AN ABSTRACT OF THE THESIS OF

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Title: "Development of Technologies to Evaluate Hot Mix Asphalt Layer Adhesion through Tack Coat"

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Erdem Coleri

Flexible pavements consist of multilayers, which form the pavement structures. Since the strength of the bond at interface between layers plays a significant role in improving the structural integrity and the performance of pavement structures, tack coat materials and methods used for their application during construction are important in providing an adequate bond strength between pavement lifts. Tack coat is a bituminous liquid asphalt (a mixture of water, asphalt binder, and an emulsifying agent) and usually applied to provide a bond between pavement lifts. The absence of the tack coat adhesion at the interface between layers leads to increased stresses in the pavement structure. An inspection procedure to monitor the performance of the interlayer bond during the pavement use phase and identifying bond failures is critical to improve pavement management systems and develop more effective pavement design strategies. In this study, two different devices were developed at Oregon State University to evaluate the tack coat performance in the field.

First, the wireless Oregon Field Tack Coat Tester (OFTCT) device was developed to predict the long-term performance of the in-situ tack coat bond strength and to evaluate the impact of pavement surface cleanliness before tack coat application on bond strength. Correlations between OFTCT field test results and the results of laboratory shear tests conducted with cores taken from

the field were investigated to determine the effectiveness of the OFTCT tests. A new heating system (an adjustable heat gun and environmental chamber) was developed to reduce the tack coat's curing time in the field and control temperature during testing. The results indicated that the OFTCT device can be successfully utilized in the field to differentiate between clean and dusty surfaces before tack coat application. By using wireless sensors controlled by a laptop, practicality of the device was improved to reduce the testing time. The correlation between OFTCT and laboratory shear test results was determined to be statistically significant ($R^2 = 0.5189$). OFTCT was able to identify the tack coats with high and low interlayer shear strength (ISS).

Second, a new low cost field test device, Oregon Field Torque Tester (OFTT), was developed to evaluate the long-term post-construction tack coat performance of pavement sections. Correlations between OFTT field test results and the results of laboratory shear tests conducted with cores taken from the field were investigated to determine the effectiveness of the OFTT tests. The peak torque values at failure measured by the OFTT were observed to be highly correlated with the measured lab shear strengths. To conclude, both of the developed devices are expected to be adapted as field tests to evaluate the performance of tack coats in the field and to mitigate pavement distresses observed on roadways.

“Development of Technologies to Evaluate Hot Mix Asphalt Layer Adhesion through Tack Coat”

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Head of the School of Civil and Construction Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes the release of my thesis to any reader upon request.

Aiman Mustafa H. Mahmoud, Author

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CONTRIBUTION OF AUTHORS

David Covey assisted with data collection and interpretation of the data for both manuscripts. David's assistance with field and laboratory experiments was a huge part of making this a successful project. The technical development of both OFTCT and OFTT devices was made by James Batti. Mr. Batti also helped write section 3.5.2 in the second manuscript.

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1 CHAPTER 1 - INTRODUCTION

Tack coat is usually an asphaltic emulsion consisting of asphalt binder, water and a low amount of emulsifying agent (such as soap). Asphalt emulsions, paving grade asphalt binders, and cutback asphalts are materials that have also been used as tack coats. In this study, the properties of only asphalt emulsions are investigated since it is the most commonly used tack coat type in Oregon. Asphalt emulsions are used to provide an adhesive bond between the new and old pavement lifts. This bond helps the pavement system to behave as a monolithic structure and improves the structural integrity. Increased structural integrity leads to increased pavement life. Inadequate application rates and non-uniform distributions lead to reduced bonding between pavements lifts and therefore results in a reduction of pavement life. This phenomenon drives the pavement to be more exposed to distresses such as cracking, rutting, and potholes (Tashman et al. 2006). This study investigates several factors that are critical to improve the tack coat performance. These factors are tack coat material type, application rate, and curing time.

1.1 Tack coat materials

Emulsions, paving grade asphalt binders, and cutback asphalts are the materials used as tack coats. Due to environmental concerns, cutback asphalts (asphalts dissolved in solvents such as kerosene) are not allowed to be used as tack coats by many states. Paving grade asphalt binders are also not commonly used since excessive heating of the asphalt cement is required to achieve proper viscosity for spraying (Leng et al., 2008). According to a survey conducted by Mohammad and Button (2005), all of the responding agencies were using asphalt emulsions as tack coats. Asphalt binders were used by 26% and cutbacks were used by 21% of the responding states. In this project, the properties of only asphalt emulsions are investigated since it is the most commonly used tack coat type in Oregon.

Asphalt emulsion is produced by mixing asphalt and water with an emulsifying agent such as soap. The two most commonly used types of asphalt emulsions are anionic and cationic (Krebs & Walker, 1971). Asphalt surface charge is negative for anionic emulsions while it is positive for cationic emulsions. Anionic emulsions typically work well with positively charged aggregates such as limestone. Cationic emulsions bond best with negatively charged aggregates such as gravel, sand, and basalt. According to a survey conducted by the International Bitumen Emulsion Federation (Roffe & Chaignon, 2002), the most commonly used tack coat type is the cationic emulsion.

Rapid setting (RS), medium setting (MS), and slow setting (SS) are the three general grades used to classify asphalt emulsions (Krebs & Walker, 1971). The type and amount of emulsifying agent control the curing (set) time. The most common types of rapid setting emulsions used for tack coats in the United States are RS-1, RS-2, CRS-1, CRS-2, CRS-2P (polymer-modified), and CRS-2L (latex-modified) while SS-1, SS-1h, CSS-1, and CSS-1h are the most common slow-setting grades (Mohammad et al. 2012). Since the viscosity of slow-setting emulsions can be reduced by dilution, they can be easily sprayed during construction. In addition, slow-setting emulsions are more suitable for lower residual application rates since the total emulsion volume required for the distributor to function can be achieved by dilution (USACE, 2008). On the other hand, it might take several hours for slow setting emulsions to break and completely set. Thus, slow-setting emulsions are more vulnerable to slippage during their early life (USACE, 2008). Breaking and curing time, change in bond strength over time, and the impact of set time on tracking, the pick-up of bituminous material by construction vehicle tires, should be investigated for different tack coat types to develop a standard for tack coat type selection and application procedures.

Mohammad et al. (2012) compared the performance of trackless tack coat (a polymer-modified emulsion with a hard base asphalt cement) to SS-1h, SS-1, CRS-1, and a paving grade asphalt binder (PG64-22). It was concluded that trackless tack coat exhibited the highest shear strength while CRS-1 resulted in the lowest strength. Cortina (2012) also reported higher shear strength for trackless tack coat. However, improper handling of the trackless tack coat clogged the distributor trucks for several days. Cortina (2012) recommended a spraying temperature of 175°F to avoid clogging problems. The “New” emulsions evaluated in this study show properties that are similar to trackless tack coats.

1.2 Application rate

Using the optimum amount of tack coat is vital to achieving a full bond between two pavement layers. Slippage problems start to arise when an excessive amount of tack coat material is sprayed during construction. On the other hand, inadequate amount of tack coat can result in debonding problems over the design life (especially in the wheel paths) of the pavement structure (Tashman et al. 2006). Thus, optimum residual application rates should be determined by considering surface (texture and age) and environmental (temperature, humidity, and the wind) conditions. Mohammad et al. (2012) recommended to use different residual application rates for i) new or subsequent layers, ii) existing relatively smooth, and iii) old, oxidized, cracked, and milled pavement surfaces.

The effect of application rate on interface shear strength is investigated by Mohammad et al. (2012). The results indicate that increasing application rates create a considerable increase in interface shear strength for SS-1h and trackless tack coats. However, interface shear strength for CRS-1 is not sensitive to residual application rates. A non-uniform residual rate results in reduced pavement life and increased stress on the pavement surface.

1.3 Tack coat curing time

There is no consensus on the importance of tack coat curing time. Several research studies (FPO, 2001; TxDOT, 2001) suggested having a cured tack coat layer before constructing the overlay to achieve high bond strengths. Sholar et al. (2004) evaluated the impact of curing on tack coat shear strength and observed a considerable increase in shear resistance with curing time. On the other hand, several other research studies (Lavin, 2003; USACE, 2000) indicated that since water in the emulsion will immediately evaporate after placing the overlay material on the tacked asphalt surface, there is no need to wait several hours for the tack coat to cure. Under most circumstances, an emulsion is expected to set in 1 to 2 hours (USACE, 2000). Alaska DOT specified a maximum setting period of 2 hours for CSS-1 while Arkansas DOT specified a maximum setting period of 72 hours for SS-1. Texas DOT specified a maximum setting time of 45 minutes for SS-1 (Mohammad et al. 2012). It should be noted that in Europe, asphalt emulsions are applied underneath the paver just before the HMA to minimize tracking problems (Mohammed et al. 2012).

1.4 Research summary

Tension and shear modes are the two mechanisms causing tack coat bond failures in the field. Tension, direct shear, and torsional shear are the loading mechanisms investigated and evaluated in the literature to assess the performance of the tack coat bond strength. But there still remains limitations (heating system, wired connection, manually operated, poor correlations between direct shear tests and current testing devices) in the current devices and test procedures to assess the performance of bond strength. The Oregon Field Tack Coat Tester (OFTCT) device developed in this study was used to characterize the bond strength in tension mode and overcome limitations of the current tension mode test devices. The Oregon Field Torque Tester (OFTT) device, also developed in this study, was used to characterize the strength in shear mode (torsional shear or torque) and overcome limitations of the current torque test devices. Devices and test procedures developed in this study are expected to improve the understanding of the in-situ tack coat performance and to be adopted as QC/QA procedures to evaluate the performance of tack coats in the field.

2 CHAPTER 2 - DEVELOPMENT OF A WIRELESS FIELD TACK COAT TESTER TO EVALUATE IN-SITU TACK COAT PERFORMANCE

Aiman Mahmoud; Erdem Coleri; James Batti; and David Covey

Abstract: In this study, Oregon Field Tack Coat Tester (OFTCT) was developed by using the Louisiana Tack Coat Quality Tester (LTCQT) device as a reference in order to create a practical method and test system to evaluate and improve the long-term tack coat performance in Oregon. The OFTCT system was developed to predict the long-term performance of tack coats based on the results of tests conducted during construction. In addition, the OFTCT device was used to evaluate the impact of pavement surface cleanliness before tack coat application on bond strength. Wireless sensors installed on the OFTCT significantly improved the mobility and practicality of the device in the field. In order to reduce the tack coat's curing time in the field and control temperature during testing, an adjustable heat gun, and environmental chamber were developed. The results indicated that the new temperature control system resulted in a 12% reduction in measurement variability. The results further revealed that using the new heating system provided consistent and reliable temperature control, and prevented excessive heating of the tacked surface. It was also determined that the OFTCT can be successfully utilized in the field as a test to quantify the cleanliness of the pavement surfaces before tack coat application. The correlation between OFTCT and laboratory shear test results is determined to be statistically significant (R2 = 0.5189). However, more field experiments need to be conducted to implement it as a test to predict in-situ interlayer shear strength (ISS).

Key Terms: Tack coat, bond strength, tension, lab shear test, wireless, pavement texture, emulsion

2.1 Introduction

Tack coats are the bituminous materials applied between pavement lifts to provide an adequate bond between the two surfaces. Strong adhesion between two pavement layers helps the structure to respond to heavy truckloads as a single unit and reduces surface displacements. Reduced displacement slows down crack initiation and propagation in the pavement structures and increases the pavement life. However, poor bonding between adjacent layers results in reduction in the shear strength resistance and leads to increased distresses on the pavement surface such as cracking, rutting, and potholes (Tashman et al. 2006).

Using computational modeling, Hachiya and Sato (1997) showed that high tension and shear forces created by heavy truckloads can break the bond between the two layers when the applied stresses exceed the shear and tensile strength of the tack coat. When the bond between the two layers (new and existing) is broken, the two pavement layers start to act independently. This change in the pavement structure shifts the critical strain location from the bottom of the asphalt structure to the failed bond location (Mohammad et al. 2012). The shear and tensile stresses created under the truck tires damage the tack coats over time and result in bond failures. For this reason, laboratory and field experiments focus on both shear and tensile strength of the tack coats to evaluate the long-term resistance.

In this study, several test procedures and technologies were used to evaluate the performance of tack coats. The study aims to develop a Wireless Field Tack Coat Tester to measure the quality and performance characteristics of tack coats in the laboratory and the field. The device will also be used to evaluate the impact of pavement surface cleanliness before tack coat application on bond strength.

2.2 Objectives

The objectives of this study are to:

- Develop a low cost field test device;
- Develop a user friendly software to wirelessly control the developed field test device;
- Evaluate the effectiveness of standard infrared reflective lamp heating system;
- Evaluate the correlation between OFTCT results and lab shear test results; and

- Evaluate the possibility of using the OFTCT device to quantify the effect of dust on tack coat bond strength.

2.3 Current tack coat tester technologies

Several research studies have been conducted in different states to develop an in-situ test method to investigate the bonding characteristics of different tack coat types. Texas pull-off, ATACKER™ device, and Louisiana Tack Coat Quality Tester (LTCQT) tests are the major devices developed for tack coat performance evaluation and are discussed below:

2.3.1 *Texas pull-off test*

Texas Pull-off test device was developed at the University of Texas at El Paso (UTEP) (Deysarkar, 2004) to measure the tensile strength of applied tack coat before constructing a new overlay. First, the tack coat is applied on to the pavement surface; the tack coat layer is then left to set. After proper curing time, the device is then placed on the tacked surface. The load plate being lowered onto the tacked pavement surface creates the initial contact. A 40-pound load is then applied on the device for ten minutes prior to testing to create adequate bonding between the test plate and the pavement surface. Once ten minutes has passed, the load is removed and the torque wrench is manually rotated in a counter-clockwise direction to move the plate in a vertical direction. The torque value required to break the bond between the plate and the pavement surface is recorded and converted to bond strength using a calibration factor.

Tashman et al. (2006) conducted several Florida direct shear and Texas pull-off tests on milled and non-milled test sections to investigate the effectiveness of Texas pull-off test for interface bond strength characterization. Test results showed that although measured interface bond strength values for the Florida direct shear test are higher for the milled sections (as expected), tack coat strength values measured by Texas pull-off test during construction appeared to be lower for the milled test sections. This result suggested that smaller contact area for the milled sections (due to high texture) increased the applied stresses and resulted in early failure at lower load levels for the milled sections. Mohammad et al. (2012) avoided this problem by attaching a polyethylene foam to the loading plate to increase contact area for milled sections.

