface of the base and the HMA pavement layer. Two were found to still be operational, in the wheel paths on the east end of the pit. The lead wires designated them as No. 6 and No. 16. Based on the strain values they return, it is believed that No. 6 is placed longitudinally while No. 16 is transverse to the loading direction. Although these gages do not reveal the behavior of the existing HMA–new HMA interface, they do provide reassurance that the strain values found are reasonable, as these line up with the strain values in the CISL No. 14 project report.

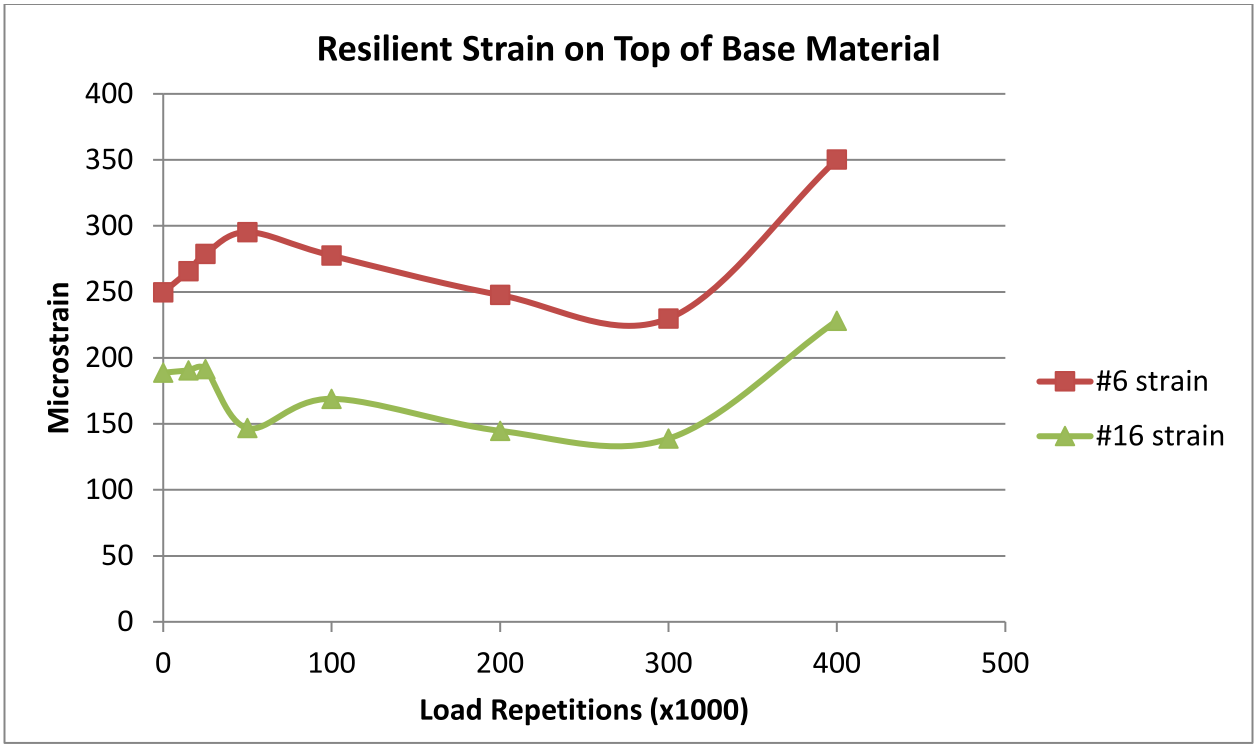

Figure 5.23: Strain at Bottom of HMA on East Side of Pit

Table 5.6: Microstrain Values during Loading

Load Repetitions (x 1,000)	NE	SE	SM	NW	#16	#6
0	69.74	123.98	140.95	79.70	188.76	249.59
15	68.91	107.39	230.76	81.32	190.47	265.74
25		95.88	245.39	74.33	191.54	278.67
50	66.89		209.78	64.00	146.77	295.25
100	48.10		246.20	47.38	168.97	277.44
200	36.73		258.82	40.48	144.71	247.59
300			218.73	28.93	138.79	229.83
400	73.32		406.53	86.00	228.18	350.37

The strain values suggest that the bond in the SM section, with 0.05 gal/yd^2 (0.23 lpm^2) SS-1HP, is not as good as the NE and NW sections, which maintain low strain values. The No. 6 and No. 16 gages, which are 2.5 in. (64 mm) deeper, show higher strain than the NW and NE which are embedded at the HMA interface halfway down.

5.2.3 Bond Strength

After 400,000 repetitions, a 6-inch (150-mm) diameter core was extracted from the outer edge of each section and tested in the same way as described in the lab section: taking three cores of 2-inch (50-mm) diameter, epoxying them to the metal plates, and testing in uniaxial tension in the UTM machine. Additionally, several 2-inch (50-mm) diameter cores were drilled to just below the interface layer. These were tested in-situ using a portable battery powered ComTen pull-off tester that is used by KDOT for field testing following KT-78 test procedure. Aluminum pucks were epoxied to the 2-inch (50-mm) diameter cores and pulled in direct tension at 0.8 in./min (20 mm/min) as specified in KT-78 (Figure 5.24).

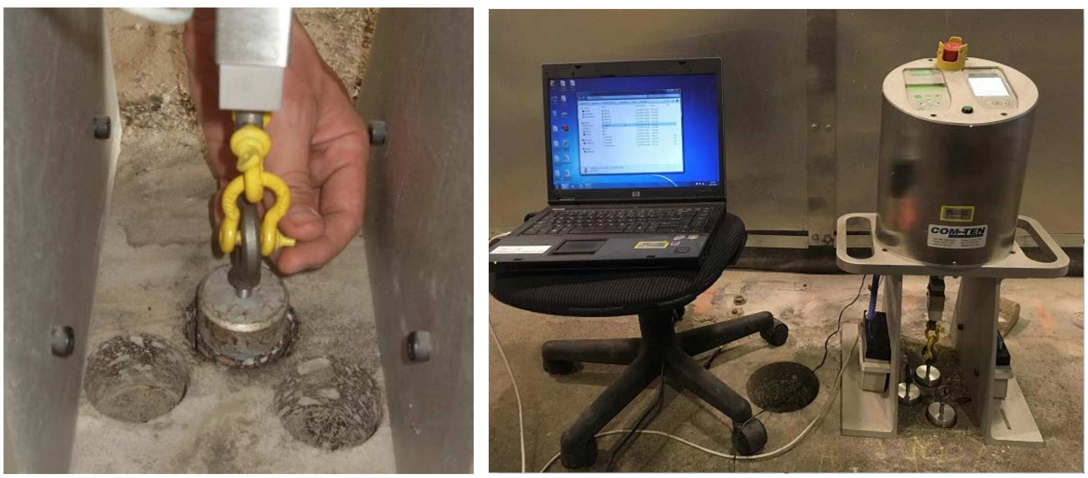

Figure 5.24: (a) ComTen Pull-Off Tester Load Cell Attached to Epoxied Aluminum Puck, (b) ComTen Pull-Off Tester Connected to Laptop

The bond strength values for the sections are illustrated in Figure 5.25. The EBL sections in the north lane have bond strengths similar to that found in the lab, though the idealized lab settings showed higher strength, which is somewhat expected. For SS-1HP though, the difference is staggering. The bond is very weak in all SS-1HP sections, and there were several debonding incidents while coring. All of these values are well below KDOT recommendations for the interface bond strength. This could be from inadequate cleaning of the milled surface and/ or from non-uniform tack distribution.

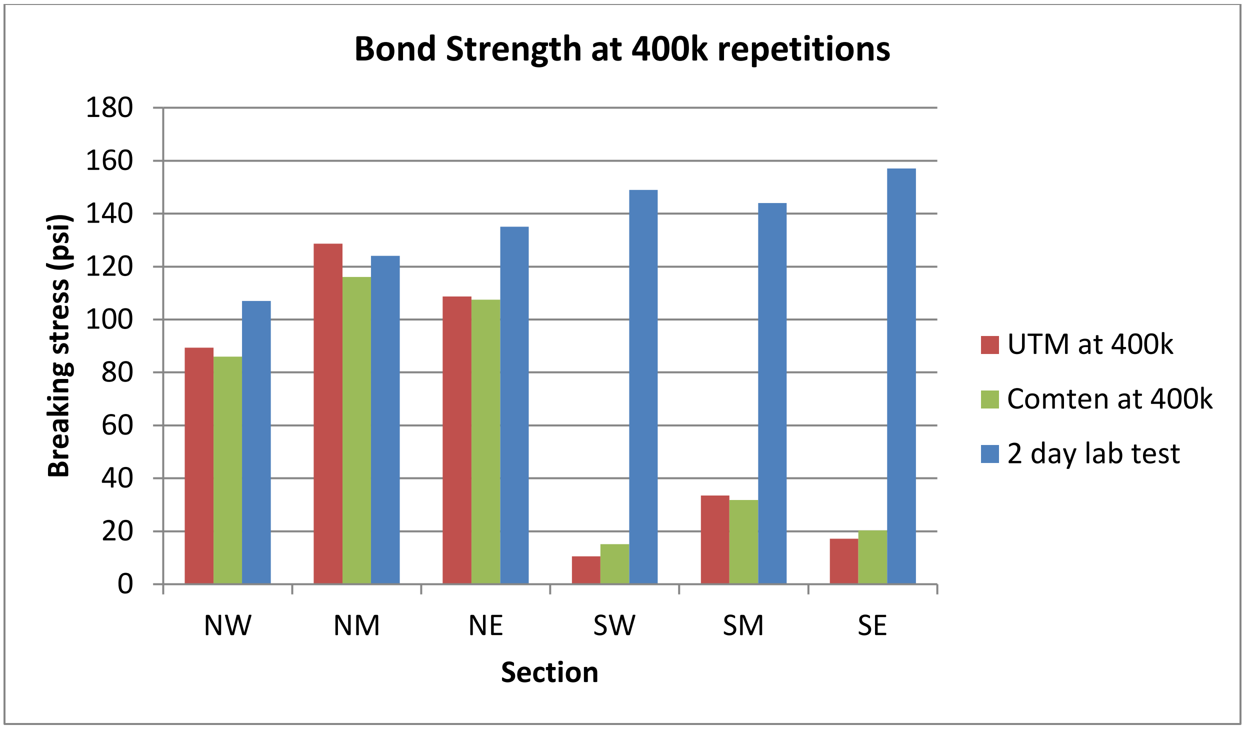

Figure 5.25: Bond Strength of CISL Sections after Loading

Figure 5.26: Edge of SE Section Easily Debonded during Milling

The coring for testing bond strength after loading revealed the final HMA overlay thicknesses as well. Although 1.5 in. (38 mm) was the target overlay thickness, it ended up being 2 in. (50 mm) thick over most of the pit as tabulated in Table 5.7. The consistency is reassuring that sections are mostly similar.

Table 5.7: Pavement Thickness as Revealed by Coring Outside the Wheel Paths

NW	NM	NE
2” top 3” base 5” total	2” top 2.25” base 4.25–4.5” total	1.75” top 3.5” base 5.25–5.75” total
SW	**SM**	**SE**
2” top 3.25” base 5.25” total	2” top 3” base 5–5.5” total	1.75” top 3.25” base 5” total

5.2.4 Distress Survey (Cracking)

At 200,000 load repetitions, the wheel paths were carefully inspected for indications of failure. Only a couple cracks were found, in the SE and SM sections (Figure 5.27). At 300,000 and 400,000 load repetitions, more hairline cracks were found, though most were not visible except when closely searched for as illustrated in Figures 5.28 and 5.29.

