IMPLEMENTATION OF ODOT TACK COAT TECHNOLOGIES AND PROCEDURES TO IMPROVE LONG-TERM PAVEMENT PERFORMANCE

Final Report

PROJECT SPR 818

Oregon Department of Transportation

IMPLEMENTATION OF ODOT TACK COAT TECHNOLOGIES AND PROCEDURES TO IMPROVE LONG-TERM PAVEMENT PERFORMANCE

Final Report

PROJECT SPR 818

by

Erdem Coleri, PhD
Blaine Wruck; Shashwath Sreedhar; Richard Villarreal; Sunny Lewis; Vikas Kumar

School of Civil and Construction Engineering
Oregon State University
101 Kearney Hall
Corvallis, OR 97331

for

Oregon Department of Transportation
Research Section
555 13th Street NE, Suite 1
Salem OR 97301

and

Federal Highway Administration
1200 New Jersey Ave, SE
Washington, DC 20590-0003

February 2020

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-OR-RD-20-03		

4. Title and Subtitle

IMPLEMENTATION OF ODOT TACK COAT TECHNOLOGIES AND PROCEDURES TO IMPROVE LONG-TERM PAVEMENT PERFORMANCE

5. Report Date

February 2020

6. Performing Organization Code

7. Author(s)

Erdem Coleri - 0000-0002-1904-878X
Richard Villarreal - 0000-0003-1241-2689
Vikas Kumar - 0000-0002-8480-2654
Blaine Wruck - 0000-0002-6996-1681
Shashwath Sreedhar - 0000-0003-1786-6372
Sunny Lewis - 0000-0003-2352-0749

8. Performing Organization

9. Performing Organization Name and Address

Oregon Department of Transportation
Research Section
555 13th Street NE, Suite 1
Salem, OR 97301

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

Oregon Dept. of Transportation
Research Section
555 13th Street NE, Suite 1
Salem, OR 97301

Federal Highway Admin.
1200 New Jersey Avenue SE
Washington, DC 20590

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

Abstract: Using direct shear testing, this study quantified the impact of new emulsions from three companies on bond strength as compared to emulsions traditionally used in Oregon. Additionally, this study focuses on developing and implementing a more robust set of specifications and QC provisions for tack coats. By improving upon and implementing the **OreTackBond** (formerly known as OFTT), a rigorous in-situ test for tack coat quality is validated for large-scale implementation as part of the highway construction inspection process. In this study, a wireless scale system that can be controlled from a tablet computer, (**OreTackRate**) was also developed to measure application rate accuracy and uniformity during construction. A field test procedure using OreTackRate was also developed to determine tack coat curing time to avoid tracking during construction. Using the OreTackRate system, **a distributor truck certification and validation process** was also developed. A construction surface cleanliness test (**OreTackClean**) and a test procedure were also developed in this study to reduce tracking and achieve more uniform tack coat distributions that will ultimately improve long-term tack coat performance. This study will advance the knowledge of engineered emulsion performance, usher in more precision in highway construction in Oregon and promote sustainability of the asphalt industry by creating pavement structures that meet or exceed their structural design lives by facilitating proper interlayer shear strength from well-controlled tack coat application.

17. Key Words

Tack coat, emulsions, bond strength, shear, distributor truck, coverage, cleanliness, milled surface.

18. Distribution Statement

Copies available from NTIS, and online at www.oregon.gov/ODOT/TD/TP_RES/

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	234	

Technical Report Form DOT F 1700.7 (8-72) Reproduction of completed page authorized ♲Printed on recycled paper

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
~NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

The authors would like to thank the Oregon Department of Transportation (ODOT) for providing funding for this research. The authors thank the members of the ODOT Project Technical Advisory Committee and ODOT research for their advice and assistance in the preparation of this report. In particular, Norris Shippen, Larry Ilg, Chris Duman, Tim Earnest, Anthony Boesen, John Hickey, Dave Zhal, Keven Heitschmidt, and Andy Clayton participated on the TAC. The authors would also like to thank Greyson Termini and James Batti of OSU for their help with the development of the OregonTackBond test system. The authors also show immense gratitude to Matthew Haynes, Jacob Virrell, Jonathon Schwartz, Diane Fankhanel, Alex Sutherland, Douglas Keys, Ihsan Obaid, and Erick Moreno for their assistance with field pavement testing. The authors would also like to thank Andrew Johnson and Tim Flowerday for their assistance with sample procurement. Authors would also like to thank Mike Stennett and James Gunter for their help with field testing.

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Asphalt emulsion, commonly known as tack coat, is the bituminous material applied between asphalt concrete pavement layers that facilitates interlayer bonding. This material is an interlayer membrane which serves as a glue between pavement layers, allowing successive pavement layers to adhere together and behave as a monolithic structure (FHWA 2016). This minimizes tensile strains at the bottom of the asphalt layer, which can cause premature bottom-up fatigue cracking and ultimately lead to early pavement failure. Bonding at the pavement layer interface is known to control the mechanical properties, durability and fatigue characteristics of asphalt pavements (Hu et al. 2017).

The tack coat bond is known to dictate the longevity of asphalt pavements. Proper interlayer bonding prevents successive pavement layers from acting independently of one another and creating non-uniform stress and strain profiles in the pavement structure (FHWA 2016). Current structural pavement design methodologies assume that the pavement structure behaves monolithically (100% bonding between all pavement layers), which testifies to the importance of proper interlayer bonding using tack coat (FHWA 2016). Poor bonding between pavement layers can result in various pavement failures such as slippage cracking, debonding and early fatigue cracking, all of which contribute to a reduced pavement fatigue life (Al-Qadi et al. 2012b). King and May (2003) purport that a 50% reduction in pavement fatigue life can be expected when tack coat bond strength is reduced by 10%.

Tack coats, although immensely important for pavement longevity, are comparatively inexpensive in the scheme of construction costs on a paving project. FHWA (2016) suggested that tack coat comprises about 1-2% of the total project cost for mill and overlay projects and only 0.1-0.2% of total cost for new construction or reconstruction projects. This cost is negligible in comparison to the costs associated with replacing a poorly bonded pavement layer, which can range from 30-100% of the total initial project cost. This replacement cost is exacerbated by the costs incurred by road users as a result of delays from additional construction activities and lane closures. For these reasons, the costs of a repair due to poor tack coat bonding can easily match or surpass the initial cost of the project. This fact further emphasizes the importance of proper tack coat bonding in asphalt pavements.

Application of tack coats and bond quality are very sensitive to the tack coat type and application rate selected for the specific project. Various types of tack coat materials exist that suit a variety of purposes. Paving grade asphalt, asphalt emulsions and cutback asphalts are the three tack coat types that have been used historically, although cutback asphalts are frowned upon due to their negative environmental and health effects. Emulsions are the most widely used tack coat material in the world and are preferential in most cases due to their ease of application. Emulsions contain asphalt, water and surfactants that lower the viscosity of the asphalt binder and allow the material to be sprayed. It can also be further diluted using additional water when lower application rates are desired in order to facilitate uniform spraying more easily (Mohammad et al. 2012).

Application rates are important for specifying the amount of material required to facilitate adequate bonding (Coleri et al. 2017). Rates can be specified in terms of direct application or residual application. When applying emulsified tack coat, the residual asphalt is what remains after the tack coat has broken and set, otherwise known as the point at which all water has evaporated. The choice between application rate and residual application rate is at the discretion of the managing agency, however it was suggested that residual rates be used in order to accurately specify the amount of residual asphalt that is available for bonding between layers. This residual rate should also be selected in advance so that the proper application rate can be selected for construction (Mohammad et al. 2012).

Control of application rates and application procedures is crucial in determining the quality of the tack coat bond after construction. Results from Coleri et al. (2017) showed that quality control (QC) processes are elemental for obtaining uniformity in application rates and that QC processes have significant implications on bond strength. Poor control over tack coat application rates can lead to applied amounts of tack coat that are either in excess or deficiency of the target rate. Incongruence in application rates on the paving project studied by Coleri et al. (2017) led to lower interlayer shear strength and high variability in bond quality throughout the project.

A multitude of field conditions encountered during construction can govern the quality of the tack coat application and resulting bond strength. Factors such as pavement surface condition, presence of contaminants (dust or moisture), aging, temperature and coverage all have significant bearing on the quality of the resulting tack coat bond and pavement structure. A milled surface and overlay surface will exhibit different interface shear strength (ISS), as milled surfaces tend to facilitate higher interface friction and hence higher ISS (Al-Qadi et al. 2012b). Milled surfaces also tend to require higher application rates due to higher surface area because of the higher texture (FHWA 2016). Excessively aged pavement surfaces tend to absorb tack coat, driving down the effective amount of tack coat available to facilitate interlayer bonding (Mohammad et al. 2012). Pavement temperature can also affect emulsion break and set times (also called as curing) during construction and can change the rheological properties of the tack coat, affecting bond strength after construction (Al-Qadi et al. 2012a).

A variety of laboratory tests exist to quantify the quality of the interlayer bond under the various conditions listed above. Direct shear testing (DST) is a common method of measuring bond strength between pavement layers and has been utilized by many researchers. Monotonic DST refers to measurement of peak shear strength of the interlayer bond using a load applied at a constant displacement rate (Amelian and Kim 2017). This test yields several useful parameters that aid in characterizing the tack coat bond. Cyclic DST is a novel method of bond strength measurement and is more representative of loading experienced by the interlayer in the field. These test types are discussed in greater detail in this report.

Tack coat, despite its immense importance for the pavement lifespan, currently has minimal specifications for construction provisions in comparison to Hot Mix Asphalt (HMA). This lack of specification causes contractors to overlook the relevance of tack coat placement variables, such as application rate and application uniformity. In Oregon, there are specifications for range of acceptable application rates and application procedures, including application rate per unit area, lap coverage specifications and cleanliness specifications (ODOT 2015). However, these specifications are brief and non-descriptive, leaving much ambiguity in how the specifications should be met. For this reason, contractors often view tack coat application as auxiliary to HMA paving operations. The current specifications also lack practicality since many of the tack coat distributor trucks do not utilize equipment that allows for accurate control of the application rate and spray distribution. Even if distributor trucks are outfitted with state-of-the-art control equipment, tack coat distributor operators can be unfamiliar with proper equipment operation, as there is no formal training for tack coat distributor operators. This causes excess variability in tack coat application, which hinges on what distributor truck is used during construction and who is operating the truck. These factors lend themselves to poor control over tack coat application rate and coverage distribution. The lack of control over these factors can lead to a pavement structure that does not perform as designed.

Problems also occur with spray equipment on tack coat distributor trucks. A lack of cleaning and maintenance causes clogging of spray nozzles, which greatly affects the coverage distribution of tack coat in the transverse direction. Also, contractors have been known to use multiple different tack coat distributor trucks on a single project, inherently causing variability in tack coat application throughout different areas of the project (Coleri et al. 2017), as the equipment outfitted on each truck do not all necessarily have equivalent performance. Even if a single distributor truck is used, contractors can use multiple operators, some of whom may not have sufficient experience or knowledge of best practices for tack coat application. This can cause a number of coverage and variability issues.

Verification of in-situ tack coat bond strength is also a worthwhile implementation into tack coat specifications. A novel device to quantify this property, namely the OreTackBond [formerly known as Oregon Field Torque Tester (OFTT)] previously developed by Coleri et al. (2017), was improved upon in this study. The OreTackBond was previously shown to have merit for quantifying the bond strength between new and underlying pavement layers (Mahmoud et al. 2017a). However, more experiments with this device are needed in order to verify its performance and address issues with practicality, including field bond strength tests in the domains of time, temperature and wireless control of the device. The effectiveness of Oregon Field Tack Coat Tester (OFTCT) (developed by Mahmoud et al. 2017b) for bond strength quantification was also determined in this study.

A more robust set of specifications is needed for tack coat application that addresses the shortcomings of tack coat distributor equipment and distributor operators. Tack coat distributor equipment needs requirements for regular maintenance and calibration, and distributor truck operators need basic training and certification to ensure the equipment is used properly. This study aims to address these issues by examining various solutions that can easily be introduced to the current specifications and implemented in the field. Implementation of the OreTackRate (for distributor truck application rate accuracy and uniformity measurement) and OreTackClean (for surface cleanliness measurement) technologies and test procedures and the proposed distributor truck certification process developed in this study are expected to address these issues and improve the long-term performance of pavements in Oregon.

1.1 KEY OBJECTIVES OF THIS STUDY

The main objectives of this study are to:

- Implement OreTackBond [formerly known as Oregon Field Torque Tester (OFTT) developed in SPR 782 – Coleri et al. 2017] as a tool to monitor the long-term post-construction tack coat performance,

- Implement OreTackBond as a tool to be used for quality control (QC) during construction,

- Implement a curing time measurement method to reduce tracking,

- Test and evaluate the performance of new (engineered emulsions that are tracking less) and existing tack coat types commonly used in Oregon,

- Determine the impact of nonuniform coverage/streaking, presence of dust on pavement surface, and rainfall on tack coat bond quality,

- Develop a weighing based system to measure tack coat application accuracy and uniformity,

- Develop guidelines for distributor truck certification and validation, and

- Develop a cleanliness test to quantify surface cleanliness before tack coat application during construction.

1.2 MAJOR RESEARCH PRODUCTS DEVELOPED IN THIS STUDY

The major research products developed in this study are given as follows:

- Recommendations regarding the effectiveness of different tack coat types from three tack coat emulsion producers,

- An innovative laboratory specimen preparation process that involves simulation of adverse construction conditions and their impact on bond quality,

- OreTackBond [formerly known as Oregon Field Torque Tester (OFTT)] test system with updated hardware and software,

- A tack coat bond quality control (QC) process using OreTackBond,

- A wireless scale system controlled from a tablet computer (OreTackRate) for tack coat application uniformity and accuracy quantification,

- A test procedure for tack coat application uniformity and accuracy measurement using the OreTackRate,

- A distributor truck certification and validation process,

- A procedure for measuring tack coat curing time using the OreTackRate system to reduce tracking, and

- A cleanliness test procedure (OreTackClean) to quantify surface cleanliness during construction.

1.3 ORGANIZATION OF THE REPORT

This report is organized as follows:

- This introductory chapter is followed by the literature review;
- Performance of tack coats at the manufacturer recommended application rates for milled surfaces are discussed in Chapter 3.0;
- Chapter 4.0 presents the results of tests and analysis investigating the impact of emulsion type, application rate and adverse conditions on tack coat performance;
- Improvement and implementation of OreTackBond for tack coat bond QC is discussed in Chapter 5.0;
- Development of technologies and procedures to avoid tracking and achieve uniform and accurate tack coat application is discussed in Chapter 6.0;
- Finally, Chapter 7.0 presents the conclusions, summary of the research study and recommendations.

2.0 LITERATURE REVIEW

2.1 TACK COAT BOND CHARACTERISTICS AND FAILURE MECHANISMS

The bond at the interface between successive asphalt pavement layers, known as the interlayer bond, is subjected to tensile stresses and shear stresses that are imparted by traffic loads. Tack coat is the principal component in the pavement structure that facilitates bonding between pavement layers and helps to resist these load-related stresses. Bonding at the layer interface directly controls the mechanical properties, durability and fatigue characteristics of asphalt pavements (Hu et al. 2017). Good bonding between pavement layers is characterized by dispersion of stresses from the pavement surface to underlying layers (Wang et al. 2017). Poor bonding leads to a nonuniform stress profile, where excessive stresses and strains develop at the bottom of layers closest to the pavement surface (FHWA 2016). Alterations in the stress profile due to poor bonding can shift the critical strain location from the bottom of the asphalt structure where stresses are minimal to the debonded location where high stresses occur (Mohammad et al. 2012). This leads to premature formation of distresses such as early fatigue cracking, which contributes to a reduced pavement fatigue life (Wang et al. 2017; Al-Qadi et al. 2012b). Fatigue cracking and rutting are the two most common failure mechanisms caused by inadequate tack coat bond strength due to strain accumulation at the top and bottom of the poorly bound layer (FHWA 2016).

Current empirical and mechanistic-empirical pavement design methods assume full bonding between successive pavement layers (Wang et al. 2017). However, previous research in the area of interlayer bonding has shown that this assumption is often inaccurate. Full bonding between the overlay and existing layer cannot always be achieved during construction. In addition, the bond between successive pavement layers can be damaged over time due to high truck loads and moisture. Debonding is more prone to occur at high temperatures and/or high traffic loads, especially when there are problems with interlayer bonding due to inadequacy of tack coat materials or application rates (Celaya et al. 2010).

Quality of tack coat bond strength is a critical consideration for different overlay design thicknesses. Proper tack coat application is known to be particularly important for thin overlays, especially when they are applied to aged existing pavement surfaces (Coleri et al. 2017; Amelian and Kim 2017). In particular, overlays with a thickness of less than 50.8mm (2 inches) are susceptible to early fatigue failure from poor bonding. Increasing the overlay thickness creates significant reductions in shear strain at the layer interface and also shifts the critical strain location from the layer interface to the mid-overlay region (Coleri et al. 2017).

2.2 FACTORS CONTROLLING IN-SITU BOND PERFORMANCE

Asphalt pavement interlayers undergo different fatigue mechanisms when subjected to heavy traffic loads. Stresses created under the tire induce shear stresses at the layer interface and tensile stresses in front of the tire. For this reason, laboratory and field experiments focus on both shear and tensile strength of the tack coats to evaluate the long-term resistance of the interlayer bond. Characterization of the tack coat bond is widely accepted to be subject to these two failure modes (Coleri et al. 2017). Figure 2.1 shows a diagram of shear and tensile strength modes under field conditions.

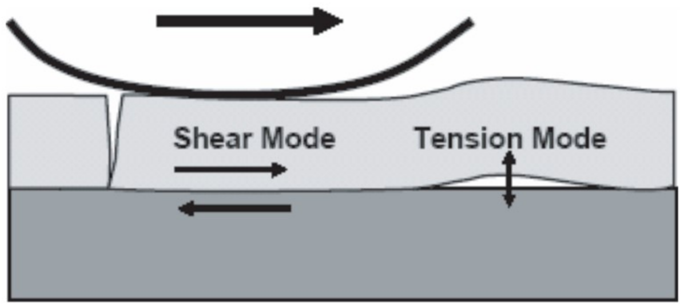


Figure 2.1: Diagram of shear and tensile strength modes under field conditions (Mohammad et al. 2012).

Various research studies have suggested that an absence of bonding between pavement layers can result in a pavement fatigue life reduction of 60-75% (Roffe and Chaignon 2002; Brown and Brunton 1984). A mere reduction in bond strength can also significantly affect fatigue life, reducing it by 50% with only a 10% reduction in bond strength (King and May 2003). This phenomenon has been validated in field studies as well. Willis and Timm (2006) performed an investigation into a premature pavement fatigue failure on the National Center for Asphalt Technology (NCAT) test track. It was determined that the early failure exhibited in the test section was caused by debonding between pavement layers due to tack coat inadequacy.

Covey et al. (2017) investigated the effect of environment and loading on bond strength by obtaining field cores from the same location after time periods of three and seven months after construction. It was found through direct shear testing of the interlayer bond that an average reduction in ISS of up to 39% occurred during this time period. This reduction is attributed to environmental and loading factors that pavements were subjected to in the field. The authors also suggest that this reduction could amplify over time and result in a structural failure of the pavement. These results point out the importance of monitoring tack coat bond performance of pavements.

Excessive tack coat application can also create problematic conditions for other types of pavement distress. Slippage cracking is a failure that occurs from tack coat being over-applied, whereby slick spots in the pavement structure are created that are prone to movement under heavy acceleration and braking (Al-Qadi et al. 2012b). Figure 2.2 shows an example of slippage cracking caused by excessive tack coat application.

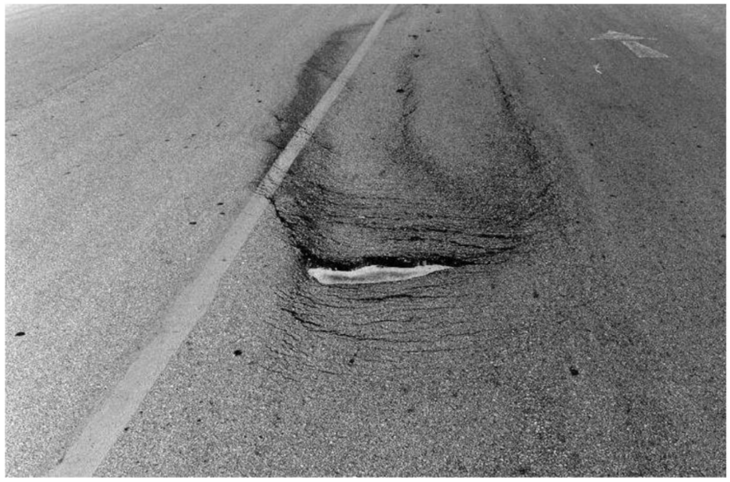


Figure 2.2. Slippage cracking caused by excessive tack coat (Al-Qadi et al. 2012b).

Aging of tack coats in-situ was evaluated for implications on bond strength by Wang et al. (2017) in order to determine the long-term bond performance of tack coats. The authors suggest that aging of tack coat can increase shear strength of the interlayer bond. In the field, tack coat aging was shown to increase the bond strength and the author suggested that this result could be validated in the lab with long-term oven aging. Using a linear model, it was shown that tack coat aging can increase bond strength by 1% over a 10-year period.

2.2.1 Tack coat type

Depending upon the environmental and site conditions present, agencies may be inclined to select a certain type of tack coat material. Tack coat selection in the current highway construction framework is primarily based on experience, empirical judgment and convenience of the contractor (Mohammad et al. 2012). Various types of tack coat materials exist that cater to different requirements. There are three principal types of tack coat materials that have been commonly used: paving grade asphalt, asphalt emulsions and cutback asphalts. Cutback asphalts are lesser-used in current construction practices due to their negative environmental effects and potential health hazards (Mohammad et al. 2012; Coleri et al. 2017). Some states use paving grade binders as tack coat materials, although this is primarily done in southern states (FHWA 2016). Use of paving grade binders also necessitates heating of the binder prior to application in order to achieve a viscosity appropriate for spraying, inducing additional energy requirements and reducing sustainability (Coleri et al. 2017).

Asphalt emulsions are by far the most widely used tack coat material and are employed by several developed countries and most United States paving agencies. Emulsions are comprised of asphalt and water mixed with emulsifying agents. They are less viscous than paving-grade asphalt and can easily be sprayed. They allow contractors to have greater control over factors such as application rate and coverage uniformity (Coleri et al. 2017; FHWA 2016). Use of emulsions is common in tack coat practices employed by many states, but its use is dependent on site-specific conditions such as pavement surface condition, environmental conditions and location (Amelian and Kim 2017). Also, since emulsions require additional time for the water to separate and evaporate from the residual asphalt, they create a logistical complication during paving operations.

The two most common types of asphalt emulsions are anionic and cationic (Krebs and Walker 1971). The 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 and Chaignon 2002), the most commonly used tack coat type in the world is the cationic emulsion.

Emulsions can be further diluted using additional water to aid in achieving proper distribution of tack coat. Diluted emulsions are useful when lower application rates are desired (Mohammad et al. 2012). Diluted emulsions also help with application uniformity, as they are more easily sprayed and are less prone to cause spray nozzle clogging (FHWA 2016). Some states have provisions in their construction specifications that provide allowable dilution levels. ODOT (2015) specifies a maximum dilution level of 1:1. However, the dilution level must be carefully tracked so that the residual application rate can be accurately calculated. For this reason, it is not advisable to dilute tack coat in the field and dilution should only be performed by the supplier who can control the dilution level for the purpose of calculating residual application rates (FHWA 2016). In calculating the dilution level, standardization to a temperature of 60°F is required in order to account for expansion and contraction of liquid materials during heating and cooling of tack coat (FHWA 2016). An industry survey by Mohammad et al. (2012) showed that 49% of agencies who responded allow dilution only by the tack coat supplier. 45% of agencies allow tack coat to be diluted in the distributor truck tank. Once diluted, only 39% of agencies verify the dilution level of the tack coat. Of these agencies, 29% allow the contractors to verify the dilution rate, which might encourage contractors to add excess water to emulsions as a cost-saving measure.

Special emulsion types exist that are purported to reduce set times and also reduce tracking. These emulsion types are indicated by alphanumeric designations which describe the pertinent properties of the emulsion. Emulsions typically have a SS (slow set) or RS (rapid set) designation which indicates the time required for the emulsion to break and set before construction. 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). The "h" designation describes a "hard" tack coat which is meant to be less susceptible to tracking. Similarly, a "vh" designation indicates a "very hard" emulsion which is even more resistant to tracking (Al-Qadi et al. 2012a). Emulsions with proprietary blends of stiff binders and/or chemical modifications are used to combat tracking issues. These emulsion types have the designation NT or TT, although no standardization on this nomenclature currently exists (FHWA 2016). New engineered emulsion types have taken on a unique naming scheme, such as HPT which refers to "high performance tack". Polymer modification is sometimes used in emulsions in order to achieve specialty properties and have a "P" designation (FHWA 2016).

Different tack coat materials have inherent rheological characteristics that can have implications on bond quality. Covey et al. (2017) investigated the effect of tack coat rheological properties on interlayer shear strength (ISS). It was found that ISS was positively correlated with tack coat rheological properties such as rotational viscosity, softening point and G^*. ISS was also negatively correlated with penetration. In general, as the rotational viscosity, softening point and stiffness of the tack coat material increased, the ISS increased as well. However, these relationships were only applicable to overlay surfaces, since the milled surface texture was too influential on ISS to determine rheological relationships.

Mohammad et al. (2010) investigated the role of tack coat type in the shear strength at the layer interface and found that the trackless tack coat yielded the highest interface shear strengths of those tested (SS-1h, SS-1, CRS-1, trackless and PG64-22) for existing HMA layers. The authors correlate this finding with the viscosity of the tack coat materials, insinuating that higher viscosity tack coats exhibit higher interface shear strengths. Mohammad et al. (2012) found through laboratory testing of cylindrical core samples using the Louisiana Interlayer Shear Strength Tester (LISST) that the bond strengths of trackless tack coat emulsions were higher than that of rapid-setting emulsions and found a connection with these results to the viscosity of the tack coats at the testing temperature. To that effect, material properties were found to be highly indicative of tack coat tensile strength; increased viscosity and/or softening point of the tack coat resulted in higher ISS. Similarly, Hu et al. (2017) correlated higher ISS with increased tack coat binder viscosity, which was found to be especially important for bond strengths at high temperatures.

Amelian and Kim (2017) studied different types of tack coats, namely CRS-2P, a rapid-setting emulsion, and CFS-1, a modified CSS-1 with a fast set time, to evaluate new emulsion types and their effect on bond strength. This study showed that rapid setting emulsion types at high application rates (0.16 gal/yd^2) were superior to all other tack types tested. This was also the case for CFS-1 at the standard application rate (0.08 gal/yd^2).

2.2.2 Tack coat curing time

Emulsions are temporally constraining since the break and set times, otherwise known as curing time, must be reached before paving operations can ensue. Break time of emulsions refers to the time needed for the water to separate from the asphalt, whereas set time refers to the point at which all water is completely evaporated. Diluted emulsions require higher break and set times due to the additional water content. The residual asphalt, defined as the effective amount of asphalt available to facilitate interlayer bonding, is what remains after the water has evaporated, or when the tack coat has set. Emulsions which have not had sufficient time to break and set also give rise to the "tracking" phenomenon, where emulsion is picked up on construction vehicle tires, effectively reducing the amount of tack coat on the pavement surface (FHWA 2016). This occurs mostly in the wheelpaths where interlayer bonding is most critical. The severity of tracking is determined mostly by the emulsion properties and the curing time allotted before construction (Covey et al. 2018). Figure 2.3 shows an example of tack coat tracking by construction vehicles.

Figure 2.3: Tracking by haul truck during pavement construction (Mohammad et al. 2012).

Mohammad et al. (2012) suggested that abiding by the break and set times of the tack coat emulsion and applying tack coat uniformly are also important considerations for facilitating proper bond strength. In relation to break and set times, the controlling factors, in order of importance, are ambient and pavement surface temperatures, dilution rate, application rate, humidity and wind velocity (Mohammad et al. 2012; Coleri et al. 2017; Covey et al. 2018).

Al-Qadi et al. (2012a) investigated curing time as a factor affecting tack coat bond strength. Results of this study yielded a two-hour optimum curing time for all emulsion types tested. This was determined by allowing the different emulsion types to cure at 25°C for 15min, 2hr and 24hr time periods. A notable increase in shear strength was apparent with the 2hr curing time versus the 15min curing time, but a decrease in shear strength was observed for the 24hr curing time. However, the authors noted that the optimum curing time was a function of the tack coat itself and is best to be specified by the manufacturer. Al-Qadi et al. (2012a) also suggested optimum residual application rates for various tack coat types, however no reference was made to the curing times used.

Covey et al. (2018) studied the effect of curing times for different tack coats in the laboratory using evaporation tests to develop linear regression models for curing times of tack coats used in Oregon. It was found that new engineered emulsions exhibited longer curing times than traditional emulsions used in Oregon (CSS-1 and CSS-1H) for all application rates evaluated. These results were subsequently used to create a smartphone app for predicting curing time in the field which serves as a quality control tool for contractors during construction.

An industry perspective on break/set times and tracking was gained in a study by Mohammad et al. (2012). All respondents of the industry survey indicated that ambient temperature and pavement temperature are the two factors controlling break and set times of tack coat emulsions. However, only 26% of respondents hold paving operations until the tack coat has properly set. In terms of tack coat tracking, 67% of respondents agree that tracking is a continuing problem in paving operations, yet only 38% require tack coat to set completely before being opened for traffic by haul trucks. This gives rise to increased tracking of tack coat material by construction vehicles.

2.2.3 Application Rate

Tack coat application rates, also called dosages in some literature (Raposeiras et al. 2012), are the primary means of designating the amount of asphalt that will be available to facilitate bonding between pavement layers. They are largely dependent upon the condition of the existing pavement surface (e.g. milled, new or existing), where higher application rates generally correspond to milled or aged pavements (Mohammad et al. 2012). Application rates/dosages are typically specified on a per unit area basis. The residual application rate refers to the effective amount of asphalt left on the pavement surface after the tack coat has cured and set (after water has evaporated). Application rate is language that indicates the application of a tack coat emulsion which includes water (Al-Qadi et al. 2012b).

In relation to application rate specifications, FHWA (2016) noted that language used when specifying application rates must be clear. Ambiguous language can lead to incongruences in tack coat application and resulting quality. Rates should be specified in terms of either residual asphalt, undiluted emulsion or diluted emulsion in order to clearly indicate to the contractor the intended tack coat application. FHWA (2016) recommends that specifications be stated in terms of residual asphalt, as this most accurately represents the effective amount of tack coat material applied and available for interlayer bonding. Specifications should also be specific about allowance of diluted emulsions and who is allowed to control the dilution. Mohammad et al. (2012) suggested that, in general, the application rates of undiluted emulsions should be 1.5 times greater than the desired residual rate and application rates for diluted emulsions should be three times greater than the desired residual rate, although this depends on the water content of the emulsion prior to dilution.

Tack coat application rates should be varied according to site conditions such that an optimum amount of residual asphalt is obtained which will help avoid interlayer bond-related pavement failures (Al-Qadi et al. 2012b; Asphalt Institute 1989). Slippage problems start to arise when an excessive amount of tack coat material is sprayed during construction. This problem is prevalent particularly with slow-setting emulsions (Covey et al. 2018). On the other hand, an inadequate amount of tack coat can result in debonding problems (especially in the wheel paths) over the design life of the pavement structure (Tashman et al. 2006). Agencies typically specify a range of application rates that are acceptable. ODOT (2015) specifies an application rate between 0.05 and 0.20 gal/yd^2 in their construction specifications. Application rates are also dependent upon the surface type and tack coat materials used and should be varied according to these parameters. Explanation of surface type implications are discussed in the following section.

Application rates of tack coat emulsions are also highly influential on the break and set times of the emulsion. Amelian and Kim (2017) showed that break and set times of emulsions were increased as the application rate increased. This was consistent for both laboratory and field conditions.

The industry survey conducted by Mohammad et al. (2012) showed that although most agencies monitor and control their application rates, 2% of agencies do not monitor their tack coat application rates and 2% of them monitor application rates visually. Furthermore, the majority of agencies (56%) admit that they do not change the target application rate during construction for any reason, such as change in surface type or level of oxidization of the existing pavement.

2.2.3.1 Surface type & application rate

Asphalt repaving as a maintenance strategy typically occurs on existing pavements whose surface conditions can vary significantly. The two common types of asphalt pavement maintenance are inlays, where existing pavement is milled to a certain depth to remove damaged or failed pavement layers and replaced, or overlays, where new HMA is applied over an underlying pavement layer. In Oregon, it is common for these two maintenance strategies to occur in conjunction with one another, where a milling and inlay takes place followed by an overlay construction.

Both inlay and overlay constructions have unique underlying surface textures to which the new pavement is applied. Each surface texture can influence the required tack coat application rate to achieve a particular bond strength. Aging and surface roughness are two parameters that influence the application rate. Since surface texture increases with aging and milling, application rates also increase accordingly (Coleri et al. 2017; Mohammad et al. 2010). The overlay surface is relatively smooth and has little variation in macrotexture. Since milled surfaces are much more irregular and typically exhibit a higher degree of texture, the texture depth for milled surfaces has higher variability (Coleri et al. 2017). A typical milled pavement surface is shown below in Figure 2.4.

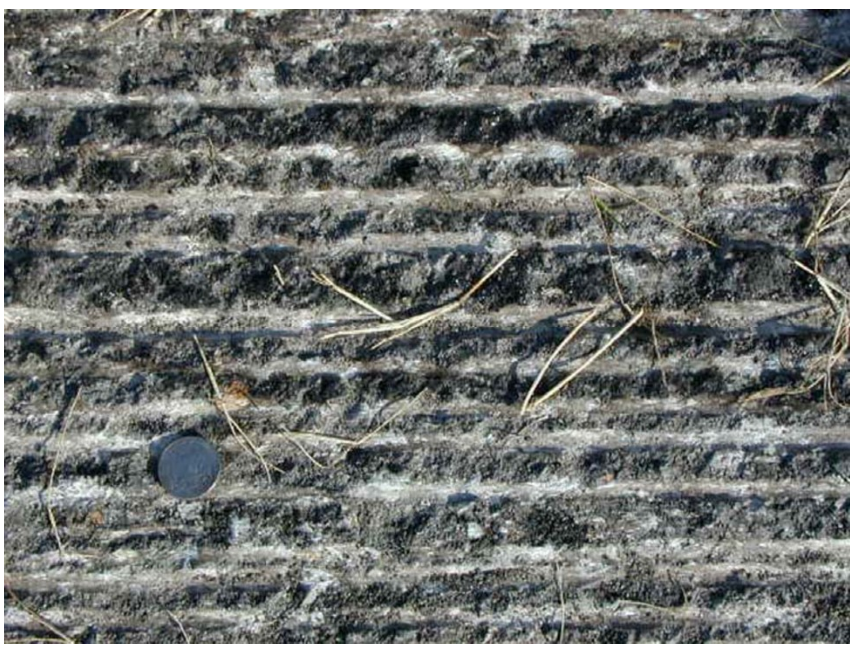


Figure 2.4: Typical milled pavement surface texture (Mokarem 2006).

Several researchers have verified that the condition (aging and surface roughness) of the existing pavement surface dictates the tack coat application rate. McLeod (1969) claimed that empirical adjustment in emulsion application rates of up to 0.06 gal/yd^2 (0.272 L/m^2) should be considered for pavement surfaces that are oxidized. Rawls et al. (2016) suggested that application rate adjustments should be made for aged/oxidized surfaces since a portion of applied tack coat is absorbed into the underlying pavement which changes the effective amount of tack coat that is available for interlayer bonding. This effect is exacerbated by the existing pavement surface texture. Song et al. (2015) showed that for surfaces with increased roughness, the optimum tack coat application rate also increased.

NCHRP Report 712 (as cited by FHWA 2016) suggested that residual application rates should vary depending on surface type and also that current application rates used today are too low. For surfaces with higher surface roughness, higher application rates are generally required to achieve optimal bonding between pavement layers due to a greater surface area.

2.2.3.2 Determination of an optimum application rate

Previous research has sought to determine an optimum application rate that would achieve the highest possible degree of bonding between layers. An optimum application rate should be determined in light of surface conditions such as texture and age of the pavement, as well as environmental conditions such as wind, humidity and temperature during construction. The optimum rate should be taken as the maximum bond strength and corresponding application rate (Coleri et al. 2017). Suggested application rates for tack coats used in Oregon from Coleri et al. (2017) is shown below in Table 2.1.

Table 2.1: Suggested Application Rates for Oregon (Coleri et al. 2017).

Tack Coat Material	Surface Type	[1]Effective Rate (gal/yd2)
CO1_CSS 1H_a	Milled	0.08
CO1_New_a	Milled	0.16
CO2_New	Milled	0.12
CO1_CSS 1H_b	Overlay	0.07
CO1_New_b	Overlay	0.05
CO2_CSS 1H	Overlay	0.10

Note: [1]All suggested, “effective rates” are application rates and not residual rates.

A study by Mohammad et al. (2010) noted that it was difficult to pinpoint a specific residual application rate that encompassed optimum bonding conditions between the overlay and underlying pavement layers. This was due to the positive increasing trend of bond strength with increases in residual application rate. Since the bond strengths did not plateau within the range of application rates selected for this study, an optimum application rate could not be discerned. Overall, it was determined that the residual application rate should be sufficient enough that shear strength surpasses the shear stresses predicted from environmental and traffic loading scenarios.

Determination of optimum application rates is often muddled by surface texture effects as well. Mohammad et al. (2012) noted that determination of an optimum application rate was difficult due to oxidization of the HMA surface at the testing location. The oxidized surface tended to require higher application rates than were expected. The authors suggested that this may be indicative of the actual optimum application rates in the field being higher than predicted under laboratory conditions. However, excessively high application rates had little payoff and actually caused tack coat to migrate into the new HMA layer, decreasing the air void content of the mixture. This could potentially cause compaction issues and affect the performance of the new constructed asphalt layer. Raposeiras et al. (2012) suggested that application rates higher than the optimum rate exhibited worse performance for a surface with high macrotexture. However, the authors did note that higher macrotextures required higher optimum application rates since the tack coat must fill the surface voids in the existing pavement.

The study by Al-Qadi et al. (2012a) found that the optimum residual application rate was 0.04 gal/yd^2 (0.18 L/m^2) for unmilled aged surfaces, both exposed and unexposed to traffic. Milled aged surfaces had an optimum rate of 0.06 gal/yd^2 (0.27 L/m^2). Both of these application rates were determined using a SS-1vh (very hard) trackless tack coat. The study found that increasing the residual application rate beyond the aforementioned values does not exhibit any increase in interlayer shear strength (ISS), due to excessive tack coat causing slippage between the pavement layers. This result was consistent for all tack coat types tested in the study, which included SS-1vh (slow-setting trackless tack coat), HFE (high-float emulsion), SS-1hp (a high performance slow-setting emulsion) and paving grade PG 64-22 asphalt binder.

Excess applied tack coat can also cause other extraneous problems during construction. Excess tack can cause an effective decrease in the air void content of the layer due to the emulsion seeping into the new pavement layer during compaction and traffic. Excess tack can also amplify tracking problems, since it is easily tracked onto construction vehicle tires and displaced to other locations nearby the construction area, which can compromise pavement marking legibility and cause safety issues (Mohammad et al. 2010). Figure 2.5 shows an example of excessive tack coat application and its exacerbation of tracking problems.

Figure 2.5: Excessive tack coat application (Mohammad et al. 2012).

2.2.4 Effect of surface texture on bond strength

The condition of the underlying pavement surface can have significant implications on tack coat bond strength. Since surface type/texture has significant bearing on tack coat application rates, it is conceivable that it also has ramifications for interface shear strength (ISS) as well. In general, a greater degree of surface texture is typically favorable for higher ISS, as is shown in various research studies presented below.

Milled surface textures are beneficial for interlayer bonding in that they generally facilitate higher ISS than do overlay surfaces. This is due to the macrotexture of the milled surface interlocking with the new pavement layer, which contributes to better interlayer bonding (Coleri et al. 2017; FHWA 2016; Mohammad et al. 2010). Since the milled surface has a greater degree of contact friction with the new pavement layer, it exhibits higher ISS (Al-Qadi et al. 2012b). Al-Qadi et al. (2012a) suggested that milling of the pavement surface, although it does give way to higher variability in shear test results, results in an ISS increase of 20 psi when compared to an unmilled surface.

For overlays, construction can occur on both existing aged and new pavement surfaces, depending on the maintenance strategy employed by the agency. Conceivably, overlays on aged existing asphalt surfaces exhibit weaker bonds than milled surfaces since the surfaces do not exhibit the interlock effect. Overlays constructed on new asphalt surfaces that are already coated with fresh asphalt yield ISS that is better than aged existing asphalt surfaces, but is still inferior to that of milled surfaces (Mohammad et al. 2010).

The effect of interlock with the milled surface is dependent upon the type of asphalt mixture used. Song et al. (2015) concluded that ISS increases with surface roughness, especially at intermediate to high pavement temperatures where the effect of tack coat application rate was diminished. This effect is especially apparent when coarse surface mixes were used, where the aggregate interlock effect is more prominent (West et al. 2005; Sholar et al. 2004). In regards to aggregate size, Al-Qadi et al. (2012a) showed that an asphalt mix with nominal maximum aggregate size (NMAS) below 3/8in (9.5mm) yields reduced tack coat bond shear strength, due to a reduction in aggregate interlock of larger aggregate particles. However, in order to capitalize on the aggregate interlock effects of milled surfaces, an adequate level of compaction is necessary (Kruntcheva et al. 2005).

Sensitivity of ISS to tack coat application rates can be affected by surface texture as well. Coleri et al. (2017) noted that the effect of application rate was less pronounced for milled surfaces due to the contribution of strength from pavement texture effects. Overall, it was found that the tack coat bond strength for milled surfaces was 112 psi, whereas the bond strength for overlay surfaces was 60 psi. Covey et al. (2017) showed through laboratory testing of field core samples that the milled surface texture impacted the bond strength. It was shown that an increase in surface texture caused a corresponding increase in ISS, indicating a positive relationship between these two variables. However, due to this effect, there were no reliable conclusions to be made regarding the effect of application rate on bond strength on milled surfaces due to the prominence of texture in ISS results. Al-Qadi et al. (2008) investigated the effect of surface texture on the tack coat bond strength between Portland Cement Concrete (PCC) pavement surfaces and HMA overlays. The authors found that application rate plays a bigger role in shear strength at the layer interface when tack coat is applied to smooth PCC surfaces than for milled PCC surfaces. This is again due to the interlock of aggregates in HMA with the rougher milled surface. It is important to note that ISS results from this study were not obtained from samples subjected to a normal load (horizontal confinement) during shear testing, but the authors expected that a normal load would further enhance the shear strength due to the interlock effect. This is important since the bond at the layer interface is in its most critical state when subjected to traffic loads. Additionally, this study only considered an underlying PCC pavement layer, whose surface texture may not be fully representative of asphalt pavement.

Quantification of Texture Depth

A common method of quantifying the texture is the Sand Patch Test (ASTM E965, 2015). Figure 2.6 shows the sand patch test being applied to a milled pavement surface in the field.

Figure 2.6: Sand patch testing on milled pavement surface (Coleri et al. 2017).

Since surface texture has been shown by several researchers to influence ISS, it would behoove the research area to first quantify the macrotexture of pavement samples in order to accurately investigate this effect in laboratory testing. Covey et al. (2017) investigated the differences in surface texture between overlay and milled pavement surfaces. It was determined that the overlay surface had a mean texture depth (MTD) that was 82% less than that of the milled surface, based on field measurements using the Sand Patch Test. Furthermore, the variance in MTD measurements for the milled surface was much higher than the overlay surface, indicating that the milled surface has a greater degree of irregularity.

A report by West (2010) discusses some considerations for milled pavement surface texture characteristics. It was suggested that a texture should have no more than ½ in. between peaks and valleys of the milled surface, as is specified by some agencies as a texture verification check during the inspection process. Milling texture can also affect the properties of the finished pavement roughness. A micro-milling drum is said to produce a smoother finished pavement surface texture, whereas a standard milling drum can create irregularities in smoothness of thin pavement layers, stemming from the deep grooves it produces in the resulting surface texture. A uniform texture was suggested to be imperative for the compactibility of thin overlays on a milled pavement surface. Worn or damaged milling drums can create nonuniform milled surface textures, which can cause problems for compaction of thin overlays and also create potential hazards for motorcycles if the milled surface is opened to traffic during construction. Figure 2.7 shows an example of pavement milling equipment in the field.

Figure 2.7: Pavement milling operations in the field (West 2010).

A report by Mokarem (2006) investigated the performance of milled surfaces subjected to traffic using surface characterization techniques, including the Sand Patch Test. One finding of this report was that the average macro-milled surface MTD was 3.231 mm. This was based on several pavement sections milled with a conventional pavement milling machine. Another finding was that the milled surface can be plagued by a phenomenon known as "scabbing". This occurs when the pavement milling machine flakes off existing pavement from the underlying layer at the layer interface, leaving inconsistencies in texture which can compromise bonding with the new asphalt overlay. An example of scabbing after milling is shown below in Figure 2.8.

Figure 2.8: Scabbing of existing pavement after milling (Shiells 2015).

Through use of the tack lifter device, Rawls et al. (2016) showed that an inverse trend exists between mean profile depth (MPD) of the pavement surface and the amount of emulsion that is available for bonding due to emulsion absorption. Additionally, the amount of emulsion that soaks into existing pavement surfaces was shown to be approximately 0.06 gal/yd^2 in regions with high MPD, which is indicative of the need for application rate adjustment on high-texture or cracked pavement surfaces.

2.2.5 Coverage

A lack of adequate tack coat coverage can have direct implications on the quality of the tack coat bond. It is an important consideration for quality assurance since it is the most visually apparent factor for monitoring tack coat quality in-situ. Visual acceptance of coverage is the primary means for tack coat quality assurance during construction in Oregon. Coverage that is nonuniform can give rise to high variability in interlayer bonding characteristics.

According to FHWA (2016), it is important that application of tack coat materials is uniform in all directions (transverse and longitudinal). Figure 2.9 shows acceptable and unacceptable uniformity in tack coat application.

(a) (b)

Figure 2.9: Tack coat application uniformity (a) Acceptable tack coat application uniformity (uniform), and (b) unacceptable tack coat application uniformity (non-uniform).

Tack coat coverage directly affects the strength of the interlayer bond. Mohammad and Button (2005) note that the maximum bond strength between layers occurred when 90-95% coverage was achieved at the optimum application rate. Mohammad et al. (2012) found that when tack coat coverage was reduced to 50% of the subject area, the interface shear strength (ISS) at the tack coat bond was reduced 50% to 70%. Nonuniform bonding characteristics at the layer interface were also noted as a ramification of reduced coverage.

Coverage specifications have implications on application rates as well. A greater degree of coverage will generally necessitate a higher application rate. However, this increase in coverage and application rate can bode poorly for bond strength at the interlayer. Amelian and Kim (2017) noted that the shear strength and tangential modulus of the interlayer bond decreased when the application rate changed after switching from single coverage to double coverage. The authors attribute this to the increased amount of binder that is present between the pavement layers. The excess binder could cause issues with bond quality based on these results, although the authors acknowledge that more research in this area should be conducted to yield conclusive results.

Problems with construction equipment can also impact coverage. Mohammad et al. (2012) suggested that the main factors influencing coverage uniformity are nozzle clogging, nozzle orientation/size and speed of the distributor truck during application. Covey et al. (2017) showed in a field study in Oregon that the distributor truck used by the contractor did not apply the tack coat uniformly and was unable to achieve the target application rate. This resulted in lower bond strengths for that particular pavement section when compared to a different section where a newer distributor truck provided by the tack coat manufacturer was used and appropriate coverage and application was achieved.

Properties of tack coat materials can also impact coverage. Mohammad et al. (2012) suggested that diluted emulsions are beneficial when uniform application at ambient temperatures is desired, since the diluted emulsions are sprayed more easily and are less apt to clog spray nozzles on tack coat distributor trucks.

Mohammad et al. (2012) also conducted an industry survey inquiring about agencies' practices relating to verifying application coverage. Only 64% of respondents were able to confirm that application coverage is at least 90% of the pavement surface area. To help ensure this, measures of lap coverage, spray nozzle angle and spray bar height specifications are pursued, which are reportedly employed by only 25%, 12% and 10% of responding agencies, respectively.

2.2.6 Presence of dust on existing pavement surface during construction

Surface contaminants, such as dust, can significantly affect the tack coat bond strength exhibited between pavement layers. Provided that all other factors are befitting, such as tack coat application rate, coverage and curing time, minimizing the amount of dust on the pavement surface can help to ensure that adequate tack coat bond strength is achieved. This is particularly important for milled pavement surfaces, where excess dust is produced from the milling of existing pavement layers. According to FHWA (2016), milling of existing pavement is shown to generate high amounts of dust which can impact bond strength. To combat this, milled surfaces require adequate cleaning, commonly done by sweeping, to ensure that bonding is not compromised (FHWA 2016). As it stands, contractors typically clean the pavement surface using one of two methods: sweeping/vacuuming and air blasting (Al-Qadi et al. 2012b). Figure 2.10 shows these two methods being employed in the field during paving operations.

(a) **(b)**

Figure 2.10: Cleaning methods (a) Sweeping and vacuuming and (b) air blasting (Al-Qadi 2012b).

Air blast cleaning was suggested by Salinas et al. (2013) as an effective measure for removing dust from the pavement surface prior to construction. This suggestion was based on results from a field study that compared the pavement surface cleanliness of sweeping and air blasting and the effect on tack coat bond strength and required application rate. However, although this study suggests that air blasting can improve bond performance at lower residual application rates (below 0.04 gal/yd^2 for SS-1h), it is also time-consuming and can cause health and safety hazards in urban environments due to dust clouds. Air blasting also had inferior bond performance compared to sweeping at higher application rates.

The effect of surface cleanliness on bond performance was evaluated by Mohammad et al. (2012). The authors used uniformly graded sand to simulate dust on the pavement surface and found that ISS was enhanced by the presence of dust. This result was attributed to the effect of dust combining with residual asphalt and creating a mastic with a viscosity exceeding that of the residual asphalt alone, which provided greater shear resistance. This, combined with grittiness of sand particles providing extra frictional resistance, yielded a higher ISS. However, due to the use of a uniformly graded sand to simulate dust effects, actual field conditions may not be represented by these results. The authors suggested that cleaning and sweeping of the pavement surface prior to construction is worthwhile to avoid any problems related to the presence of dust.

Dust can also affect the propensity of tracking during construction operations. A dustier surface can induce additional tracking, as the dust coating the existing pavement surface readily adheres to tack coat materials which are easily picked up by construction vehicles during paving operations (Mohammad et al. 2012). This tracked debris accumulates and falls off construction vehicle tires, creating inconsistencies in the pavement surface and additional debris on the roadway. Figure 2.11 shows an example of tracking by a paver during construction due to excess dust on the pavement surface.

Figure 2.11: Tracking on paver wheels due to excess dust (Mohammad et al. 2012).

Excessive time delay between construction intervals has been shown to create bonding issues due to contaminants on the pavement surface. Hachiya et al. (1997) showed that bond strength at the layer interface decreased as the time interval between paving successive lifts increased due to dust accumulation on the pavement surface.

2.2.7 Moisture during Construction

The presence of moisture on the pavement surface prior to tack coat application can have effects on bond strength and tack coat quality. Water on the pavement surface during construction can be caused by rainy weather or emulsions that have not had sufficient time to set. The type of tack coat material used is indicative of the magnitude of moisture effects on bond strength. Paving grade binders are more sensitive to the presence of moisture, whereas emulsions are less affected by moisture since they contain water. Water on the pavement surface was suggested to have possible negative effects on layer adhesion (Wang et al. 2017). Sholar et al. (2004) showed that moisture on the pavement surface under rainy conditions reduced the shear strength of the tack coat bond.

Conversely, Mohammad et al. (2012) found that moisture presence on the pavement surface prior to construction does not negatively impact the interlayer shear strength (ISS). The authors note that a small amount of water is readily evaporated by the heat from placed HMA. The authors did not investigate this effect with Warm Mix Asphalt (WMA), however. Also, moisture on the pavement surface was simulated using a small quantity of water which may not represent actual rainy conditions in the field. Therefore, Mohammad et al. (2012) recommends that the pavement surface be clean and dry prior to construction.

Moisture content of the existing pavement was a consideration of the study by Mohammad et al. (2010). In some cases, the study noted that wet conditions actually yielded higher interface shear strengths than dry conditions, but attributes this to the presence of coarse aggregates at the pavement surface increasing the frictional resistance.

2.2.8 Pavement Temperature during the Use Phase

Since asphalt is a viscoelastic material, its properties are largely dependent upon temperature. In the same way that pavement design takes into account climate as a controlling factor for asphalt binder selection, tack coat material selection should also be done in light of climate effects. Research by Song et al. (2015) suggested that temperature is the most important factor controlling tack coat bond strength, followed by surface texture. Amelian and Kim (2017) found that tack coat interlayers behaved differently at different temperatures. Coleri et al. (2017) showed that pavement temperature is the most influential property affecting critical shear strain and that climate should be considered when selecting tack coat materials.

Investigation of pavement temperature effects by Song et al. (2015) showed that interlayer shear strength (ISS) tends to be higher at low temperatures due to increased stiffness of the tack coat residual asphalt. At higher temperatures, particularly those surpassing the softening point of the residual asphalt, ISS is reduced since the tack coat becomes less viscous. Temperature disparities were also found to illuminate an inverse relationship between the shear strength contribution of surface texture and that of application rate. At high temperatures, surface texture became more significant than application rate in controlling bond strength, whereas at very low temperatures, the application rate governed the shear strength and the effect of surface texture was benign. The authors also demonstrated that the contribution of application rate to shear strength was significant at a pavement temperature of 25°C. Al-Qadi et al. (2012a) also showed that, in general, ISS decreases with an increase in temperature due to a decrease in tack coat moduli at higher temperatures. However, excessively low temperatures (-15°C) can induce brittle tack coat behavior, causing bond failure.

Amelian and Kim (2017) concluded that tack coat interlayer samples tested in the lab at low temperatures exhibited a rapid reduction in shear strength after the peak shear strength occurred. Conversely, samples tested at intermediate temperatures displayed a slow reduction in shear strength after the peak. This result is indicative of the sensitivity of tack coat material to low temperatures.

Coleri et al. (2017) noted that increasing pavement temperature makes the tack coat bond more prone to failure, as shear strain is amplified with a pavement temperature increase from 86°F to 113°F. This result indicates that tack coat failures are more likely during summertime when pavement temperatures are higher.

Mohammad et al. (2012) noted that ISS at the tack coat bond was inversely proportional to temperature. This yields the conclusion that decreases in temperature result in increased tack coat bond strength. Furthermore, high temperature shear strength results were more pronounced for trackless tack coat emulsions than for rapid-setting emulsions, likely due to the high viscosity of residual asphalt. The authors also found that tack coat tensile strength increased with increasing temperature until an optimum temperature, where the tensile strength then began to reduce.

2.3 LABORATORY AND FIELD TEST METHODS

2.3.1 Laboratory sample preparation

2.3.1.1 Laboratory application of tack coat

Laboratory testing to evaluate the influence of tack coat application rate on bond strength necessitates an accurate method of applying tack coat to the specimen surface. Past research has employed several different methods for applying tack coat to laboratory samples. Some of these methods are summarized below.

A study by Mohammad et al. (2010) details sample preparation procedures consisting of procuring cylindrical samples using the Superpave Gyratory Compactor (SGC) in a two-lift structure. The bottom 55mm of the 100mm samples were compacted and allowed to cool before tack coat was applied at the manufacturer-specified temperature at various application rates. Tack coat materials were applied to the samples using a paint brush. The top portion of the sample was then compacted on top of the cooled and coated bottom half. Al-Qadi et al. (2012a) also prepared cylindrical samples in the laboratory and tack coat was applied to samples using a paint brush. The quantity of tack coat material applied was determined using the following equation:

$$Weight\ of\ tack\ coat = 2.9205 \times \frac{Targeted\ residual\ application\ rate \times Area \times Specific\ gravity}{Dilution\ rate\ of\ tack\ coat}$$

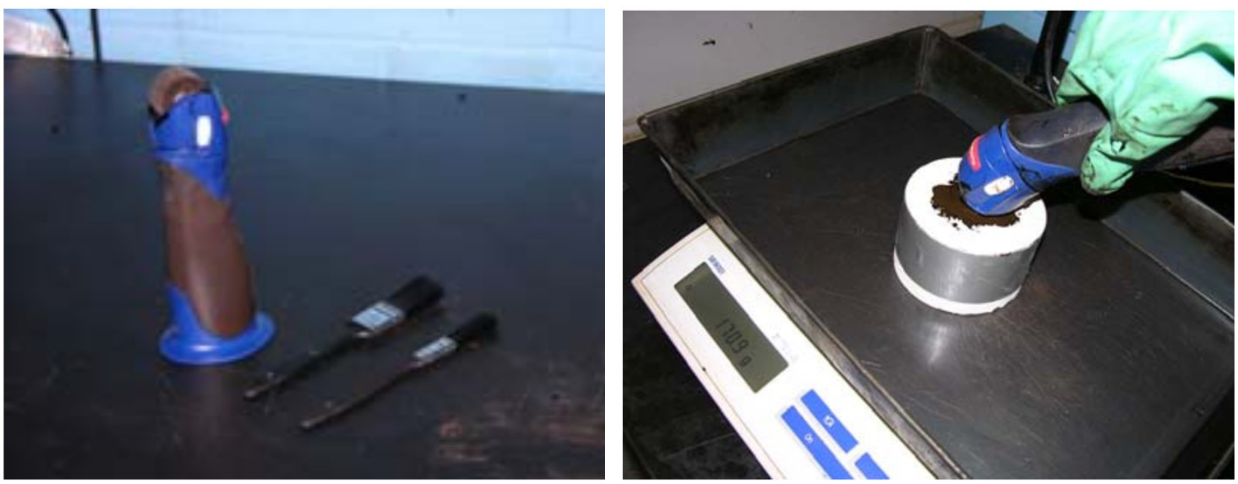
(2-1)

Where:

- Weight of tack coat is the weight in grams of the tack coat material applied on the bottom layer (existing surface);
- Targeted residual application rate is the application rate that is aimed to be achieved (gal/yd^2);

- Area is the cross-sectional area of the specimen (in^2);
- Specific gravity is that of the tack coat, based on its specifications;
- Dilution rate of tack coat is the amount of residual asphalt to water in the tack coat material; and
- The constant is used to convert gallons to liters and yd^2 to in^2 to maintain consistency in the units.

Al-Qadi et al. (2008) devised a way of applying tack coat to PCC core samples using a sponge roller. First, samples were cleaned with water and wiped clean to eliminate surface contaminants. The specimen edges were then wrapped in tape to prevent dripping of tack coat along the sides. Specimens were then placed on a scale where tack coat was applied using the sponge roller device, which allowed for uniform application of the tack coat. The application rate per unit area was calculated based on the known sample area. Specimens were then allowed to sit for 15 minutes in order for the tack coat emulsion to break. Figure 2.12 shows the sponge roller device and application method used in this study.



(a) (b)

Figure 2.12: (a) Sponge roller device used for application, and (b) sponge roller applying tack coat to pavement surface (Al-Qadi et al. 2008).

Rawls et al. (2016) employed a pneumatic sprayer device in order to distribute tack coat to pavement surfaces in the laboratory. Figure 2.13 shows the application system employed by Rawls et al. (2016). Coleri et al. (2017) also experimented with this method but did not achieve good results due to clogging of the spray nozzle and uneven distribution of the tack coat.

Figure 2.13: Application of tack coat in the laboratory (Rawls et al. 2016).

2.3.1.2 Laboratory procurement of moisture test samples

Evaluating the presence of moisture on tack coat bond strength in the laboratory requires consistent methodology for obtaining uniformly saturated samples. A study by Al-Qadi et al. (2008) utilized temperature-controlled water baths to procure samples with a saturation level between 70% and 80%. First, samples were placed in a conditioning chamber with 68°F water for 5-10min. Saturation levels were then measured using Equation **Error! Reference source not found.**, shown below.

$$\boldsymbol{S = \frac{100 \times J}{V_a}}$$

(2-2)

Where,

S	=	degree of saturation, percent, %;
J	=	volume of absorbed water, in^3; and
V_a	=	volume of air voids, in^3.

Samples meeting the 70-80% saturation criteria were then placed in a 140°F water bath for 24hrs followed by a 68°F water bath for 2hrs prior to testing. Figure 2.14 shows photographs of the water bath conditioning chambers used for this process.

(a) **(b)**

Figure 2.14: Samples conditioning in 140°F water bath prior to testing (Al-Qadi et al. 2008).

2.3.1.3 Shear strength of laboratory-prepared test samples versus field-cored samples

An important point to consider is whether or not laboratory application procedures are representative of field conditions. A disparity is present in the shear strength of laboratory-produced samples versus field-extracted core samples (Mohammad et al. 2012; Mohammad et al. 2010). In these studies, the authors used gyratory compacted samples for laboratory tests, which may differ significantly from roller-compacted samples in the field. In general, the laboratory-prepared samples overestimated the shear strength of the tack coat bond at the layer interface by a factor ranging from 2 to 10 for a given application rate. This is due to the difference in compaction methods and tack coat application methods between laboratory-prepared samples and field-cored samples. Additionally, whereas increased application rates generally resulted in higher ISS for field cores, increased application rates actually decreased ISS for lab samples, likely due to slippage effects.

Some other auxiliary findings of the study by Al-Qadi et al. (2012a) are also notable. One such finding regarding laboratory sample preparation is that the temperature of the compaction mold has an effect on tack coat bond strength. As suggested by the authors, excess heat from the compaction mold causes the tack coat to form a stronger bond with the pavement surfaces, creating artificially high shear strength results and a greater degree of bonding between the pavement layers. For this reason, this study subsequently used cold compaction molds to more realistically quantify tack coat bond shear strengths between pavement layers.

2.3.2 Bond strength test devices

Various devices have been developed and employed in previous research studies to quantify the tack coat bond strength at the pavement layer interface and in-situ tack coat quality. These devices aim to quantify the tack coat parameters in several different failure modes such as shear, torque and tension. Although it is difficult to simulate the behavior of the tack coat bond under actual traffic loading conditions (Amelian and Kim 2017), shear testing of the tack coat bond is the most commonly employed test (Wang et al. 2017). Figure 2.15 below shows a diagram of the various failure modes commonly used for testing.

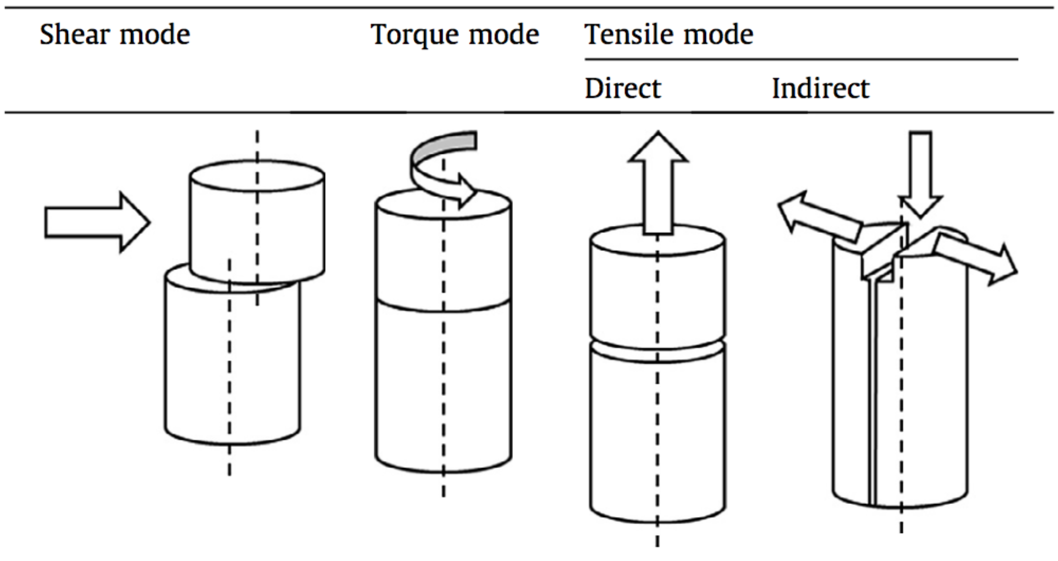


Figure 2.15: Diagram of various tack coat bond failure modes (Wang et al. 2017).

2.3.2.1 Shear strength test devices

2.3.2.1.1 Measurement of peak shear strength using monotonic shear tests

The shear mode has been the most commonly tested mode of failure since it is most representative of real-world pavement interlayer slippage (Wang et al. 2017). Historically, several test devices have been developed and used to quantify the shear strength of the tack coat bond at the layer interface, such as the Uzan device in 1978 and a widely-used device, the German Leutner shear device, in the late 1970s (Wang et al. 2017). These devices employed constant displacement rates in order to shear a two-layer pavement sample at the bond location and measure the peak load required to break the bond. This process is known as monotonic direct shear testing (DST) (Amelian and Kim 2017). This principle is still the foundational approach to measuring peak interface shear strength (ISS) of multi-layer asphalt pavement samples in the lab. Since the advent of this test method, several other shear test devices and procedures have been developed to encompass different fatigue measures, environmental conditions, sample dimensions and sample configurations. Various types of shear test devices are discussed below.

Direct shear testing under normal load

The basic monotonic direct shear test for cylindrical core samples is performed in a simple jig where one pavement layer is fixed and the other layer is subjected to loading at a constant displacement rate. A normal load, or confining pressure, is also integrated into the test jig in order to simulate a static traffic load from a vehicle tire. A basic iteration of this test was employed by Romanoschi and Metcalf (2001), who studied direct shear testing of two-layer asphalt concrete samples under normal load (confining pressure). The authors found that three parameters from the direct shear test could be used to explain the behavior of the interlayer bond. The maximum shear strength, the slope of the stress-displacement curve prior to peak shear stress and the friction coefficient between the layers all characterized the interlayer bond before, during and after shear failure. Shear stress and displacement were found to be proportional until the peak shear stress was reached. After that point, the friction coefficient was the explanatory variable which depicted post-peak behavior. This parameter was found to be unaffected by the normal load. Furthermore, it was found that for interfaces bonded with tack coat, the effect of normal load was less significant. It was only for those samples without tack coat that the normal load played a role in shear strength of the interlayer. The authors also note that the linear relationship between the number of loading cycles and the permanent shear deformation (PSD) indicated that the interlayer bond may also fail in fatigue.

Florida direct shear test

The Florida direct shear test (or FDOT shear tester) was developed by Florida Department of Transportation (Sholar et al. 2004) to measure the interface bond strength by applying a shear load in the vertical direction (Figure 2.16). Two-layered specimens with a diameter of 6 in. (152.4 mm) were tested in shear by moving one of the loading collars (loading frame) in the vertical direction. The gap between the loading frame and the reaction frame was specified to be 4.8 mm. A loading rate of two inches per minute (50.8mm/min.) was used.

Field cores with RS-1 emulsion were tested at 25°C. Residual application rates were 0.00, 0.02, 0.05, and 0.08 gal/yd^2. The emulsion was applied on wet and dry surfaces to investigate the effect of water on bond strength. The major conclusions of the study were:

- Water reduced bond strengths. Wet sections with a 0.08 gal/yd^2 application rate have significantly higher bond strengths than the wet sections with lower application rates.

- Tack coats applied on milled surfaces had higher bond strengths.

- The standard deviation of the measured interface bond strengths was determined to be 9.6 psi.

- The interface bond strength difference between the sections with no tack coat (0.00 gal/yd^2) and 0.02 gal/yd^2 application rate were measured to be minimal. However, increasing the application rate to 0.05 gal/yd^2 created a significant increase in measured bond strengths.

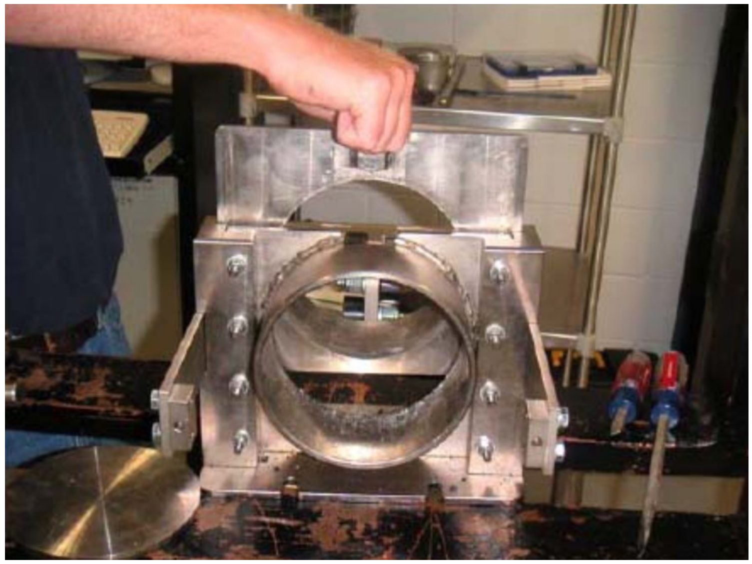


Figure 2.16: Florida direct shear test device (Tashman et al. 2006).