2.3.2 *ATACKER ™ device*

InstroTek® Inc improved the Texas pull-off device and developed ATACKER ™ (Buchanan and Woods 2004). The development was in accordance to the American Society of Testing and Materials (ASTM) specification D4541, “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers (ASTM D4541).” Their test procedure was easy to follow and started by applying a specified application rate and then a variety of curing times were considered for each of the emulsions. Subsequently, a normal pressure was applied to move the loading platen downwards on the tacked surface. The loading platen was then pulled up and the tensile stress or torque required to separate the loading platen from the tacked surface was recorded (Buchanan and Woods 2004). In this version, the limited ranges of the applied normal force, Tack Coat Evaluation Device (TCED) force gauge load capacity, and inaccurate loading rates were determined to be the major factors reducing test results accuracy and precision.

2.3.3 *Louisiana tack coat quality tester (LTCQT)*

Mohammad et al. (2012) developed the LTCQT device by further improving the ATACKER™ device by:

- Using a load cell with a lower noise level;
- Using a new actuator and driving motor to minimize the errors in displacement rate;
- Attaching a polyethylene foam to the loading plate to increase contact area for milled sections;
- Developing a user-friendly software to control the system and help collect the data automatically; and
- Developing an infrared reflective heating system to control the temperature in both the field and laboratory.

Mohammad et al. (2012) conducted several field experiments to evaluate the effectiveness of LTCQT for tack coat quality evaluation. More than three replicate tests were conducted on each section. Comparison of LTCQT results to the results of Louisiana Interlayer Shear Strength Tester (LISST) and rheological tests showed that LTCQT is a viable method for tack coat quality evaluation during construction. The LTCQT was recommended to be used as a tool to determine the most effective tack coat application methods and rates in the field. Variability of LTCQT test results was also determined to be acceptable, with an average coefficient of variation of less than 11%. Mohammad et al. (2012) recommended conducting LTCQT at the tack coat base asphalt softening point in order to get comparable results for different tack coat types. Although LTCQT was suggested to be a reliable system for tack coat performance evaluation, practicality, variability, and effectiveness of LTCQT need to be improved to increase the widespread use of this system to evaluate the long-term performance of tack coats.

2.4 Proposed solution and challenges

The prior results from the Texas pull-off tests indicated that the presence of dust on the pavement surface before tack coat application results in lower bond strengths (Tashman et al. 2006). In our study, proof-of-concept testing was conducted at the OSU parking lot to determine the possibility of using Oregon Field Tack Coat Tester (OFTCT) as a quality control (QC) and quality assurance (QA) test during construction to evaluate the degree of cleanliness of pavement surfaces before tack coat application. The developed procedure is expected to provide a method to quantify pavement surface cleanliness before tack coat application, improve bond strength, and increase pavement life.

In addition, research showed that using an infrared reflective heating lamp in the field results in less control of the temperature during the field tests and a significant increase in the variability of measured tack coat bond strength. This was due to the difficulty of controlling the tacked surface temperature at the softening point temperature during the tests and exposure to excessive heating. In this study, an adjustable heat gun and an environmental chamber were developed to maintain a steady temperature during the field tests.

The OFTCT device was developed at Oregon State University. A user-friendly software and wireless sensors (controlled via a tablet computer) were used to maintain a constant displacement rate and accurately control the movement of the loading platen. These contributions improved the reliability and repeatability of the experiments and enhanced the practicality of the OFTCT in the field. Finally, the development of the OFTCT device was very economical compared to the cost of the current technologies. The device gave acceptable and reliable results; hence, it can be adopted as a QC/QA test to evaluate the cleanliness of the pavement surface before tack coat application and predict the long-term performance of tack coats in the field.

2.5 Materials and methods

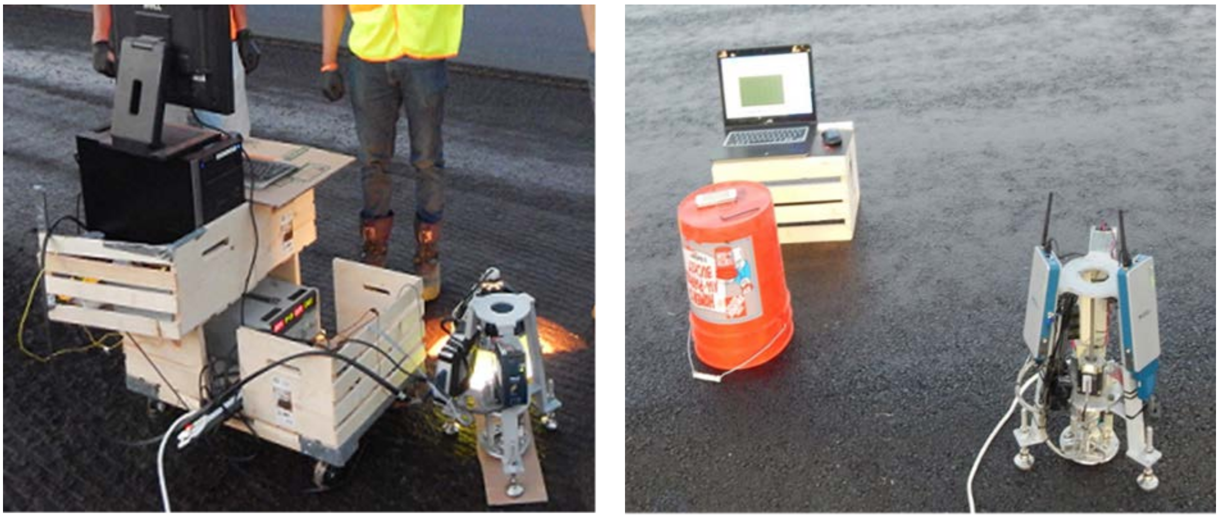
2.5.1 *Development of Oregon Field Tack Coat Tester (OFTCT)*

2.5.1.1 Prototype version

The prototype version of the OFTCT device was developed at OSU by using the specifications of the LTCQT (Figure 2-1a). In addition, several types of foams for the contact surface were evaluated and a high-density polyethylene foam was found to give the best adhesion among all the assessed materials. The prototype version of the OFTCT device was used to conduct all field experiments during construction. The reliability and repeatability of the test results were controlled using a control system and electronic sensors to ensure that the target displacement rate was applied accurately. The prototype version of OFTCT tester provided accurate displacement rates after being calibrated. A user-friendly software was developed to control the device and collect test data. The prototype OFTCT was connected to a computer using a cable. Difficulty in the movement of the wired OFTCT tester in the field was observed, which resulted in practicality issues such as reduced mobility and increased testing time. Using an infrared reflective heating lamp also resulted in excessive heating of the applied tack coat material and resulted in high-test results' variability.

2.5.1.2 Wireless Version

Several modifications were implemented in the new OFTCT device to overcome some technical issues that were observed in the prototype version of the OFTCT device (Figure 2-1a). The mobility and practicality issues were solved by installing a wireless acquisition and control system to facilitate the movement and the operation of the OFTCT device. Development of a user-friendly software also reduced the testing time and provided accurate results. Furthermore, the variability of the test results was reduced by developing an environmental chamber with an adjustable mobile heat gun to control the temperature of the tacked surface during testing. A procedure was then developed to determine the optimum curing time for the specified emulsion and determine the reasonable contact time between the loading platen and the tacked surface. Figure 2-1b illustrates the new wireless version of the OFTCT device.



(a) (b)

FIGURE 2-1: OFTCT SYSTEM IMPROVEMENTS (A) OFTCT PROTOTYPE VERSION (B) OFTCT WIRELESS VERSION

2.5.1.3 OFTCT hardware

The main device has the following components (Figure 2-2)

- The load cell (S-shape) was attached with three displacement transducers (pots) to measure the displacement rates of the very bottom plate. The average of the readings was automatically calculated to ensure that the displacement rate is applied accurately.
- Upper plate, which was used as a reference plate to measure the vertical displacement.
- Stepper modder, which creates the up and down movement. It was attached to power the phase of the stepper (Electric sensor for load and displacement).
- Frame with three adjustable legs, which were used to level the device.
- Loading platen, which was used to provide a proper contact surface between the glued circular foam and the tacked surface.
- Moveable loading cells to provide sufficient resistance against the tensile forces.
- Sensor controller device (wireless data acquisition) to wirelessly transfer the collected data (load and time) to the computer and control the device.
- An environmental chamber and exhaust pipe were developed to maintain a constant temperature.

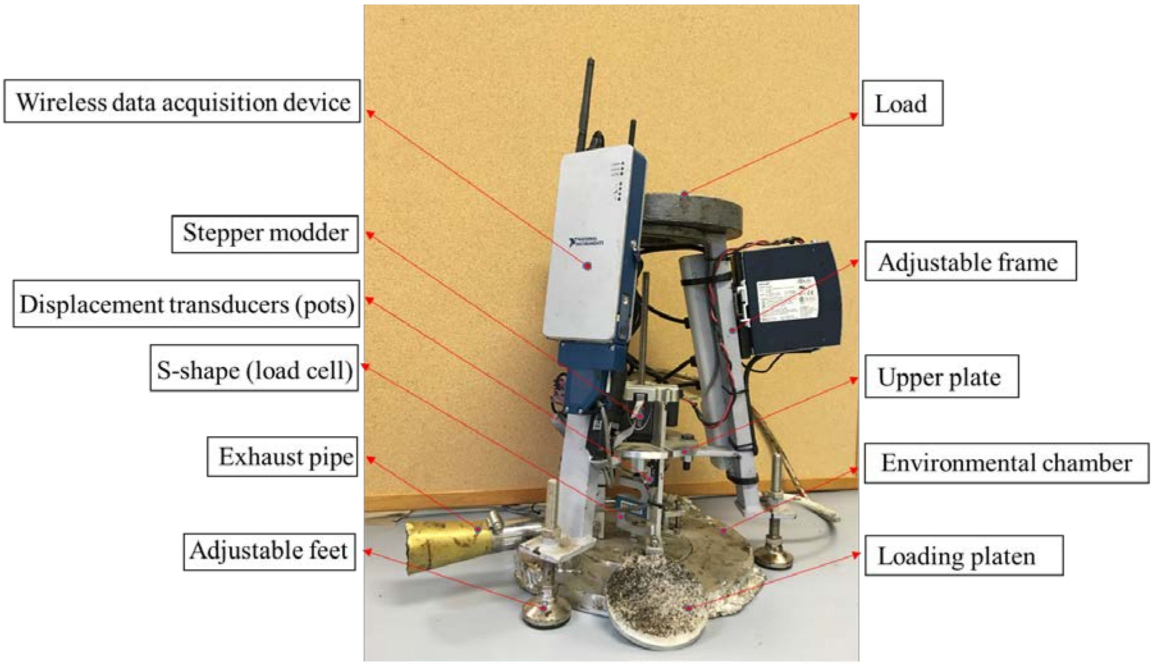


FIGURE 2-2: OFTCT DEVICE

2.5.1.4 OFTCT acquisition software

The developed software was designed to wirelessly collect all data from the OFTCT (Figure 2-3). The software allowed the users to change the displacement rate, control the device, deliver graphical results, and collect data transferred from the data acquisition system.

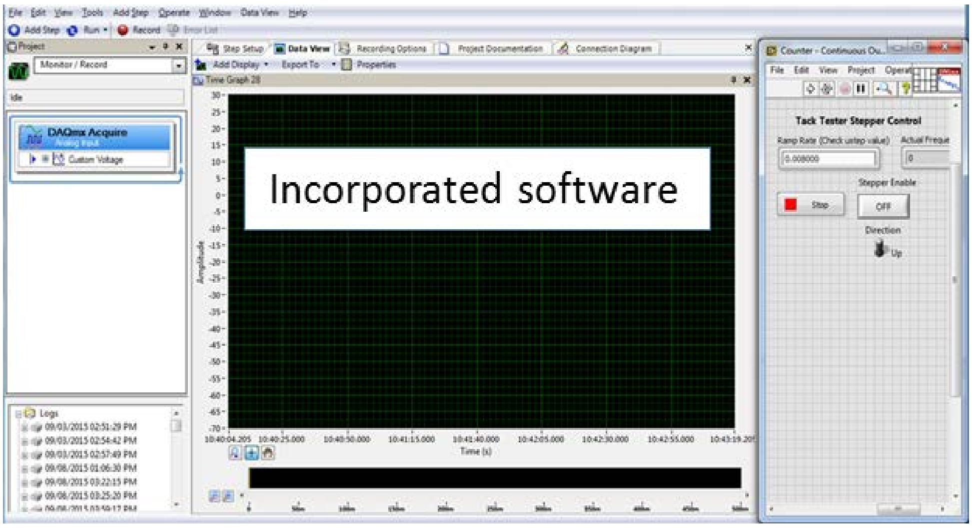


FIGURE 2-3: DEVELOPED SOFTWARE TO CONTROL THE OFTCT AND COLLECT DATA

2.5.2 *OFTCT field test procedure and tested sections*

The general layout of the experimental design is summarized in Table 2-1. In total, testing and sampling were conducted at three locations in the field. Asphalt overlays were constructed with two lifts. First lift (2.5 inches thick) was placed on a milled surface while the second lift (2 inches thick) was built on the new lift (without any milling) about a month after the construction of the first lift. Each location had the same tests performed for the milled and overlay surfaces. A test location consisted of three 200-foot sections, each of which contained a different target application rate (Table 2-1). Four to six replicate experiments were conducted on every section to reduce the impact of spatial variability on calculated average strength values. Location 1 and Location 2 were operating at normal highway speeds, northbound and southbound lanes respectively. Vehicle speeds on Location 3 were lower because it was located within a turning lane at an intersection. The six tack coat types considered in this study are shown in Table 2-1. Generic tack coat type labels are used to conceal the identity of the company providing the material. CSS-1H emulsions are the most commonly used slow-setting grades in Oregon. "New" emulsions are the engineered emulsions recently developed in Oregon to reduce tracking and increase interlayer shear strengths. After applying the tack coats, the OFTCT device was used to conduct replicate experiments on the milled and overlay surfaces.