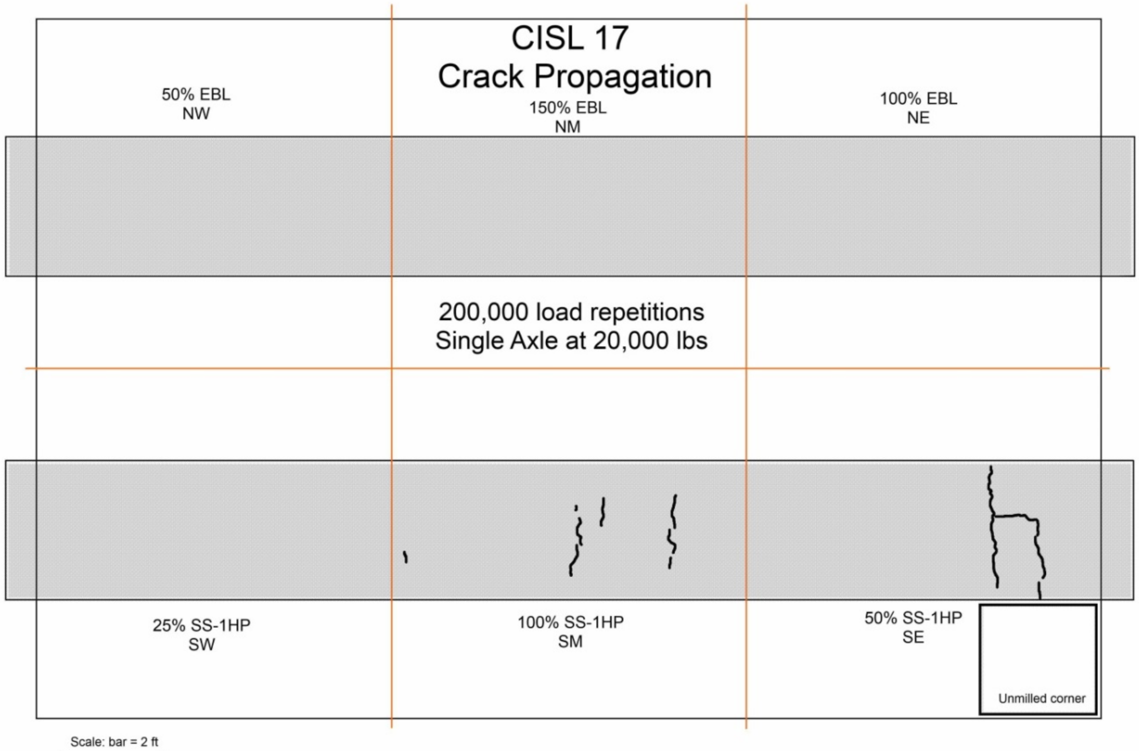

Figure 5.27: Cracks at 200,000 Load Repetitions

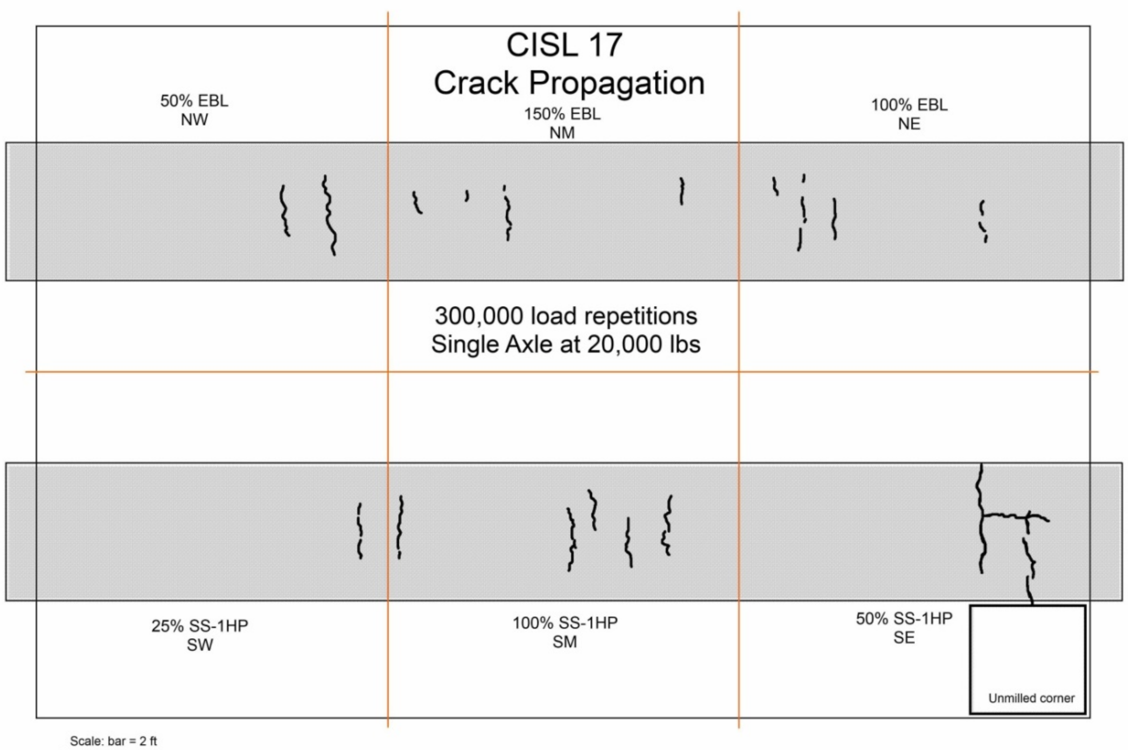

Figure 5.28: Cracks at 300,000 Load Repetitions

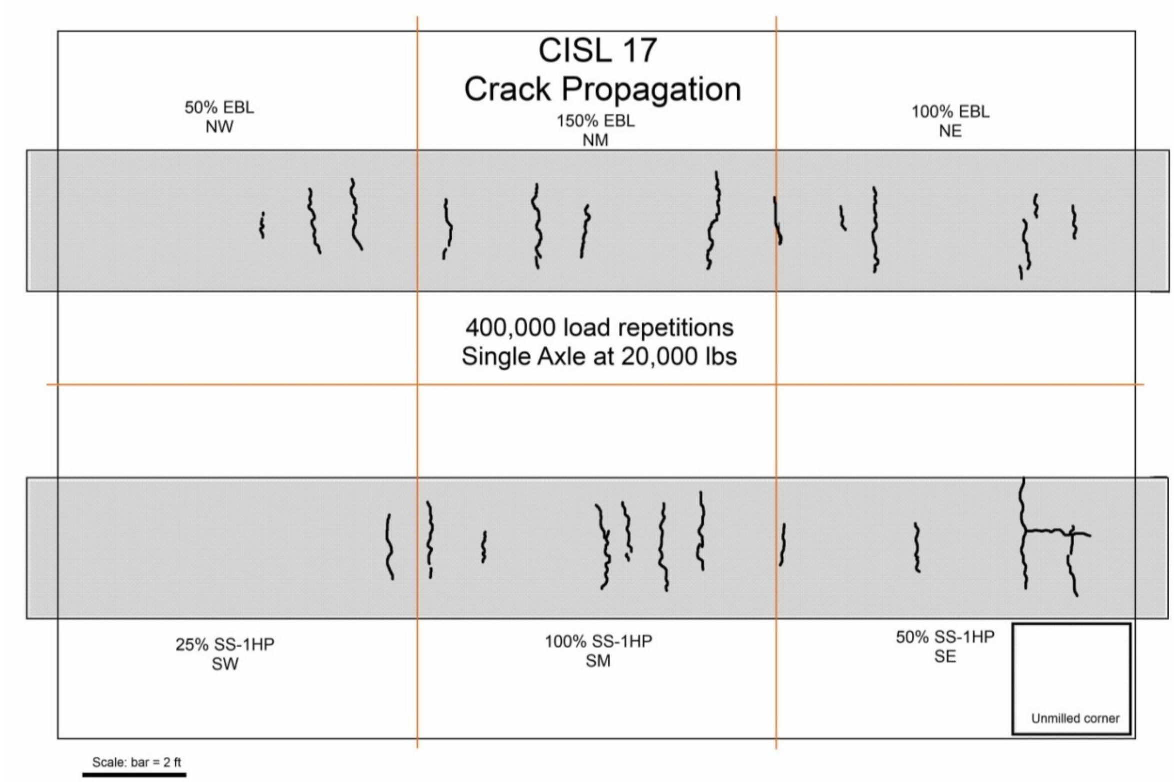

Figure 5.29: Cracks at 400,000 Load Repetitions

The cracking first appeared on the south lane (SS-1HP side), but soon was apparent on all test sections. The section with the least amount of tack materials, SW, had the fewest number of cracks. This goes against what is expected, since the bond strength was so low. The entire north lane, which maintained satisfactory bond strength, also showed cracks, indicating that there are other factors causing cracking besides the tack quality and quantity.

Chapter 6: Reconstruction of CISL#17 Experiment

6.1 Reconstruction of the Test Sections

6.1.1 Test Section Layout and Construction

In this part of the experiment, the existing HMA was milled off to remove the overlay placed for the previous CISL#17 experiment (Mealiff, 2014). The surface was then thoroughly brushed with a power broom, and then further cleaned with compressed air. The pit was divided into four test sections each with selected rates of SS-1HP as shown in Figure 6.1. The four tack rates used represent 50%, 100%, 160%, and 240% of the current KDOT-recommended rate of 0.05 gal/yd^2 (0.23 lpm^2). The 50% rate mimics the loss of tack materials due to pick up by HMA delivery trucks after spraying tack at 0.05 gal/yd^2 (0.23 lpm^2). The heavier tack rate of 160% would simulate a situation where even after pick up of tacks by the construction traffic, the tack rate would be close to 100% (0.05 gal/yd^2). The heaviest tack rate of 240% represents application of SS-1HP tack at a rate comparable to EBL tested earlier in the first APT bond experiment. Each test section was 7 ft. (2.13 m) wide and 10 ft. (3.05 m) long. SS-1HP tack material was applied using a hand-pumped pressure sprayer. Spray rate was verified by measuring the weight of tack used with even coverage. Figure 6.2 shows the tack application process.

6.1.2 Instrumentation

Twelve H-Bar strain gauges from Tokyo Sokki Kenkyujo Co., Ltd., were placed to measure strain at the interface between the existing asphalt pavement and the HMA overlay layer. Details of these gages have been discussed in Section 4.2. The stock lead wires were replaced with high-quality shielded wiring that can withstand heat of HMA better. The soldered connection at the base of the strain gauge was also covered by heat shielding. Each strain gauge was epoxied to two notched aluminum bars, and the gauge and bars were attached to the milled surface using metal staples. Two strain gages were installed per section, as illustrated in Figure 6.3. The gauges were covered with loose HMA mix and hand-compacted in order to protect them from the paver.

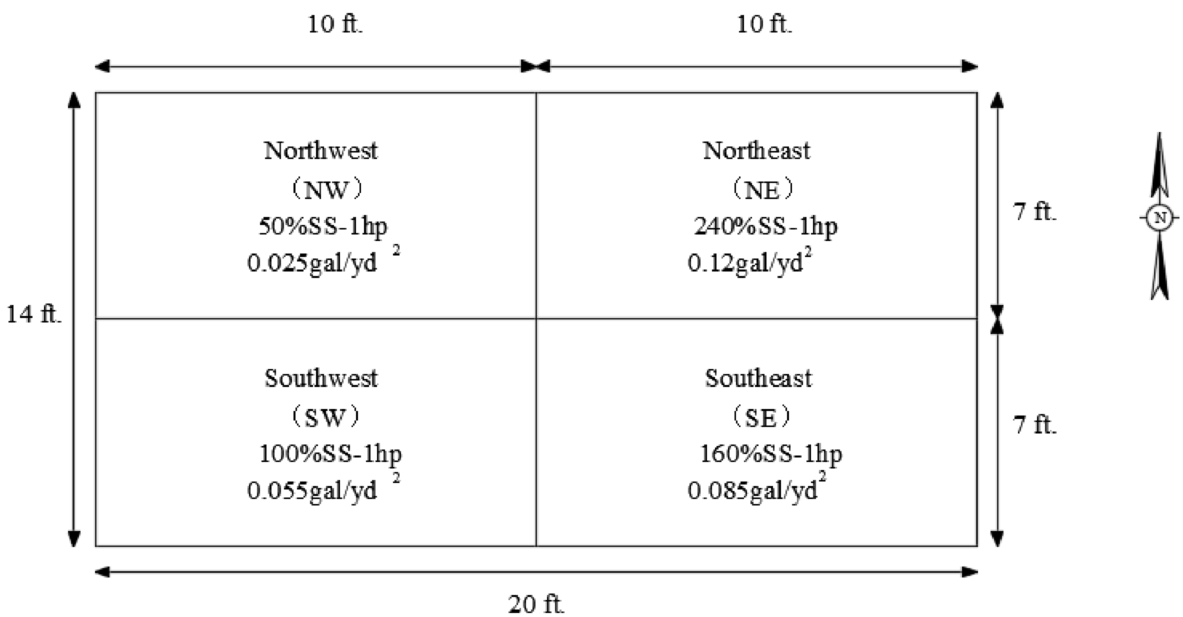

Figure 6.1: SS-1HP Tack Coat Test Section Layout

Figure 6.2: SS-1HP Tack Coat Application

Figure 6.3: Installed Strain Gauges

6.1.3 Construction

The overlay test sections were paved with a 12.5-mm NMAS Superpave mixture containing 25% Recycled Asphalt Pavement (RAP; SR-12.5A) and PG 58-28 binder. The mixture is similar to the one used in the previous experiment and was placed in a 2-inch (50-mm) nominal thickness lift. The mat was compacted with a steel-drum vibratory roller in order to reach the targeted 7% in-situ air voids. A nuclear density gauge was used to check the density of the mat after rolling.