National center for asphalt technology (NCAT) bond strength test

West et al. (2005) developed the NCAT bond strength test to determine the best tack coat material and optimum application rates. The NCAT bond strength test (Figure 2.17) is a shear type test in which shear load was applied with a universal testing machine (UTM). The major difference from the FDOT shear tester is the horizontal load (perpendicular to the direction of shear) applied as a normal (confining) pressure. The major purpose of using normal pressure is to determine the impact of surface texture on bond strength. A loading rate of two inches per minute (50.8mm/min) was used to conduct the test with a Marshall press (when a UTM is not available).

Two types of emulsion (CRS-2 and CSS-1) and a PG 64-22 asphalt binder were tested at 10, 25, and 60°C. Residual application rates were 0.02, 0.05, and 0.08 gal/yd^2. Applied constant normal pressures were 0, 10, and 20 psi. The major conclusions of the study were:

- The normal pressure did not significantly affect the measured bond strengths at 10 and 25°C test temperatures. On the other hand, at 60°C, increasing normal pressure increased bond strengths.
- CRS-2 and CSS-1 had lower bond strengths than PG 64-22, especially at 60°C.
- Increasing temperature reduced bond strengths.
- Tack coats applied on milled surfaces had higher bond strengths.

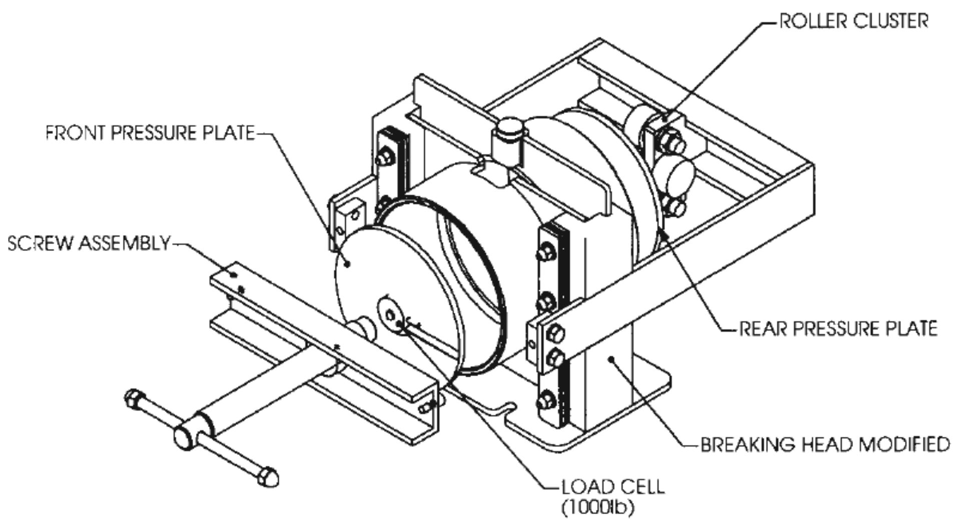


Figure 2.17: NCAT bond strength test device (West et al. 2005).

Louisiana interlayer shear strength tester (LISST)

A notable test device developed recently for tack coat ISS measurement was used in research by Mohammad et al. (2012), called the Louisiana Interface Shear Strength Tester (LISST). This device, comprised of a simple jig, measures the shear strength of the tack coat bond using monotonic strain-controlled loading. The authors examined the effect of variables such as surface type/texture, tack coat type, surface cleanliness and paving method on the ISS. ISS was evaluated with the interface shear strength test using the LISST and with the torque bond test, a test device used to quantify the shear resistance of the tack coat bond using an applied torque to cylindrical samples, with great success. These test devices have since been used by several researchers to quantify the bond strength of tack coats. Figure 2.18 shows a diagram of the LISST.

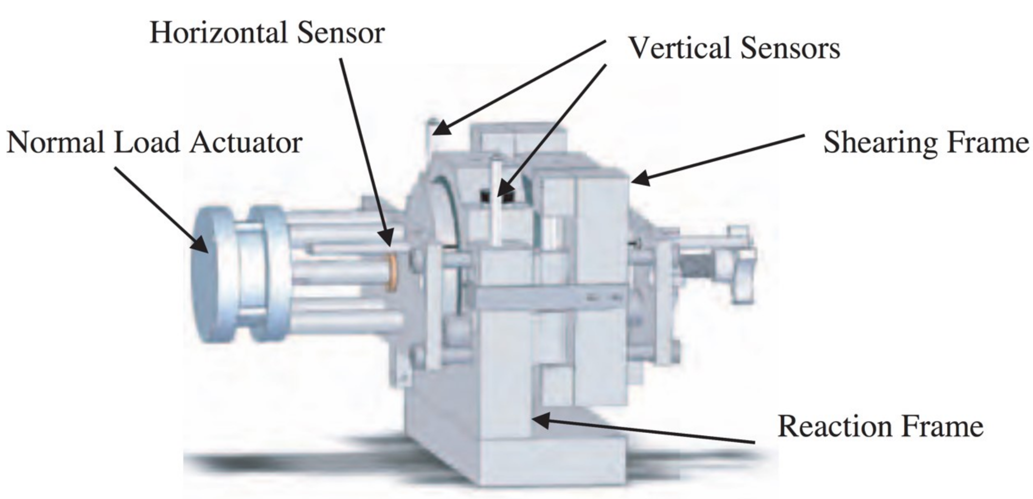


Figure 2.18: Diagram of LISST test device (Mohammad et al. 2012).

Mohammad et al. (2012) used the LISST to characterize interface bond properties under shear loads. The major difference from the NCAT bond strength test was the reduced loading rate (2.54 mm/min) and improved test fixture with less friction. Using 2D finite element simulations and laboratory testing at different displacement rates (2 in/min, 0.1 in/min, and 0.02 in/min), the authors recommended the use of 0.1 in/min (2.54 mm/min) as the displacement rate to be able to effectively simulate the slow rate of loading encountered at the interface in the field. Two-layered specimens with a diameter of 6 in. (152.4 mm) were tested in shear by moving one of the loading collars (loading frame) in the vertical direction. The gap between the loading frame and the reaction frame was specified to be 0.5 in. (12.7 mm).

Mohammad et al. (2012) conducted several experiments on field-prepared samples under different conditions to investigate the effects of surface type, tack coat type, application rate, cleanliness, water, confinement, and tack coat coverage on interface bond strength. The major conclusions of the LISST experiments were:

- Trackless tack coat created the highest interface bond strength while CRS-1 had the lowest strength.

- The difference between measured interface bond strengths for confined and unconfined tests was statistically significant. It was concluded that unconfined tests provided a conservative estimate of the bond strengths.

- Dusty conditions exhibited higher bond strength than the clean cases. However, this conclusion was indicated to be a result of the clean sand particles with uniform sizes used for creating the dusty conditions. Sand particles mixed with the applied tack coat formed a mastic which has a higher viscosity than the tack coat. This increased viscosity was indicated to be the reason for increased bond strength.

- The effect of water on bond strength was not statistically significant.

- The increased surface texture was observed to increase bond strength. Measured interface bond strength for milled HMA was the highest followed by Portland cement concrete (PCC), old HMA, and new HMA surfaces.

- Increasing temperature reduced bond strengths.

The effect of confining pressure on ISS of core samples is also of interest within this research area. Since tack coat bonds are likely to fail in shear when subjected to traffic loads, it makes sense to evaluate the bond shear strength when the two-layer pavement samples are subjected to a normal load. Mohammad et al. (2012) found that shear strengths for cores tested with confining pressure applied in the LISST device were always greater than that of unconfined tests, indicating that unconfined tests provide conservative estimates of ISS. Confining pressure was also noted to have significant implications on ISS as the application rate decreased, allowing the surface roughness and aggregate interlock effects to be more pronounced in these cases. Very high application rates did not exhibit this response under confining pressure, which is attributed to slippage brought on by the lubrication effect of excessive tack coat material reducing the roughness and aggregate interlock contributions to ISS.

Coleri et al. (2017) also used a variation of the NCAT bond strength test device, but used LISST test procedures (2.54 mm/min loading rate) in laboratory testing of their samples. This device also employed a confining pressure actuator. However, the confining pressure load in this actuator is driven by a spring, whereas the LISST is a pneumatically operated. The device used by Coleri et al. (2017) is shown below in Figure 2.19.

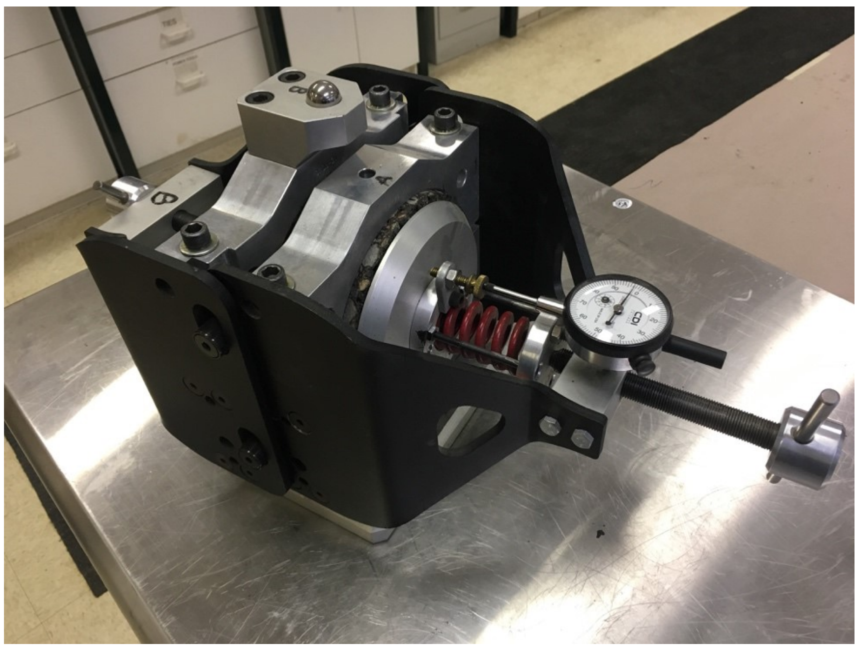


Figure 2.19: Shear test device used by Coleri et al. (2017).

Amelian and Kim (2017) found that fatigue of the tack coat bond is highly dependent upon the load-induced strain experienced by the interlayer. The authors found a useful parameter that can be extracted from the load-displacement curve yielded by the LISST, known as the interlayer bond energy, can yield the dissipated energy in the tack coat bond as it resists shear loads. Interlayer bond energy is defined as the area under the load-displacement curve up to the peak shear strength observed, as is shown below in Figure 2.20.

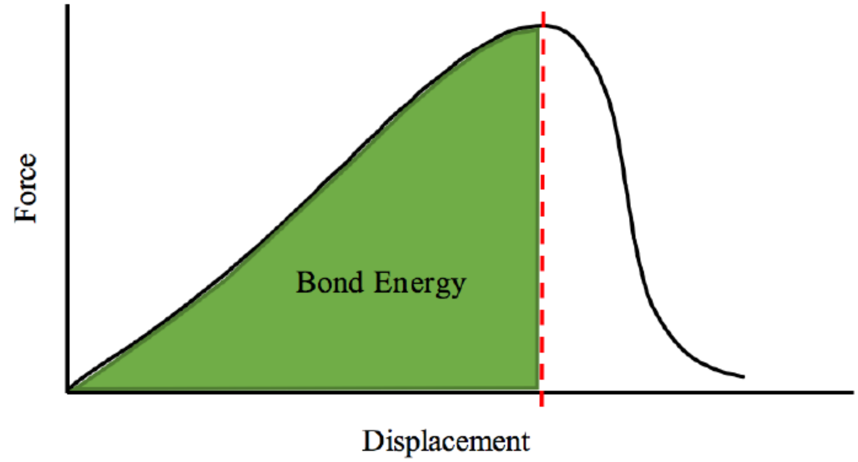


Figure 2.20: Interlayer bond energy shown graphically on the force-displacement curve (Amelian and Kim 2017).

The interlayer bond energy parameter encompasses the peak shear strength and corresponding displacement and can also be compared to other fatigue analysis tests. Amelian and Kim (2017) obtained a high correlation ($R^2 = 0.8$) between the interlayer bond energy and their chosen fatigue failure criteria, suggesting that interlayer bond energy is the most explanatory parameter that can be obtained from monotonic shear testing of the tack coat interlayer bond.

Despite their widespread use, there is a concern over the practicality of shear test devices. In all shear tests, there is an underlying assumption that the shear stresses are uniform across the bonded layer interface, which is not necessarily the case. Localized strains will be present in any sample regardless of how sophisticated the testing device is (Wang et al. 2017). Although there are several laboratory shear test methods for interface bond strength evaluation, the Florida direct shear, the National Center for Asphalt Technology (NCAT) bond strength test and the Louisiana Interlayer Shear Strength Tester (LISST) are the most commonly accepted experiments due to their simplicity. The use of normal pressure in NCAT bond strength test and LISST to simulate in-situ confinement improved the results of experiments conducted at high temperatures (West et al. 2005; Mohammad et al. 2012).

2.3.2.1.2 Measurement of shear strength under cyclic loading

Another method of quantifying the shear strength of the tack coat bond is cyclic loading. Under cyclic loading, the tack coat bond is expected to exhibit fatigue behavior that is more similar to actual traffic loading conditions (Amelian and Kim 2017).

Amelian and Kim (2017) used cyclic Direct Shear Testing (DST) to evaluate tack coat performance in the laboratory. The same testing apparatus that is used for monotonic shear tests was also used for cyclic DST. This test was conducted at a temperature of 25°C. The test differed from the monotonic ISS test in that the test was controlled by load instead of displacement.

To conduct the test, Amelian and Kim (2017) first applied a 50 N contact load, followed by a cyclic peak load of 0.75 kN until fatigue failure occurred or 150,000 cycles was reached. Fatigue failure of the samples was characterized by two criteria: permanent shear deformation (PSD) and interface stiffness (IS). Two linear variable differential transformers (LVDTs) affixed to the sample were used to measure the average displacement, which was then used to determine the PSD and IS. The PSD fatigue failure criterion was characterized by indicators similar to that of the Flow Number permanent deformation test for cylindrical asphalt concrete samples (AASHTO TP 79-13). Fatigue failure was defined as the point when the secondary flow stage ends and tertiary flow begins and is calculated using the Francken model (Amelian and Kim 2017).

The second criterion in the study by Amelian and Kim (2017) for characterizing fatigue failure, called interface stiffness (IS), was taken as the ratio between force amplitude and the product of displacement amplitude and interface area. The relationship is shown below in Equation 2-3)

$$\boldsymbol{IS} = \frac{\Delta \boldsymbol{F}}{\boldsymbol{A} \times \Delta \boldsymbol{u}} \tag{2-3}$$

This study by Amelian and Kim (2017) also considered a fatigue failure criterion of 50% reduction in initial stiffness, but the authors found that the 50% reduction in stiffness often occurred just before the point of complete debonding in the sample under the cyclic DST.

Amelian and Kim (2017) also examined the correlation between interlayer maximum shear force as measured by Montonic DST and the fatigue failure criteria from the Cyclic DST described above. These correlations were examined under two different criteria. Criterion 1 was the permanent shear deformation (PSD) criterion and Criterion 2 was the interface stiffness (IS), as described above. Under these two criteria, the authors were able to obtain correlation coefficients of $R^2 = 0.75$ for Criterion 1 and $R^2 = 0.67$ for Criterion 2.

Tozzo et al. (2014) also studied shear strength of asphalt interlayers under cyclic loading and normal load. This study employed two response parameters from the cyclic shear test to evaluate interlayer bond fatigue response: the number of load repetitions at the interface failure point ($N_{failure}$) and the number of load repetitions at the point of 50% reduction in shear stiffness in the linear decreasing range (N_{50}). In general, it was determined that the applied shear load and $N_{failure}$ were inversely related, meaning that a higher shear load amplitude resulted in a reduced number of repetitions before interface failure occurred. Furthermore, under the $N_{failure}$ criteria, as the confining stress applied to the sample was varied under a constant shear load amplitude, different fatigue responses were elicited, which indicated a strong dependence of interlayer fatigue behavior on confining stress. In general, it was observed that an increase in confining stress applied to the sample resulted in an increased fatigue resistance.

Tozzo et al. (2014) found that the normal load had a considerable impact on the fatigue resistance of the interlayer based on their N_{50} failure criteria as well. The authors also proposed a 3D linear regression model to estimate the combinations of normal load and shear stress that would yield equivalent fatigue damage. The authors displayed this result graphically by creating an "isodamage" plot, where equality in the different combinations of shear and normal stress were visualized. The isodamage plot is shown below in Figure 2.21. Finally, the authors compared the normal load sensitivity of cyclic DST to monotonic DST and observed a similarity in response, indicating the normal load had equivalent sensitivity in both of the tests. This similarity is also shown in Figure 2.21 and is represented by the equivalent slopes of the isodamage lines with the monotonic yield line.

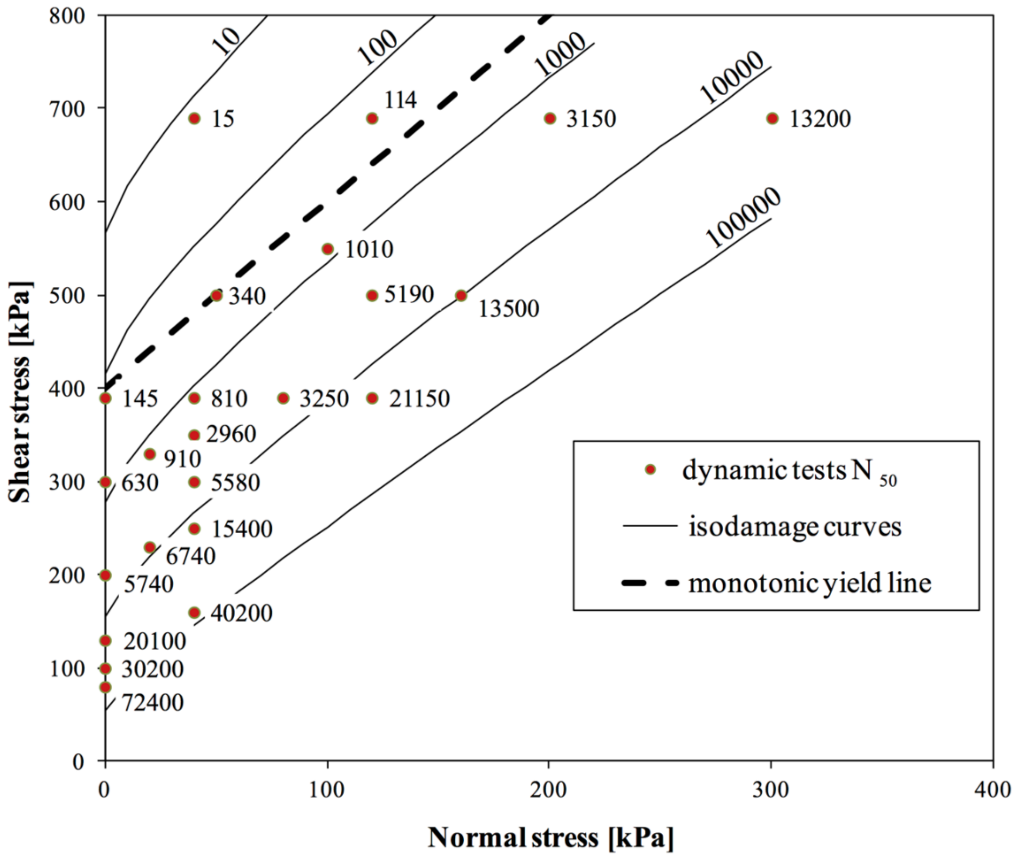


Figure 2.21: Isodamage plot for N_{50} failure criteria for 10 to 10,000 loading cycles (Tozzo et al. 2014).

Diakhate et al. (2011) studied cyclic shear testing of the interlayer bond between thin asphalt overlays and underlying pavement layers. This study obtained strong correlations between the number of loading cycles to a defined level of interface shear stiffness modulus reduction and the applied shear stress using a power law. This result is shown graphically in Figure 2.22 below. This was true for the two testing temperatures of 10°C and 20°C used in this study. The authors also note that at 10°C, a reduced amount of tack coat will lead to a reduction in bond strength, testifying to the importance of tack coat for improving shear strength at lower temperatures.

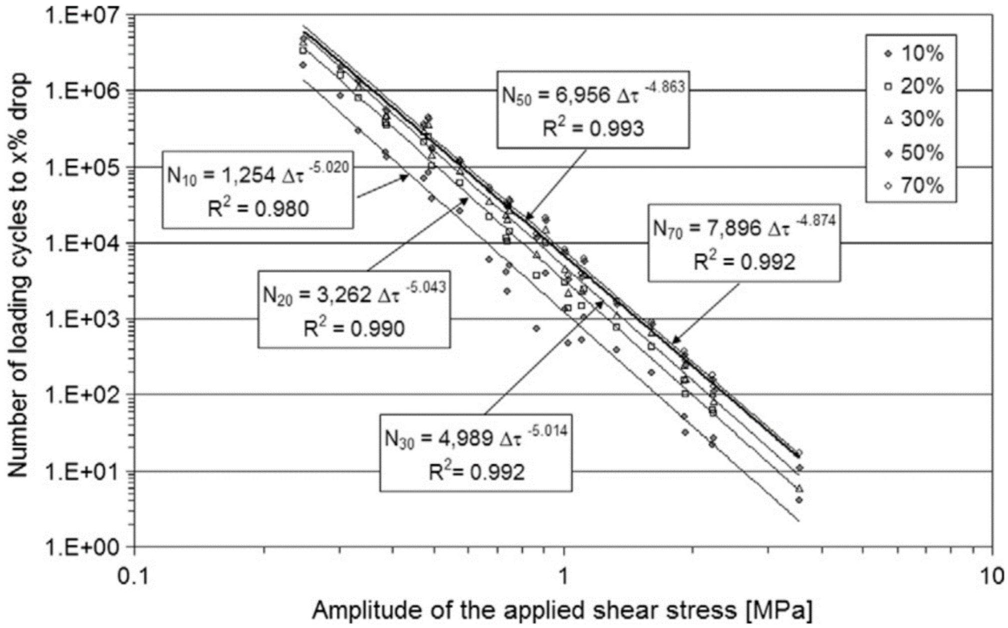


Figure 2.22: Number of loading cycles to predefined interface shear stiffness modulus reduction versus applied shear stress (Diakhate et al. 2011).

2.3.2.2 Tensile strength test devices

Tensile strength devices were employed to test resistance of tack coats to tensile forces, another common layer interface distress. The Schnek-Trebel device and its subsequent permutations quantified tensile strength of tack coat bonds but was impractical due to erroneous results from eccentricity that resulted from its complicated sample restraints (Wang et al. 2017). Tschegg (1997) developed the pull-off test device to measure the in-situ tensile strength of the tack coat bond. Tschegg (1997) also developed the wedge-splitting test to examine the fracture energy of the tack coat bond. Some of the more prominent tensile strength test devices are discussed below.

Texas pull-off test

The Texas Pull-Off test device (Figure 2.23) was a field test device 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. After the tack coat is applied on the pavement surface, the tack coat layer was left to set. After it was set, the device was placed on the tacked surface. The load plate was lowered to come in contact with the tacked pavement surface. Then, a 40-pound load was applied on the device for 10 minutes prior to testing to create bonding between the test plate and the pavement surface. After 10 minutes, the load was removed and a torque wrench was manually rotated in the counter-clockwise direction to move the plate in the vertical direction. The torque required to break the bond between the plate and the pavement surface was recorded and converted to bond strength using a calibration factor. A problem with this test method is that the rate of displacement applied to the core is subjective. It is impossible to control the displacement rate accurately using a manual torque wrench, resulting in high variability in shear strength results. A stepper motor is necessary to provide greater control over the displacement rate in this test.

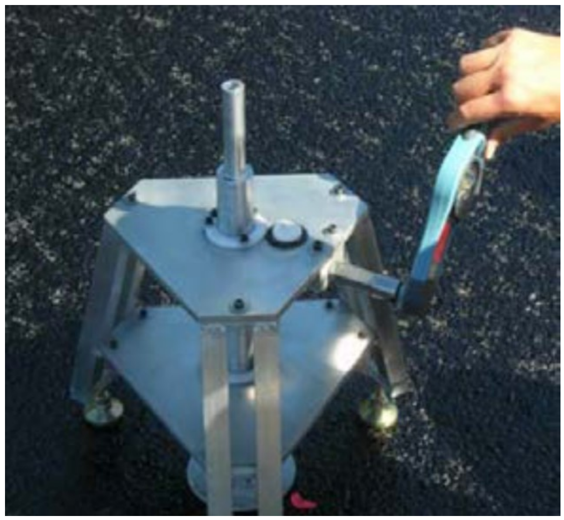


Figure 2.23: Texas pull-off test (Tashman et al. 2006).

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.

Tension tests, although very useful for comparing the quality of different tack coat types, is not very indicative of in-situ tack coat bond performance. Especially for milled surfaces, the effect of surface texture on the bond strength is not represented since there is no applied shear load. The results of tensile tests are dependent mainly on the tack coat quality and the contact area.

Louisiana tack coat quality tester (LTCQT)

Similar to the pull-off test, the Louisiana Tack Coat Quality Tester (LTCQT) was developed to measure tensile strength in the field and was found to accurately distinguish between bond strengths of different tack coat types (Wang et al. 2017). Texas pull-off and torque bond tests were improved to develop a test system known as the ATacker (Buchanan and Woods 2004; Mohammad and Button 2005). Mohammad et al. (2012) developed the LTCQT by further improving the ATacker in the following ways:

- using a load cell with a lower noise level;
- using a new actuator and driving motor to minimize the errors in displacement rate; and
- attaching a polyethylene foam to the loading plate to increase contact area for milled sections.

Mohammad et al. (2012) conducted several field experiments to evaluate the effectiveness of the LTCQT for tack coat quality evaluation. Tested sections were clean and dry. SS-1h, CRS-1, and trackless were the tack coats tested with LTCQT. More than three replicate tests were conducted on each section. Comparison of LTCQT results to the results of rheological tests showed that the 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%. The authors recommended conducting LTCQT tests at the tack coat residual asphalt softening point in order to get comparable results for different tack coat types. Although the LTCQT was suggested to be a reliable system for tack coat performance evaluation, the practicality, variability, and effectiveness of the LTCQT need to be improved to increase the widespread use of this system to evaluate the long-term performance of tack coats.

Oregon field tack coat tester (OFTCT)

Coleri et al. (2017) also developed a wireless tack coat tensile strength test device, the Oregon Field Tack Coat Tester (OFTCT), to evaluate bond strength in the field. The OFTCT, which is similar to the pull-off test and LTCQT, measures the tensile strength of the tack coat after the emulsion has set and was previously used to quantify the effect of surface cleanliness on tack coat bond strength (Mahmoud et al. 2017b). This device employed a computer-controlled strain rate and a wireless load-displacement sensor system to allow for in-situ evaluation of the tack coat tensile bond strength. Figure 2.24 shows the OFTCT being used in the field.

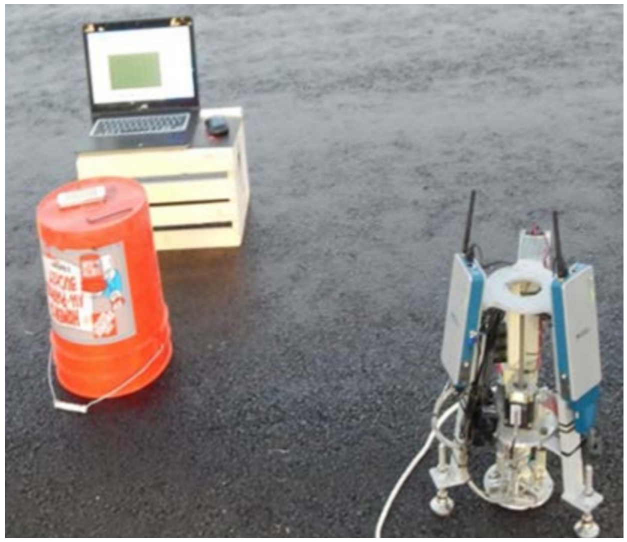


Figure 2.24: OFTCT in the field (Coleri et al. 2017).

2.3.2.3 Torque test devices

Shear strength of the tack coat bond can also be measured by applying a torque to the surface layer. This can often be done in the field with common torque test configurations. The Torque Bond Test was developed by Washington Department of Transportation (WashDOT) to perform in-situ shear strength tests using a handheld torque wrench and has been shown to be useful in past research (Tashman et al. 2006).

Torque bond test

The torque bond test was developed in Sweden and used as an in-situ test method to evaluate field bond strength. The test was adopted by the UK as a part of the approval system for tack coats (Walsh and Williams 2001). After an asphalt overlay is constructed, it is cored about one-half inch deeper than the layer interface. A loading plate is glued to the overlay surface using fast setting epoxy. Torque is manually applied to the surface at a constant rate using a torque wrench. The torque at failure is used as a parameter to characterize interface bond shear strength. The torque bond test can also be conducted on laboratory samples under controlled temperature. Manual load application with the torque wrench was later replaced by a servo motor actuator in the ATacker device to improve repeatability (Buchanan and Woods 2004). Figure 2.25 shows a photo of the torque bond test device.

Figure 2.25: Torque bond test device (Tashman et al. 2006).

Although the torque bond test captured the effect of milling on tack coat strength, the correlation between the measured torque values and the bond strength values from the Florida direct shear test was not statistically significant (Tashman et al. 2006). Weak correlation might be a result of the variability and bias introduced by manual load application. In addition, since the limit of the torque wrench was reached for most of the experiments, correlations at high bond strengths were not investigated.

Oregon field torque tester (OFTT)

More recently, Coleri et al. (2017) developed a novel torque test device, the Oregon Field Torque Tester (OFTT), to evaluate the post-construction tack coat bond shear strength in the field. The OFTT is a highly refined version of the torque bond test that measures the shear strength of the bond shortly after construction using torque applied at a constant displacement rate. Making use of a stepper motor, the torque can be applied consistently for each test, thereby reducing the variability that is inherent with a manually-operated handheld torque wrench. This device is controlled from a laptop computer using a software developed at Oregon State University. This device was found to yield shear strengths with a high correlation to laboratory-observed shear strengths ($R^2 = 0.6544$), suggesting that that the OFTT can be an effective, low-cost, less destructive and practical technology to monitor long-term in-situ bond strength (Mahmoud et al. 2017a). Figure 2.26 shows the OFTT and its principal components. Figure 2.27 shows a plot of laboratory shear strengths versus OFTT-measured shear strengths and their correlation.

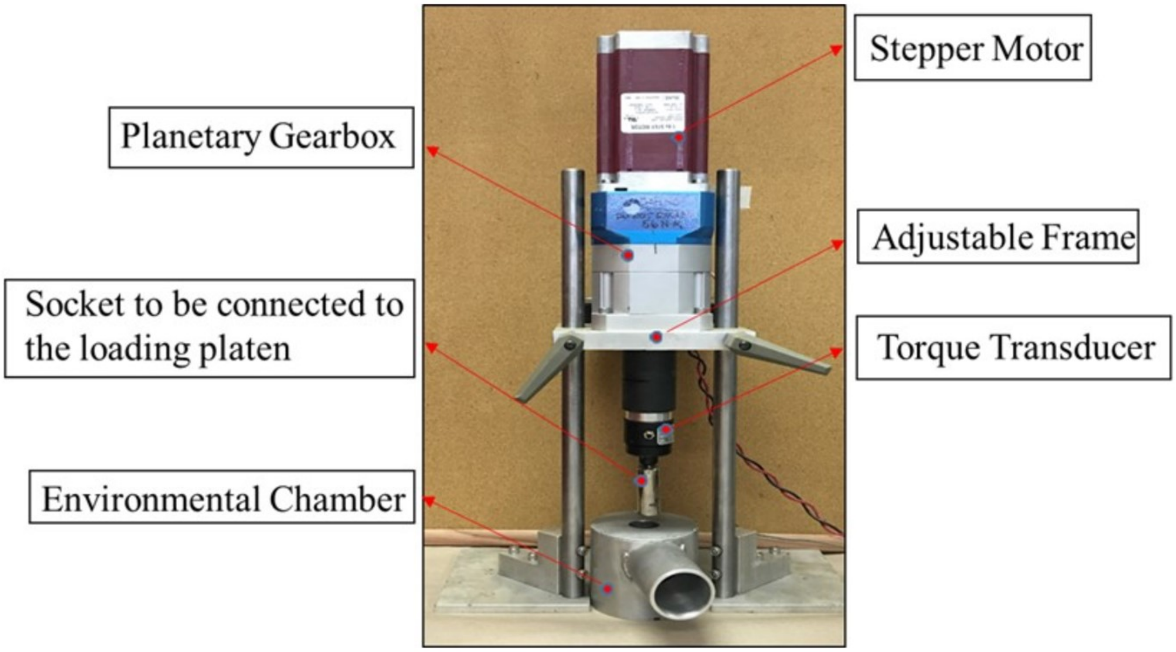


Figure 2.26: OFTT test device (Coleri et al. 2017).

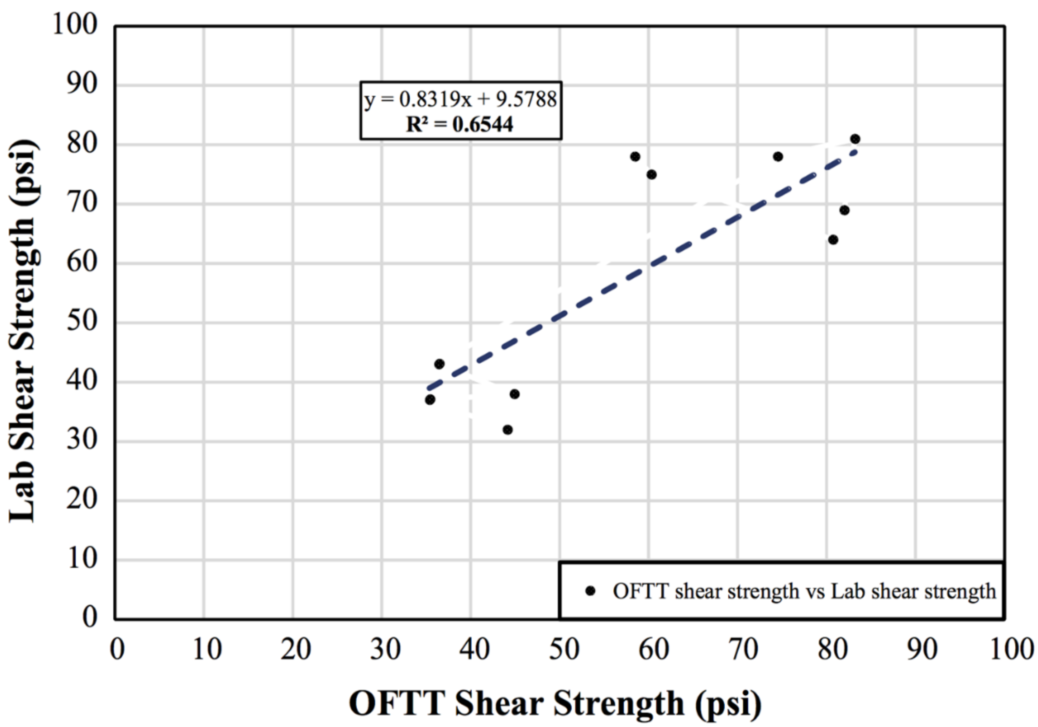


Figure 2.27: Correlation between laboratory shear strengths and OFTT-measured shear strengths (Mahmoud et al. 2017a).

2.3.2.4 Non-destructive testing for bond strength evaluation

Failure of the tack coat bond between pavement layers and the associated premature fatigue cracking can necessitate more frequent maintenance intervals. This phenomenon breeds necessity for a means of monitoring debonding problems using non-destructive testing (Celaya et al. 2010). Various techniques exist to characterize the pavement layer interface bond using non-invasive testing procedures that do not require pavement coring.

One such method of assessing debonding in pavement layers is Falling Weight Deflectometer (FWD) testing, which was used by Johnson et al. (2015) to characterize pavement layer bonding on an overlay surface at various time periods after construction. This study was meant to evaluate the effects of tack coat application rate and presence of contaminants on bond quality. In order to compare the FWD deflections from each time after construction, a normalized area factor (A_{36}) was devised to quantify the differences in pavement interlayer response. FWD measurements were conducted on various locations on the lane: the inner wheelpath, the outer wheelpath and the mid-lane. Area factor values close to 36 indicate that the deflections are similar throughout the deflection "basin", or the area around the applied load. Area factor values will be closer to 6 when the deflection varies significantly as the distance from the point load application increases. The authors note that for layer interfaces with proper tack coat bonding, the A_{36} factor should be close to 36. The area factor is calculated as follows in Equation 2-4):

$$\boldsymbol{A_{36} = 6\left(1 + 2\left(\frac{D_{12}}{D_0} + \frac{D_{24}}{D_0}\right) + \frac{D_{36}}{D_0}\right)} \qquad \textbf{(2-4)}$$

Where,

D0 = Deflection measured at the center of FWD load plate

D12 = Deflection measured 12 in. (305 mm) from the center of FWD load plate

D24 = Deflection measured 24 in. (610 mm) from the center of FWD load plate

D36 = Deflection measured 36 in. (914 mm) from the center of FWD load plate

The A_{36} measurement taken the day following paving construction decreased by 6%, on average, from the initial measurement taken immediately after construction. Two weeks after paving, the A_{36} increased by about 8%, on average, from the initial measurement. A reduction in the deflection at the load plate was also noted at two weeks after construction. Measurements taken at six months after construction were inconclusive due to freeze-thaw conditions at the test site. Since these measurements were observed in an area of higher tack coat application rate, the sudden decrease in the area factor after construction indicated that bond quality is reduced when the application rate is excessively high. Johnson et al. (2015) attributes this to the excess tack coat not acting to help bond strength.

Celaya et al. (2010) employed four NDT techniques to evaluate layer debonding in HMA pavement in a prepared case study. Pavement sections were purposefully constructed with varying levels of bonding using various contaminant materials such as talcum powder, grease, oil and clay in order to determine the sensitivity of the NDT techniques to detect debonding. The four chosen NDT techniques were Ground Penetrating Radar (GPR), Impulse Response (IR), Ultrasonic Surface Waves (USW) and Infrared Thermography. Detailed descriptions of test procedures for each technology can be found in Celaya et al. (2010). GPR measurements were found to be most sensitive to locations with severe debonding issues and locations with dielectric constants vastly different from that of HMA. GPR measurements were able to detect 33% of the debonded areas tested. For this reason, GPR was suggested as a qualitative NDT method for pavement layers with severe debonding or those with moisture present along the layer interface. IR measurements indicated that 59% of the fully debonded and partially debonded locations were able to be identified at varying depths, suggesting that the technology is useful for identifying more severe debonding issues. USW testing was found to capture 53% of the debonded locations and was most sensitive for identifying debonding at shallow depths, as a reduction in pavement modulus was evident at depths just below the layer interface. Finally, infrared thermography measurements were found to be less sensitive to detecting debonding, as only some of the severely debonded locations were detected. However, the authors note that the FLIR thermal imaging camera used had poor precision in temperature measurements and the use of a more sensitive thermal camera may improve the results for this technology. FWD testing was also employed for interlayer bonding evaluation as an auxiliary part of the study. It was found that the FWD was able to identify 46% of the debonded locations within the test site. The authors make note that the FWD, IR and USW techniques do require temperature corrections, as the results of these tests are dependent upon environmental conditions.

2.3.2.5 Computer modeling techniques for bond strength evaluation

Several computer models have been developed to investigate the impacts of different variables (such as temperature, layer thicknesses, stiffness, loads, etc) on the critical stresses and strains at layer interfaces. King and May (2003) investigated the effect of bonding on fatigue life using the software BISAR (De Jong, 1973). They have modeled 40 kN and 53.4 kN dual tire loads on a flexible pavement structure with two 100 mm HMA layers (an overlay and an existing HMA layer) over a 150 mm aggregate base and a subgrade. Simulations were conducted for several bonding levels ranging from no-slip condition (100 % bonding) to full slip (0 % bonding). Results of the analysis showed that fatigue life decreases by 50 % when the bond is reduced by 10 %. Roffe and Chaignon (2002) conducted similar analysis using the French pavement design program ALIZE and concluded that pavement service life can reduce from 20 years to 7 years due to the lack of bond between two asphalt layers.

Using 3D finite element modeling, Tayebali et al. (2004) investigated the effects of layer thickness and stiffness on the stress-strain-displacements fields. It was concluded that delamination problem can be reduced by increasing overlay thickness. Increased overlay thickness reduces critical interface shear stresses and minimizes the risk of bond failure. The impact of increased layer thickness (higher material costs) and increased fatigue life (longer service life) on pavement life cycle costs should be investigated to evaluate the effectiveness of different design strategies.

Mohammad et al. (2012) investigated the effect of tack coat interface bond characteristics on pavement responses using 2D finite element modeling. Aggregate base and subgrade layers were modeled as elastic layers while HMA overlay and the existing layers were modeled as viscoelastic materials using a generalized Kelvin model. Tack coat interface shear bond characteristics were modeled by using the results of laboratory shear tests. Results of the analysis showed that trackless, SS-1h, and PG 64-22 tack coats had the best performance while the sections with CRS-1 tack coat were predicted to experience early fatigue failures. It was also concluded that tack coat performance is controlled by the pavement design. Tack coat type and application rates are determined to be more important for structures with thin overlays.

2.4 QUALITY CONTROL AND QUALITY ASSURANCE METHODS

2.4.1 OFTT testing to evaluate in-situ bond performance after construction

In the current scheme of highway construction practice, there is no means of evaluating tack coat bond quality immediately after construction. For this reason, there is nothing to hold the contractor accountable for performing appropriate tack coat application. However, other aspects of highway construction have been incentivized with great success. The advent of intelligent compaction has offered a new means of assessing construction quality of HMA as it occurs. It has also fostered a new accountability system for the contractor, making them more cognizant of the implications of poor compaction on the resulting pavement and on their project profits. Contractors will be rewarded if they perform good quality construction that results in properly compacted HMA and a smooth roadway. They will also be penalized if construction quality is poor and either of these considerations are not meeting expectations. A similar system exists for pavement smoothness, whereby an inertial laser profiler will identify areas of localized roughness after paving construction has been completed. Using a special software (ProVal), these areas of localized roughness can be identified. The contractor is then responsible for repairing these areas and ensuring that the roughness level, as measured by the International Roughness Index (IRI), is below a certain threshold. The contractor is rewarded for very smooth pavements and penalized for pavements not meeting the maximum IRI specification.

A similar system could be implemented for evaluating tack coat quality after construction using the OFTT device, developed by Coleri et al. (2017). The OFTT device was previously shown to have a strong correlation with laboratory-measured interlayer shear strength of field pavement cores (Coleri et al. 2017; Mahmoud et al. 2017). This device could be easily implemented as a QC/QA tool following construction, in order to evaluate if tack coat application was performed adequately. A similar accountability system could be implemented for this device in Oregon, following the same premise as the intelligent compaction and smoothness bonus systems. For instance, if a desired level of interlayer shear strength (ISS) is chosen in advance, the contactor will be rewarded or penalized depending on the ISS measured by the OFTT. If the ISS is extraordinarily low, the contractor should then be responsible for repairing or reconstructing the pavement in order to attain an acceptable bond strength. If the ISS is well-above the predefined threshold, then the contractor would be rewarded.

ODOT has also begun to use site control software as an inspection tool, which allows inspectors to monitor intelligent compaction and other construction activities throughout the project area. The QA/QC system using the OFTT could easily be integrated into site control software as well, providing the inspector even greater oversight and control over the construction project and allowing them to identify areas with bonding problems in real-time.

The OFTT has been improved since its field implementation in Coleri et al. (2017). It was further implemented in the field as part of this study with the intention of proving its worth as a QA/QC tool. The OFTT can become an integral part of Pavement Condition Surveys (PCS) for highways in Oregon, both immediately after construction and during regular condition surveys. The latest version of the OFTT is called as the OreTackBond in this report.

2.4.2 Application rate measurement using textile pads

Measuring the application rate of tack coat in the field has previously been accomplished by using textile pads of a known area and weight on which the distributor truck sprays tack coat emulsion during construction. The textile pads are then subsequently weighed to determine the amount of tack coat applied per unit area to the pavement surface (Coleri et al. 2017). This process, which is currently the only standardized approach to verifying quality control of tack coats in the field, is outlined in the ASTM D2995 specification. However, this method is limited in its practicality due to the manual labor required and safety hazards present in placing, collecting and weighing the textile pads.

Coleri et al. (2017) investigated the variability in tack coat application rates in the field using procedures outlined in ASTM D2995. It was found that application rates were not consistent. For milled surfaces, application rates were above the target rate for all instances tested, with an increasing trend in application rate with each successive test. Actual application rates for one of the overlay surfaces were determined to be inaccurate. This was due to the contractor's use of an old distributor truck that did not respond to changes in the target application rate and also did not provide uniform application (streaking). The actual rates applied by this truck were lower than the target rates selected. Shear strength of the tack coat bond in the area sprayed by the old distributor truck was significantly lower than those sections sprayed with the newer distributor truck. This fact illustrates the importance of equipment selection and maintenance on variability of tack coat quality.

Rawls et al. (2016) discusses problems inherent to current application rate measurement procedures. It is asserted that ASTM D2995 can lead to erroneous results with emulsions due to water evaporating from the substrate before weighing occurs, which underestimates the actual application rate.

The process of placing and removing textile pads on the roadway surface takes time and can complicate construction operations. The inspector must spend time placing and collecting the pads, which takes them away from other construction activities. The textile pads, when removed, also create an area on the pavement surface without any tack coat coverage, which forces the distributor truck to reapply tack coat to this area. This creates variability in tack coat coverage within the localized region due to cut-in and cut-off of the sprayer. It also induces additional wheel tracking in the newly sprayed and uncured tack coat emulsion. Most importantly, the manual placement and removal of the textile pads puts the inspector at higher risk exposure to dangerous situations involving construction traffic and heavy equipment.

In order to minimize the chance of injury to inspection staff, this method should be automated through use of automatic weight measurement equipment that eliminates the need for an inspector to perform the operations by hand. Automated pickup can be accomplished by means of a robotics which pick up and weigh the textile pads without exposing humans to construction traffic. Similarly, magnetic operated pickup can be accomplished, where the textile pad is picked up using electromagnets, weighed in-place and placed on a telescoping platform which stores the pads for later discard. In any of these cases, measurements can be stored digitally on a computer affixed to the distributor truck and used textile pads can be stored temporarily to be discarded later.

2.4.3 Coverage and uniformity detection

Oregon construction specifications do not have any specific qualitative provisions for what constitutes acceptable tack coat coverage. The specifications only discuss requisite tack coat distributor equipment capabilities and application rates (ODOT 2015). As it stands, the criteria for acceptance of tack coat are visually based and subject to the judgment of the on-site construction inspector. While inspectors do undergo a fairly rigorous training program, it is possible that not all inspectors would agree on what classifies as acceptable in terms of tack coat coverage and uniformity. Additionally, highway construction projects are often hectic environments with many different construction activities occurring simultaneously. For this reason, the inspector(s) may not always be present to visually inspect and approve the tack coat prior to paving. The safety of construction operations is also a paramount consideration in the inspection process. Upholding worker safety on the construction site is of great importance to paving agencies, giving rise to a need for low-risk processes of tack coat inspection that do not place inspectors in harm's way.

Solutions to these issues can be found by introducing automation into the tack coat acceptance process. Various technologies exist in other industries for detecting coverage, thickness and uniformity of materials. In this study, methods of measuring application rates of aqueous materials in other industries are examined to determine their viability for field detection of tack coat coverage in roadway paving operations. Also, more precise methods of controlling the application rate from the distributor truck through specifications governing speed and spray rate control are investigated.

2.4.4 Potential technologies for application rate measurement and coverage detection

2.4.4.1 Ultrasonic film thickness measurement

A United States patent by Trulson et al. (1991) describes a technology that uses ultrasonic sound pulses to determine the thickness of paint materials on a metal surface. This method of determining material thickness emits ultrasonic sound waves to the surface where the material is applied. A digital oscilloscope is used to analyze the waveforms of echoed ultrasonic pulses from the material. Several echo pulse waveforms are averaged before they are sent to the computer. A computer program identifies layer interfaces based on characteristic reference waveforms that are stored in the system. By comparing the echo waveforms with the reference waveforms, the system can identify similar waveform shapes that correspond to different layer interfaces. This method was intended for use in the automotive painting industry to provide a more efficient and practical means of checking the thickness of paint layers on automotive panels. However, Trulson et al. (1991) states that the process is applicable for other layered products. According to Trulson et al. (1991), this method has been previously used to detect layer thickness of plastic materials between 0.001 to 0.005 inches.

This process could be applied to tack coat detection with little modification to the methodology. The ultrasonic layer detection system can be useful for detecting whether the specification for lap coverage has been met, as well as for approximating thickness of coverage/application rate. These ultrasonic sensors could be positioned in between the spray nozzles on the distributor truck spray bar, such that the tack coat thickness could be detected immediately after spraying. The measured thickness could then be compared to the expected thickness for the lap coverage specified. An algorithm could also be generated to relate the thickness of tack coat to the application rate per unit area, such that it could be compared against the target application rate. This would provide an in-situ check of the tack coat application rate and protect against issues resulting from improper spray bar height, improper application rate or clogging of spray nozzles.

The only issue with employing this technology for rate measurement and coverage detection is that the ultrasonic thickness gauges are not appropriate for wet film thickness measurement. The tack coat would have to be cooled to a point where it becomes solid before accurate thickness measurements could be obtained with ultrasonic devices.

2.4.4.2 Infrared thermography for coverage detection

In the paving industry, there has been a gradual shift toward intelligent technologies to detect and govern inconsistencies that occur during highway paving construction. The advent of intelligent compaction and thermal profiling has changed the way DOTs and contractors approach paving jobs, from a bidding standpoint and from the constructability perspective. One new technology in particular utilizes thermal imaging to collect temperature data of asphalt pavement exiting the screed and uses this data to detect areas of thermal segregation based on pre-defined temperature differentials.

The Ohio Department of Transportation has evaluated a variant of this technology, called Pave-IR, in various projects to determine its effectiveness in identifying density variability due to segregation. According to Landefeld (2014), discrete measurement criteria are used to evaluate the thermal uniformity profiles in asphalt mats at 10ft intervals as they are placed. 150ft sublots are considered as analysis units since a change of trucks can be captured in this length. The maximum and minimum temperatures of the profiles are then used to determine the temperature differential and relate this to levels of segregation in the asphalt mat. By correlating the results obtained from the Pave-IR scanner with nuclear gauge density measurements for each 150ft sublot, this study was able to conclude that thermal imaging is effective for determining suspect areas of thermal segregation, allowing the inspector to evaluate the problems and hold the contractor accountable for any problems (Landefeld 2014). Figure 2.28 shows an example of the thermal gradient yielded by the thermal imaging system.

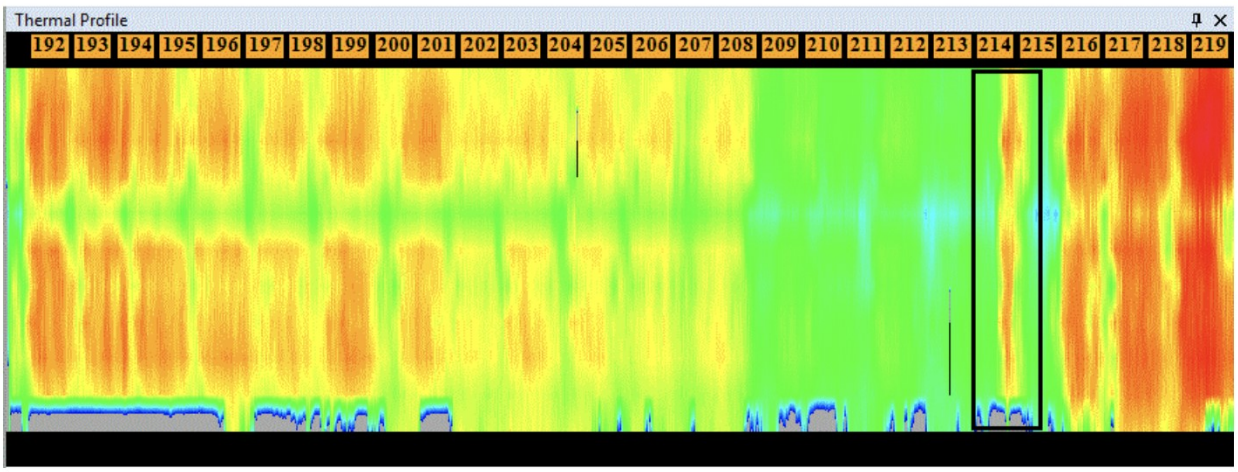


Figure 2.28: Thermal gradient of placed HMA (Landefeld 2014).

This technology is therefore useful for determining temperature differentials in asphalt materials in real-time as they are placed. A permutation of this technology could be applied to tack coat placement in order to determine gaps in coverage after application. Although temperature differentials between tack coat and the pavement surface are not as drastic as that of freshly placed HMA, thermal imaging cameras capable of detecting minute differences in temperature do exist, some of which are handheld (FLIR 2017). Thermal imaging would be a viable way of detecting the level of tack coat coverage across the width of the lane being paved. A bonus system similar to that of thermal segregation and density variability detection could also be implemented to provide the contractor with more incentive to ensure the tack coat is applied properly.

Another notion not discussed in this study, but worth mentioning, is the fact that contractor accountability is a primary way of making this technology viable. By holding the contractor accountable for inconsistencies, the pavement structure can be constructed more precisely, ultimately resulting in a more homogeneous roadway. Additionally, a bonus system would be easy to implement based on this technology. Much like asphalt density bonuses based on nuclear density gauge readings, which are commonly enacted by state DOTs, a bonus for low thermal differentials could incentivize the contractor to do an above average job when paving.

Research by Barreira and Freitas (2007) explored the use of infrared thermography for evaluating temperature distributions in building materials. Through the use of an infrared camera, the superficial temperature throughout objects can be examined. Infrared thermography captures thermal gradients in materials, which are affected by material parameters such as temperature, emissivity, reflectivity and color.

The study by Barreira and Freitas (2007) found that the emissivity of a material is a particularly important parameter if quantitative thermal measurements are of interest. This means that if numeric temperature distributions are desired, emissivity can influence thermography measurements drastically. However, if a more qualitative analysis of temperature distributions is desired, then emissivity is a less important parameter to consider. A general finding was that if the emissivity of a material is above 0.85, then a clear and accurate thermal image was produced.

Thermography measurements are also fairly moisture sensitive. Barreira and Freitas (2007) showed through their lab experiments that ambient temperature and relative humidity can affect thermal gradient measurements due to superficial evaporation. Since evaporation is an endothermic process, it can influence infrared thermography measurements.

Another finding of the study was that reflectivity is a parameter affecting thermography measurements, but only when the emissivity of the material is low. The study also found that color only affected thermography measurements when the temperature differential between materials was significant.

The purpose of this study by Barreira and Freitas (2007) was to evaluate the utility of infrared thermography for building materials in vertical structures, but it can be applied to tack coat emulsions to detect coverage after spraying as well. Tack coat material is subject to all the parameters that Barreira and Freitas (2007) investigated in their study. Temperature is a notable material parameter of tack coat application that has implications for infrared thermography. According to Barreira and Freitas (2007), materials that vary in temperature from their surroundings by at least 1°C can be detected using infrared thermography. Since tack coat is applied at ambient temperature onto a pavement surface that can be warmer or cooler than the tack coat (Al-Qadi et al. 2012), the temperature differential would facilitate infrared thermography measurements. It is also important to note that since emissivity is a measure of a material's ability to reflect infrared energy, asphalt emulsion would be a good candidate for infrared thermography since it has a high emissivity due to its dark color. Also resulting from tack coat's dark color is low reflectivity, which also bodes well for thermography measurements.

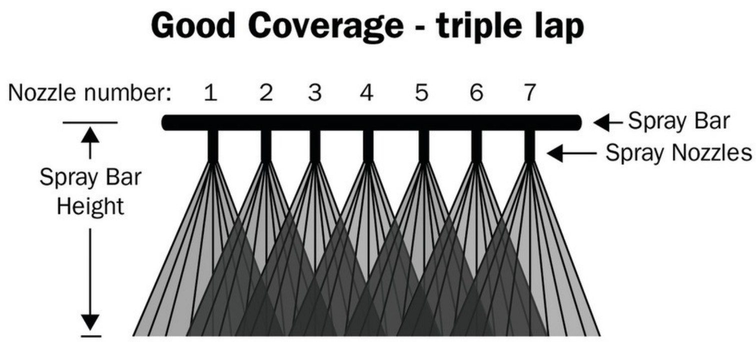
Handheld infrared cameras exist that would be applicable to the purpose of detecting tack coat coverage. Some cameras have accuracy of less than 0.15°C (FLIR 2017). The collected infrared images during construction could be wirelessly transmitted and processed on a nearby computer in real time to determine if there is any inconsistency in coverage as shown by the thermal gradient.

2.4.5 Distributor truck and operator certification

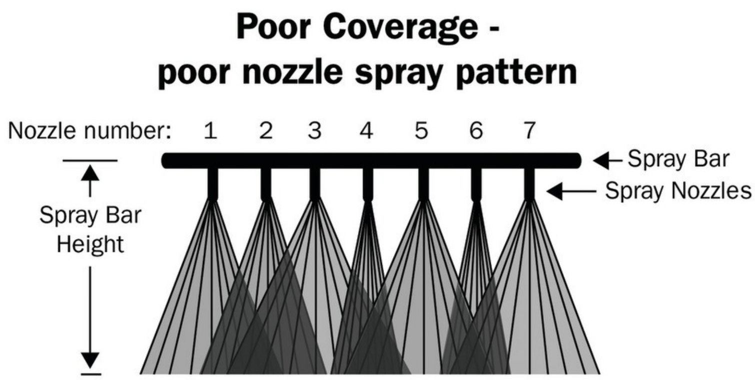
2.4.5.1 Current specification provisions

Despite the immense use of tack coat as a constituent in asphalt paving, there are no specifications with provisions for tack coat bond strength in laboratory or field settings. Since tack coat bond strength quality is dictated by a culmination of material and environmental factors, it is difficult to create specifications for (Wang et al. 2017).

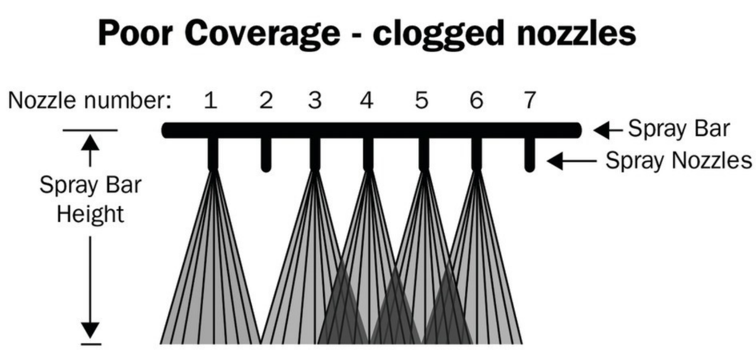
The assurance of a uniform tack coat application to a pavement surface is governed by geometric and hydraulic factors of the equipment: spray nozzle patterns, spray bar height and distribution pressure (Mohammad et al. 2012). ODOT defines minimal specifications for the geometry of tack coat applicators on distributor trucks. They specify that applicators shall be adjustable both horizontally and vertically and shall be capable of applying “triple lap coverage” (ODOT 2015). “Triple lap coverage” refers to the overlap of three spray streams at the pavement surface interface (Mohammad et al. 2012). Different examples of coverage and how they are affected by nozzle geometry and clogging are shown below in Figure 2.29.



(a)



(b)



(c)

Figure 2.29: (a) Triple lap coverage; (b) Improper spray nozzle pattern from different nozzle angles; (c) Clogged nozzles (ForConstructionPros.com 2018).

One problem with current tack coat distributor truck spray geometry is the spray bar height. As the distributor truck sprays tack coat, its weight is reduced which alters the distance between the spray bar and the ground due to suspension decompression. This change in spray bar height can impact the coverage pattern, resulting in a spray pattern that does not meet the lap coverage specification. This leads to a nonuniform distribution of tack coat emulsion longitudinally along the paved area and across the entire width of the spray bar.

Geometric specifications are useful in ensuring that theoretical tack coat application is adequate. However, the construction specifications fall short on requirements for tack coat distributor truck control equipment. Not all tack coat distributor vehicles are equipped with the same spray control technology, which can lead to inherent variability in target application rate between trucks. Also, contractors, when in the height of construction season, often do not maintain their tack coat distributor equipment regularly. Long shifts and hectic schedules cause maintenance and cleaning of equipment to be deferred. This leads to tack coat spray nozzles that become clogged which ultimately causes nonuniform coverage in the transverse direction, often termed "streaking", during tack coat application. This streaking phenomenon causes early pavement failure due to poor interlayer bonding. An example of streaking is shown below in Figure 2.30.

Figure 2.30: Tack coat streaking due to clogged nozzles (Mohammad et al. 2012).

Construction specifications for tack coat also have no provisions for operator training or certification. Operators of the tack coat distributor truck are often construction workers who are unaware of the application rate specifications and of how to best control the application rate with the given equipment. Operator inexperience and misuse of distributor truck equipment can lead to high variability in tack coat coverage throughout the pavement area.

Quality control (QC) and quality assurance (QA) practices are performed on a voluntary basis and hence are rarely employed by contractors. These two factors lend themselves to the possibility of substandard tack coat bond strength at the pavement layer interface. Mohammad et al. (2012) conducted an industry survey of paving agencies in the United States who reported on their tack coat construction practices. The survey suggested that the only QC practice enacted by many agencies (51%) for measuring application rate is measurement of change in tack coat volume or weight in distributor trucks before and after construction shifts. Field verification techniques employed by agencies consist of meters on the distributor, visual inspection of tack coat levels and dipstick readings before and after application. Furthermore, 18% of respondents surveyed stated that they have no tack coat QC practice in place. Only 2% of respondents reported using ASTM D2995, the only current specification for application rate measurement, as a QC measure. For coverage requirements, most agencies (66%) relay that visual-based acceptance is the primary means of ensuring surface coverage adequacy. Other agencies simply check to verify that nozzles are not clogged.

The issues described above illustrate the necessity of imposing more stringent specifications for the distributor truck and its operator. Specifications need to incorporate more specific geometry requirements that account for change in spray bar height through use of more sophisticated vertically adjustable spray bars that self-adjust based on the weight of the tack coat remaining in the tank. Distributor truck certification is also a necessary safeguard against tack coat coverage variability. Requiring the tack coat distributor truck to be inspected and calibrated regularly to ensure cleanliness and proper function of equipment used to control application rate is a worthwhile provision to enforce. Finally, basic training and certification of the tack coat distributor truck operator should be required to ensure that equipment is operated properly to ensure a uniform application rate.

2.4.5.2 Distributor truck certification criteria

As tack coat distribution is performed with equipment that is widely used across the paving industry, it is in the best interest of the industry that standardized procedures for distributor truck certification be implemented. The vast majority (98%) of respondents to the survey conducted by Mohammad et al. (2012) confirm that the spray bar affixed to a distributor vehicle is the most common technique for applying tack coat materials during construction. However, 4% of respondents also use spray pavers (spray bar affixed to paver equipment), which eliminate concerns over tracking. Figure 2.31 shows a photograph of spray paver equipment.

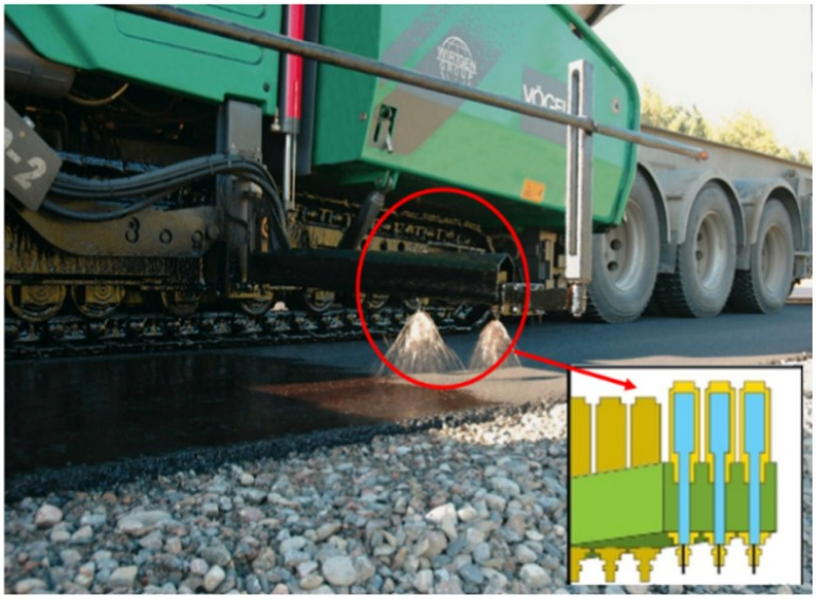


Figure 2.31: Spray paver (Wang et al. 2017).

Mohammad et al. (2012) suggested that spray bar height depends on the nozzle configuration, speed of distributor truck and application pressure used. Spray bar height should be adjusted according to the amount of tack coat in the distributor truck tank, due to decompression of the truck's suspension as tack coat weight is reduced.

Mohammad et al. (2012) stated that some agencies require certification of distributor trucks before they are allowed for use during construction. This certification ensures that all equipment on the distributor truck, namely the spray bar and nozzles, are functioning properly. Calibration of the spray equipment should be conducted in the transverse and longitudinal directions using ASTM D2995 before construction begins to ensure uniformity of tack coat application.

A technical report by Holtrop and Patrick (2014) on behalf of Austroads details the specifications for pump-actuated bitumen distributor trucks, or sprayer trucks that are currently enforced in Australia. Austroads specifies that sprayers shall be annually inspected by an accredited facility before being used in construction activities. This inspection involves issuing calibration certificates for each truck which certify the equipment meets necessary requirements. These certificates are valid for 12 months and sprayers are subject to random audits throughout the 12-month period. The certification takes into account the width of the spray bar and all components of the spray system, such as nozzle arrangement and angle, in ensuring that the target application rate can be met with the geometry of the sprayer. The certificate information is published to an online database for public reference. If out of specification, Austroads requires re-calibration or field audit testing before the sprayer truck is allowed for use in construction. Austroads also specifies that sprayer trucks should be able to ascend 10% grades while fully loaded without compromising uniform application rate. Austroads also has provisions for effective width of the spray bar, accounting for the outside edges of the spray bar where lap coverage is reduced. They specify that the uniform spray rate shall be the same across the entire effective width. A diagram showing the effective width of a spray bar is shown below in Figure 2.32.

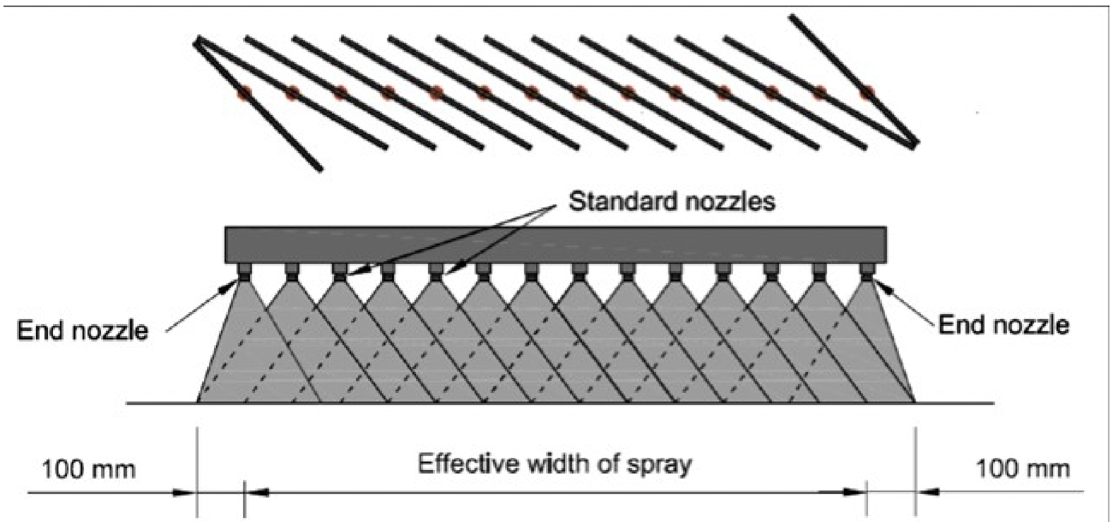


Figure 2.32: Effective width of spray bar and nozzle distribution (Holtrop and Patrick 2014).