TABLE 2-1: SITE LAYOUT FOR FIELD TESTING

Surface	Location	Tack Coat Type	Application Rates (gal/yd^2)
Milled	1	CO1_CSS 1H_a	0.08, 0.10, 0.12
	2	CO1_New_a	0.08, 0.12, 0.16
	3	CO2_New	0.08, 0.12, 0.16
Overlay	1	CO1_CSS 1H_b	0.05, 0.07, 0.10
	2	CO1_New_b	0.05, 0.07, 0.09
	3	CO2_CSS 1H	0.05, 0.07, 0.10

In addition, several experiments at Oregon State University's (OSU) laboratory and parking lot were performed to develop a test procedure for the OFTCT device. The procedure for operating the OFTCT device is given as follows (Figure 2-4):

- Circular pieces of high density thick foam were cut to approximately four inches in diameter.
- The circular foam was then glued to the loading platen using a fast setting high bond strength glue.
- A proper amount of time was allowed for the glue to cure before attaching the loading platen to the load frame (Figure 2-4a).
- After the tack coat application, random locations were selected within the section to conduct the experiments.
- The emulsion was heated for eight minutes at the specified softening point temperature to evaporate the water component in the tack coat (Figure 2-4b).
- An 80 lb. weight was placed on top of the frame to provide enough resistance against the tensile force (Figure 2-4c).
- The loading platen was lowered down, and a compressive load of 60 lbs. was applied for three minutes using the developed software (Figure 2-4d).
- A constant displacement rate of 0.008 in/sec was applied to pull the loading platen up, and the maximum tensile stress applied to break the bond was recorded. Figure 2-4e shows the surface of the tacked pavement after the conducted experiment in the field. Figure 2-4f shows a typical test result from a field experiment.

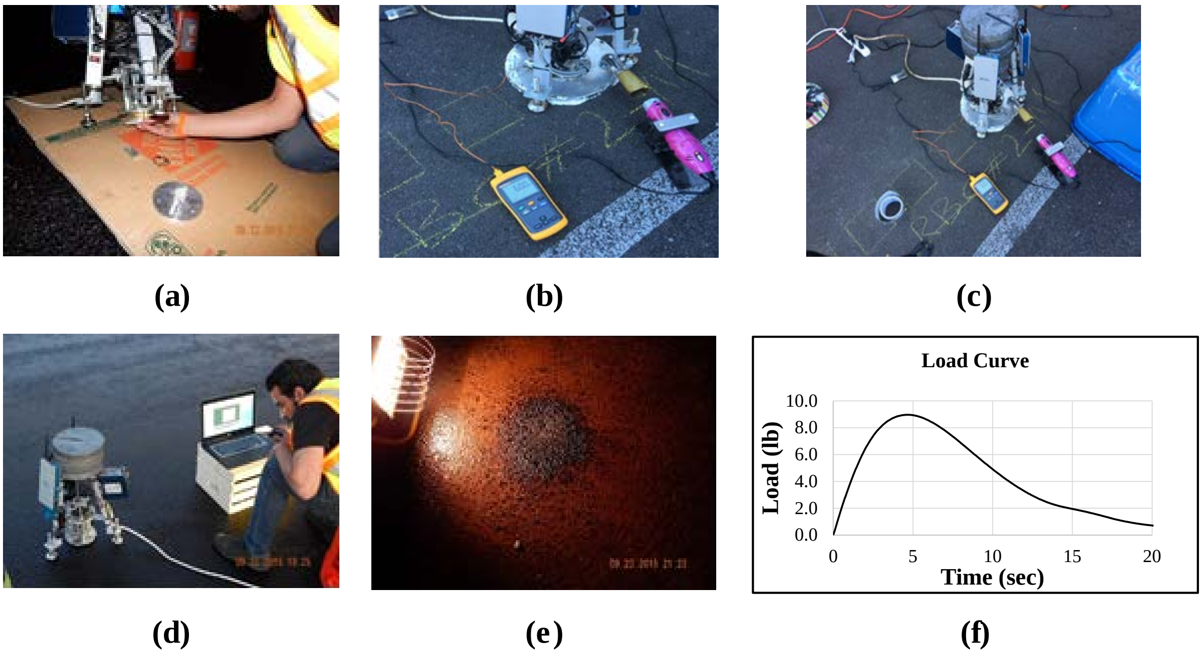


FIGURE 2-4: GENERAL PROCEDURE FOLLOWED FOR OFTCT FIELD EXPERIMENTS

2.5.3 *Procedure for measuring the application rates*

The purpose of this experiment was to ensure that the target application rate was achieved during construction. The following steps describe the procedure that was followed to measure the actual application rates for each location and section (ASTM Standard D2995, 2014):

- Before the distributor truck began applying the tack coat, 12-inch by 12-inch geotextile pads were weighed and placed end to end in the travel lane in the transverse direction (Figure 2-5a & b).
- The placed geotextile pads were weighed again, immediately after applying the emulsion on the pavement surface, using a high accuracy scale. An application rate was calculated by using the weight of the textile pad before and after spraying.

(a)

(b)

FIGURE 2-5: FIELD APPLICATION RATE MEASUREMENT

2.5.4 *Procedure for measuring mean texture depth (sand patch test)*

Prior to the testing, a traditional sand patch test was conducted in the field to measure the mean texture depth (MTD) of the pavement surface to be able to evaluate the effect of texture on bond strength (ASTM 965-96, 2015). Eight tests were performed at random spots within each of the three site locations. A known volume of sand was carefully spread over the pavement surface in a circular pattern to fill surface voids. Diameter readings of the circle were recorded on four axes, and the values were averaged. Calculated values were then used to calculate the MTD. Equation (2-1) was used to calculate the average macrotexture depth of the pavement surface.

$$MTD = \frac{4V}{\pi D^2} \tag{2-1}$$

Where;

- MTD = Texture depth (in).
- D = average diameter of sand patch circle (in).
- V = volume of sand used (in^3), (Weight of Sand/ Density of Sand**).**

2.5.5 *Lab shear test device and test procedure*

According to AASHTO TP114 (2015), the lab shear test was performed to evaluate the correlation between the results from OFTCT tests and lab shear tests. The results from the lab shear tests were considered as reference data (ground truth). For the purpose of this study, shear test equipment was developed by installing the load cell, transducers, and a data acquisition unit (Figure 2-6). A software was developed by Oregon State University to control the system and for automated data acquisition. Thirty full depth six inch diameter cores were taken from each location (a total of 90 cores from all three sections) (Table 2-1) (Figure 2-7a & b). The samples were then taken to the OSU laboratory where the shear testing was performed to evaluate the tack coat bond strength for milled and overlay surfaces.

(a) (b) (c)

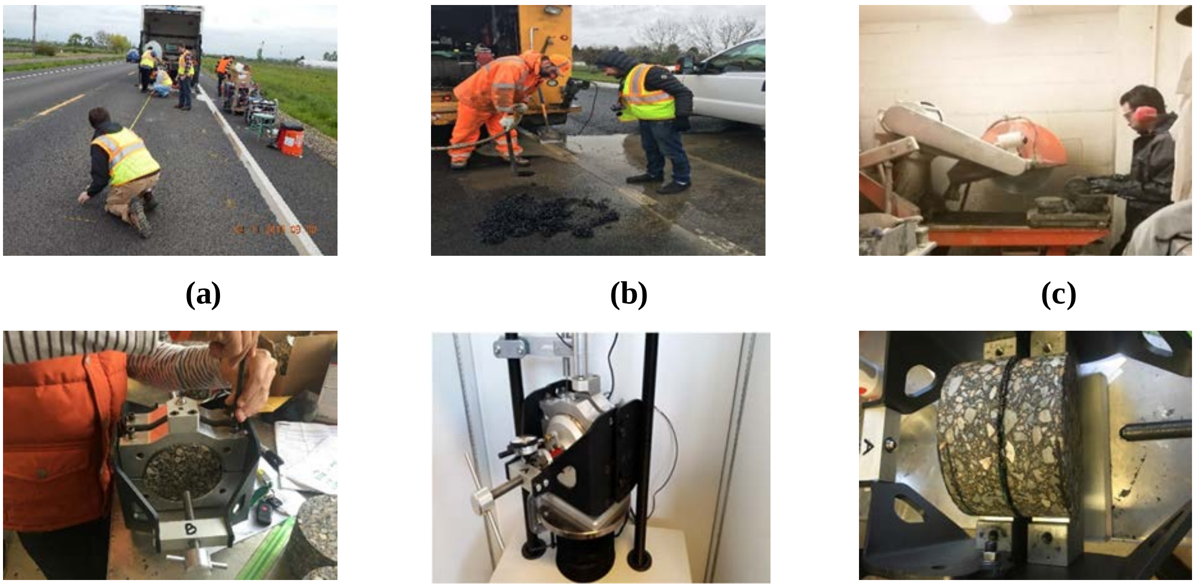
FIGURE 2-6: LAB SHEAR DEVICE

To prepare the samples, asphalt cores were sawn in the laboratory to provide the target dimensions necessary for testing (Figure 2-7c). The cores were placed inside the shear device with the direction of traffic arrow facing down (shearing direction) and the surface on the shearing side (Figure 2-7d). Then, the samples were positioned inside an environmental chamber where vertical and horizontal displacement sensors (LVDTs) were secured. The samples were left to be conditioned at 25°C for two hours (Figure 2-7e). A constant confining pressure (horizontal loading) of 20 psi was applied to the cores. Then, a constant displacement rate of 0.1in/min was applied until failure occurred (Figure 2-7f). After performing the lab direct shear test, the raw test data showed a high frequency noise. A Matlab filtering code was then used to reduce the noise interference. The shear strength was obtained using the following equation (2-2):

$$S = \frac{4P\ Max}{\pi\ D^2} \tag{2-2}$$

Where:

- S is the shear strength (psi)
- PMax is the maximum load applied to specimen (lb.)
- D is the specimen diameter (in).



(a) (b) (c)

(d) (e) (f)

FIGURE 2-7: STEP-BY-STEP PROCEDURE FOR THE LAB SHEAR TESTS

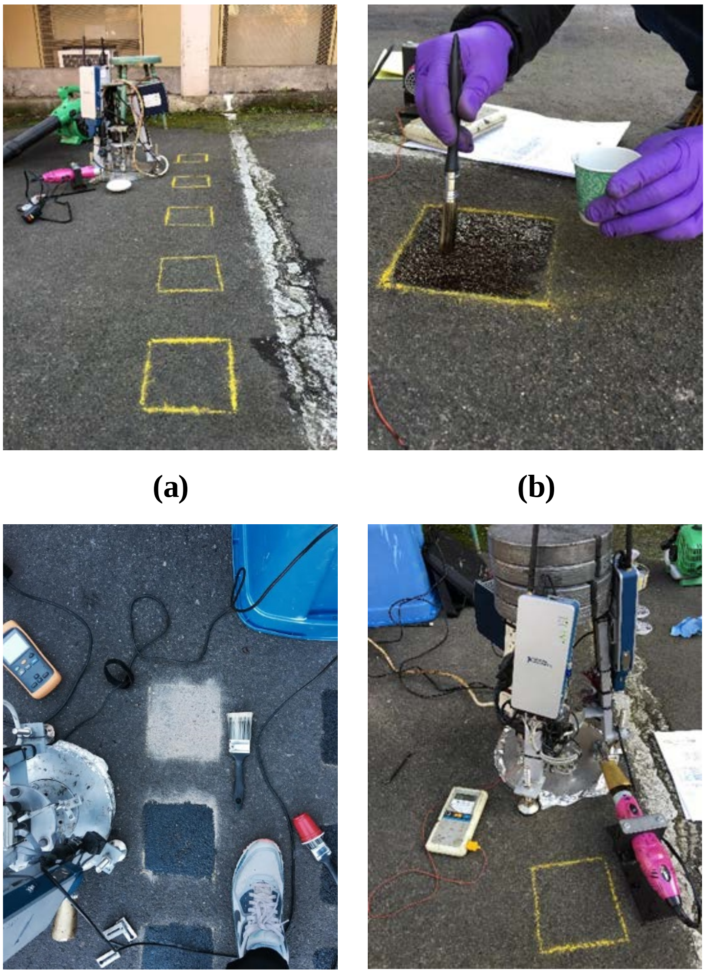
2.6 Temperature control system to reduce test results variability

A new temperature control system was developed to reduce measurement variability. Several replicate tests with CO1_CSS 1H_b emulsion at a medium rate were conducted. Six-inch by six-inch squares were drawn on a steel plate surface, and a medium application rate (0.07 gal/yd2) of CO1_CSS 1H_b emulsion was applied on the squares using a paint brush. The new temperature system was used to break the emulsion and control temperature during testing. To determine the contribution of using the new temperature control system to reduce test results' variability, results of the tests conducted with an adjustable heat gun with the aluminum chamber (new heating system) was examined and compared with the standard infrared reflective lamp. After spraying the emulsion, both the infrared reflective lamp and the adjustable heat gun were used to break the emulsion and control the temperature on 6-inch by 6-inch test squares for eight minutes. After eight minutes, the loading platen was lowered down to come into contact with the tacked surface for three minutes to create an adequate contact surface between the loading platen and the tacked surface. Then, the loading platen was raised upward and the tensile strength of the tack coat was measured. Using an adjustable heat gun heating system (Figure 2-8) allowed for accurate temperature control and provided an adequate means to prevent the tacked surface from the excessive heating.

FIGURE 2-8: A NEW TEMPERATURE CONTROL SYSTEM FOR OFTCT TO REDUCE MEASUREMENT VARIABILITY AND BIAS

2.7 OFTCT cleanliness experiments

Proof-of-concept testing was conducted at the OSU parking lot to determine the possibility of using OFTCT as a quality control (QC) and quality assurance (QA) test during construction to evaluate the degree of cleanliness of pavement surfaces before tack coat application. To determine the impact of cleanliness on measured tensile strength, three control experiments were conducted on the pavement surface cleaned by sweeping and washing. CO1_CSS 1H_b emulsion at a medium application rate (0.07 gal/yd^2) was used for testing. 6-inch by 6-inch squares were drawn on the pavement (Figure 2-9a) and calculated application rate was applied using a paintbrush (Figure 2-9b). To be able to determine the effect of cleanliness on the bond strength, again CO1_CSS 1H_b emulsion was applied at a medium application rate after applying the dust. A 0.07 lb/ft^2 of dust was applied using a paintbrush on a 6-inch by 6- inch square (Figure 2-9c) before applying the specified emulsion. Average tensile strength from the locations with and without dust was compared to evaluate the impact of cleanliness on bond strength. Figure 2-9d shows the OFTCT setup during testing.