6.2 APT Testing

The test was conducted at room temperature and dry condition. Because the pavements were constructed in pits and the asphalt concrete surface layer was paved wall-to-wall, the moisture content in the subgrade soil remained relatively constant during APT. This was confirmed by the Time Domain Reflectometry (TDR) gauges installed in the tested pavement structure subgrade that indicated no change in volumetric moisture content in the previous experiment (Romanoschi, Lewis, Gedafa, & Hossain, 2014).

APT load was applied bi-directionally. Transverse profiles were taken intermittently using a digital Linear Variable Differential Transformer (LVDT) with a roller attachment at the end that could be mounted on a leveled beam, as illustrated in Figure 4.8. Two transverse profiles were taken for each test section with respect to the benchmarks that were epoxied to the concrete floor to ensure a consistent location unaffected by loading. Elevation at every 0.5 in. (12.5 mm) was measured across the entire section. The APT was run at 20 kip (89 kN) loading in increasing increments with periodic strain measurements. The sections were also inspected at fixed intervals for any signs of cracking. A total of 1.5 million repetitions of APT load were applied.

6.3 Results and Analysis

6.3.1 Rut Depth and Permanent Deformation

Permanent deformation, the difference between identical elevation points at different times (or load repetitions), is illustrated in Figure 6.4. The largest difference between these identical elevation points was the reported value of rut depth, which was taken because of the lack of noticeable heaving on the sections. Figure 6.5 shows the rut depth progression on the test sections with loading. The SS-1HP sections with 50% and 100% of tack rate as required by KDOT (0.05 gal/yd^2 or 0.23 lpm^2) experienced the most deformation over time up to 800,000 repetitions. The sections with 100% and 160% tack rate (0.05 and 0.08 gal/yd^2, or 0.23 and 0.36 lpm^2) performed similarly with respect to rutting after 1.5 million repetitions. The section with 240% tack rate (0.12 gal/yd^2 or 0.54 lpm^2) performed better in rutting.

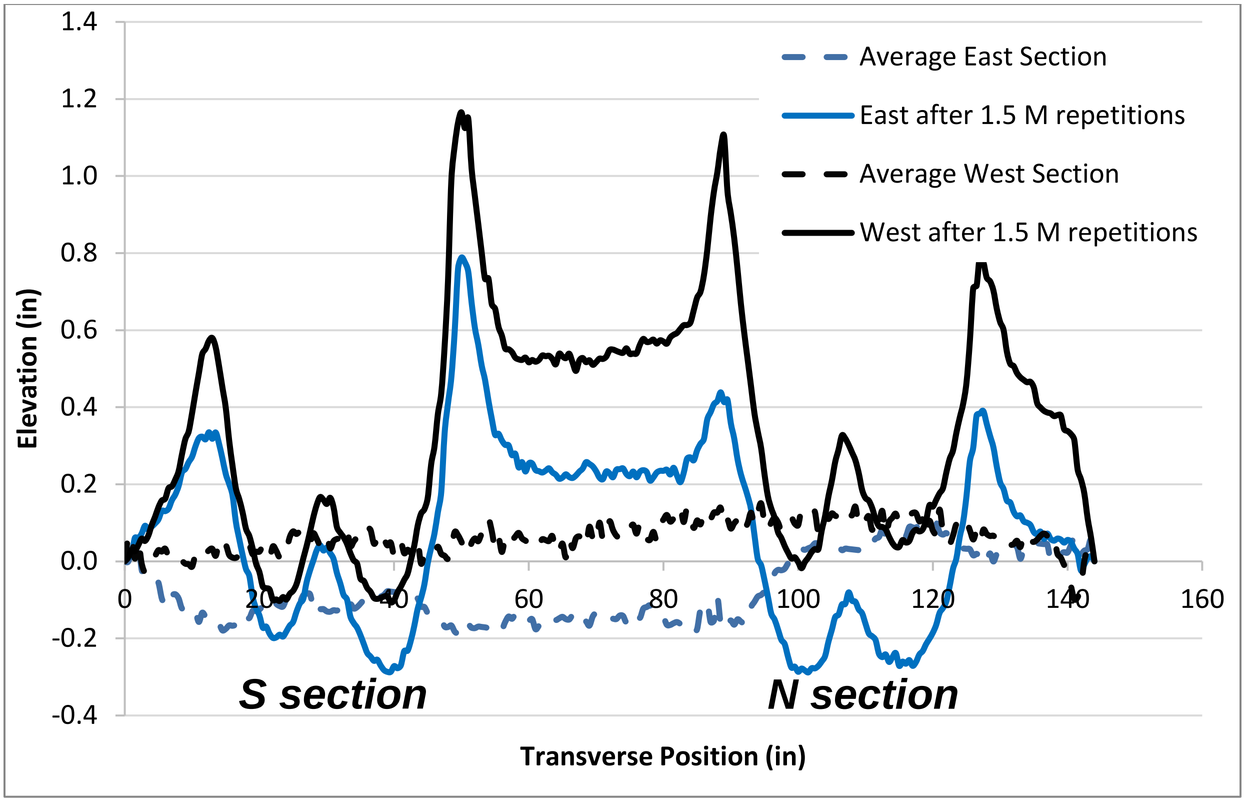

Figure 6.4: Original and Permanently Deformed Profiles after 1.5 Million Repetitions

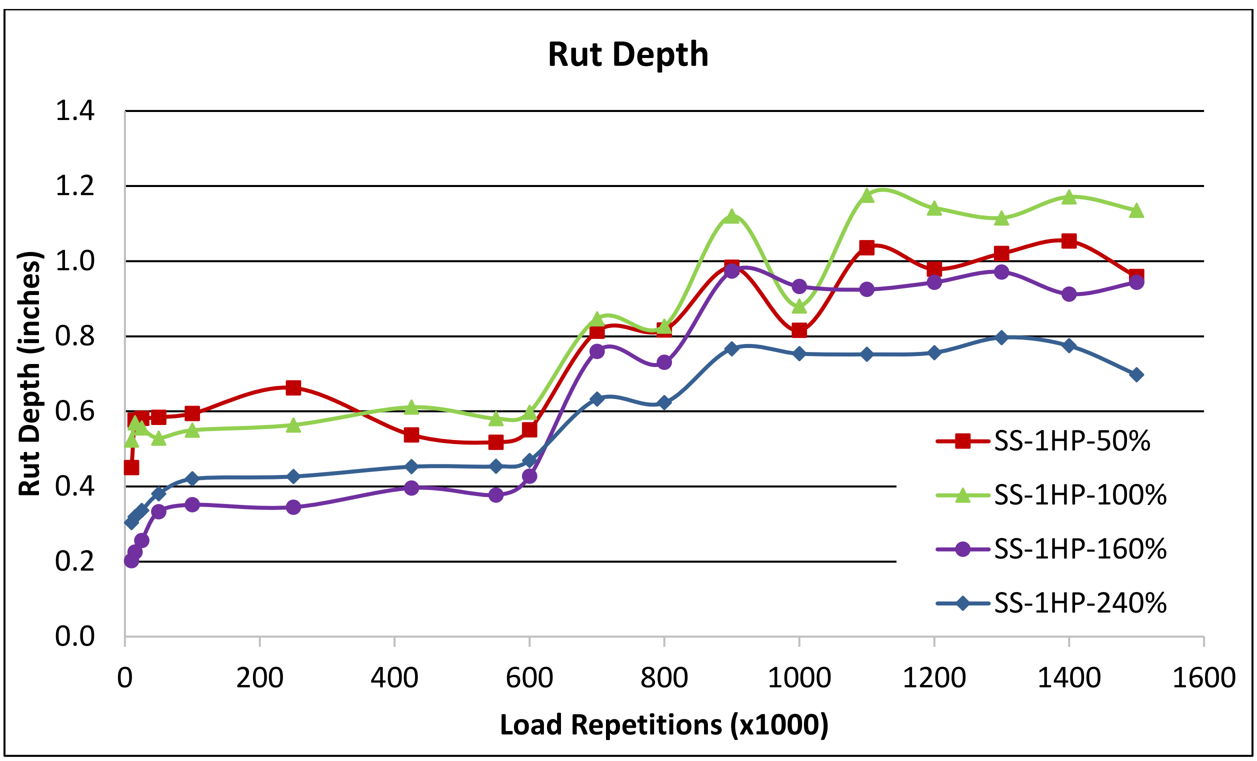

Figure 6.5: SS-1HP Rut Depth (Highest Minus Lowest Point)

6.3.2 Resilient Strain

In this study, although 12 gauges were installed (two per section), only eight gauges were operational after construction, potentially due to soldering issues and stress from the construction equipment. No gauges on the section with 240% tack rate survived, probably due to the heavy tack application shorting those gauges. Strain outputs from the remaining gauges are shown in Figure 6.6. As mentioned in the Section 5.2.2, the results shown here are the median strain values for a 90-second interval aligned with the baseline for that unit of time. This strain was measured for an entire wander cycle, or 676 load repetitions. The top 50 strains for a wander cycle were averaged and plotted, as tabulated in Table 6.1 and illustrated in Figure 6.6.

The results clearly demonstrated that the section with the KDOT-specified tack rate (0.05 gal/yd^2 of SS-1HP) showed lowest strain after 1.5 million APT load repetitions. The section with 160% tack rate showed a large increase in strain after loading began and another jump in strain after 400,000 repetitions, likely due to slippage. A large increase in strain after 400,000 repetitions was also observed for the section with 50% tack rate. Although the section with 100% SS-1HP showed one sudden spike at 700,000 and gradual increases between 900,000 and 1.3 million repetitions, the strain readings returned to a low stable value after that.

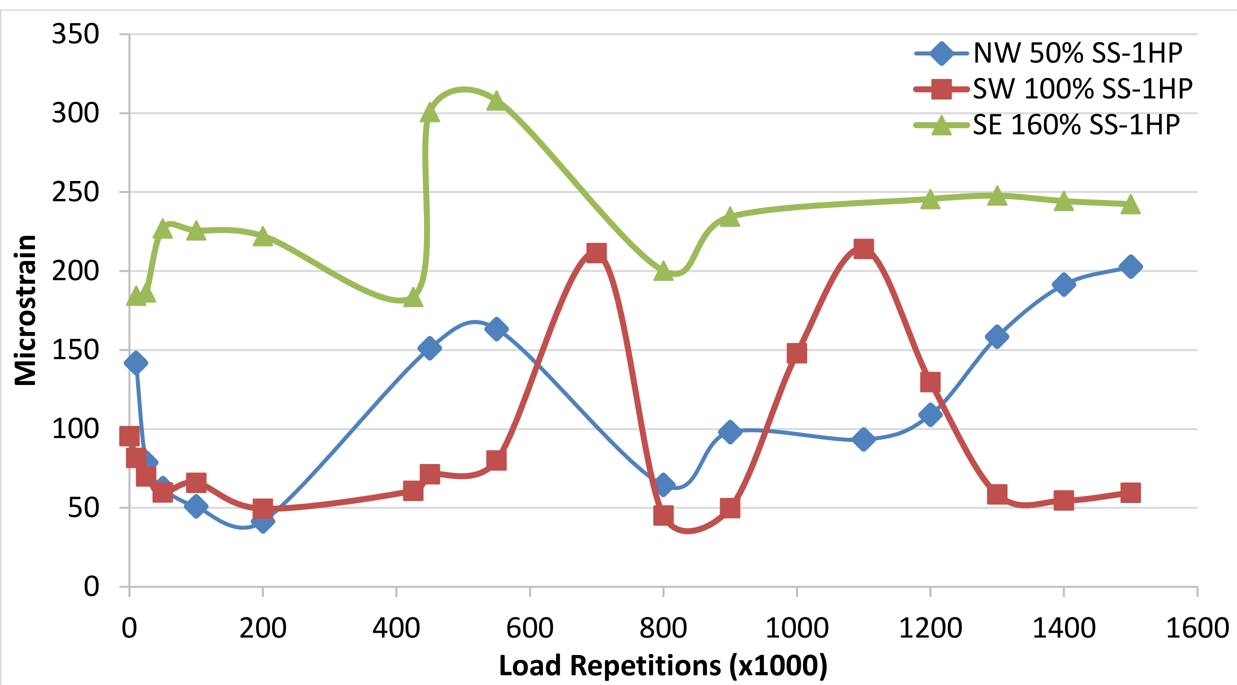

Figure 6.6: Strain During Loading

Table 6.1: Microstrain Values During Loading

Load Repetitions (x 1,000)	NW (50% SS-1HP)	SW (100% SS-1HP)	SE (160% SS-1HP)	NE (240 % SS-1HP)
0	*	96	50	No strain gauges survived
10	142	82	184	
25	79	70	187	
50	63	60	227	
100	51	66	226	
200	41	49	222	
425	*	61	184	
450	151	71	301	
550	163	80	308	
700	*	211	*	
800	64	45	200	
900	98	50	234	
1000	*	148	*	
1100	93	214	*	
1200	109	130	246	
1300	158	58	248	
1400	191	55	244	
1500	203	60	242	