To account for variability in spray rate during startup and shut-off, Austroads (Holtrop and Patrick 2014) also details specifications for cut-in and cut-off distances, which refer to the distance covered by the distributor truck when initiating and stopping the flow of tack coat from the spray bar. Distributor trucks are required to reach the target uniform spray rate within 1.2m of startup and shall be able to return to a zero-spray rate within 0.5m of shut-off (Holtrop and Patrick 2014). This ensures that localized variability in coverage is minimized. The pump driving the bitumen spray stream should also be able to provide discharge that is at least 10% greater than the maximum application rate of the spray nozzles and spray bar configuration. For modern sprayer systems, there should also be an interdependence between the spray bar discharge rate and the speed of the truck, such that the discharge rate is variable and matches changes in the speed of the truck. The relationship between specified change in tack coat output and change in speed is shown below in Table 2.2.

Table 2.2: Bar Output Related to Change in Forward Speed (Holtrop and Patrick 2014).

Change in sprayer forward speed (%)	Change in total output for width of bar (%)
-10	-8 to -12
-5	-4 to -6
+5	+4 to +6
+10	+8 to +12

In terms of equipment controls, Austroads (Holtrop and Patrick 2014) has several specifications that address pertinent issues with tack coat distributor trucks. They specify that the operator of the truck shall be able to control discharge of bitumen to within ±2% of the measured output. Austroads also requires that speed control equipment be affixed to the sprayer truck, capable of providing accurate speed measurements to within ±2.5%. Finally, temperature control equipment for the emulsion tank should be accurate to ±4°C throughout a range of 10°C to 230°C.

As is described above, Australia has a rigorous set of specifications and standards for their tack coat distributor trucks. These standards for pump-actuated bitumen distributor trucks in Australia could be applicable in the United States, since the tack coat sprayer equipment is relatively similar in both countries.

A major limitation to this study, however, is that the distributor truck certification program has no provisions for routine maintenance and cleaning of spray nozzles within the 12-month certification period. It is a common problem in construction activities that spray nozzles become clogged due to lack of maintenance and cleaning. These specifications could be improved by incorporating requirements for regular cleaning of spray nozzles after each use.

Mohammad et al. (2012) suggested that the equipment on distributor trucks, such as nozzles and spray bars, should be checked for proper function and calibration on a control section before tack coat is applied during construction. This means that tack coat should be applied to a trial area to ensure distributor trucks are functioning properly, especially if the truck has been unused for some time.

2.4.5.3 Measures to prevent clogged nozzles

Efforts to achieve uniform and predictable tack coat application is for naught if the equipment is not functioning properly. Clogged spray nozzles are a problem commonly affecting application uniformity and causing streaking issues (Mohammad et al. 2012). Often times this is caused by lack of maintenance. For this reason, FHWA (2016) advises that tack coat should be applied to a control area as a test for equipment operability before construction begins. This will help to ensure that nozzles are spraying correctly and are in the correct orientation. This should be performed on an annual basis at minimum. Nozzles should also be inspected for clogging on a regular basis, both before application and during application. Problems with nozzle clogging should be corrected immediately before tack application continues. Mohammad et al. (2012) suggested that distributor truck operators should carry extra nozzles and replace them as soon as clogging problems occur. It is easier to replace the nozzles with spares and clean the clogged nozzles at a later time.

Improper tack coat handling procedures is also a cause of nozzle clogging. In a field study by Cortina (2012), improper handling of the trackless tack coat (SS-1vh) clogged the distributor trucks for several days. Cortina (2012) recommended a spraying temperature of 175°F to avoid clogging problems.

Equipment selection should be based on the type of tack coat material used and the desired application rate. FHWA (2016) suggested that different nozzles should be used for different tack types and target application rates. Coordination with contractors should be done in advance to ensure that the nozzles outfitted on the distributor truck are adequate to suit the tack coat material being used and achieve the desired application rate. Figure 2.33 shows different nozzle sizes that correspond to different application rates.

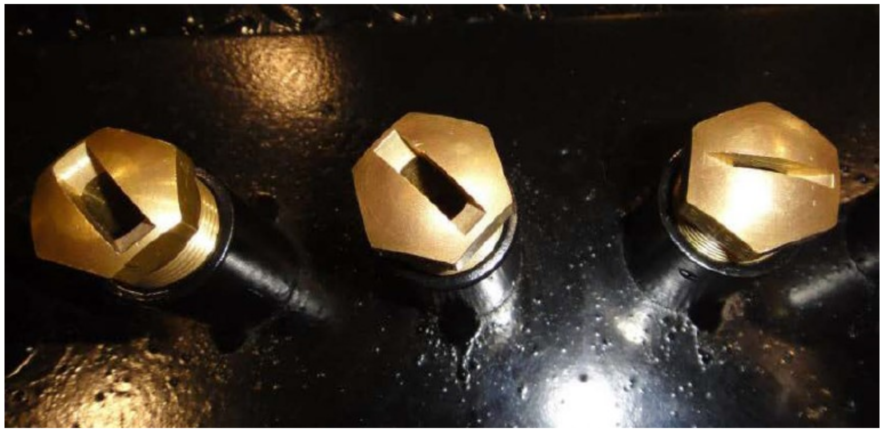


Figure 2.33: Various nozzle sizes corresponding to different application rates (FHWA 2016).

Spray nozzles were a consideration in the study by Mohammad et al. (2012). Various spray nozzle types are available to suit a variety of application and flow rates. It is important that the proper nozzles be selected according to the desired range of target application rates and the capabilities of the distributor equipment. Selection of nozzle sizes should also be done in light of recommendations from the tack coat and distributor truck manufacturers. Figure 2.34 shows an example of different nozzle types from Etnyre that are employed for different application and flow rates.

Ref.	Part No.	Description	Application (per square yard)	Application (Metric) Liters per square meter	Flow Gallons per minute per foot
1	3353788	V Slot Tack Nozzle	0.05 - 0.20	0.19 - 0.75	3.0 to 4.5
2	3351008	S36-4 V Slot	0.10 - 0.35	0.38 - 1.30	4.0 to 7.5
3	3351009	S36-5 V Slot	0.18 - 0.45		7.0 to 10.0
4	3352368	Multi-Material V Slot	0.15 - 0.40	0.57 - 1.50	6.0 to 9.0
5	3351015	3/32-inch Coin Slot	0.15 - 0.40	0.57 - 1.50	6.0 to 9.0
6	3352204*	Multi-Material V Slot	0.35 - 0.95	1.30 - 3.60	12.0 to 21.0
7	3352205*	Multi-Material V Slot	0.20 - 0.55	0.75 - 2.08	7.5 to 12.0
8	3352210	End Nozzle	0.20 - 0.55	0.75 - 2.08	7.5 to 12.0
9	3351014	3/16-inch Coin Slot	0.35 - 0.95	1.30 - 3.60	12.0 to 21.0
10	3351010	¼-inch" Coin Slot	0.40 - 1.10	1.50 - 4.16	15.0 to 24.0

* Recommended nozzles for chip seal when using emulsified asphalt

Figure 2.34: Nozzle types for different application rates/flow rates (Mohammad et al. 2012).

Nozzle orientation should also be checked to ensure they are within the 15-30° offset range from the spray bar, as suggested by FHWA (2016). Proper nozzle orientation ensures that spray streams from adjacent nozzles do not conflict with one another. Mohammad et al. (2012) suggested that all nozzles be set at the same angle, typically 30° for most equipment. However, calibration of the distributor truck is still necessary after nozzle orientation to verify proper application rates. Figure 2.35 shows a diagram of proper nozzle orientations in relation to the spray bar.

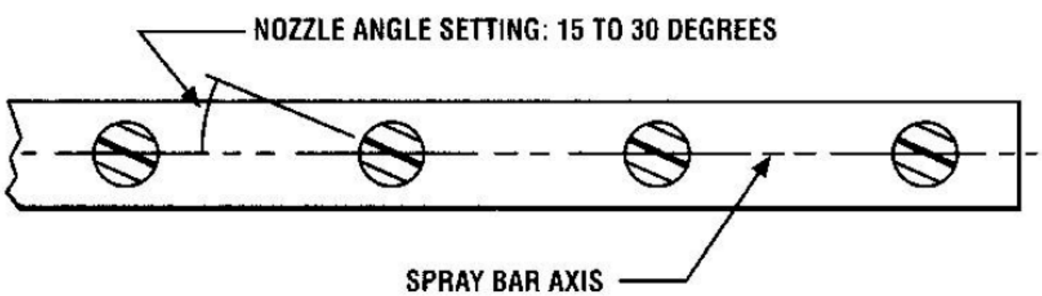


Figure 2.35: Proper nozzle orientation (FHWA 2016).

A technical guide to spray equipment maintenance and calibration by Hofman and Solseng (2004) details requirements for maintenance of spray equipment used in agricultural pesticide application. According to Hofman and Solseng (2004), the proper way to clean nozzles is to remove them and either clean them with a soft-bristled brush by hand or use compressed air to clear any clogs that may be present in the nozzle. If nozzles are not cleaned properly, the distribution pattern of the spray can be compromised and streaking can result. Hofman and Solseng (2004) also suggested that using mesh screens are an effective means of preventing nozzle clogging. They are meant as a precautionary measure to prevent any debris that may be present in the liquid from clogging the nozzle. Hofman and Solseng (2004) suggest that nozzle screens need not have a smaller mesh size than the nozzle opening. They also suggest using self-cleaning line strainers, which remove clogs in the feed system using system pressure and discard any clogged materials from the system. A diagram of a self-cleaning line strainer is shown below in Figure 2.36.

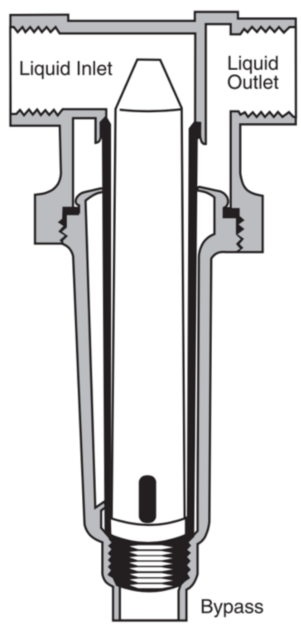


Figure 2.36: Self-cleaning line strainer (Hofman and Solseng 2004).

Although these technical specifications apply specifically to agricultural equipment, they can also be applied to tack coat application. Nozzles used for pesticide spraying in agriculture are not dissimilar to tack coat spray nozzles, in that they are meant to regulate flow and disperse the liquid into a desirable spray pattern (Hofman and Solseng 2004). The cleaning methods outlined in this guide can be applicable to tack coat nozzles. The use of mesh screens to prevent nozzle clogging is also applicable, since coagulated pieces of tack coat may find themselves in the distributor line and potentially clog the nozzle. The major shortcoming of this guide, however, is that no timeframe for regular cleaning of nozzle components is specified.

2.4.5.4 Surface cleanliness

Measures to improve tack coat application uniformity and distributor truck accuracy are meaningless if the pavement surface is unsuitable to facilitate good bonding. Coleri et al. (2017) used a novel device, called the Oregon Field Tack Coat Tester (OFTCT), to quantify the tack coat bond strength under different pavement cleanliness conditions. Conditions studied were a cleaned and washed pavement surface and a pavement surface with granular contaminants present, such as dust and sand. This device used a metal platen with foam substrate to adhere to the tack coat and a load cell measured the tensile strength of the bond as the platen was pulled upward and away from the pavement surface (see Figure 2.24). The main finding was that dust on the pavement surface prior to application of tack coat can result in a tack coat tensile strength reduction of up to 20% (Coleri et al. 2017). This occurs because the dust particles contribute to poor adhesion between the tack coat and the pavement surface (Coleri et al. 2017). What this means for the pavement structure as a whole is that the successive layers will not adhere together properly and significant tensile stresses will accumulate at the bottom of the new asphalt layer, resulting in excessive fatigue and early pavement failure.

This study was limited in that the experimental results for a milled surface were not able to be validated with lab experiments (Mahmoud 2016). For the quantification of bond strength subject to contaminants such as dust, this limitation is a key consideration as it hinders the practicality of this experiment for use in the field on milled surfaces.

Also, a more accurate way of quantifying the amount of dust present should be investigated, such as using a pre-weighed moist sponge to pick up dust and contaminants from a specific area of the pavement surface. The moist sponge could then be weighed to determine the weight of contaminants, which could be averaged over the area cleaned to obtain dust and contaminant coverage per unit area.

2.5 SUMMARY

In this literature review, the multitude of factors affecting the quality and longevity of tack coat interlayer bonding were evaluated. Material-specific considerations were first explored. Tack coat emulsions, the most commonly used type of tack coat, come in several types and grades that suit a variety of purposes. Key considerations for tack coat emulsions are the water content, dilution level and selected residual application rate. Careful selection of these properties must be exercised, as this determines the effective amount of asphalt on the pavement surface available for interlayer bonding. Tack coat curing time is another important consideration, as curing time will dictate the propensity of tracking during construction which will ultimately affect the tack coat bond quality.

Tack coat quality under different surface conditions and under the presence of contaminants was also evaluated. Milled surfaces typically require higher application rates to achieve a particular bond strength, due to the higher surface area of the texturized surface. Milled surfaces are said to amplify bond strengths due to interlock of aggregates. However, excess dust is produced during milling operations which can impact tack coat quality. Dust will prevent tack coat from bonding to the original pavement layer and can give rise to increased tracking. Tack coat coverage and the factors that impact uniformity were also explored. The uniformity in coverage is mainly subject to the type and quality of distributor equipment used. Improperly maintained equipment can cause streaking and clogging of nozzles which prevents the pavement from achieving uniform bonding in the transverse and longitudinal directions. Moisture from environmental conditions was also explored and it was noted that presence of moisture during tack coat application may have implications on bond quality. Temperature impacts on long-term tack coat performance were identified. Tack coats exhibit higher shear strength when temperatures are lower. Higher temperatures are more critical for tack coat shear strength due to reduction in stiffness of tack coats as temperature increases.

A review of laboratory sample preparation methodologies used in past research was also conducted. Most previous research in this area has utilized a Superpave Gyratory Compactor (SGC) for core sample preparation. This method was noted to artificially amplify bond strength by two to 10 times when compared to field-extracted cores. A comprehensive review of bond strength test equipment and procedures was also conducted. The most notable shear strength and tensile strength test devices were examined, such as the NCAT bond strength test device and LISST device for testing interlayer shear strength (ISS) of core samples, the OFTT for in-situ evaluation of ISS, the OFTCT for tensile strength evaluation in-situ and several non-destructive test methods to determine bond quality. Some computer modeling techniques were also explored.

Finally, the current state of tack coat specifications were reviewed. Shortcomings of the Oregon specifications for tack coat application that cause inconsistency in tack coat quality and asphalt pavement longevity were identified. Certification criteria and key considerations for tack coat distributor equipment were also examined. Improvements to certification criteria and construction specifications were suggested, drawing on the criteria and provisions of other agencies. Potential methods of improving tack coat coverage uniformity and spray rate detection were explored by looking at various technologies used in other industries and assessing their applicability to tack coats, as well as expanding upon previous methodology used in tack coat application rate detection.

3.0 EVALUATION OF MILLED SURFACE TACK COAT PERFORMANCE AT MANUFACTURER-RECOMMENDED APPLICATION RATES

3.1 INTRODUCTION

Tack coats, or asphalt emulsions, are the principal element that facilitates bonding between new and old asphalt pavement layers. Proper bonding between pavement layers is necessary to achieve the intended structural design life of a pavement. Failure to achieve proper bonding between pavement layers can result in significant reductions in pavement lifespan. Some research suggests that the life of a pavement can be reduced by up to 50% with a mere 10% reduction in tack coat bond strength (King and May 2003). Tack coat emulsions are commonly used, but new engineered tack coats that are purported to improve bond characteristics are not widely adopted at this time. In Oregon, CSS-1H is the most commonly used type of tack coat emulsion. Proprietary blends of polymer modifiers and/or stiff binders comprise engineered tack coats, which are elements of the emulsions that are meant to create improved bonding between the pavement layers.

Pavement maintenance and rehabilitation practices in Oregon typically involve removal of existing fatigued and/or aged pavements. A milled pavement surface is created as part of a common pavement maintenance strategy where aged existing asphalt pavement layer is removed from the pavement structure. This process creates a highly-texturized surface that has a greater degree of macrotexture than asphalt surface layers. Milled surface textures are beneficial for tack coat interlayer bonding in that they generally facilitate higher interlayer shear strength (ISS) than do overlay surfaces. This is due to the macrotexture of the milled surface interlocking with aggregates in the new pavement layer, which contributes to better interlayer bonding (Coleri et al. 2017; FHWA 2016; Mohammad et al. 2010). Since the milled surface has a greater degree of contact friction with the new pavement layer, it exhibits higher ISS (Al-Qadi et al. 2012b). Al-Qadi et al. (2012a) suggested that milling of the pavement surface, although it does give way to higher variability in shear test results, results in an ISS increase of 20 psi when compared to an unmilled surface.

The effect of interlock with the milled surface is dependent upon the type of asphalt mixture used. Song et al. (2015) concluded that ISS increases with surface roughness, especially at intermediate to high pavement temperatures where the effect of tack coat application rate was diminished. This effect is especially apparent when coarse surface mixes were used, where the aggregate interlock effect is more prominent (West et al. 2005; Sholar et al. 2004). In regards to aggregate size, Al-Qadi et al. (2012a) showed that an asphalt mix with nominal maximum aggregate size (NMAS) below 3/8in (9.5mm) yields reduced tack coat bond shear strength, due to a reduction in aggregate interlock of larger aggregate particles. However, in order to capitalize on the aggregate interlock effects of milled surfaces, an adequate level of compaction is necessary (Kruntcheva et al. 2005).

Sensitivity of ISS to tack coat application rates can be affected by surface texture as well. Coleri et al. (2017) noted that the effect of application rate was less pronounced for milled surfaces due to the contribution of strength from pavement texture effects. Overall, it was found that the tack coat bond strength for milled surfaces was 112 psi, whereas the bond strength for overlay surfaces was 60 psi. Covey et al. (2017) showed through laboratory testing of field core samples that the milled surface texture impacted the bond strength. It was shown that an increase in surface texture caused a corresponding increase in ISS, indicating a positive relationship between these two variables. However, due to this effect, there were no reliable conclusions to be made regarding the effect of application rate on bond strength on milled surfaces due to the prominence of texture in ISS results. Al-Qadi et al. (2008) investigated the effect of surface texture on the tack coat bond strength between Portland Cement Concrete (PCC) pavement surfaces and HMA overlays. The authors found that application rate plays a bigger role in shear strength at the layer interface when tack coat is applied to smooth PCC surfaces than for milled PCC surfaces. This is again due to the interlock of aggregates in HMA with the rougher milled surface. It is important to note that ISS results from this study were not obtained from samples subjected to a normal load (confining load) during shear testing, but the authors expected that a normal load would further enhance the shear strength due to the interlock effect. This is important since the bond at the layer interface is in its most critical state when subjected to traffic loads.

In light of the inherent variability in ISS that is consequential of milled surfaces, it is worthwhile to further investigate the impact of milled surface texture on tack coat bond quality, as measured by Interlayer Shear Strength (ISS) and Interlayer Bond Energy (IBE). This study focused on interlayer shear testing of new engineered tack coats that were specific to milled surfaces at manufacturer-recommended application rates. Tack coats from three companies were sampled for the purpose of this study. Both conventional and engineered tack coats were tested on milled surfaces using application rates that were suggested by each company. The purpose of this study is to evaluate the performance of each tack coat on a milled surface in order to identify how tack coat bond quality is impacted by surface texture and how bond quality is enhanced by the use of engineered tack coats. Additionally, the suggested application rates of each tack coat manufacturer are evaluated for adequacy.

Rheological tests were also conducted on asphalt binders distilled from tack coats produced for both milled and overlay surfaces provided by three different companies. A total of four rheological test methods were performed, including penetration, softening point (SP), rotational viscosity (RV), and dynamic shear rheometer (DSR). Correlations between each of the rheological tests were evaluated to determine the relationships between each asphalt binder test method. As part of this study, newly engineered emulsions from each of the companies were evaluated for their performance, at the binder level, as well with the ISS parameter obtained by testing laboratory-compacted samples. The measured ISS values representing in-situ bond strength were also compared to the tack coat binder rheological test results in order to determine correlations between each of the tests. Based on these results, effectiveness of all rheological tests that could potentially be used to predict the in-situ tack coat performance was identified.

3.2 OBJECTIVES

This study encompasses several objectives that are pertinent to predicting the performance of engineered tack coats on in-service pavements. These objectives are as follows:

- Develop a laboratory sample preparation methodology using a hydraulic laboratory roller compactor and laboratory milling that closely replicates field conditions,
- Characterize the performance of engineered tack coats on milled surfaces using monotonic direct shear testing (DST),
- Compare the performance of engineered tack coats to tack coats conventionally used in Oregon,
- Determine the rheological properties of all tack coat binders, and
- Determine the effectiveness of four different rheological tests in predicting the in-situ tack coat performance.

3.3 EXPERIMENTAL DESIGN

Engineered tack coats, as well as other tack coats conventionally used in Oregon, were sampled from three companies for the purpose of this study. Milling of laboratory-produced samples was performed in order to closely replicate the actual texture of milled surfaces in the field. Milling texture was quantified using the Sand Patch Test (ASTM 2015a). Tack coats were applied to the samples using manufacturer-recommended application rates. The experimental plan for this study is shown in Table 3.1. A general naming system was set to conceal the identity of the companies (labeled “CO#”). CSS-1H tack coats were named as-is, as they are commonly used in Oregon. New tack coats engineered to improve the ISS and reduce tracking were termed “ENGR”. Additionally, tack coats intended for overlay were denoted by “O” and those intended for milled surfaces were denoted by “M”.

Table 3.1: Experimental Plan for Milled Surface Tack Coats.

Company	Tack Types and Application Rates (gal/yd^2)	Surface Type	Replicates	# of Tests
CO1	0.060 - CSS1H 0.065 - ENGR-M	Milled	6	12
CO2	0.080 - ENGR-M1/2	Milled	6	12
CO3	0.058 - CSS1H 0.059 - CSS1 0.061 - ENGR-OM	Milled	6	18

It should be noted that not all companies provided the same number of tack coats for laboratory ISS testing. This is represented in the above table. Company 1 and Company 2 provided engineered tack coats that were specific to milled surfaces (designated as ENGR-M in the above table). Company 2 provided two different engineered tack coats for milled surfaces. These tack coats had the same binder type as one another and only differed in their water contents. As was suggested by the manufacturer, CO2-ENGR-M1 utilized a low application rate whereas CO2-ENGR-M2 was applied at a higher application rate. Company 3 provided an engineered tack coat designed for use on both overlay and milled surfaces (designated as ENGR-OM in the above table). Additionally, Company 3 requested that the residual rates of Company 1 be matched. The residual rate for CSS-1H for Company 1 was used for Company 3's CSS-1 tack coat. Residual rates for Company 1 tack coats were back-calculated using the water content of the emulsion and Equation **Error! Reference source not found.**, shown below. Average water contents and densities of the tack coat emulsions were measured in this study and are shown in Table 3.2.

$$\textit{Residual Rate} = \textit{Application Rate} * (1 - \textit{Water Content}) \quad \textbf{(3-1)}$$

Table 3.2: Summary of Tack Coat Emulsion Water Contents and Densities

Tack Coat Type	Initial Mass (g)[a]	Water Distilled (g)	Water Content (%)	Density (g/mL)
CO1-CSS1H	93.0	36.0	38.7	0.991
CO1-ENGR-M	95.7	39.3	41.1	0.920
CO2-ENGR-M1	94.3	83.5	88.5	1.007
CO2-ENGR-M2	93.8	64.5	68.8	1.023
CO3-CSS1	92.5	33.9	36.7	0.971
CO3-CSS1H	92.0	34.7	37.7	1.000
CO3-ENGR-OM	91.5	30.8	33.7	0.956

[a] 1.0 g = 2.20x10^{-3} lbs

3.4 MATERIALS AND METHODS

3.4.1 Laboratory shear test sample preparation

This section details the sample preparation and shear test procedure for producing and testing two-layer asphalt core samples. Figure 3.1 shows photos of the sample preparation and shear testing processes. Each step is described in detail below.

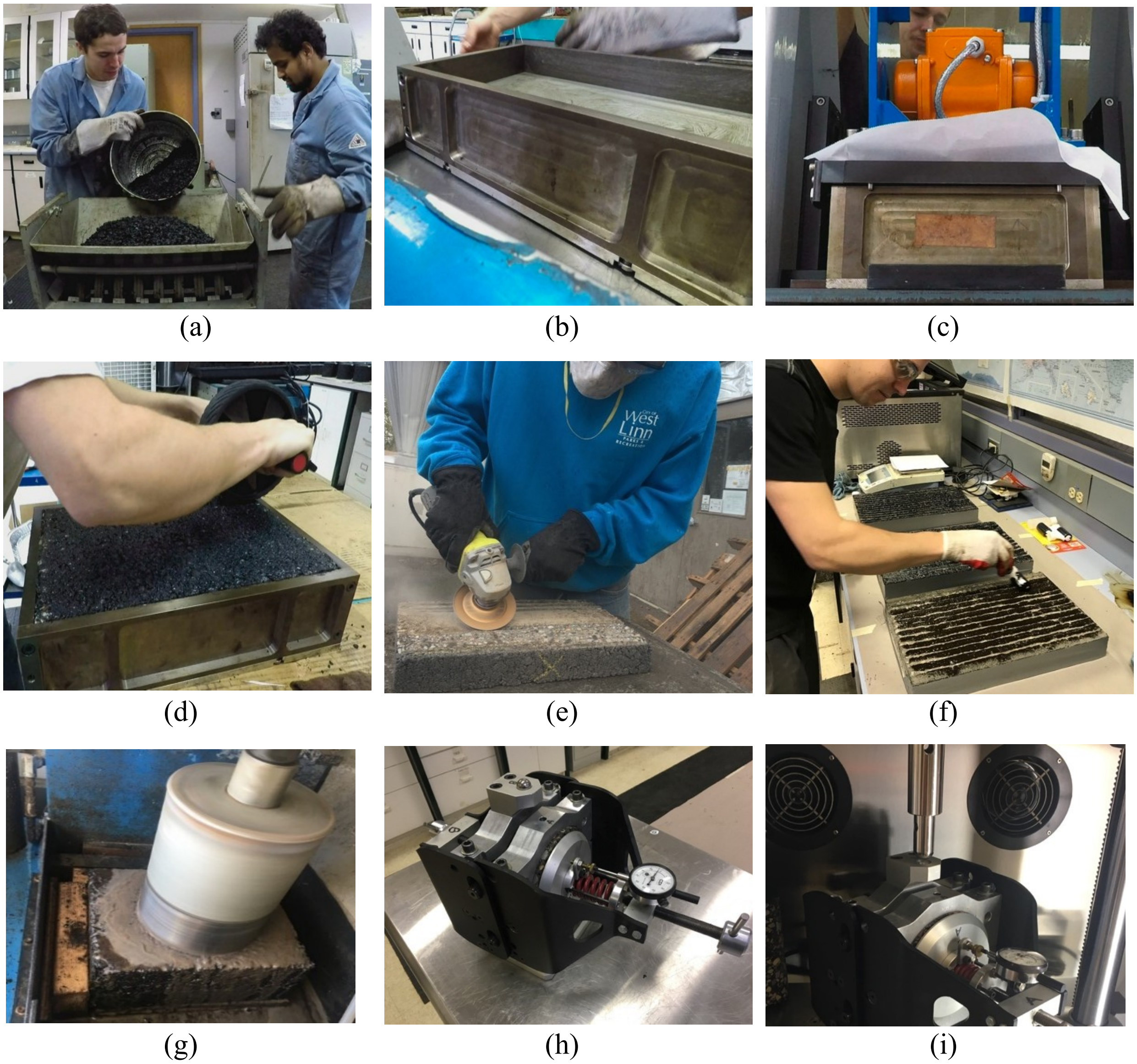


Figure 3.1: General sample preparation process for laboratory shear test samples.

3.4.1.1 Asphalt sampling and preparation

A ½" (12.7 mm) dense graded production asphalt mixture was sampled from River Bend Sand and Gravel-Oldcastle Materials in Salem, OR for this study. The sampled mixture was placed in five-gallon steel pails. The lids of the pails were wrapped with electrical tape to reduce asphalt aging during storage of the mix.

Prior to compaction, the production mix pails were heated in the oven at 110 °C (230 °F) for four hours and put through a mechanical splitter in order to obtain uniform sampling of the mixture. Figure 3.1a shows mechanical splitting of the production mixture.

The theoretical maximum specific gravity (G_{mm}) of the mixture was measured in the lab using a CoreLok device according to AASHTO T 209 (AASHTO 2012). Three replicate G_{mm} measurements (2.520, 2.494, and 2.515) were taken and the average (2.510) was used as the asphalt mixture G_{mm}. Required amounts for first and second lift compactions were then weighed out based on the measured average G_{mm} of the mixture and the selected 7% air void content. The 7% air void content was chosen since it is commonly specified during construction in Oregon. Weighed amounts were split equally into two pans to facilitate homogeneous heating of the mixture to compaction temperature.

3.4.1.2 First lift compaction of block samples

Pavement structures consisting of two lifts (layers) were compacted in custom 260 mm x 400 mm x 100 mm (10.2 in x 15.7 in x 3.93 in) compaction molds. A custom spacer 50.8 mm (2.0 in) in height was used in the mold to compact the first lift. Figure 3.1b shows the custom mold with spacer.

Prior to compaction, the pre-weighed pans of mixture were placed in the oven at compaction temperature for 2.5 hours along with the compaction mold. The mold was removed from the oven and grease was applied to all interior surfaces of the mold to prevent the asphalt from sticking inside the mold. The heated asphalt mixture was then loaded into the mold and spread evenly throughout the mold. The loaded mold was then placed into the roller compactor and secured.

Parchment paper was placed between the roller surface and the asphalt mixture to avoid any contamination of the first lift asphalt surface with grease or oils that may have been present on the roller compactor. Mold dimensions were input to the roller compactor. A target number of passes was selected to facilitate full compaction of the mixture to the target air void content. The compaction was performed by applying pressure to the asphalt using an adjustable dial on the roller compactor until the sample was compacted to the specified height. Figure 3.1c shows compaction taking place using the laboratory roller compactor.

Once compacted, the mold was removed from the roller compactor and allowed to cool until the internal temperature of the sample fell below the softening point of the asphalt binder used in the mixture. This was done to ensure that the sample would not unravel when removed from the mold.

Before removing the sample from the mold, a rubber wheel was rolled across the entire area of the first lift surface eight times to remove any fresh asphalt from the pavement surface. This simulated traffic on the pavement surface between lifts, as is commonly seen in the field. This step was particularly important for tack coats applied to an overlay surface, since additional residual asphalt could amplify bond strength. Figure 3.1d shows the rubber wheel being applied to the first lift samples. The mold was disassembled after the sample had cooled sufficiently [below 40 °C (104 °F)]. Completed samples were placed aside for milling (when appropriate) and tack coat application.

3.4.1.3 Milling of first lift block samples

Milling was performed on first lift samples accordingly. Milling was only performed on those samples which were intended for milled surface tests. A milled surface texture with a mean texture depth (MTD) of 0.07 in - 0.09 in (1.78 mm - 2.29 mm) was targeted in order to closely replicate actual milled surface textures in the field (Coleri et al. 2017). Milling was performed using a 4.5 in (114.3 mm) angle grinder with a concrete cutting wheel. The grinder was held at a 45° angle to produce straight grooves on the samples, similar to the pattern of milled surfaces in the field. Figure 3.1e shows milling taking place on first lift samples. Figure 3.2 below shows a comparison of laboratory milled surface samples to an actual milled surface in the field.

(a) (b)

Figure 3.2: Comparison of milled pavement surfaces (a) in the field (Mokarem 2006) and (b) in the laboratory.

After milling, the sample was cleaned with a coarse wire brush to simulate sweeping in the field. Sand patch testing, according to ASTM E965 (ASTM 2015a), was performed after milling in order to quantify the MTD of each sample for later use. Although milling of the samples increased the volume of the second lift in the compaction mold, no adjustments were made to the amount of HMA in the second lift. It was assumed that a similar phenomenon would result in the field as a result of milling.

3.4.1.4 Tack coat application and second lift compaction of block samples

Before tack coat application, duct tape was placed around the perimeter of the first lift sample to avoid dripping of tack coat which would cause the first lift sample to stick in the mold (Al-Qadi et al. 2008). Tack coats sampled from the manufacturer were agitated for five minutes prior to tack coat application to facilitate homogeneous mixing of the water, residual asphalt and emulsifying agents. Densities of each tack coat were measured using a 100-mL graduated cylinder and a high-accuracy scale. Three replicate densities were obtained for each tack coat. Average densities for each tack coat can be found in Table 3.2.

The required amount of tack coat by weight was then calculated based on the densities of the tack coats, target application rates and the known sample area. Application rates chosen for this study were for undiluted tack coat solution and were not residual application rates. Tack coats were then applied to the first lift block samples using a foam art roller. Using a high-accuracy scale, the amount of tack coat applied to each sample was carefully tracked until the required amount had been applied to achieve the target application rate. Figure 3.1f shows a tack coat being applied to a first lift block sample. Tack coat application for overlay surface samples followed the same process as for milled surface samples.

All tack coats were allowed to break and set for two hours prior to second lift compaction. This break and set time was chosen based on knowledge of field construction practices and past experiences from Coleri et al. (2017). Once the tack coat had cured, the block sample was loaded into the heated and greased mold immediately prior to compaction. The second lift was compacted atop the first lift. Steps for second lift compaction were the same as first lift compactions, but the custom spacer was excluded, with the first lift block sample taking its place.

3.4.1.5 Coring of block samples

Completed two-lift block samples were allowed to rest at room temperature for two weeks prior to coring. The direction of traffic was marked on each block sample prior to coring to allow for consistency in shear testing (ALDOT 2008). Block samples were cored on a stationary core drill using a six-inch (152.4 mm) core drill bit. In order to fit the blocks into the core drill jig, the block samples were cut in half along the midpoint of the sample. Six-inch cores were then taken from the block samples using the core drill. Core samples were then allowed to dry at room temperature for at least three days prior to testing. Figure 3.1g shows coring taking place on a block sample.

3.4.2 Laboratory shear testing

Before testing, the diameter of each sample was measured and recorded for the purpose of calculating interlayer shear strength (ISS). The location of the interlayer was then marked on each sample using a permanent marker. Samples were then conditioned at 25 °C (77 °F) for 24 hours in an environmental chamber. On the day of testing, each sample was loaded into the testing jig with the direction of traffic positioned downward and the wearing course positioned on the shearing side (ALDOT 2008). Figure 3.3 shows the sample loading configuration for shear testing.

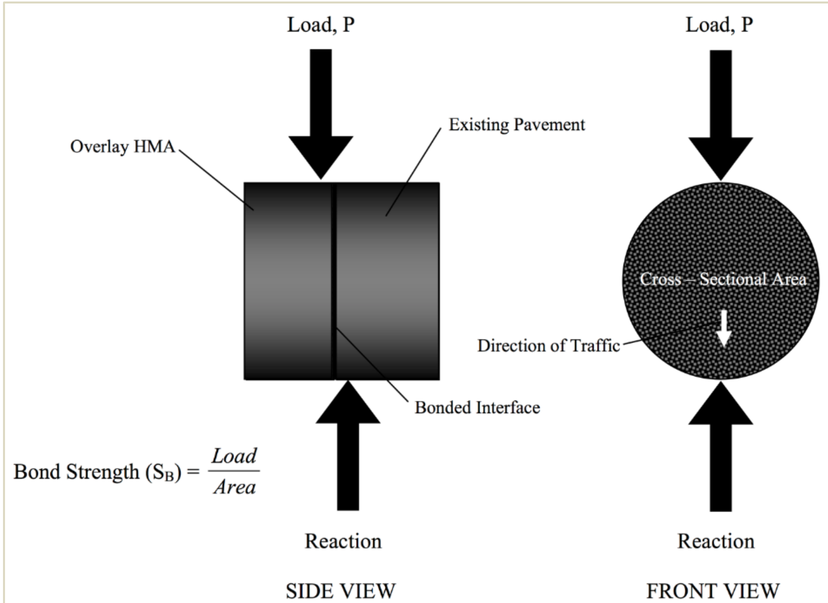


Figure 3.3: Sample loading configuration for shear testing (ALDOT 2008).

Confining pressure was applied to the sample using the spring actuator and calibrated dial on the testing jig. The sample was then placed back in the environmental chamber for one hour prior to testing to allow the sample's temperature to re-equilibrate to 25 °C (77 °F). Figure 3.1h shows the shear test jig used for testing.

Shear tests were then performed using a Universal Testing Machine (UTM) at a strain-controlled constant displacement rate of 2.54 mm/min (0.1 in/min) (AASHTO 2016). The peak load, as well as the load-displacement curve, were captured and recorded for each sample. Tests were terminated before the loading plate made contact with the bottom of the jig to avoid damaging the jig or the UTM. Following completion of the test, the sheared sample was removed and another sample was loaded, following the same procedures described above. Figure 3.1i shows shear testing taking place in the UTM environmental chamber.

3.4.3 Measurement of tack coat binder properties

3.4.3.1 Experimental design for rheological tests

Three tack coat emulsions were analyzed from three different companies, resulting in a total of nine different tack coat types. The tack coat types considered in this study, as well as the overall layout of the experimental design for rheological tests, is summarized in Table 3.3. A general naming system was set to conceal the identity of the companies (labeled "CO#"). CSS-1H emulsions were named as-is, as they are commonly used in Oregon. New emulsions engineered to improve the ISS and reduce tracking were termed "ENGR". Additionally, emulsions intended for overlay were denoted by "O" and those intended for milled surfaces were denoted by "M". Each binder underwent extensive testing via a series of experiments that evaluated its rheological properties. The same rheological tests were conducted on both overlay-intended binders and those specified for milled surfaces while only the tack coats for milled surfaces were used for laboratory shear testing.

Table 3.3. Experimental Design for Rheological Testing

Test Type	Replicates	Tack Coat Type
Penetration	4	CO1-CSS1H CO1-ENGR-O CO1-ENGR-M CO2-ENGR-O CO2-ENGR-O#2[b] CO2-ENGR-M CO3-CSS1[c] CO3-CSS1H CO3-ENGR-OM
Softening Point	3	
Rotational Viscosity	2	
Dynamic Shear Rheometer[a]	2	

[a] Each tack coat type was tested at temperatures of 68 °F (20 °C), 86 °F (30 °C), 104 °F (40 °C), 122 °F (50 °C), 140 °F (60 °C), and 158 °F (70 °C), and 16 different frequencies
[b] A second binder intended for overlay provided by the same company
[c] CSS-1 emulsions are slow-setting binders commonly used in Oregon. These binders are softer than CSS-1H binders ("H" signifying "hard)

3.4.4 Sample preparation for rheological tests

3.4.4.1 Tack coat distillation

Isolation of the tack coat binders was done by distillation at 60 °C (140 °F) (ASTM D7497 2016) (Figure 3.4). Water contents were measured for three replicate samples for each tack coat type and averages are summarized in Table 3.4. This low temperature distillation method was preferred over the conventional standard (ASTM D6997 2012) due to its decreased level of heat. The use of high temperatures has the potential to change the binder's rheological properties and increase chances of inconsistent test results. A previous study compared distillation temperatures of 338 °F (170 °C) and 500 °F (260 °C) and found that the temperature of the distillation process had insignificant effects on the viscosities of the binders (Covey 2017). However, the authors of this study also concluded that these temperatures were too high to properly recover binder from new engineered emulsions with high polymer contents.

In order to have proper control over the application rates for tack coats for laboratory shear test sample preparation, the density of each tack coat was also measured. Three replicate density measurements were made for each emulsion and averages are given in Table 3.4. Since the tack coats for overlay surfaces are not used for laboratory shear test specimen production, densities for the overlay tack coats were not measured.

Figure 3.4. Tack coat binder after low temperature distillation

Table 3.4. Summary of Tack Coat Emulsion Water Contents

Tack Coat Type	Initial Mass (g)[a]	Water Distilled (g)	Water Content (%)	Density (g/mL)
CO1-CSS1H	93.0	36.0	38.7	0.991
CO1-ENGR-O	92.7	31.0	33.4	-
CO1-ENGR-M	95.7	39.3	41.1	0.920
CO2-ENGR-O	94.0	36.1	38.4	-
CO2-ENGR-O#2	94.6	38.2	40.4	-
CO2-ENGR-M	94.3	83.5	88.5	1.007
CO3-CSS1	92.5	33.9	36.7	0.971
CO3-CSS1H	92.0	34.7	37.7	1.000
CO3-ENGR-OM	91.5	30.8	33.7	0.956

[a] 1.0 g = 2.20×10^{-3} lbs

Due to its high water content (88.5 %), CO2-ENGR-M was distilled and tested using a concentrate emulsion. Though a low temperature distillation process was used, the chemical properties of this tack coat emulsion had the potential to experience higher rheological damage and aging than that of the other emulsions. Therefore, in order to stay consistent across all of the binders, a concentrate emulsion was distilled and used for testing.

3.4.5 Rheological test methods

A total of nine tack coats were tested and analyzed. Each tack coat emulsion was distilled according to ASTM D7497 (2016) in order to extract their binder from the tack coat. Softening point and rotational viscosity tests were performed according to ASTM D36 (2014) (Figure 3.5a) and ASTM D4402 (2015) (Figure 3.5b), respectively. Penetration and Dynamic Shear Rheometer tests were also conducted, in accordance with ASTM D5 (2013) (Figure 3.5c) and ASTM D7175 (2015) (Figure 3.5d), respectively.

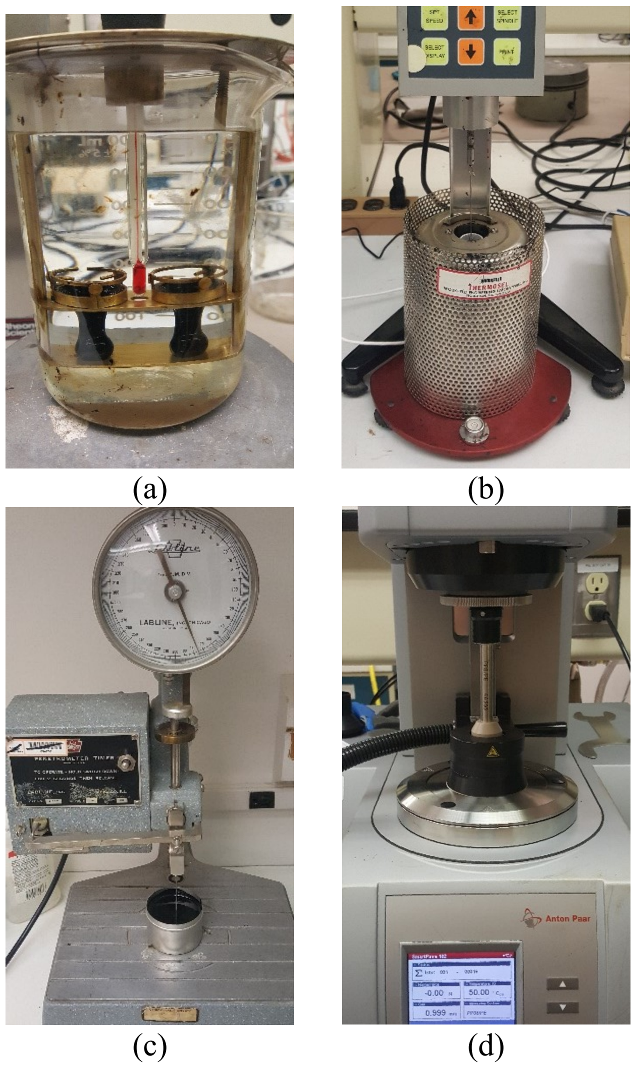


Figure 3.5. Rheological tests conducted: (a) Softening point, (b) Rotational viscosity, (c) Penetration (d) DSR

3.4.5.1 Softening Point (SP)

The softening point test was done to determine the temperature at which the tack coat binder was soft enough to flow under a given weight. Due to the viscoelastic nature of the binder, rising temperatures give way to softer and less viscous binder (ASTM D36 2014).

Low values typically indicate soft binders, while high values generally suggest stiffer binders. Defining the softening point for each of the tack coat binders allowed to determine the minimum temperature required to be able to pour and shape the binder samples to conduct additional binder tests. In this way, over heating of the binders was avoided.

3.4.5.2 Rotational Viscosity (RV)

In order to determine the viscosity of each tack coat binder at short-term aging temperatures, rotational viscosity tests were conducted. Higher viscosity readings, as determined by more resistance to rotation, suggested a stiffer binder (ASTM D4402 2015).

3.4.5.3 Penetration

The consistency of each of the binders was determined by penetration testing. Higher values of penetration indicated softer binders, while low values suggested stiffer binders (ASTM D5 2013).

3.4.5.4 Dynamic Shear Rheometer (DSR)

DSR tests were conducted in order to obtain the complex shear modulus (G^*) and phase angle (δ) for each of the tack coat binders at various temperatures and loading frequencies (ASTM D7175 2015). These parameters are factors that describe the expected performance of the binders, such as the resistance to shear deformation when a load is applied (complex shear modulus), and the time lag between the peak shear stress that is applied to the sample and the resulting peak shear strain that is experienced by the sample (used to calculate phase angle) (Pavement Interactive 2012).

A frequency sweep test was conducted on each of the binders at temperatures ranging from 20 °C – 70 °C (68 °F – 158 °F) at 10 °C (50 °F) intervals. This test allowed for the measuring of binder properties at a variety of frequencies, including 0.016 Hz, 0.025 Hz, 0.040 Hz, 0.063 Hz, 0.100 Hz, 0.159 Hz, 0.251 Hz, 0.399 Hz, 0.633 Hz, 1.00 Hz, 1.59 Hz, 2.51 Hz, 3.99 Hz, 6.33 Hz, 10.0 Hz, and 15.92 Hz. Frequencies of interest included 0.1 Hz, 1 Hz, and 10 Hz, and were selected to be used for the purposes of this study.

3.5 RESULTS—MEASURED BOND STRENGTH AND ENERGY

Through laboratory monotonic direct shear testing (DST), the interlayer shear strength (ISS) and interlayer bond energy (IBE) of each tack coat were obtained.

3.5.1 Peak interlayer shear strength (ISS) results

As a result of monotonic direct shear testing (DST), the shear strength of the tack coat bond was obtained for each sample tested. Figure 3.6 shows the average peak shear strength results for all tack coats tested. The colored bars represent the average strength from six replicate experiments while the length of the error bar on each bar represents the variability of the measured strength for each tack coat type (error bar length = two standard deviations).

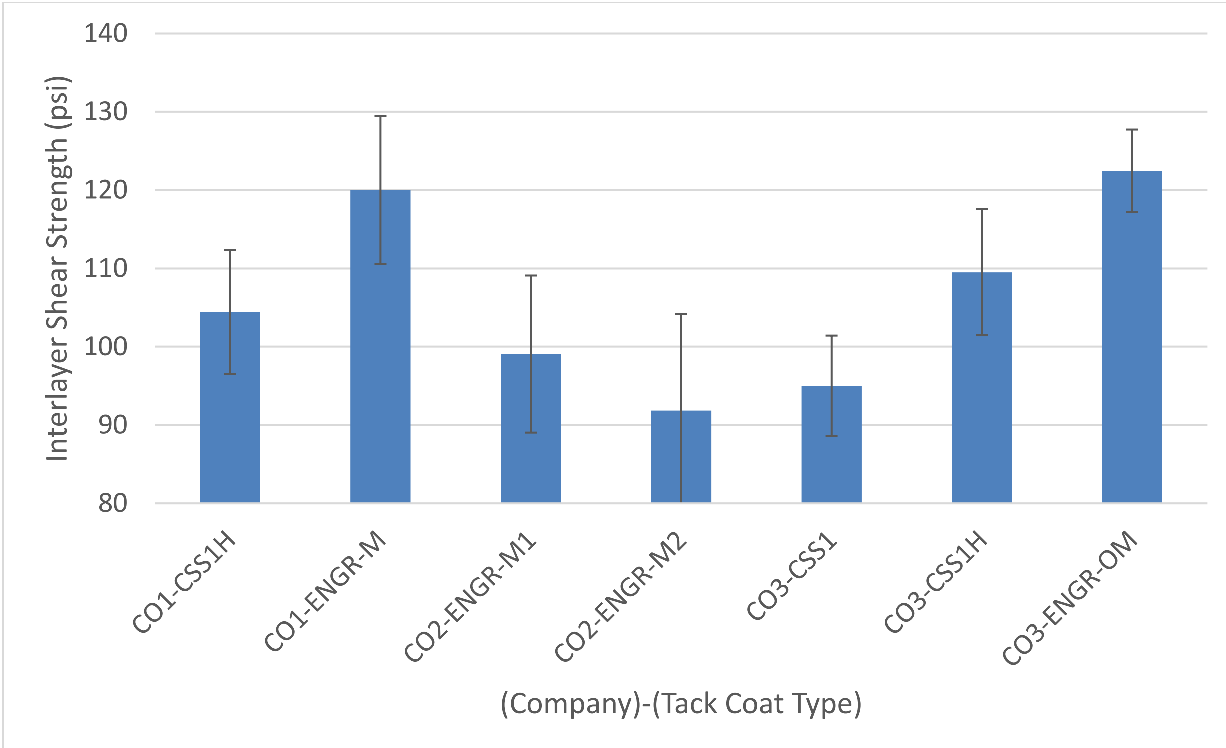


Figure 3.6: Average ISS results for all tack coats with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa)

As can be seen in Figure 3.6 above, the engineered tack coats for Company 1 and Company 3 had ISS values higher than all other tack coats tested, with Company 3 having a slightly higher ISS than Company 1. The standard deviation of ISS for the six Company 3 replicates was also less than that of Company 1. The engineered tack coats provided by Company 2 did not have measured ISS values as high as the engineered or CSS1H tack coats from Company 1 and Company 3. This result is attributed to the high water content of the Company 2 engineered tack coats and the possible need to increase the residual application rates. Additional research is required to determine the optimum application rates for Company 2's engineered tack coats.

The mean texture depth (MTD) of each sample, as measured by the Sand Patch Test (ASTM 2015a), was recorded before second lift compactions took place. MTD measurements were compared with the ISS of each sample to identify any relationships between the two variables. The MTD results are compared with peak shear strengths of each sample below in Figure 3.7.

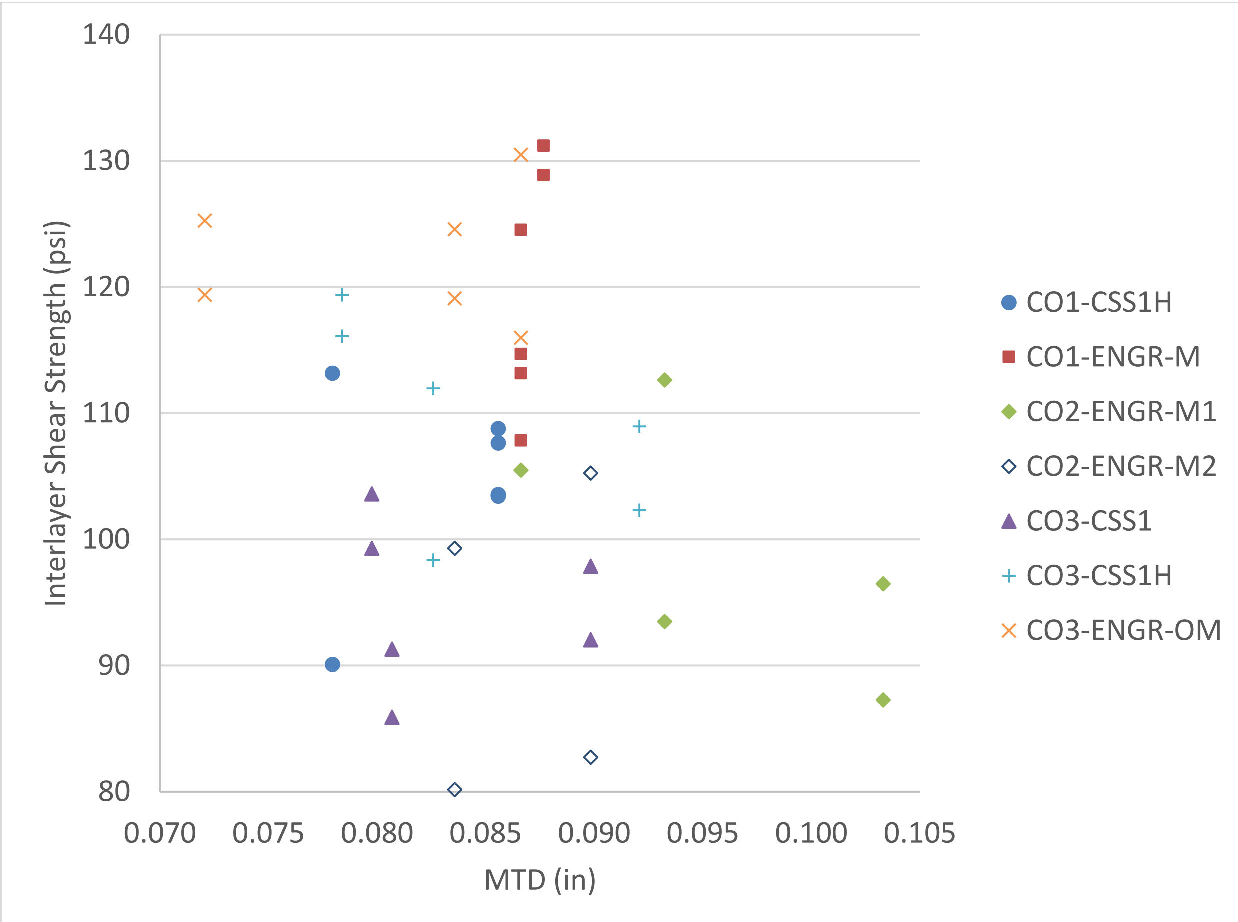


Figure 3.7: Peak shear strength versus MTD for each tack coat type (1.0 psi = 6.89 kPa; 1.0 in = 2.54 cm)

As can be seen in Figure 3.7 above, ISS was not highly correlated with MTD for any of the tack coat types tested. This indicates that MTD is not controlling bond strength and that laboratory milling practices did not create any bias in the results.

In order to assess the significance of peak shear strength for each tack coat tested, a Welch modified two-sample t-test was performed between each tack coat type to determine significant differences, if any, between the shear strengths for different tack coat types. Suppose that the two peak shear strength distributions for the tack coat types under comparison (suppose F_1 and F_2 are two distributions) can be represented by the following null and alternative hypotheses:

$$\boldsymbol{H_0: F_1(x) = F_2(x)} \tag{3-2}$$

$$\boldsymbol{H_A: F_1(x) \neq F_2(x)} \tag{3-3}$$

A decision rule was adopted for the two-sample t-test. The decision rule is as follows:

$$\textit{Reject } H_0 \textit{ if } p < 0.05 \tag{3-4}$$

$$\textit{Fail to reject } H_0 \textit{ if } p \geq 0.05 \tag{3-5}$$

In the case where the null hypothesis was rejected, it was concluded that the peak shear strengths of the tack coats under comparison were significantly different from one another. Table 3.5 shows the p-values returned for the two-sample t-test for each tack coat type at a 95% significance level.

Table 3.5: P-values from two-sample T-test Comparing Peak Shear Strength of each Tack Coat Type.

Tack Coat Type	CO1-CSS1H	CO1-ENGR-M	CO2-ENGR-M1	CO2-ENGR-M2	CO3-CSS1	CO3-CSS1H	CO3-ENGR-OM
CO1-CSS1H	1.000	**0.012**	0.297	0.134	0.048	**0.297**	0.001
CO1-ENGR-M	0.012	1.000	0.003	0.010	0.001	0.065	**0.600**
CO2-ENGR-M1	0.297	0.003	1.000	0.360	0.390	0.060	0.001
CO2-ENGR-M2	0.134	0.010	0.360	1.000	**0.663**	0.055	0.011
CO3-CSS1	0.048	0.001	0.390	0.663	1.000	0.007	**0.000**
CO3-CSS1H	0.297	0.065	0.060	0.055	0.007	1.000	**0.010**
CO3-ENGR-OM	0.001	0.600	0.001	0.011	0.000	0.010	1.000

As can be seen in Table 3.5, the engineered tack coat provided by Company 1 had significantly superior ISS when compared to their CSS-1H tack coat since the p-value returned from the two-sample t-test was less than 0.05. It can be said with 95% confidence that Company 1's engineered tack coat had better shear strength performance than their CSS-1H tack coat.

When comparing Company 1's engineered tack coat to that of Company 3, Figure 3.6 showed that Company 3's tack coat had slightly better performance. However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.600 from a two-sample t-test at a 95% confidence level.

When comparing Company 1's CSS-1H tack coat to that of Company 3, Figure 3.6 showed that Company 3's tack coat had slightly better performance. However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.297 from a two-sample t-test at a 95% confidence level. Tack coat binder tests conducted with CSS-1H tack coats from Company 1 and 3 also showed that these two tack coats have almost identical properties.

Company 3's engineered tack coat was found to have significantly better performance as compared to their CSS1 and CSS-1H tack coats. Based on the p-values reported in Table 3.5 from a two-sample t-test, there was a significant difference in peak shear strengths between the Company 3 engineered tack coat and the CSS1/CSS-1H tack coats at a 95% confidence level.

CO2-ENGR-M2 was found to have no significant difference in ISS when compared to CO3-CSS1, as is indicated by a p-value of 0.663 at a 95% confidence level, indicating that this engineered emulsion did not exhibit better performance than traditional emulsions.

3.5.2 Interlayer bond energy results

From the load-displacement curves obtained for each laboratory shear test, another useful parameter, interlayer bond energy, was extracted to characterize the tack coat bond performance. Interlayer bond energy takes into account the peak strength of the tack coat bond, as well as the associated displacement endured before bond failure. This parameter has been shown to be highly correlated ($R^2 = 0.8$) with fatigue failure criteria for tack coat interlayer bonds and is highly indicative of the fatigue-related shear resistance of tack coats (Amelian and Kim 2017). The interlayer bond energy is calculated as the area under the load-displacement curve up to the peak load.

Figure 3.8 shows the average interlayer bond energy results for all tack coats tested. The columns represent the average interlayer bond energy from six replicate experiments while the length of the error bar on each column represents the variability of the measured energy for each tack coat type (error bar length = two standard deviations).

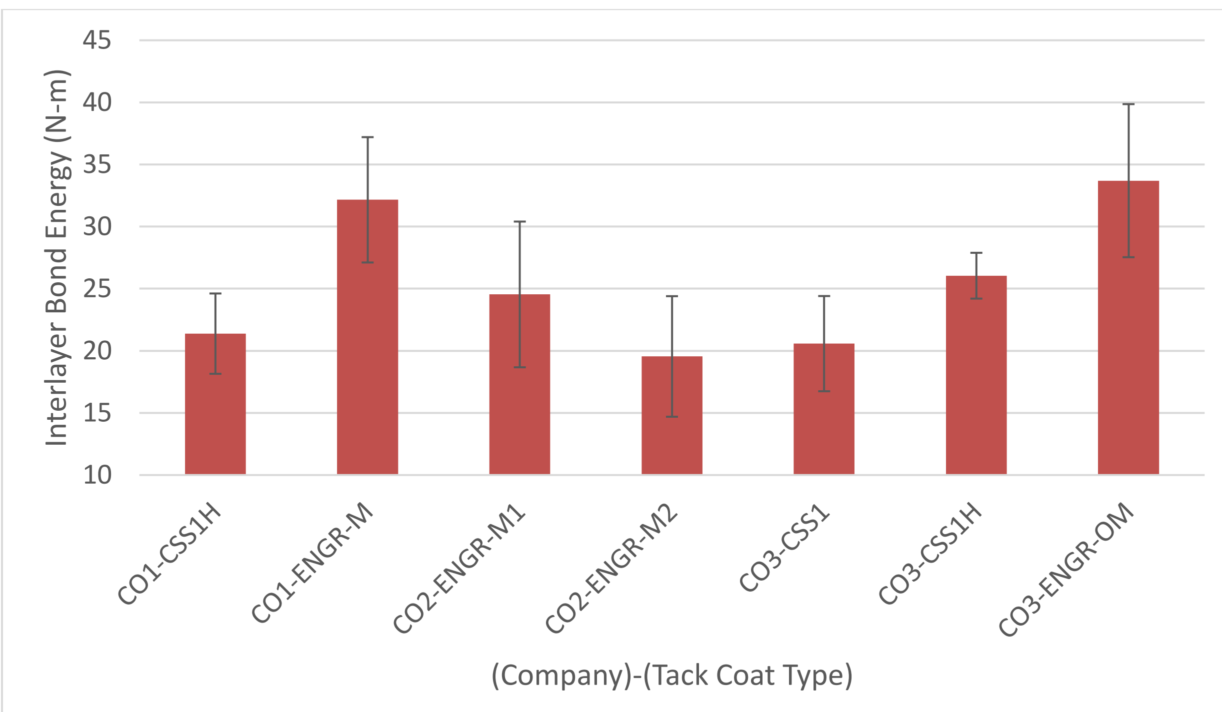


Figure 3.8: Average interlayer bond energy results for all tack coats with error bars indicating ± 1 standard deviation (1.0 N-m = 8.85 in-lbs).

Interlayer bond energy was also compared with MTD results from the Sand Patch Test (ASTM 2015a). This was done to identify any relationships between interlayer bond energy and MTD for the samples tested. Figure 3.9 shows the relationship between interlayer bond energy and MTD for each tack coat type.

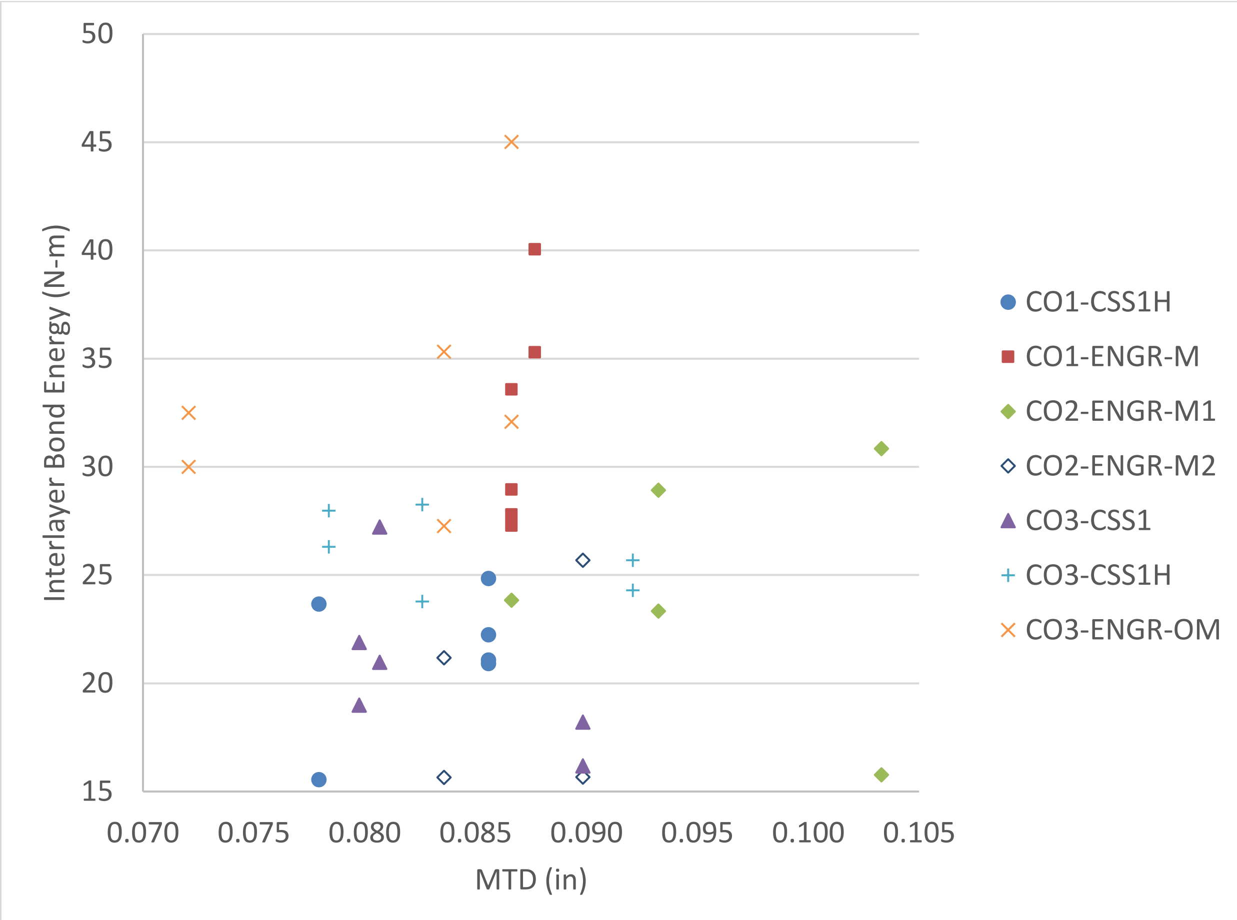


Figure 3.9: Interlayer bond energy versus MTD for each tack coat type (1.0 N-m = 8.85 in-lbs; 1.0 in = 2.54 cm).

Similar to ISS, IBE was not highly correlated with MTD for any of the tack coat types tested. This indicates that MTD was not influential on the interlayer bond energy of the tack coats.

Two-sample t-tests were also performed for interlayer bond energy results for each of the tack coat types. The same decision rule was adopted for these comparisons as was used in Section 3.5.1. Table 3.6 shows the p-values returned for the two-sample t-tests at a 95% confidence level.

Table 3.6: P-values from two-sample T-tests of Interlayer Bond Energy for all Tack Coat Types

Tack Coat Type	CO1-CSS1H	CO1-ENGR-M	CO2-ENGR-M1	CO2-ENGR-M2	CO3-CSS1	CO3-CSS1H	CO3-ENGR-OM
CO1-CSS1H	*1.000*	**0.002**	0.244	0.537	0.703	0.016	0.003
CO1-ENGR-M	0.002	*1.000*	0.028	0.006	0.001	0.030	**0.646**
CO2-ENGR-M1	0.244	0.028	*1.000*	0.205	0.169	0.530	0.020
CO2-ENGR-M2	0.537	0.006	0.205	*1.000*	**0.734**	0.070	0.004
CO3-CSS1	0.703	0.001	0.169	0.734	*1.000*	0.016	**0.002**
CO3-CSS1H	0.016	0.030	0.530	0.070	0.016	*1.000*	**0.028**
CO3-ENGR-OM	0.003	0.646	0.020	0.004	0.002	0.028	*1.000*

Table 3.6 shows that the engineered tack coat provided by Company 1 exhibited significantly better interlayer bond energy performance as compared to the CSS-1H tack coat. The two-sample t-test p-value of this comparison was well below 0.05. Thus, the interlayer bond energy of the Company 1 engineered tack coat is different from the CSS-1H bond energy at a 95% confidence level.

The engineered tack coat provided by Company 3 appeared to have superior bond energy performance when compared to that of Company 1 based on Figure 3.8. However, a two-sample t-test confirms that the difference in interlayer bond energy of these two tack coats is not statistically significant at a 95% confidence level. This is illustrated by the high p-value (0.646) shown in Table 3.6.

Similar to the shear strength results, the engineered tack coat provided by Company 3 was found to be significantly better in terms of interlayer bond energy than the CSS-1 and CSS-1H tack coats provided by Company 3. A two-sample t-test returned p-values that indicated significant differences in interlayer bond energies between the engineered tack coat and the CSS-1/CSS-1H tack coats provided by Company 3 at a 95% confidence level.

3.5.3 Comparison of laboratory peak shear strength with field results

A research study by Mohammad et al. (2012) revealed that testing bond strength of two layered asphalt specimens prepared with SGC can artificially amplify bond strength by 2 to 10 times when compared to field-extracted cores. In order to assess the viability of the laboratory sample preparation procedures (using a hydraulic roller compactor) for predicting field performance of tack coats, the peak interlayer shear strength results obtained in this study were compared with interlayer shear strengths of field-cored samples from Coleri et al. (2017). The field cores were taken from a construction project in Oregon where a new overlay was constructed on a milled surface. For the field construction project, Company 1 provided a CSS-1H tack coat and an engineered tack coat (shown as CO1_ENGR_Field in Figure 3.10). Company 2 provided an engineered tack coat only (shown as CO2_ENGR_Field in Figure 3.10). Different application rates were used for each tack coat and are represented in this comparison. The field-cored samples from Coleri et al. (2017) were tested in the same jig under the same loading rate and temperature as the laboratory-produced samples. Figure 3.10 shows a plot of peak shear strength versus application rate for field-cored samples from Coleri et al. (2017) and laboratory-produced samples from this study.