(a) **(b)**

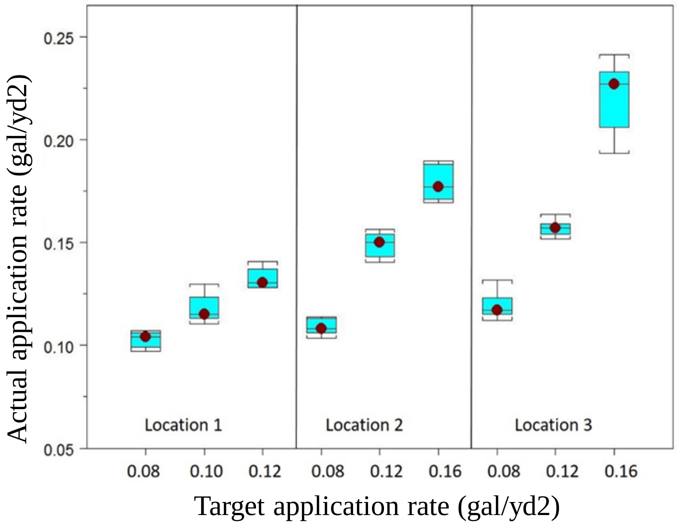
(c) **(d)**

FIGURE 2-9: STEP-BY-STEP PROCEDURE TO DETERMINE THE EFFECT OF DUST ON TENSILE BOND STRENGTH

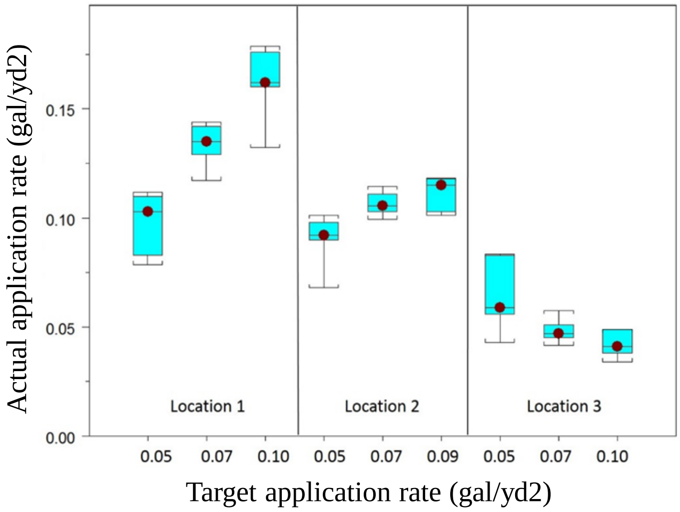
2.8 Results and discussion

2.8.1 *Measured application rates*

Figure 2-10 illustrates a boxplot of target versus actual application rates. Results show that there is a significant lack of control in tack coat application rates. Actual tack coat application rates for milled surfaces were consistently above the target values (Figure 2-10a) and showed an increasing trend from one rate to the next. Overlay surface spraying exhibited this same pattern only at Location 1. Location 2 overlay spraying showed that the actual rates are consistently above the target value, but there was no increasing trend from one rate to the next. Overlay surface spraying at Location 3 showed that application rates were consistently above the target values, but a decreasing trend was observed (Figure 2-10b). An increasing trend from one rate to the next, similar to Location 1 of the milled surface, is expected. Observable differences in actual application rates can be seen from the boxplots in all the milled surface locations and the overlay surfaces at Locations 1 and 2. These significant differences in target application rates allow the effects of application rate on interlayer shear strength to be observed. Overlay surface results at Location 3 exhibit no increasing trend from one rate to the next, which is unexpected. Results related to the effects of application rate on interlayer shear strength at Location 3-Overlay were inconclusive due to inaccurate tack application. Inaccurate application rates for Location 3-Overlay may be attributed to the use of the contractor's distributor truck (old truck) for this location only. Figure 2-11 illustrates the non-uniform tack coat application with the contractor's distributor truck.



(a)



(b)

FIGURE 2-11: BOXPLOT OF TARGET VS. ACTUAL APPLICATION RATES

(a) **(b)**

FIGURE 2-10: IMPACT OF DISTRIBUTOR TRUCK ON TACK COAT UNIFORMITY (A) NON-UNIFORM APPLICATION WITH STREAKS (CONTRACTOR'S DISTRIBUTOR TRUCK) (B) UNIFORM APPLICATION WITH THE NEW DISTRIBUTOR TRUCK

2.8.2 *Sand patch test*

Figure 2-12 shows the distributions of the mean texture depths (MTD) for all three overlay and all three milled test locations. At least eight replicate tests were conducted on each location and results are presented in Figure 2-12. It is apparent that there are not significant differences between the values of the measured MTDs on all overlay surface locations. When comparing the boxplots for the milled surfaces in Figure 2-12, it displays significant variability between all the tested locations. In addition, the milled surfaces had significantly higher MTD than all the overlay surfaces (Figure 2-12).

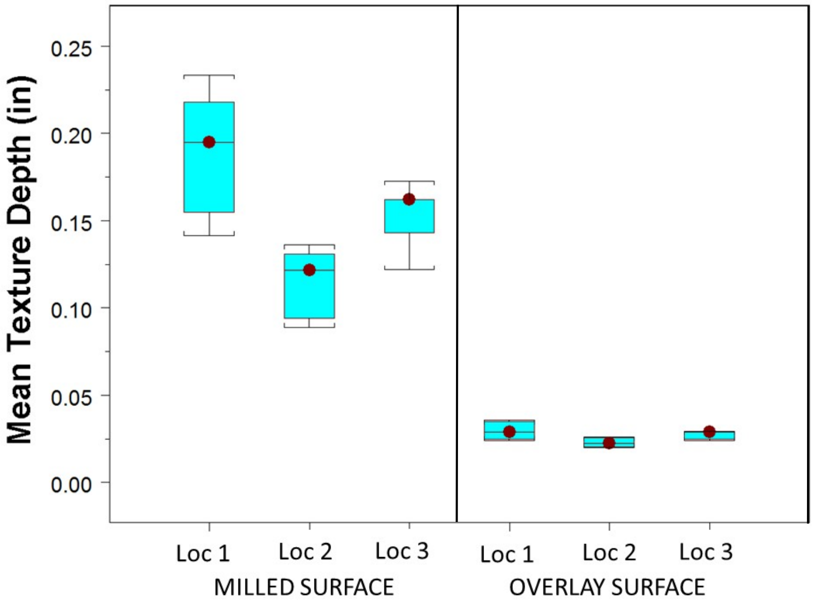


FIGURE 2-12: BOXPLOT OF THE MEAN TEXTURE DEPTH VS. LOCATIONS

2.8.3 *Correlation between the OFTCT and laboratory shear test results*

The correlation between the OFTCT and laboratory shear test results for the milled surface tests was observed to be low due to the impact of milled surface texture on laboratory shear test results. Since the OFTCT measures the tensile strength of the tack coat, the impact of texture on bond strength is not captured while texture effect is simulated in the lab shear tests. For this reason, only the correlations for the tests conducted on overlay surfaces are presented.

Average measured OFTCT strengths and average shear strengths measured from field cores from all nine test sections are shown in Figure 2-13. It can be observed that the correlation between OFTCT and laboratory shear test results is not statistically significant with a coefficient of determination of 0.1427. However, when the results from the section sprayed with the contractor's distributor truck (Figure 2-10b) Location 3-Overlay, were excluded from the comparisons, the correlation between OFTCT and laboratory shear test results becomes statistically significant with a coefficient of determination of 0.5189 (See Figure 2-14). Since the contractor's distributor truck was not able to apply the tack coat uniformly (Figure 2-11), OFTCT results from this section had a very high variability, which resulted in low correlations. It should be noted that OFTCT was able to identify the tack coat type with the highest ISS. The lower correlation for OFTCT (R^2 = 0.5189) can be related to the following factors:

- Different loading mechanisms: Tensile loading mechanism for the OFTCT is entirely different from the shear loading mechanism. In addition, tensile loads for the OFTCT are applied directly on the tacked surface while the shear loads are applied between the two layers of pavement after construction. Thus, the impact of surface texture on ISS cannot be directly measured by OFTCT.
- The use of the old infrared heating system for the field tests might have increased the variability in the OFTCT results since it was not possible to accurately control the temperature during the experiments. In addition, the excessive heating of the tacked surface might have created unreliable test results. The new temperature control system developed in this study is expected to minimize these problems.

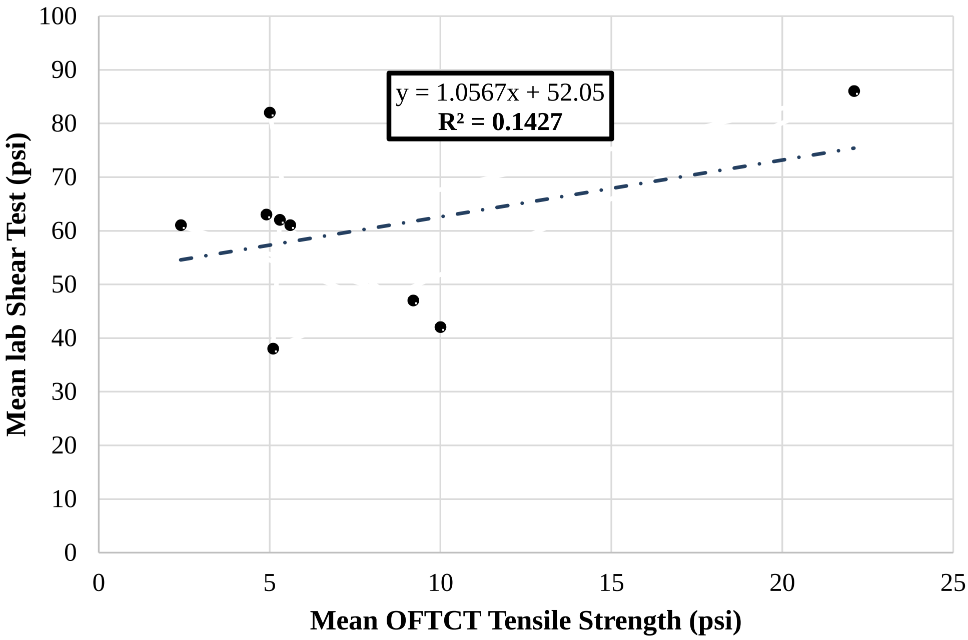


FIGURE 2-13: COMPARISON OF MEAN OFTCT TENSILE STRENGTH AND MEAN LABORATORY SHEAR STRENGTH MEASURED ON OVERLAY SURFACES

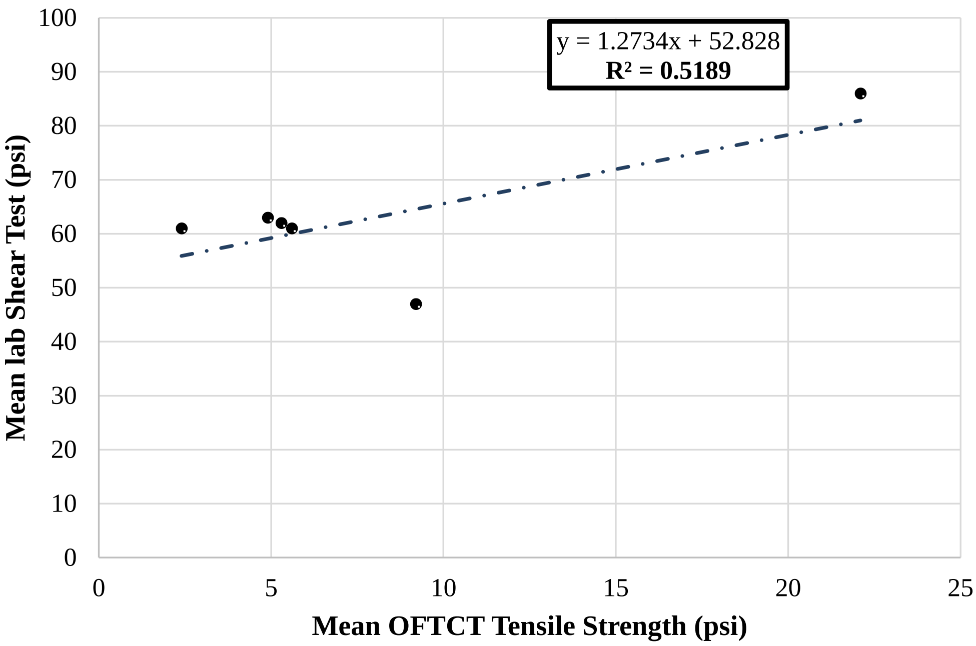


FIGURE 2-14: COMPARISON OF MEAN OFTCT TENSILE STRENGTH AND MEAN LABORATORY

2.8.4 *Comparison of test results' variability for the standard and new heating systems*

Figure 2 15 shows the results of the tests conducted by using an adjustable heat gun with the aluminum chamber (new system) and infrared reflective heating lamp (standard system). It can be observed that using the new temperature system provided a reduction of approximately 12% in total measurement variability when compared with the infrared reflective heating lamp. However, using the new system resulted in lower strength values. The reduction in the measurement variability helps to provide a more reliable evaluation of the tack coat performance. In addition, results revealed that using the new heating system provided a more accurate control of the test temperature. This contribution is expected to enhance the reliability of the test results.

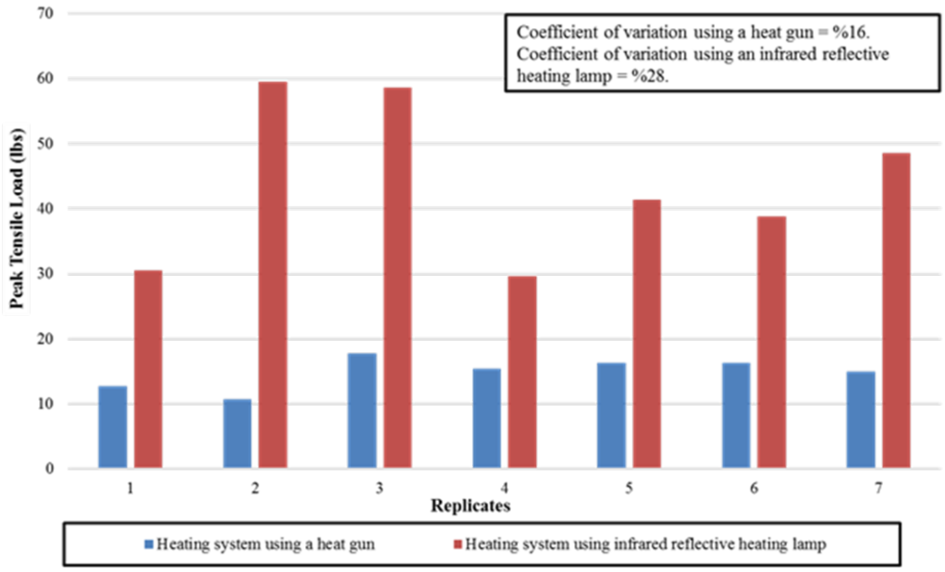


FIGURE 2-15: HEAT GUN SYSTEM VS. INFRARED REFLECTIVE HEATING LAMP

2.8.5 *OFTCT cleanliness experiments*

Results of the cleanliness experiments showed that having dust on the pavement surface before tack coat application created a significant reduction (about 10 to 20 %) in the measured tensile strength of the tested tack coat (CO1_CSS 1H_b) (Figure 2-16). The applied dust breaks the bond between the pavement surface and the applied tack coat and creates a lower bond strength. The same experiment can be conducted in the field during construction to evaluate the cleanliness of the pavement surface before tack coat application. After milling and sweeping the pavement surface during construction, one side of the pavement can be cleaned by washing to conduct control experiments. Test results from the actual pavement surface (without further cleaning) can be compared with the results from the cleaned surface to evaluate the cleanliness of the pavement surface. An allowable percentage reduction in tensile strength (should be less than 10%) can be set to use this experiment as a QC/QA tool during construction to evaluate cleanliness. If the measured percent reduction in strength is higher than the allowable value, further sweeping and cleaning can be done to increase the bond strength.