6.4 Field and Laboratory Pull-Off Tests

6.4.1 Field Pull-Off Test

After 1.5 million repetitions, several 2-inch (50-mm) diameter cores were drilled to just below the interface layer. These were tested in-situ using a portable, battery-powered ComTen pull-off tester that is used by KDOT for field testing following the KT-78 test procedure. Aluminum pucks were epoxied to the 2-inch (50-mm) diameter cores and pulled in direct tension at 0.8 in./min (20 mm/min) as specified in KT-78. The test setup is the same as that shown in Figure 5.24. Table 6.2 shows the average bond strength results and Figure 6.7 illustrates the results. The KDOT-specified 100% SS-1HP tack rate (0.05 gal/yd^2 or 0.23 lpm^2) shows the highest bond strength closely followed by 50% of this rate whereas the section with 240% tack rate (0.12 gal/yd^2 or 0.54 lpm^2) shows the lowest bond strength.

Table 6.2: In-Situ Bond Strength of CISL SS-1HP Sections after 1.5 million Repetitions

Section	NW	SW	SE	NE
SS-1HP	**50%**	**100%**	**160%**	**240%**
Peak Stress (psi)	154.16	159.69	137.73	118.43
Peak Stress (kPa)	1062.90	1101.02	949.61	816.55

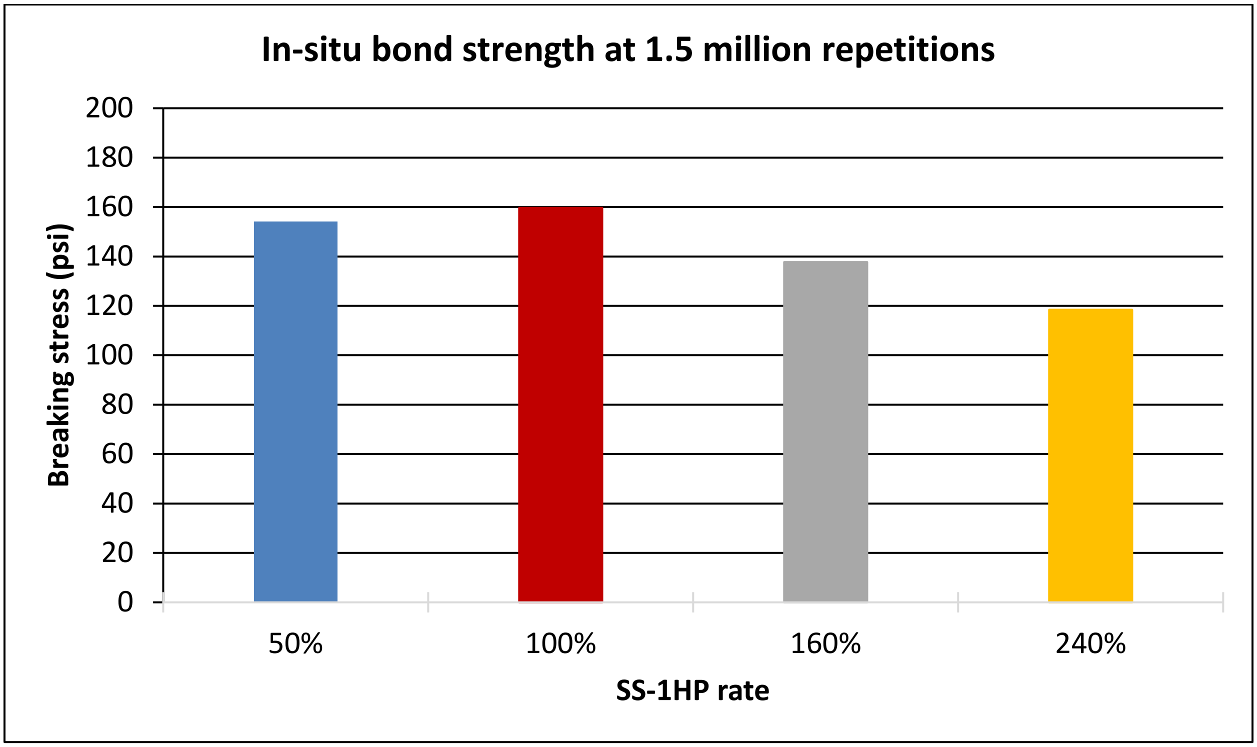

Figure 6.7: In-Situ Bond Strength of CISL SS-1HP Test Sections

6.4.2 Laboratory Pull-Off Tests

After 1.5 million repetitions, one 6-inch (150-mm) diameter core was extracted from the outer edge of each section and tested in the same way as described in the laboratory study section for field cores: taking three cores of 2-inch (50-mm) diameter, epoxying them to the metal plates, and testing in uniaxial tension in the UTM-25 machine. Table 6.3 shows the average laboratory bond strength and bond energy results and Figure 6.8 illustrates these results. The KDOT-specified 100% SS-1HP tack rate (0.05 gal/yd^2 or 0.23 lpm^2) shows the highest bond strength as well as bond energy closely followed by 50% of this rate. The section with 240% (0.12 gal/yd^2 or 0.54 lpm^2) tack rate shows the lowest bond strength and the section with 160% (0.08 gal/yd^2 or 0.36 lpm^2) tack rate shows the lowest bond energy.

6.5 Cracking

No cracking was found on the sections of this second experiment to date (after 1.5 million load repetitions). It is to be noted that SS-1HP was also tested earlier at 50% and 100% rates in the first experiment and started to show signs of cracking after only 200,000 repetitions. This was not the case in the second experiment. The difference between these two experiments had been the surface preparation; the test sections in the second experiment have been cleaned thoroughly after milling. Thus, cleanliness of the milled surface appears to be a big contributor to the interface bonding.

Table 6.3: Laboratory Bond Strength of CISL SS-1HP Sections after 1.5 Repetitions

Section	NW	SW	SE	NE
SS-1HP	**50%**	**100%**	**160%**	**240%**
Bond Strength (kPa)	1184.50	1331.05	999.58	946.10
Bond Strength (psi)	171.80	193.05	144.98	137.22
Energy (J)	1.64	1.95	0.91	0.93
Bond Energy (J/m^2)	831.57	991.19	462.71	640.36

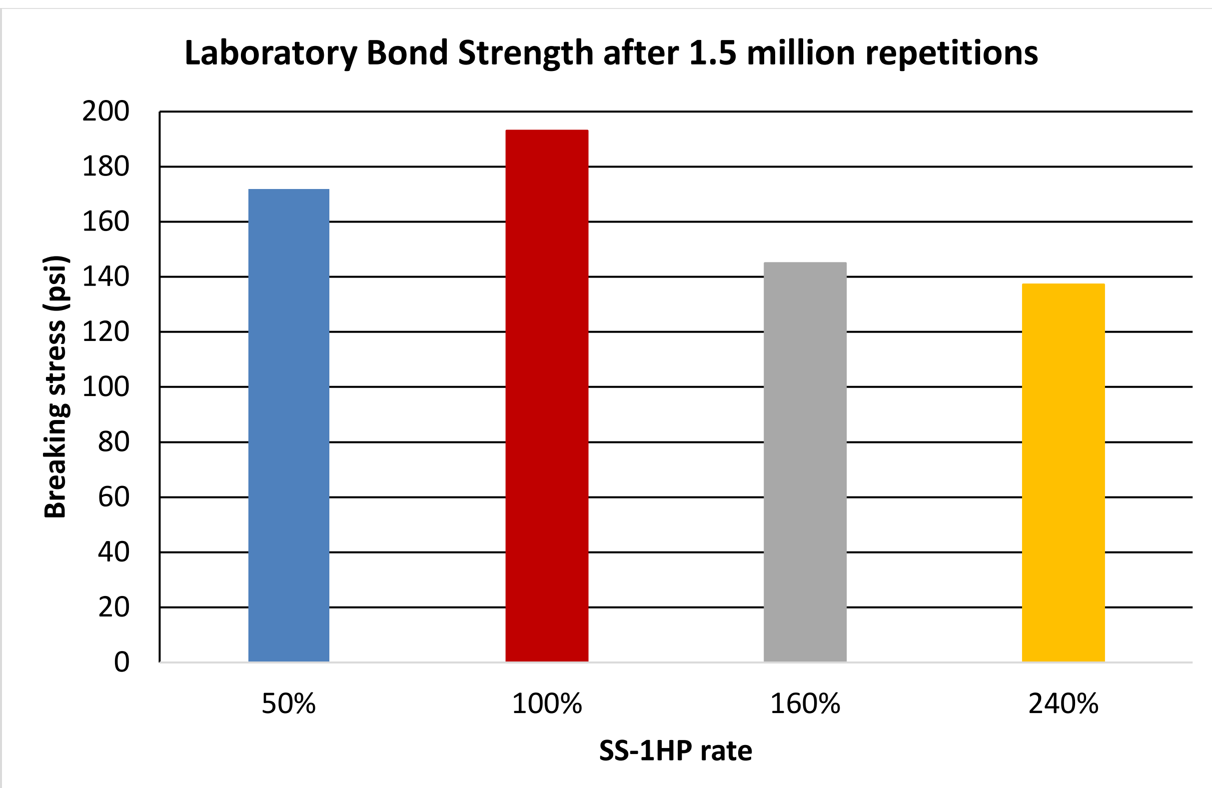

Figure 6.8: Bond Strength of CISL Section after 1.5 Repetitions (UTM-25)

Chapter 7: Conclusions and Recommendations

7.1 Summary and Conclusions

Cores were taken from several Kansas highways and used to test varying application rates of SS-1HP and EBL tack coats, as well as limited amounts of Trackless tack. An HMA layer was compacted on top of the cores using an SGC, and 2-inch (50-mm) diameter cores were tested in direct tension at two days. SS-1HP samples showed that bonds with milled surfaces are stronger than on the non-milled cores, but did not reveal tack rates to be statistically significant. EBL showed that on non-milled surfaces, less tack results in stronger bond, but on milled surfaces, the recommended 0.14 gal/yd^2 (0.634 lpm^2) yields the highest strength. Trackless tack showed no significant difference between the surface textures. Bond energy was calculated for comparison to other studies, but had no different conclusions than those derived from the peak breaking stress when analyzed statistically.

A full-scale test with accelerated pavement testing showed a minimal amount of rut formation, though initial overcompaction might have prevented this. Strain gages failed often, but showed the SS-1HP section of 0.05 gal/yd^2 (0.23 lpm^2) to have much higher strain than those in the EBL sections. Small cracks formed on all test sections, seemingly unrelated to the quality of tack. No visible signs of debonding occurred until coring and milling later, wherein all three SS-1HP sections preformed terribly. EBL did well in all aspects, though it was not applied in a spray paver as in the industry.

Further APT testing with variable application rates of SS-1HP indicated that the KDOT-recommended rate of 0.05 gal/yd^2 (0.23 lpm^2) showed good performance as a tack coat material based on the in-situ strain, in-situ bond strength, laboratory bond strength, and bond energy. Strain at the overlay interface and the existing HMA pavement was lowest for this rate. Comparison of performance of the SS-1HP test sections in the two experiments indicates that the cleanliness of the milled surface is a big contributor to interface bonding.

Although EBL showed good performance as a tack coat material as far as rutting is concerned in a previous APT experiment, similar results could be obtained by increasing the amount of SS-1HP. However, such high rate tends to decrease the interface bond strength as evaluated in-situ as well as in the laboratory.