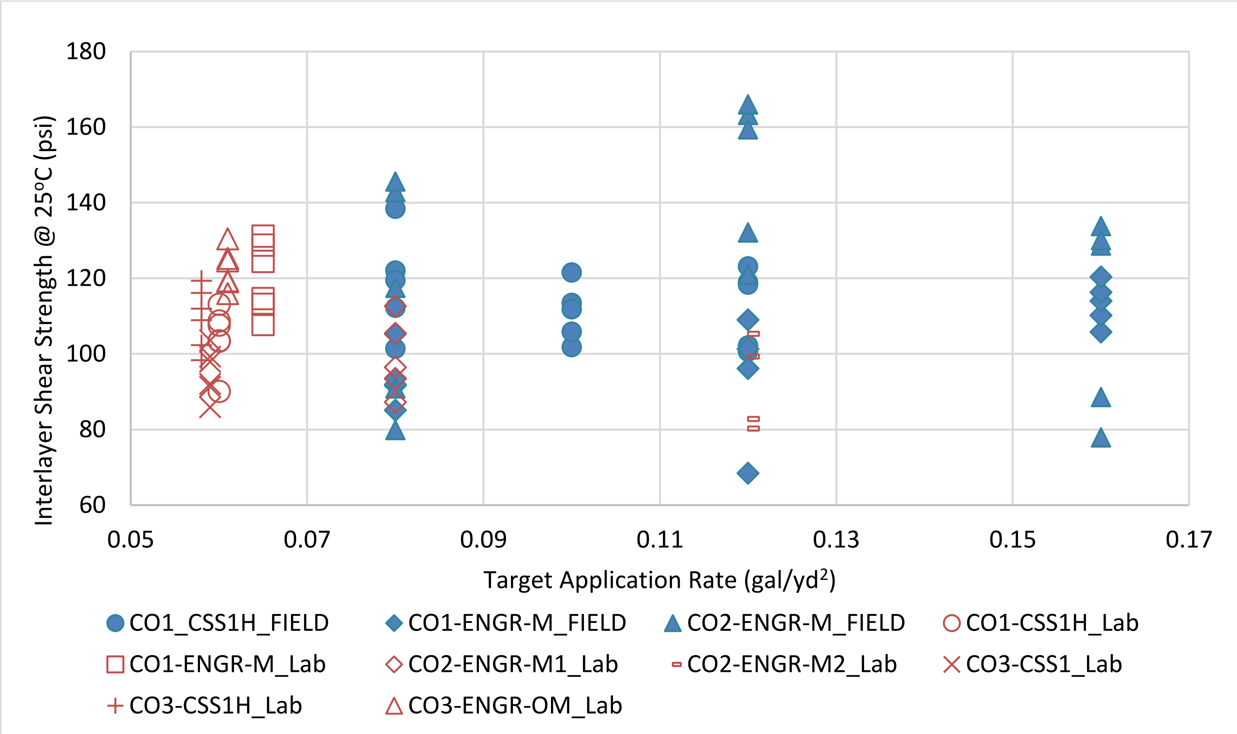


Figure 3.10: Peak shear strength versus application rate for field-cored samples and laboratory-produced samples (25 °C = 77 °F; 1.0 psi = 6.89 kPa; 1.0 gal/yd^2 = 4.53 L/m^2)

As can be seen in Figure 3.10 above, the ISS of the laboratory-produced samples were not dissimilar to that of the field-cored samples. The laboratory-produced samples had shear strengths that were well within the domain of shear strengths yielded from the field-cored samples. This indicates that the sample procurement procedures of this study (using a laboratory roller compactor and laboratory milling procedures) produced shear strength results that are similar to what is observed under field conditions. It should be noted that the figure above shows ISS values that were not corrected for MTD. However, normalization of shear strength by MTD is not expected to change the findings of this comparison.

Additionally, Figure 3.10 does not illustrate a discernable trend between ISS and application rate. For laboratory-produced samples, the ISS responses of CO2-ENGR-M1 and CO2-ENGR-M2, which were applied at higher rates, were low in comparison to the ISS of tack coats applied at lower rates. This was due to the poor performance of CO2 engineered tack coats on laboratory-produced samples, which exhibited low ISS due to their low residual asphalt content/high water content. ISS responses of field samples were highly variable, since there is less control over construction issues such as nonuniform tack coat coverage and dust on the pavement surface prior to tack coat application. Field-cored samples were also obtained from different pavement construction projects in Oregon where construction conditions may have varied significantly between each project.

3.6 RESULTS—MEASURED TACK COAT BINDER PROPERTIES

3.6.1 Rheological properties of distilled tack coat emulsions

Each of the nine tack coat emulsions were analyzed via a series of rheological tests, including softening point, rotational viscosity, penetration, and dynamic shear rheometer (DSR). Relationships between each of nine rheological results were evaluated in order to determine the correlations between the results of all rheological tests.

3.6.1.1 Softening Point (SP)

Binders that displayed higher softening points indicated a more viscous binder. The engineered binders displayed the highest softening point values, while the CSS-1H binders gave the lowest (Figure 3.11). This suggests that these tack coat binders are softer than the newly engineered binders.

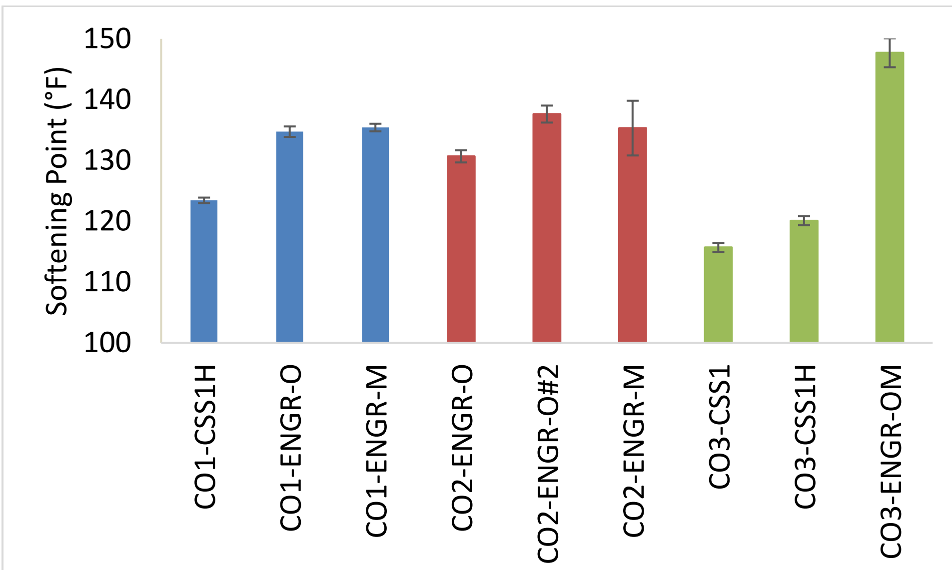
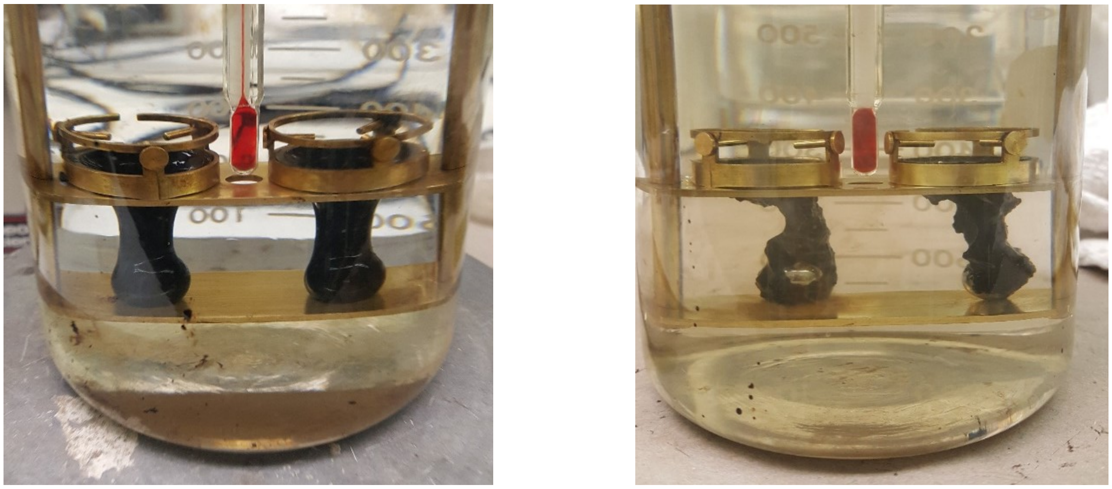


Figure 3.11: Softening point test results (77 °F = 25 °C)

A discrepancy in the results for the softening point test can be seen in the values displayed for the CO2-ENGR-M distilled emulsion. This particular binder did not have a smooth consistency when poured (Figure 3.12a), as was typical with the other binders, presumably due to the binder being polymer-modified and not able to withstand the sample preparation temperatures. As a result, the binder was not evenly distributed throughout the test rings. During the testing process, the deformed CO2-ENGR-M binder around the steel balls softened, resulting in the steel balls to break through the binder (Figure 3.12b). This resulted in inconsistent values to be obtained, and may explain the high variability in test results associated with this particular tack coat binder. Additionally, as the binder softened and the steel balls broke through, the binder released a residue that diffused throughout the water.



(a) (b)

Figure 3.12: Softening point experiment of (a) CO1-CSS1H (b) CO2-ENGR-M

3.6.1.2 Rotational Viscosity (RV)

Figure 3.13 illustrates the results of the RV test. Rotational viscosity values for the engineered binders are higher than CSS-1H binders, again implying that these binders are stiffer.

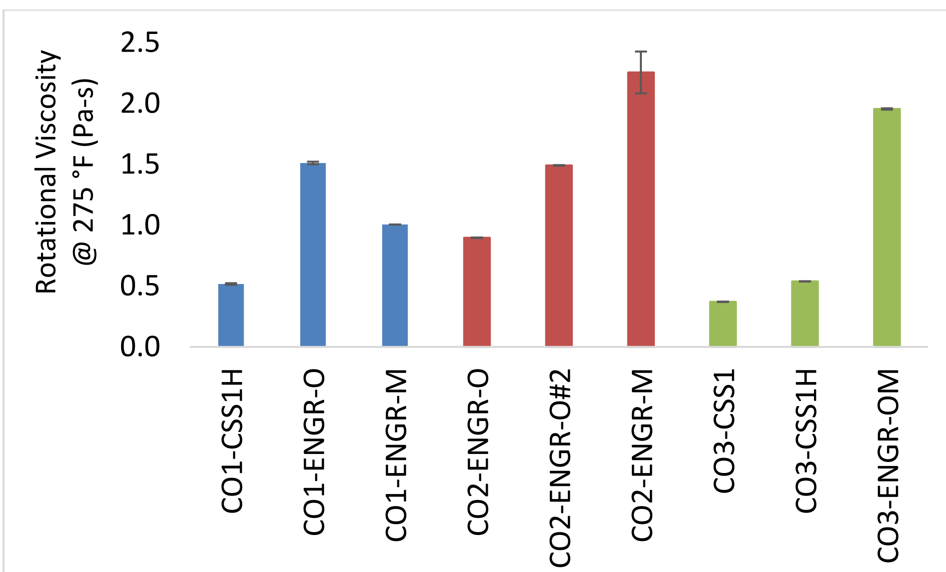


Figure 3.13: Rotational viscosity test results

Company 3 displays consistent results between RV and SP. On the other hand, Company 2 had slightly skewed results between RV and SP tests. CO2-ENGR-M displayed very high RV values as well as large amounts of variation within these results. The test was conducted at 275 °F (135 °C), a temperature that may have been too high for this particular binder to withstand. Therefore, the viscosity may be higher than expected and shows a large deviation due to the lack of fluidity and consistency that the binder may have maintained at elevated temperatures.

3.6.1.3 Penetration

Penetration results are illustrated in Figure 3.14. Again, results from Company 3 are consistent with the results from the previous tests. CO1-ENGR-M shows a relatively lower penetration than most other tack coat binders, signifying a stiff binder, which is consistent with the RV results.

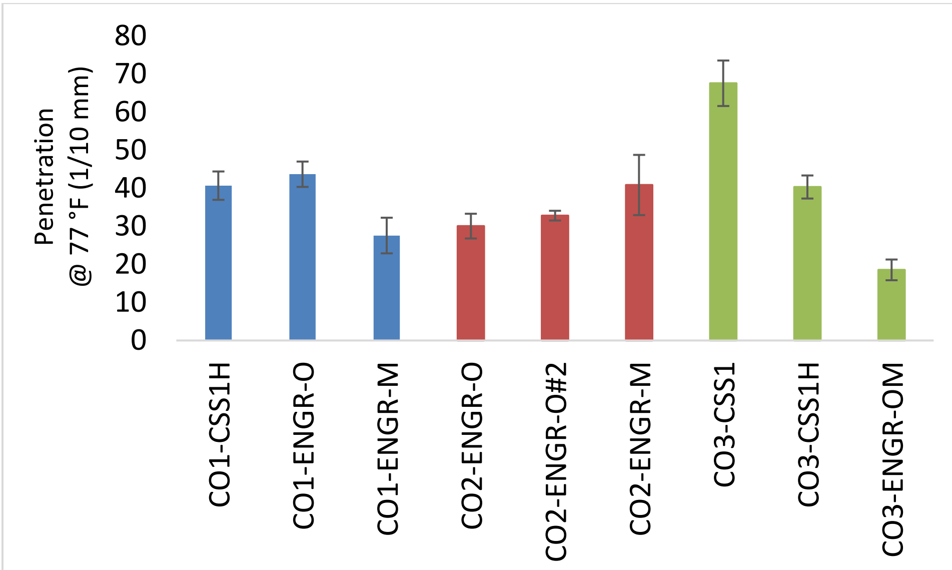


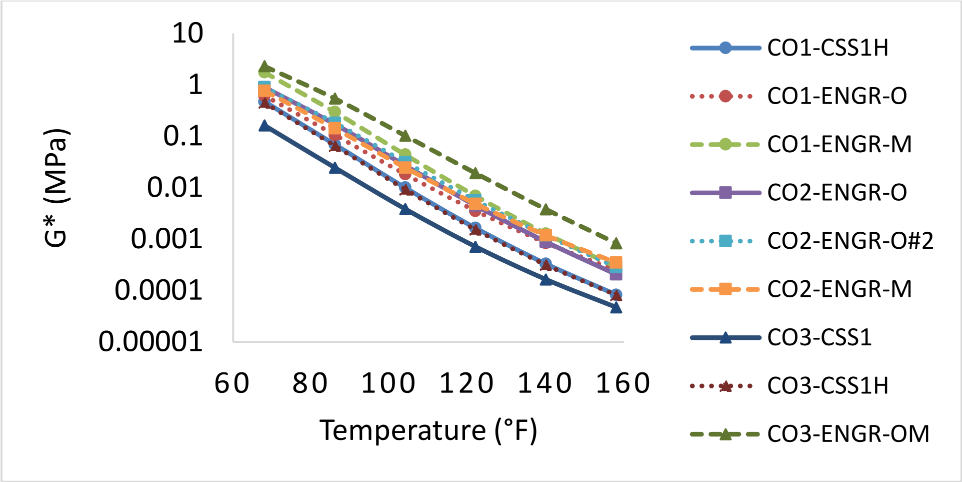
Figure 3.14: Penetration test results (77 °F = 25 °C; 1.0 mm = 3.94×10^{-2} in)

The test results obtained for the CO2-ENGR-M distilled emulsion had high variability, as can be seen by the error bar associated with the results (Figure 3.14). The surface of the binder was not smooth, which made it difficult to pinpoint areas to perform the test (Figure 3.15). The non-uniformity of the binder may have contributed to the high variability seen in the results. Additionally, penetration test results for this binder did not align with the results from the other rheological tests, as the values obtained from this test suggest a soft binder.

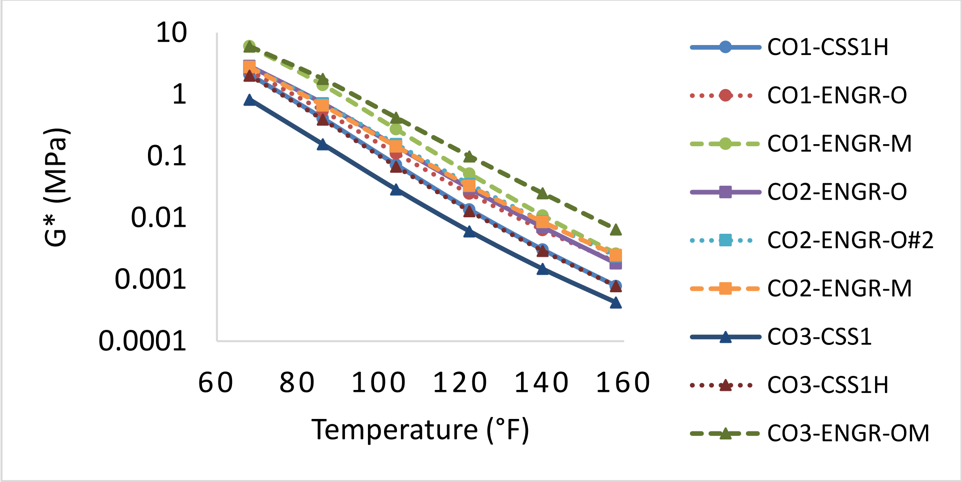
Figure 3.15: Comparison of CO2-ENGR-M binder (left) and CO1-CSS1H binder (right)

3.6.1.4 Dynamic Shear Rheometer (DSR)

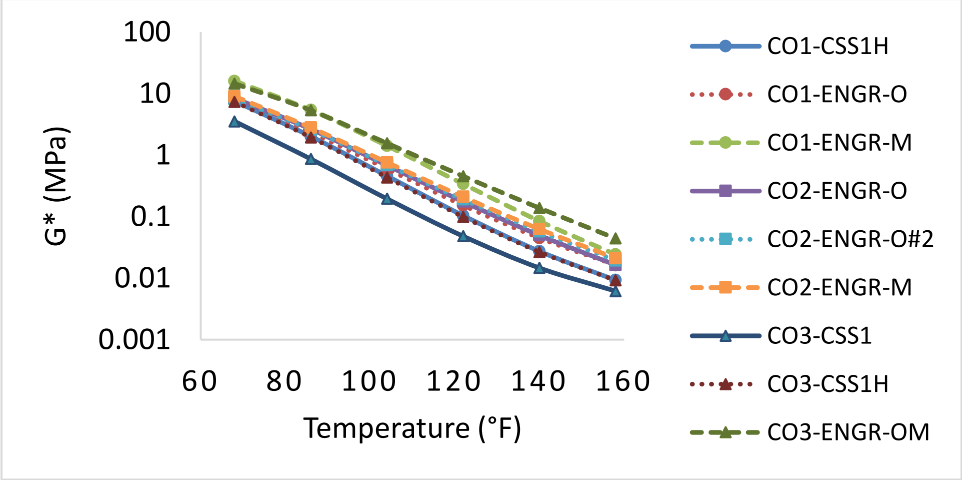
The results given by DSR testing allowed for comparisons to be made between each of the tack coat binders in terms of complex shear modulus (G*) and phase angle (δ). Binders with smaller G* values were expected to be softer while smaller phase angles were expected to be less viscous. Figure 3.16 shows the G* values for each of the tack coat binders at various temperatures and frequencies. The general trend is similar between each of the frequencies. Stiffer binders like CO3-ENGR-OM were observed to have higher G* values while softer binders like CO3-CSS1 had lower G* values. CO1-CSS1H and CO3-CSS1H had almost identical phase angles and G* values for all loading frequencies and temperatures.



(a)



(b)



(c)

Figure 3.16: DSR results for complex shear modulus results at (a) 0.1 Hz, (b) 1 Hz (c) 10 Hz (1.0 MPa = 145.0 psi; 77 °F = 25 °C)

G* was also plotted against frequency. Figure 3.17 shows the results of the test at 104 °F (40 °C).

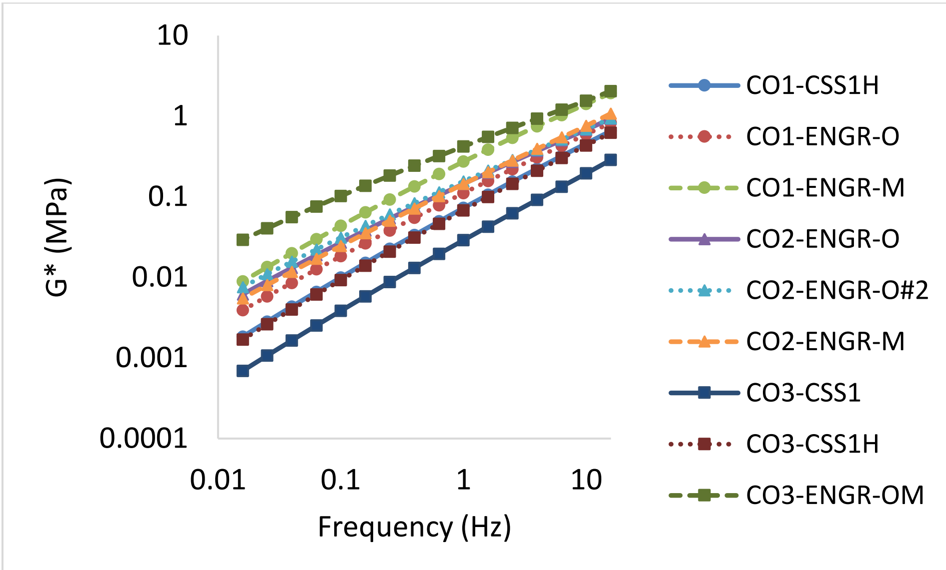
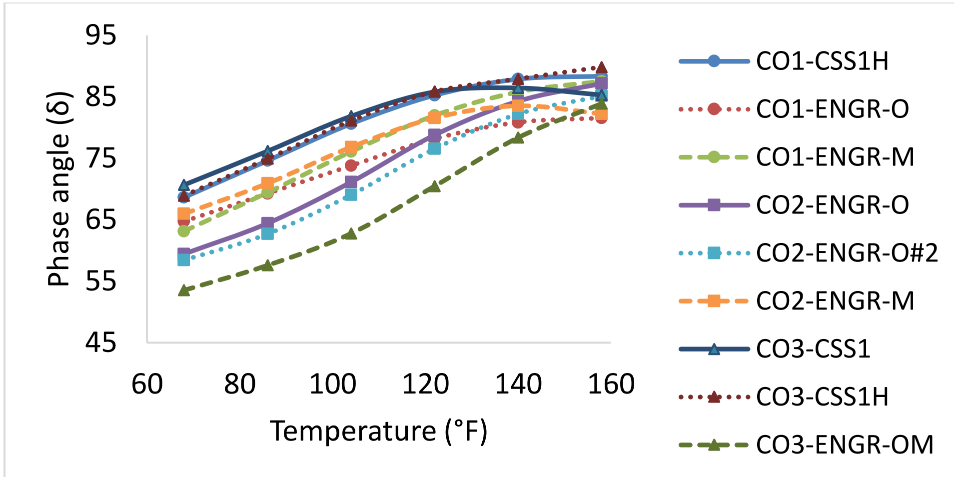
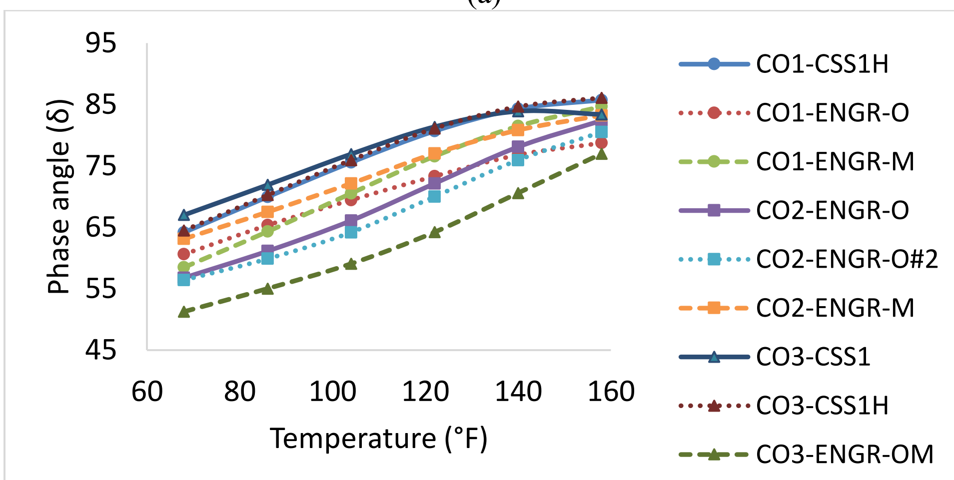


Figure 3.17: DSR results for complex shear modulus results at 104 °F (40 °C) (1.0 MPa = 145.0 psi)

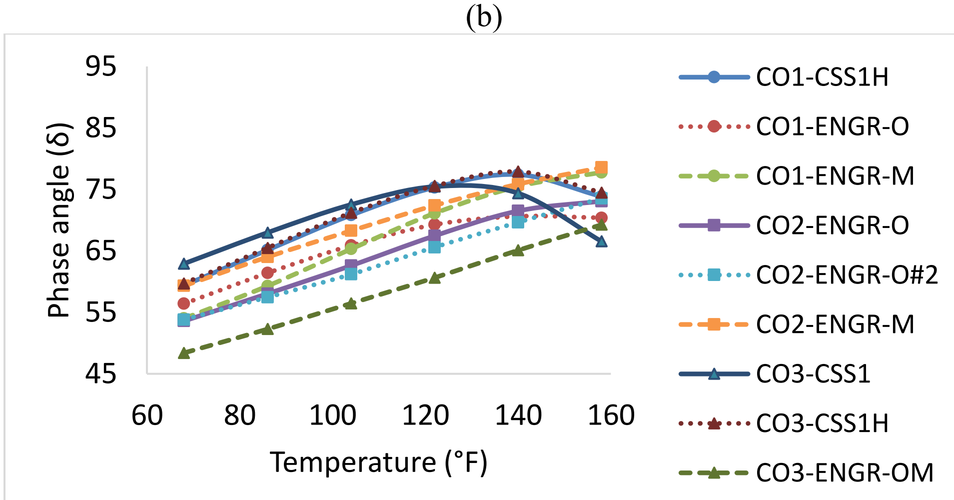
Figure 3.18 shows the phase angle values for each of the tack coat binders at various temperatures and frequencies. A lower phase angle indicates more elastic behavior. However, as the temperature increases, the viscosity of the binder decreases, which can also be easily identified at lower frequencies for the softer binders (Figure 3.18). For some binders, phase angles increase with increasing temperature but then start to decrease after reaching a peak value. This is due to the changing mechanical properties of the binder with the changes in temperature. Asphalt binder is acting more like an elastic material (low phase angles) at lower temperatures, and then it starts to turn into a viscoelastic material (higher phase angles) with increasing temperature. At very high temperatures, it starts behaving more like a low viscosity material (more like a fluid), which starts reducing the phase angles after reaching the peak. It can be observed that CSS-1H and CSS-1 binders have the highest phase angles (more delayed elastic and viscous behavior and less elastic behavior).



(a)



(b)



(c)

Figure 3.18: DSR results for phase angle at (a) 0.1 Hz, (b) 1 Hz (c) 10 Hz (77 °F = 25 °C)

Phase angle was also plotted against frequency. Softer binders can be found at the top of the plot as they display higher phase angles, while stiffer binders can be found near the bottom with lower phase angles (Figure 3.19). As temperature increases, the consistency of these results become skewed, most noticeably in the softer binders, likely due to the changing viscoelastic properties of the binders.

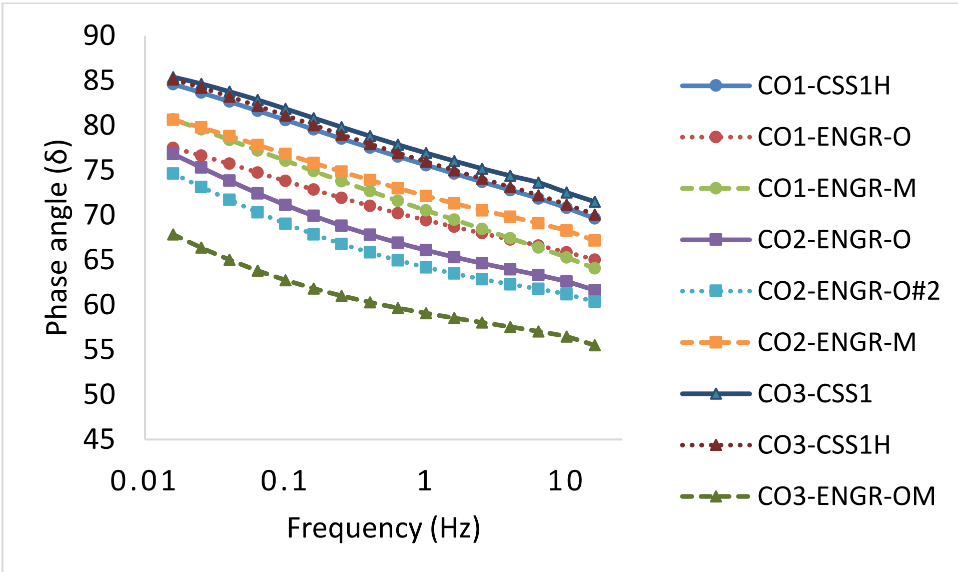


Figure 3.19: DSR results for phase angle at 104 °F (40 °C)

3.6.2 Correlations between rheological tests

The results of each of the rheological tests were compared against each other in order to assess the relationships between the results of different tests and the impact of test temperature differences on correlations (Figure 3.20). These correlations allow for the tack coat types to be directly compared with each other, as well as with the corresponding tests. In this manner, it is simple to identify areas in which the tack coat binder test results are highly correlated and where outliers may arise.

The results from penetration and softening point testing show a negative relationship (Figure 3.20). This is expected, as higher softening point values give way to lower penetration results. The values obtained for each of the tack coat types show an acceptable correlation, with an R^2 value of 0.65. A negative relationship is also observed when comparing rotational viscosity and penetration test results (Figure 3.21). This is expected, as softer binders have lower viscosity readings. However, in this comparison, CO2-ENGR-M did not necessarily follow the trend that was seen in the other tack coat binders. This may be due to the unusually high rotational viscosity value that was obtained for this particular tack coat. An R^2 value of 0.23 suggests that these tests were not well correlated (Figure 3.21a), presumably due to the large difference in temperature between each of the tests [RV test temperature was 275 °F (135 °C) and penetration test temperature was 77 °F (25 °C)]. However, when the point representing CO2-ENGR-M was excluded, the coefficient of determination for the relationship between rotational viscosity and penetration almost doubled to 0.44 (Figure 3.21b). Results from rotational viscosity and softening point experiments were positively correlated, as lower softening points gave way to lower viscosity readings (Figure 3.22). Again, CO2-ENGR-M stood out from the general trend, though the R^2 value for these tests was still 0.64 (Figure 3.22a). However, excluding this point from the plot allowed the relationship between the tests to become stronger, with a strong correlation of 0.91 (Figure 3.22b). The discrepancy in this particular data point (CO2-ENGR-M) may be due to the unexpected values obtained from both tests.

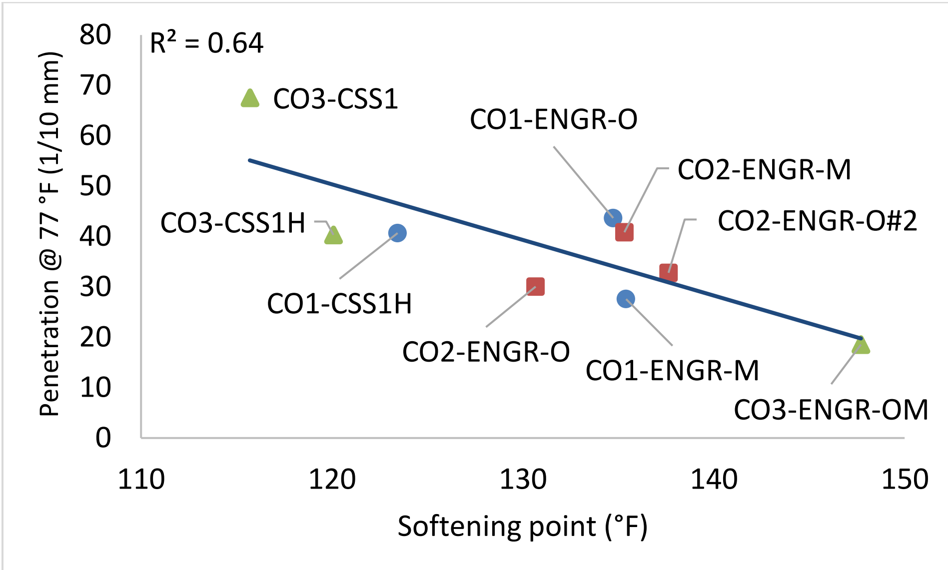
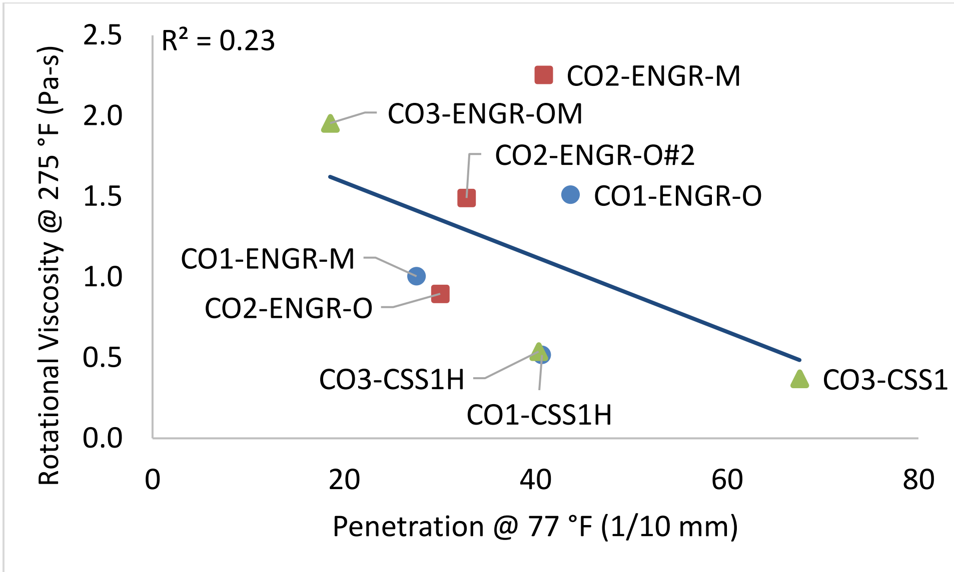
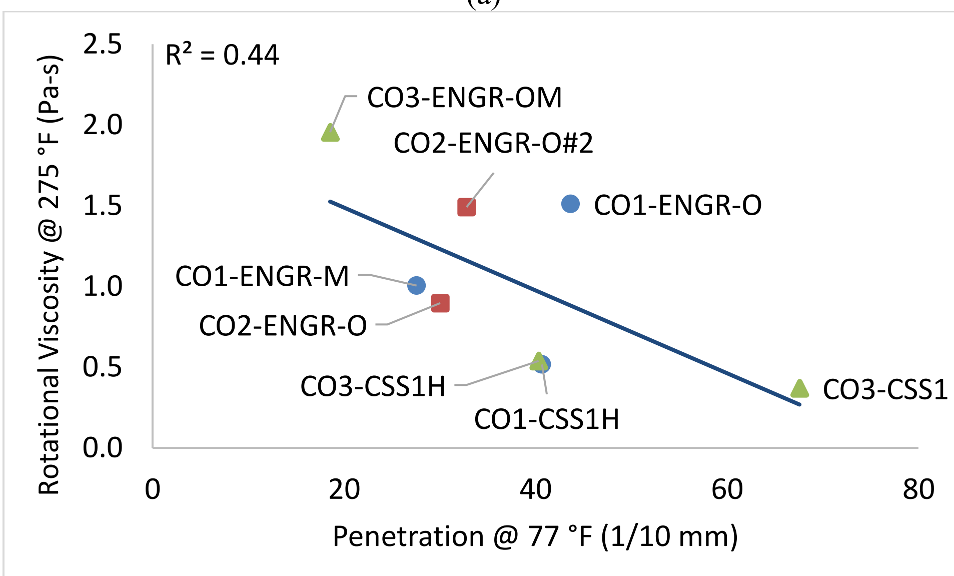


Figure 3.20: Relationship between penetration and softening point tests (1.0 mm = 3.94x10^{-2} in; 77 °F = 25 °C)

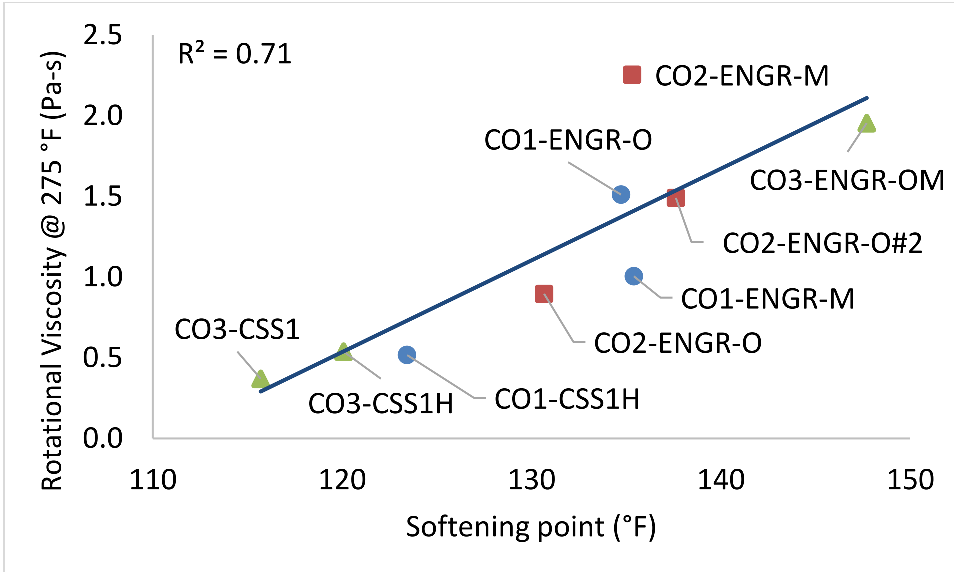


(a)

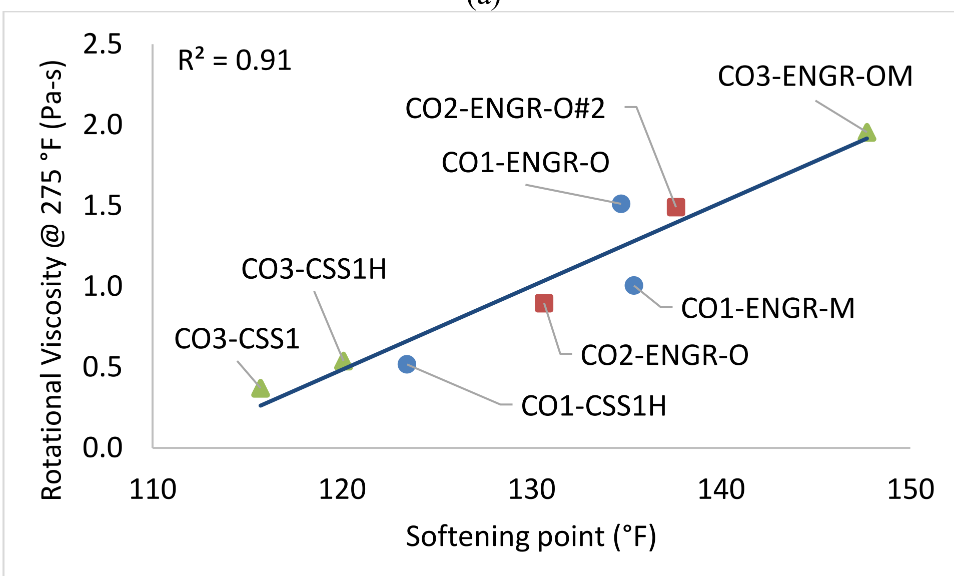


(b)

Figure 3.21: Relationship between rotational viscosity and penetration tests (a) including CO2-ENGR-M (b) excluding CO2-ENGR-M (77 °F = 25 °C)



(a)

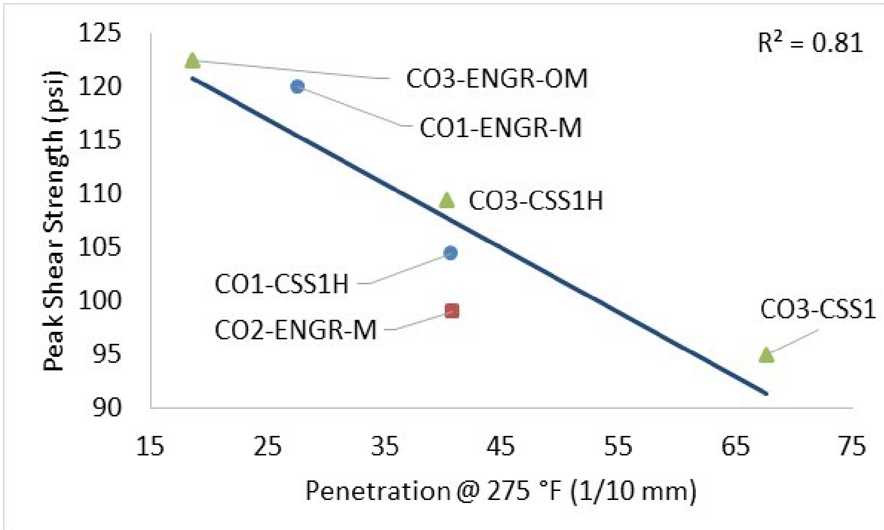


(b)

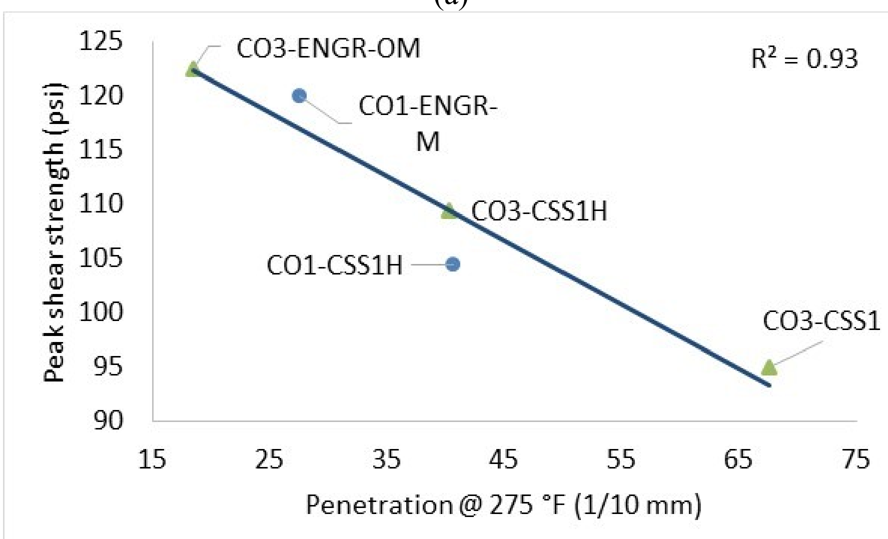
Figure 3.22. Relationship between rotational viscosity and softening point tests (a) including CO2-ENGR-M (b) excluding CO2-ENGR-M (77 °F = 25 °C)

3.7 CORRELATIONS BETWEEN MEASURED INTERLAYER SHEAR STRENGTH AND RHEOLOGICAL TEST RESULTS

In this section, the possibility of using simpler rheological test results to evaluate in-situ tack coat performance was determined. In order to determine the relationship between ISS and the rheological test results, correlation plots were developed. A negative correlation between shear strength and penetration can be observed, with an R^2 value of 0.81 (Figure 3.23a). Similar to the correlation plots in the rheological study discussed above, CO2-ENGR-M stood out from the general trend when comparing ISS with penetration, likely due to the skewed value obtained from the penetration experiment. Without this point, the R^2 value increases to 0.93, suggesting that penetration test results are highly correlated with the tack coat's ISS (Figure 3.23b) and can be used to predict in-situ tack coat performance. Bond energy and penetration were also compared, resulting in similar trends.



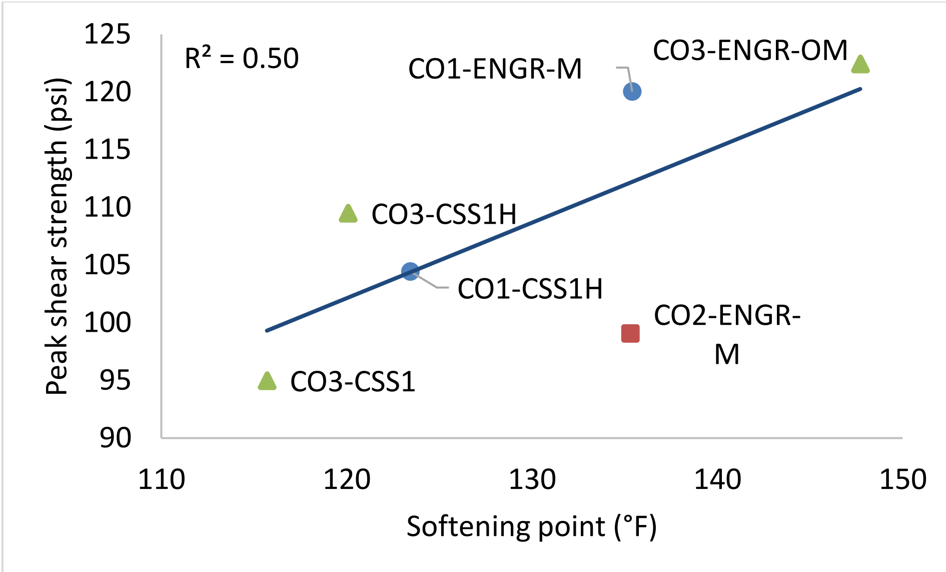
(a)



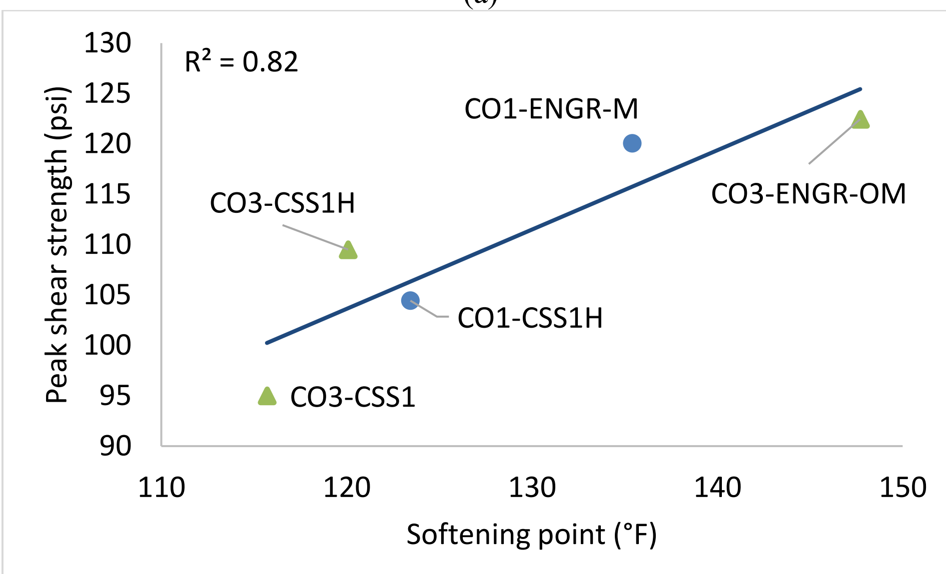
(b)

Figure 3.23. Relationship between ISS and Penetration (a) with CO2-ENGR-M (b) without CO2-ENGR-M (1.0 psi = 6.89 kPa; 77 °F = 25 °C; 1.0 mm = 3.94×10^{-2} in)

A positive correlation is illustrated for the relationship between shear strength and softening point (Figure 3.24). Again, the discrepancy seen with CO2-ENGR-M can be attributed to the inaccurate softening point value obtained, resulting in an R^2 of 0.50. The R^2 increases to 0.82 when this point is excluded, suggesting that softening point is a satisfactory test that can be used to predict the bond performance of tack coats. Correlations between bond energy and SP were also made, and resulted in similar trends.



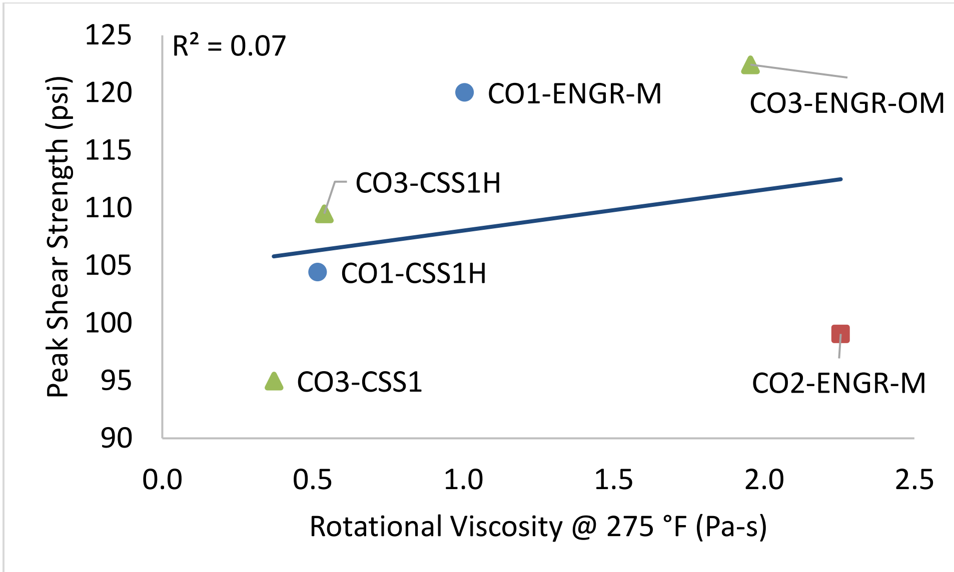
(a)



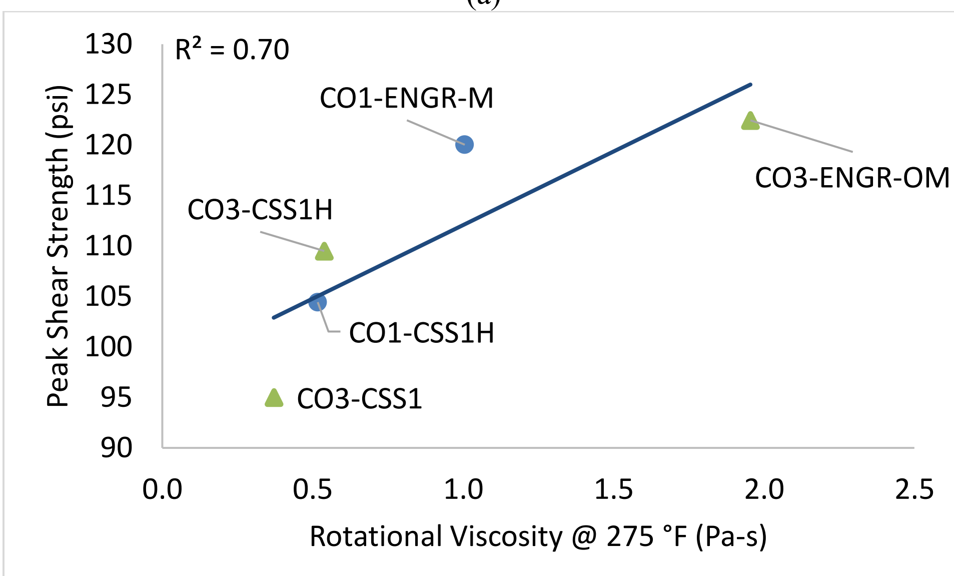
(b)

Figure 3.24. Relationship between ISS and SP (a) with CO2-ENGR-M (b) without CO2-ENGR-M (1.0 psi = 6.89 kPa; 77 °F = 25 °C)

Results plotted for shear strength of the tack coat emulsions and rotational viscosity of the binder tests indicated that CO2-ENGR-M is an outlier, likely due to the skewed results from the rotational viscosity test for this particular binder (Figure 3.25a). When excluded from the plot, it is clear to see that a positive relationship exists between the shear strength of the tack emulsions and that of the rotational viscosity results (Figure 3.25b).



(a)



(b)

Figure 3.25. Relationship between ISS and RV results (a) including CO2-ENGR-M (b) excluding CO2-ENGR-M (1.0 psi = 6.89 kPa; 77 °F = 25 °C)

To further confirm, the relationships depicted in each of the correlation plots discussed above, a correlation table was created using a statistical software, S+ (Table 3.7) (Insightful 2001). This table analyzes the relationships between the ISS and each of the rheological tests for each tack coat type, including DSR. All of the temperatures and frequencies analyzed by DSR were evaluated with this software while Table 3.7 includes only a sample of the most critical values. For most of the temperatures, G* values obtained at 10 Hz were used. At 68 °F (20 °C), the highest value was observed at 1 Hz and is included in the table. In order to directly compare values, the slightly lower value at 10 Hz is also included. Overall, it can be concluded that frequency does not have a significant effect on the correlations between G* and laboratory measured ISS of tack coats. However, results for DSR tests conducted with 10Hz loading frequency are more correlated with laboratory shear test results.

The major factor affecting the relationship between the rheological tests and the tack coat's ISS was temperature. Shear tests were conducted at 77 °F (25 °C). Table 3.7 shows binder tests that were conducted at or near this temperature displayed the highest correlations. Penetration testing was also performed at 77 °F (25 °C), and gave the highest correlation at 89.8%. Similarly, DSR results at 68 °F (20 °C) and 86 °F (30 °C) showed high correlations at 89.9% and 89.6%, respectively. On the other hand, RV displayed a low correlation value to ISS (25.9%), likely due to the high temperature of 275 °F (135 °C) in which this test was conducted. Based on these results, penetration tests can be used as a low cost and more practical alternative to the more complicated ISS experiments of tack coats.

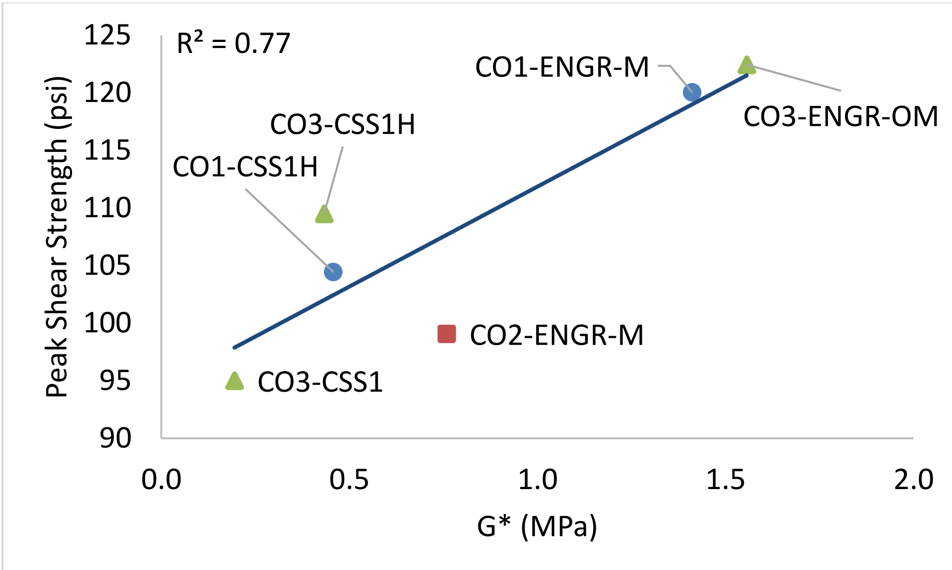
Table 3.7 also indicates the trends and whether DSR results for G* were correlated with the other rheological tests. General trends were similar across each of the frequencies for each test, though most of the frequencies were excluded from the table. At 10 Hz, the correlations between DSR and ISS decreased with increasing temperature, while the correlations between RV and DSR increased with increasing DSR test temperatures. This is expected, as the stiffness and viscosity of binders is temperature dependent and results of different tests conducted at closer temperatures are more correlated. Correlations between SP and G* values generally increased with increasing DSR test temperatures, though there was a slight decrease in the correlation from 140 °F (60 °C) to 158 °F (70 °C). Overall, G* was highly correlated with SP and penetration values across all of the tack coat types.

Table 3.7. Summary of Correlations between ISS and Rheological Tests

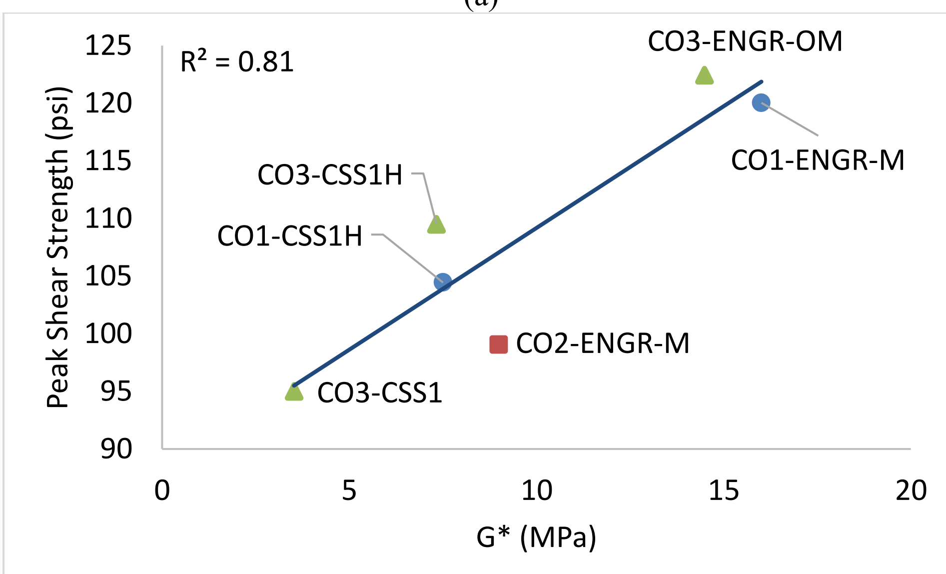
	ISS	Pen[a]	RV	SP	G.T68.F1[b]	G.T68.F10	G.T86.F10	G.T104.F10	G.T122.F10	G.T140.F10	G.T158.F10
ISS	1.000	**-0.898**	0.259	0.705	0.910	**0.899**	**0.896**	0.875	0.840	0.793	0.750
Pen	-0.898	1.000	-0.551	-0.853	-0.888	-0.905	-0.892	-0.882	-0.868	-0.843	-0.817
RV	0.259	-0.551	1.000	0.840	0.525	0.513	0.558	0.614	0.683	0.733	0.761
SP	0.705	-0.853	0.840	1.000	0.879	0.853	0.892	0.927	0.961	0.972	0.970
G.T68.F1	0.910	-0.888	0.525	0.879	1.000	0.989	0.999	0.992	0.963	0.915	0.872
G.T68.F10	0.899	-0.905	0.513	0.853	0.989	1.000	0.992	0.973	0.927	0.867	0.816
G.T86.F10	0.896	-0.892	0.558	0.892	0.999	0.992	1.000	0.994	0.965	0.918	0.876
G.T104.F10	0.875	-0.882	0.614	0.927	0.992	0.973	0.994	1.000	0.987	0.954	0.921
G.T122.F10	0.840	-0.868	0.683	0.961	0.963	0.927	0.965	0.987	1.000	0.990	0.971
G.T140.F10	0.793	-0.843	0.733	0.972	0.915	0.867	0.918	0.954	0.990	1.000	0.995
G.T158.F10	0.750	-0.817	0.761	0.970	0.872	0.816	0.876	0.921	0.971	0.995	1.000

[a]Abbreviation used for Penetration
[b]Notation for DSR results as follows: G = G*; T# = Temperature at which test was conducted; F# = Frequency at which test was conducted

A visual representation of the correlation between ISS and G* is illustrated in Figure 3.26. As mentioned above, the correlation between ISS and G* is stronger at temperatures closest to the laboratory shear testing temperature of 77 °F (25 °C). This is depicted by the R^2 values of 0.77 and 0.81 for 104 °F (40 °C) and 68 °F (20 °C), respectively.



(a)



(b)

Figure 3.26. Relationship between interlayer shear strength and complex shear modulus at 10 Hz for (a) 104 °F (40 °C) (b) 68 °F (20 °C) (1.0 psi = 6.89 kPa)

3.8 SUMMARY AND CONCLUSIONS

In Oregon, CSS-1H tack coats are the most commonly used tack coats for construction. This particular tack coat is a slow-setting grade of tack coat emulsion. Improvements to tack coats are continuously sought in order to strengthen the bond between each of the layers, as well as reduce tracking. New engineered tack coats have been developed in Oregon according to their intended use in overlays and milled surfaces in hopes of obtaining better performance in the field. These new tack coats are designed to be stiffer than the typical CSS-1H tack coats and better withstand the shear stresses that the interface between each of the layers experience. This part of the study aims to quantify the impact of new engineered tack coats specifically designed for milled surfaces on tack coat bond quality. This was done by comparing the interlayer shear strength (ISS), a parameter correlated with a tack coat's ability to bond an existing and new pavement layer, and interlayer bond energy (IBE), a parameter that accounts for the shear resistance of tack coat interlayer bonds and the associated displacement endured before bond failure, of new tack coats to tack coats conventionally used in Oregon. Laboratory shear testing was conducted on laboratory-produced core samples to obtain the ISS and IBE response for each tack coat type. The ISS and IBE results for engineered tack coats were then compared with that of tack coats typically used in Oregon to identify the benefits of using the engineered tack coats. Comparisons were also made between ISS of laboratory-produced samples to that of field-cored samples to determine if the novel sample preparation methodology developed in this study (using a hydraulic laboratory roller compactor and laboratory milling procedures) was simulating field conditions.

Rheological tests were also conducted on asphalt binders distilled from tack coats produced for both milled and overlay surfaces provided by three different companies. A total of four rheological test methods were performed, including penetration, softening point (SP), rotational viscosity (RV), and dynamic shear rheometer (DSR). Correlations between each of the rheological tests were evaluated to determine the relationships between each asphalt binder test method. As part of this study, newly engineered emulsions from each of the companies were evaluated for their performance, at the binder level, as well with the ISS parameter obtained by testing laboratory-compacted samples. The measured ISS values representing in-situ bond strength were also compared to the tack coat binder rheological test results in order to determine correlations between each of the tests. Based on these results, effectiveness of all rheological tests that could potentially be used to predict the in-situ tack coat performance was identified.

Conclusions based on the experimental and analytical findings are as follows:

Tack Coat Core Tests:

1. Engineered tack coats were found to have superior performance over tack coats traditionally used in Oregon. Engineered tack coats provided by Company 1 and Company 3 exhibited the highest ISS and IBE.

2. The engineered tack coats for Company 1 and Company 3 had ISS values higher than all other tack coats tested, with Company 3 having a slightly higher ISS than Company 1. However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.600 from a two-sample t-test at a 95% significance level.

3. When comparing Company 1's CSS-1H tack coat to that of Company 3 based on laboratory shear test results, Company 3's tack coat had slightly better performance.

However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.297 from a two-sample t-test at a 95% confidence level.

4. The engineered tack coats provided by Company 2 did not achieve the performance of the engineered or CSS-1H tack coats provided by the other two companies. This result is attributed to the high water content of the Company 2 engineered tack coat and the possible need to increase the residual application rates. Additional research is required to determine the optimum application rates for Company 2's engineered tack coat.

5. CO2-ENGR-M1/2 were found to have no significant difference in ISS and IBE when compared to CO3-CSS1, indicating that these engineered tack coats did not exhibit better performance than traditional tack coats.

6. Conclusions 1 to 5 stated above also hold when the interlayer bond energy was used as the performance parameter rather than the ISS.

7. The engineered tack coat provided by Company 1 had significantly superior peak shear strength when compared to their CSS-1H tack coat.

8. Company 3's engineered tack coat was found to have significantly better performance as compared to their CSS-1 and CSS-1H tack coats.

9. There was no significant correlation between peak shear strength and MTD, as is suggested by the low correlation coefficient. This indicates that MTD is not controlling bond strength and that laboratory milling practices did not create any bias in the results.

10. The peak shear strengths of the laboratory-produced samples were not dissimilar to that of the field-cored samples. The laboratory-produced samples had shear strengths that were well within the domain of shear strengths yielded from the field-cored samples. This indicates that the sample procurement procedures of this study (using a laboratory roller compactor and laboratory milling procedures) produce shear strength results that are similar to what is observed under field conditions.

Tack Coat Binder Tests:

1. The engineered binders displayed the highest softening point and RV values, while the CSS-1H binders gave the lowest. This suggests that these tack coat binders are softer than the newly engineered binders.

2. A discrepancy in the results for the softening point test can be seen in the values displayed for the CO2-ENGR-M distilled emulsion. This particular binder did not have a smooth consistency when poured, as was typical with the other binders, presumably due to the binder being polymer-modified and not able to withstand the

sample preparation temperatures. As a result, the binder was not evenly distributed throughout the test rings.

3. Company 3 displays consistent results between RV and SP. On the other hand, Company 2 had slightly skewed results between RV and SP tests. CO2-ENGR-M displayed very high RV values as well as high variability within these results. The test was conducted at 275 °F (135 °C), a temperature that may have been too high for this particular binder to withstand. Therefore, the viscosity may be higher than expected and shows a large deviation due to the lack of fluidity and consistency that the binder may have maintained at elevated temperatures.

4. Results for Company 3 binders are consistent across all binder tests. CO1-ENGR-M shows a relatively lower penetration than most other tack coat binders, signifying a stiff binder, which is consistent with the RV results.

5. The major factor affecting the relationship between the rheological tests and the tack coat's ISS was temperature. Shear tests were conducted at 77 °F (25 °C). Binder tests that were conducted at or near this temperature displayed the highest correlations. Penetration testing was also performed at 77 °F (25 °C), and gave the highest correlation at 89.8%. Similarly, DSR results at 68 °F (20 °C) and 86 °F (30 °C) showed high correlations at 89.9% and 89.6%, respectively. On the other hand, RV displayed a low correlation value to ISS (25.9%), likely due to the high temperature of 275 °F (135 °C) in which this test was conducted. Based on these results, penetration tests can be used as a low cost and more practical alternative to the more complicated ISS experiments of tack coats.

4.0 THE IMPACT OF EMULSION TYPE, APPLICATION RATE AND ADVERSE CONDITIONS ON TACK COAT BOND PERFORMANCE

4.1 INTRODUCTION

Tack coats, or asphalt emulsions, serve as a glue between asphalt pavement layers which bonds the layers together into a monolithic structure (FHWA 2016). This helps to facilitate the uniform distribution of stresses and strains from heavy truck wheel loads through the entire pavement structure. Failure to facilitate proper bonding between asphalt pavement layers can cause localization of stresses and strains at the layer nearest to the surface, which can create premature fatigue cracking and ultimately cause early pavement failure (Al-Qadi et al. 2012). In Oregon, CSS-1H tack coats are the most commonly used tack coat materials in asphalt pavement construction. This particular tack coat is a slow-setting grade of tack coat emulsion. Improvements to tack coats are continuously sought in order to strengthen the bond between each of the layers, as well as reduce the pick-up of bituminous material by construction vehicle tires, which is commonly known as "tracking". New engineered tack coats have been developed in Oregon according to their intended use on overlay and milled surfaces in hopes of obtaining better performance in the field and reduced tracking. These new tack coats are designed to be stiffer than commonly used CSS-1H tack coats and better withstand the shear stresses and strains experienced by the interface between each of the pavement layers.

In current construction practices, engineered tack coats are not widely used. Their development is still in its infancy and they have not been adopted by many contractors or agencies, presumably due to their escalated cost, which can be up to 1.4 times as much as widely-used conventional tack coats such as CSS-1H. Although this additional expenditure may be cost-prohibitive in some cases, it is suggested by tack coat manufacturers that new engineered tack coats will perform better and improve the longevity of asphalt pavements. FHWA (2016) suggested that tack coat comprises about 1-2% of the total project cost for mill and overlay projects and only 0.1-0.2% of total cost for new construction or reconstruction projects. This cost is negligible in comparison to the costs associated with replacing a poorly bonded pavement layer, which can range from 30-100% of the total initial project cost. This replacement cost is exacerbated by the costs incurred by road users as a result of delays from additional construction activities and lane closures. For these reasons, the costs of a repair due to poor tack coat bonding can easily match or surpass the initial cost of the project. With cognizance of this fact, it is worth investigating the prospect of using engineered tack coats if they can increase the reliability and longevity of asphalt pavements, in which case the additional expenditure would be justified.