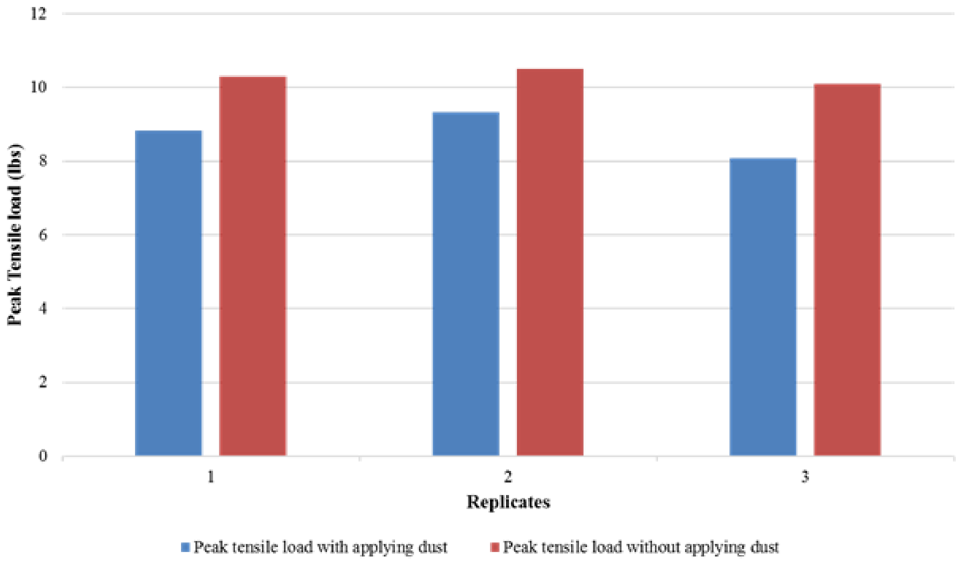


FIGURE 2-16: THE EFFECTIVENESS OF DUST ON PEAK TENSILE LOAD AT MEDIUM APPLICATION RATE

2.9 Summary and conclusions

In this study, Oregon Field Tack Coat Tester (OFTCT) was developed by using the Louisiana Tack Coat Quality Tester (LTCQT) device as a reference in order to create a practical method and test system to evaluate and improve the long-term tack coat performance. The OFTCT system was developed to predict the long-term performance of tack coat bonds based on the results of tests conducted during construction. In addition, the OFTCT device was used to evaluate the impact of pavement surface cleanliness before tack coat application on bond strength. Wireless sensors installed on the OFTCT significantly improved the mobility and practicality of the device in the field. In order to reduce the tack coat's curing time in the field and control temperature during testing, an adjustable heat gun and environmental chamber were developed. The results indicated that the new temperature control system resulted in a 12% reduction in measurement variability. The results further revealed that using the new heating system provided consistent and reliable temperature control, and prevented excessive heating of the tacked surface. It was also determined that the OFTCT can be successfully utilized in the field as a test to quantify the cleanliness of the pavement surfaces before tack coat application. The correlation between OFTCT and laboratory shear test results is determined to be statistically significant ($R^2 = 0.5189$). However, more field experiments need to be conducted to implement it as a test to predict in-situ interlayer shear strength (ISS). It should be noted that OFTCT was able to identify the tack coat type with the highest ISS.

2.10 Future work

The following future work is required to improve the OFTCT and start using it for long-term tack coat performance monitoring and cleanliness evaluation:

- Conduct more experiments with the new wireless version of the OFTCT and the new temperature control system on milled and overlay surfaces to evaluate the impact of system improvements on test results.
- Cleanliness experiments should be conducted in the field during construction to determine the effectiveness of this test as QC/QA tool to increase bond strength.
- After conducting several field experiments with the OFTCT and using the test results from this study, a minimum acceptable tensile strength limit should be specified to determine the quality of the tack coat used during construction.
- The OFTCT device should be evaluated by conducting tests with several different tack coat types to create a better understanding of the effectiveness of OFTCT as a QC/QA tool to assess long-term tack coat performance.

2.11 References

ASTM. ASTM D4541 – 09 Standard Test Method for Pull-Off Strength of Coatings Using Portable AdhesionTesters1. Section 2 in August 2010.

ASTM Standard D2995. (2014). Standard Practice for Estimating Application Rate of Bituminous *Distributors* and Residual Application Rate of Bituminous Distributors. West Conshohocken, PA: ASTM International.

ASTM Standard E965. (2015). Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique.

AASHTO TP114. (2015). Standard Method of Test for Determining the Interlayer Shear Strength (ISS) of Asphalt Pavement Layers. Washington, D.C.: AASHTO.

Buchanan, S. and M. Woods. "Field Tack Coat Evaluator (ATACKer™)", Final Report, FHWA/MS-DOT-RD-04-168, December 2004

Cortina, A.S. 2012. Optimization of In-Situ Tack Coat Application Rate and Installation. Master's Thesis. University of Illinois.

Deysarkar, I. (2004). Test set-up to Determine Quality of Tack Coat. Univeristy of Texas at El Paso. Retrieved from http://search.proquest.com/docview/305103314

FPO. (2001). Technical Bulletin: Proper Tack Coat Application. Dublin, OH.

Hachiya, Y., & Sato, K. (1997). Effect of Tack Coat on Bonding Characteristics at Interface between Asphalt Concrete Layers. In 8th International Conference on Asphalt Pavements (pp. 349–362). Retrieved from https://trid.trb.org/view.aspx?id=50163

Krebs, R. D., & Walker, R. D. (1971). *Highway Materials*. New York, New York: McGrawHill Inc.

Leng, Z., Al-Qadi, I. L., Carpenter, S. H., & Ozer, H. (2008). Interface Bonding Between Hot-Mix Asphalt and Various Portland Cement Concrete Surfaces. Transportation Research Record: Journal of the Transportation Research Board, 46–53. http://doi.org/10.3141/2127-03

Mohammad, L. N., & Button, J. (2005). Optimization of Tack Coat for HMA Placement. In NCHRP 9-40. Washington, D.C.: National Cooperative Highway Research Program (NHCRP), Transportation Research Board, National Research Council.

Mohammad, L. N., Elseifi, M. A., Bae, A., Patel, N., Button, J., & Scherocman, J. A. (2012). Optimization of Tack Coat for HMA Placement (NCHRP Report 712). In NCHRP Report 712. Washington, D.C.: National Cooperative Highway Research Program (NHCRP), Transportation Research Board, National Research Council.

Roffe, J. C., & Chaignon, F. (2002). Characterization tests on bond coats: worldwide study, impact, test, and recommendations. In 3rd International Conference of Bituminous Mixtures and Pavements. Thessaloniki. Retrieved from https://trid.trb.org/view.aspx?id=681964

Sholar, G., Page, G., Musselman, J., P, U., & H, M. (2004). Preliminary Investigation of a test method to evaluate bond strength of bituminous tack coats (with discussion). Association of Asphalt Paving Technologies, 73, 771–806. Retrieved from https://trid.trb.org/view.aspx?id=750009

Tashman, L., Nam, K., & Papagiannakis, T. (2006). Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength Between Pavement Layers. Report prepared for Washington State Department of Transportation #WCAT 06-002.

TxDOT. (2001). Proper Use of Tack Coat. Texas Department of Transportation.

USACE. (2008). Bituminous Tack and Prime Coats. In Unified Facilities Guide Specifications (pp. 1–17). U.S. Army Corps of Engineers. http://doi.org/10.1017/CBO9781107415324.004

Walsh, I. D., & Williams, J. T. (2001). HAPAS certificates for procurement of thin surfacing. Highways and Transportation, 48(7-8), 12–14. Retrieved from https://trid.trb.org/view.aspx?id=715783

3 CHAPTER 3 - DEVELOPMENT OF A FIELD TORQUE TEST TO EVALUATE IN-SITU TACK COAT PERFORMANCE

Aiman Mahmoud; Erdem Coleri; James Batti; and David Covey

Abstract:
Tack coats are bituminous materials applied between pavement lifts to provide adequate bonding between the two surfaces. The adhesive bond between the two layers helps the pavement system to behave as a monolithic structure and improves the structural integrity of the pavement. The absence, inadequacy or failure of this bond result in a significant reduction in the shear strength resistance of the pavement structure, making the system more vulnerable to distress types such as rutting, cracking and potholes. For this reason, monitoring the performance of the interlayer shear strength (ISS) during the use phase and identifying bond failures are critical to improving pavement management systems and develop more efficient pavement design strategies. It is crucial to monitor the performance of tack coats regularly and measure the changes over time. However, testing cores taken from roadways in the laboratory is not economical and practical. In addition, removal of full depth cores can affect the structural integrity of the pavement and can create localized failures. In this study, a low cost, practical, and less destructive field test device, the Oregon Field Torque Tester (OFTT), is developed to evaluate the long-term post-construction tack coat performance of pavement sections. Correlations between OFTT field test results and the results of laboratory shear tests conducted with cores taken from the field were investigated to determine the effectiveness of the OFTT tests. The peak torque values measured by the OFTT were observed to be highly correlated with the measured laboratory shear strengths. The OFTT shear strength values calculated by using the torque test results and a theoretical equation were determined to be close to the measured laboratory shear strengths.

Key Terms: Emulsion, application rate, lab shear test, tack coat, bond strength, torsional, and torque.

3.1 Introduction

Flexible pavements are generally comprised of multiple hot-mix asphalt (HMA) layers on top of aggregate base and subgrade layers. The strength of the bond at the interface between the HMA layers plays a significant role in improving the integrity and the performance of the structure. A tack coat is a thin layer of asphalt emulsion that is applied during construction to bond the pavement lifts. Commonly, tack coats are applied between the existing HMA layer and the new overlay to provide bonding, allowing the pavement structure to act as a monolithic unit (www.pavementinteractive.org).

Tack coat types, surface texture, application rate, and environment are the factors that affect the performance of the adhesive bond between pavement layers and are the subjects of investigation. The lack of an accurate quality control procedure to ensure tack coat performance in the field results in a greater probability of observing cracking and deformation in the pavement structure. As a result, the absence of tack coat adhesion at the layer interface creates slippage between pavement layers. Slippage results in enormous reduction in shear strength and therefore the pavement structure will be exposed to severe failures and distresses such as cracking, rutting, and potholes (Tashman et al. 2006). A 10% reduction in bond strength at the layer interface decreases fatigue life of the pavement structure by 50% (King et al. 2003). Furthermore, the absence of the bond between layers can reduce pavement life from 20 years to seven or eight years (Chaignon et al.2001). As it stands, there is a lack of experiments being conducted that evaluate the in-situ performance of tack coats. Hence, it is very important to regularly monitor the performance of tack coats and to measure the changes over time. However, testing full-depth cores taken from roadways in the laboratory is not economical and practical. In addition, removal of full depth cores can reduce the structural performance of pavement and can create localized failures. In this study, a practical and less destructive test device (Oregon Field Torque Tester) is developed to measure the long-term performance of tack coats in the field and in the laboratory.

3.2 Objectives

The objectives of this study are to:

- Develop a new low-cost technology, the Oregon Field Torque Tester (OFTT), to evaluate the long-term tack coat performance of pavement sections after construction. This new technology allows for a more practical test method and is less destructive as compared to the laboratory shear testing;
- Investigate the effectiveness of OFTT by evaluating the correlations between the laboratory shear and OFTT test results; and
- Provide recommendations to improve the developed system further.

3.3 Current torque tester technologies

The current laboratory shear testing technologies to determine tack coat bond strength require full depth field cores, which reduce the structural integrity of the pavement. Changing the structural integrity of the pavement by taking cores can damage/weaken the subgrade layer when water penetrates through the core holes. Even though the OFTT developed in this study also requires coring, it is still less destructive when compared to the laboratory direct shear tests, because full-depth cores are not needed for testing, and the diameter of the cores are only 2.5 inches.

The torque bond test was created in Sweden; it is a testing method used to evaluate field bond strength. The UK adopted this method and it became a part of the approved testing system for tack coats (Walsh et al., 2001). After construction, cores were drilled to a depth of half an inch below the layer interface and left in contact with the pavement. Then, the loading platen was glued to the drilled core by using a fast setting epoxy. A constant torque rate was manually applied to the cored surface using a wrench until failure occurred (Walsh et al., 2001). This test procedure is based on the British Board of Agreement guidelines document SG3/98/173. However, since it is difficult to control the constant torque rate manually, high variability in test results can be observed. The measured peak torque is used as a parameter to characterize the interlayer shear strength (ISS) at the layer interface.

Another study compared results from Florida's laboratory shear test against those of the manual bond torque test (Tashman et al. 2006). It was found that the correlation between the Florida laboratory shear test and the torque bond test results were not statically significant even though the effect of the milled surface on ISS was captured in the data (Tashman et al. 2006). However, both tests provided different ISS values at the interface due to the differences in their loading mechanisms. The difficulty of maintaining a constant torque rate manually was another reason for the low correlation. In addition, since the torque bond tester was not able to apply the high torque levels required to break the bonds with high strength levels, it was difficult to get reliable results for cores with high bond strengths.

Muslich (2010) developed an automatic laboratory torque device to evaluate the tack coat bond strength. In the laboratory test procedure, specimens with 100mm diameter were used. Gluing the cylindrical loading platen, 100mm in diameter and 10mm in thickness, to the top and bottom of the specimens allowed for easy and secure placement into the test frame. After the applied glue had been cured, the core was placed inside a temperature-controlled cabin for five hours. To ensure that the test was conducted at a constant torque rate (600Nm/mm), a constant vertical force was applied to the rack with a steady and continual torque rate. To test the constant rotation rate (180^{o}/min), a constant vertical displacement rate was applied to the rack. Use of a load cell and an LVDT incorporated into the axial testing machine allowed for measurement of the vertical force and the corresponding displacement. The results from both torque and shear experiments indicated that there was a high correlation ($R^2 = 0.89$) between the two methods and illustrated that the nominal shear strength obtained at 180^{o}/min was 1.9 times higher than the nominal shear strength measured at 600Nm/mm (Muslich, 2009). Although the developed torque test equipment provided reliable results, it can only be used to conduct experiments in the laboratory.