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Appendix A: Pull-Off Data

Table A.1: Two Day EBL Data

ID	Stress (kPa)	Energy (J)	J/m2	tack	texture	Gal/yd^2	Wheel path	Block
C2#1	779.7	0.60	300	EBL	no-mill	0.07	inner	1
C2#2	819.7	0.55	276	EBL	no-mill	0.07	inner	1
C2#3	879.9	0.69	348	EBL	no-mill	0.07	inner	1
C5#1	420.9	0.29	144	EBL	no-mill	0.14	inner	1
C5#2	658.6	0.36	180	EBL	no-mill	0.14	inner	1
C5#3	645.6	0.45	224	EBL	no-mill	0.14	inner	1
C8#1	555.8	0.31	156	EBL	no-mill	0.21	inner	1
C8#2	620.5	0.37	184	EBL	no-mill	0.21	inner	1
C8#3	593.5	0.34	172	EBL	no-mill	0.21	inner	1
C11#1	1010.2	0.81	404	EBL	no-mill	0.07	outer	2
C11#2	973.2	0.69	344	EBL	no-mill	0.07	outer	2
C11#3	943.1	0.67	336	EBL	no-mill	0.07	outer	2
C14#1	1045.6	0.74	368	EBL	no-mill	0.14	outer	2
C14#2	1040.3	0.72	360	EBL	no-mill	0.14	outer	2
C14#3	1028.8	0.77	388	EBL	no-mill	0.14	outer	2
C17#1	696.3	0.45	224	EBL	no-mill	0.21	outer	2
C17#2	769.8	0.45	224	EBL	no-mill	0.21	outer	2
C17#3	751.9	0.52	260	EBL	no-mill	0.21	outer	2
A11#1	627.7	0.36	180	EBL	milled	0.07	inner	3
A11#2	644.9	0.41	204	EBL	milled	0.07	inner	3
A11#3	601.1	0.38	188	EBL	milled	0.07	inner	3
A14#1	891.3	0.64	320	EBL	milled	0.14	inner	3
A14#2	912.3	0.72	360	EBL	milled	0.14	inner	3
A14#3	847.9	0.60	300	EBL	milled	0.14	inner	3
A17#1	839.1	0.57	284	EBL	milled	0.21	inner	3
A17#2	726.4	0.43	212	EBL	milled	0.21	inner	3
A17#3	793.1	0.57	284	EBL	milled	0.21	inner	3
11B#1	902.4	0.56	280	EBL	milled	0.07	outer	4
11B#2	823.9	0.50	252	EBL	milled	0.07	outer	4
11B#3	843.7	0.52	260	EBL	milled	0.07	outer	4
14B#1	1040.7	0.83	412	EBL	milled	0.14	outer	4
14B#2	1030.0	0.73	368	EBL	milled	0.14	outer	4
14B#3	863.9	0.53	264	EBL	milled	0.14	outer	4
17B#1	976.7	0.66	328	EBL	milled	0.21	outer	4
17B#2	1343.9	1.61	804	EBL	milled	0.21	outer	4
17B#3	882.2	0.56	280	EBL	milled	0.21	outer	4

Table A.2: SS-1HP Pull-Off Data

ID	Stress (kPa)	Energy (J)	J/m2	tack	texture	Gal/yd^2	Wheel path	Block
9A#1	578.6	0.30	148	SS-1HP	milled	0.0125	inner	5
9A#2	741.6	0.47	236	SS-1HP	milled	0.0125	inner	5
9A#3	670.8	0.37	184	SS-1HP	milled	0.0125	inner	5
15A#1	844.5	0.66	332	SS-1HP	milled	0.025	inner	5
15A#2	913.8	0.61	304	SS-1HP	milled	0.025	inner	5
15A#3	1082.9	0.94	472	SS-1HP	milled	0.025	inner	5
18A#1	919.9	0.60	300	SS-1HP	milled	0.05	inner	5
18A#2	889.0	0.65	324	SS-1HP	milled	0.05	inner	5
18A#3	939.7	0.78	388	SS-1HP	milled	0.05	inner	5
12B#1	1369.8	1.14	572	SS-1HP	milled	0.0125	outer	6
12B#2	1280.6	0.93	464	SS-1HP	milled	0.0125	outer	6
12B#3	1519.5	1.22	608	SS-1HP	milled	0.0125	outer	6
15B#1	1456.2	1.13	564	SS-1HP	milled	0.025	outer	6
15B#2	1193.0	1.08	540	SS-1HP	milled	0.025	outer	6
15B#3	971.3	0.67	332	SS-1HP	milled	0.025	outer	6
18B#1	1186.5	0.86	428	SS-1HP	milled	0.05	outer	6
18B#2	1036.1	0.69	344	SS-1HP	milled	0.05	outer	6
18B#3	981.6	0.68	340	SS-1HP	milled	0.05	outer	6
C9#1	539.752	0.21	108	SS-1HP	no-mill	0.0125	inner	7
C9#2	625.457	0.26	128	SS-1HP	no-mill	0.0125	inner	7
C9#3	458.237	0.18	88	SS-1HP	no-mill	0.0125	inner	7
C15#1	1005.606	0.62	308	SS-1HP	no-mill	0.05	outer	7
C15#2	794.962	0.47	236	SS-1HP	no-mill	0.05	outer	7
C15#3	847.909	0.46	232	SS-1HP	no-mill	0.05	outer	7
C18#1	922.949	0.56	280	SS-1HP	no-mill	0.025	outer	7
C18#2	982.371	0.65	324	SS-1HP	no-mill	0.025	outer	7
C18#3	692.116	0.47	232	SS-1HP	no-mill	0.025	outer	7
W12#1	706.972	0.33	164	SS-1HP	no-mill	0.0125	inner	8
W12#2	549.3	0.17	88	SS-1HP	no-mill	0.0125	inner	8
W12#3	309.3	0.08	40	SS-1HP	no-mill	0.0125	inner	8
W15#1	696.687	0.33	164	SS-1HP	no-mill	0.025	inner	8
W15#2	709.3	0.40	200	SS-1HP	no-mill	0.025	inner	8
W15#3	587.366	0.24	120	SS-1HP	no-mill	0.025	inner	8
W18#1	817.436	0.43	212	SS-1HP	no-mill	0.05	inner	8
W18#2	822.769	0.51	252	SS-1HP	no-mill	0.05	inner	8

Table A.3: Trackless Pull-Off Data

ID	Stress (kPa)	Energy (J)	J/m2	tack	texture	Gal/yd^2	Wheel path	Block
3A#1	705.829	0.34	172	Trackless	milled	0.08	inner	9
3A#2	966.372	0.55	276	Trackless	milled	0.08	inner	9
3A#3	528.324	0.23	112	Trackless	milled	0.08	inner	9
6A#1	537.085	0.25	124	Trackless	milled	0.08	inner	9
6A#2	820.864	0.45	224	Trackless	milled	0.08	inner	9
6A#3	728.303	0.37	188	Trackless	milled	0.08	inner	9
3B#1								
3B#2	1764.763	1.74	872	Trackless	milled	0.08	outer	10
3B#3	1733.528	1.60	800	Trackless	milled	0.08	outer	10
6B#1	911.902	0.57	284	Trackless	milled	0.08	outer	10
6B#2	962.182	0.49	244	Trackless	milled	0.08	outer	10
6B#3	935.138	0.49	244	Trackless	milled	0.08	outer	10
C3#1	508.517	0.21	104	Trackless	no-mill	0.08	inner	11
C3#2	835.339	0.43	216	Trackless	no-mill	0.08	inner	11
C3#3	926.377	0.54	268	Trackless	no-mill	0.08	inner	11
C6#1	810.961	0.41	204	Trackless	no-mill	0.08	inner	11
C6#2	734.778	0.32	160	Trackless	no-mill	0.08	inner	11
C6#3	444.524	0.13	64	Trackless	no-mill	0.08	inner	11
W3#4	896.285	0.63	316	Trackless	no-mill	0.08	outer	12
W3#5	689.45	0.36	180	Trackless	no-mill	0.08	outer	12
W3#6	697.068	0.43	216	Trackless	no-mill	0.08	outer	12
W6#4	872.668	0.55	276	Trackless	no-mill	0.08	outer	12
W6#5	871.525	0.61	304	Trackless	no-mill	0.08	outer	12
W6#6	721.065	0.43	212	Trackless	no-mill	0.08	outer	12

Table A.4: SS-1HP Pull-Off Data

ID	Stress (kPa)	Energy (J)	J/m^2	tack	texture	Gal/yd^2	Wheel path	Block
17A#1	910.05	1.07	543	SS-1HP	milled	0.025	outer	A
17A#2	1479.04	2.52	1283	SS-1HP	milled	0.025	outer	A
17A#3	1164.30	1.32	669	SS-1HP	milled	0.025	outer	A
17B#1	859.95	0.88	447	SS-1HP	milled	0.055	outer	B
17B#2	1458.68	2.18	1105	SS-1HP	milled	0.055	outer	B
17B#3	1674.53	2.80	1422	SS-1HP	milled	0.055	outer	B
17C#1	1018.65	1.02	519	SS-1HP	milled	0.085	outer	C
17C#2	1055.92	0.97	493	SS-1HP	milled	0.085	outer	C
17C#3	924.18	0.74	376	SS-1HP	milled	0.085	outer	C
17D#1	828.22	0.81	409	SS-1HP	milled	0.12	outer	D
17D#2	910.29	0.68	344	SS-1HP	milled	0.12	outer	D
17D#3	1099.78	1.42	717	SS-1HP	milled	0.12	outer	D

Appendix B: Permanent Deformation and Rut Depth after 1.5 Million Repetitions

Table B.1: Rut Measurements (SS-1HP 50%)