In recent research, there has been a significant disconnect in the relation of laboratory sample preparation processes to real-world construction practices. Some research has attempted to replicate field conditions in laboratory tack coat testing but has been unable to achieve results comparable to field performance. A disparity is present in the shear strength of laboratory-produced samples versus field-extracted core samples in previous studies (Mohammad et al.

2012; Mohammad et al. 2010). In these studies, the Superpave Gyratory Compactor (SGC) was used to procure samples for laboratory tests, which differs significantly from roller-compacted pavements in the field in terms of the compaction mechanism. In general, the laboratory-prepared samples overestimated the shear strength of the tack coat bond at the layer interface by a factor ranging from 2 to 10 for a given application rate. This is due to the difference in compaction methods and tack coat application methods between laboratory-prepared samples and field-cored samples.

In light of these sample preparation issues noted by the literature, this study employs a sample preparation method which uses a hydraulic laboratory roller compactor to procure two-layer pavement block samples. The block samples were cored after compaction to obtain cylindrical samples for interlayer shear testing. In this way, the nuances of roller compaction and coring in the field were better encompassed in the resulting samples, providing a more realistic sample preparation procedure that is better correlated with field tack coat performance than previous methodologies from other research.

A variety of laboratory tests exist to quantify the quality of the interlayer bond. Direct shear testing (DST) is a common method of measuring bond strength between pavement layers in a laboratory setting and has been utilized by many researchers. Monotonic DST refers to measurement of peak shear strength and energy of the interlayer bond using a load applied at a constant displacement rate (Amelian and Kim 2017). This test yields several useful parameters that aid in characterizing the tack coat bond. Cyclic DST is a novel method of bond strength measurement and is more representative of loading experienced by the interlayer in the field.

In this study, several types of tack coats which are used in Oregon are evaluated in a laboratory setting under a diverse set of conditions. New engineered tack coats are paired against tack coats that are conventionally used in Oregon in order to identify the benefits of engineered tack coats in light of variables such as pavement surface type (overlay versus milled), application rate and adverse construction conditions such as presence of dust on the pavement surface, nonuniform coverage/streaking and rainfall. A robust experimental factorial encompasses these variables. This study prescribes monotonic DST as a means for evaluating the performance of each tack coat under each of these conditions.

Two response parameters were yielded from monotonic DST and were used to quantify the bond quality of each tack coat. Interlayer Shear Strength (ISS) and Interlayer Bond Energy (IBE), both of which are highly correlated with tack coat bond quality, were the parameters chosen to evaluate the tack coats tested in this study (Coleri et al. 2017; Amelian and Kim 2017). Each tack coat was assessed according to their performance as measured by ISS and IBE, and comparisons were drawn between each tack coat in order to identify the tack coats that provided the best bond quality under each set of conditions.

From the load-displacement curves obtained for each laboratory shear test, IBE was extracted to characterize the tack coat bond performance. IBE is calculated as the area under the load-displacement curve up to the peak load. IBE takes into account the peak strength of the tack coat bond, as well as the associated displacement endured before bond failure. This parameter has been shown to be highly correlated ($R^2 = 0.8$) with fatigue failure criteria for tack coat interlayer bonds and is highly indicative of the fatigue-related shear resistance of tack coats (Amelian and Kim 2017). Figure 4.1 shows a graphical representation of interlayer bond energy.

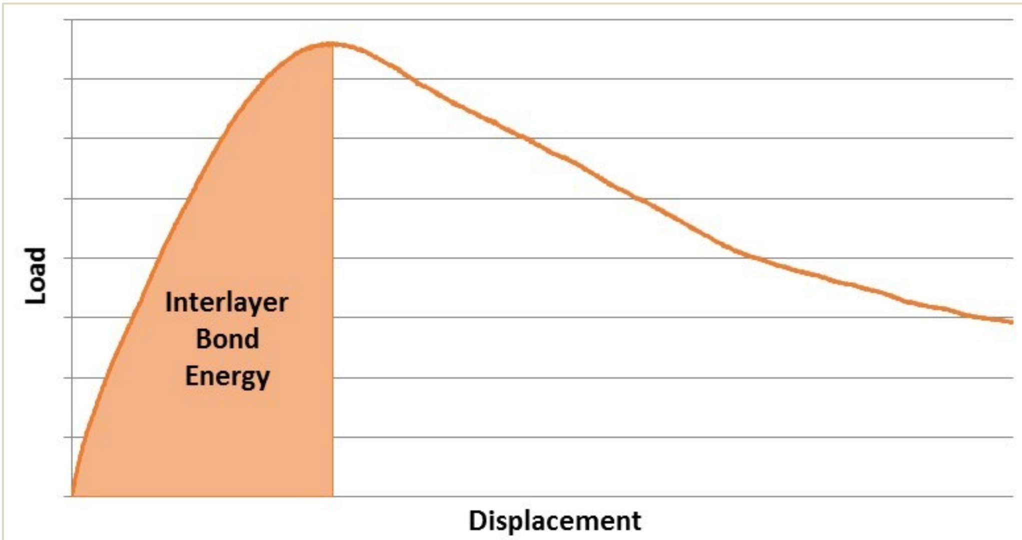


Figure 4.1: Graphical representation of interlayer bond energy

An auxiliary component of this study was to examine the performance of tack coats used in Oregon, both conventional and engineered, under special scenarios that emulate real-world construction conditions. In Oregon, there are three prevalent construction issues that plague tack coat performance and pavement longevity, which are termed in this study as adverse construction conditions.

Firstly, the presence of dust on milled surfaces during construction is a significant problem that directly impacts the quality of highway pavements in Oregon. Milling/grinding of existing pavements, where existing aged or fatigued pavement is removed from the pavement structure, is often performed as a precursor to overlay or inlay ("mill and fill") projects in Oregon. This process creates large amounts of dust and particulate matter resulting from the crushing of aggregates by the diamond cutting heads of milling machines. A considerable amount of dust is left behind on the pavement surface after milling, which is then removed using sweeper trucks after milling occurs (FHWA 2016). However, the sweepers often do not remove all dust particles. Retained dust particles effectively act as a contaminant on the pavement surface, as tack coats applied to a dusty surface will readily stick to high surface area dust particles instead of the underlying pavement, which reduces the tack coat's ability to bond the new and existing pavement layers (FHWA 2016).

Two principal methods of removing dust from the pavement surface currently exist. As it stands, contractors typically clean the pavement surface using one of two methods: sweeping/vacuuming and air blasting (Al-Qadi et al. 2012). Figure 4.2 shows these two methods being employed in the field during paving operations.

(a) (b)

Figure 4.2. Common field cleaning methods: (a) Sweeping and vacuuming and (b) air blasting (Al-Qadi et al. 2012).

Air blast cleaning was suggested by Salinas et al. (2013) as an effective measure for removing dust from the pavement surface prior to construction. This suggestion was based on results from a field study that compared the pavement surface cleanliness of sweeping and air blasting against the effect on tack coat bond strength and required application rate. However, although this study suggests that air blasting can improve bond performance at lower residual application rates (below 0.04 gal/yd^2 for a SS-1H tack coat), it is also time-consuming and can cause health and safety hazards in urban environments due to dust particulate clouds. Air blasting also resulted in inferior bond performance when compared to sweeping at higher application rates.

The effect of surface cleanliness on bond performance was evaluated by Mohammad et al. (2012). The authors used uniformly graded sand to simulate dust on the pavement surface and found that ISS was enhanced by the presence of dust. This result was attributed to the effect of dust combining with residual asphalt and creating a mastic with a viscosity exceeding that of the residual asphalt alone, which provided greater shear resistance. This, combined with grittiness of sand particles providing extra frictional resistance, yielded a higher ISS. However, due to the use of a uniformly graded sand to simulate dust effects, actual field conditions may not be represented by these results. In any case, the authors suggested that cleaning and sweeping of the pavement surface prior to construction is worthwhile to avoid any problems related to the presence of dust.

Additionally, the effect of dust on the pavement surface can contribute to increased tracking of tack coats during construction, whereby tack coat sticks to construction vehicle tires and is removed from the underlying pavement surface to which it is applied. This phenomenon effectively reduces the amount of tack coat on the pavement surface that is available for interlayer bonding. Tracking is exacerbated by dust particles on the pavement surface, since vehicle tires will pick up tack coats stuck to dust particles much more readily than if the tack coat was properly adhered to the underlying pavement surface (Mohammad et al. 2012). The tracked debris accumulates and falls off construction vehicle tires, creating inconsistencies and additional debris on the milled pavement surface prior to paving. Since the issue of dust is highly prevalent in Oregon, this study evaluates the impact of dust on interlayer bond quality. Figure 4.3 shows an example of tracking by a paver during construction due to excess dust on the pavement surface.

Figure 4.3: Tracking on paver wheels due to excess dust (Mohammad et al. 2012).

Another issue that is common during asphalt pavement construction in Oregon is nonuniform tack coat coverage, which is often termed as “streaking”. Streaking occurs when the applicator nozzles on tack coat distributor trucks become clogged, which can be due to poor maintenance practices or highly viscous tack coat materials. When clogging of an applicator nozzle occurs, it can affect the spray distribution of the nozzle. Instead of a uniform fan-shaped distribution, the distribution becomes a singular stream of tack coat which does not cover the entire pavement surface area. In this way, there is less tack coat on the pavement surface area that can aid in bonding the new and existing pavement layers. Additionally, streaking directly impacts the lap coverage of the tack coat, which is a key construction specification in Oregon (ODOT 2015). Mohammad et al. (2012) suggested that the main factors influencing coverage uniformity are nozzle clogging, nozzle orientation/size and speed of the distributor truck during application.

Properties of tack coat materials can also impact coverage. Mohammad et al. (2012) suggested that diluted tack coat emulsions (tack coats with added water) are beneficial when uniform application at ambient temperatures is desired, since the diluted emulsions are sprayed more easily and are less apt to clog spray nozzles on tack coat distributor trucks. Mohammad et al. (2012) also conducted an industry survey inquiring about agencies’ practices relating to verifying application coverage. Only 64% of respondents were able to confirm that application coverage is at least 90% of the pavement surface area.

Tack coat, despite its immense importance for the pavement lifespan, currently has minimal provisions for construction specifications in comparison to Hot Mix Asphalt (HMA). The lack of specifications causes contractors to overlook the relevance of tack coat placement variables, such as application rate and application uniformity. In Oregon, the section on tack coat specifications in the Oregon Department of Transportation (ODOT) Standard Specifications for Construction omits many important considerations for quality tack coat application (ODOT 2015). For this reason, contractors often view tack coat application as auxiliary to HMA paving operations. The current specifications also lack practicality since many of the tack coat distributor trucks do not utilize equipment that allows for accurate control of the application rate and spray distribution. Contractors have been known to use multiple different tack coat distributor trucks on a single project, inherently causing variability in tack coat application throughout different areas of the project (Coleri et al. 2017), as the equipment outfitted on each truck do not all necessarily have equivalent performance. Covey et al. (2017) showed in a field study in Oregon that the distributor truck used by the contractor did not apply the tack coat uniformly and was unable to achieve the target application rate. This resulted in lower bond strengths for that particular pavement section when compared to a different section where a newer distributor truck provided by the tack coat manufacturer was used and appropriate coverage and application rate were achieved. Even if distributor trucks are outfitted with state-of-the-art control equipment, operators of this equipment can be unfamiliar with proper equipment operation, as there is no formal training for tack coat distributor operators. This causes excess variability in tack coat application, which hinges on what distributor truck is used during construction and who is operating the truck. These factors lend themselves to poor control over tack coat application rate and coverage distribution. The lack of control over these factors can lead to a pavement structure that does not perform as designed.

A lack of adequate tack coat coverage can have direct implications on the quality of the tack coat bond. Mohammad and Button (2005) note that the maximum bond strength between layers occurred when 90-95% coverage was achieved at the optimum application rate. Coverage is an important consideration for quality assurance (QA) since it is the most visually apparent factor for monitoring tack coat quality during construction. Visual acceptance of coverage is the primary means for tack coat quality assurance during construction in Oregon. Coverage that is nonuniform can give rise to high variability in interlayer bonding characteristics. According to FHWA (2016), it is important that application of tack coat materials is uniform in all directions (transverse and longitudinal). In light of the ramifications of nonuniform tack coat coverage/streaking, it was of specific interest in this study to evaluate this phenomenon in the laboratory. Figure 4.4 shows acceptable and unacceptable uniformity in tack coat application.

(a) (b)

Figure 4.4: Tack coat application uniformity: (a) Acceptable tack coat application uniformity, and (b) unacceptable tack coat application uniformity (streaking) (FHWA 2016).

Finally, the effect of rainfall on tack coat bond quality was investigated in this study. This is an issue during highway construction in Oregon during the spring and fall months when rainfall is common. Water on the pavement surface during construction can be caused by rainy weather or tack coats that have not had sufficient time to set. Excess moisture on the pavement surface after tack coat application can complicate paving operations temporally by impacting the break and set times of applied tack coat emulsions. More importantly, the applied tack coat can be washed away from the pavement surface by a rainfall event due to the flow of runoff on the roadway profile slope, effectively removing tack coat that would otherwise be available to facilitate interlayer bonding. Some research suggests that if moisture remains on the existing pavement surface as paving occurs that bond quality could be reduced (Wang et al. 2017; Sholar et al. 2004). Other research suggests that moisture on the pavement surface does not impact bond quality, as excess moisture is readily evaporated during HMA placement (Mohammad et al. 2012). However, the question of a significant rainfall event's impact on tack coat bond quality is largely unanswered. In this study, a rainfall event occurring after tack coat application was replicated in the laboratory on a milled surface texture and the resulting bond quality was quantified and compared to results with no rainfall.

This study evaluates tack coat performance in light of these variables described above (coverage/streaking, presence of dust, rainfall/moisture during construction) on a milled surface texture. The purpose of this study is to identify how the bond quality of different tack coats (engineered and conventional) vary when subjected to these real-world scenarios at different application rates using laboratory monotonic direct shear testing (DST). The tack coat bond quality is evaluated in terms of Interlayer Shear Strength (ISS) and Interlayer Bond Energy (IBE), which are two response parameters that are highly correlated with tack coat bond quality (Coleri et al. 2017; Amelian and Kim 2017). The performance of each tack coat under each of these conditions is then compared to a reference condition.

4.1.1 Objectives

The major outcomes of this study are as follows:

- Identify performance benefits of using engineered tack coats over tack coats conventionally used in Oregon under a variety of conditions,
- Determine which tack coats exhibit the best performance,
- Identify how tack coat bond quality varies with application rate and pavement surface type,
- Utilize a laboratory sample preparation methodology that closely replicates field performance of tack coats to achieve realistic results that are comparable to in-service pavements,
- Identify how tack coat bond quality varies on a milled surface under the following real-world adverse conditions,
    - Nonuniform coverage/streaking
    - Presence of dust on pavement surface
    - Rainfall during construction

- Quantify the influence of application rate on bond quality under each of these conditions,
- Identify tack coats with the most optimal performance under each of these conditions, and
- Provide perspective on how these common construction issues will affect the longevity of asphalt pavements in Oregon.

4.2 MATERIALS AND METHODS

4.2.1 Experimental design

In this study, it was intended to highlight the performance benefits of new engineered tack coats as compared to conventional tack coats used in Oregon by evaluating them on both milled and overlay surfaces at different application rates. Tack coats sampled from three different companies were compared. In this way, a broadly encompassing view of engineered tack coat performance under different conditions was gained.

In order to evaluate the performance of each tack coat, a comprehensive experimental factorial was designed, which took into account different tack coat types from three different companies, two application rates and two pavement surface textures (overlay and milled surface textures). Table 4.1 shows the experimental design for this study. Under tack coat type, "O" designates tack coats designed specifically for overlay surfaces and "M" designates tack coats designed for milled surfaces.

Table 4.1: Experimental Design for Tack Coat Type & Application Rate Tests.

Company	Tack Coat Types	Application Rate (gal/yd^2)	Surface Type	Replicates	# of Tests
CO1	CSS1H ENGR-O ENGR-M	Overlay: 0.05 (Low) & 0.09 (High) Milled: 0.09 (Low) & 0.15 (High)	Overlay, Milled	4	48
CO2	ENGR-O1 ENGR-O2 ENGR-M1		Overlay, Milled	4	48
CO3	CSS1H CSS1 ENGR-OM		Overlay, Milled	4	48

A general naming system was set to conceal the identity of the companies (labeled "CO#"). CSS-1H tack coats were named as-is, as they are commonly used in Oregon. New tack coats engineered to improve bond quality and reduce tracking were termed "ENGR". This study uses a notation of "-M" to denote tack coats intended for milled surfaces, "-O" to denote those designed for overlay surfaces and "-OM" to denote tack coats for both milled and overlay surfaces.

The application rates used in this study were chosen based on experiences from Coleri et al. (2017) and based on construction specifications in Oregon (ODOT 2015). Rates for milled surfaces were higher than overlay surfaces, since the increased surface area of a milled surface texture necessitates a greater amount of tack coat to achieve proper bonding (FHWA 2016). For overlay surfaces, the low rate was 0.05 gal/yd^2 and the high rate was 0.09 gal/yd^2. For milled surfaces, the low rate was 0.09 gal/yd^2 and the high rate was 0.15 gal/yd^2. Application rates used in this study were for undiluted and uncured tack coats and do not represent residual application rates.

It should be noted that not all companies provided the same tack coats for laboratory shear testing. Company 1 and Company 2 provided engineered tack coats that were specific to milled surfaces. Company 1 also provided an engineered tack coat that was designated for use on overlay surfaces. Company 3 provided an engineered tack coat designed for use on both overlay and milled surfaces. Additionally, Company 3 requested that the residual rates of Company 1 be matched. The residual rate for Company 1's CSS-1H tack coat was used for Company 3's CSS-1 tack coat. Residual rates for Company 1 tack coats were back-calculated using the water content of the emulsion and Equation 4-1, shown below. Average water contents and densities of the tack coat emulsions were measured in this study and are shown in Table 4.2.

$$\text{Residual Rate} = \text{Application Rate} * (1 - \text{Water Content}) \tag{4-1}$$

Table 4.2: Summary of Tack Coat Emulsion Water Contents and Densities

Tack Coat Type	Initial Mass (g)[a]	Water Distilled (g)	Water Content (%)	Density (g/mL)
CO1-CSS1H	93.0	36.0	38.7	0.991
CO1-ENGR-O	92.7	31.0	33.4	-
CO1-ENGR-M	95.7	39.3	41.1	0.920
CO2-ENGR-O	94.0	36.1	38.4	-
CO2-ENGR-O#2	94.6	38.2	40.4	-
CO2-ENGR-M1	94.3	83.5	88.5	1.007
CO2-ENGR-M2	93.8	64.5	68.8	1.023
CO3-CSS1	92.5	33.9	36.7	0.971
CO3-CSS1H	92.0	34.7	37.7	1.000
CO3-ENGR-OM	91.5	30.8	33.7	0.956

[a] 1.0 g = 2.20x10^{-3} lbs

To examine the impact of adverse conditions (dust, streaking/reduced coverage, rainfall/moisture), a separate experimental factorial was developed. Results from the experimental factorial proposed in Table 4.1 were used as reference (control) cases for testing each of these adverse conditions. Table 4.3 below shows the experimental plan for evaluating the adverse construction conditions cases outlined previously.

Table 4.3: Experimental Design for Adverse Conditions Evaluation.

Test Type	Tack Type	Company	Application Rate	Surface Type	Dust Level	Coverage Level	Rainfall	Replicates	Total Tests
Coverage/Streaking	CSS1H, ENGR	CO1	[1]Low, High	Milled	None	100%, 50%	None	4	32
Dust	CSS1H, ENGR	CO1	Low, High	Milled	None, 15g Dust	100%	None	4	32
Rainfall	CSS1H, ENGR	CO1	Low, High	Milled	None	100%	None, 2hr	4	32

Note: [1] Low rate: 0.09 gal/yd^2; High rate: 0.15 gal/yd^2

For this portion of the study, tack coats from Company 1 were chosen to evaluate each of the cases described above. Both conventional and engineered tack coats were used to evaluate the effect of nonuniform coverage/streaking, presence of dust and rainfall to identify any advantages that engineered tack coats had over conventional tack coats in the adverse conditions of interest. Low/high application rates for adverse conditions tests were the same as those used in Table 4.1. Sample preparation methodology for adverse construction conditions cases is shown in Chapter 4.2.3.

In order to replicate field conditions, this study employed a hydraulic laboratory roller compactor to create two-layer (two-lift) pavement structures in the laboratory. In this way, nuances of roller compaction in the field could be better represented in the resulting cylindrical core samples than is possible using a Superpave Gyratory Compactor (SGC). A research study by Mohammad et al. (2012) revealed that the bond strength of two layered asphalt specimens prepared with SGC can be artificially amplified by 2 to 10 times when compared to field-extracted cores. In this study, asphalt samples for shear testing prepared by a laboratory roller compactor was determined to provide interlayer shear strength (ISS) results that are better correlated with field core samples as compared to SGC-prepared samples. Furthermore, the equipment cost for the roller compactor was slightly lower than the SGC, offering another reason why the roller compactor was a more practical choice for sample preparation.

This study focused on monotonic direct shear testing (DST) for evaluation of new engineered tack coats against tack coats conventionally used in Oregon. Milling of laboratory-produced samples was performed in order to closely replicate the actual texture of milled surfaces in the field. Milling texture was quantified using the Sand Patch Test (ASTM 2015a).

4.2.2 Laboratory shear test sample preparation

Each step of the general sample preparation process is described in detail in Section 3.4.1.

4.2.3 Sample preparation for adverse conditions cases

This section outlines the special steps taken during the sample preparation stage for each of the adverse conditions cases evaluated in this study. First/second lift compaction and coring processes remained the same for these samples as they were described in Section 3.4.1.

4.2.3.1 Dust sample preparation

Dust is a problematic byproduct of milling during pavement construction and is therefore of specific interest in this study. In order to realistically simulate a dusty pavement surface, dust was collected and reserved from laboratory milling operations in order to capture a dust type that was representative of what is seen under field conditions. The reserved dust was sieved and the portion passing the #200 sieve was used for dust simulation. A 15g quantity of dust was chosen to apply to the milled pavement surface samples. The choice to use 15g of dust was borne out of trial and error and visual comparison to field conditions. Dust was spread around the pavement surface uniformly using a dry paint brush. Figure 4.5 shows dust being applied to milled surface samples.

Tack coats were then applied atop of the dust using the same procedures outlined in Section 3.4.1.

Figure 4.5: Dust being applied to pavement surface.

4.2.3.2 Streaking sample preparation

Streaking reduces the effective pavement surface area that is coated with tack coat, thereby reducing the propensity for proper interlayer bonding from tack coat. In this study, streaking was simulated in the laboratory during tack coat application. A condiment bottle was used to apply tack coat in streak-like patterns to mimic clogged tack coat applicator nozzles in the field. Figure 4.6 below shows tack coat application using the condiment bottle for streaking samples. For streaking samples, the amount of tack coat applied was the same as was used for samples with standard tack coat application (full coverage). Since a clogged nozzle should not impact the volumetric flow rate of the tack coat, it was assumed that the amount of tack coat applied to the surface would be the same under streaking conditions.

Figure 4.6: Application of tack coat using condiment bottle for coverage/streaking samples.

4.2.3.3 Rainfall/Moisture sample preparation

Because rainfall is prevalent at the beginning and end of the construction season in Oregon, it was of interest in this study to identify how rainfall on the pavement surface after tack coat application would impact tack coat bond quality of the finished pavement. To investigate this effect, first lift samples were placed in a rainfall simulator five minutes after tack coat was applied to the pavement surface. Rainfall simulation was allowed to run for 2hrs prior to compaction at a rainfall intensity similar to what is observed in the Portland, Oregon climate (0.48 in/hr). A 2hr rainfall duration was selected in order to replicate a rainfall event duration that would commonly be observed in this region late in the construction season during the fall months. The rainfall intensity in the simulator was measured and adjusted to match the intensity of a 25-year precipitation event in Portland, OR for the selected rainfall duration by adjusting the pump system of the rainfall simulator (ODOT 2014). The 25-year rainfall intensity was selected to simulate an extreme rainfall event in order to highlight the impact of rainfall on tack coat bond quality in a severe circumstance. Also, the rainfall simulator platform was oriented at a 2% slope to simulate a common roadway profile slope which would facilitate the action of rainfall runoff. After rainfall ensued, the sample was removed from the rainfall simulator and compaction took place immediately. Figure 4.7 shows first lift samples being conditioned in the rainfall simulator after tack coat application.

Figure 4.7: First lift samples in the rainfall simulator.

4.2.4 Laboratory shear testing

Before testing, the diameter of each sample was measured and recorded for the purpose of calculating interlayer shear strength (ISS). The location of the interlayer was then marked on each sample using a permanent marker. Samples were then conditioned at 25 °C (77 °F) for 24 hours in an environmental chamber. On the day of testing, each sample was loaded into the testing jig with the direction of traffic positioned downward and the wearing course positioned on the shearing side (ALDOT 2008). Figure 4.8 shows the sample loading configuration for shear testing.

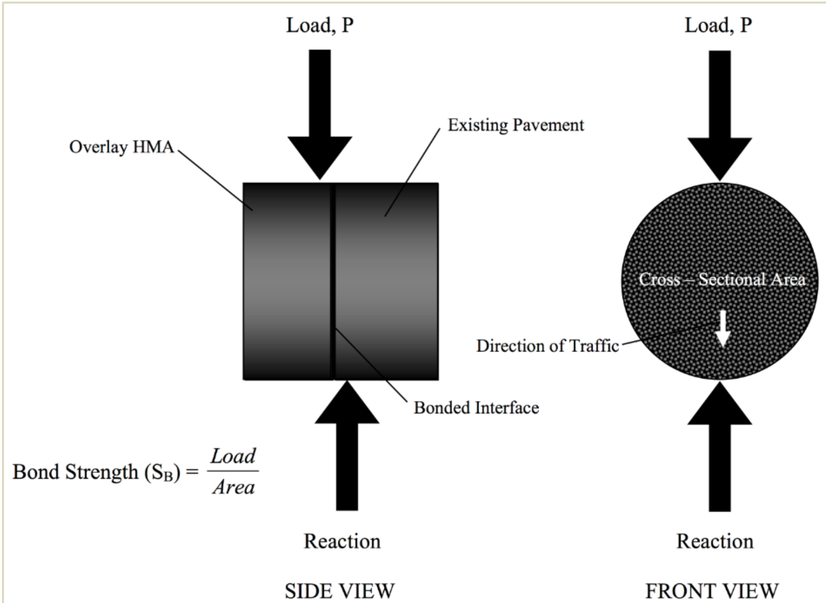


Figure 4.8: Sample loading configuration for shear testing (ALDOT 2008).

Confining pressure was applied to the sample using the spring actuator and calibrated dial on the testing jig. The sample was then placed back in the environmental chamber for one hour prior to testing to allow the sample's temperature to re-equilibrate to 25 °C (77 °F). Figure 3.1h shows the shear test jig used for testing.

Shear tests were then performed using a Universal Testing Machine (UTM) at a strain-controlled constant displacement rate of 2.54 mm/min (0.1 in/min) according to AASHTO TP 114 (AASHTO 2016). The peak load, as well as the load-displacement curve, were captured and recorded for each sample. Tests were terminated before the loading plate made contact with the bottom of the jig to avoid damaging the jig or the UTM. Following completion of the test, the sheared sample was removed and another sample was loaded, following the same procedures described above. Figure 3.1i shows shear testing taking place in the UTM environmental chamber.

4.3 RESULTS

Results from each company's tack coats were collected and grouped individually. Load-displacement results for each sample were filtered for noise in the data using a Matlab code that used a loess smoothing function with a smoothing coefficient of 0.08. The smoothed data was used to extract interlayer shear strength (ISS) and also calculate interlayer bond energy (IBE) using the developed code. The ISS and IBE results from four replicate samples for each tack coat type were averaged.

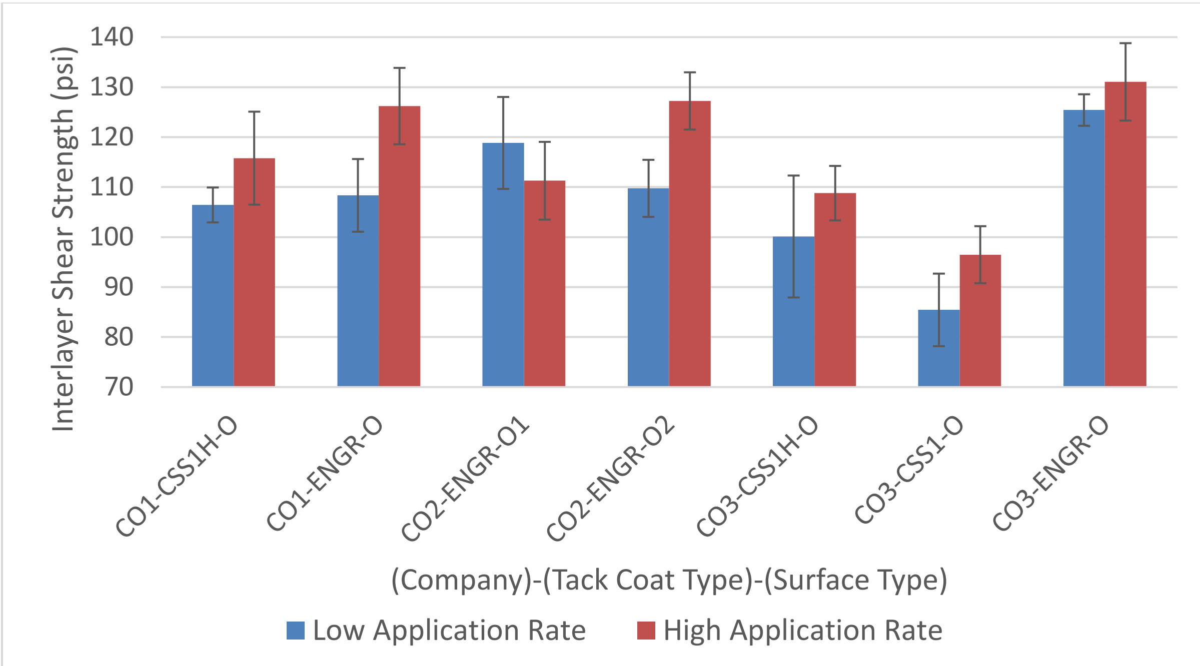
The following sections display plots that show the ISS and IBE response for each tack coat type for Company 1, Company 2 and Company 3. Correlation matrices for each company's tack coats were also developed in order to determine the significant differences, if any, between the ISS/IBE responses for each tack coat. In this way, tack coats which exhibited superior performance over others could be easily identified.

4.3.1 Company-wise comparisons of ISS and IBE

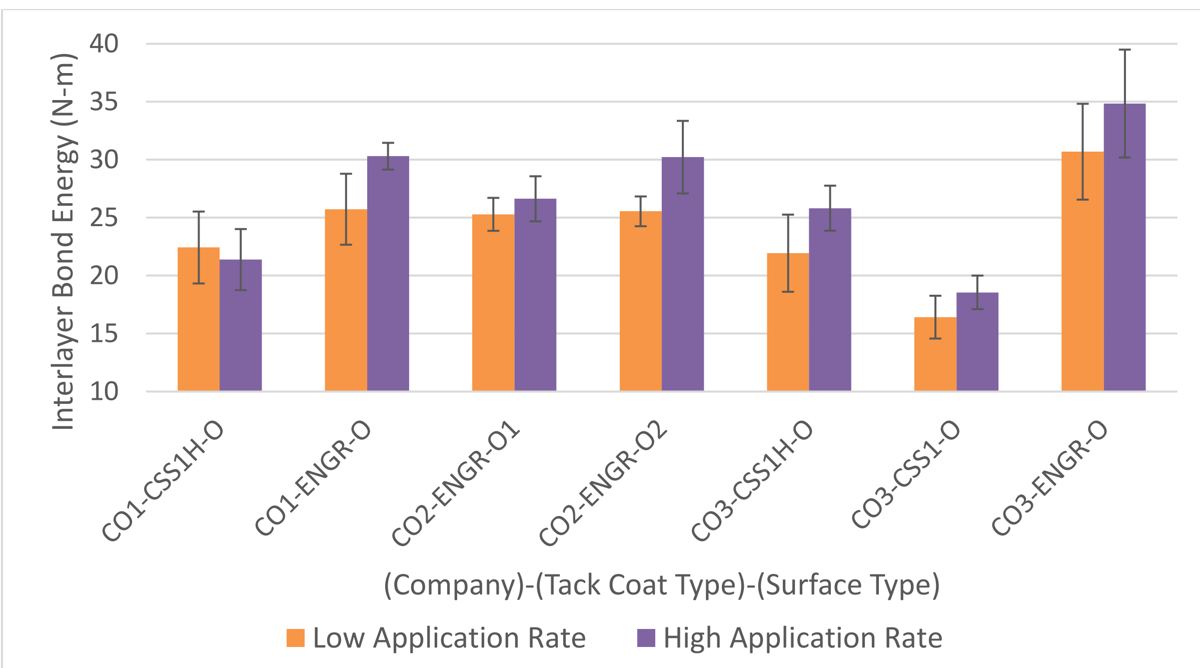
Evaluating the bond performance of tack coats provided by each company was done by comparing each company's tack coats against one another. In order to determine the best-performing tack coats from all companies, the ISS and IBE response of all tack coats tested were compared using bar charts and correlation matrices. Company-wise tack coat comparisons were grouped into overlay surface results and milled surface results, which are shown in the figures and tables that follow.

4.3.1.1 Tack coats applied to an overlay surface

Figure 4.9 shows the ISS and IBE response for all tack coats applied to overlay surfaces at two application rates (low rate of 0.05 gal/yd^2 and high rate of 0.09 gal/yd^2). Error bars indicate ± 1 standard deviation. The "-O" designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to an overlay surface, and does not depict the intended design surface type of these tack coats. The "-O1" and "-O2" designations on CO2 tack coats indicate the two different engineered tack coats for overlay surfaces.



(a)



(b)

Figure 4.9: Overlay surface tack coat response for (a) ISS and (b) IBE at two application rates with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N-m = 8.85 in-lbs).

From Figure 4.9 above, it is readily apparent that engineered tack coats are performing markedly better than conventional tack coats on overlay surfaces. The performance of the CO1-ENGR-O is noticeably better than the CO1-CSS1H tack coat. It is also clear that the CO3-ENGR-O tack coat showed the best performance for the overlay surface. CO2-ENGR-O2 exhibited slightly better IBE performance than CO2-ENGR-O1, and was also nearly equivalent to CO1-ENGR-O in terms of ISS and IBE. A peculiar ISS result is exhibited with CO2-ENGR-O1; the high application rate performed worse than the low application rate. This trend is not consistent with what is seen in the IBE results, suggesting that IBE may be a better indicator of bond quality than ISS. Most tack coats tended toward improved ISS/IBE at a higher application rate, except the ISS response of CO2-ENGR-O1 and the IBE response for CO1-CSS1H-O, where the high application rate slightly diminished the result. This observation lends itself to the conclusion that the low rate (0.05 gal/yd^2), although within the range of specifications for construction in Oregon (ODOT 2015), is not adequate and should be increased. The optimum application rates for most tack coats in this study are likely much higher than the low rate (0.05 gal/yd^2) selected for use in this study. Optimum application rates should be sought for each of the tack coat types tested in this study. Further research is needed to determine optimum application rates for each tack coat.

It was noted during sample preparation that the CO1-ENGR-O tack coat caused clogging problems with the foam tack coat applicator. This was due to the presence of polymer modifiers in the tack coat, which tended to coagulate and cause the applicator nozzle to become clogged. This may have ramifications for field application of tack coats, as the spray nozzles on the distributor trucks could easily become clogged in the same way and cause problems with tack coat coverage uniformity (streaking).

Correlation matrices were developed for all overlay and milled tack coats tested at a low application rate (0.05 gal/yd^2 for overlay surface, 0.09 gal/yd^2 for milled surface) to aid in highlighting tack coats which had significantly better performance than others. The low application rate was chosen since these rates are more likely to occur in the field than high application rates. They are also within the range of application rates specified in the ODOT Standard Specifications for Construction (ODOT 2015). In order to assess the significance of the ISS and IBE response parameters for each tack coat tested, a Welch modified two-sample t-test was performed between each tack coat type to determine significant differences, if any, between the ISS and IBE for different tack coat types. Suppose that the two ISS or IBE distributions for the tack coat types under comparison (suppose F_1 and F_2 are two distributions) can be represented by the following null and alternative hypotheses:

$$\boldsymbol{H_0}: \boldsymbol{F_1}(\boldsymbol{x}) = \boldsymbol{F_2}(\boldsymbol{x}) \quad \textbf{(4-2)}$$

$$\boldsymbol{H_A}: \boldsymbol{F_1}(\boldsymbol{x}) \neq \boldsymbol{F_2}(\boldsymbol{x}) \quad \textbf{(4-3)}$$

A decision rule was adopted for the two-sample t-test. The decision rule is as follows:

$$\text{Reject } H_0 \text{ if } p < 0.05 \tag{4-4}$$

$$\text{Fail to reject } H_0 \text{ if } p \geq 0.05 \tag{4-5}$$

In the case where the null hypothesis was rejected, it was concluded that the ISS or IBE of the tack coats under comparison were significantly different from one another.

Table 4.4 and Table 4.5 below show correlation matrices for the ISS and IBE of all tack coats tested on an overlay surface at a low application rate (0.05 gal/yd^2). The "-O" designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to an overlay surface, and does not depict the intended design surface type of these tack coats. A p-value of less than 0.05 indicates a significant difference between the two tack coats under comparison.

Table 4.4: Correlation Matrix for ISS of all Overlay Surface Tack Coats at a low Application Rate.

Tack Coat Type	CO1-CSS1H-O-Low	CO1-ENGR-O-Low	CO2-ENGR-O1-Low	CO2-ENGR-O2-Low	CO3-CSS1-O-Low	CO3-CSS1H-O-Low	CO3-ENGR-O-Low
CO1-CSS1H-O-Low	*1.000*	**0.6667**	**0.0683**	**0.3869**	**0.0222**	0.3868	**0.0023**
CO1-ENGR-O-Low	0.6667	*1.000*	0.1263	**0.7724**	**0.0116**	0.3002	**0.0118**
CO2-ENGR-O1-Low	0.0683	0.1263	*1.000*	**0.1538**	**0.0031**	0.0528	0.2564
CO2-ENGR-O2-Low	0.3869	0.7724	0.1538	*1.000*	**0.0102**	0.2220	**0.0064**
CO3-CSS1-O-Low	0.0222	0.0116	0.0031	0.0102	*1.000*	0.1055	**0.0045**
CO3-CSS1H-O-Low	0.3868	0.3002	0.0528	0.2220	0.1055	*1.000*	**0.0211**
CO3-ENGR-O-Low	0.0023	0.0118	0.2564	0.0064	0.0045	0.0211	*1.000*

Table 4.5: Correlation Matrix for IBE of all Overlay Surface Tack Coats at a low Application Rate.

Tack Coat Type	CO1-CSS1H-O-Low	CO1-ENGR-O-Low	CO2-ENGR-O1-Low	CO2-ENGR-O2-Low	CO3-CSS1-O-Low	CO3-CSS1H-O-Low	CO3-ENGR-O-Low
CO1-CSS1H-O-Low	*1.000*	**0.1806**	**0.1654**	**0.1366**	**0.0251**	0.8512	0.0207
CO1-ENGR-O-Low	0.1806	*1.000*	0.8065	**0.9189**	**0.0044**	0.1939	0.1060
CO2-ENGR-O1-Low	0.1654	0.8065	*1.000*	**0.7953**	**0.0031**	0.2158	0.0739
CO2-ENGR-O2-Low	0.1366	0.9189	0.7953	*1.000*	**0.0033**	0.1927	0.0840
CO3-CSS1-O-Low	0.0251	0.0044	0.0031	0.0033	*1.000*	0.0836	**0.0027**
CO3-CSS1H-O-Low	0.8512	0.1939	0.2158	0.1927	0.0836	*1.000*	**0.0274**
CO3-ENGR-O-Low	0.0207	0.1060	0.0739	0.0840	0.0027	0.0274	*1.000*

The correlation matrix above yields some interesting conclusions about the performance of each overlay tack coat at a low application rate. It is notable that in Table 4.4, CO3-ENGR-O had significantly better ISS performance than all tack coats (p-value less than 0.05), other than CO2-ENGR-O1, at a 95% confidence level. Interestingly enough, CO1-ENGR-O did not exceed the performance of CO1-CSS1H-O based on the p-value of 0.6667 for ISS (Table 4.4) and 0.1806 for IBE (Table 4.5) at 95% confidence. Also, CO1-CSS1H-O had equivalent performance to CO2-ENGR-O2 in terms of both ISS and IBE based on the high p-values shown in Table 4.4 and Table 4.5 at a 95% confidence level, which is consistent with the observation made in Figure 4.9. CO2 engineered tack coats were also not significantly different from each other at a 95% confidence level. Additionally, it can be said with 95% confidence that CO3-CSS1-O had inferior ISS and IBE performance when compared to all other tack coats other than CO3-CSS1H-O, based on p-values shown in Table 4.4 and Table 4.5. From the correlations presented in Table 4.4 and Table 4.5 above, it was discerned that engineered tack coats do not significantly improve interlayer bond performance on overlay surfaces, although at face value they appeared to improve ISS and IBE (Figure 4.9).

Table 4.6 and Table 4.7 below show correlation matrices for the ISS and IBE of all tack coats tested on an overlay surface at a high application rate (0.09 gal/yd^2). The "-O" designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to an overlay surface, and does not depict the intended design surface type of these tack coats. A p-value of less than 0.05 indicates a significant difference between the two tack coats under comparison.

Table 4.6: Correlation Matrix for ISS of all Overlay Surface Tack Coats at a High Application Rate.

Tack Coat Type	CO1-CSS1H-O-High	CO1-ENGR-O-High	CO2-ENGR-O1-High	CO2-ENGR-O2-High	CO3-CSS1-O-High	CO3-CSS1H-O-High	CO3-ENGR-O-High
CO1-CSS1H-O-High	*1.000*	0.1913	**0.5547**	0.1581	0.0625	0.3321	0.0966
CO1-ENGR-O-High	0.1913	*1.000*	0.0589	**0.8470**	**0.0015**	**0.0119**	0.4525
CO2-ENGR-O1-High	0.5547	0.0589	*1.000*	0.0507	0.0825	**0.6649**	**0.0355**
CO2-ENGR-O2-High	0.1581	0.8470	0.0507	*1.000*	**0.0019**	**0.0107**	0.5336
CO3-CSS1-O-High	0.0625	0.0015	0.0825	0.0019	*1.000*	**0.0402**	**0.0052**
CO3-CSS1H-O-High	0.3321	0.0119	0.6649	0.0107	0.0402	*1.000*	**0.0180**
CO3-ENGR-O-High	0.0966	0.4525	0.0355	0.5336	0.0052	0.0180	*1.000*

Table 4.7: Correlation Matrix for IBE of all Overlay Surface Tack Coats at a High Application Rate.

Tack Coat Type	CO1-CSS1H-O-High	CO1-ENGR-O-High	CO2-ENGR-O1-High	CO2-ENGR-O2-High	CO3-CSS1-O-High	CO3-CSS1H-O-High	CO3-ENGR-O-High
CO1-CSS1H-O-High	*1.000*	**0.0159**	**0.0504**	**0.0212**	0.1947	0.0777	**0.0052**
CO1-ENGR-O-High	0.0159	*1.000*	**0.0272**	**0.9693**	0.0001	**0.0132**	0.1445
CO2-ENGR-O1-High	0.0504	0.0272	*1.000*	0.1741	0.0008	**0.5761**	**0.0310**
CO2-ENGR-O2-High	0.0212	0.9693	0.1741	*1.000*	0.0132	0.1170	0.1775
CO3-CSS1-O-High	0.1947	0.0001	0.0008	0.0132	*1.000*	**0.0013**	**0.0038**
CO3-CSS1H-O-High	0.0777	0.0132	0.5761	0.1170	0.0013	*1.000*	**0.0230**
CO3-ENGR-O-High	0.0052	0.1445	0.0310	0.1775	0.0038	0.0230	*1.000*

In Table 4.6 and Table 4.7 above, it is evident that engineered tack coats generally demonstrated improved performance over conventional tack coats at a high application rate on overlay surfaces. Notably, CO1-ENGR-O and CO3-ENGR-O tack coats improved bond quality over conventional tack coats when IBE was used as the response parameter. These statistically significant differences are highlighted by the p-values of less than 0.05 in Table 4.7 at a 95% confidence level. Additionally, the above tables show that CO2-ENGR-O1 produced bond quality that was essentially the same as CSS-1H tack coats provided by Company 1 and Company 3, based on the high p-values for both ISS and IBE at the 95% confidence level. CO1-ENGR-O and CO2-ENGR-O2 were noted to have equivalent performance as well, with p-values of 0.8470 for ISS and 0.9693 for IBE at the 95% confidence level. This result confirms observations made in Table 4.4, Table 4.5 and Figure 4.9.

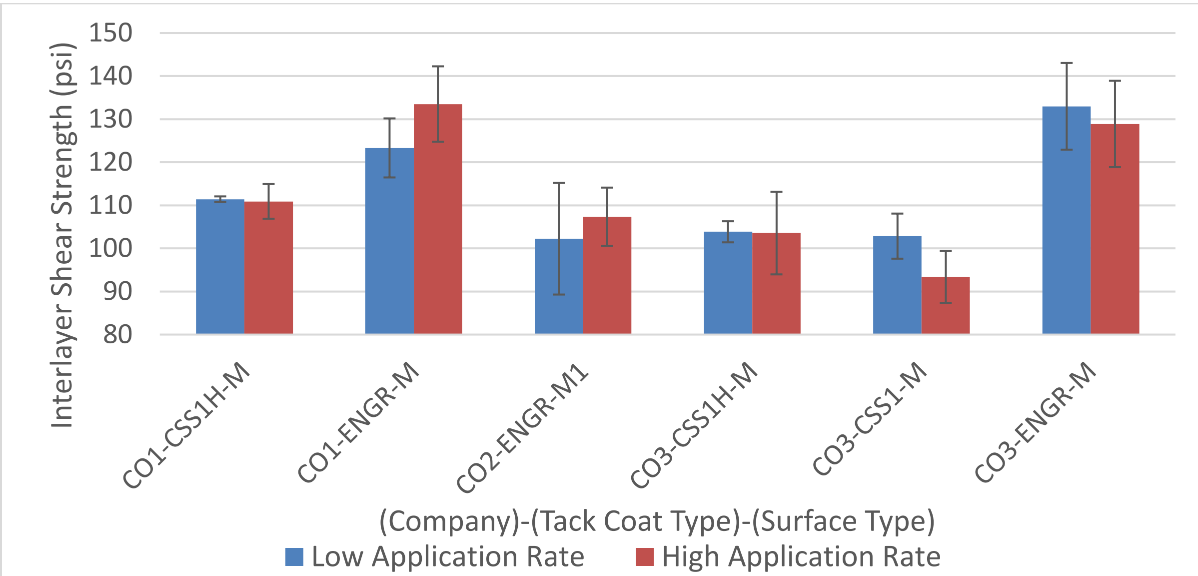
In general, the higher application rate utilized for overlay surfaces did change the statistical significance of several comparisons when compared to comparisons made for the low application rate. Comparisons that changed to achieve statistical significance at a 95% confidence level when using the high application rate versus the low application rate are as follows:

- IBE of CO1-ENGR-O against CO1-CSS1H-O (p-value of 0.0159)
- ISS/IBE of CO1-ENGR-O against CO3-CSS1H-O (p-values of 0.0119 for ISS and 0.0132 for IBE)
- ISS/IBE of CO3-CSS1H-O against CO3-CSS1-O (p-values of 0.0402 for ISS and 0.0013 for IBE)
- ISS of CO2-ENGR-O2 against CO3-CSS1H-O (p-value of 0.0107)
- IBE of CO2-ENGR-O1 against CO1-ENGR-O (p-value of 0.0272)
- ISS/IBE of CO3-ENGR-O against CO2-ENGR-O1 (p-values of 0.0355 for ISS and 0.0310 for IBE)

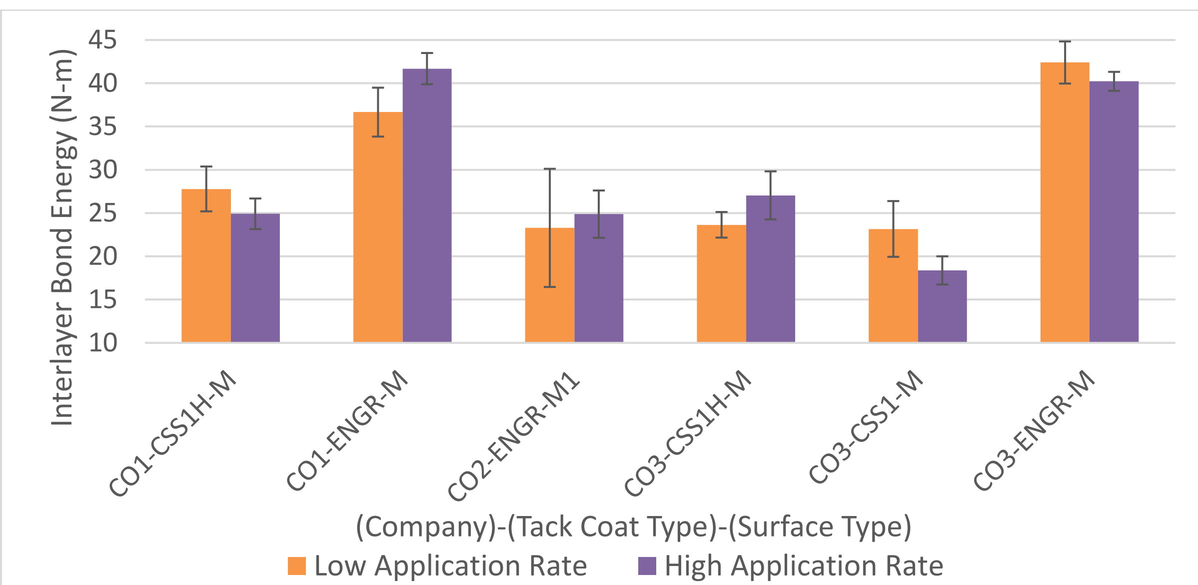
The fact that several of these rankings changed when using the high application rate versus the low application rate indicates that the low application rate is not adequate for overlay surfaces and that overlay surfaces are more sensitive to the effect of application rate. The heightened sensitivity of smooth overlay surfaces to application rate is consistent with other research that suggests application rate plays a bigger role in ISS when tack coats are applied to smooth pavement surfaces versus surfaces with high macrotexture (Al-Qadi et al. 2008). The higher application rate on overlay surfaces accentuates the differences in performance of engineered and conventional tack coats and better represents the expected trends in bond performance. This result suggests that in order to capitalize on the improved performance of engineered tack coats on an overlay surface, a higher application rate should be used. Furthermore, the IBE parameter appears to provide a better indication of bond performance based on the expected trends. This suggests that IBE is a more useful parameter for gauging tack coat performance.

4.3.1.2 Tack coats applied to a milled surface

Figure 4.10 shows the ISS and IBE response for all tack coats tested applied to milled surfaces at two application rates (low rate of 0.09 gal/yd^2 and high rate of 0.15 gal/yd^2). The “-M” designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of these tack coats. Error bars indicate ± 1 standard deviation.



(a)



(b)

Figure 4.10: Milled surface tack coat response for (a) ISS and (b) IBE at two application rates with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N-m = 8.85 in-lbs).

As can be seen in Figure 4.10, CO2-ENGR-M1 did not have performance that was congruent with the other two companies' engineered tack coats. This tack coat yielded ISS/IBE results that were within the range of conventional tack coats (CSS-1 and CSS-1H) provided by other companies. This contradicts the expected result, as milled surfaces typically exhibit better bond quality due to aggregate interlock of the new pavement layer with the coarse milled surface texture (Coleri et al. 2017; FHWA 2016; Mohammad et al. 2010). This result is attributed to the tack coat's low residual asphalt content. This tack coat was observed to have a very high water content in comparison to other engineered tack coats, which translates into a low amount of residual asphalt binder that is available to facilitate interlayer bonding once the tack coat sets. Additionally, it was noted during sample preparation that the CO2-ENGR-M1 tack coat permeated through the voids of the first lift samples during tack coat application, causing some of the tack coat to soak through to the bottom of the sample instead of being retained on the pavement surface. This may have reduced the effective amount of residual asphalt available for bonding at the interlayer, since some of the residual asphalt soaked through the voids of the underlying asphalt layer. This phenomenon is likely due to the high water content of this tack coat. The tack coat flowed much more readily through the voids of the first lift samples since it had a lower viscosity than other tack coats used on milled surfaces.

From Figure 4.10 above, a clear advantage is exhibited for engineered tack coats from Company 1 and Company 3, in terms of both ISS and IBE. It is also clear to see in Figure 4.9 and Figure 4.10 that the CO3 engineered tack coat had superior performance as compared to conventional CSS-1 and CSS-1H tack coats, both in terms of ISS and IBE. The CSS-1 tack coat did not achieve the performance of the CSS-1H or engineered tack coats. CSS-1H tack coats also exhibited similar performance on both milled and overlay surfaces, whereas the engineered tack coats tended towards slightly higher ISS/IBE on milled surfaces.

On milled surfaces, higher application rates did not necessarily translate into beneficial gains in ISS/IBE. In most cases, the ISS of milled surface tack coats decreased at higher application rates (CO1-CSS1H-M, CO3-CSS1-M, CO3-CSS1H-M and CO3-ENGR-M). The IBE also decreased at higher application rates for several of the tack coats tested (CO1-CSS1H-M, CO3-CSS1-M and CO3-ENGR-M), indicating that excessively high tack coat application rates on milled surfaces do not improve bond quality. This result is consistent with conclusions from other research, which suggest that variation of application rates is less pronounced for milled surfaces (Coleri et al. 2017; Covey et al. 2017; Al-Qadi et al. 2008). Another inference from this result is that optimum application rates for tack coats applied to milled surfaces in this study must be close to the low rate (0.09 gal/yd^2) due to the diminishing returns brought on by increased application rates. This suggests that 0.09 gal/yd^2 is a good choice for milled surfaces. However, seeking an optimum application rate for maximizing bond quality for each tack coat is a worthwhile endeavor. More research is needed in order to determine the optimum application rates for each of the tack coats in this study.

Table 4.8 and Table 4.9 below show correlation matrices for the ISS and IBE of all tack coats tested on milled surfaces at a low application rate (0.09 gal/yd^2). The "-M" designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of these tack coats. A p-value of less than 0.05 indicates a significant difference between the two tack coats under comparison. The decision rule for significance was the same as was used for comparisons for overlay tack coats.

Table 4.8: Correlation Matrix for ISS of all Milled Surface Tack Coats at a low Application Rate.

Tack Coat Type	CO1-CSS1H-M-Low	CO1-ENGR-M-Low	CO2-ENGR-M1-Low	CO3-CSS1-M-Low	CO3-CSS1H-M-Low	CO3-ENGR-M-Low
CO1-CSS1H-M-Low	*1.000*	**0.0393**	**0.2517**	0.0455	0.0278	0.0230
CO1-ENGR-M-Low	0.0393	*1.000*	0.0386	0.0038	**0.0066**	**0.1704**
CO2-ENGR-M1-Low	0.2517	0.0386	*1.000*	**0.9344**	**0.8217**	0.0106
CO3-CSS1-M-Low	0.0455	0.0038	0.9344	*1.000*	0.7507	0.0043
CO3-CSS1H-M-Low	0.0278	0.0066	0.8217	0.7507	*1.000*	0.0077
CO3-ENGR-M-Low	0.0230	0.1704	0.0106	0.0043	0.0077	*1.000*

Table 4.9: Correlation Matrix for IBE of all Milled Surface Tack Coats at a low Application Rate.

Tack Coat Type	CO1-CSS1H-M-Low	CO1-ENGR-M-Low	CO2-ENGR-M1-Low	CO3-CSS1-M-Low	CO3-CSS1H-M-Low	CO3-ENGR-M-Low
CO1-CSS1H-M-Low	*1.000*	**0.0036**	**0.2877**	0.0687	0.0461	0.0009
CO1-ENGR-M-Low	0.0036	*1.000*	0.0244	0.0008	0.0007	0.0362
CO2-ENGR-M1-Low	0.2877	0.0244	*1.000*	**0.9754**	**0.9251**	0.0069
CO3-CSS1-M-Low	0.0687	0.0008	0.9754	*1.000*	0.8044	0.0003
CO3-CSS1H-M-Low	0.0461	0.0007	0.9251	0.8044	*1.000*	0.0009
CO3-ENGR-M-Low	0.0009	0.0362	0.0069	0.0003	0.0009	*1.000*

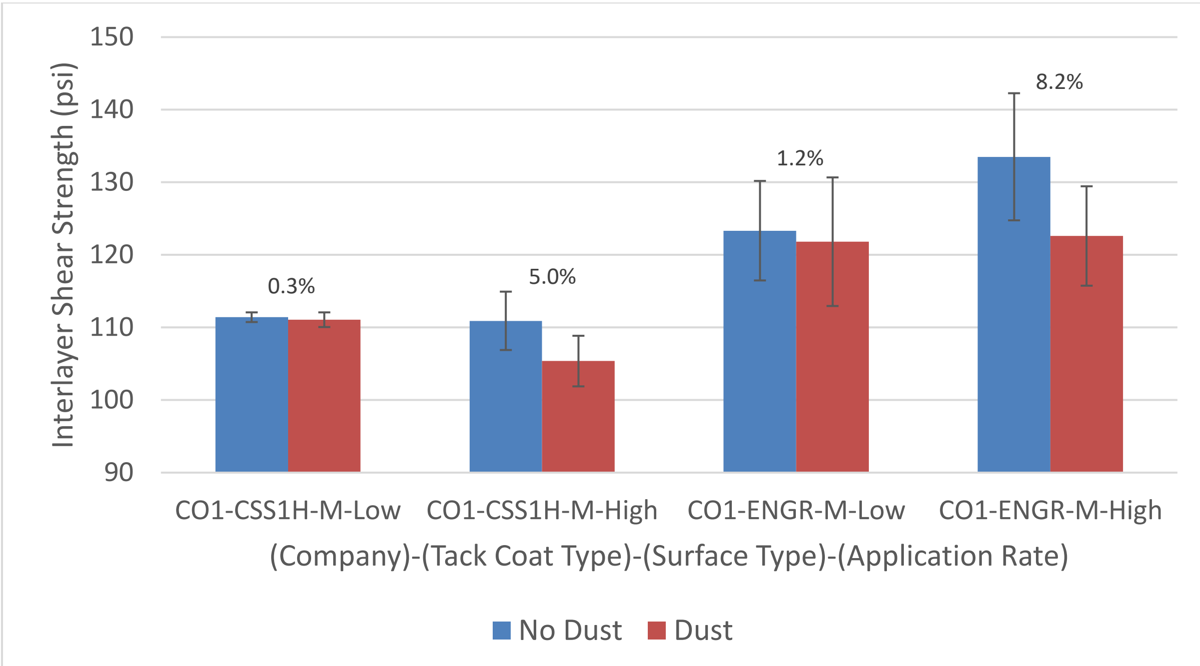
Correlations between milled surface tack coats showed that CO3-ENGR-M had superior ISS and IBE performance as compared to all other tack coats applied on milled surfaces at a 95% confidence level, based on the p-values below 0.05 shown in Table 4.8 and Table 4.9. The only exception to this was the ISS of CO1-ENGR-M, which was not statistically different from CO3-ENGR-M at the 95% confidence level based on the p-value of 0.1704. Another notable conclusion is that CO1's ENGR-M tack coat performed significantly better than all other CSS-1 and CSS-1H tack coat at the 95% confidence level based on the p-values less than 0.05 in Table 4.8 and

Table 4.9. This result indicates that Company 1's engineered tack coat for milled surfaces will improve bond quality over conventional tack coats. Also, an important conclusion is that CO2-ENGR-M1 did not exhibit improved performance like engineered tack coats of Company 1 and Company 3. This tack coat did not have significantly different performance from CO1-CSS1H-M, CO3-CSS1-M or CO3-CSS1H at the 95% confidence level, as can be seen from the high p-values shown in Table 4.8 and Table 4.9. These statistical comparisons also reaffirm the conclusion suggested earlier that the low application rate (0.09 gal/yd^2) must be close to the optimum rate for tack coats applied to milled surfaces, since all of the expected trends in tack coat performance are represented in these comparisons. However, it is still a worthwhile endeavor in future research to determine the optimum application rates for each tack coat tested in this study.

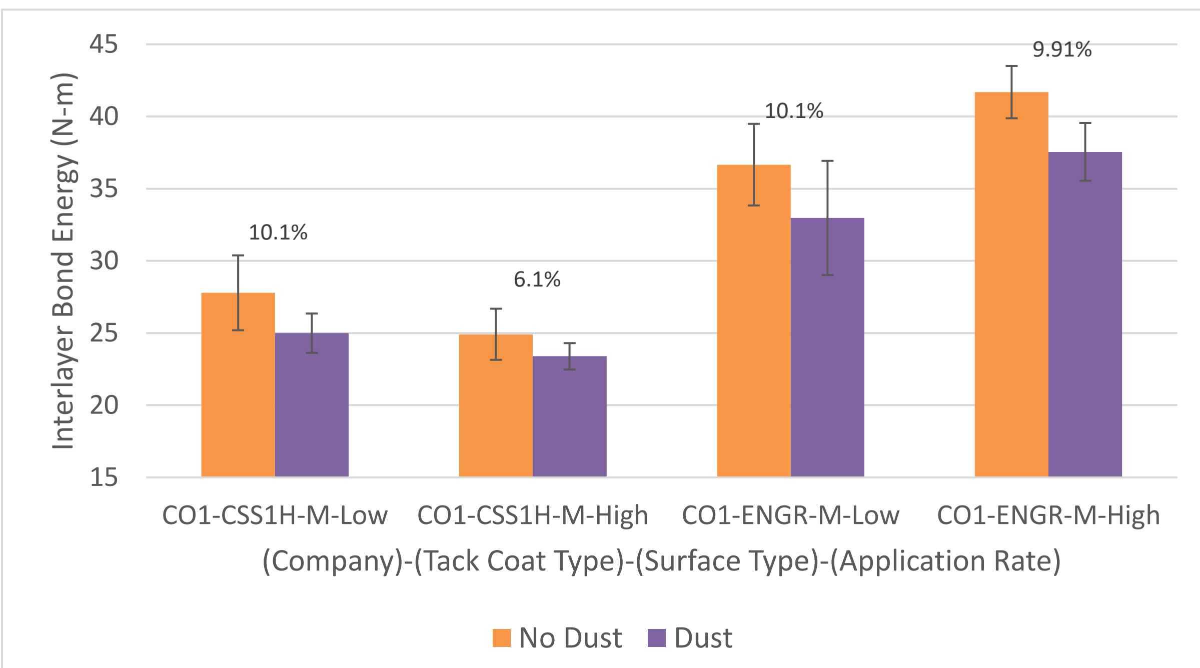
Comparisons of ISS/IBE performance of tack coats applied at high application rates on milled surfaces were not made since the trends exhibited in the comparisons for the low application rate were representative of the expected results and the low application rate was deemed appropriate for milled surfaces.

4.3.2 Effect of dust on tack coat bond quality

Figure 4.11 shows the average ISS/IBE responses for CO1 tack coats on milled surfaces in the presence of dust and without dust at two application rates (low rate of 0.09 gal/yd^2 and high rate of 0.15 gal/yd^2). The "-M" designation on the CSS-1H tack coat is merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of this tack coat. Error bars indicate ±1 standard deviation. Percentage differences for dust/no dust cases are shown above the columns.



(a)



(b)

Figure 4.11: Milled surface tack coat response for (a) ISS and (b) IBE with and without dust at two application rates, with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N-m = 8.85 in-lbs).

From Figure 4.11, it can be deduced that dust does impact tack coat bond quality. There is no discernable difference in ISS/IBE reduction between engineered and conventional tack coats, indicating that engineered tack coats are not helping to improve bond quality when the underlying pavement surface is dusty prior to paving and compaction. This result may indicate that engineered tack coats have the same propensity as conventional tack coats to stick to dust particles on the pavement surface, perhaps due to electrochemical properties of the polymer modifiers in the engineered tack coats.

Additionally, the reduction in ISS is benign for low application rates. This is true for both engineered and conventional tack coats. This result could be due to the tack coat blending with the dust particles and forming a mastic, which is suggested to increase bond strength (Mohammad et al. 2012). At higher application rates, there was a more pronounced reduction in both ISS and IBE. This observation can also be attributed to the earlier conclusion that an application rate of 0.09 gal/yd^2 is likely close to the optimum application rate for tack coats tested in this study. In general, the presence of dust seems to be more problematic at higher application rates, as greater reductions in ISS and IBE can be seen for tack coats applied at high application rates in the presence of dust. This result allows the inference that tack coats applied at high rates lead to a portion of the tack coat membrane that is not actively bonding the two pavement layers.

In general, dust did not significantly impact the bond quality of tack coats. The reduced impact of dust on ISS for low application rates is illustrated by the low percentage differences shown in Figure 4.11. Percentage differences are generally higher for high application rates. Percentage differences for IBE were slightly higher for low application rates, indicating that IBE may be better representing the difference in performance for dust/no dust cases. Table 4.10 and Table 4.11 below show correlation matrices for the ISS and IBE of Company 1 tack coats tested on milled surfaces with and without dust present at a low application rate (0.05 gal/yd^2). A p-value of less than 0.05 indicates a significant difference between the two cases under comparison. The decision rule for significance was the same as was used for comparisons shown in Section 4.3.1.1.

Table 4.10: Correlation Matrix for ISS of all Tack Coats Tested with Dusty Surface.

Tack Coat Type	CO1-CSS1H-NoDust-Low	CO1-CSS1H-Dust-Low	CO1-ENGR-M-NoDust-Low	CO1-ENGR-M-Dust-Low
CO1-CSS1H-NoDust-Low	*1.000*	**0.5925**	0.0393	0.1001
CO1-CSS1H-Dust-Low	0.5925	*1.000*	0.0358	**0.0928**
CO1-ENGR-M-NoDust-Low	0.0393	0.0358	*1.000*	**0.7960**
CO1-ENGR-M-Dust-Low	0.1001	0.0928	0.7960	*1.000*

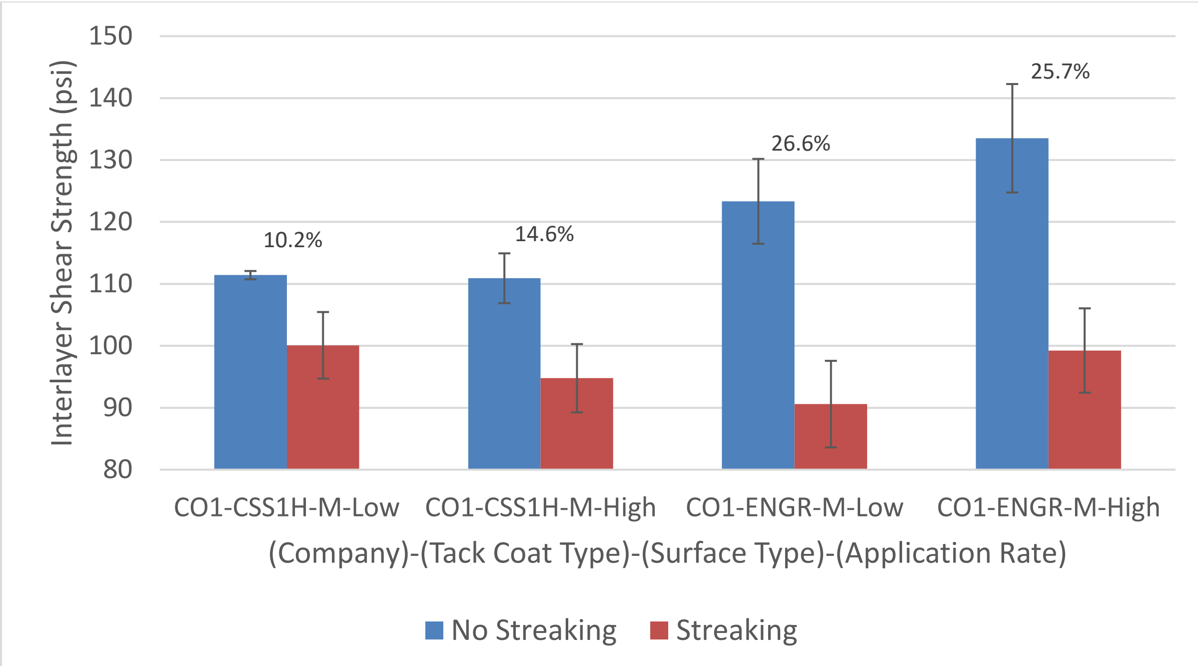
Table 4.11: Correlation Matrix for IBE of all Tack Coats Tested with Dusty Surface.