3.4 Proposed solution and challenges

This study focused on developing a new low-cost technology that would be used to evaluate the long-term post-construction tack coat performance of pavement sections. The OFTT device is specifically designed to measure in-situ ISS comparable to those of other destructive tests. The OFTT combines several proprietary technologies including software and automated rotation rate control, allowing the device to be used easily in the field. This practical software was developed to control the rotational speed rate and the movement of the platen relative to the cored sample. A small platen of 2.5 inches in diameter was considered to reduce the cost, test timing, and to reach the peak torque with less energy. The reduction of the diameter results in less damage to the pavement structure compared with laboratory shear tests, which requires extracting full-depth 6-inch diameter cores from the pavement. In addition, the developed OFTT device system was designed to carry out multiple experiments in less than two hours in both field and laboratory settings. An adjustable heat gun and temperature control box were also developed to control the temperature for testing. In the final analysis, the device gave acceptable and reliable results; hence, it can be adopted as a test to evaluate the long-term bond performance of pavement structures.

The system needed to be designed to overcome several challenges:

- Practical issues such as drying the samples before testing: A blower and a vacuum were used to remove the water from coring and dry the samples without removing them from the pavement.
- Temperature control in the field was a significant concern, hence; a temperature control box with an adjustable heat gun and a thermometer were used to maintain/regulate the temperature.
- A practical software needed to be developed to allow the use of the OFTT device easily in the field.
- The design of a light adjustable frame was required to allow for comfortable mobility.
- All samples were cored at one inch below the interface to avoid the failure at the bottom of the cored specimen. Doing so provided a confining pressure between the lower part of the core and the layers below at comparable stress levels within the pavement structure.
- Multiple platens needed to be developed to be able to conduct more experiments in a shorter period of time.
- The best adhesive significantly stronger than the tack coat bond was necessary to minimize adhesive deformation and failure in the test. In addition, the curing time for the adhesive was required to be less than half an hour to be able to conduct several field experiments in a short period of time.

3.5 Materials and methods

3.5.1 *Development of Oregon Field Torque Tester device (OFTT)*

Universally, the tack coat bond failure mechanism is characterized by three mechanisms: direct shear, direct tension and torque shear tests. For the research conducted, the bond strength at the interface between pavement layers was determined using two types of testing: a lab direct shear test and an OFTT in-situ torque test.

The OFTT device was developed at Oregon State University. The hardware of the device was developed by installation of, automatic step motor, planetary gearbox, transducers, torque sensor and amplifier, data acquisition and control system, and an adjustable frame as shown in (Figure 3-1). Figure 3-2 reveals the software that was developed to control the rotation speed of the system and facilitate connection between the loading platen and the core sample surface. In addition, the software was designed to display real time plot to allow real-time viewing and analysis of the data.

3.5.1.1 OFTT hardware

Stepper motor

The initial torque is produced by a Nema Size 34K high torque, bipolar stepper motor rated at 134 in-lbs. of torque. Step size can be as large as 1.8 degree/step or reduced through micro-stepping technology to accommodate the required load rate.

Stepper driver (Not Shown)

The bipolar microstep driver accepts stepper timing, enable and direction signals from the control system and produces the necessary current to drive the stepper motor accordingly. Microstepping technology is used to produces slower rotational speeds along with smoother motion. The rotational speed of the stepper is determined by the frequency of a pulse train generated by the data acquisition and control system.

Planetary gearbox

The planetary gearbox was designed to interface directly with the NEMA 34K stepper motor. It produces a 50:1 reduction in angular velocity while increasing the available torque by the same ratio. It is important to understand that the maximum torque of drive system is affected by the angular velocity of the stepper motor and the microstepping.

Torque sensor, transducer, and amplifier

The torque sensor is capable of sensing torques in the range of 0 – 500 in-lbs. and outputs a proportional voltage. The Amplifier provides gain and conditioning of the torque sensor signal making it suitable to record by a data acquisition system.

Data Acquisition and Control System (Not Shown)

The system consists of a laptop running the data acquisition and control software, which communicates through a USB interface with a multipurpose device that provides digitization of the torque sensor amplifier signal as well as timing and control signals for the stepper motor driver. The multipurpose device digitizes the incoming torque voltage to 16-bit resolution at a scan rate of 50Hz and sends the digital values to the laptop for logging on a hard drive. The multipurpose device also receives control commands from the laptop and outputs the required digital control signals to the stepper driver.

Environmental chamber

It is used to maintain the core sample at specified temperature 25^{o}C using a heat gun.

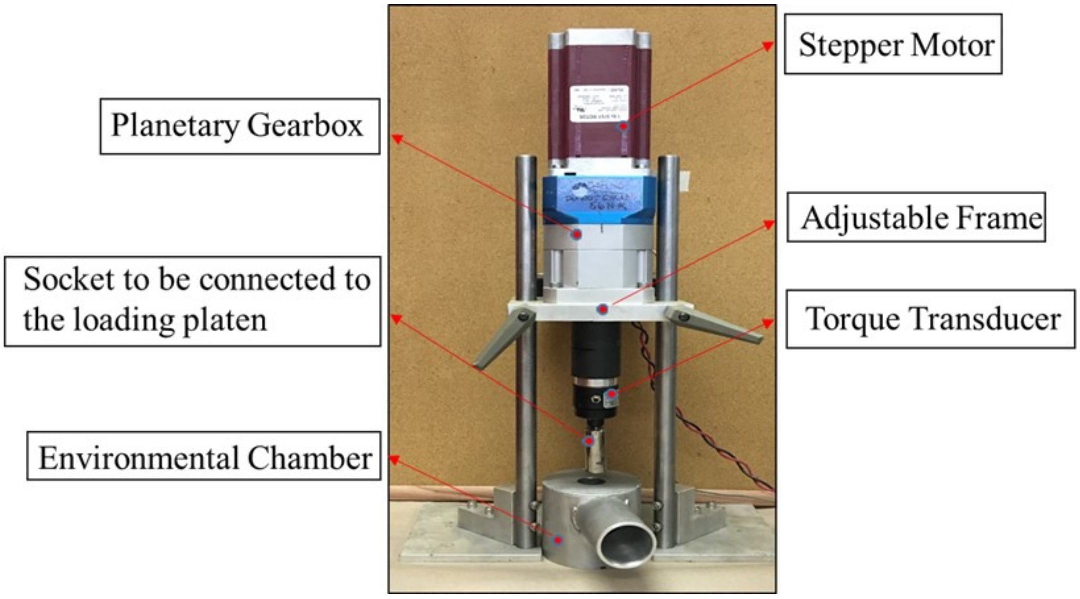


FIGURE 3-1: OFTT DEVICE

3.5.1.2 OFTT acquisition software

Control software

The control software is a GUI written in Lab view and allows the operator to enable the stepper, change the direction of rotation as well as the rotational speed. The desired rotational speed is entered by the operator in the appropriate and simple on/off toggle switches allow the operator to enable the stepper or change its direction of rotation.

Data acquisition software

The data acquisition software is a GUI written in LabVIEW and allows the operator to specify the proper conversion factor for the torque sensor voltage into physical units as well as the data acquisition scan rate and the name of the data output file on the hard drive. A real time plot is also provided allowing real time viewing and analysis of the data (Figure 3-2).

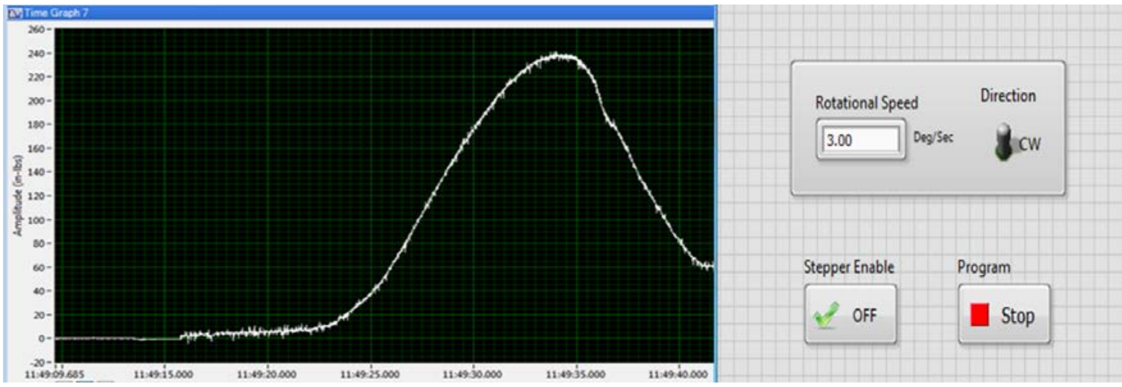


FIGURE 3-2: OFTT SOFTWARE

3.5.2 *OFTT field test procedure and tested sections*

According to several surveys, slow setting emulsions such as SS-1, SS-1h, CSS- 1, and CSS-1h are the most commonly used tack coat materials (Tashman et al. 2006, Mohammad et al. 2012). The selection of tack coat type is important to ensure sufficient adherence between pavement lifts. Slow setting emulsions are materials that are more favorable because they resist fracture longer than rapid setting emulsions. In the experimental plan of this study, two emulsions were sprayed during construction at two different locations. One location was sprayed with CO1_CSS 1H_b emulsion at medium and high application rates of 0.07 and 0.1 gal/yd2. CO1_New_b emulsion is an engineered emulsion recently developed in Oregon. This emulsion allowed for reduced tracking and increased bond strengths. It was sprayed at one location at a medium application rate of 0.07 gal/yd2.

The general procedure followed for OFTT field experiments is illustrated with photographs in Figure 3-3. The step-by-step procedure for the OFTT field testing is described as follows:

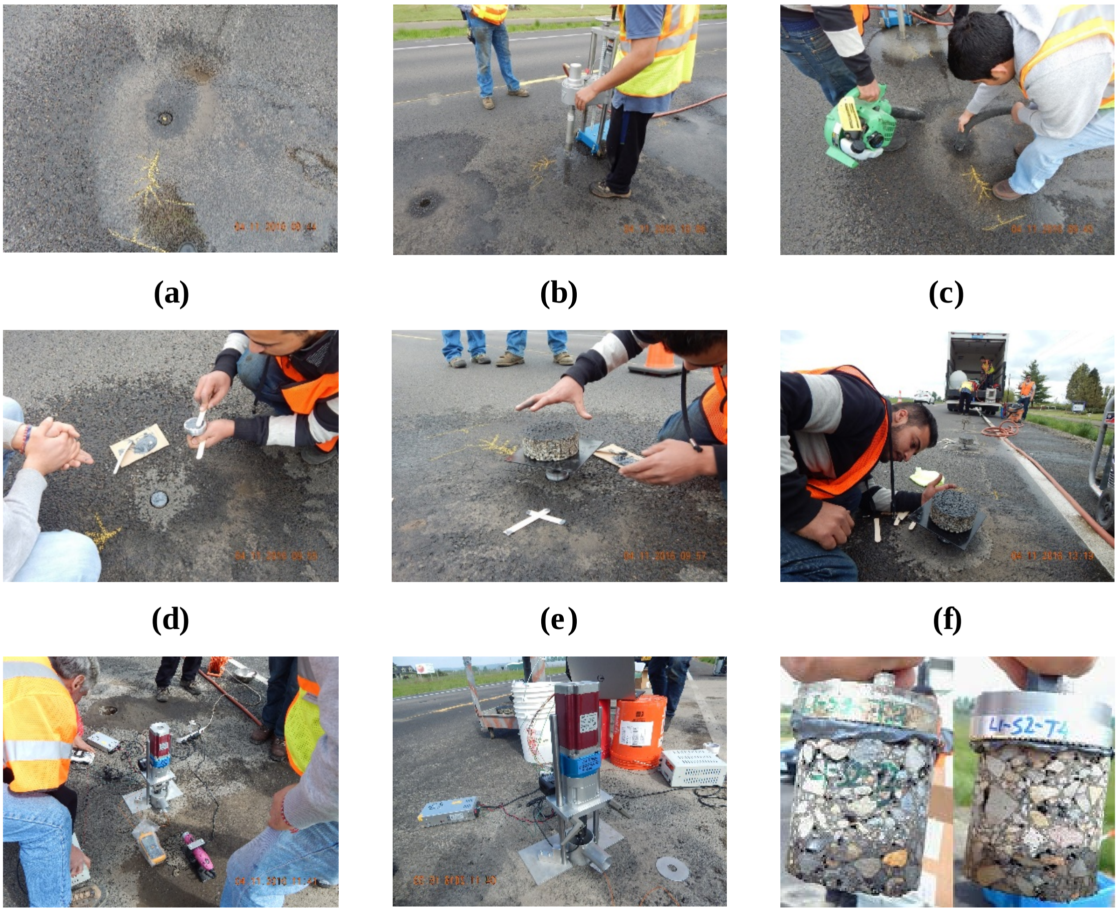
- Seven months after construction, torque tests were conducted on new asphalt overlays. In order to minimize the effect of spatial variability on laboratory versus in-situ test results comparisons, a total of eleven, 2.5-inch diameter cores were drilled at a distance of one foot from each of the 6 inch cores that were used for laboratory shear testing (Figure 3-3 a).

- Each of the 2.5-inch diameter cores was drilled to a depth of one inch below the layer interface and at least three locations were drilled on every section (Figure 3-3b).
- After drying the sample area by using a vacuum and blower (Figure 3-3c), a fast setting epoxy mix was used to glue the platen to the cored sample surface (Figure 3-3d).
- Weight was applied for one hour to cure and strengthen the contact surface between the loading platen and core sample (Figure 3-3 e).
- Multiple platens were glued to be able to conduct several experiments in a short period of time (Figure 3-3f).
- A thermometer, temperature control box, and portable heat gun were used to maintain/regulate the temperature at 25°C (Figure 3-4g)
- The OFTT experiment was performed to measure the peak torque stress (strength) at the interface between pavement layers (Figure 3-3h).
- (Figure 3-3i) shows the failure interface after performing the OFTT test. It can be observed that no shear bands were formed on the sample during the test and the maximum measured torque can be expected to provide the actual strength of the tack coat bond.
- After obtaining the peak torque strength for each sample, the measured torque strength (Nm) was converted to OFTT shear strength (kPa) using the Equation (3-1) given below (Muslich, 2010):

$$\tau = \frac{12M \times 10^6}{\pi D^3} \tag{3-1}$$

Where;

- τ is the inter-layer bond strength (OFTT shear strength) (kPa);
- M is the peak torque at failure (N.m);
- D is the diameter of the core (mm).