North Esat Pit 3	SS-1HP-50%																		
Repetutions (x1000)	Initial	10	15	25	50	100	250	425	550	600	700	800	900	1000	1100	1200	1300	1400	1500
Large N Lane																			
1	0.752	0.056	0.067	0.034	0.110	0.017	0.037	0.056	0.005	0.065	0.021	0.045	0.030	0.000	0.000	0.000	0.000	0.000	0.022
2	0.743	0.011	0.032	0.033	0.066	0.015	0.033	0.000	0.000	0.000	0.011	0.017	0.013	-0.043	-0.002	-0.114	-0.051	-0.073	0.000
3	0.730	0.000	0.007	0.028	0.059	0.000	0.022	-0.030	-0.010	-0.064	0.000	0.000	0.000	-0.120	-0.194	-0.215	-0.059	-0.134	-0.006
4	0.716	-0.016	0.000	0.026	0.019	-0.006	0.018	-0.052	-0.031	-0.136	-0.101	-0.022	-0.061	-0.130	-0.200	-0.219	-0.197	-0.138	-0.122
5	0.715	-0.120	-0.010	0.025	0.005	-0.016	0.003	-0.052	-0.052	-0.204	-0.156	-0.185	-0.135	-0.136	-0.205	-0.220	-0.199	-0.144	-0.130
6	0.714	-0.148	-0.020	0.023	0.000	-0.016	0.000	-0.195	-0.185	-0.262	-0.256	-0.206	-0.183	-0.151	-0.215	-0.223	-0.200	-0.148	-0.148
7	0.713	-0.284	-0.031	0.016	-0.102	-0.020	-0.021	-0.258	-0.270	-0.326	-0.269	-0.223	-0.187	-0.157	-0.220	-0.224	-0.203	-0.152	-0.151
8	0.712	-0.354	-0.069	0.000	-0.155	-0.093	-0.034	-0.334	-0.334	-0.335	-0.271	-0.227	-0.189	-0.159	-0.226	-0.228	-0.204	-0.153	-0.155
9	0.712	-0.392	-0.137	-0.034	-0.230	-0.231	-0.119	-0.341	-0.360	-0.341	-0.282	-0.234	-0.204	-0.165	-0.228	-0.229	-0.210	-0.157	-0.158
10	0.709	-0.443	-0.230	-0.042	-0.293	-0.332	-0.210	-0.348	-0.363	-0.351	-0.283	-0.238	-0.207	-0.169	-0.229	-0.231	-0.215	-0.157	-0.164
Small N Lane																			
1	-0.005	-0.747	-0.765	-0.776	-0.781	-0.790	-0.814	-0.811	-0.718	-0.815	-1.011	-1.005	-1.116	-1.179	-1.195	-1.169	-1.166	-1.183	-1.101
2	0.000	-0.728	-0.755	-0.770	-0.748	-0.754	-0.800	-0.803	-0.715	-0.805	-0.971	-0.977	-1.114	-1.150	-1.192	-1.162	-1.153	-1.161	-1.093
3	0.015	-0.722	-0.751	-0.763	-0.730	-0.735	-0.796	-0.776	-0.708	-0.793	-0.960	-0.975	-1.096	-1.138	-1.189	-1.160	-1.144	-1.154	-1.093
4	0.020	-0.718	-0.748	-0.759	-0.720	-0.731	-0.782	-0.776	-0.707	-0.789	-0.949	-0.959	-1.081	-1.131	-1.188	-1.132	-1.138	-1.144	-1.032
5	0.068	-0.715	-0.746	-0.758	-0.717	-0.719	-0.768	-0.771	-0.703	-0.769	-0.945	-0.957	-1.071	-1.129	-1.185	-1.115	-1.132	-1.143	-0.984
6	0.123	-0.714	-0.742	-0.750	-0.716	-0.718	-0.758	-0.758	-0.700	-0.753	-0.928	-0.950	-1.068	-1.101	-1.182	-1.085	-1.130	-1.121	-0.980
7	0.185	-0.714	-0.739	-0.746	-0.713	-0.714	-0.756	-0.745	-0.691	-0.751	-0.917	-0.949	-1.065	-1.098	-1.176	-1.078	-1.128	-1.110	-0.961
8	0.240	-0.708	-0.732	-0.744	-0.704	-0.696	-0.728	-0.721	-0.685	-0.740	-0.908	-0.947	-1.047	-1.092	-1.122	-1.051	-1.095	-1.101	-0.941
9	0.370	-0.704	-0.731	-0.739	-0.689	-0.693	-0.724	-0.715	-0.684	-0.736	-0.902	-0.937	-1.014	-1.091	-1.093	-1.039	-1.041	-1.049	-0.912
10	0.404	-0.702	-0.729	-0.731	-0.687	-0.682	-0.719	-0.710	-0.680	-0.734	-0.899	-0.910	-0.985	-1.018	-1.041	-1.013	-1.016	-1.029	-0.895
Rut Depth	**0.580**	**0.548**	**0.705**	**0.764**	**0.668**	**0.655**	**0.737**	**0.603**	**0.539**	**0.573**	**0.780**	**0.829**	**0.953**	**0.990**	**0.984**	**0.910**	**0.961**	**0.994**	**0.898**
North West Pit 4 Large S Lane																			
1	0.040	0.000	0.053	0.008	0.001	0.035	0.089	0.000	0.000	0.001	0.107	0.010	0.000	0.000	0.087	0.081	0.265	0.109	0.165
2	0.009	-0.012	0.047	0.001	0.000	0.028	0.042	-0.105	-0.001	0.000	0.069	0.005	-0.005	-0.037	0.082	0.066	0.263	0.095	0.159
3	0.000	-0.043	0.035	0.000	-0.001	0.000	0.031	-0.122	-0.035	-0.117	0.045	0.003	-0.005	-0.108	0.082	0.061	0.257	0.093	0.154
4	-0.016	-0.068	0.030	-0.023	-0.019	-0.031	0.025	-0.127	-0.194	-0.239	0.044	0.000	-0.010	-0.109	0.073	0.050	0.256	0.078	0.149
5	-0.200	-0.224	0.000	-0.130	-0.021	-0.116	0.000	-0.128	-0.196	-0.239	0.041	-0.008	-0.014	-0.111	0.073	0.046	0.254	0.074	0.141
6	-0.310	-0.320	-0.089	-0.294	-0.064	-0.189	-0.186	-0.139	-0.200	-0.248	0.030	-0.013	-0.016	-0.112	0.069	0.035	0.252	0.071	0.137
7	-0.352	-0.350	-0.204	-0.296	-0.248	-0.195	-0.195	-0.141	-0.201	-0.252	0.030	-0.021	-0.021	-0.113	0.066	0.031	0.249	0.070	0.130
8	-0.365	-0.352	-0.258	-0.339	-0.276	-0.200	-0.200	-0.147	-0.203	-0.252	0.019	-0.025	-0.022	-0.115	0.057	0.030	0.244	0.060	0.128
9	-0.366	-0.375	-0.295	-0.339	-0.280	-0.200	-0.210	-0.147	-0.205	-0.255	0.000	-0.039	-0.024	-0.116	0.050	0.023	0.242	0.055	0.121
10	-0.378	-0.377	-0.320	-0.342	-0.283	-0.205	-0.212	-0.149	-0.206	-0.255	-0.001	-0.041	-0.028	-0.119	0.050	0.009	0.240	0.032	0.117
Small S Lane																			
1	-0.551	-0.657	-0.570	-0.578	-0.686	-0.682	-0.731	-0.649	-0.683	-0.754	-0.910	-0.885	-1.086	-0.789	-1.096	-1.114	-0.913	-1.133	-1.115
2	-0.544	-0.580	-0.553	-0.577	-0.641	-0.681	-0.719	-0.629	-0.675	-0.750	-0.901	-0.875	-1.086	-0.787	-1.093	-1.103	-0.909	-1.126	-1.053
3	-0.539	-0.569	-0.551	-0.577	-0.636	-0.674	-0.709	-0.621	-0.669	-0.748	-0.827	-0.875	-1.082	-0.778	-1.087	-1.090	-0.877	-1.109	-0.988
4	-0.534	-0.556	-0.549	-0.576	-0.627	-0.665	-0.705	-0.620	-0.661	-0.741	-0.809	-0.844	-1.075	-0.760	-1.079	-1.089	-0.876	-1.086	-0.941
5	-0.530	-0.553	-0.546	-0.576	-0.626	-0.656	-0.698	-0.589	-0.636	-0.731	-0.786	-0.823	-1.065	-0.757	-1.045	-1.052	-0.874	-1.073	-0.845
6	-0.529	-0.551	-0.545	-0.575	-0.612	-0.642	-0.656	-0.587	-0.632	-0.717	-0.778	-0.782	-1.028	-0.740	-1.041	-1.042	-0.863	-1.048	-0.821
7	-0.525	-0.548	-0.544	-0.573	-0.612	-0.625	-0.637	-0.560	-0.621	-0.686	-0.776	-0.781	-0.994	-0.721	-0.980	-0.958	-0.805	-1.010	-0.821
8	-0.521	-0.548	-0.543	-0.571	-0.588	-0.603	-0.615	-0.555	-0.613	-0.682	-0.772	-0.780	-0.993	-0.690	-0.957	-0.908	-0.774	-0.980	-0.745
9	-0.519	-0.547	-0.542	-0.567	-0.587	-0.595	-0.613	-0.553	-0.610	-0.670	-0.763	-0.777	-0.981	-0.685	-0.908	-0.849	-0.716	-0.918	-0.745
10	-0.519	-0.545	-0.540	-0.563	-0.581	-0.583	-0.608	-0.553	-0.608	-0.669	-0.759	-0.753	-0.904	-0.651	-0.901	-0.837	-0.673	-0.908	-0.721
Rut Depth	**0.337**	**0.353**	**0.448**	**0.398**	**0.500**	**0.533**	**0.587**	**0.471**	**0.497**	**0.529**	**0.847**	**0.805**	**1.015**	**0.642**	**1.088**	**1.047**	**1.080**	**1.113**	**1.020**
Average Rut Depth (50%)	**0.459**	**0.451**	**0.576**	**0.581**	**0.584**	**0.594**	**0.662**	**0.537**	**0.518**	**0.551**	**0.813**	**0.817**	**0.984**	**0.816**	**1.036**	**0.979**	**1.020**	**1.053**	**0.959**

Table B.2: Rut Measurements (SS-1HP 100%)