Tack Coat Type	CO1-CSS1H-NoDust-Low	CO1-CSS1H-Dust-Low	CO1-ENGR-M-NoDust-Low	CO1-ENGR-M-Dust-Low
CO1-CSS1H-NoDust-Low	*1.000*	**0.1203**	0.0036	0.1355
CO1-CSS1H-Dust-Low	0.1203	*1.000*	0.0013	**0.0627**
CO1-ENGR-M-NoDust-Low	0.0036	0.0013	*1.000*	**0.2508**
CO1-ENGR-M-Dust-Low	0.1355	0.0627	0.2508	*1.000*

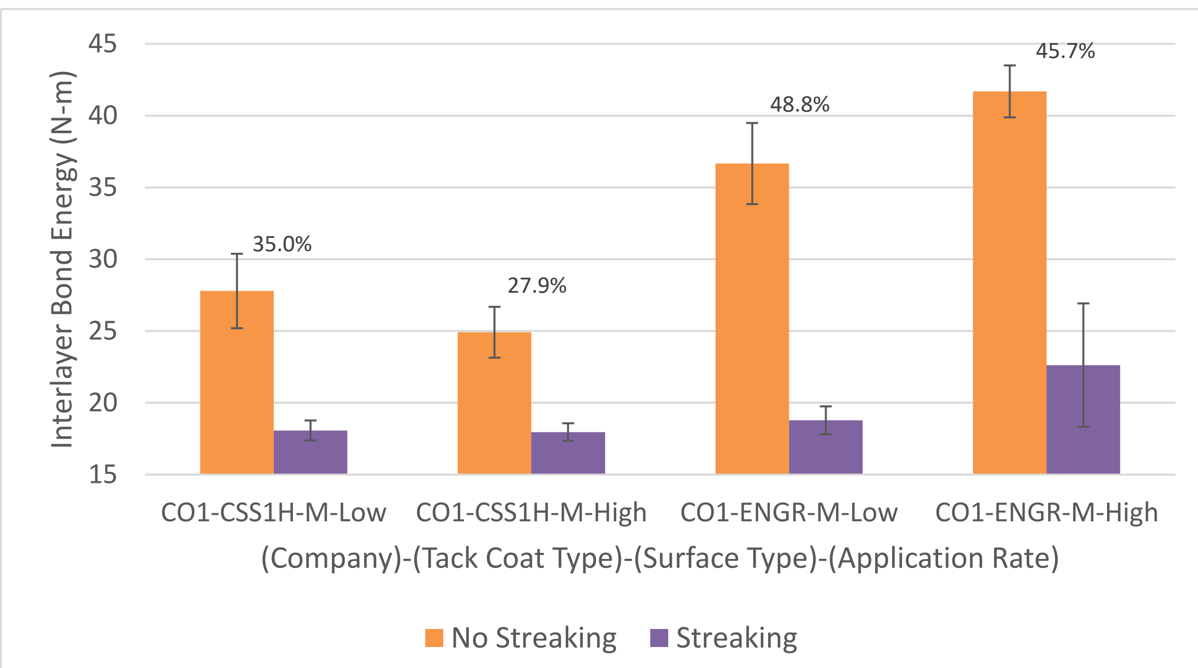
Based on the correlation matrices for ISS and IBE of tack coats applied at a low application rate with and without dust, the impact of dust on bond quality is further explained. Interestingly, the impact of dust on ISS and IBE for CO1-CSS1H was not statistically significant at a 95% confidence level, based on p-values of 0.5925 for ISS and 0.1203 for IBE. Similarly, dust did not have a statistically significant effect on ISS/IBE performance of CO1-ENGR-M based on p-values of 0.7960 and 0.2508, respectively. Another interesting conclusion pointed out in these correlation matrices was the change of correlation between CO1-CSS1H and CO1-ENGR-M when dust was present. Recall from in Table 4.8 and Table 4.9 that there was strong statistical evidence to show that CO1-CSS1H-M and CO1-ENGR-M had significantly different ISS and IBE from one another based on the p-values that were less than 0.05 for both ISS and IBE. However, when dust is present for both of these tack coats, the statistical significance is nullified at a 95% confidence level, based on the p-values of 0.0928 for ISS and 0.0627 for IBE. This result may give credence to the conclusion suggested by Mohammad et al. (2012) about dust forming a mastic with tack coat and enhancing bond strength.

4.3.3 Effect of streaking/non-uniform coverage on tack coat bond quality

Figure 4.12 shows the average ISS/IBE responses for CO1 tack coats on milled surfaces under streaking and no streaking conditions at two application rates (low rate of 0.09 gal/yd^2 and high rate of 0.15 gal/yd^2). Again, the "-M" designation on the CSS-1H tack coat is merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of this tack coat. Error bars indicate ±1 standard deviation. Percentage differences for streaking/no streaking cases are shown above the columns.



(a)



(b)

Figure 4.12: Milled surface tack coat response for (a) ISS and (b) IBE with and without streaking at two application rates, with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N-m = 8.85 in-lbs).

Figure 4.12 clearly shows that streaking of tack coats is significantly reducing the interlayer bond quality on milled surfaces, both in terms of ISS and IBE. It also appears that the engineered tack coat (ENGR-M) experienced greater reductions in ISS/IBE than did the conventional tack coat (CSS-1H). This is represented by the higher percentage differences for engineered tack coats at both low and high application rates. Reductions in IBE are more pronounced than ISS, but in general, there are undeniable negative ramifications of tack coat streaking in both parameters based on these results. These results testify to the importance of ensuring proper spray nozzle function on distributor trucks. Reductions in bond quality of this magnitude will undoubtedly impact the longevity of pavements in the field if streaking occurs.

The results for samples with streaking/reduced coverage also have implications for tracking in the field, where tack coat is picked up by construction vehicle tires. Tracked tack coats lead to an irregularity in the transverse distribution of tack coat coverage that is similar to streaking. Since tracking is effectively reducing the amount of tack coat on the pavement surface, it is expected that similar trends would be exhibited in the bond quality of tack coats that were subjected to tracking.

Table 4.12 and Table 4.13 below show correlation matrices for the ISS and IBE of Company 1 tack coats tested on milled surfaces with and without streaking at a low application rate (0.05 gal/yd^2). A p-value of less than 0.05 indicates a significant difference between the two cases under comparison. The decision rule for significance was the same as was used for comparisons shown in Chapter 4.3.1.1.

Table 4.12: Correlation Matrix for ISS of Tack Coats with and without Streaking at a low Application Rate.

Tack Coat Type	CO1-CSS1H-NoStreaking	CO1-CSS1H-Streaking	CO1-ENGR-M-NoStreaking	CO1-ENGR-M-Streaking
CO1-CSS1H-NoStreaking	*1.000*	**0.0234**	0.0393	0.0348
CO1-CSS1H-Streaking	0.0234	*1.000*	0.0021	0.1278
CO1-ENGR-M-NoStreaking	0.0393	0.0021	*1.000*	**0.0025**
CO1-ENGR-M-Streaking	0.0348	0.1278	0.0025	*1.000*

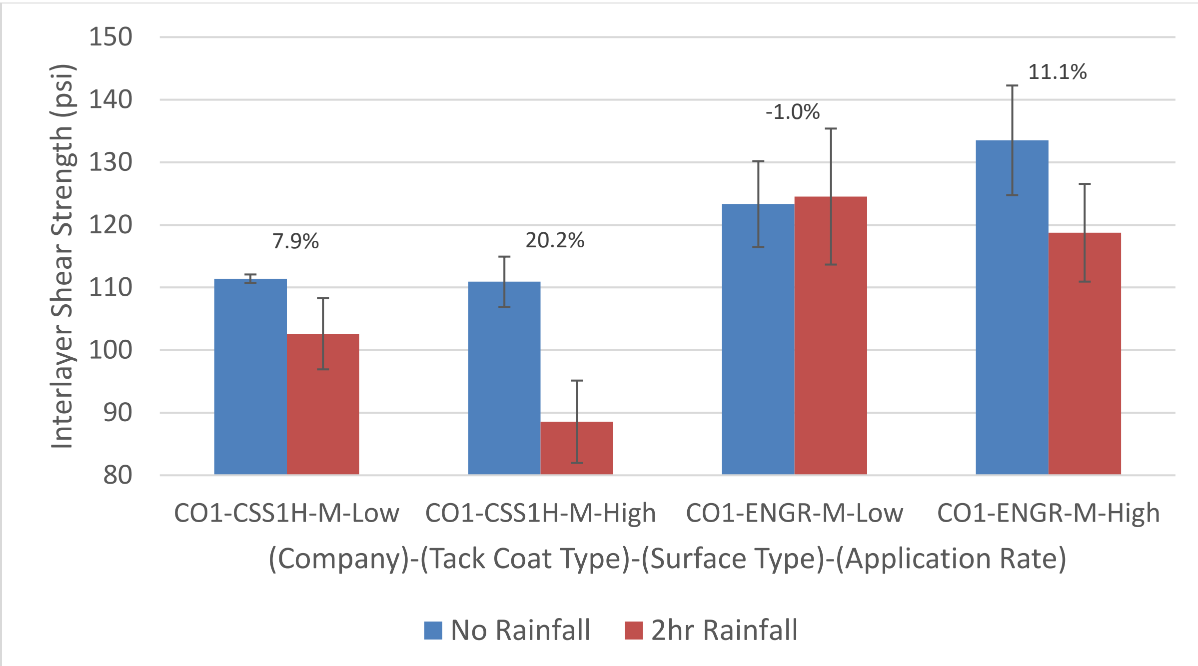
Table 4.13: Correlation Matrix for IBE of Tack Coats with and without Streaking at a low Application Rate.

Tack Coat Type	CO1-CSS1H-NoStreaking	CO1-CSS1H-Streaking	CO1-ENGR-M-NoStreaking	CO1-ENGR-M-Streaking
CO1-CSS1H-NoStreaking	*1.000*	**0.0031**	0.0036	0.0031
CO1-CSS1H-Streaking	0.0031	*1.000*	0.0005	0.3701
CO1-ENGR-M-NoStreaking	0.0036	0.0005	*1.000*	**0.0004**
CO1-ENGR-M-Streaking	0.0031	0.3701	0.0004	*1.000*

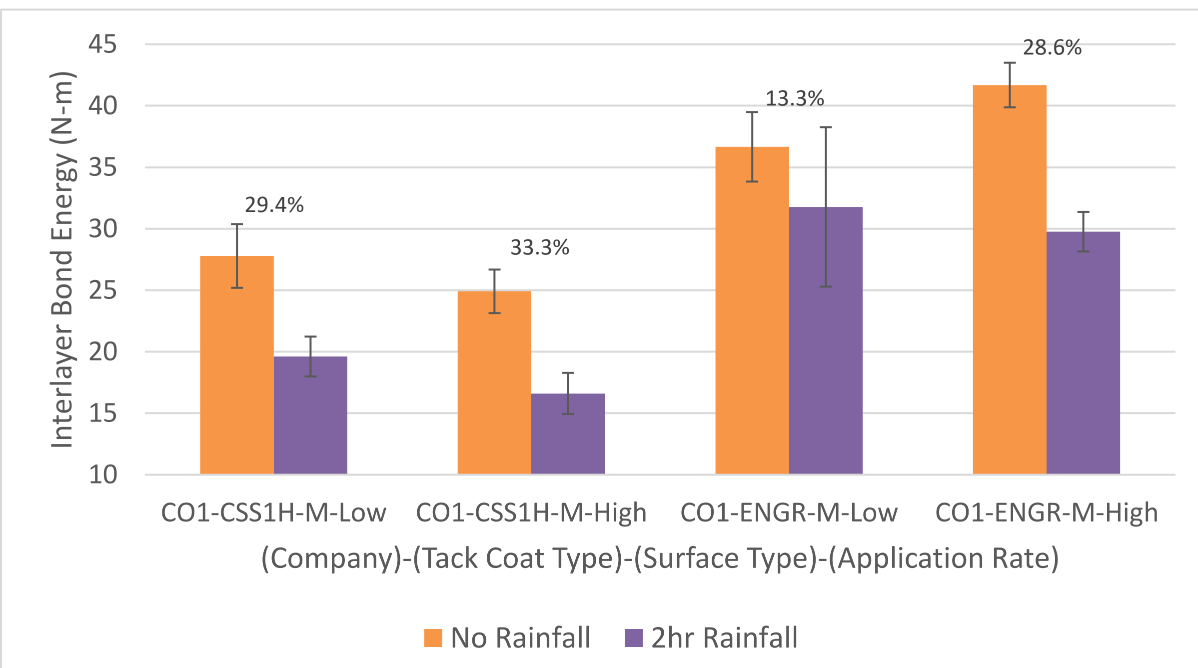
These results shown in the correlation matrices for tack coats subject to streaking and no streaking conditions illustrates a definite and discernable decrease in bond quality as measured by ISS and IBE. For CO1-CSS1H, there is strong evidence to suggest that streaking is reducing the resulting ISS and IBE, based on p-values of 0.0234 for ISS and 0.0031 for IBE at a 95% confidence level. It can also be said with 95% confidence that there is overwhelming evidence of a significant decrease in ISS and IBE under streaking conditions for CO1-ENGR-M, based on p-values of 0.0025 for ISS and 0.0004 for IBE. These results confirm the observations made in Figure 4.12. It also reaffirms the importance of preventing streaking during construction of pavements in the field through more thorough inspection of tack coat distributor truck equipment and finding ways to avoid tracking.

4.3.4 Effect of rainfall on tack coat bond quality

Figure 4.13 shows the average ISS/IBE responses for Company 1 tack coats on milled surfaces under 2hr rainfall and no rainfall conditions at two application rates (low rate of 0.09 gal/yd^2 and high rate of 0.15 gal/yd^2). Again, the "-M" designation on the CSS-1H tack coat is merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of this tack coat. Error bars indicate ±1 standard deviation. Percentage differences for rainfall/no rainfall cases are shown above the columns.



(a)



(b)

Figure 4.13: Milled surface tack coat response for (a) ISS and (b) IBE with 2hr rainfall after tack coat application and no rainfall at two application rates, with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N-m = 8.85 in-lbs).

Figure 4.13 shows that, in general, ISS and IBE are reduced when rainfall occurs after tack coat application. The only exception to this is the ISS of CO1-ENGR-M-Low, which remained essentially the same for the 2hr rainfall case as for the no rainfall case. However, the IBE results for this case paint a different picture, indicating that bond quality was indeed diminished.

It is clear to see that in general, rainfall after tack coat application was not favorable for resulting bond quality after paving and compaction. It was noted during the rainfall simulation phase of the sample preparation process that a large amount of the tack coat was effectively washed off the samples, leaving only a small amount of tack coat residue behind. This phenomenon was indicative that there would be less tack coat available on the pavement surface to bond the two layers after compaction, and the results seem to verify this notion. Additionally, high application rates appeared to have a greater reduction in bond quality due to this effect, which is represented by the higher percentage differences for both tack coats at high application rates. This is likely due to the increased amount of tack coat that is washing away from the pavement surface due to rainfall runoff.

It is very important to make one distinction about the impact of rainfall on engineered tack coat performance. From the plots in Figure 4.13 above, it was observed that the reductions in ISS and IBE for the engineered tack coats were of much less magnitude than that of the conventional tack coats. This interesting result can be attributed to the presence of polymer modifiers in the engineered tack coats. The polymers had a higher propensity of sticking to the aggregates on the milled pavement surface, indicating that engineered tack coats are less susceptible to bond quality issues in the presence of rainfall. Although it appeared that the tack coat was washing off the pavement surface during the rainfall simulation, it is clear that some of the polymer residue remained on the pavement surface after rainfall, indicating that engineered tack coats were more difficult to wash away with rainfall, likely due to the electrochemical properties of the polymers and their propensity to stick to aggregates. This result is extremely important in the context of highway pavement construction in Oregon. Since engineered tack coats are performing better under post-rainfall conditions after tack coat application, it can have significant implications for the productivity of the asphalt paving industry in Oregon. Since the industry wants to maximize their available time with which to perform pavement construction, the use of engineered tack coats could aid in extending the construction window in Oregon into seasons with more inclement weather, effectively increasing productivity and profitability of the asphalt pavement industry in Oregon. However, the possibility of extending the construction season only applies to tack coats. The performance of hot mix asphalt (HMA) constructed in rainfall conditions may be negatively impacted and is not investigated in this study.

Table 4.14 and Table 4.15 below show correlation matrices for the ISS and IBE of Company 1 tack coats tested on milled surfaces under the 2hr rainfall case and the no rainfall case at a low application rate (0.05 gal/yd^2). A p-value of less than 0.05 indicates a significant difference between the two cases under comparison. The decision rule for significance was the same as was used for comparisons shown in Chapter 4.3.1.1.

Table 4.14: Correlation Matrix for ISS of Tack Coats with and without Rainfall.

Tack Coat Type	CO1-CSS1H-NoRainfall	CO1-CSS1H-Rainfall	CO1-ENGR-M-NoRainfall	CO1-ENGR-M-Rainfall
CO1-CSS1H-NoRainfall	*1.000*	**0.1143**	0.0393	0.1714
CO1-CSS1H-Rainfall	0.1143	*1.000*	0.0077	0.0531
CO1-ENGR-M-NoRainfall	0.0393	0.0077	*1.000*	**0.8774**
CO1-ENGR-M-Rainfall	0.1714	0.0531	0.8774	*1.000*

Table 4.15: Correlation Matrix for IBE of Tack Coats with and without Rainfall.

Tack Coat Type	CO1-CSS1H-NoRainfall	CO1-CSS1H-Rainfall	CO1-ENGR-M-NoRainfall	CO1-ENGR-M-Rainfall
CO1-CSS1H-NoRainfall	*1.000*	**0.0039**	0.0036	0.4014
CO1-CSS1H-Rainfall	0.0039	*1.000*	0.0002	0.0752
CO1-ENGR-M-NoRainfall	0.0036	0.0002	*1.000*	**0.3220**
CO1-ENGR-M-Rainfall	0.4014	0.0752	0.3220	*1.000*

The correlation matrices above show that rainfall did not produce statistically significant differences in ISS for CO1-CSS1H or CO1-ENGR-M, based on p-values of 0.1143 and 0.8774 at a 95% confidence level. The IBE response of CO1-CSS1H was indeed statistically different from the reference case, however, which is confirmed by the p-value of 0.0039 at a 95% confidence level. Another notable observation is that the p-values for the comparison of rainfall to no rainfall cases for CO1-ENGR-M were much higher than for CO1-CSS1H. This result affirms the conclusion from Figure 4.13 that engineered tack coats are affected less by rainfall than are conventional tack coats due to the presence of polymers which are sticking to the aggregates better than conventional tack coats under rainfall conditions.

4.4 SUMMARY AND CONCLUSIONS

This study evaluated new engineered tack coats against conventional tack coats used in Oregon subject to varying application rates and different underlying pavement surface types (overlay and milled) in a laboratory setting in order to identify the performance benefits of engineered tack coats. Monotonic direct shear testing (DST) was employed as a means for evaluating tack coat performance in the laboratory. Interlayer bond quality was measured by Interlayer Shear Strength (ISS) and Interlayer Bond Energy (IBE) response parameters from monotonic DST, which are parameters that are highly indicative of tack coat interlayer bond performance. These parameters were quantified for conventional and engineered tack coats sampled from three different companies for each case. Laboratory-produced samples were compacted using a hydraulic laboratory roller compactor, which better simulated the nuances of roller compaction in the field and yielded interlayer shear core samples that are mimicking the performance of field cores. For milled surface samples, a method of milling in the laboratory was utilized which closely replicated the mean texture depth (MTD) of milled surfaces in the field.

The ISS and IBE of all tack coats were compared using simple bar charts, which clearly highlighted the differences in the response parameters for each case (tack coat type, application rate, and surface type). Statistical analyses were also conducted (Welch two-sample t-test) to produce correlation matrices in order to identify statistically significant differences in tack coat performance between each case.

This study also investigated the impact of adverse conditions on tack coat bond quality, namely presence of dust on the pavement surface, nonuniform coverage/streaking and rainfall after tack coat application. The purpose of this portion of the study was to determine how adverse conditions impact tack coat bond quality, and also identify if newly engineered tack coats are exhibiting better performance than conventional tack coats under these adverse conditions. These conditions, which are issues that commonly arise during asphalt pavement construction in Oregon, were evaluated in a laboratory setting on a laboratory-milled pavement surface using conventional and engineered tack coats at varying application rates. Monotonic DST and ISS/IBE response parameters were again employed to evaluate these adverse conditions. Results from adverse conditions cases were compared to corresponding reference (control) cases. Statistical comparisons between the adverse conditions cases and reference cases were also drawn.

The major conclusions of this study are as follows:

1. The ISS and IBE of engineered tack coats was found to be higher than that of conventional tack coats, in general.

2. Engineered tack coats provided by Company 1 and Company 3 exhibited the best performance for milled surfaces.

3. Engineered tack coats provided by Company 1 and Company 2 exhibited similar performance for overlay surfaces while the performance for Company 3's engineered tack coat was slightly higher than both companies for overlay surfaces.

4. Increased application rates significantly improved the bond quality of tack coats applied to overlay surfaces, indicating that the optimum tack coat application rate for overlay surfaces must be much higher than the low rate (0.05 gal/yd^2) selected for use in this study. More research is needed to determine optimum application rates for each of the tack coats tested in this study.

5. Increased application rates did not necessarily result in improved bond performance in all cases. This was especially true for milled surfaces, where the higher application rate provided diminishing returns in bond quality. Higher application rates actually

decreased ISS/IBE in some cases for milled surfaces, suggesting that the optimum application rate for milled surface tack coats must be close to the low rate (0.09 gal/yd^2) chosen in this study. More research is required to determine optimum application rates for each of the tack coats tested in this study.

6. The Company 2 milled surface tack coat stood out from general trends exhibited by Company 1 and Company 3 milled surface tack coats. Company 2's milled surface tack coat did not achieve better performance than their overlay tack coats or tack coats provided by the other two companies. This result may be attributed to the high water content/low residual asphalt content of Company 2's milled surface tack coat and the possible need to increase the suggested application rate for this tack coat. Additionally, this tack coat was noted to penetrate through the voids of the first list during tack coat application due to its high water content/low viscosity. More research is needed to determine the optimum application rate for this particular tack coat.

7. Engineered tack coats designed for milled surfaces exhibited a foaming action during application which was noted to provide excellent coverage uniformity.

8. The presence of dust on the pavement surface prior to tack coat application resulted in reductions in both ISS and IBE for both conventional and engineered tack coats. These reductions were more discernable at higher application rates. However, these reductions were not statistically significant at a 95% confidence level.

9. Tack coat streaking/nonuniform coverage was found to significantly impact bond quality. Considerable reductions in ISS and IBE were observed at both low and high application rates in both tack coat types (conventional and engineered). Statistical comparisons also showed strong evidence of these conclusions at a 95% confidence level. This result is testament to the importance of uniform coverage and proper tack coat applicator maintenance during construction.

10. The effect of rainfall after tack coat application was determined to negatively impact bond quality for all tack coats. ISS reductions were observed for all samples except CO1-ENGR-M-Low. However, IBE reductions were apparent for all samples, including CO1-ENGR-M-Low. This indicates that IBE may be a better indicator of bond performance than ISS.

11. Rainfall on the freshly tacked pavement surface was noted to rinse away the tack coat, effectively reducing the amount of tack coat available for bonding. However, engineered tack coats were noted to be more difficult to wash away than were conventional tack coats. This observation may suggest that use of engineered tack coats when rainfall is prevalent could help to extend the construction window into seasons with more inclement weather.

12. Engineered tack coats were less susceptible to reductions in ISS and IBE under rainfall conditions than were conventional tack coats, indicating that engineered tack coats are more suitable for pavement construction during inclement weather.

5.0 QUANTIFYING IN-SITU TACK COAT PERFORMANCE USING THE ORETACKBOND, CYCLIC DIRECT SHEAR TESTING AND THE OREGON FIELD TACK COAT TESTER (OFTCT)

5.1 INTRODUCTION

Tack coats are the asphaltic emulsions used during asphalt pavement construction to facilitate bonding between successive asphalt pavement layers. It is applied as an interlayer membrane before pavement construction ensues. It is a paramount consideration for ensuring that pavement layers behave monolithically to transmit stresses and strains from heavy wheel loads through the entire pavement structure instead of localizing at the layers nearest to the surface, which can cause premature fatigue cracking and early pavement failure.

Currently, tack coats are often overlooked during pavement construction. Mohammad et al. (2012) conducted an industry survey on tack coat practices which revealed that a minority of agencies and contractors verify their application rates and coverage uniformity. Furthermore, the survey suggested that the only QC practice enacted by many agencies (51%) for measuring application rate is measurement of change in tack coat volume or weight in distributor trucks before and after construction shifts. 18% of respondents indicated they do not have any QC protocol in place for tack coats. These industry statistics indicate that there is a high degree of inherent variability that plagues tack coat application and verification practices during pavement construction that emanate from disregard of tack coat importance.

In Oregon, issues during construction commonly arise that can compromise tack coat bond quality after the pavement in constructed. During pavement milling operations, where an existing aged pavement is removed from the pavement structure, high amounts of dust are produced. Sweeping and cleaning is a typical practice after milling, but it is common for a significant amount of dust to be retained on the pavement surface after cleaning and before tack coat application. Applied tack coats readily bond to high surface area dust particles, reducing the ability of the tack coat to adequately bond the two pavement layers. Dust also exacerbates tracking, where tack coat material is picked up by construction vehicle tires, since the tack coat has formed a bond with dust particles and fails to stick to the underlying milled pavement surface to which it was applied. Additionally, nonuniform tack coat coverage can create inconsistent bond quality throughout the newly constructed asphalt pavement. Nonuniform coverage, often termed streaking, occurs when tack coat distributor truck applicator nozzles become clogged due to poor maintenance and inspection practices. This causes tack coats to exit the nozzle in a singular stream instead of a fan-shaped distribution that is commonly specified in construction provisions (ODOT 2015). The inability of the tack coat applicator to evenly distribute the tack coat across the pavement surface leaves areas with an absence of tack coat. These barren areas do not have the ability to bond well with the new asphalt layer after construction.

In light of the various quality control/quality assurance (QC/QA) issues pertaining to tack coats that occur during highway pavement construction, there is a need for a means of verifying interlayer bond quality in-situ. Despite the immense use of tack coat as a constituent in asphalt paving, there are no construction specifications with provisions for quantification of tack coat bond quality in laboratory or field settings. Since tack coat bond quality is dictated by a culmination of material and environmental factors, it is difficult to create specifications to achieve high bond quality (Wang et al. 2017). QC and QA practices during construction are performed on a voluntary basis and hence are rarely employed. These two factors lend themselves to the possibility of substandard tack coat bond quality at the pavement layer interface.

In the current scheme of highway construction practice, there is no means of evaluating tack coat bond quality immediately after construction. For this reason, there is nothing to hold the contractor accountable for performing acceptable tack coat application. However, other aspects of highway pavement construction have been incentivized with great success. The advent of intelligent compaction has offered a new means of assessing construction quality of hot mix asphalt (HMA) as it occurs. It has also fostered a new accountability system for the contractor, making them more cognizant of the implications of poor compaction on the resulting pavement and on their project profits. Contractors will be rewarded if they perform good quality construction that results in properly compacted HMA and a smooth roadway. They will also be penalized if construction quality is poor and either of these considerations are not meeting expectations.

Different methods and technologies have been used by ODOT to conduct verification tests as a quality approval for construction methods and materials. Payment for materials and construction is made by following a percent within limits (PWL) specification. Pay factors for asphalt materials are determined by using the test results for asphalt content (26%), aggregate gradation (26%), asphalt moisture content (8%), and in-place density (40%). ODOT is currently in the process of changing the specifications to reduce the asphalt content tolerance from ± 0.5% to ± 0.35% to improve production precision and quality.

A reward/penalization system exists for pavement smoothness in Oregon, whereby an inertial laser profiler will identify areas of localized roughness after pavement construction has been completed. Using a special software called ProVal (ProVal 2018), these areas of localized roughness can be identified. The contractor is then responsible for repairing these areas and ensuring that the roughness level, as measured by the International Roughness Index (IRI), is below a certain threshold. The contractor is rewarded for very smooth pavements and penalized for pavements not meeting the maximum IRI specification. The reward system is built into the project contract as a bid item.

A similar system could be implemented to evaluate tack coat quality after construction using the OreTackBond device [formerly known as Oregon Field Torque Tester (OFTT)], developed by Coleri et al. (2017). The OreTackBond device was previously shown to have a strong correlation with laboratory-measured interlayer shear strength (ISS) of field pavement cores (Coleri et al. 2017; Mahmoud et al. 2017). Figure 5.1 shows the first version of OFTT device developed by Coleri et al. (2017).

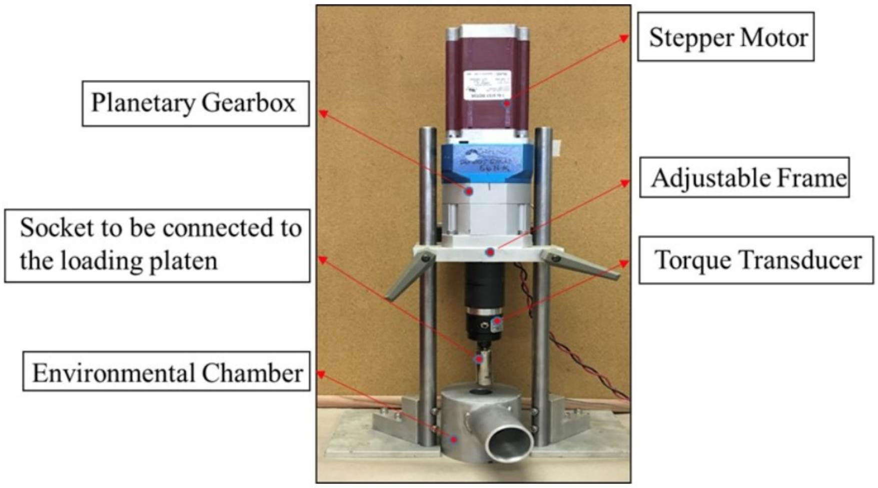


Figure 5.1: First generation OFTT device developed by Coleri et al. (2017).

This device could be easily implemented as a QC/QA tool following construction, in order to evaluate if tack coat application was performed adequately. A similar contractor accountability system could be implemented for this device in Oregon, following the same premise as the intelligent compaction and smoothness bonus systems. For instance, if a desired level of ISS is chosen in advance (which is introduced in this Chapter), the contactor will be rewarded or penalized depending on the ISS measured by the OFTT immediately after construction. If the ISS is extraordinarily low, the contractor should then be responsible for repairing or reconstructing the pavement in order to attain an acceptable bond strength. If the ISS is well-above the predefined threshold, then the contractor would be rewarded with a bonus. In this study, a procedure was proposed to implement OreTackBond (formerly known as OFTT) test for tack bond QC during construction.

ODOT has also begun to use site control software as an inspection tool, which allows inspectors to monitor intelligent compaction and other construction activities throughout the project area remotely from a tablet computer. The tack coat bond QC process developed in this study could easily be integrated into site control software as well, providing the inspector even greater oversight and control over the construction project and allowing them to identify areas with bonding problems in real-time.

5.1.1 Improvements to the OFTT – Development of the OreTackBond system

The Oregon Field Torque Tester (OFTT) is a novel device which facilitates testing of the tack coat interlayer bond shortly after highway pavement construction. This device addresses the need for quantification of tack coat bond quality in the field. The OFTT developed by Coleri et al. (2017) at Oregon State University was updated in this study to improve its practicality and utility for bond strength measurement in the field under various conditions, such as different pavement surface types. The second version of the OFTT was designed with portability and practicality in mind. This latest version was named as **OreTackBond**. OreTackBond name will also be used in this report from now on. The device was fitted to a portable chassis for ease of movement and setup in the field. The device also was affixed with a higher capacity adjustable torque sensor that is better suited for typical bond strengths exhibited by both overlay and milled surface textures and also allows for a simpler test setup. Additionally, the device is now capable of applying a normal load, or confining pressure, to core samples in the field. In this way, the device can capture the interlayer bond behavior in its most critical state, which is under the presence of a truck axle load. A new control module cabinet, motor control software and data acquisition system complement all of these improvements. No external components are needed for operation of the OreTackBond other than a power supply and a laptop computer for data collection. Figure 5.2 shows the newly updated OreTackBond device.

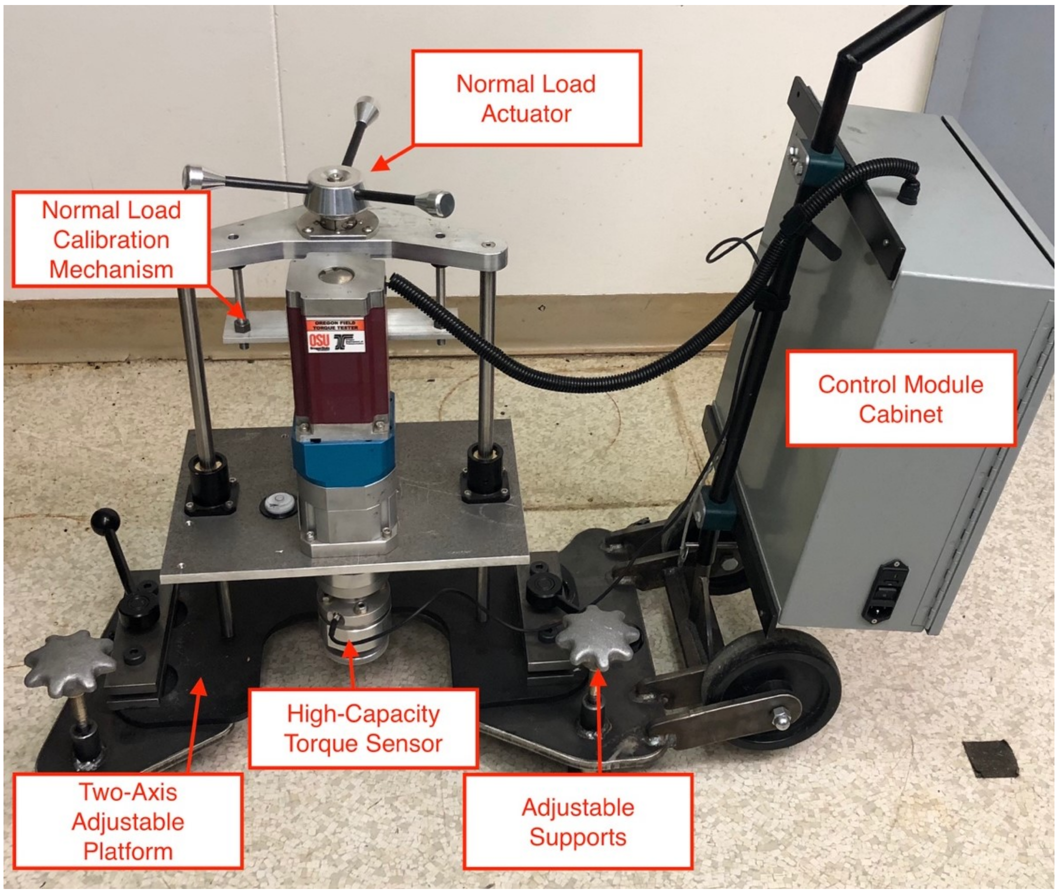


Figure 5.2: 2nd generation OreTackBond device.

A challenge with the first iteration of the OreTackBond in Coleri et al. (2017) was the matching of the OreTackBond torque unit with the metal platen glued on the pavement surface. The hex-shaped platen requires that the torque unit be perfectly lowered onto the platen in a particular orientation such that the male hex pattern of the platen lines up with the female hex pattern of the torque unit. Failure to perform this action properly can result in poor test results.

The newly refined OFTT (called as OreTackBond) now allows for biaxial adjustment of the torque unit to line up the male and female hex patterns in the plane of the pavement surface. An adjustable torque unit allows rotation of the torque sensor to line up the hex patterns perfectly once roughly centered above the platen. Additionally, the normal load actuator allows the torque sensor to be easily lowered down onto the platen once all components are aligned properly. Figure 5.3 shows the metal platens used for OreTackBond testing.

(a) (b) (c) (d)

Figure 5.3: Metal platen used in OreTackBond testing showing (a) hex-shaped shaft, (b) core contact area, (c) platen glued to pavement surface and (d) inspection of failed OreTackBond sample.

In this study, the newly improved OreTackBond is employed to test tack coats in laboratory and field settings. Both newly engineered tack coats and tack coats traditionally used in Oregon were sampled from three companies and tested on both milled and overlay surfaces at manufacturer-recommended application rates. In laboratory tests, two-layer pavement structures were procured in the laboratory and tested in a temperature-controlled environment to quantify tack coat bond quality using an interlayer shear strength (ISS) response parameter. Results of laboratory OreTackBond tests were then compared with corresponding laboratory monotonic direct shear test (DST) results to highlight the suitability of the OreTackBond for accurately quantifying bond quality in the field. Additionally, six field paving projects were visited, where in-situ interlayer bond tests were conducted with the OreTackBond to determine the tack coat bond quality in each case. The results obtained from field tests were then compared against laboratory OFTT test results to identify any bond quality issues that were prevalent on each of the projects. An in-situ tack coat bond quality control process was also developed and proposed in this study.

5.1.2 Oregon Field Tack Coat Tester (OFTCT)

The Oregon Field Tack Coat Tester (OFTCT) was developed previously by Coleri et al. (2017). This wireless device is meant to capture the tack coat bond quality prior to construction of a new pavement layer. It employs a vertical pull-off mechanism to examine the peak tensile resistance of the tack coat to a vertical load. This experiment simulates the tack coat's response to tensile stress of a pavement layer, which commonly occurs ahead of a moving wheel load. This failure mode is shown below in Figure 5.4.

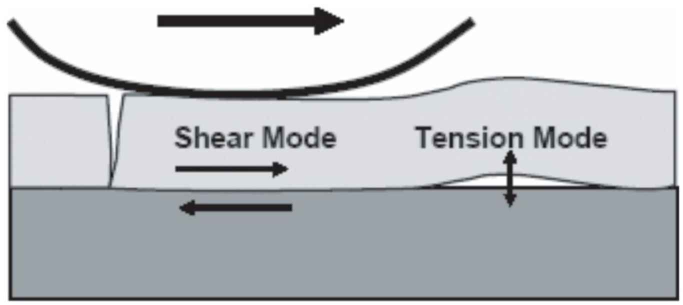


Figure 5.4. Diagram of shear and tensile strength modes under field conditions (Mohammad et al. 2012).

The OFTCT device was employed in this study to evaluate tack coat bond quality in a laboratory setting. Laboratory tests using the OFTCT on several tack coats, both conventional and engineered, were correlated with laboratory monotonic DST results to highlight similarities, if any, in the prediction of tack coat bond quality before construction.

5.1.3 Cyclic DST

Cyclic DST is a novel method of bond strength measurement and is more representative of loading experienced by the interlayer in the field. This test method simulates a real-world scenario where the interlayer bond is subjected to repeated loading from traffic and will help to estimate in-situ bond performance over time. This test protocol was adopted in this study to identify the fatigue performance of engineered and conventional tack coats on milled and overlay surfaces. Results from this test were also compared against monotonic DST results in order to evaluate the comparability of results between the two tests for various tack coat types and application rates.

5.1.4 Objectives

The objectives of this study are as follows:

- Implement improvements to the first-generation OreTackBond device to improve its mobility, practicality and function under different pavement surface conditions,
- Quantify tack coat bond quality using the OreTackBond in a laboratory setting,
- Compare results of laboratory OreTackBond and OFTCT tests to monotonic DST laboratory tests to determine the effectiveness of OreTackBond and OFTCT in predicting interlayer bond strength in the field,
- Quantify the fatigue performance of tack coats using cyclic DST and draw comparisons between cyclic DST and monotonic DST results,
- Test bond quality of tack coats in-situ using OreTackBond on various field paving projects in Oregon and compare these results to laboratory OreTackBond tests,

- Using the OreTackBond field test results, develop and propose an in-situ tack coat bond quality control process, and

- Identify tack coat bond quality issues that were prevalent at each of the field projects.

5.2 MATERIALS AND METHODS FOR ORETACKBOND TESTING

5.2.1 Laboratory OreTackBond testing

Field pavement testing presents a unique set of challenges. It is impossible to predict what conditions will be present on a highway paving construction site, whether it be construction delays, equipment issues or environmental conditions. In terms of problems affecting the asphalt interlayer bond specifically, delays can impact the amount of time available to perform milling of existing pavement, sweeping, tack coat application and proper tack coat curing time. Equipment problems can create variability in the milling depth, cleanliness of the pavement surface or the uniformity of tack coat application and rate. Finally, environmental conditions can be ever-changing, creating inconsistencies in temperature, humidity, wind speed and rainfall events, all of which directly impact the curing time of tack coats and the performance of the interlayer bond. For these reasons, obtaining information about the pavement interlayer bond in the field can be challenging, and due to the myriad of factors that can influence the results, the information yielded can be highly variable. It is therefore desired to test tack coat interlayer bond performance in ideal conditions using the OreTackBond in a laboratory setting. In this way, the factors discussed above can be controlled and their impact on variability in the results can be minimized such that high-quality data about tack coat performance can be obtained, with the ultimate goal of implementing a field interlayer bond test protocol that will accurately gauge the quality of tack coat bonding in the field after construction.

5.2.1.1 Experimental design for laboratory OreTackBond testing

In this study, it was of specific interest to test a variety of tack coats, both conventional and engineered, in a laboratory setting using the OreTackBond to identify the aptitude of this device to accurately predict tack coat bond quality. Testing using the updated 2nd generation OreTackBond device was performed in the laboratory in order to determine the correlation between OreTackBond and monotonic direct shear test results. Monotonic direct shear testing (DST) provides a peak shear strength parameter from which to make meaningful comparisons to bond strength obtained from OreTackBond testing. Table 5.1 below shows the experimental plan set forth for this study.

Table 5.1. Experimental Plan for Laboratory OreTackBond Testing.

Test Type	Company & Tack Coat Type	Surface Type	Application Rate (gal/yd^2)	Replicates	# of Tests
OreTackBond	CO1-CSS1H CO1-ENGR-O/M CO2-ENGR-O1/M2 CO3-CSS1 CO3-ENGR-OM	Overlay, Milled	Overlay: 0.05	5	50
Monotonic DST			Milled: Manufacturer-Suggested Rate (Table 5.2)	4	40

Company 1 provided one conventional tack coat (CSS-1H) and two engineered tack coats specific to overlay and milled surfaces (ENGR-O and ENGR-M). Company 2 provided two engineered tack coats, one that was specific to overlay surfaces (ENGR-O1) and one designed for use on milled surfaces (ENGR-M2). Company 3 provided a conventional CSS-1 tack coat and one engineered tack coat designed for use on both overlay and milled surfaces (ENGR-OM).

The application rate selected for overlay surfaces was chosen based on experiences from Coleri et al. (2017) and was also based on the range of application specified by the Oregon Standard Specifications for Construction (ODOT 2015). Milled surface application rates followed manufacturer-recommended rates. Application rates used were for undiluted tack coat and do not represent residual application rates. Manufacturer-recommended application rates for milled surfaces are shown below in Table 5.2.

Table 5.2: Manufacturer-recommended Application Rates for Milled Surfaces.

Company	Tack Coat Types	Application Rate (gal/yd^2)
CO1	CSS1H ENGR-M	0.060 0.065
CO2	ENGR-M2	0.080
CO3	CSS1 ENGR-OM	0.059 0.061

Additionally, Company 3 requested that the residual rates of Company 1 be matched. The residual rate for CSS-1H for company 1 was used for Company 3's CSS-1 tack coat. Residual rates for Company 1 tack coats were back-calculated using the water content of the emulsion and Equation 5-1, shown below. Average water contents and densities of the tack coat emulsions were measured in this study and are shown in Table 5.3.

$$\text{Residual Rate} = \text{Application Rate} * (1 - \text{Water Content}) \quad \textbf{(5-1)}$$

Table 5.3: Summary of Tack Coat Emulsion Water Contents and Densities

Tack Coat Type	Initial Mass (g)[a]	Water Distilled (g)	Water Content (%)	Density (g/mL)
CO1-CSS1H	93.0	36.0	38.7	0.991
CO1-ENGR-O	92.7	31.0	33.4	-
CO1-ENGR-M	95.7	39.3	41.1	0.920
CO2-ENGR-O2	94.6	38.2	40.4	-
CO2-ENGR-M2	93.8	64.5	68.8	1.023
CO3-CSS1	92.5	33.9	36.7	0.971
CO3-ENGR-OM	91.5	30.8	33.7	0.956

[a] 1.0 g = 2.20×10^{-3} lbs

The mean texture depth (MTD) of each laboratory milled surface OreTackBond sample tested was collected and recorded. Laboratory milling processes were precise enough to replicate MTD of milled surfaces in the field and therefore addressed any texture-related bias that may exist in field interlayer bond quality.

5.2.2 OreTackBond field testing

Tack coat bond quality issues that have become increasingly prevalent in Oregon, increasing the propensity for early fatigue cracking to develop and impacting the longevity of asphalt pavements on Oregon highways. A lack of specifications for verification of tack coat application during construction is one of the contributing factors to this problem. Other than visually-based criteria, no measures are taken to quantify the tack coat bond quality during or after highway pavement construction. In order to address the rapidly-emerging issue of premature fatigue cracking of Oregon pavements, it is necessary to implement an accurate and reliable method of determining tack coat bond quality in pavements after construction ensues so that bond quality issues can be identified and rectified before pavements enter their service life. In light of the issues noted above, the OreTackBond was employed in a field study to test the tack coat bond quality. The OreTackBond has showed promise in previous studies to accurately quantify tack coat bond quality immediately after construction and identify potential debonding issues that might develop during the pavement's service life (Coleri et al. 2017; Mahmoud et al. 2017).

In this study, OreTackBond testing was conducted to evaluate the in-situ performance of engineered tack coats applied for newly-placed asphalt pavements in various regions of Oregon. Engineered tack coats are gradually being implemented in Oregon and the bond quality of these materials in a real-world field setting was of specific interest in this study. OreTackBond results obtained from field testing were then compared with results from OreTackBond laboratory test results. This comparison was meant to identify if the results from OreTackBond field testing are capturing the expected response from each tack coat type and to provide understanding about how bond quality in field pavements could be improved, since laboratory OreTackBond tests represent ideal conditions for interlayer bonding.

5.2.2.1 Experimental design for field OreTackBond testing

In this study, OreTackBond tests were conducted at six different construction projects across Oregon (See Table 5.4). Except Project#3, all tack coat bond tests were conducted on the milled surfaces. However, since the pavement surface for Project#3 had a mean texture depth (MTD) close to the average MTD for all other sections with milled surfaces (MTD for Project#3 was 0.088inches while the MTD average from all sections was 0.083inches), results from Project#3 were also included in the final implementation analysis for milled surfaces. In other words, the bond layer for Project#3 was assumed show a response that is similar to the milled surfaces due to its high texture. The use of each company's emulsion was project-dependent. Table 5.4 below summarizes the experimental plan for OreTackBond field testing for each paving project.

Table 5.4: Experimental Plan for OreTackBond Field Testing.

Projects	Company	Tack Types	Target application rate (gsy)	Surface Type
3	CO3	ENGR	0.066	Overlay
4	CO2	ENGR	0.065	Milled
5	CO1	CSS1	0.065	Milled
6	CO1	CSS-1H	0.120	Milled
7	CO1	CSS1	0.090	Milled
8	CO1	ENGR	0.065	Milled

To characterize tack coat bond quality from field OreTackBond tests, an interlayer shear strength (ISS) response parameter was considered. The OreTackBond field results were compared against the OreTackBond results obtained in laboratory testing for corresponding tack coat types and surface types. Laboratory OreTackBond samples had engineered tack coats that were applied at manufacturer-recommended application rates (Table 5.2). Field application rates are summarized in Table 5.4. Since no laboratory OreTackBond test results were available for Project 5 and Project 7 tack coats (CO1-CSS1), corresponding laboratory test results for these two projects were not presented.

5.2.3 OreTackBond sample preparation and testing methodology

The OreTackBond is versatile in the sense that it can be applied to laboratory-produced samples or pavements in the field. Since it only requires shallow-depth 2.5-inch diameter pavement cores, the test is considered to have a low damage impact in comparison to more conventional pavement testing methodologies that require full-depth 6-inch diameter pavement cores. To quantify tack coat bond quality, the OreTackBond uses a torsional force applied at a constant angular displacement rate to target failure at the pavement layer interface where tack coat is applied. In this way, the shear resistance of the tack coat bond can be quantified using an algorithm to convert the torsional resistance to an interlayer shear strength (ISS) [Equation 5-2]. The only prerequisite information required for this test is the thickness of the surface course pavement layer.

The following sections describe the methodology for procuring and testing OreTackBond samples in the laboratory and in the field.

5.2.3.1 Sample preparation for OreTackBond lab tests

OreTackBond testing in the lab was performed on two-layer asphalt pavement samples with both milled and overlay surfaces. Each step of the sample preparation process for pavement samples is described in detail in Section 3.4.1. The steps involved with laboratory and field OreTackBond testing are detailed below and shown pictorially in Figure 5.5

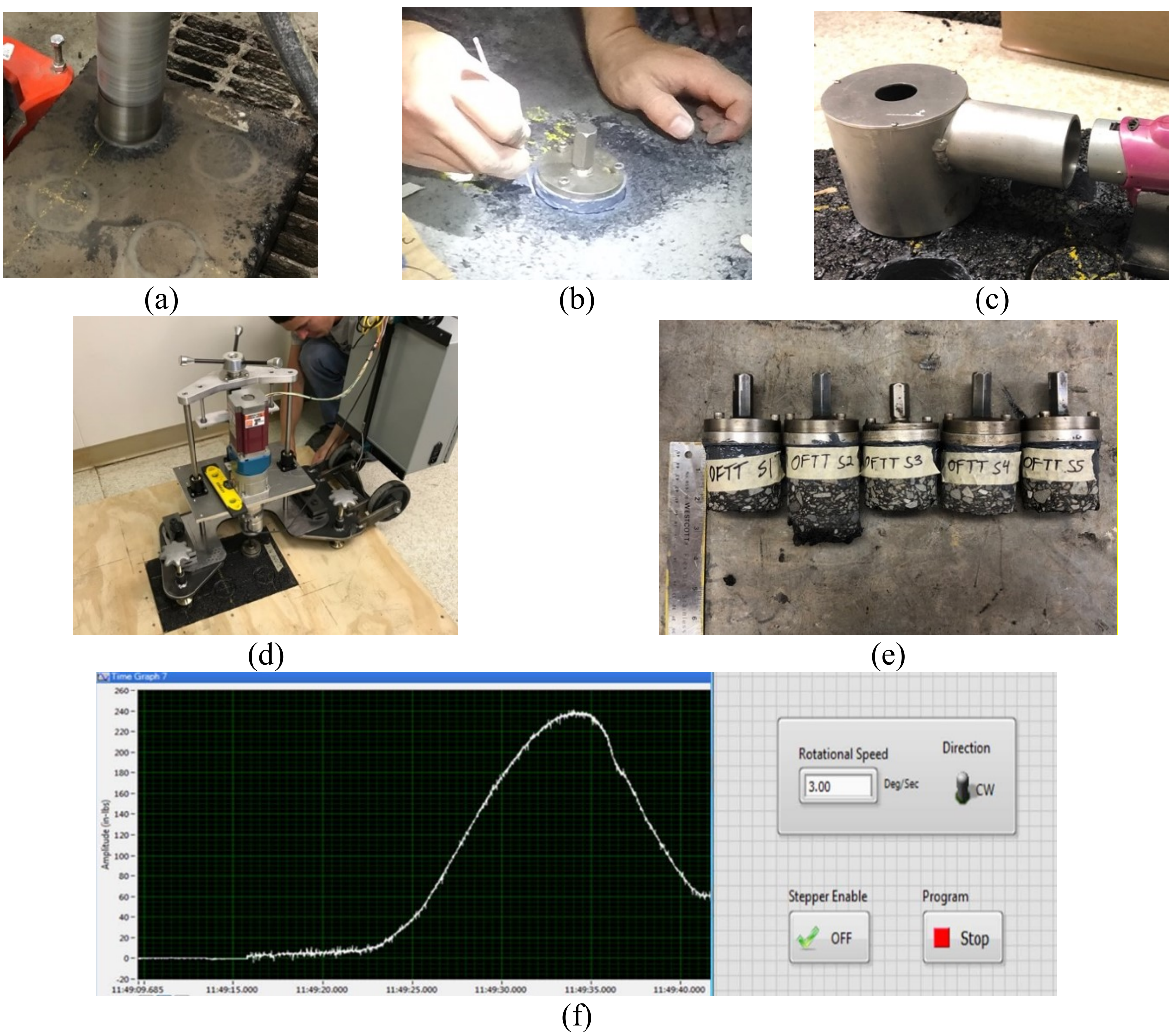


Figure 5.5: General sample preparation and testing procedure for OreTackBond tests in the laboratory and field.

5.2.3.2 Coring and gluing of platens

To test the shallow-depth pavement core, custom metal platens (Figure 5.3) are glued to the surface of the pavement core using high-strength epoxy, such that the applied torsional force will translate through the pavement core to the tack coat bond. First, the pavement is cored to a depth that is 0.25 inches below the location of the pavement layer interface using a 2.5-inch diameter core drill bit. Since the core is not full-depth, the core is retained in the pavement. The core and tack coat bond are checked for damage before cleaning the core thoroughly of sediment and debris. The core is also dried thoroughly using a blower. Figure 5.5a shows coring of shallow-depth OreTackBond samples taking place.

Once the core was clean and dry, the metal platens were glued to the pavement surface. To avoid torsional failure at the interface between the platen and the epoxy, a specific amount of epoxy was used for gluing that was discovered by trial and error. The sides of the core were encased in 20g of epoxy and the platen/core interface was bonded by 15g of epoxy. The sample was encased in epoxy around the circumference of the core to avoid failure from the asphalt layer, which occurred in couple of cases in newly placed pavements during the development of this research. This was done very carefully to avoid any contact of the epoxy between the core and the pavement. In this way, failure is forced to occur at the tack coat bond. Epoxy was allowed to cure for the manufacturer-recommended curing time of one hour. Figure 5.5b shows the OreTackBond platen being glued to the pavement core surface.

5.2.3.3 Temperature conditioning of OreTackBond samples

The target temperature for OreTackBond testing was 25°C. Temperature conditioning was performed as needed for OreTackBond samples. In the laboratory, samples were stored and tested in a temperature-controlled environment, so additional conditioning was not necessary. In the field, temperature and climatic conditions were much more variable, so conditioning was necessary in some cases. Cooling of the pavement was performed using ice. Trials in the laboratory with regular ice and dry ice showed that regular ice produced the optimal rate of cooling and was selected for use in the field. Heating of the pavement surface was done using a custom chamber and an adjustable heat gun. Figure 5.5c shows the temperature conditioning apparatus. A testing temperature tolerance of ± 1°C was adopted, consistent with laboratory shear testing specifications (ALDOT 2008).

5.2.3.4 OreTackBond setup and testing

Once the epoxy was fully cured and testing temperature was reached, the OreTackBond was roughly positioned over the hex shaft of the platen. The biaxial adjustment of the OreTackBond was utilized to position the torque sensor directly over the platen shaft. The torque sensor was lowered onto the platen shaft after rotating the torque sensor to align the male and female hex patterns. Although the OreTackBond is capable of applying controlled vertical confining pressure on the platen using a calibrated spring system, no confining pressure was used for OreTackBond laboratory tests. Figure 5.5d shows the setup of the OreTackBond in the field.

Torsional displacement at a constant rate was applied to the pavement core until failure was reached. Custom data acquisition and motor control software was used to perform the test. Torque testing was performed at a constant angular displacement rate of 2 deg/sec. Trial and error led to this decision, as the displacement rate of 3 deg/sec used previously in Coleri et al. (2017) and Collop et al. (2011) for overlay surfaces was not suitable for milled surfaces. This higher angular displacement rate was causing failure from the asphalt layer instead of the tack coat bond. Reducing the displacement rate in this study was found to eliminate this problem and was adequate for both milled and overlay surfaces. The test was allowed to run long enough to capture the full torque-displacement curve. Figure 5.6 shows an example of the raw torque-displacement data obtained in the OreTackBond software.

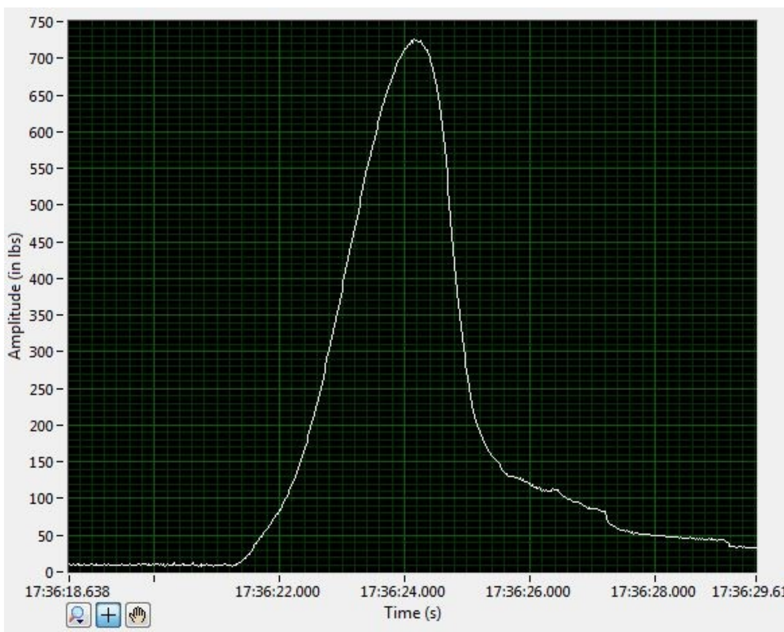


Figure 5.6: Raw torque-displacement data obtained from OreTackBond testing in custom software.

After completion of the test, the failed pavement core was removed and inspected to ensure that failure indeed occurred at the tack coat bond and not in the asphalt layer. Figure 5.5e shows inspection of OreTackBond samples after testing. Figure 5.5f shows an example of the torque-displacement curve output by the OreTackBond data collection software.

Results from OreTackBond tests were interpreted using a custom algorithm to convert the torsional resistance curve of the tack coat bond to a stress-displacement curve. Equation **Error! Reference source not found.**, below shows the expression used to convert torque to shear strength. The curve was filtered for noise using a Matlab code which employed a loess smoothing function with a smoothing coefficient of 0.08. It was found through trial and error that this function and smoothing coefficient provided adequate noise filtering while still fitting the curve well. From the smoothed curve, peak shear strength and interlayer bond energy parameters were extracted.

$$\tau = \frac{12M \times 10^6}{\pi D^3} \tag{5-2}$$

5.2.4 OFTCT sample preparation and testing methodology

5.2.4.1 Experimental plan for OFTCT testing

Table 5.5 below shows the experimental plan for OFTCT testing in the laboratory.

Table 5.5. Experimental Plan for OFTCT Testing

Company	Tack Types and Application Rates (gal/yd^2)	Surface Type	Replicates	# of Tests
CO1	0.060 - CSS1H 0.065 - ENGR-M	Overlay	6	12
CO2	0.080 - ENGR-M1/2	Overlay	6	12
CO3	0.058 - CSS1H 0.059 - CSS1 0.061 - ENGR-OM	Overlay	6	18

OFTCT testing occurred on single-layer asphalt block samples with an overlay surface. Sample preparation for asphalt block samples is detailed in Section 3.4.1.

The OFTCT device was positioned above the asphalt sample after tack coat application and curing. A foam platen was affixed to the overlay surface on the cured tack coat. The wireless device was actuated from a custom software. The peak tensile load observed before bond failure was recorded for each case.

5.2.5 Cyclic DST sample preparation and testing methodology

5.2.5.1 Experimental plan for cyclic DST

A comprehensive experimental plan was developed for evaluation of tack coat bond quality using cyclic DST. Cyclic DST was performed on both overlay and milled surfaces using conventional and engineered tack coats at various application rates. Table 5.6 below shows the experimental plan for cyclic DST.

Table 5.6. Experimental Plan for Cyclic DST

Test Type	Company & Tack Coat Type[1]	Surface Type	Application Rate (gal/yd^2)	Replicates	# of Tests
Cyclic DST	CO1-CSS1H CO1-ENGR-O/M CO2-ENGR- M2 CO3-CSS1 CO3-ENGR-OM	Overlay, Milled	Overlay: 0.05 (Low) 0.09 (High) Milled: Manufacturer-Suggested Rate (Table 5.2)	4	40
Monotonic DST				4	40

[1] Only engineered tack coats were used on overlay surface tests.

For cyclic DST, only engineered tack coats were used on the overlay surface, since their performance under a repeated loading condition was of specific interest.

5.2.5.2 Sample Preparation for Cyclic DST Samples

Sample preparation for cyclic DST samples followed the same procedure outlined in Section 3.4.1.

5.2.5.3 Cyclic DST Testing Methodology

Cyclic DST was performed using the same jig and testing equipment as was used for monotonic DST (Section 3.4.2). A custom UTM software template was utilized which applied a 1.25 kN load at a 10 Hz loading frequency. A maximum of 200,000 cycles was adopted for the cyclic test in order to examine the primary, secondary and tertiary flow stages of permanent deformation at the tack coat interlayer (Amelian and Kim 2017). A fatigue failure criteria of permanent strain accumulated at 200,000 cycles was adopted to quantify the fatigue performance of tack coats. In cases where the sample failed at less than 200,000 cycles, the data was extrapolated out to 200,000 cycles using linear interpolation.

5.3 RESULTS OF ORETACKBOND TESTING

5.3.1 ISS results from OreTackBond lab testing

The response parameter used for quantifying tack coat bond quality in OreTackBond testing was interlayer shear strength (ISS). Figure 5.7 shows the average ISS response for each tack coat tested on both milled and overlay surfaces. The "-O" designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to an overlay surface, and does not depict the intended design surface type of these tack coats. Error bars indicate ±1 standard deviation.

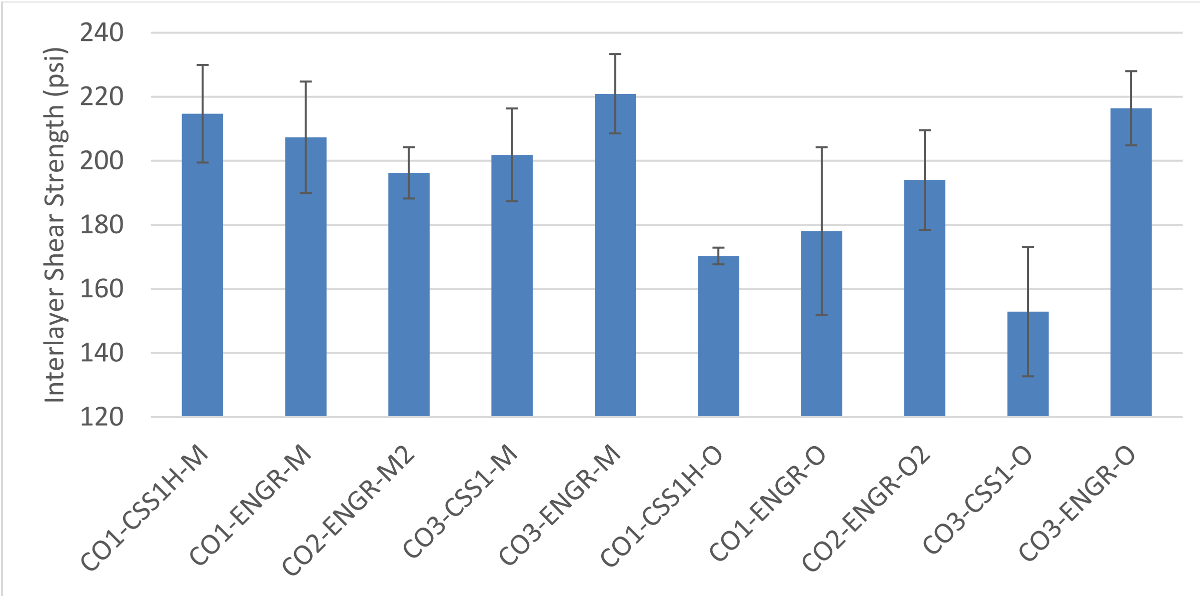


Figure 5.7: Average ISS response from OreTackBond testing for all tack coats with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa).

As can be observed in Figure 5.7 above, tack coats applied to milled surfaces exhibited considerably better ISS than did tack coats applied to overlay surfaces. This is expected, since the increased surface texture of milled surfaces serves to improve the tack coat bond strength due to aggregate interlock (Coleri et al. 2017; FHWA 2016; Mohammad et al. 2010). Also, considering the nature of the torque test, where the cylindrical core sample is rotated about its central axis to target torsional failure of the tack coat bond, the impact of aggregate interlock becomes more dominant, as the grooves of the milled surface provide additional resistance against the rotating core.

Also evident from Figure 5.7 is the improved bond quality of engineered tack coats. Engineered tack coats generally hold an advantage over conventional tack coats in terms of ISS. This conclusion was also made from the results of monotonic DST which are discussed in Chapters 3.0 and 4.0. One exception to this is CO2-ENGR-M2, which has a slightly lower ISS than CO3-CSS1-M. This result suggests that this particular tack coat is not improving bond quality beyond what is seen with conventional tack coats. This tack coat had a very high water content, which translated into a low amount of residual asphalt available for interlayer bonding at the manufacturer-recommended application rate. This result indicates that an optimum application rate should be determined for this tack coat. More research is needed to determine optimum application rates for tack coats tested in this study.

5.3.1.1 Comparison of OreTackBond ISS with monotonic DST

In order to determine if OreTackBond laboratory testing was capturing the true response of each tack coat type in this study, OreTackBond ISS results were compared against monotonic DST ISS results. In this way, the suitability of OreTackBond testing for capturing the true behavior of each tack coat type on milled and overlay surfaces could be identified. Comparisons between the test types was done by plotting OreTackBond ISS against monotonic DST ISS to determine, in general, if the results obtained from each of these tests possessed similar trends for each tack coat and surface type tested.

Figure 5.8 shows correlation plots for ISS of OreTackBond and monotonic DST for tack coats tested on overlay surfaces only, and tack coats tested on milled surfaces only. Coefficients of determination are displayed on each plot to gauge the strength of the correlation between the two test types. Error bars indicate ± 1 coefficient of variation (COV).

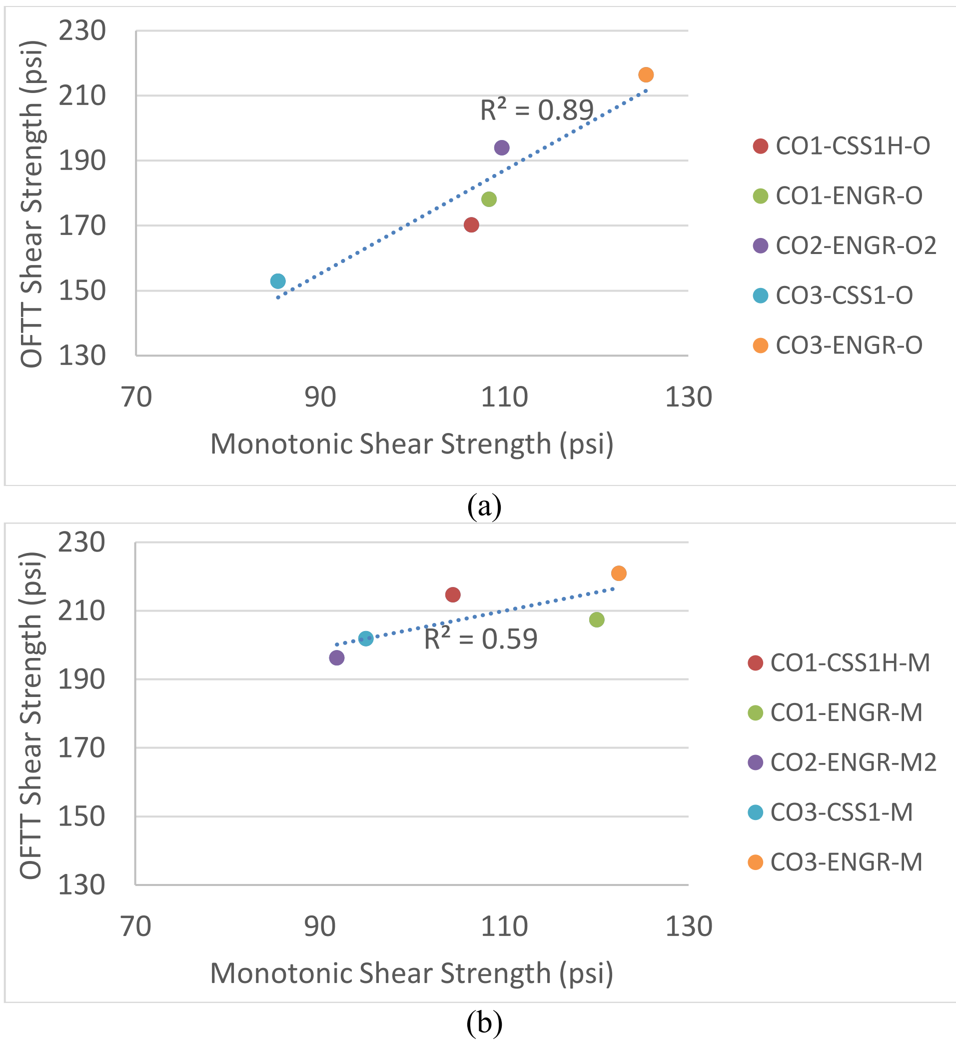


Figure 5.8: Correlation plots for ISS of OreTackBond and monotonic DST for (a) tack coats tested on overlay surfaces only, and (b) tack coats tested on milled surfaces only (1.0 psi = 6.89 kPa).