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

FIGURE 3-3: GENERAL PROCEDURE FOLLOWED FOR OFTT FIELD EXPERIMENTS

3.5.3 *Procedure for measuring the application rates*

The purpose of this experiment was to ensure that the target application rate was applied properly. For a quality assurance (QA) process, this procedure was performed prior to testing. The following steps describe the procedure that was followed to measure the actual application rates for each location and section (ASTM Standard D2995, 2014) :

- Before the distributor truck began applying the tack coat, 12 inch by 12-inch geotextile pads were weighed and placed end to end in the travel lane in the transverse direction (Figure 3-4a & b).
- The placed geotextile pads were weighed again, immediately after applying the emulsion on the pavement surface, using a high accuracy scale. An application rate was calculated by using the weight of the textile pad before and after spraying.

(a) (b)

FIGURE 3-4: FIELD APPLICATION RATE MEASUREMENT

3.5.4 *Procedure for measuring mean texture depth (sand patch test)*

Prior to the testing, a traditional sand patch test was conducted in the field to measure the mean texture depth (MTD) of the pavement surface to be able to evaluate the effect of texture on bond strength (ASTM 965-96, 2015). Eight tests were performed at random spots within each of the three site locations. A known volume of sand was carefully spread over the pavement surface in a circular pattern to fill surface voids. Diameter readings of the circle were recorded on four axes, and the values were averaged. Calculated values were then used to calculate the MTD. Equation (3-2) was used to calculate the average macrotexture depth of the pavement surface.

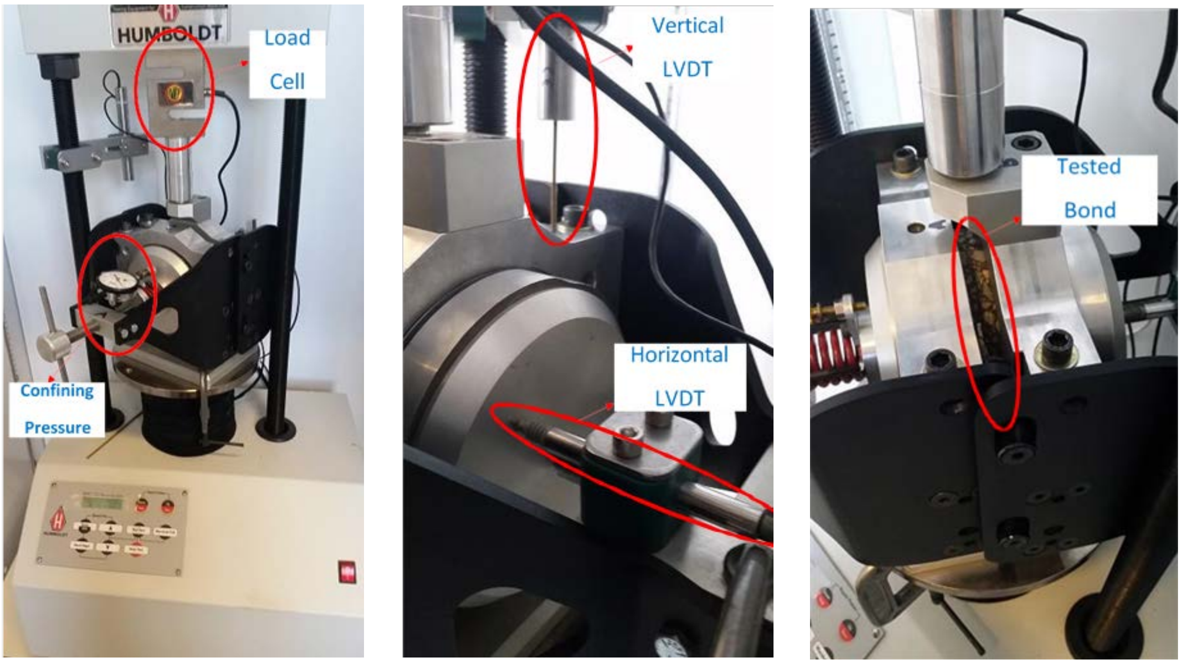
$$MTD = \frac{4V}{\pi D^2} \tag{3-2}$$

Where;

- MTD = Texture depth (in).
- D = average diameter of sand patch circle (in).
- V = volume of sand used (in^3), (Weight of Sand/ Density of Sand**).**

3.5.5 *Lab shear test device and test procedure*

According to AASHTO TP114 (2015), the lab shear test was performed to evaluate the correlation between the results from OFTT tests and lab shear tests. The results from the lab shear tests were considered as reference data (ground truth). For the purpose of this study, shear test equipment was developed by installing a load cell, transducers, and a data acquisition unit (Figure 3-5).



(a) **(b)** **(c)**

FIGURE 3-5: LAB SHEAR DEVICE

A software was developed to be able to control the system. Eleven full depth six-inch diameter cores were taken from each location (Figure 3-6a & b). The samples were then taken to the OSU laboratory where the shear testing was performed to evaluate the tack coat bond strength for milled and overlay surfaces.

To prepare the samples, asphalt cores were sawn in the laboratory to provide the target dimensions necessary for testing (Figure 3-6c). The cores were placed inside the shear device with the direction of traffic arrow facing down (shearing direction) and the surface on the shearing side (Figure 3-6d). Then, the samples were positioned inside an environmental chamber where vertical and horizontal displacement sensors (LVDTs) were secured. The samples were left to be conditioned at 25°C for two hours (Figure 3-6e). A constant confining pressure (horizontal loading) of 20 psi was applied to the cores. Then, a constant displacement rate of 0.1in/min was applied until failure occurred (Figure 3-6f). After performing the lab direct shear test, the raw test data showed a high frequency noise. A Matlab filtering code was then used to reduce the noise interference. The shear strength was obtained using the following Equation (3-3):

$$S = \frac{4PMax}{\pi \, D^2} \tag{3-3}$$

Where;

- S is the shear strength (psi)
- PMax is the maximum load applied to specimen (lb.)
- D is the specimen diameter (in).

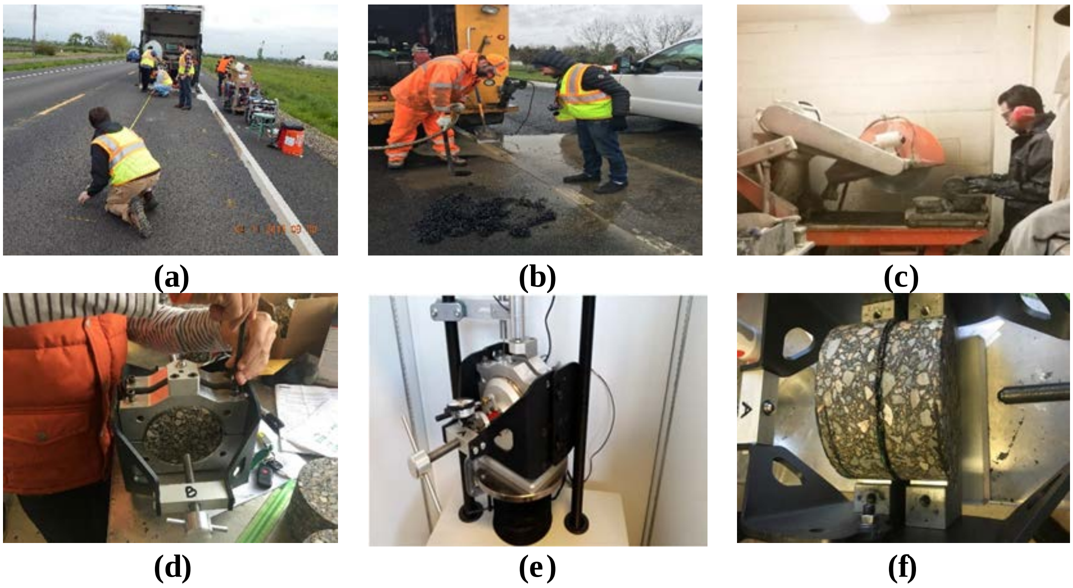


FIGURE 3-6: STEP BY STEP PROCEDURE FOR THE LABORATORY SHEAR TESTING

3.6 Results and discussion

3.6.1 *Measured application rate*

Figure 3-7 exhibits a boxplot of target vs. actual application rate, it is observed that there is a significant difference between target and actual application rates. It should be noted that inaccurate application rate can lead to bond delamination or slippage problems (Tashman et al. 2006).

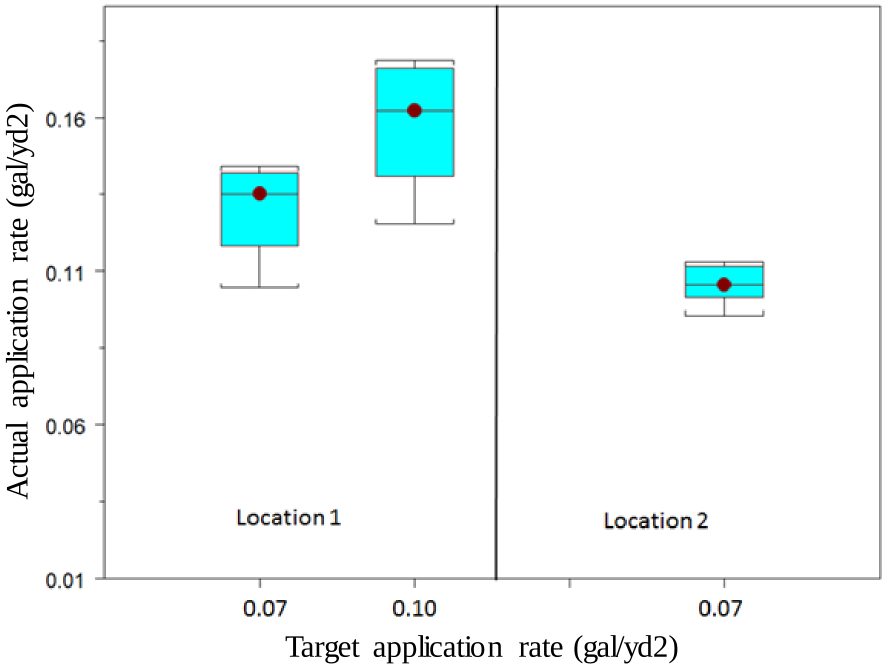


FIGURE 3-7: BOXPLOT OF TARGET VS. ACTUAL APPLICATION RATES

3.6.2 *Sand patch test*

Figure 3-8 shows a boxplot of the measured surface textures of the two locations. The results indicated that the difference in the MTD values for both locations is significant. Location 2 has a significantly lower MTD than Location 1.

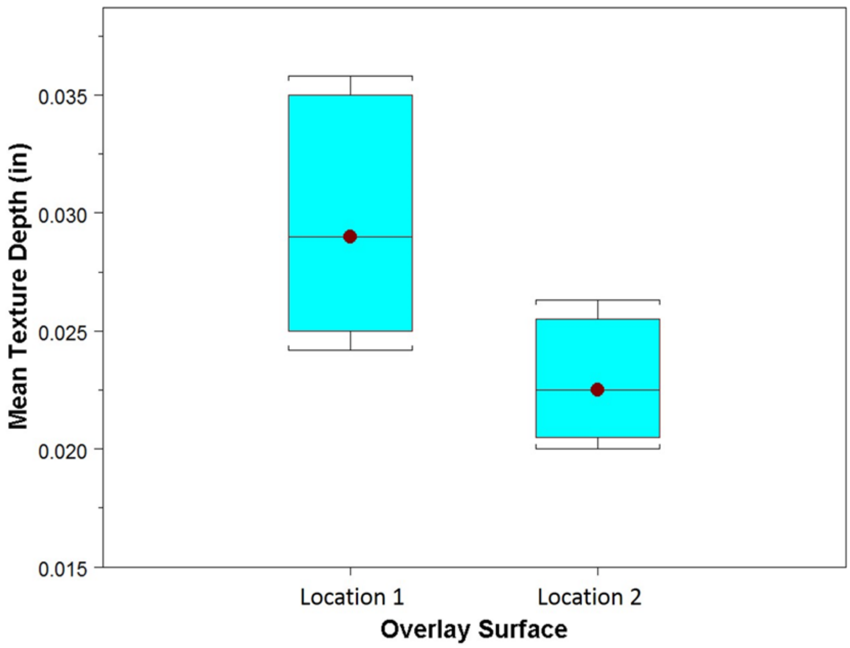


FIGURE 3-8: BOX PLOT OF THE MEAN TEXTURE DEPTH VS. LOCATIONS

3.6.3 *Correlation between OFTT and laboratory shear test results*

Figure 3-9 shows the comparison of results that were obtained by OFTT and laboratory shear tests. The experiments were conducted on sections with two types of emulsions and different application rates. In order to minimize the effect of spatial variability on laboratory vs. in-situ measurement comparisons, all cores for both tests were drilled at a close distance to each other. Results from OFTT and laboratory shear tests for these adjacent cores were compared in Figure 3-9, with the laboratory shear test results being considered as reference bond strength (ground truth data). The peak measured torque was converted to shear strength using Equation (3-1). The laboratory shear test results demonstrated that CO1_New_b emulsion with a medium application rate (0.07 gal/yd²) had the highest shear strength, followed by CO1_CSS 1H_b with a high application rate and CO1_CSS 1H_b with a medium application rate. These results were similar to that of the OFTT shear test results. From Figure 3-9, it can be observed that the correlation between the OFTT test results and the laboratory shear strength results is statistically significant with a coefficient of determination (R^2 value) of 0.6544. It should be noted that for the first field OFTT experiment, the research team had problems in setting up (leveling) the portable core drill to prepare the first 2.5-inch core. For this reason, result from the first core is not presented in Figure 3-9.