South East Pit 3	SS-1HP-100%																		
Repetutions (x1000)	Initial	10	15	25	50	100	250	425	550	600	700	800	900	1000	1100	1200	1300	1400	1500
Large S Lane																			
1	0.713	0.000	0.000	0.016	0.000	0.004	0.000	0.000	0.000	0.014	0.000	0.034	0.019	0.018	0.049	0.022	0.014	0.035	0.028
2	0.713	-0.024	-0.003	0.000	-0.013	0.000	-0.002	-0.015	-0.004	0.012	-0.008	0.015	0.000	0.011	0.035	0.016	0.014	0.028	0.028
3	0.712	-0.044	-0.023	0.000	-0.033	-0.018	-0.008	-0.018	-0.004	0.000	-0.014	0.004	-0.001	0.000	0.032	0.015	0.010	0.024	0.027
4	0.692	-0.061	-0.048	-0.021	-0.055	-0.030	-0.024	-0.024	-0.028	-0.020	-0.014	0.000	-0.003	-0.007	0.027	0.014	0.006	0.021	0.024
5	0.692	-0.068	-0.051	-0.055	-0.058	-0.048	-0.061	-0.038	-0.055	-0.043	-0.023	-0.004	-0.004	-0.008	0.015	0.012	0.005	0.012	0.018
6	0.684	-0.078	-0.051	-0.062	-0.067	-0.049	-0.061	-0.047	-0.060	-0.052	-0.026	-0.015	-0.004	-0.012	0.005	0.012	0.003	0.000	0.012
7	0.682	-0.083	-0.061	-0.066	-0.082	-0.051	-0.066	-0.064	-0.070	-0.055	-0.026	-0.015	-0.005	-0.026	0.000	0.010	0.001	0.000	0.010
8	0.679	-0.087	-0.077	-0.067	-0.091	-0.051	-0.068	-0.070	-0.074	-0.077	-0.027	-0.017	-0.006	-0.027	-0.010	0.007	0.000	-0.001	0.005
9	0.676	-0.091	-0.085	-0.075	-0.099	-0.055	-0.076	-0.070	-0.075	-0.083	-0.027	-0.021	-0.007	-0.029	-0.013	0.000	0.000	-0.006	0.005
10	0.672	-0.115	-0.092	-0.084	-0.115	-0.058	-0.092	-0.076	-0.078	-0.086	-0.032	-0.021	-0.016	-0.031	-0.018	0.000	-0.003	-0.016	0.004
Small S Lane																			
1	0.000	-0.685	-0.701	-0.703	-0.633	-0.624	-0.662	-0.694	-0.632	-0.697	-0.890	-0.901	-1.106	-1.164	-1.161	-1.103	-1.079	-1.131	-1.083
2	0.046	-0.682	-0.694	-0.697	-0.630	-0.621	-0.660	-0.687	-0.630	-0.679	-0.882	-0.888	-1.100	-1.134	-1.156	-1.103	-1.043	-1.098	-1.065
3	0.053	-0.681	-0.693	-0.695	-0.621	-0.618	-0.658	-0.686	-0.628	-0.678	-0.871	-0.881	-1.084	-1.126	-1.127	-1.080	-1.043	-1.095	-1.036
4	0.090	-0.670	-0.688	-0.690	-0.619	-0.613	-0.650	-0.679	-0.623	-0.675	-0.855	-0.860	-1.070	-1.104	-1.119	-1.067	-1.034	-1.073	-1.033
5	0.092	-0.659	-0.684	-0.687	-0.617	-0.602	-0.647	-0.668	-0.621	-0.664	-0.843	-0.830	-1.022	-1.075	-1.105	-1.045	-1.008	-1.061	-0.983
6	0.098	-0.650	-0.679	-0.683	-0.616	-0.601	-0.644	-0.668	-0.616	-0.658	-0.831	-0.803	-1.017	-1.062	-1.004	-1.000	-0.975	-0.989	-0.942
7	0.114	-0.647	-0.679	-0.682	-0.614	-0.601	-0.639	-0.660	-0.598	-0.652	-0.828	-0.784	-0.927	-0.966	-0.963	-0.964	-0.877	-0.941	-0.937
8	0.122	-0.646	-0.673	-0.678	-0.613	-0.600	-0.635	-0.658	-0.593	-0.649	-0.800	-0.759	-0.847	-0.910	-0.916	-0.900	-0.871	-0.905	-0.842
9	0.155	-0.646	-0.672	-0.677	-0.613	-0.596	-0.633	-0.654	-0.591	-0.648	-0.746	-0.747	-0.843	-0.830	-0.859	-0.831	-0.815	-0.853	-0.834
10	0.159	-0.645	-0.672	-0.670	-0.611	-0.594	-0.629	-0.654	-0.590	-0.643	-0.710	-0.714	-0.756	-0.822	-0.854	-0.810	-0.783	-0.818	-0.801
Rut Depth	**0.599**	**0.596**	**0.634**	**0.645**	**0.557**	**0.572**	**0.600**	**0.629**	**0.567**	**0.625**	**0.807**	**0.813**	**0.974**	**1.008**	**1.039**	**1.001**	**0.958**	**1.006**	**0.972**
South West Pit 4 Large S Lane																			
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.041	0.000	0.000	0.077	0.145	0.132	0.000	0.158	0.139	0.232	0.172	0.198
2	0.000	-0.021	-0.054	-0.008	-0.014	-0.028	-0.012	0.028	-0.012	-0.007	0.067	0.119	0.131	-0.014	0.158	0.129	0.230	0.169	0.194
3	-0.036	-0.059	-0.068	-0.042	-0.027	-0.049	-0.026	0.000	-0.044	-0.029	0.062	0.060	0.121	-0.014	0.152	0.119	0.228	0.164	0.192
4	-0.052	-0.061	-0.079	-0.049	-0.053	-0.049	-0.035	-0.004	-0.049	-0.073	0.061	0.057	0.119	-0.015	0.151	0.118	0.223	0.162	0.186
5	-0.055	-0.080	-0.080	-0.055	-0.074	-0.068	-0.041	-0.007	-0.065	-0.084	0.060	0.057	0.117	-0.016	0.140	0.118	0.223	0.161	0.185
6	-0.078	-0.084	-0.089	-0.067	-0.079	-0.088	-0.054	-0.022	-0.075	-0.090	0.058	0.044	0.110	-0.019	0.136	0.111	0.218	0.160	0.184
7	-0.085	-0.115	-0.095	-0.080	-0.097	-0.091	-0.064	-0.026	-0.076	-0.095	0.056	0.043	0.108	-0.019	0.135	0.110	0.215	0.157	0.182
8	-0.089	-0.125	-0.098	-0.090	-0.102	-0.098	-0.073	-0.035	-0.081	-0.125	0.052	0.036	0.105	-0.020	0.135	0.109	0.213	0.143	0.182
9	-0.108	-0.140	-0.132	-0.093	-0.109	-0.099	-0.076	-0.035	-0.082	-0.142	0.051	0.030	0.100	-0.027	0.131	0.108	0.212	0.142	0.180
10	-0.111	-0.141	-0.138	-0.111	-0.113	-0.100	-0.076	-0.042	-0.082	-0.150	0.050	0.029	0.100	-0.030	0.114	0.097	0.212	0.125	0.179
Small S Lane																			
1	-0.661	-0.563	-1.037	-0.534	-0.605	-0.643	-0.607	-0.698	-0.725	-0.696	-0.934	-0.927	-1.306	-0.835	-1.299	-1.330	-1.215	-1.354	-1.266
2	-0.587	-0.541	-0.550	-0.531	-0.584	-0.640	-0.600	-0.666	-0.717	-0.690	-0.920	-0.850	-1.301	-0.834	-1.281	-1.301	-1.199	-1.345	-1.242
3	-0.582	-0.540	-0.542	-0.531	-0.580	-0.631	-0.596	-0.655	-0.685	-0.688	-0.914	-0.835	-1.289	-0.824	-1.263	-1.289	-1.196	-1.291	-1.217
4	-0.580	-0.535	-0.542	-0.529	-0.578	-0.613	-0.594	-0.636	-0.675	-0.666	-0.869	-0.812	-1.259	-0.802	-1.259	-1.283	-1.153	-1.267	-1.216
5	-0.573	-0.531	-0.542	-0.528	-0.573	-0.606	-0.579	-0.618	-0.666	-0.665	-0.857	-0.809	-1.236	-0.801	-1.245	-1.243	-1.115	-1.245	-1.216
6	-0.570	-0.530	-0.538	-0.527	-0.563	-0.587	-0.561	-0.569	-0.645	-0.646	-0.834	-0.803	-1.110	-0.766	-1.232	-1.101	-1.069	-1.242	-1.137
7	-0.558	-0.528	-0.536	-0.525	-0.559	-0.569	-0.556	-0.566	-0.618	-0.635	-0.822	-0.739	-1.091	-0.747	-1.097	-1.095	-1.019	-1.068	-1.059
8	-0.555	-0.526	-0.534	-0.524	-0.548	-0.558	-0.552	-0.566	-0.617	-0.633	-0.727	-0.702	-1.015	-0.722	-1.057	-1.029	-0.905	-1.057	-0.956
9	-0.554	-0.525	-0.532	-0.523	-0.542	-0.557	-0.545	-0.541	-0.580	-0.597	-0.710	-0.694	-0.997	-0.694	-1.016	-1.025	-0.835	-0.981	-0.915
10	-0.549	-0.520	-0.531	-0.521	-0.541	-0.546	-0.543	-0.519	-0.579	-0.588	-0.692	-0.628	-0.902	-0.682	-0.969	-0.967	-0.815	-0.958	-0.908
Rut Depth	**0.515**	**0.451**	**0.505**	**0.468**	**0.501**	**0.528**	**0.528**	**0.593**	**0.594**	**0.571**	**0.887**	**0.842**	**1.265**	**0.753**	**1.313**	**1.282**	**1.273**	**1.336**	**1.299**
Average Rut Depth (100%)	**0.557**	**0.524**	**0.570**	**0.556**	**0.529**	**0.550**	**0.564**	**0.611**	**0.581**	**0.598**	**0.847**	**0.827**	**1.120**	**0.881**	**1.176**	**1.142**	**1.115**	**1.171**	**1.135**

Table B.3: Rut Measurements (SS-1HP 160%)

South East Pit 1	SS-1HP-160%																		
Repetutions (x1000)	Initial	10	15	25	50	100	250	425	550	600	700	800	900	1000	1100	1200	1300	1400	1500
Large S Lane																			
1	0.011	0.010	0.000	0.000	0.008	0.015	0.041	0.015	0.103	0.153	0.503	0.480	0.236	0.317	0.325	0.358	0.330	0.272	0.298
2	0.004	0.000	-0.051	-0.024	0.002	0.007	0.038	0.013	0.084	0.085	0.389	0.368	0.234	0.310	0.287	0.355	0.329	0.268	0.288
3	0.000	-0.012	-0.062	-0.035	0.000	0.006	0.032	0.012	0.077	0.082	0.212	0.214	0.229	0.299	0.284	0.346	0.323	0.261	0.288
4	-0.021	-0.035	-0.070	-0.047	-0.001	0.001	0.029	0.012	0.069	0.072	0.207	0.204	0.229	0.291	0.284	0.345	0.319	0.239	0.285
5	-0.029	-0.050	-0.077	-0.048	-0.001	0.000	0.018	0.010	0.064	0.064	0.198	0.197	0.227	0.287	0.274	0.344	0.317	0.237	0.284
6	-0.050	-0.067	-0.081	-0.049	-0.001	-0.003	0.018	0.004	0.064	0.023	0.197	0.195	0.221	0.283	0.272	0.339	0.313	0.232	0.279
7	-0.069	-0.090	-0.082	-0.053	-0.002	-0.005	0.005	0.000	0.063	0.021	0.190	0.193	0.217	0.281	0.264	0.331	0.302	0.221	0.265
8	-0.070	-0.093	-0.089	-0.055	-0.015	-0.006	0.005	0.000	0.061	0.015	0.187	0.184	0.212	0.270	0.257	0.327	0.300	0.218	0.265
9	-0.083	-0.105	-0.091	-0.057	-0.016	-0.006	0.002	-0.010	0.052	0.013	0.183	0.177	0.207	0.265	0.253	0.318	0.297	0.217	0.265
10	-0.084	-0.110	-0.093	-0.064	-0.018	-0.009	0.000	-0.011	0.051	0.012	0.171	0.157	0.205	0.248	0.244	0.317	0.297	0.216	0.247
Small S Lane																			
1	-0.256	-0.285	-0.297	-0.328	-0.329	-0.354	-0.332	-0.410	-0.309	-0.397	-0.717	-0.712	-1.047	-1.025	-0.978	-0.956	-1.002	-1.012	-0.968
2	-0.247	-0.279	-0.294	-0.311	-0.313	-0.342	-0.322	-0.401	-0.292	-0.389	-0.677	-0.709	-0.994	-0.957	-0.917	-0.875	-0.997	-0.965	-0.958
3	-0.243	-0.271	-0.287	-0.303	-0.311	-0.337	-0.318	-0.392	-0.292	-0.381	-0.642	-0.622	-0.982	-0.897	-0.880	-0.855	-0.919	-0.964	-0.926
4	-0.241	-0.268	-0.283	-0.298	-0.310	-0.333	-0.315	-0.372	-0.290	-0.355	-0.636	-0.575	-0.938	-0.859	-0.796	-0.831	-0.910	-0.860	-0.859
5	-0.240	-0.268	-0.282	-0.278	-0.307	-0.322	-0.308	-0.361	-0.289	-0.353	-0.602	-0.566	-0.812	-0.735	-0.781	-0.743	-0.801	-0.765	-0.767
6	-0.234	-0.264	-0.281	-0.276	-0.294	-0.320	-0.294	-0.361	-0.289	-0.349	-0.581	-0.549	-0.798	-0.730	-0.755	-0.700	-0.762	-0.734	-0.721
7	-0.231	-0.264	-0.272	-0.275	-0.294	-0.302	-0.291	-0.341	-0.283	-0.343	-0.534	-0.492	-0.746	-0.710	-0.698	-0.641	-0.760	-0.717	-0.686
8	-0.228	-0.261	-0.272	-0.275	-0.276	-0.295	-0.282	-0.339	-0.273	-0.335	-0.520	-0.462	-0.730	-0.680	-0.670	-0.639	-0.661	-0.702	-0.635
9	-0.225	-0.260	-0.272	-0.273	-0.274	-0.286	-0.275	-0.310	-0.270	-0.327	-0.461	-0.454	-0.666	-0.610	-0.562	-0.595	-0.639	-0.678	-0.609
10	-0.225	-0.255	-0.270	-0.270	-0.274	-0.281	-0.275	-0.305	-0.264	-0.315	-0.416	-0.433	-0.586	-0.510	-0.538	-0.474	-0.546	-0.571	-0.572
Rut Depth	**0.198**	**0.212**	**0.211**	**0.245**	**0.294**	**0.317**	**0.320**	**0.364**	**0.354**	**0.408**	**0.822**	**0.794**	**1.052**	**1.056**	**1.032**	**1.069**	**1.112**	**1.035**	**1.047**
South West Pit 2 Large S Lane																			
1	0.100	0.000	0.036	0.006	0.147	0.144	0.113	0.154	0.197	0.194	0.360	0.298	0.434	0.236	0.233	0.282	0.248	0.257	0.290
2	0.096	-0.005	0.029	0.000	0.146	0.144	0.103	0.142	0.192	0.143	0.243	0.281	0.334	0.235	0.231	0.278	0.242	0.253	0.285
3	0.076	-0.014	0.027	-0.001	0.139	0.141	0.100	0.135	0.187	0.142	0.242	0.277	0.322	0.226	0.229	0.275	0.239	0.249	0.285
4	0.048	-0.014	0.026	-0.002	0.137	0.138	0.097	0.132	0.185	0.141	0.215	0.273	0.320	0.224	0.227	0.273	0.235	0.248	0.278
5	0.000	-0.016	0.021	-0.003	0.135	0.137	0.094	0.129	0.183	0.139	0.202	0.272	0.317	0.222	0.227	0.268	0.228	0.246	0.277
6	-0.012	-0.023	0.019	-0.006	0.132	0.133	0.093	0.128	0.180	0.137	0.201	0.270	0.313	0.222	0.224	0.261	0.227	0.244	0.275
7	-0.012	-0.023	0.018	-0.007	0.128	0.130	0.090	0.124	0.179	0.136	0.194	0.267	0.308	0.214	0.224	0.256	0.227	0.244	0.269
8	-0.013	-0.024	0.013	-0.010	0.126	0.126	0.089	0.122	0.177	0.126	0.193	0.259	0.304	0.214	0.222	0.253	0.225	0.244	0.267
9	-0.013	-0.027	0.012	-0.012	0.124	0.122	0.086	0.120	0.173	0.124	0.186	0.257	0.288	0.212	0.221	0.250	0.225	0.243	0.264
10	-0.014	-0.030	0.012	-0.017	0.123	0.116	0.085	0.118	0.172	0.122	0.184	0.256	0.280	0.209	0.220	0.248	0.222	0.241	0.264
Small S Lane																			
1	-0.217	-0.236	-0.224	-0.337	-0.255	-0.293	-0.297	-0.358	-0.272	-0.353	-0.549	-0.458	-0.654	-0.689	-0.698	-0.663	-0.694	-0.648	-0.663
2	-0.199	-0.233	-0.223	-0.289	-0.243	-0.289	-0.293	-0.332	-0.256	-0.346	-0.508	-0.442	-0.650	-0.665	-0.640	-0.624	-0.652	-0.604	-0.619
3	-0.198	-0.212	-0.219	-0.285	-0.238	-0.282	-0.291	-0.328	-0.246	-0.332	-0.505	-0.438	-0.625	-0.625	-0.640	-0.606	-0.638	-0.592	-0.588
4	-0.196	-0.210	-0.218	-0.284	-0.237	-0.258	-0.288	-0.323	-0.237	-0.324	-0.504	-0.431	-0.622	-0.616	-0.638	-0.597	-0.634	-0.586	-0.585
5	-0.188	-0.207	-0.217	-0.276	-0.236	-0.257	-0.287	-0.308	-0.215	-0.305	-0.496	-0.423	-0.610	-0.587	-0.637	-0.579	-0.621	-0.549	-0.579
6	-0.187	-0.202	-0.216	-0.254	-0.236	-0.250	-0.278	-0.304	-0.215	-0.285	-0.477	-0.399	-0.558	-0.583	-0.608	-0.545	-0.618	-0.546	-0.577
7	-0.183	-0.202	-0.215	-0.252	-0.236	-0.242	-0.255	-0.304	-0.209	-0.285	-0.448	-0.385	-0.547	-0.572	-0.549	-0.519	-0.583	-0.530	-0.570
8	-0.179	-0.201	-0.214	-0.250	-0.235	-0.219	-0.255	-0.255	-0.190	-0.278	-0.428	-0.341	-0.537	-0.545	-0.535	-0.507	-0.549	-0.512	-0.528
9	-0.179	-0.200	-0.214	-0.246	-0.234	-0.219	-0.251	-0.241	-0.179	-0.277	-0.420	-0.319	-0.483	-0.508	-0.502	-0.450	-0.519	-0.447	-0.490
10	-0.176	-0.197	-0.212	-0.246	-0.234	-0.213	-0.250	-0.225	-0.166	-0.270	-0.418	-0.319	-0.447	-0.482	-0.467	-0.448	-0.475	-0.418	-0.454
Rut Depth	**0.216**	**0.193**	**0.239**	**0.267**	**0.372**	**0.385**	**0.369**	**0.428**	**0.401**	**0.446**	**0.697**	**0.666**	**0.895**	**0.809**	**0.817**	**0.818**	**0.830**	**0.790**	**0.841**
Average Rut Depth (160%)	**0.207**	**0.202**	**0.225**	**0.256**	**0.333**	**0.351**	**0.345**	**0.396**	**0.377**	**0.427**	**0.760**	**0.730**	**0.973**	**0.933**	**0.925**	**0.944**	**0.971**	**0.912**	**0.944**