As can be seen in Figure 5.8 above, ISS results obtained from OreTackBond testing were well correlated ($R^2 = 0.89$) with monotonic DST ISS results for overlay surfaces. This is not unreasonable to believe, as overlay surfaces typically have lower variation in macrotexture, so the contribution of surface texture to ISS is minimal.

The milled surface did not exhibit as good of a correlation ($R^2 = 0.59$) between OreTackBond and monotonic DST ISS results although the correlation was statistically significant. Although this correlation is lower than that of OreTackBond/monotonic DST ISS on overlay surfaces, it is still significant. The reduced coefficient of determination can be attributed to the surface texture of milled surface samples, which is inherently less uniform then overlay surfaces. This nonuniform texture can create additional aggregate interlock, which has the propensity to skew the ISS results for milled surface tack coats, especially when considering the difference between failure modes for monotonic DST and OreTackBond tests. The rotational aggregate interlock brought on by the torsional failure mode of the OreTackBond tests may also be imparting additional variability into the results for these tests. Since monotonic DST tests do not create a torsional twisting motion, they are less susceptible to the lateral aggregate interlock that occurs against the grooves of the milled surface. Another important detail to point out regarding OreTackBond ISS results on milled surfaces is that these tests were performed without confining pressure, whereas the monotonic DST tests were performed with 20psi confining pressure. Applying confining pressure in OreTackBond tests inherently introduces more variability due to the torsional failure mode of the OreTackBond samples. This key difference in testing methodology may also explain the ISS correlation between these two test types, although the ISS correlations between monotonic DST and OreTackBond tests were generally strong.

5.3.2 OreTackBond field tests versus OreTackBond lab tests

Results from OreTackBond testing were obtained from six construction projects in Oregon. OreTackBond field test results were compared with OreTackBond laboratory test results to determine, in general, if field OreTackBond tests were capturing the expected response from each tack coat type and also identify if tack coat bond quality in the field is adequate.

Figure 5.9 below shows the average ISS response for OreTackBond field tests and OreTackBond laboratory tests. Error bars for field test results indicate one standard deviation.

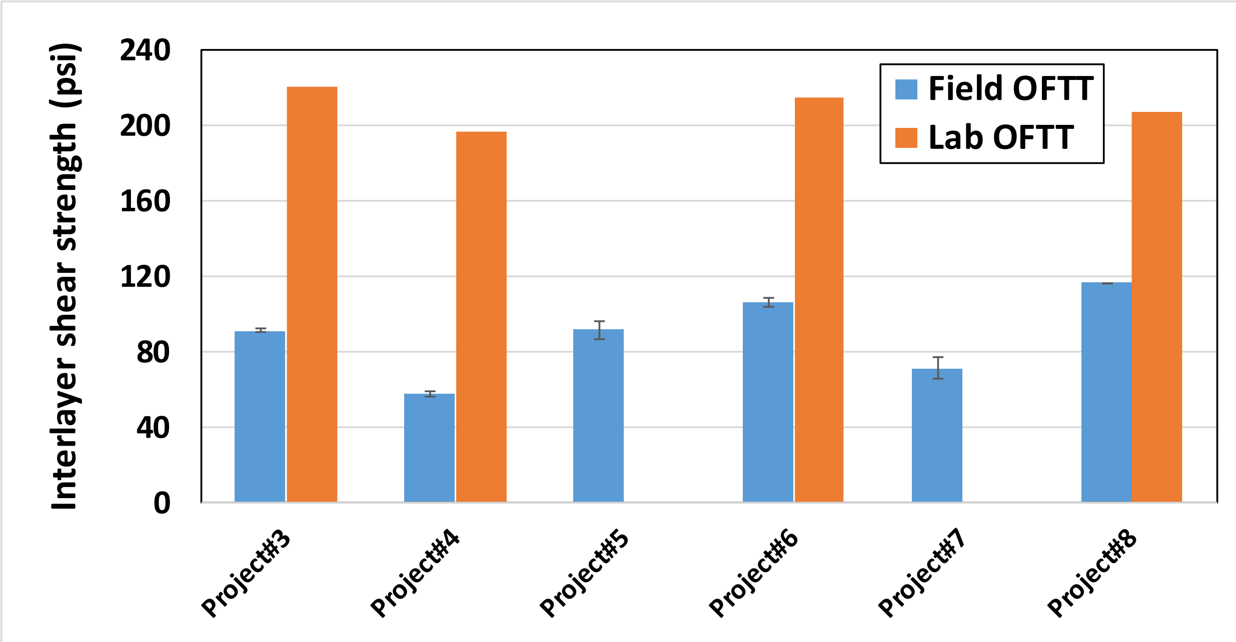


Figure 5.9: Average ISS response of OreTackBond field tests versus OreTackBond lab tests, with error bars indicating one standard deviation (1.0 psi = 6.89 kPa).

As can be seen in Figure 5.9 above, the average ISS of field-tested OreTackBond samples was significantly less than that of OreTackBond laboratory tests. This disparity is due to the ideal conditions in which laboratory sample preparation and testing took place. Field conditions are much more variable (presence of dust on pavement surface, nonuniform tack coat coverage, environmental conditions) and hence interlayer bond quality is likely to be diminished in field-measured results. Also, application rates for CO2-ENGR (Project#4) and CO3-ENGR (Project#3) were fairly close to the application rates used for OreTackBond lab testing, so a disparity in application rates is likely not the cause of the difference in average ISS for these tack coats.

Considering the diminished bond quality captured by OreTackBond tests in the field, it can be inferred that tack coat bond quality in the field is significantly affected by extraneous variables during construction. Laboratory tests offered excellent control over factors such as surface contaminants, tack coat coverage uniformity and environmental conditions. Since control over these factors was monitored less intently during field construction of pavements, the tack coat bond in the field did not achieve the desired level of performance. Three of the field projects occurred on milled surfaces, where the presence of dust on the pavement surface may have been a factor impacting tack coat bond quality. All projects may have experienced nonuniform tack coat coverage or streaking, as this issue commonly occurs in the field due to lack of maintenance and inspection of tack coat distributor equipment. These results highlight the importance of rigorous inspection of surface condition, equipment and materials placement during tack coat application in the field and the need to implement more stringent specifications for tack coat application in highway pavement construction.

5.4 PROPOSED ORETACKBOND TEST IMPLEMENTATION PROCESS FOR QC

In this section, an implementation process developed for OreTackBond (formerly known as Oregon Field Torque Test - OFTT) for tack coat bond quality control is presented. The OreTackBond testing process described in Section 5.2.3 should be followed for conducting the field experiments. In this study, OreTackBond tests were conducted at six different construction projects across Oregon (See Table 5.4). Except Project#3, all tack coat bond tests were conducted on the milled surfaces. However, since the pavement surface for Project#3 had a mean texture depth (MTD) close to the average MTD for all other sections with milled surfaces (MTD for Project#3 was 0.088inches while the MTD average from all sections was 0.083inches), results from Project#3 were also included in the final implementation analysis for milled surfaces. In other words, the bond layer for Project#3 was assumed to show a response that is similar to the milled surfaces due to its high texture. Figure 5.9 shows the average interlayer shear strength (ISS) from all six construction projects. The length of the errors brackets on each bar represents one standard deviation for the test results from this project. The small lengths for all error brackets point out the repeatability of OreTackBond tests. It can be observed that the highest ISS was observed in Project#8 while the lowest one was for Project#4.

Figure 5.10 shows the probability density for the test results from all six projects. It can be observed that developed distribution is close to a normal distribution although there is a local peak closer to the global peak point. Since the global peak of the distribution matches the average ISS for all six projects (88.8psi) and the distribution resembles a normal distribution, a cumulative distribution developed from the mean (88.8psi) and standard deviation (21.8psi) of ISS values from all six projects was assumed to represent the ISS distribution for milled surfaces in Oregon. Based on the conducted probabilistic analysis (using the mean and standard deviation from six projects), a cumulative probability curve shown in Figure 5.11 was developed for the implementation of the in-situ quality control process. It can be observed from Figure 5.11 that 50%, 75%, and 90% reliability levels match with 88.8psi, 103.5psi, and 116.7psi ISS values, respectively. In a future construction project, an average ISS of 103.5psi from all replicate field OreTackBond tests means that ISS of this particular project is higher than 75% of the Oregon construction projects for milled surfaces while it has an ISS lower than 25% of the projects. Developed curve can also be used to determine the reliability level (cumulative probability value for a specific average ISS value) for any average ISS from a construction project. This corresponding reliability level can be used in pay factor analysis to reward the contractors with high average ISS values.

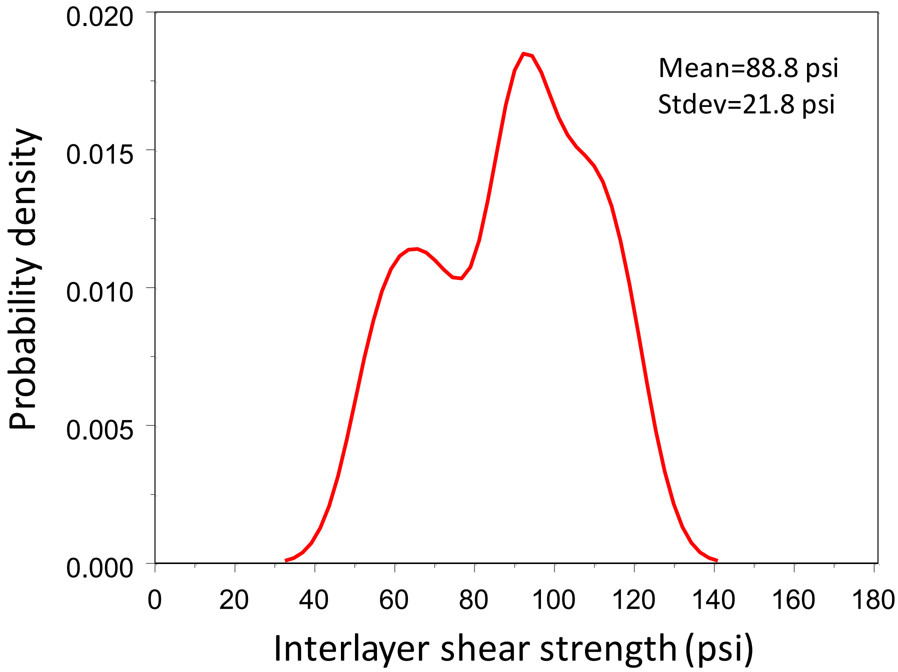


Figure 5.10: Probability density for the test results from all six projects.

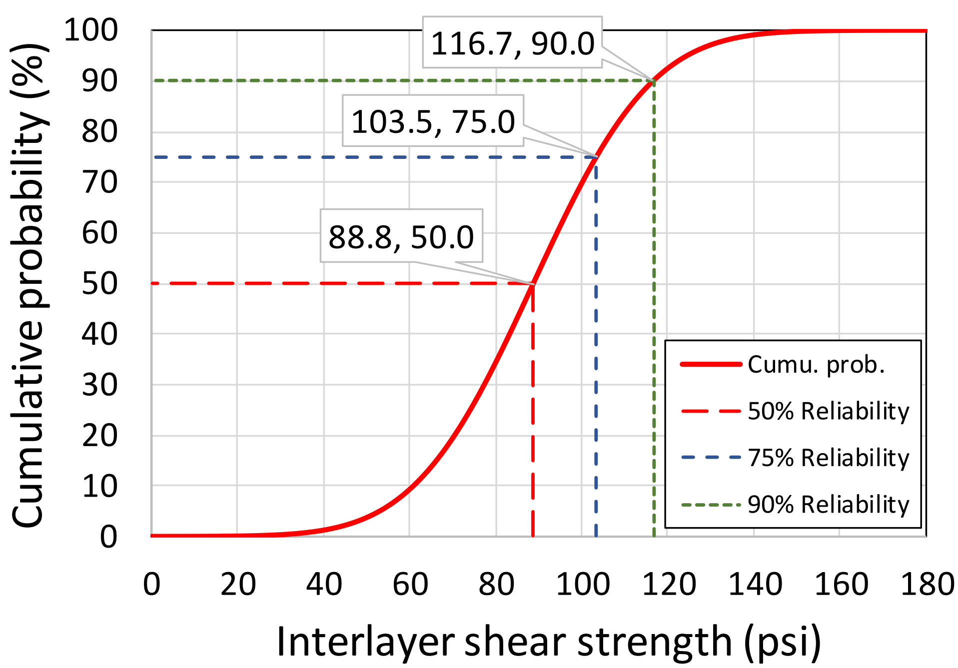


Figure 5.11: Cumulative probability curve representing milled surface bond strength distribution in Oregon.

For the quality control (QC) process proposed in this study, OreTackBond tests should be conducted on the cold mat one day after the overlay construction (preferably within the first couple of days after the start of the construction project). At the start of the QC implementation process, an acceptance threshold of 88.8psi (50% reliability level) can be used in a “shadow” specification. ISS values for two of the construction projects evaluated in this study fail to meet this threshold while the other four projects meet the criterion. If the contractor fails to meet this threshold, a second set of OreTackBond tests can be conducted within the next two construction days. During this two day period, contractor will be allowed to change anything related to the tack coat application process (distributor truck adjustments, changes to sweeper systems, changing tack coat application rates, using a different tack coat type, etc.). If the average ISS from the second trial is higher than 88.8psi, tack coat quality will be approved. If the average ISS is again under the threshold, contractor can be penalized for low bond strength. The process can also be set to reward the contractors significantly exceeding the ISS threshold. It is recommended that this QC process should be implemented as a “shadow” specification for the first year before incorporating it into current construction specifications. The data collected within the first year can also be used to modify the cumulative probability curve (Figure 5.11) developed in this study.

Implementation of this proposed QC process (with the implementation of other QC technologies and procedures developed in this study and presented in Chapter 6.0) is expected to reduce delamination related distresses in Oregon and improve the overall longevity of pavement structures. ISS acceptance threshold can be increased over the years as the new tack coat QC technologies are implemented (described in 6.0) and newer emulsion types are introduced. Measured ISS values will also provide valuable information for ODOT’s pavement management system (PMS). The correlation between ISS and long-term pavement performance can be determined based on the PMS data that will be collected during the 6-7 year period after the implementation of this process.

5.5 RESULTS OF OFTCT TESTING

OFTCT testing was performed in the laboratory using tack coats and application rates described in Table 5.5. Results of OFTCT tests were correlated against monotonic DST test results from Section 3.5. A plot showing the correlation between these results is presented below in Figure 5.12.

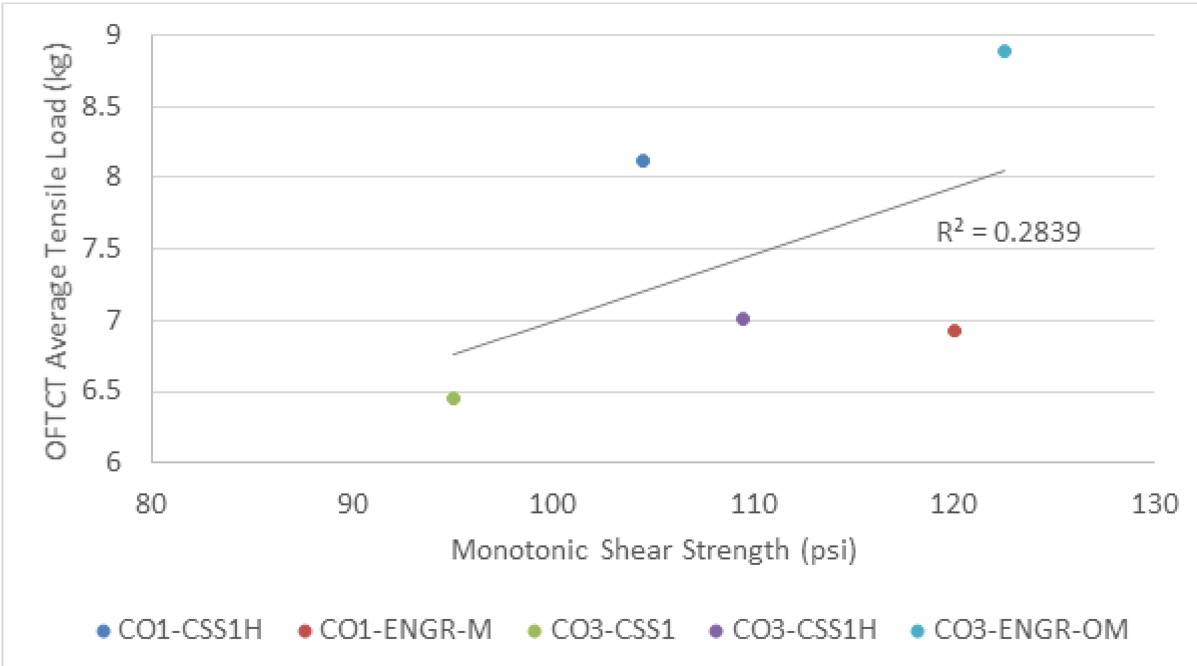


Figure 5.12: Correlation plot of OFTCT and monotonic DST results.

Since monotonic DST is a well-accepted testing methodology adopted by many researchers, it serves as a ground-truth measurement of tack coat bond quality and hence is suitable for comparison against the OFTCT results. As can be seen above in Figure 5.12, the correlation between OFTCT and monotonic DST results was not strong. This indicates that OFTCT testing is likely not a reliable means of quantifying tack coat bond quality before construction.

One key difference between the OFTCT and monotonic DST results is that the monotonic DST results were from tack coats applied to a milled surface, whereas the OFTCT results which were obtained from testing on an overlay surface. Since a milled surface texture contains grooves, it has a much lower contact area with a flat surface, which would result in a much lower measured peak tensile strength. OFTCT tests were performed on an overlay surface only because it would provide the greatest contact area between the tack coat and the flat platen of the OFTCT, such that the tack coat's peak tensile strength response could be accurately quantified. However, since the purpose of this evaluation was to examine the correlation between OFTCT and monotonic DST results, the effect of texture is not influential on the results of the correlation.

These results conclude that the OFTCT is not recommended for field evaluation of tack coat bond quality before construction due to the poor correlation with monotonic DST results. Poor correlations were also observed in previous research which employed this device (Mahmoud et al. 2017). The results from this research and the results obtained in this study are indicative that the OFTCT is not suitable for tack coat bond quality evaluation.

5.6 RESULTS OF CYCLIC DIRECT SHEAR TESTING (DST)

Cyclic DST results were correlated with monotonic DST results to identify the ability of cyclic DST to capture the true response of each tack coat. This correlation was performed to examine if the fatigue performance results obtained from cyclic DST were comparable to the peak ISS results obtained from monotonic DST. Figure 5.13 below shows a correlation plot of cyclic DST fatigue results against monotonic DST ISS results.

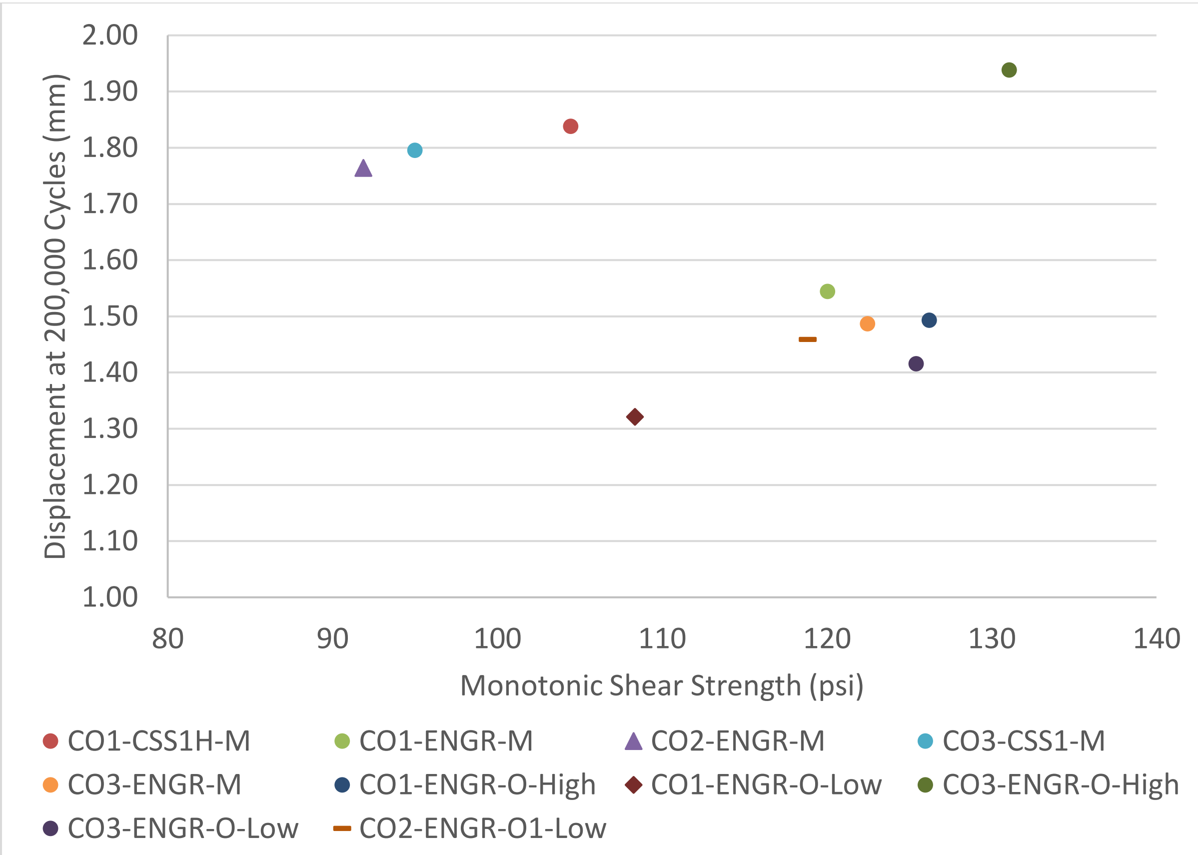


Figure 5.13. Correlation plot of cyclic DST and monotonic DST results.

As can be seen in the figure above, the correlation between cyclic DST and monotonic DST results is not strong. This results suggests that the tack coat fatigue response captured by cyclic DST is not congruent with the ISS behavior of each tack coat. These results may suggest the need to define a different fatigue failure criteria for tack coats. Since this experiment has not been adopted widely, the defining fatigue characteristics of the tack coat interlayer bond are not well documented. More research is needed in this area in order to develop a realistic fatigue failure criteria for cyclic DST testing that will be representative of tack coat fatigue behavior in the field.

5.7 SUMMARY AND CONCLUSIONS

In this study, the performance of engineered tack coats was evaluated in the laboratory and in the field using the Oregon Field Torque Tester (OreTackBond), a novel tack coat bond strength test device developed at Oregon State University. The OreTackBond device was improved in this study by adding features that render it more practical, portable, accurate and better suited for a variety of pavement surface conditions (overlay and milled surfaces). Tack coats sampled from three companies were used for the purposes of this study. Engineered tack coat performance was compared to that of tack coats conventionally used in Oregon on both milled and overlay surface types. The suitability of the OreTackBond device for capturing the true response of each tack coat was first evaluated by comparing results from OreTackBond laboratory tests to monotonic DST tests on laboratory-produced samples. Correlations between the two test types were developed. OreTackBond testing was performed in the field on six paving projects which utilized engineered and conventional tack coats according to each project. Average ISS results from OreTackBond field tests were compared with that of OreTackBond tests on laboratory-produced samples in order to identify if tack coat field performance suffers from diminished bond quality due to extraneous issues during construction. A construction QC process for tack coat bond performance was also developed and proposed in this study.

The major conclusions of this study are as follows:

1. The newly updated OreTackBond was confirmed to successfully capture tack coat bond quality on both milled and overlay surfaces in the laboratory and in the field.

2. Engineered tack coats were noted to perform better than tack coats conventionally used in Oregon.

3. ISS results extracted from OreTackBond laboratory tests were found to capture the expected trends in tack coat performance on both milled and overlay surfaces.

4. ISS results from OreTackBond field tests were significantly diminished from results of OreTackBond tests performed on laboratory-produced samples, indicating that problems with tack coat application in the field are hindering performance of in-service pavements in Oregon.

5. The OFTCT device is not suitable for field evaluation of tack coat performance prior to construction.

6. Cyclic DST results were not well-correlated with monotonic DST results, suggesting the need to develop a more robust fatigue failure criteria for tack coats in future research.

6.0 DEVELOPING TECHNOLOGIES AND PROCEDURES TO AVOID TRACKING AND ACHIEVE UNIFORM AND ACCURATE TACK COAT APPLICATION

6.1 INTRODUCTION

Results of the tests conducted in Chapter 4.0, showed that tack coat uniformity is the most important factor controlling tack coat bond strength and performance. Uniform tack coat distribution and accurate application rates during construction can be achieved by: i) applying the tack coat emulsion uniformly by avoiding clogged nozzles and achieving a reasonable overlap between nozzles (by adjusting nozzle bar height and/or adjusting nozzle positions and spray directions); and ii) reducing tracking. Tracking can be reduced by properly cleaning the pavement surface before tack coat application and not allowing any construction vehicle traffic before the tack coat is cured. Recently developed engineered tack coats can also reduce tracking related issues during construction (Coleri et al. 2017).

In this part of the study, a wireless scale system (OreTackRate) that can be controlled from a tablet computer was developed to measure tack coat application rate accuracy and uniformity. Developed wireless scale system was recommended to be used during construction for application rate accuracy and uniformity validation. In addition, a distributor truck certification process was developed and presented in this Chapter. Developed scale system can also be used to determine whether the applied tack coat is cured at any time point during construction. A surface cleanliness test (OreTackClean) was also developed and proposed in this Chapter to reduce tracking during construction. Implementation of all these tests, procedures, and technologies are expected to improve the tack coat uniformity during construction and improve the overall longevity of the pavement structure. Developed procedures and technologies can also be used to reward contractors who complete projects with high tack coat application uniformity and accuracy in the first bonding-based pay factor analysis in the U.S.

6.2 DEVELOPMENT OF A DISTRIBUTOR TRUCK VALIDATION AND CERTIFICATION PROCESS

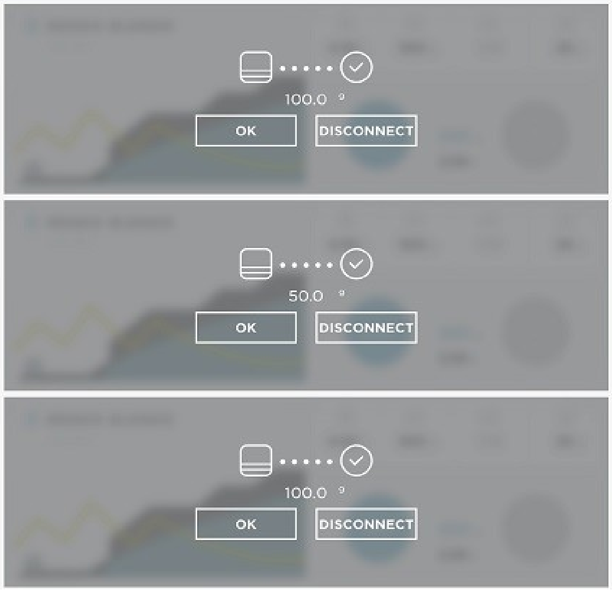
6.2.1 Wireless scale system (OreTackRate) development for application rate uniformity and accuracy measurement

In this study, a wireless scale system (OreTackRate) that can be controlled from a tablet computer was developed to measure tack coat application rate accuracy and uniformity. The scale produced by Acaia was used to develop the OreTackRate system. Because the height of the scale can affect the tack coat application rate measurements depending on the spray overlap between adjacent nozzles, a thin scale was selected and used for application rate measurements in this study. The dimensions of the wireless scale were 105mm(W) x 105mm(L) x 15.5mm(H) [4.13in(W) x 4.13in(L) x 0.61in(H)]. The scale was able to provide measured weights in 0.1g increments and had a weight measurement limit of 2,000g. Up to three scales can be wirelessly controlled from a tablet computer via an app. Photo of the scale system and the version with the asphalt shingle surface is shown in Figure 6.1. For the weight measurement of applied tack coat during construction, a 11.2inch by 11.2inch plastic plate with asphalt shingles taped on top was attached to the top of each scale using Velcro (Figure 6.1c). The reason for selecting the asphalt shingle surface is described in Section 6.3.1.

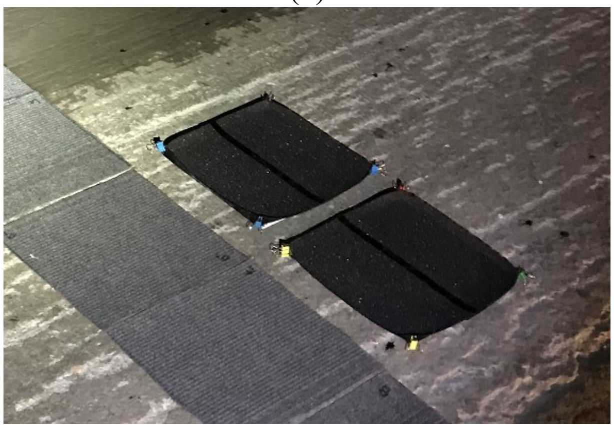
When scales are not properly leveled with the surface, it is possible to get scale readings with errors. For this reason, sensitivity of the scale readings to surface slope was determined in the laboratory. Wireless scale was placed on 1,7%, 3.4%, 5.2%, and 6.9% slopes (close to the slopes observed in a construction section) and 10g, 20g, 30g, and 50g reference weights were placed on top of the scales. None of the cases had any kind of measurement error for any of the cases. This result suggested that selected scales can provide reliable measurements on sections with different levels of slopes.

Wireless scales were controlled from a tablet app as shown in Figure 6.1. A Bluetooth connection was established between the scales and the tablet computer. The tablet computer app is capable of connecting up to three scales. Tablet computer should not be more than 15 meters away from the scales to keep the connection active during measurements.

(a)



(b)



(c)

Figure 6.1: OreTackRate system for application rate measurement (a) Wireless scale set up with the table computer (b) App interface for weight measurements (c) Scale system with asphalt shingles before tack coat application in the construction lane.

6.2.2 Identification of required number of scales and their positions along the construction section for accurate and precise measurements

Uniformity and amount of application are two elements required to achieve proper bond strength (Cortina 2012). Laboratory test results presented in Chapter 4.0 also showed that coverage/uniformity is the most important factor controlling bond performance and strength. For this reason, a quality control process to validate/calibrate the accuracy and uniformity of tack coat application process before construction needs to be established. To be able to use the developed wireless scale system for tack coat weight measurements for this purpose, the number of scales and their positions required to achieve precision and accuracy outputs that reflect the entire width of the lane needed to be determined.

By placing textile pads along the construction site and weighing them before and after tack coat application, uniformity and amount of applied tack coat can be measured during construction (Coleri et al. 2017; ASTM D2995 2014). Although this process accurately provides the actual application rate and the uniformity of application, it is not generally adapted as a quality control test due to practicality concerns. Measurements generally require several textile pads to be taped (using special aluminized tapes) on the surface of the pavement before tack coat application. Textile pads also need to be weighed before and after tack coat application to determine the weight of tack coat applied on each pad. In this study, a wireless scale system is developed to improve the practicality of the application rate and uniformity measurements. The ultimate goal of this study is to develop a process for certifying and validating distributor trucks for application rate accuracy and uniformity before construction.

6.2.2.1 Field application rate measurements according to ASTM standard D2995

Application rate measurements were taken by placing 12 inch by 12-inch textile pads end to end in the travel lane in the transverse direction (Figure 6.2a). An applied tack coat weight for each textile pad was calculated by using the weight of the textile pad before and after tack coat application (ASTM Standard D2995 2014). A sample of the applied tack coat was taken before the start of the construction to determine the density of the tack coat. This measured density was used to convert the applied tack coat weight to volume to be able to achieve application rates in gallons per square yard. To measure the volume of the applied tack coat, a graduated cylinder was weighed. Then, the graduated cylinder was filled with the tack coat up to 50ml volume level. Formation of bubbles on the surface of the tack coat sample needs to be avoided to be able to achieve accurate measurements. After the 50ml volume is achieved, the weight of the graduated cylinder with the tack coat sample was measured. By subtracting the empty graduated cylinder weight from the weight with the tack coat, the weight of the 50ml tack coat sample was determined. By dividing the weight by the volume (50ml) of the tack coat sample, density of the tack coat was determined. Measured tack coat densities were used to convert the applied tack coat weight on each textile pad to volume.

(a) (b)

Figure 6.2: Tack coat application rate measurements (a) ASTM D2995 method (b) Developed wireless scale system adjacent to the textile pads.

In this study, textile pad readings were taken from seven construction projects by following ASTM D2995. All construction projects were in Oregon while the exact locations are not provided in order to conceal the identity of the contractors. Table 6.1 provides general information about the tack coats and the application rates for all construction projects.

Table 6.1: Tack Coats and Application Rates from all 7 Construction Projects

Projects	Company	Tack Types	Target application rate (gsy)	Average measured application rate (gsy)	Transverse application variability in COV[1]	Surface Type
1	CO1	CSS-1H	0.070	0.048	0.251	Overlay
2	CO1	CSS-1H	0.080	0.102	0.063	Milled
3	CO3	ENGR	0.066	0.066	0.188	Overlay
4	CO2	ENGR	0.065	0.068	0.121	Milled
5	CO1	CSS1	0.065	0.074	0.266	Milled
6	CO1	CSS-1H	0.120	0.099	0.107	Milled
7	CO1	CSS1	0.090	0.053	0.079	Milled

Note: [1] COV: Coefficient of variation.

It can be observed from Table 6.1 that Project#2 had the lowest application variability in the transverse direction (meaning highest uniformity) while Project#5 had the highest. Projects#3 and #4 achieved the highest application accuracy with very close target and actual average application rates.

shows the location and numbering of all textile pads and wireless scales.

Figure 6.4 shows the tack coat application rates for all textile pads placed in the transverse direction. Textile pad #1 was closest to the adjacent lane while the textile pad with the largest number was closest to the shoulder (ascending order from adjacent traffic lane to the shoulder or slow traffic side). Target application rates for all projects were also shown in Figure 6.4 with straight horizontal lines.

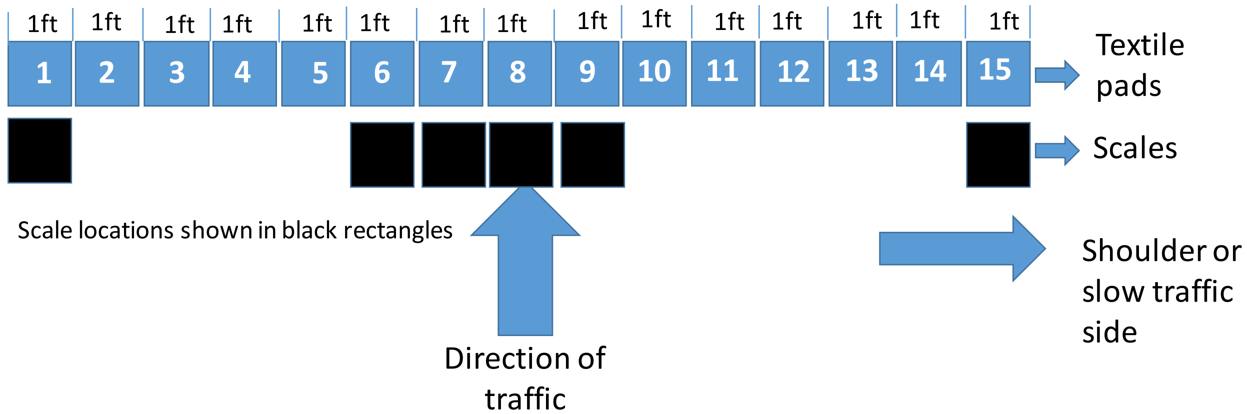
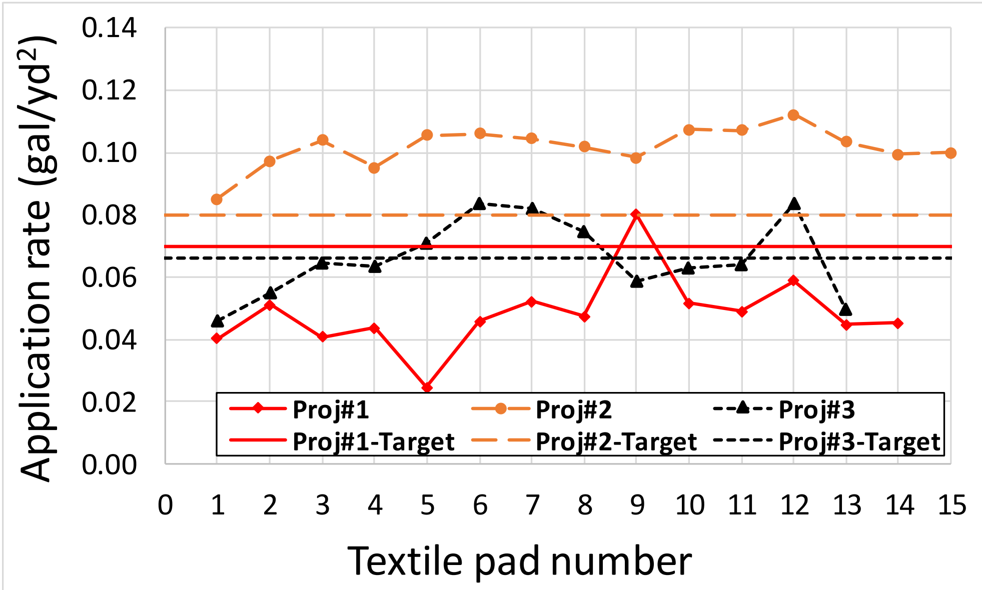
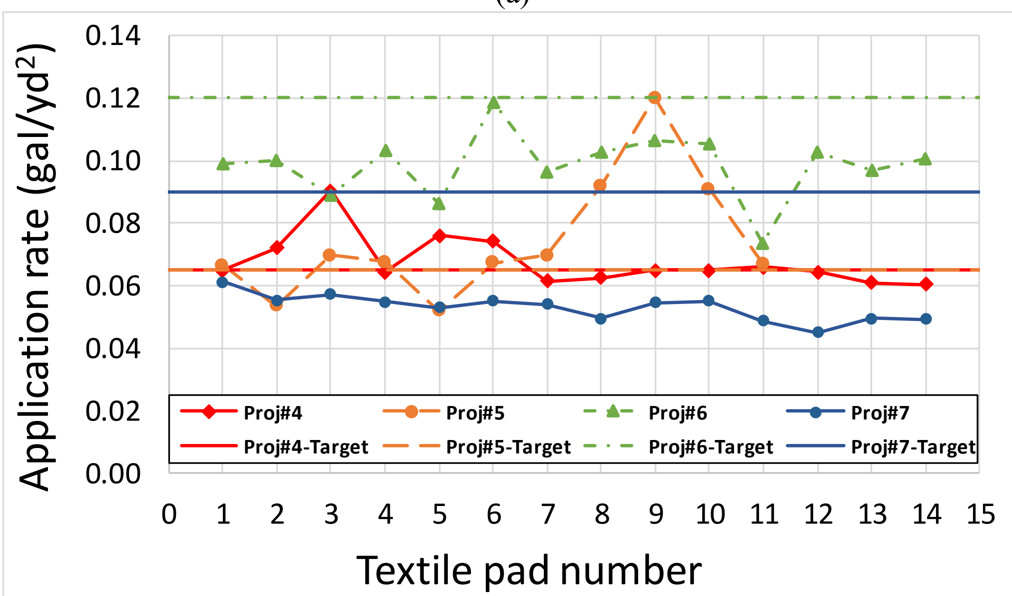


Figure 6.3: Textile pad and wireless scale (OreTackRate) locations.



(a)



(b)

Figure 6.4: Tack coat application rates measured by using textile pads (a) Projects #1, #2, and #3 (b) Projects #4, #5, #6, and #7.

6.2.2.2 Accuracy of wireless scale system (OreTackRate) measurements

It was required to validate the accuracy of OreTackRate measurements during construction. Validations were performed by placing the wireless scale systems with attached asphalt shingles close to the textile pads (Figure 6.1c and Figure 6.2b). Measurements from the textile pads were assumed to be the reference (ground truth) measurements and used to validate the measurements of the developed wireless scale system (OreTack Rate). Wireless scales were placed adjacent to textile pads #1, #6, and

#7. Figure 6.5 shows the correlation between wireless scale and textile pad measurements from Projects #5, #6, and #7. It can be observed that results from textile pads are almost identical to the application rates measured by the wireless scale system with a coefficient of determination of 0.99. This result proves the effectiveness of OreTackRate system for in-situ tack coat application rate measurement.

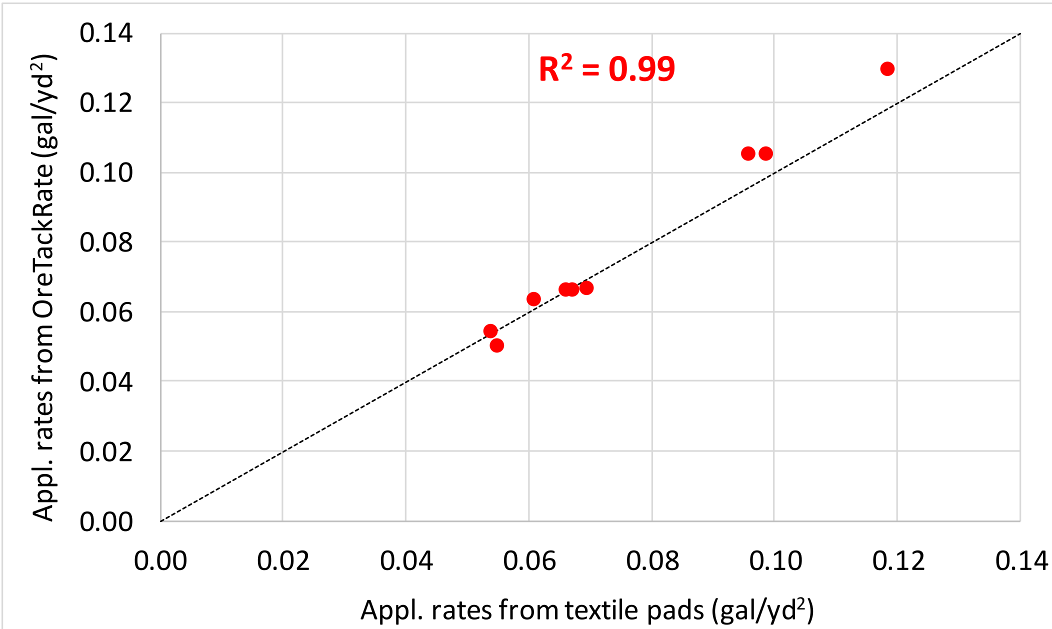


Figure 6.5: Comparison of OreTackRate measurements to application rates from textile pad measurements.

6.2.2.3 Required number of scales and their positions to achieve accurate weight measurements

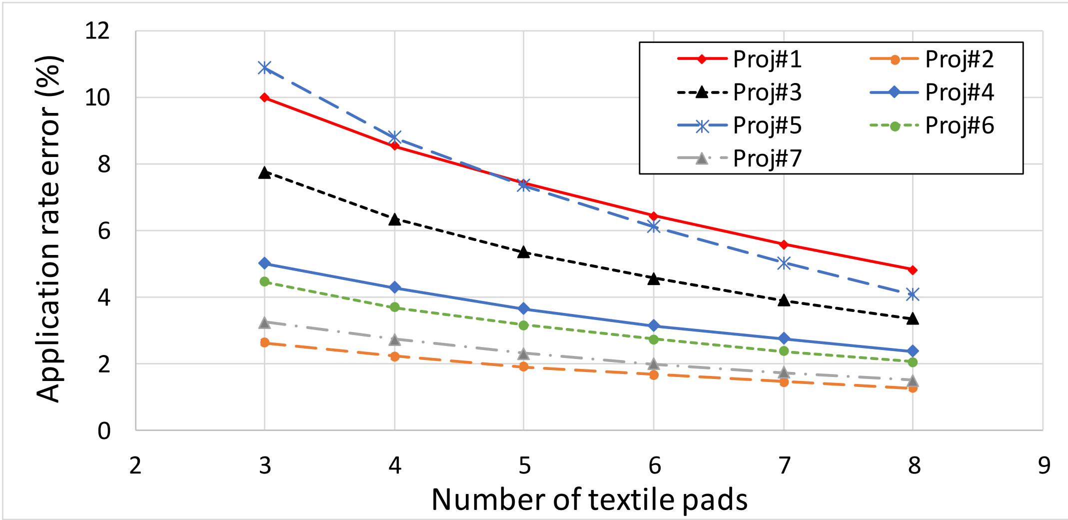
In this study, a wireless scale system was developed to improve the practicality of tack coat application rate measurements to be able to implement the developed system for distributor truck certification and validation. Developed OreTackRate system is capable of accurately measuring application rates from three scales at a time. Although the number of scales can be increased, a limit of three scales is suggested in this study to achieve high levels of practicality and keep the system development cost at lower levels. However, the effectiveness of the developed system in measuring the average application rate and transverse uniformity [in coefficient of variation (COV)] needed to be determined.

An algorithm in Matlab software was developed to determine the impact of having more scales (or textile pads in the ASTM D2995 procedure) on average application rate and COV. The algorithm takes one of the seven construction projects given in Table 6.1. Using the textile pad measurements shown in Figure 6.4, developed algorithm randomly selects "n" number of textile pad measurements (for example, if n is selected as 4 by the analyst, 4 carpets are randomly selected from the dataset). Then, the algorithm calculates the average application rate and the COV for those "n" randomly selected pads. The errors between the calculated average application rate and COV from those "n" pads and the actual average application rate and COV (given in Table 6.1) from all textile pads were calculated by using Equations **Error! Reference source not found.**) and **Error! Reference source not found.**):

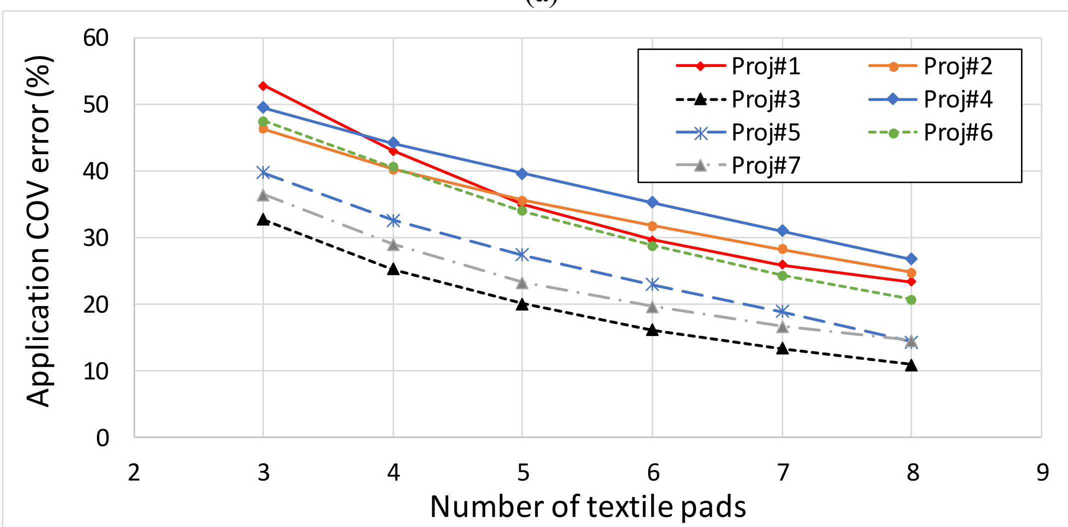
$$\%\textbf{Error for average rate} = \frac{|(\boldsymbol{OreTackRate_{ave}} - \boldsymbol{Pad_{ave}})|}{\boldsymbol{Pad_{ave}}} \times \mathbf{100} \tag{6-1}$$

$$\%\textbf{Error for COV} = \frac{|(\boldsymbol{OreTackRate_{COV}} - \boldsymbol{Pad_{COV}})|}{\boldsymbol{Pad_{COV}}} \times \mathbf{100} \tag{6-2}$$

This process was repeated for 1 million times using the developed algorithm and percentage error for application rate average and COV were recorded for each case. Finally, the algorithm outputs the average of the percentage error for average rate [Equation 6-1] and the average of the percentage error for COV [Equation 6-2]. It is expected that increasing the number of textile pads will reduce these two average error rates for application rate and uniformity. However, it was important to conduct these analyses to determine the required number of textile pads to achieve reasonable percentage error rates. Figure 6.6 shows the impact of increasing number of textile pads on application rate and uniformity (COV) error rates. It can be observed that error rates for average application rates were lower than 12 percent for all construction projects (Figure 6.6a). This result suggested that average application rate calculated from three textile pads (or OreTackRate system with three scales) provides a reasonable average application rate estimate with a low error rate. However, it can be observed from Figure 6.6b that error rates for COV (uniformity) are significantly higher than the average application rate errors. This result suggested that more than three textile pads maybe needed to achieve reliable COV (tack coat application uniformity) estimates.



(a)



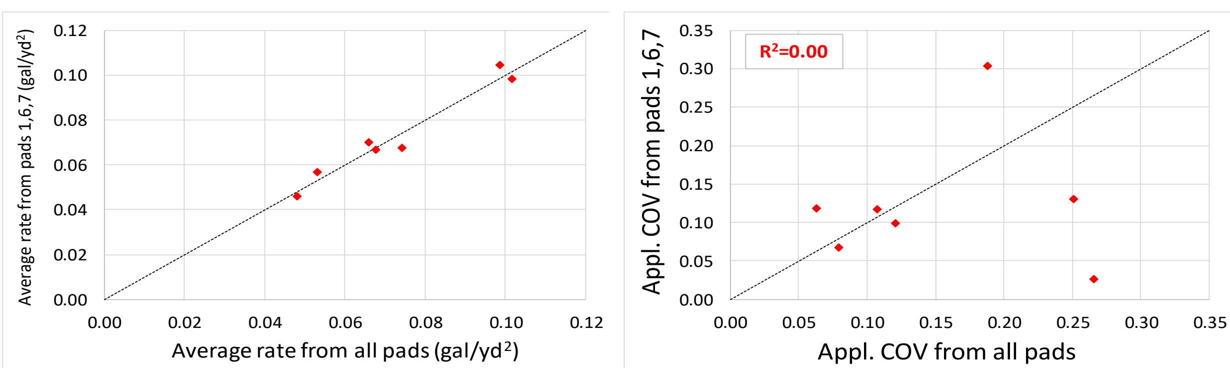
(b)

Figure 6.6: The impact of increasing number of textile pads on (a) application rate and (b) uniformity (COV) error rates.

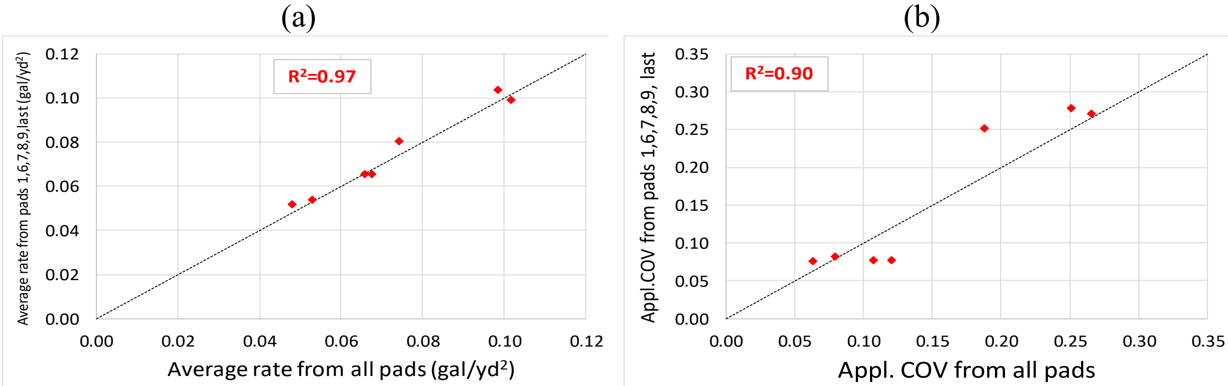
To directly determine the accuracy of the OreTackRate system for application rate and uniformity measurement, average application rates and uniformity measurements (in terms of COV) from the textile pads 1, 6, and 7 (same position as the wireless scales were placed) were compared to the average application rates and COVs from all textile pads. Results for average rate and COV comparisons are shown in Figure 6.7a and Figure 6.7b, respectively. It can be observed that average application rate from three scales in positions 1, 6, and 7 (positions are shown in

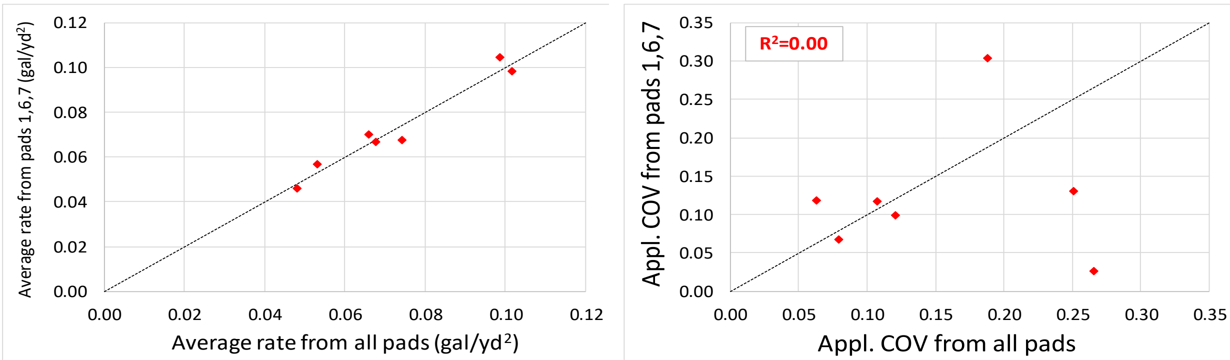
) provides an accurate average rate estimate that is very close to the average rate from all textile pads. The coefficient of determination for the correlation was 0.95. However, the correlation between COVs from the same three scales (positions 1, 6, and 7) were not correlated with the COVs from all textile pads (see Figure 6.7b) for the seven construction projects. The coefficient of determination for the correlation was 0.00, which pointed out no statistically significant correlation. This result again suggests that more than three scales are required to achieve reliable uniformity measurements.

Figure 6.7c and Figure 6.7d shows the correlations for six textile pads. By comparing Figure 6.7a and Figure 6.7c, it can be concluded that having three scales in positions 1, 6, and 7 provides average application rates that are close to the average from all textile pads. However, to achieve reliable uniformity (COV) estimates for the distributor truck, six wireless scale measurements from positions 1, 6, 7, 8, 9, and the scale closest to the slowest lane or shoulder (called as “last” in the plots) are required. This result suggested that for distributor truck certification for application rate accuracy and uniformity, two OreTackRate system would be required. Since each OreTackRate system with three scales and a tablet computer costs around $1,000, having a second system would increase the cost by another $1,000. Alternatively, to reduce the total cost, readings for positions 1, 6, and 7 can be taken during the first pass of the distributor truck during the certification process. Then, the scales can be placed in positions 8, 9, and “last” to collect the application rates from the right side of the truck. Using those six measurements, application rate accuracy and uniformity can be accurately quantified. However, during construction, to measure and calibrate/validate application rate accuracy, having three scales positioned in 1, 6, and 7 would provide reliable average application rate estimates. Proposed distributor truck certification process is given in Section 6.2.3 below.



(a) (b)





(c) (d)

Figure 6.7: Impact of increasing the number of scales on application rate and uniformity measurement accuracy (a) average application rate comparison for three scales (b) COV (uniformity) comparison for three scales (c) average application rate comparison for six scales (d) COV (uniformity) comparison for six scales.

6.2.3 Proposed distributor truck validation and certification process

In this study, using the developed OreTackRate wireless scale system, a distributor truck certification and validation process was developed. Distributor truck certifications should be performed once a year and a certificate and a decal (that will be placed on the distributor truck) will be provided to the operator at the end of the process. Proposed process is going to evaluate the distributor truck for application rate accuracy and uniformity. Application rate uniformity and accuracy measurements from seven construction projects were provided in Section 6.2.2. Results from those projects showed that it was possible to achieve high uniformity levels in some of the projects while application uniformity was very low in three of the construction projects (projects #1, #3, and #5). Figure 6.8 shows the distribution of application COV values from all seven construction projects. It can be observed that there are two obvious data clusters (shown with two peaks in the normal distribution). These two data clusters were assumed to represent "uniform" and "non-uniform" applications and the boundary between those two clusters was selected as the threshold for uniformity ***[a COV of 0.175 from six scale (positions 1, 6, 7, 8, 9, and "last") measurements]***. COVs from projects #1, #3, and #5 fail to meet this criterion while the COVs for the remaining four projects meet the criterion.

The error for target and measured application rates for all seven projects are shown in Figure 6.9. The average percentage error for all seven projects was 19.4. For this reason, ***19.4% error rate for application rate accuracy was selected as the threshold for distributor truck certification***. Since application rates can easily be modified by the operator during the certification process to get closer to the target application rates, it is expected that majority of the operators will fulfill this requirement without any major issues during the certification process. It should also be noted that both thresholds for application rate accuracy and uniformity can be revised based on the failure and acceptance rates observed during the first year of the certification process.

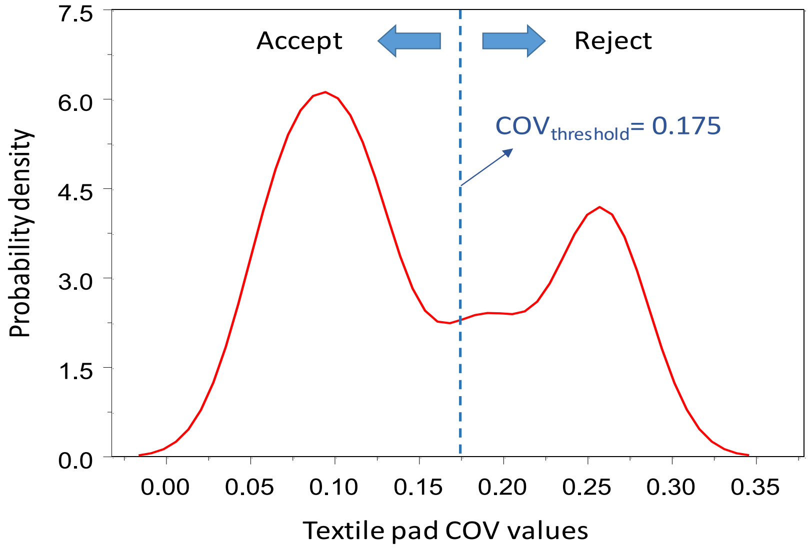


Figure 6.8: Distribution of application COV (representing uniformity) values for all seven construction projects.

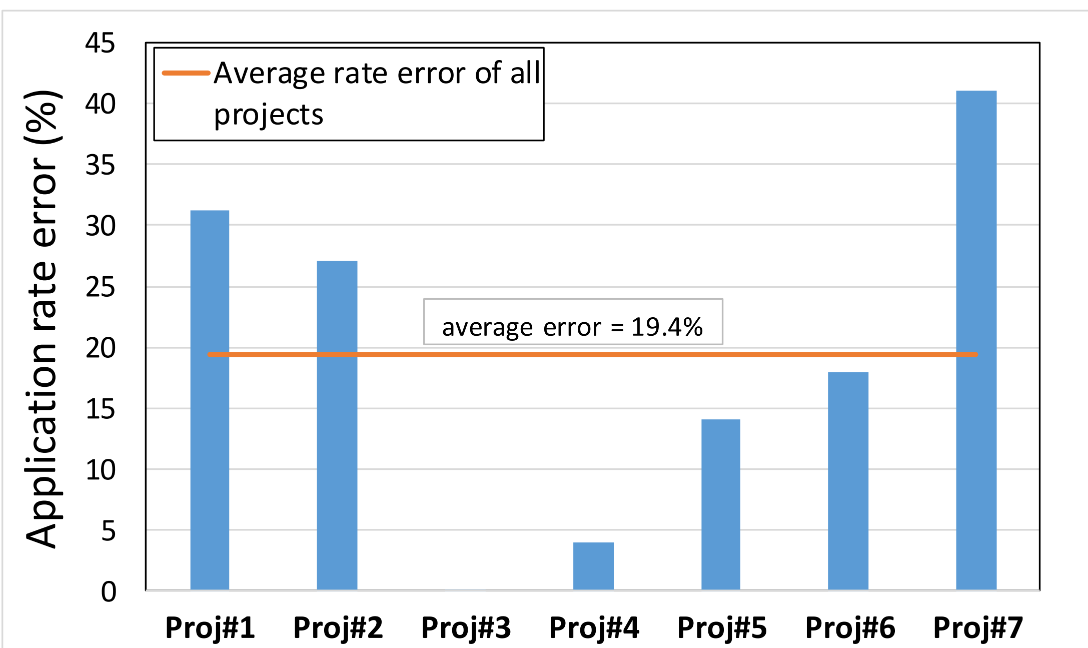


Figure 6.9: Error for target and measured application rates for all seven construction projects.

Proposed distributor certification process is outlined below:

1. Place a white strip of paper along the lane and apply tack coat with 0.06gal/yd^2 application rate. Inspect the applied tack coat for obvious signs of streaking. If

streaking is observed, operator is responsible for cleaning the nozzles and/or adjusting the nozzle height to reduce streaking. Once the streaking is avoided/reduced, certification process can resume.

2. A sample from the tack coat needs to be taken to determine the density of the emulsion. Using one of the wireless scales, empty weight of the graduated cylinder that is capable of holding at least 50ml volume will be determined. This measured weight in grams will be entered into the "Graduated cylinder weight (g) – Cell G2" cell in the spreadsheet developed for distributor truck certification (Figure 6.10). Graduated cylinder will be filled with the tack coat sample up to 50ml volume level. Formation of bubbles on the surface should be avoided in order not to compromise the volume measurement process. After the tack coat emulsion with 50ml volume is poured into the graduated cylinder, weight of the cylinder with 50ml tack coat needs to be determined using one of the wireless scales. Measured weight will be entered into the "Cylinder with 50ml tack (g) – Cell H2" cell in the spreadsheet.

3. Place six scales in positions 1, 6, 7, 8, 9, and "last" ("last" is the position closest to the right end nozzle). See Figure 6.3 for required scale positions.

4. Attach the plastic plate with asphalt shingle layer on top to the surface of the scale using Velcro. Procedure followed for the preparation of plastic plates with asphalt shingle layers is described in Section 6.3 below.

5. Connect to all scales using the BrewBar tablet app that is available on app stores. Several videos describing the wireless connection procedure are available on the Acaia Youtube channel. Scale system and the tablet app will be configured in advance to get the system ready for certification. Since six scales are required for certification, two OreTackRate systems with six scales and two tablet computers will be required for certification. Total cost of the system will be around $2,000. Alternatively, one system with three scales can be used to measure application rates for positions 1, 6, and 7 and the readings for the remaining three positions (8, 9, and last) can be taken during the second pass of the distributor truck.

6. Once all six scales are connected, initial weights need to be recorded before tack coat application. Those initial weights for all scales will be entered into the spreadsheet developed for the certification process ["Initial weight (g)" column in the spreadsheet – Cells B2:B7]. It is crucial to keep the tablet computer within a 15m. distance from the scales during this process to keep the wireless communication active.

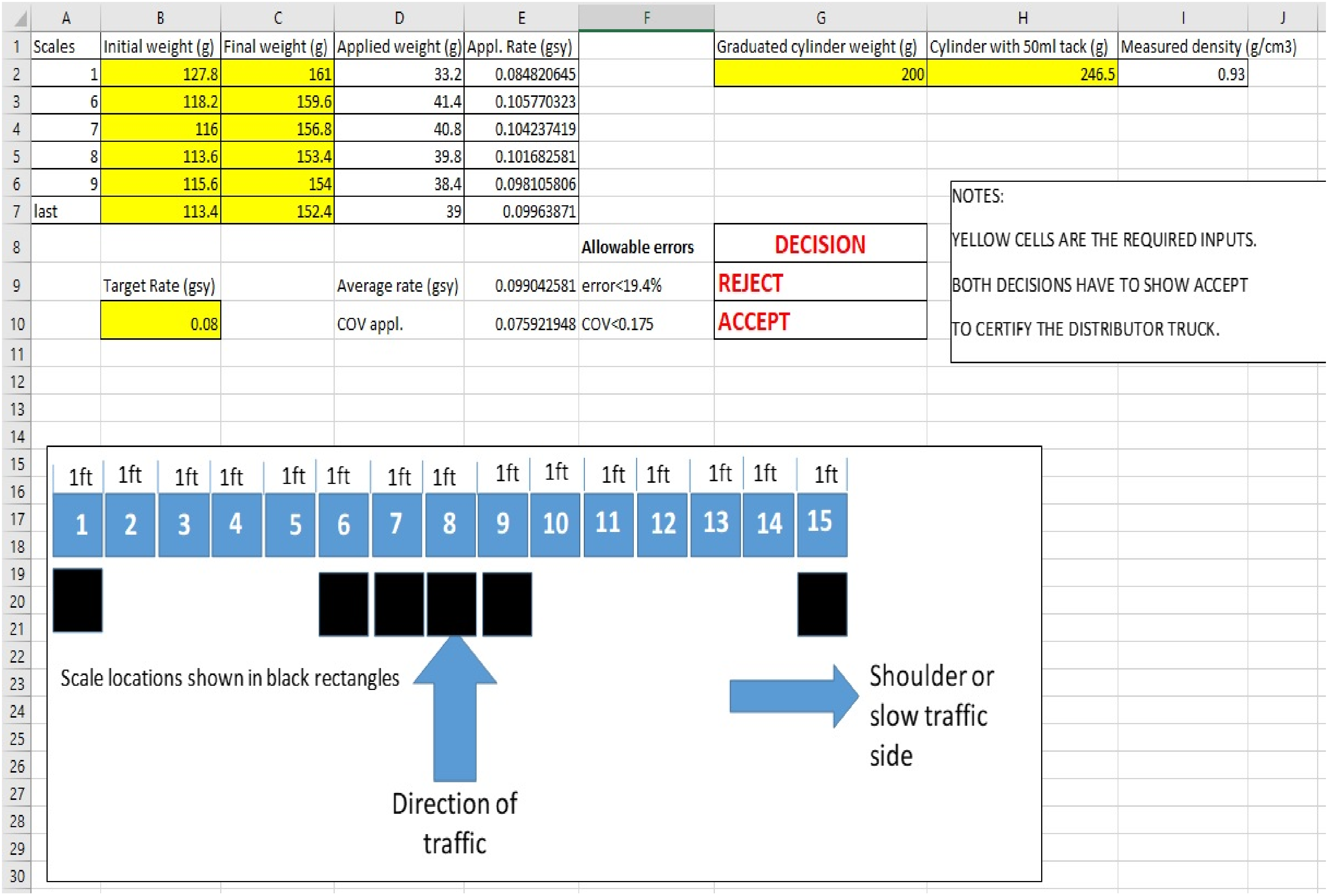
7. Operators will be required to apply two target rates during certification, 0.06gal/yd^2 and 0.12gal/yd^2. For this reason, entire application rate measurement process will be repeated two times. Plastic plate with asphalt shingle layers from the first rate measurement can also be used for the measurement of the application rates for the second run. Operators will start by applying the 0.06gal/yd^2 rate on the scales. After the tack coat application, readings from the tablet app will be entered into the Excel spreadsheet ["Final weight (g)" column in the spreadsheet – Cells C2:C7]. Target rates for the runs with 0.06gal/yd^2 and 0.12gal/yd^2 application rates needs to be

correctly entered into the "Target rate (gsy) – Cell B10" cell in the spreadsheet before evaluating the results.