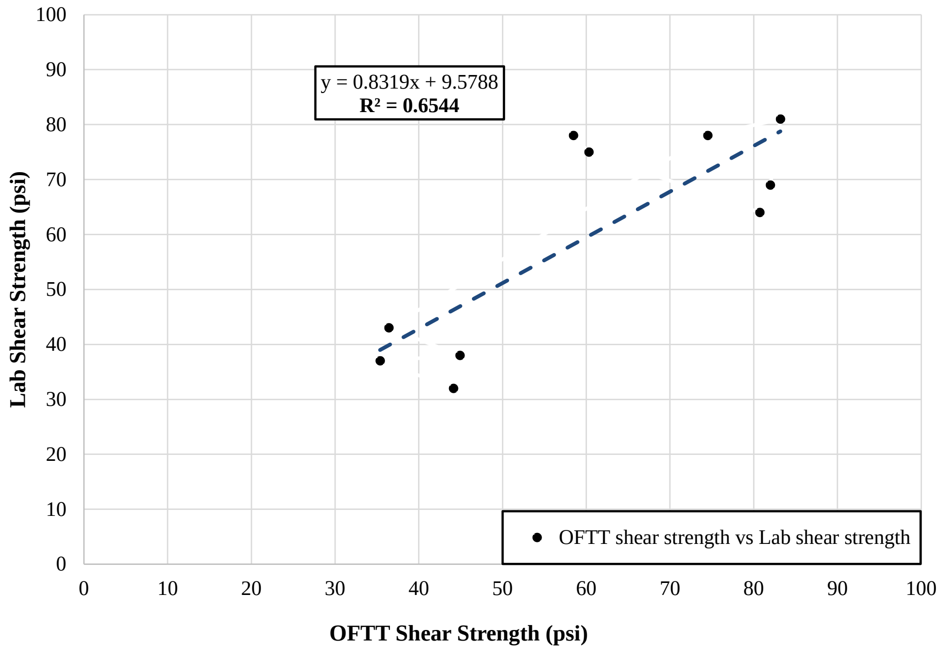


FIGURE 3-9: CORRELATION BETWEEN OFTCT SHEAR STRENGTH (PSI) AND LAB SHEAR STRENGTH (PSI)

3.6.4 *Correlation between mean OFTT and mean laboratory shear test results*

Figure 3-10 illustrates the correlation between the measured strength averages from all cores in one section for both OFTT and laboratory shear strength tests. At least three replicate tests were conducted per section for both OFTT and laboratory shear strength experiments. A high correlation (with an R^2 of 0.972) was observed between the average section results from both tests. It should be noted that parameters such as stiffness below and above the interface, thickness of the layers, material properties, and a limited number of tests could increase the variability in test results. Climate, traffic loads, and non-uniform application of tack coats during construction can also lead to non-uniformity and poor bonding, which results in increased test results' variability. The impact of test results variability on measured ISS can be reduced by increasing the number of replicate tests in the field.

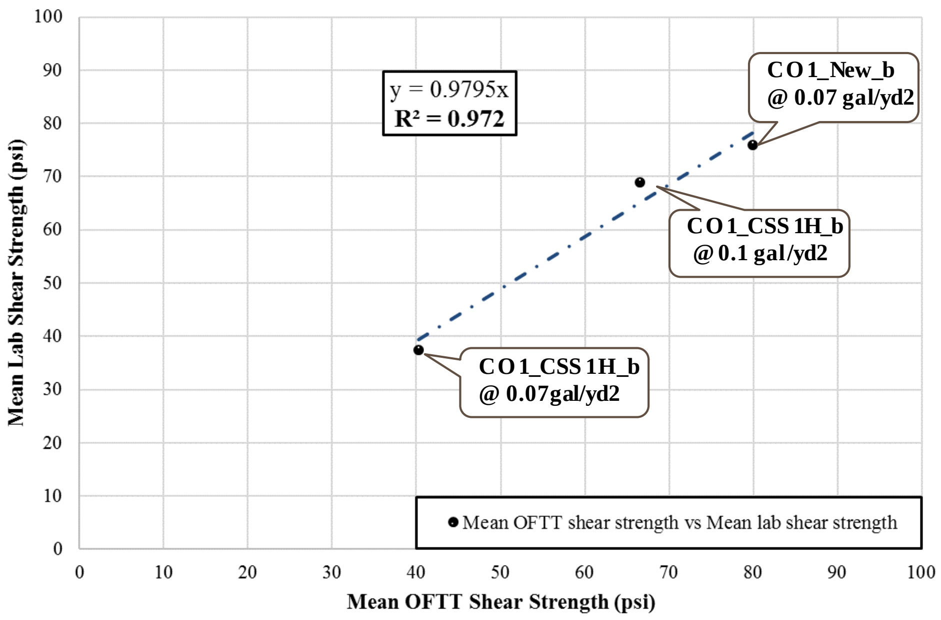


FIGURE 3-10: CORRELATION BETWEEN AVERAGE OFTT SHEAR STRENGTH (PSI) AND AVERAGE LAB SHEAR STRENGTH (PSI)

3.7 Summary and conclusions

In this study, a low cost, practical, and less destructive field test device, the Oregon Field Torque Tester (OFTT), is developed to evaluate the long-term post-construction tack coat performance of pavement sections. Correlations between OFTT field test results and the results of laboratory shear tests conducted with cores taken from the field were investigated to determine the effectiveness of the OFTT. The peak torque values measured by the OFTT were observed to be highly correlated with the measured laboratory shear strengths. The OFTT shear strength values calculated by using the torque test results and a theoretical equation were determined to be close to the measured laboratory shear strengths.

The new technology allows for a more practical test method and is less destructive compared with the typical laboratory shear test. Correlation between the OFTT test results and laboratory shear strength test results was observed to be statistically significant with a coefficient of determination (R^2 value of 0.6544). When the correlation between the measured strength averages from all cores in one section for both OFTT and laboratory shear strength tests were investigated, a significantly higher correlation (with an R^2 of 0.972) was observed. These strong correlations suggest that OFTT can be an effective, low-cost, less destructive and practical technology to monitor long-term in-situ bond strength.

Both laboratory shear and OFTT tests yielded the same conclusion, which is that the CO1_New_b emulsion with medium application rate (0.07 gal/yd^2) had the highest shear strength among the three application rates. This was followed by CO1_CSS 1H_b with a high application rate and CO1_CSS 1H_b with a medium application rate.

3.8 Future work

The following future work is required to improve the OFTT and start using it for long-term tack coat performance monitoring:

- Conduct additional experiments and identify practicality issues to improve the OFTT.
- Develop a wireless system to allow more practical testing. The wireless system could be developed by creating a tablet application that allows for the control of the OFTT device wirelessly.
- Conduct more experiments on thin asphalt layers to investigate the effectiveness of the OFTT device on thin overlay sections.
- Conduct tests at different temperatures to determine the effect of temperature on bond strength and test results' variability.

3.9 References

ASTM Standard D2995. (2014). Standard Practice for Estimating Application Rate of Bituminous Distributors and Residual Application Rate of Bituminous Distributors. West Conshohocken, PA: ASTM International.

ASTM Standard E965. (2015). Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique.

AASHTO TP114. (2015). Standard Method of Test for Determining the Interlayer Shear Strength (ISS) of Asphalt Pavement Layers. Washington, D.C.: AASHTO.

Buchanan, S. and M. Woods. Field Tack Coat Evaluator (ATACKerTM). Final report, FHWA/MS-DOT-RD-04-168, December 2004.

Chaignon, F. and J. Roffe. Characterization Test on Bond Coats: Worldwide Study, Impact, Tests, Recommendations," Canadian Technical Asphalt Association, Toronto, Canada, November, 2001.

King, G, and R. May, "New Approaches to Tack Application", presentation made to the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.

Pavement Interactive. Website address http://www.pavementinteractive.org/article/tack-coats/

Muslich, Sutanto. Assessment of bond between asphalt layers". PhD thesis, University of Nottingham, 2010.

Mohammad, L. N., Elseifi, M. A., Bae, A., Patel, N., Button, J., & Scherocman, J. A. (2012). Optimization of Tack Coat for HMA Placement (NCHRP Report 712). In NCHRP Report 712. Washington, D.C.: National Cooperative Highway Research Program (NHCRP), Transportation Research Board, National Research Council.

Tashman, L., Nam, K., & Papagiannakis, T. (2006). Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength Between Pavement Layers. Report prepared for Washington State Department of Transportation #WCAT 06-002.

4 CHAPTER 4 – SUMMARY AND CONCLUSIONS

The aim of this study was to develop technologies, devices, and methods to measure and evaluate the performance of tack coats. Developed technologies will help to enhance structural integrity of the pavements and reduce distresses.

The first study, "Development of a Wireless Field Tack Coat Tester to Evaluate In-Situ Tack Coat Performance" aimed to develop an OFTCT device to predict the long-term field performance of tack coats. The device was also used to evaluate the impact of pavement surface cleanliness before tack coats application on bond strength. In addition, a new heating system (an adjustable heat gun and environmental chamber) was developed to reduce the tack coat's curing time in the field and accurately control temperature during testing.

Results showed that the heating system developed in this study provided a consistent and reliable temperature control system and prevented the tacked surface from excessive heating. The use of different types of emulsions to calibrate the displacement rate ensured reliability and repeatability. The use of a wireless measurement system, controlled by a laptop, further improved the practicality and reduced the testing time. To characterize the bond strength of the tack coat between layers, different types of emulsions and application rates were evaluated for milled and overlay surfaces. Automated tension loading mode was used for the OFTCT device while shear loading mode was used for laboratory testing (direct shear test). The correlation between OFTCT and laboratory shear test results is determined to be statistically significant ($R^2 = 0.5189$). However, more field experiments need to be conducted to implement it as a test to predict in-situ interlayer shear strength (ISS). Both tests indicated that CO1_CSS 1H_b emulsion at high application rate has the highest tensile and shear strength. It was also determined that the OFTCT can be successfully utilized in the field as a test to quantify the cleanliness of the pavement surfaces before tack coat application.

The second study, "Development of a field torque test to evaluate in-situ tack coat performance" aimed to develop a low cost field test device. The Oregon Field Torque Tester (OFTT) was developed to evaluate the pavement structure's long-term post-construction tack coat performance. To determine the effectiveness of the OFTT tests, correlations between OFTT field test results and the results of lab shear tests conducted with cores taken from the field were investigated. The torque values at failure measured by the OFTT were observed to be highly correlated with the measured lab shear strengths.

The OFTT shear strength values calculated using the torque test results and a theoretical equation were close to the measured lab shear strengths.

The new technology allows for a more practical test method and is less destructive compared with the typical laboratory shear test. Correlation between the OFTT test results and laboratory shear strength test results was observed to be statistically significant with a coefficient of determination (R^2 value) of 0.6544. When the correlation between the measured strength averages from all cores in one section for both OFTT and laboratory shear strength tests were investigated, a significantly higher correlation (with an R^2 of 0.972) was observed. These strong correlations suggest that OFTT can be an effective, low-cost, less destructive, and practical technology to monitor long-term in-situ bond strength.

Both laboratory shear and OFTT tests yielded the same conclusion, which is that the CO1_New_b emulsion with medium application rate (0.07 gal/yd^2) had the highest shear strength among the three application rates. This was followed by CO1_CSS 1H_b with a high application rate and CO1_CSS 1H_b with a medium application rate.

5 BIBLIOGRAPHY

ASTM Standard D2995. (2014). Standard Practice for Estimating Application Rate of Bituminous Distributors and Residual Application Rate of Bituminous Distributors. West Conshohocken, PA: ASTM International.

ASTM Standard E965. (2015). Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique.

AASHTO TP114. (2015). Standard Method of Test for Determining the Interlayer Shear Strength (ISS) of Asphalt Pavement Layers. Washington, D.C.: AASHTO.

ASTM. ASTM D4541 – 09 Standard Test Method for Pull-Off Strength of Coatings Using Portable AdhesionTesters1. Section 2 in August 2010.

Buchanan, S. and M. Woods. “Field Tack Coat Evaluator (ATACKer™)”, Final Report, FHWA/MS-DOT-RD-04-168, December 2004

Chaignon, F. and J. Roffe. Characterization Test on Bond Coats: Worldwide Study, Impact, Tests, Recommendations,” Canadian Technical Asphalt Association, Toronto, Canada, November, 2001

Cortina, A.S. 2012. Optimization of In-Situ Tack Coat Application Rate and Installation. Master's Thesis. University of Illinois.

Deysarkar, I. (2004). Test set-up to Determine Quality of Tack Coat. Univeristy of Texas at El Paso. Retrieved from http://search.proquest.com/docview/305103314

FPO. (2001). Technical Bulletin: Proper Tack Coat Application. Dublin, OH.

Hachiya, Y., & Sato, K. (1997). Effect of Tack Coat on Bonding Characteristics at Interface between Asphalt Concrete Layers. In 8th International Conference on Asphalt Pavements (pp. 349–362). Retrieved from https://trid.trb.org/view.aspx?id=50163

King, G, and R. May, “New Approaches to Tack Application”, presentation made to the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.

Krebs, R. D., & Walker, R. D. (1971). Highway Materials. New York, New York: McGrawHill Inc.

Leng, Z., Al-Qadi, I. L., Carpenter, S. H., & Ozer, H. (2008). Interface Bonding Between Hot-Mix Asphalt and Various Portland Cement Concrete Surfaces. Transportation Research Record: Journal of the Transportation Research Board, 46–53. http://doi.org/10.3141/2127-03

Mohammad, L. N., & Button, J. (2005). Optimization of Tack Coat for HMA Placement. In NCHRP 9-40. Washington, D.C.: National Cooperative Highway Research Program (NHCRP), Transportation Research Board, National Research Council.

Mohammad, L. N., Elseifi, M. A., Bae, A., Patel, N., Button, J., & Scherocman, J. A. (2012). Optimization of Tack Coat for HMA Placement (NCHRP Report 712). In NCHRP Report 712.. Washington, D.C.: National Cooperative Highway Research Program (NHCRP), Transportation Research Board, National Research Council

Muslich, Sutanto. Assessment of bond between asphalt layers". PhD thesis, University of Nottingham, 2010.

Pavement Interactive. Website address http://www.pavementinteractive.org/article/tack-coats/Tashman, L., Nam, K., & Papagiannakis, T. (2006). Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength Between Pavement Layers. Report prepared for Washington State Department of Transportation #WCAT 06-002.

Roffe, J. C., & Chaignon, F. (2002). Characterization tests on bond coats: worldwide study, impact, test, and recommendations. In 3rd International Conference of Bituminous Mixtures and Pavements. Thessaloniki. Retrieved from https://trid.trb.org/view.aspx?id=681964

Sholar, G., Page, G., Musselman, J., P, U., & H, M. (2004). Preliminary Investigation of a test method to evaluate bond strength of bituminous tack coats (with discussion). Association of Asphalt Paving Technologies, 73, 771–806. Retrieved from https://trid.trb.org/view.aspx?id=750009

Tashman, L., Nam, K., & Papagiannakis, T. (2006). Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength Between Pavement Layers. Report prepared for Washington State Department of Transportation #WCAT 06-002.

TxDOT. (2001). Proper Use of Tack Coat. Texas Department of Transportation.

Walsh, I. D., & Williams, J. T. (2001). HAPAS certificates for procurement of thin surfacing. Highways and Transportation, 48(7-8), 12–14. Retrieved from https://trid.trb.org/view.aspx?id=715783

USACE. (2008). Bituminous Tack and Prime Coats. In Unified Facilities Guide Specifications (pp. 1–17). U.S. Army Corps of Engineers. http://doi.org/10.1017/CBO9781107415324.004