Table B.4: Rut Measurements (SS-1HP 240%)

North East Pit 1	SS-1HP-240%																		
Repetutions (x1000)	Initial	10	15	25	50	100	250	425	550	600	700	800	900	1000	1100	1200	1300	1400	1500
Large N Lane																			
1	0.161	0.177	0.173	0.174	0.212	0.279	0.284	0.270	0.328	0.276	0.412	0.474	0.464	0.454	0.404	0.473	0.848	0.451	0.489
2	0.160	0.172	0.168	0.173	0.212	0.267	0.282	0.269	0.326	0.256	0.342	0.464	0.403	0.444	0.403	0.453	0.515	0.447	0.478
3	0.159	0.171	0.158	0.170	0.205	0.250	0.282	0.267	0.323	0.246	0.331	0.460	0.394	0.441	0.401	0.452	0.506	0.444	0.475
4	0.158	0.169	0.158	0.166	0.204	0.247	0.274	0.266	0.320	0.237	0.329	0.457	0.385	0.440	0.393	0.447	0.489	0.443	0.471
5	0.156	0.168	0.155	0.164	0.203	0.244	0.272	0.262	0.317	0.227	0.326	0.450	0.377	0.439	0.392	0.445	0.478	0.440	0.469
6	0.155	0.167	0.155	0.159	0.203	0.243	0.271	0.260	0.308	0.218	0.323	0.449	0.376	0.428	0.391	0.445	0.478	0.439	0.468
7	0.154	0.166	0.153	0.159	0.201	0.243	0.271	0.257	0.307	0.218	0.321	0.449	0.374	0.427	0.387	0.441	0.463	0.435	0.467
8	0.154	0.163	0.153	0.152	0.200	0.240	0.269	0.253	0.305	0.217	0.321	0.449	0.359	0.424	0.386	0.440	0.452	0.435	0.465
9	0.145	0.158	0.153	0.148	0.200	0.239	0.268	0.253	0.303	0.216	0.320	0.446	0.353	0.421	0.386	0.439	0.447	0.434	0.456
10	0.145	0.157	0.149	0.146	0.199	0.234	0.266	0.251	0.295	0.212	0.316	0.445	0.341	0.417	0.381	0.433	0.442	0.431	0.456
Small N Lane																			
1	-0.175	-0.208	-0.219	-0.210	-0.193	-0.210	-0.154	-0.192	-0.134	-0.248	-0.284	-0.185	-0.396	-0.283	-0.357	-0.302	-0.332	-0.336	-0.252
2	-0.156	-0.192	-0.202	-0.208	-0.189	-0.201	-0.153	-0.172	-0.133	-0.228	-0.266	-0.168	-0.389	-0.282	-0.355	-0.290	-0.321	-0.335	-0.232
3	-0.150	-0.175	-0.186	-0.189	-0.184	-0.194	-0.147	-0.172	-0.129	-0.226	-0.263	-0.159	-0.364	-0.266	-0.340	-0.290	-0.308	-0.317	-0.205
4	-0.147	-0.172	-0.182	-0.188	-0.183	-0.190	-0.147	-0.171	-0.123	-0.214	-0.245	-0.156	-0.362	-0.265	-0.339	-0.281	-0.292	-0.312	-0.204
5	-0.143	-0.158	-0.182	-0.182	-0.181	-0.185	-0.147	-0.166	-0.122	-0.213	-0.243	-0.149	-0.361	-0.263	-0.326	-0.275	-0.291	-0.303	-0.202
6	-0.141	-0.158	-0.180	-0.179	-0.178	-0.184	-0.143	-0.158	-0.120	-0.211	-0.237	-0.145	-0.356	-0.259	-0.313	-0.267	-0.283	-0.303	-0.198
7	-0.141	-0.157	-0.178	-0.178	-0.175	-0.181	-0.140	-0.157	-0.118	-0.208	-0.228	-0.144	-0.355	-0.257	-0.310	-0.267	-0.281	-0.302	-0.198
8	-0.137	-0.153	-0.175	-0.177	-0.172	-0.181	-0.139	-0.154	-0.117	-0.208	-0.224	-0.140	-0.352	-0.253	-0.303	-0.266	-0.275	-0.295	-0.180
9	-0.134	-0.147	-0.174	-0.173	-0.168	-0.175	-0.138	-0.152	-0.116	-0.208	-0.211	-0.138	-0.350	-0.249	-0.301	-0.255	-0.262	-0.285	-0.171
10	-0.131	-0.143	-0.172	-0.171	-0.166	-0.172	-0.135	-0.146	-0.116	-0.207	-0.211	-0.128	-0.348	-0.245	-0.300	-0.249	-0.258	-0.274	-0.166
Rut Depth	**0.300**	**0.333**	**0.342**	**0.346**	**0.383**	**0.436**	**0.418**	**0.425**	**0.436**	**0.449**	**0.575**	**0.605**	**0.746**	**0.695**	**0.717**	**0.721**	**0.802**	**0.746**	**0.670**
North West Pit 2 Large N Lane																			
1	0.074	0.077	0.094	0.076	0.126	0.151	0.157	0.218	0.250	0.167	0.219	0.235	0.275	0.227	0.125	0.231	0.148	0.229	0.121
2	0.074	0.074	0.093	0.071	0.125	0.135	0.142	0.217	0.230	0.160	0.196	0.234	0.266	0.219	0.123	0.227	0.147	0.215	0.111
3	0.073	0.073	0.085	0.071	0.123	0.130	0.126	0.216	0.222	0.160	0.195	0.228	0.266	0.204	0.108	0.221	0.145	0.213	0.105
4	0.072	0.072	0.070	0.070	0.114	0.129	0.093	0.207	0.215	0.157	0.193	0.226	0.256	0.198	0.108	0.213	0.132	0.203	0.102
5	0.071	0.066	0.067	0.067	0.114	0.125	0.091	0.206	0.214	0.154	0.188	0.226	0.253	0.196	0.101	0.211	0.129	0.196	0.097
6	0.065	0.059	0.055	0.063	0.107	0.125	0.089	0.202	0.211	0.150	0.186	0.224	0.249	0.190	0.099	0.206	0.125	0.195	0.094
7	0.061	0.054	0.055	0.062	0.106	0.117	0.081	0.199	0.210	0.150	0.182	0.222	0.248	0.190	0.095	0.203	0.125	0.190	0.092
8	0.056	0.052	0.052	0.060	0.105	0.114	0.078	0.194	0.202	0.148	0.170	0.221	0.228	0.189	0.095	0.202	0.117	0.187	0.091
9	0.055	0.050	0.052	0.058	0.104	0.114	0.073	0.193	0.201	0.143	0.169	0.219	0.221	0.188	0.088	0.200	0.116	0.180	0.091
10	0.048	0.048	0.049	0.058	0.100	0.114	0.070	0.190	0.200	0.141	0.169	0.214	0.215	0.186	0.088	0.198	0.110	0.178	0.091
Small N Lane																			
1	-0.214	-0.218	-0.234	-0.266	-0.284	-0.322	-0.382	-0.327	-0.302	-0.373	-0.548	-0.459	-0.584	-0.644	-0.709	-0.601	-0.687	-0.648	-0.690
2	-0.213	-0.216	-0.233	-0.265	-0.278	-0.299	-0.372	-0.326	-0.295	-0.357	-0.542	-0.452	-0.562	-0.638	-0.704	-0.601	-0.679	-0.626	-0.679
3	-0.211	-0.212	-0.231	-0.265	-0.271	-0.290	-0.350	-0.293	-0.291	-0.353	-0.530	-0.439	-0.555	-0.630	-0.702	-0.600	-0.675	-0.623	-0.673
4	-0.207	-0.211	-0.231	-0.263	-0.265	-0.289	-0.348	-0.293	-0.291	-0.350	-0.514	-0.414	-0.546	-0.624	-0.699	-0.595	-0.672	-0.623	-0.656
5	-0.199	-0.211	-0.228	-0.259	-0.264	-0.289	-0.336	-0.291	-0.279	-0.345	-0.509	-0.410	-0.536	-0.609	-0.696	-0.590	-0.668	-0.610	-0.647
6	-0.199	-0.209	-0.228	-0.258	-0.259	-0.271	-0.333	-0.281	-0.238	-0.328	-0.502	-0.404	-0.532	-0.607	-0.691	-0.584	-0.666	-0.599	-0.611
7	-0.198	-0.209	-0.225	-0.257	-0.259	-0.269	-0.332	-0.251	-0.228	-0.322	-0.483	-0.402	-0.532	-0.607	-0.685	-0.581	-0.664	-0.596	-0.607
8	-0.197	-0.209	-0.224	-0.253	-0.258	-0.264	-0.301	-0.239	-0.224	-0.321	-0.478	-0.394	-0.527	-0.604	-0.665	-0.568	-0.652	-0.589	-0.572
9	-0.197	-0.208	-0.224	-0.253	-0.258	-0.254	-0.296	-0.236	-0.204	-0.314	-0.472	-0.394	-0.514	-0.590	-0.658	-0.562	-0.645	-0.577	-0.564
10	-0.197	-0.208	-0.224	-0.251	-0.256	-0.243	-0.294	-0.224	-0.203	-0.299	-0.453	-0.384	-0.512	-0.577	-0.629	-0.524	-0.612	-0.553	-0.562
Rut Depth	**0.268**	**0.273**	**0.295**	**0.325**	**0.378**	**0.404**	**0.435**	**0.480**	**0.471**	**0.489**	**0.690**	**0.641**	**0.788**	**0.812**	**0.787**	**0.792**	**0.791**	**0.803**	**0.725**
Average Rut Depth (240%)	**0.284**	**0.303**	**0.319**	**0.336**	**0.380**	**0.420**	**0.426**	**0.453**	**0.453**	**0.469**	**0.633**	**0.623**	**0.767**	**0.754**	**0.752**	**0.756**	**0.797**	**0.775**	**0.698**

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