8. After entering all these inputs into the developed Excel spreadsheet, results of the certification for application rate accuracy and uniformity will appear in cells G9 and G10 in the developed spreadsheet (See Figure 6.10). If "ACCEPT" appears in both cells, distributor truck has passed the certification process for the 0.06gal/yd^2 application rate and process can resume with the 0.12gal/yd^2 application rate. For the 0.12gal/yd^2 measurements, weights entered in cells B2:B7 and C2:C7 need to be replaced with the new rates for the higher application rate. Target rate in cell B10 should also be changed to 0.12. Cells for tack coat density measurement (G2 and H2) will not be changed since same tack coat will be used for the higher rate as well. Once all the initial and final weights are entered into the spreadsheet and "ACCEPT" appears in cells G9 and G10, a decal and a certificate for the distributor truck and the operator will be given to the operator. Excel output showing the final results will also be printed and given to the operator as a proof of certification. If the distributor truck fails in average application rate (Cell G9 in the spreadsheet), operator will be given two more chances to get closer to the target application rate by adjusting the speed of the truck and/or modifying inputs in the tack coat distributor system. Two additional chances will also be provided if the distributor truck fails in uniformity (COV). In this case, adjustment of the nozzle bar and/or cleaning the nozzles will be suggested. To help the operator improve the system for certification, Excel spreadsheet output will be printed and given to the operator to help him/her identify the nozzles with issues. If acceptable numbers for application rate and uniformity were not achieved after three trials, operator will need to improve the condition of the distributor truck and bring it back for certification on another day.

9. Basic training and certification of the tack coat distributor truck operator should also be required to ensure that equipment is operated properly to ensure a uniform and accurate application rate. After the distributor truck is certified by following the steps listed above (step 1 to 8) and a certificate and a decal were issued for the truck, an operator certificate will also be given to the operator of the truck. However, if multiple operators are going to operate the distributor truck, additional operators will also be required to get certified by following the process outlined above. The only difference for the certification process for additional operators will be the exclusion of running the distributor truck at the high application rate (0.12gal/yd^2). Only a 0.06gal/yd^2 rate will be used for the certification of additional operators.

Distributor truck certification will be required once a year while distributor trucks need to be checked (validated) before every construction project to ensure that accurate and uniform tack coat application can still be performed. At the beginning of the construction project, distributor truck validation process can be performed on the control strip. The 8-step process described above will also be followed for the validation while only one application rate (which is the target rate selected for the project) will be applied rather than the two rates applied during the certification process.



	A	B	C	D	E	F	G	H	I	J
1	Scales	Initial weight (g)	Final weight (g)	Applied weight (g)	Appl. Rate (gsy)		Graduated cylinder weight (g)	Cylinder with 50ml tack (g)	Measured density (g/cm3)	
2	1	127.8	161	33.2	0.084820645		200	246.5	0.93	
3	6	118.2	159.6	41.4	0.105770323					
4	7	116	156.8	40.8	0.104237419					
5	8	113.6	153.4	39.8	0.101682581					
6	9	115.6	154	38.4	0.098105806					
7	last	113.4	152.4	39	0.09963871					
8						Allowable errors	DECISION			
9		Target Rate (gsy)		Average rate (gsy)	0.099042581	error<19.4%	REJECT			
10		0.08		COV appl.	0.075921948	COV<0.175	ACCEPT			

NOTES:

YELLOW CELLS ARE THE REQUIRED INPUTS.

BOTH DECISIONS HAVE TO SHOW ACCEPT

TO CERTIFY THE DISTRIBUTOR TRUCK.

Figure 6.10: Screenshot from the distributor truck certification Excel spreadsheet.

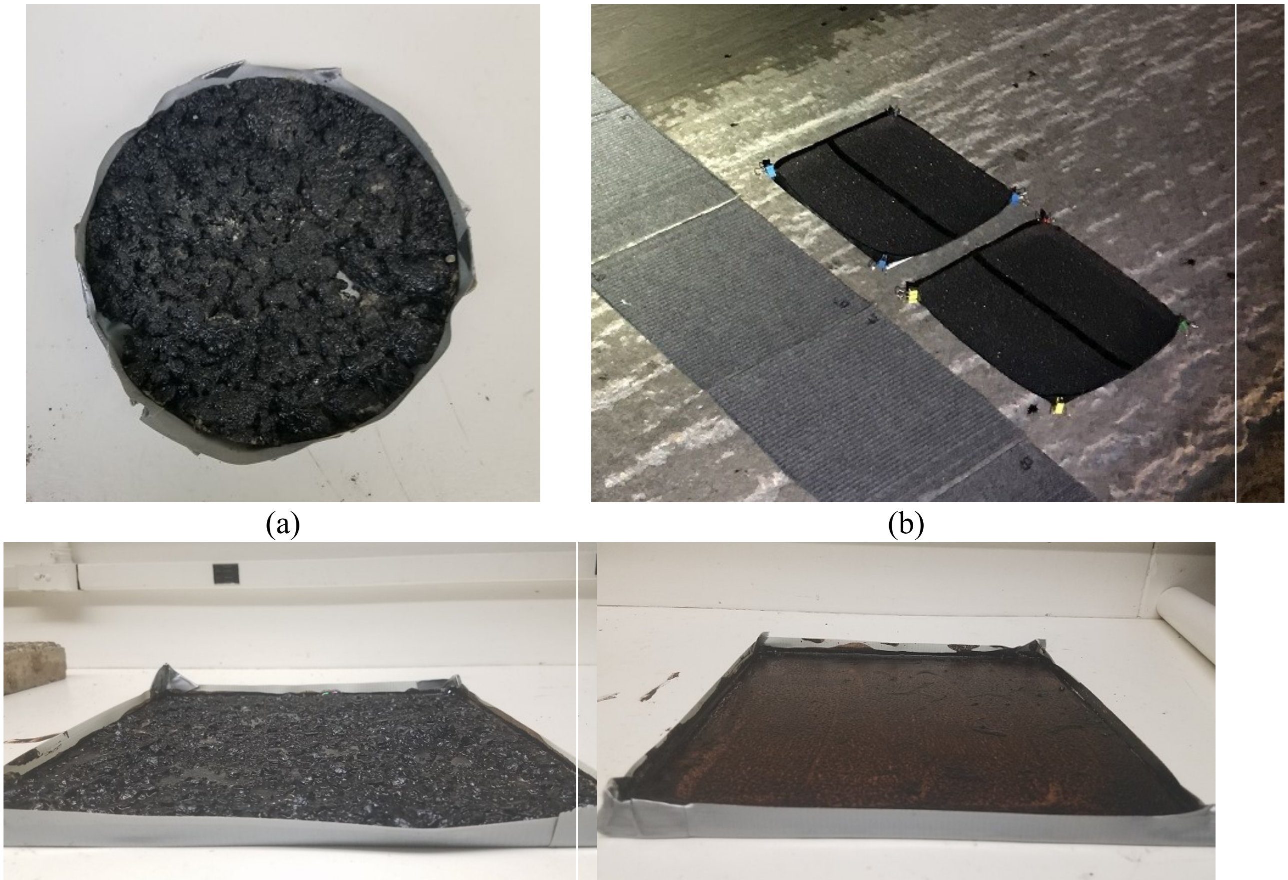
6.3 MEASUREMENT OF TACK COAT CURING TIME TO REDUCE TRACKING

Emulsions are temporally constraining since the break and set times, otherwise known as curing time, must be reached before paving operations can ensue. Break time of emulsions refers to the time needed for the water to separate from the asphalt, whereas set time refers to the point at which all water is completely evaporated. Diluted emulsions require higher break and set times due to the additional water content. The residual asphalt, defined as the effective amount of asphalt available to facilitate interlayer bonding, is what remains after the water has evaporated, or when the tack coat has set. Emulsions which have not had sufficient time to break and set also give rise to the "tracking" phenomenon, where emulsion is picked up on construction vehicle tires, effectively reducing the amount of tack coat on the pavement surface (FHWA 2016). This occurs mostly in the wheel paths where interlayer bonding is most critical. The severity of tracking is determined mostly by the emulsion properties and the curing time allotted before construction (Covey et al. 2018). By avoiding construction vehicle traffic before the calculated curing time, tracking can be minimized. For this reason, reducing tracking, by determining the appropriate curing time becomes vital to the longevity of the pavement structure.

In this part of the study, the use of OreTackRate system, developed in Section 6.2.1, for curing time identification is discussed. The procedure followed to select the plate surfacing that is closest to a pavement surface is described in detail. In addition, results from three field tests and a possible implementation process for the technology for curing time measurement is also discussed in this section.

6.3.1 Laboratory investigation

Wireless scale system, OreTackRate, developed in Section 6.2.1, can also be used to determine the curing time of the tack coat emulsions during construction. After the application of the tack coat on the plate placed on the wireless scale, weight change can be monitored periodically to determine whether the tack coat is cured. However, a surface for the plastic plate that is similar to a pavement surface was needed to be determined to achieve reasonable curing times that reflect the curing of the tack coat on the pavement surface. For this reason, laboratory curing tests were conducted with different surface types in the laboratory using a high accuracy scale. Evaluated surface types were: i) asphalt core-control; ii) plastic plate; iii) plastic plate with asphalt binder/aggregate on surface; and iv) asphalt shingle. Figure 6.11 shows the samples used for curing time testing in the laboratory.



(a) (b)

(c) (d)

Figure 6.11: Surfaces used for curing time testing in the laboratory (a) Asphalt surface used as control (b) Asphalt shingle layer adhered to a plastic plate (c) Aggregate/asphalt binder surface on a plastic plate (d) Plastic plate-No texture case.

Tack coat evaporation tests were conducted in the laboratory at 25°C temperature to determine the curing time for all four surface types at two application rates (0.05 gal/yd^2 and 0.10 gal/yd^2). Two replicate tests were conducted for each case. A total of 16 evaporation tests were conducted (for four surface types, two application rates, and two replicate tests). Curing time from the laboratory evaporation tests were determined by calculating the percentage weight of applied tack coat, plotting the result in a time versus percentage of applied tack coat plot, and then reducing the accuracy of the plot to 1%. When the percentage of applied tack coat weight for the curve with 1% accuracy does not change for 10 minutes, this time point was selected as the curing time for the tack coat. An example calculation for the curing time for an asphalt-surfaced sample with 0.1 gal/yd^2 application rate is given in Figure 6.12.

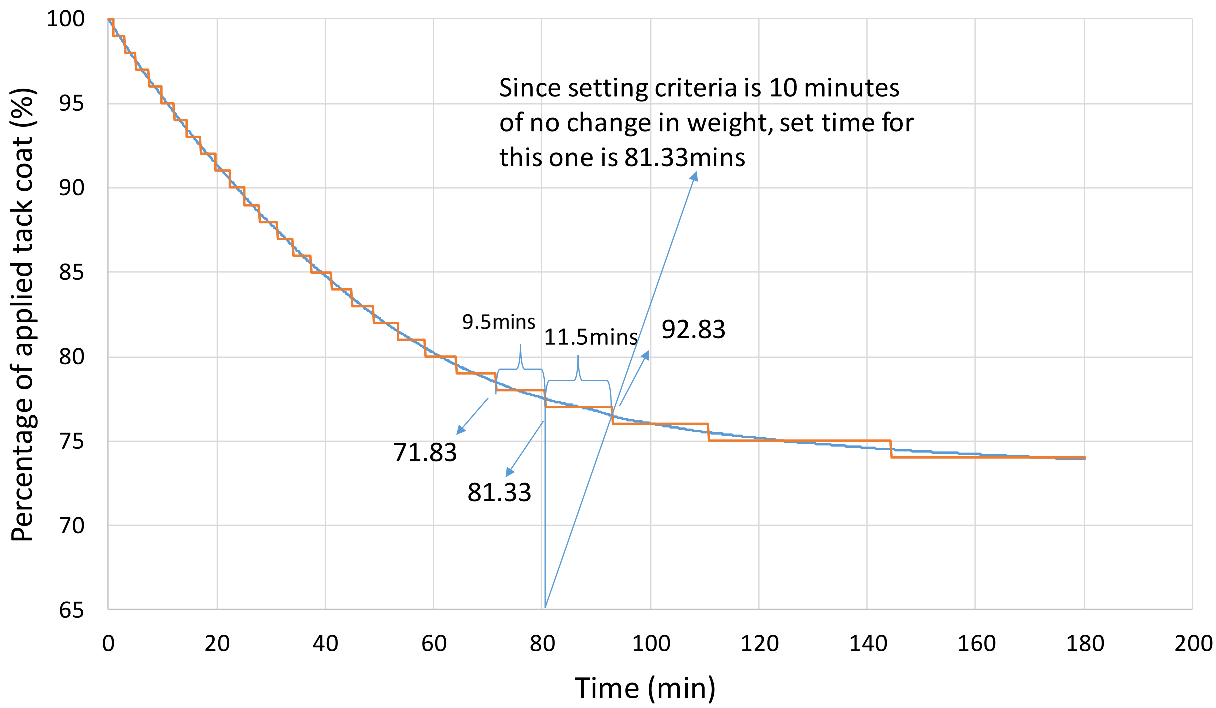
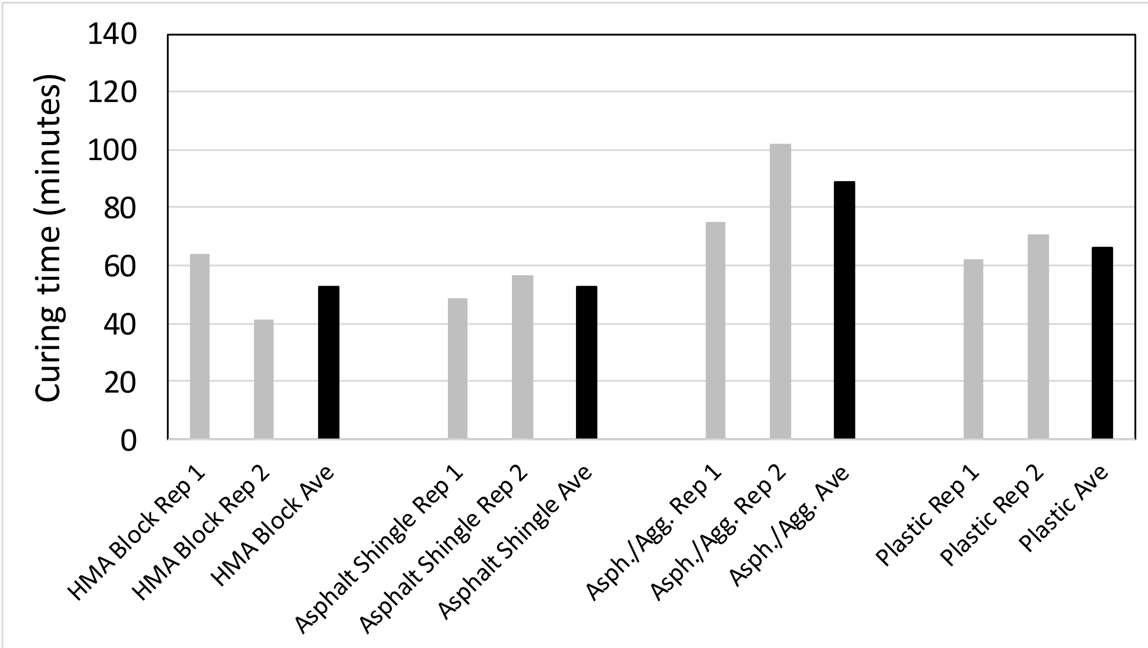
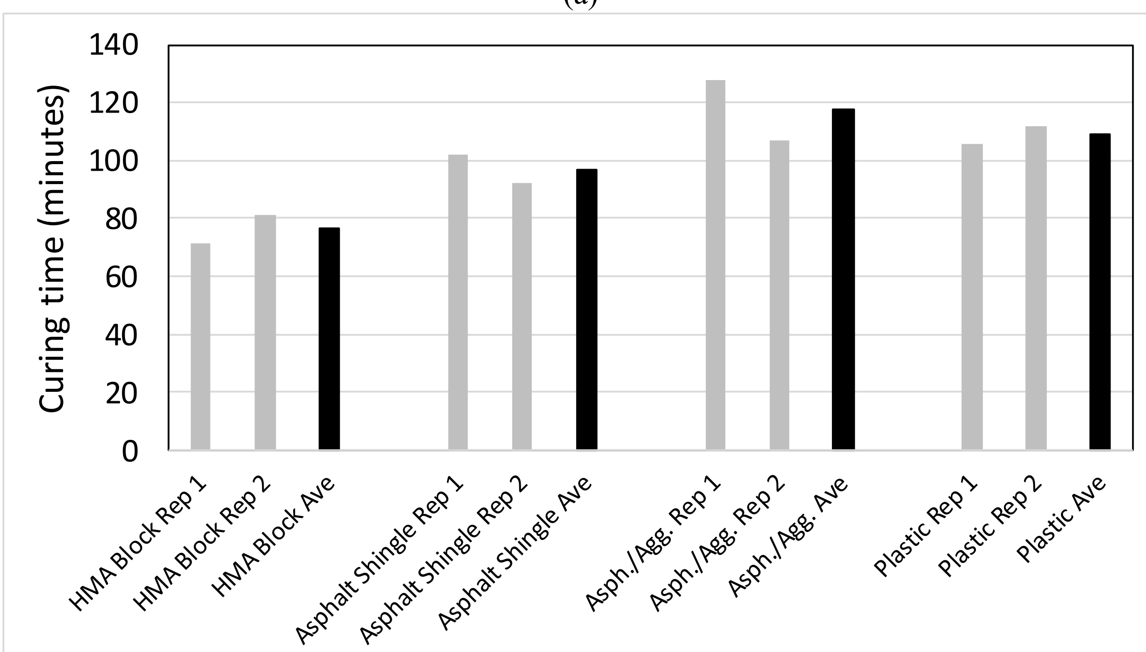


Figure 6.12: Example curing time calculation for the test with asphalt surface and 0.1 gal/yd^2 application rate.

Figure 6.13 shows the curing times from all laboratory evaporation tests. It can be observed that curing times for the plastic plate with asphalt shingle layer on top provides curing times that are closest to the curing times for the asphalt cores. Since the asphalt binder/aggregate and plastic (no texture) surfaces are impermeable, a thin layer of tack coat on the surface of the applied tack coat cures within the first 15-20 minutes and slows down the evaporation for the underlying tack coat emulsion. On the other hand, asphalt shingle and asphalt core surfaces both absorb some of the tack coat and avoids the formation of this thin tack coat layer. For this reason, cases with asphalt core and asphalt shingle surface result in closer curing times that are lower than asphalt binder/aggregate and plastic surfaces. Thus, plastic plate with asphalt shingle surfacing was selected to evaluate tack coat emulsion curing time during construction.



(a)



(b)

Figure 6.13: Curing time for all surface types (a) 0.05 gal/yd^2 application rate (b) 0.10 gal/yd^2 application rate.

6.3.2 Field investigation

OreTackRate system was also used for curing time identification during the construction projects #5, #6, and #7. After using the wireless scales for tack coat application rate measurement, scales with asphalt shingles were moved to the side of the road for curing measurements. Weight readings were taken from the tablet computer every 5 minutes to create the evaporation curves. For Project #5 (first project in which OreTackRate system was used), connection with one of the scales was lost. Readings from the second scale were also excluded due to excessive noise in the data as a result of external factors. However, for Project#5, data from one of the scales were used for curing time identification. Readings from that particular scale are shown in Figure 6.14 . It can be observed that significant fluctuations are present in the data due to the windy weather during the construction day. For this reason, a Matlab noise reduction algorithm was used to exclude the effect of wind on measurements. It should be noted that, for Projects #6 and #7, a transparent plastic wind guard was used before taking readings. Using the wind guard significantly reduced the noise in the data. Using the wind guard also eliminated the need for smoothening the noisy data using the Matlab code.

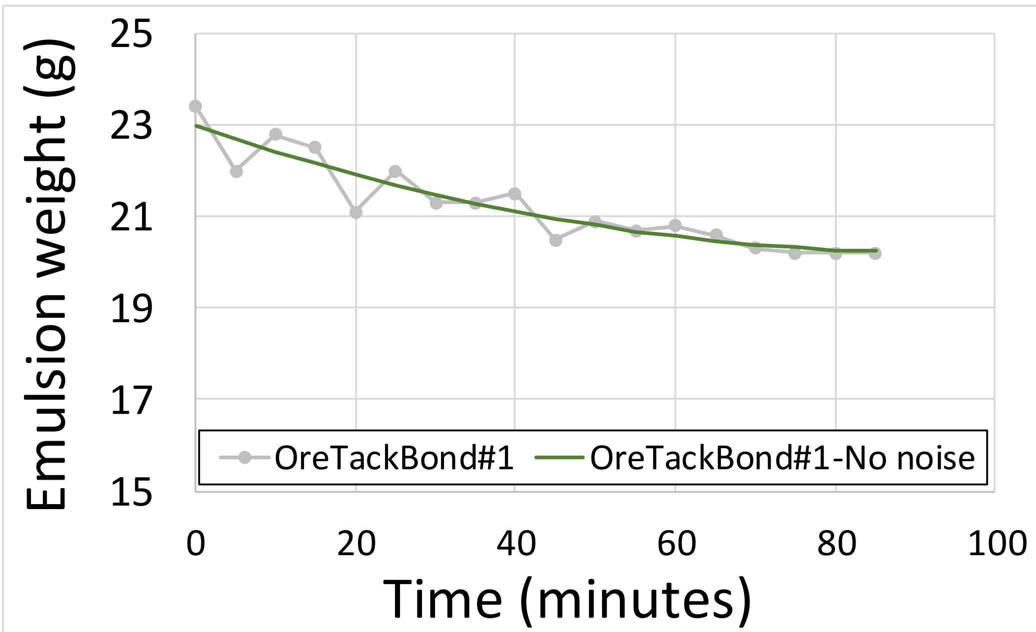


Figure 6.14: Project#5 OreTackRate evaporation data with and without noise reduction.

Weight measurements were converted to "percentage of applied tack weight" by following the process described in Section 6.3.1 (by simply dividing all weight measurements by the initial weight). Results for all three construction projects are given in Figure 6.15. It can be observed that tack coats used in Projects #5 and #7 had very low water contents (less than 15% by weight) while the tack coat used in Project#6 had a significantly higher water content (about 30-40% by weight). For this reason, curing time for Project#6 is expected to be significantly higher than the Projects #5 and #7.

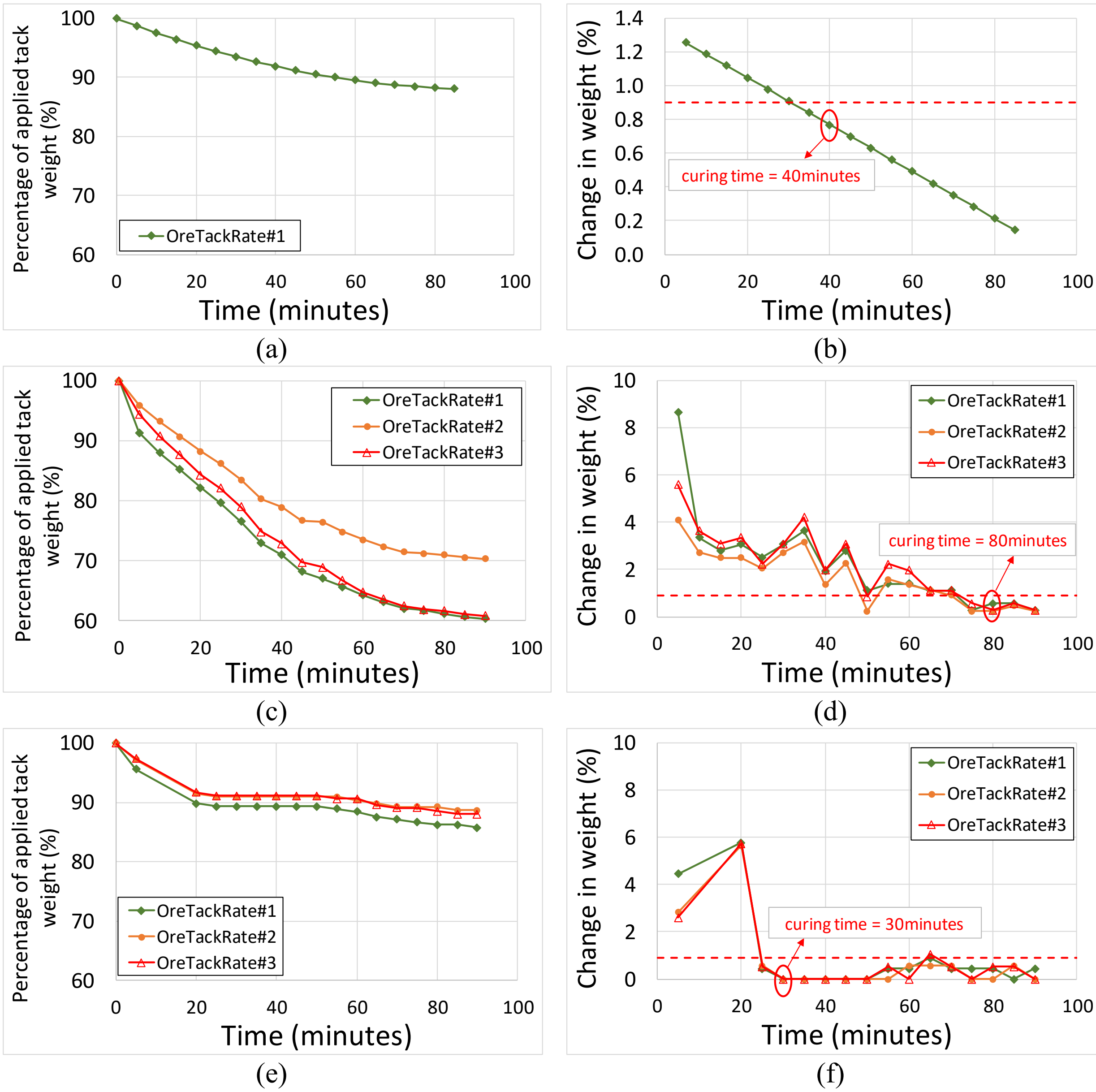


Figure 6.15: Percentage of applied tack coat and change in weight plots from all three construction projects (a) Evaporation curve for Project#5 (b) Change in weight percentage for Project#5 (c) Evaporation curve for Project#6 (d) Change in weight percentage for Project#6 (e) Evaporation curve for Project#7 (f) Change in weight percentage for Project#7.

A process similar to the laboratory curing tests was followed to determine the curing times for all field tests. First, change in weight percentage for every 5 minute internal was calculated and plotted as shown in Figure 6.15b, d, and f. The time point at which the change in weight percentage was lower than 0.9% for a 10 minute interval (based on three measurements at 5-minute intervals in a 10 minute period) was selected as the curing time. By following this process, the curing times for Projects #5, #6, and #7 were determined to be 40, 80, and 30 minutes, respectively (See Figure 6.15b, d, and f). It should be noted that all three scales used for curing time measurement (meaning three replicate measurements in Projects #6 and #7) provided the same curing times for the tack coat emulsions used in those projects. This result proves the repeatability of the process.

An Excel spreadsheet was developed to determine whether the tack coat is set during construction (Figure 6.16). The following process is developed to determine whether the tack coat is cured during construction:

1. Attach the asphalt shingle with plastic place to the scale(s) and place the scale(s) in the construction lane. Make sure to avoid wheelpaths when placing the scale(s).

2. Connect to the scale(s) via the tablet app and move to the side of the road to allow the distributor truck to apply the tack coat in the construction lane.

3. Record the initial weight of the asphalt shingle plate before tack coat application and enter the number into Cell B2 in the Excel spreadsheet. Use the wind guard before taking weight readings but make sure to remove the wind guard immediately after taking readings.

4. Apply the tack coat on the scale(s) using the distributor truck.

5. Immediately after tack coat application, start the stopwatch and record the final weight and enter it into the spreadsheet (Cell C2).

6. Move the scale(s) to the side of the road. Scale(s) and the plate(s) with tack coat must be exposed to the same ambient conditions as the pavement (Make sure not to have anything blocking the wind).

7. Make sure to keep the tablet computer within a 15m. distance from the scale(s) during the entire process to keep the wireless communication active.

8. After 20-30minutes, take the first weight reading (called as "first check" in the spreadsheet) and enter it into Cell C3 in the spreadsheet. If it is a highly diluted tack coat (similar to the one in Project #6), "first check" can be performed 50-60 minutes after tack coat application. In the example spreadsheet screenshot given in Figure 6.16, first weight check was done 50 minutes after the tack coat application (Project#6-Scale#1).

9. Five minutes after the "first check" reading, take another reading and enter it into Cell C4.

10. Ten minutes after the "first check" reading, take the final weight reading and enter it into Cell C5.

11. The spreadsheet will automatically perform the calculations based on the curing criterion described in this section and tell the user whether the tack coat is cured or not. Two possible decisions from the spreadsheet are "NOT CURED YET!!! TRY AGAIN IN 10 MINS" and "TACK CURED". The example case shown in Figure

6.16 is for Project #6-Scale#1. It can be observed that after 60 minutes, tack was still not completely cured. The measured curing time for this tack coat was 80 minutes (see Figure 6.15d).

12. About 2-3 hours after tack coat application, final weight of the tack coat can be checked to determine the weight of the residual tack coat. This measured residual weight can be used to calculate the residual tack coat application rate.

	A	B	C	D	E	F	G
1	Time	Initial weight (g)	Final weight (g)	Applied weight (g)	Change in weight (%)		
2	start weight	330.8	366.6	35.8	100		
3	first check	330.8	354.8	24	67.0		
4	first check+5mins	330.8	354.3	23.5	65.6		
5	first check+10mins	330.8	353.8	23	64.2		
6							
7					DECISION		
8			NOT CURED YET!!! TRY AGAIN IN 10MINS				
9							
10	MAKE SURE TO PLACE THE WINDGUARD						
11							
12	ON THE SCALE BEFORE TAKING MEASUREMENTS						
13							
14							

Figure 6.16: Screenshot for the Excel spreadsheet for curing identification.

6.4 DEVELOPMENT OF A SURFACE CLEANLINESS TEST (ORETACKCLEAN) TO REDUCE TRACKING

Surface contaminants, such as dust, can significantly affect the tack coat bond strength exhibited between pavement layers. Provided that all other factors are befitting, such as tack coat application rate, coverage and curing time, minimizing the amount of dust on the pavement surface can help to ensure that adequate tack coat bond strength is achieved. This is particularly important for milled pavement surfaces, where excess dust is produced from the milling of existing pavement layers. According to FHWA (2016), milling of existing pavement is shown to generate high amounts of dust which can impact bond strength. To combat this, milled surfaces require adequate cleaning, commonly done by sweeping, to ensure that bonding is not compromised (FHWA 2016). As it stands, contractors typically clean the pavement surface using one of two methods: sweeping/vacuuming and air blasting (Al-Qadi et al. 2012b).

The effect of surface cleanliness on bond performance was evaluated by Mohammad et al. (2012). The authors used uniformly graded sand to simulate dust on the pavement surface and found that ISS was enhanced by the presence of dust. This result was attributed to the effect of dust combining with residual asphalt and creating a mastic with a viscosity exceeding that of the residual asphalt alone, which provided greater shear resistance. This, combined with grittiness of sand particles providing extra frictional resistance, yielded a higher ISS. However, due to the use of a uniformly graded sand to simulate dust effects, actual field conditions may not be represented by these results. The authors suggested that cleaning and sweeping of the pavement surface prior to construction is worthwhile to avoid any problems related to the presence of dust. In this study, results of the “adverse conditions” tests also pointed out a significant reduction in bond strength when dust was present on the surface of the pavement before tack coat application (See Chapter 4.3.2). Dust can also affect the propensity of tracking during construction operations. A dustier surface can induce additional tracking, as the dust coating the existing pavement surface readily adheres to tack coat materials which are easily picked up by construction vehicles during paving operations (Mohammad et al. 2012). This tracked debris accumulates and falls off construction vehicle tires, creating inconsistencies in the pavement surface and additional debris on the roadway.

In this part of the study, a cleanliness test (OreTackClean) was developed to determine the cleanliness of the pavement surface before tack coat application. This test identifies the amount of dust/particles present on the surface of the pavement surface. Using the results of the developed cleanliness test and the developed cleanliness criterion, inspectors can make a decision on whether to have additional sweeper passes to clean the surface more or continue with the tack coat application. Developed test can also be used to identify the effectiveness of different sweeper technologies. Although it was not within the scope of this study, in a future study, a sweeper certification/approval process can also be developed using the developed cleanliness test procedure.

6.4.1 Laboratory and parking lot investigations

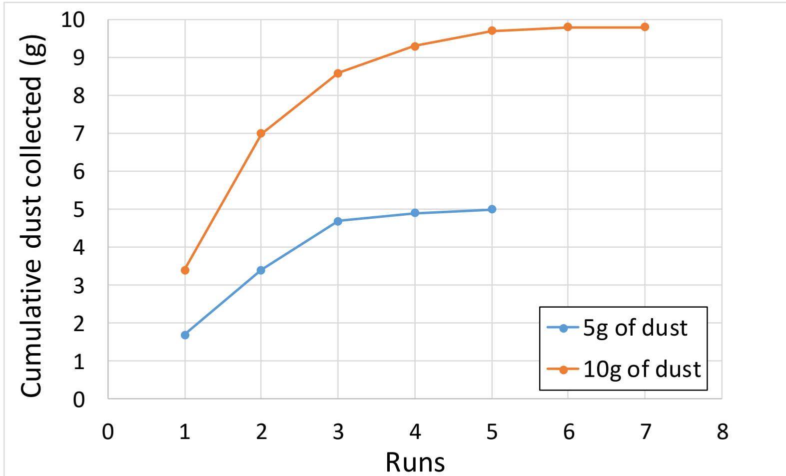
The initial idea of surface cleanliness measurement was to find a reasonable way to pick up all the dust and particles from the surface of the pavement before the application of the tack coat and determine the total weight of all those particles. For this purpose, effectiveness of the following two methods were initially investigated: i) collecting the dust using a handheld vacuum cleaner and weighing the vacuum bag before and after vacuuming the particles to determine the total weight of the particles; and ii) collecting the particles on the pavement surfacing using a special type of putty. First option did not provide reliable results since the total weight of the particles were very small to identify when compared to the weight of the vacuum bag. In addition, a significant percentage of the particles were lost while trying to get the vacuum bag out of the handheld vacuum for weighing. For this reason, second option, collecting the particles with a special putty, was selected for further investigation.

Finding the most appropriate type of putty to collect the particles on the surface was the most important task of the cleanliness measurement process development. Several different electronic cleaning putty types were tested in a parking lot to determine their effectiveness in collecting the particles on the pavement surface. A special jig was also developed to apply a constant force on the putty to get it all the way into the surface texture to be able to collect all surface dust and particles (See Figure 6.17). After cleaning the pavement surface using a vacuum cleaner and a moist rag to remove all existing particles, 5 grams of dust (aggregates passing #200 sieve) was uniformly spread on a 5inch by 5inch area using a soft brush. Putty was placed under a circular plate and the total weight of the putty and the plate were recorded. Then, the plate was placed into the circular jig as shown in Figure 6.17a and a 5lb weight was placed on the plate for about 5 minutes to let the putty completely enter into the surface texture. Results of the tests showed that majority of the putty sticks to the pavement when the pavement surface temperatures are higher than 30ºC (as shown in Figure 6.17c). In addition, when the putty with the collected surface particles was weighed at the end of the test, a very small amount of weight was observed to be picked up by the putty although all the particles on the surface of the pavement were collected. To further investigate the reason for this discrepancy, a control test was performed on a pavement surface without any particles. From the results of this control test, it was observed that majority of the water in the electronic cleaning putty was staying on the surface of the pavement while a significant percentage of the water was evaporating during the process, which was creating a significant bias in weight measurements. These results suggested that a putty without any water content needed to be used for the cleanliness tests. In addition, parking lot experiments showed that a putty that is capable of picking all the surface particles without leaving any putty sticking to the pavement surface is needed for field testing at higher pavement surface temperatures.

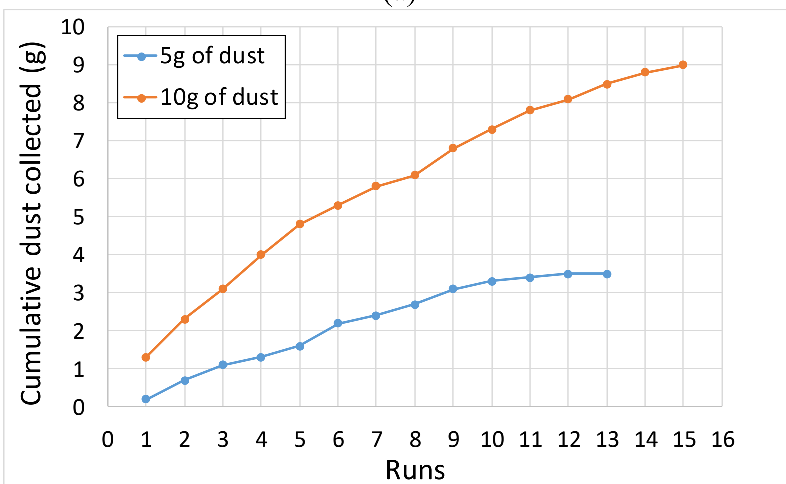
(a) (b) (c)

Figure 6.17: Testing the putty for cleaning electronics for surface dust/particle content measurement (a) Placing the sample under the loading plate (b) Applying the 5lb load on the plate (c) Removal of the plate.

To address the issues encountered with the electronic cleaning putty, a special type of eraser (generally used for erasing charcoal drawings) was used for picking up the particles on the pavement surface. This eraser was stiffer than the electronic cleaning putty and did not have any water. In addition, any remaining eraser putty on the surface can easily be picked up. Trial experiments were conducted in the laboratory to determine the effectiveness of the putty for cleanliness testing. A floor tile with high surface texture was used to simulate surface texture of a milled pavement surface. Surface of the tile was cleaned using a vacuum cleaner and a moist rag to remove all existing dust particles. Then, 5 and 10 grams of dust (percent passing #200 sieve) were uniformly spread on 5inch by 5 inch and 10inch by 10inch squares in two separate cases. With two dust weight levels (5g and 10g) and two areas (5inch by 5inch and 10inch by 10inch), a total of four cleanliness experiments were conducted in the laboratory. Results of these tests are shown in Figure 6.18. It can be observed that it will take more than 15 runs (more than 20 minutes) to collect all dust particles on the surface for the tests conducted on a 10inch by 10inch area. On the other hand, when the tests are conducted on a 5inch by 5in area, almost all the dust on the surface of the pavement can be collected in 5 runs. This result suggested that field tests needed to be conducted on a 5inch by 5inch area and at least 5 runs of dust collection should be performed during the tests to collect all the dust on the surface of the pavement.



(a)



(b)

Figure 6.18: Results of laboratory cleanliness tests (a) Tests conducted on a 5in by 5in surface (b) Tests conducted on a 10in by 10in surface.

Based on laboratory trials, the following process was developed and proposed for field cleanliness testing:

Cleanliness Field Test (OreTackClean) Procedure

Required materials

- Nine eraser putties for three replicate tests (each eraser costs about $2)
- Three rulers
- Three pairs of rubber gloves
- Crayon/Chalk

- A scale (wireless scales for tack rate measurement can also be used for taking measurements for the cleanliness tests)

Testing procedure

1. Place the scale on a flat surface and make sure to place the transparent wind guard on it when taking weight measurements outside.

2. Open and peel plastic sheet off each eraser (make sure no residual plastic is left on the erasers).

3. Put a clean surface on the scale (this will ensure erasers do not get contaminated) and place all three erasers on the plate. Then, measure the initial weight of all three erasers together and record.

4. Knead three erasers into one eraser.

5. Weigh the single eraser to make sure no weight has changed (if weight has changed, record the final weight)

Figure 6.19: Initial weight measurement of the kneaded erasers.

6. Take the weighed eraser with the clean plate to a random location in the construction lane.

7. Draw a 5 inch by 5 inch square with a ruler and a crayon.

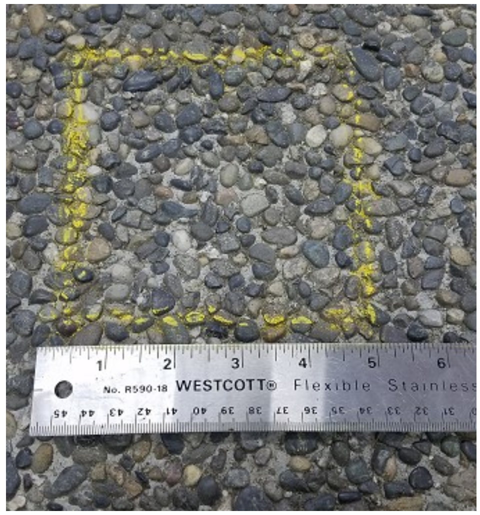
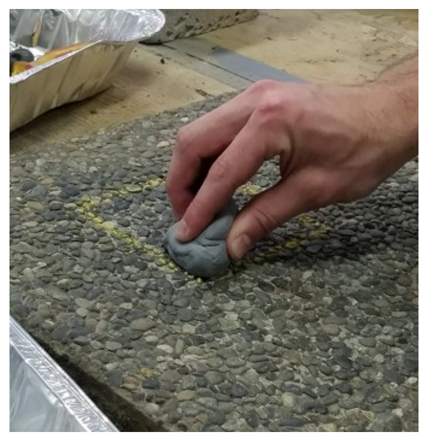


Figure 6.20: 5inch by 5inch square drawn on the pavement surface.

8. Take eraser and dab in square to collect surface dust. Make sure to dab the entire area of the square (This is Run 1).

(a)



(b)

Figure 6.21: Picking up the dust from the surface (First run).

9. Knead the dusty side of eraser to the middle by moving the interior to the outside (pushing a dusty surface constantly into the pavement surface may reduce the stickiness of the eraser)

10. Take the eraser and push it into the texture of the pavement (this is Run 2)

Figure 6.22: Picking up the dust from the surface (Run 2).

11. Do this for the entire area (make sure to knead eraser every time you place it on the surface)

12. Repeat steps 8-10 for Runs 3-5

13. Weigh the eraser with all collected particles after at least 5 runs (more runs maybe required if all visible particles on the surface are not completely removed).

14. Subtract the initial eraser weight (Step 5) from the final weight (Step 13) to calculate the weight of collected particles.

15. Entire process should be repeated at least 3 times (three operators can also perform the process independently to complete all tests in a shorter period of time) and the average collected weight should be used for the cleanliness evaluation.

6.4.2 Field investigation

By following the OreTackClean process described in the previous section, field cleanliness tests were conducted at three construction projects (Projects #5, #6, and #7). Cleanliness tests were conducted by three operators at random locations along the construction lane for Projects #6 and #7. For Project#5, only two cleanliness tests were conducted. Tests were conducted after milling (before any sweeping) and after every sweep to determine the effectiveness of the developed test method for cleanliness identification. Figure 6.23 shows the field cleanliness test results. It should be noted that for some of the cases, collected dust weight might be slightly increasing after a sweep (for example: Project#5-between 1st and 2nd sweeps for Operator#2). This unexpected result is due to conducting the tests at random locations after every sweep. However, the average collected dust amount from three replicate tests is expected to represent the overall cleanliness of the pavement surface by considering the impact of spatial variability on the test results. For this reason, average collected dust from all replicate tests is always decreasing with increasing number of sweeper passes for all three projects. It can also be observed from Figure 6.23 that Project#5 had higher collected particle weight when compared to the initial weight collected for Projects #6 and #7. In addition, the amount of collected particle weight was significantly higher for Project#5 (about 5 to 7 times higher) at the end of all sweeper passes.

Excessive amount of tracking observed for Project#5 is likely to be a result of the high amount of particles on the surface of the pavement after sweeping. Additional number of sweeper passes and/or improving the effectiveness of the sweepers might have resulted in a cleaner before tack coat application for this project. On the other hand, Projects #6 and #7 had an average of 7.3g and 5.4g of particles on the surface (for the 5inch by 5inch test area), respectively. It should be noted that less than 10grams of particles on the surface always looked visually reasonable (See Figure 6.24d) while it was easier to visually see significant amount of particles on the surface when the collected average particle weight was over 20grams (See Figure 6.24c). For this reason, **a cleanliness threshold of 10grams for a 5inch by 5inch area is suggested as the acceptance criterion in this study.** Both Projects #6 and #7 pass this requirement after sweeping while Project#5 fail to meet the criterion.

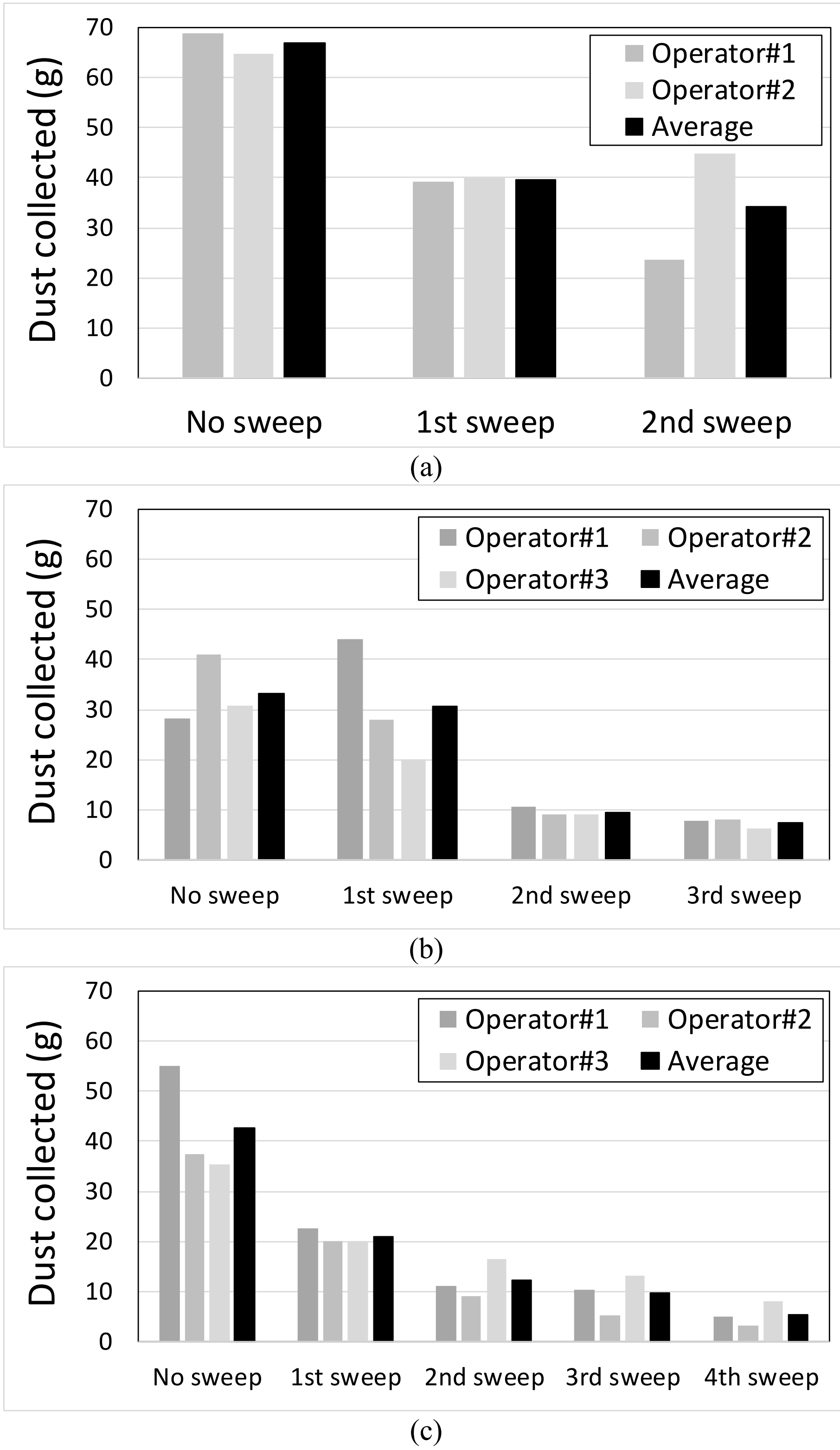
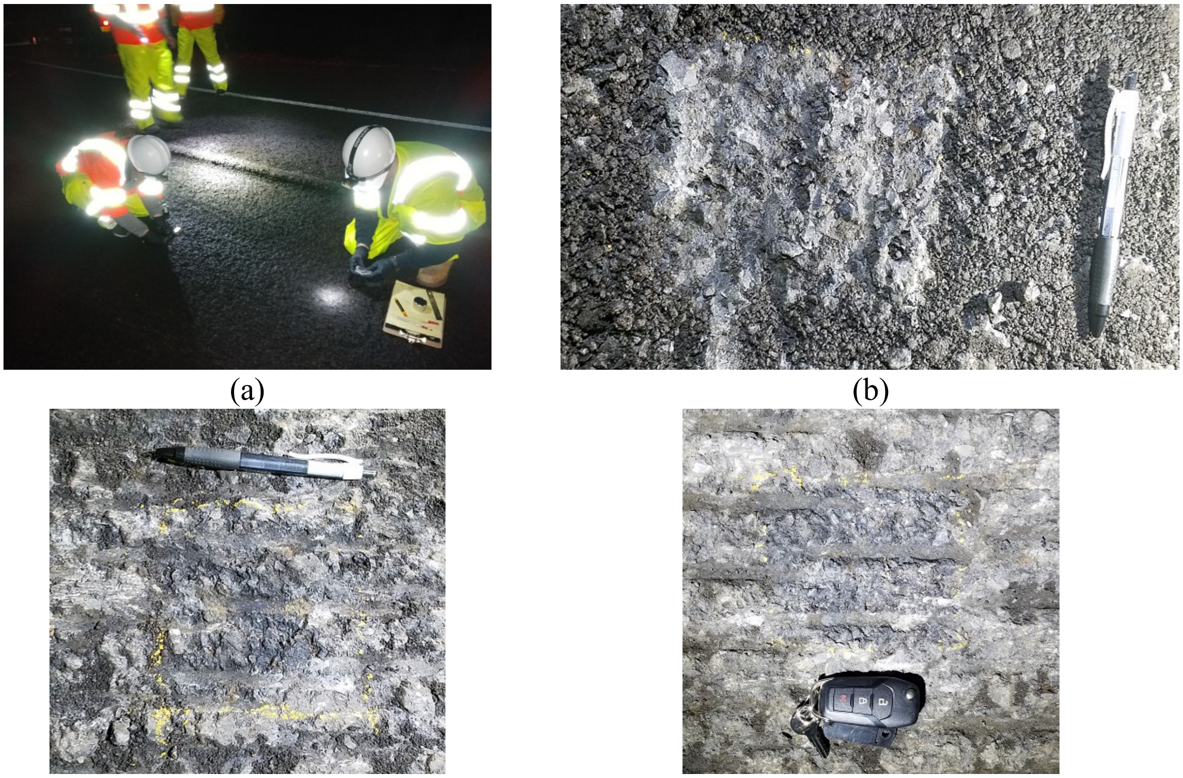


Figure 6.23: Field cleanliness test results (a) Project#5 (b) Project#6 (c) Project#7.



(a) (b) (c) (d)

Figure 6.24: Field cleanliness testing for Project#7 (a) Two operators conducting cleanliness tests (b) Pavement surface after the cleanliness test (after milling-before sweepers – 43 grams of dust) (c) Pavement surface after the 1st sweeper pass – 21 grams of dust (d) Pavement surface after the 3rd sweeper pass – 9.5 grams of dust.

6.5 SUMMARY AND CONCLUSIONS

In this part of the study, a wireless scale system (OreTackRate) that can be controlled from a tablet computer was developed to measure tack coat application rate accuracy and uniformity. Developed wireless scale system was recommended to be used during construction for application rate accuracy and uniformity validation. In addition, a distributor truck certification process was developed and presented in this Chapter. Developed scale system can also be used to determine whether the applied tack coat is cured at any time point during construction. Residual tack coat application rate can also be measured using OreTackRate during construction. A surface cleanliness test (OreTackClean) was also developed and proposed in this Chapter to reduce tracking during construction. The analyses presented in this Chapter have yielded the following conclusions:

1. Developed OreTackRate wireless scale system can accurately measure tack coat application rates during construction. OreTackRate system is also a more practical method for tack coat application rate measurement than the current application rate measurement standard with textile pads.

2. Developed tack coat application uniformity and accuracy measurement process and the proposed distributor truck certification procedure are expected to improve the long-term tack coat bond performance.

3. Developed tack coat curing time measurement process provided reasonable results for tack coats with high and low dilution rates. Field test results proved the effectiveness of OreTackRate for curing time identification.

4. Developed cleanliness test (OreTackClean) can be used to accurately measure surface cleanliness. Following the developed process and meeting the proposed cleanliness threshold requirement are expected to improve tack coat bond strength and reduce tracking during construction.

Implementation of all these tests, procedures, and technologies are expected to improve the tack coat uniformity during construction and improve the overall longevity of the pavement structure. Developed procedures and technologies may also be used to reward contractors who complete projects with high tack coat application uniformity and accuracy in the first bonding-based pay factor analysis in the U.S.

7.0 SUMMARY AND CONCLUSIONS

The major purpose of this study was to develop methods and technologies to improve the performance of tack coat bonding between pavement layers in Oregon. Improved tack coat bond performance is expected to significantly improve the longevity of pavements in Oregon. For this purpose, a post-construction tack coat bond strength measurement system (OretackBond) was developed in this study. An implementation process for the OreTackBond for QC was also developed and proposed. In addition, performance of new (engineered emulsions that are tracking less) and existing tack coat types commonly used in Oregon at different application rates were also determined in this study. The impact of nonuniform coverage/streaking, presence of dust on pavement surface, and rainfall on tack coat bond quality was also quantified.

A wireless scale system (OreTackRate) that can be controlled from a tablet computer was also developed in this study to measure tack coat application rate accuracy and uniformity. Developed wireless scale system was recommended to be used during construction for application rate accuracy and uniformity validation. In addition, a distributor truck and operator certification process was developed and presented. In addition to measuring tack coat application rates and uniformity, OreTackRate can also be used to determine residual tack coat application rates during construction. Developed scale system can also be used to determine whether the applied tack coat is cured at any time point during construction. This important information can be used to reduce tracking by only allowing construction traffic on the tack coat layer after curing. A surface cleanliness test (OreTackClean) was also developed and proposed in this study to reduce tracking during construction.

Implementation of all these tests, procedures, and technologies are expected to improve the tack coat uniformity during construction and improve the overall longevity of the pavement structures in Oregon. Developed procedures and technologies may also be used to reward contractors who complete projects with high tack coat application uniformity, accuracy, and strength in the first bonding-based pay factor analysis in the U.S.

7.1 CONCLUSIONS

The major conclusions drawn from the results of this study are:

7.1.1 Evaluation of Milled Surface Tack Coat Performance at Manufacturer Recommended Application Rates

Tack Coat Core Tests:

1. Engineered tack coats were found to have superior performance over tack coats traditionally used in Oregon. Engineered tack coats provided by Company 1 and Company 3 exhibited the highest ISS and IBE.

2. The engineered tack coats for Company 1 and Company 3 had ISS values higher than all other tack coats tested, with Company 3 having a slightly higher ISS than Company 1. However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.600 from a two-sample t-test at a 95% significance level.

3. When comparing Company 1's CSS-1H tack coat to that of Company 3 based on laboratory shear test results, Company 3's tack coat had slightly better performance. However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.297 from a two-sample t-test at a 95% confidence level.

4. The engineered tack coats provided by Company 2 did not achieve the performance of the engineered or CSS-1H tack coats provided by the other two companies. This result is attributed to the high water content of the Company 2 engineered tack coat and the possible need to increase the residual application rates. Additional research is required to determine the optimum application rates for Company 2's engineered tack coat.

5. CO2-ENGR-M1/2 were found to have no significant difference in ISS and IBE when compared to CO3-CSS1, indicating that these engineered tack coats did not exhibit better performance than traditional tack coats.

6. Conclusions 1 to 5 stated above also hold when the interlayer bond energy was used as the performance parameter rather than the ISS.

7. The engineered tack coat provided by Company 1 had significantly superior peak shear strength when compared to their CSS-1H tack coat.

8. Company 3's engineered tack coat was found to have significantly better performance as compared to their CSS-1 and CSS-1H tack coats.

9. There was no significant correlation between peak shear strength and MTD, as is suggested by the low correlation coefficient. This indicates that MTD is not controlling bond strength and that laboratory milling practices did not create any bias in the results.

10. The peak shear strengths of the laboratory-produced samples were not dissimilar to that of the field-cored samples. The laboratory-produced samples had shear strengths that were well within the domain of shear strengths yielded from the field-cored samples. This indicates that the sample procurement procedures of this study (using a laboratory roller compactor and laboratory milling procedures) produce shear strength results that are similar to what is observed under field conditions.

Tack Coat Binder Tests:

1. The engineered binders displayed the highest softening point and RV values, while the CSS-1H binders gave the lowest. This suggests that these tack coat binders are softer than the newly engineered binders.

2. A discrepancy in the results for the softening point test can be seen in the values displayed for the CO2-ENGR-M distilled emulsion. This particular binder did not have a smooth consistency when poured, as was typical with the other binders, presumably due to the binder being polymer-modified and not able to withstand the sample preparation temperatures. As a result, the binder was not evenly distributed throughout the test rings.

3. Company 3 displays consistent results between RV and SP. On the other hand, Company 2 had slightly skewed results between RV and SP tests. CO2-ENGR-M displayed very high RV values as well as high variability within these results. The test was conducted at 275 °F (135 °C), a temperature that may have been too high for this particular binder to withstand. Therefore, the viscosity may be higher than expected and shows a large deviation due to the lack of fluidity and consistency that the binder may have maintained at elevated temperatures.

4. Results for Company 3 binders are consistent across all binder tests. CO1-ENGR-M shows a relatively lower penetration than most other tack coat binders, signifying a stiff binder, which is consistent with the RV results.

5. The major factor affecting the relationship between the rheological tests and the tack coat's ISS was temperature. Shear tests were conducted at 77 °F (25 °C). Binder tests that were conducted at or near this temperature displayed the highest correlations. Penetration testing was also performed at 77 °F (25 °C), and gave the highest correlation at 89.8%. Similarly, DSR results at 68 °F (20 °C) and 86 °F (30 °C) showed high correlations at 89.9% and 89.6%, respectively. On the other hand, RV displayed a low correlation value to ISS (25.9%), likely due to the high temperature of 275 °F (135 °C) in which this test was conducted. Based on these results, penetration tests can be used as a low cost and more practical alternative to the more complicated ISS experiments of tack coats.

7.1.2 The Impact of Emulsion Type Application Rate and Adverse Conditions on Tack Coat Bond Performance

1. The ISS and IBE of engineered tack coats was found to be higher than that of conventional tack coats, in general.

2. Engineered tack coats provided by Company 1 and Company 3 exhibited the best performance for milled surfaces.

3. Engineered tack coats provided by Company 1 and Company 2 exhibited similar performance for overlay surfaces while the performance for Company 3's engineered tack coat was slightly higher than both companies for overlay surfaces.

4. Increased application rates significantly improved the bond quality of tack coats applied to overlay surfaces, indicating that the optimum tack coat application rate for overlay surfaces must be much higher than the low rate (0.05 gal/yd^2) selected for use in this study. More research is needed to determine optimum application rates for each of the tack coats tested in this study.

5. Increased application rates did not necessarily result in improved bond performance in all cases. This was especially true for milled surfaces, where the higher application rate provided diminishing returns in bond quality. Higher application rates actually decreased ISS/IBE in some cases for milled surfaces, suggesting that the optimum application rate for milled surface tack coats must be close to the low rate (0.09 gal/yd^2) chosen in this study. More research is required to determine optimum application rates for each of the tack coats tested in this study.

6. The Company 2 milled surface tack coat stood out from general trends exhibited by Company 1 and Company 3 milled surface tack coats. Company 2's milled surface tack coat did not achieve better performance than their overlay tack coats or tack coats provided by the other two companies. This result may be attributed to the high water content/low residual asphalt content of Company 2's milled surface tack coat and the possible need to increase the suggested application rate for this tack coat. Additionally, this tack coat was noted to penetrate through the voids of the first list during tack coat application due to its high water content/low viscosity. More research is needed to determine the optimum application rate for this particular tack coat.

7. Engineered tack coats designed for milled surfaces exhibited a foaming action during application which was noted to provide excellent coverage uniformity.

8. The presence of dust on the pavement surface prior to tack coat application resulted in reductions in both ISS and IBE for both conventional and engineered tack coats. These reductions were more discernable at higher application rates. However, these reductions were not statistically significant at a 95% confidence level.

9. Tack coat streaking/nonuniform coverage was found to significantly impact bond quality. Considerable reductions in ISS and IBE were observed at both low and high application rates in both tack coat types (conventional and engineered). Statistical comparisons also showed strong evidence of these conclusions at a 95% confidence level. This result is testament to the importance of uniform coverage and proper tack coat applicator maintenance during construction.

10. The effect of rainfall after tack coat application was determined to negatively impact bond quality for all tack coats. ISS reductions were observed for all samples except CO1-ENGR-M-Low. However, IBE reductions were apparent for all samples, including CO1-ENGR-M-Low. This indicates that IBE may be a better indicator of bond performance than ISS.

11. Rainfall on the freshly tacked pavement surface was noted to rinse away the tack coat, effectively reducing the amount of tack coat available for bonding. However, engineered tack coats were noted to be more difficult to wash away than were conventional tack coats. This observation may suggest that use of engineered tack coats when rainfall is prevalent could help to extend the construction window into seasons with more inclement weather.

12. Engineered tack coats were less susceptible to reductions in ISS and IBE under rainfall conditions than were conventional tack coats, indicating that engineered tack coats are more suitable for pavement construction during inclement weather.

7.1.3 Quantifying In-situ Tack Coat Performance using the OreTackBond, Cyclic Direct Shear Testing and the Oregon Field Tack Coat Tester (OFTCT)

1. The newly updated OreTackBond was confirmed to successfully capture tack coat bond quality on both milled and overlay surfaces in the laboratory and in the field.

2. Engineered tack coats were noted to perform better than tack coats conventionally used in Oregon.

3. ISS results extracted from OreTackBond laboratory tests were found to capture the expected trends in tack coat performance on both milled and overlay surfaces.

4. ISS results from OreTackBond field tests were significantly diminished from results of OreTackBond tests performed on laboratory-produced samples, indicating that problems with tack coat application in the field are hindering performance of in-service pavements in Oregon.

5. The OFTCT device is not suitable for field evaluation of tack coat performance prior to construction.

6. Cyclic DST results were not well-correlated with monotonic DST results, suggesting the need to develop a more robust fatigue failure criteria for tack coats in future research.

7.1.4 Developing Technologies and Procedures to Avoid Tracking and Achieve Uniform and Accurate Tack Coat Application

1. Developed OreTackRate wireless scale system can accurately measure tack coat application rates during construction. OreTackRate system is also a more practical method for tack coat application rate measurement than the current application rate measurement standard with textile pads.

2. Developed tack coat application uniformity and accuracy measurement process and the proposed distributor truck certification procedure are expected to improve the long-term tack coat bond performance.

3. Developed tack coat curing time measurement process provided reasonable results for tack coats with high and low dilution rates. Field test results proved the effectiveness of OreTackRate for curing time identification.

4. Developed cleanliness test (OreTackClean) can be used to accurately measure surface cleanliness. Following the developed process and meeting the proposed cleanliness threshold requirement are expected to improve tack coat bond strength and reduce tracking during construction.

7.2 MAJOR RESEARCH PRODUCT DEVELOPED IN THIS STUDY

The major research products developed in this study are given as follows:

- Recommendations regarding the effectiveness of different tack coat types from three tack coat emulsion producers,

- An innovative laboratory specimen preparation process that involves simulation of adverse construction conditions and their impact on bond quality,

- OreTackBond [formerly known as Oregon Field Torque Tester (OFTT)] test system with updated hardware and software,

- A tack coat bond quality control (QC) process using OreTackBond,

- A wireless scale system controlled from a tablet computer (OreTackRate) for tack coat application uniformity and accuracy quantification,

- A test procedure for tack coat application uniformity and accuracy measurement using the OreTackRate,

- A distributor truck certification and validation process,

- A procedure for measuring tack coat curing time using the OreTackRate system to reduce tracking, and

- A cleanliness test procedure (OreTackClean) to quantify surface cleanliness during construction.

8.0 REFERENCES

Alabama Department of Transportation (ALDOT). (2008). *Standard Test Method for Determining the Bond Strength Between Layers of An Asphalt Pavement*. ALDOT-430. Alabama Department of Transportation Bureau of Materials and Tests.

Al-Qadi, I.L., K.I. Hasiba, A.S. Cortina, H. Ozer & Z. Leng. (2012). *Best Practices for Implementation of Tack Coat: Part 1, Laboratory Study.* Research Report FHWA-ICT-12-004. Illinois Center for Transportation, Series No. 12-004.

Al-Qadi, I.L., K.I. Hasiba, A.S. Cortina, H. Ozer, Z. Leng. & D.C. Parish. (2012). *Best Practices for Implementation of Tack Coat: Part 2, Field Study.* Illinois Center for Transporatation, Springfield, IL.

Al-Qadi, I.L., S.H. Carpenter, Z. Leng & H. Ozer. (2008). *Tack Coat Optimization for HMA Overlays: Laboratory Testing.* Research Report FHWA-ICT-08-023. Illinois Center for Transportation, Series No. 08-023.

Amelian, S. and Y.R. Kim. (2017). *Evaluation of Tack Coating Practices for Asphalt Overlays in Nebraska.* Report SPR-P1(16) M039. Nebraska Department of Transportation Research Reports. 199. http://digitalcommons.unl.edu/ndor/199

American Association of State Highway and Transportation Officials (AASHTO). (2012). *Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt.* AASHTO T 209-12.

American Association of State Highway and Transportation Officials. (AASHTO) (2012). *Standard method of test for determining the dynamic modulus and flow number for Hot Mix Asphalt (HMA) using the Asphalt Mixture Performance Tester (AMPT): AASHTO designation, TP 79-12* [1] [2]. Washington, D.C.: American Association of State Highway and Transportation Officials.

American Association of State Highway and Transportation Officials (AASHTO). (2016). *Determining the Interlayer Shear Strength of Asphalt Pavement Layers.* AASHTO TP 114.

Asphalt Institute. (1989). *The Asphalt Handbook.* MS-4, Asphalt Institute, Lexington, KY.

American Society for Testing and Materials (ASTM). (2015). *Standard Practice for Estimating Application Rate and Residual Application Rate of Bituminous Distributors*, Standard D2995. DOI: 10.1520/D2995-14

American Society for Testing and Materials ASTM. (2015). *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique*, Standard E965. http://doi.org/10.1520/E0965-96R06.2

Barreira, E. and V.P. Freitas. (2007). *Evaluation of building materials using infrared thermography.* Construction and Building Materials 21, pp. 218-224.

Biligiri, K., K. Kaloush, M. Mamlouk and M. Witczak. (2007). *Rational Modeling of Tertiary Flow for Asphalt Mixtures*. Transportation Research Record: Journal of the Transportation Research Board, (2001), pp. 63-72.

Brown, S.F. and J.M. Brunton. (1984). *The influence of bonding between bituminous layers.* The Journal of the Institution of Highways and Transportation, United Kingdom, 31(5), pp. 16-17.

Buchanan, S. and M. Woods. (2004). *Field Tack Coat Evaluator (ATACKer).* Publication FHWA/MS- DOT-RD-04-168. Construction Materials Research Center. Starkville: Mississippi State University.

Celaya, M., S. Nazarian, C. Rao and H. Von Quintus. (2010). *Delamination Detection of HMA Airport Pavements with NDT Devices.* Presented for the 2010 FAA Worldwide Airport Technology Transfer Conference, Atlantic City, New Jersey, USA.

Coleri, E., D. Covey, A. Mahmoud, J. Batti and N. Anisimova. (2017). *HMAC layer adhesion through tack coat.* Final Report-SPR782. FHWA-OR-RD-17-05. Salem, OR: Oregon Department of Transportation, Research Section.

Collop, A.C., M.H. Sutanto, G.D. Airey, R.C. Elliott. (2011). *Development of an automatic torque test to measure the shear bond strength between asphalt*. Constr. Build. Mater. 25 (2) 623–629.

Cortina, A.S. (2012). *Optimization of In-Situ Tack Coat Application Rate and Installation*. Illinois at Urbana-Champaign.

Covey, D., E. Coleri and A. Mahmoud. (2017). *Tack Coat Rheological Properties and the Effects on Interlayer Shear Strength.* ASCE - Journal of Materials in Civil Engineering, 29 (11), pp.1-11, doi.org/10.1061/(ASCE)MT.1943-5533.0002054.

Covey, D., E. Coleri and A. Mahmoud. (2018). *Development of a smartphone app and device to reduce tack coat tracking.* Road Materials and Pavement Design.

De Jong, D. L. (1973). *Computer Program BISAR Layered System Under Normal and Tangential Loads.* Konin Klijke Shell-Laboratorium, Amsterdam: External Report AMSR 6.

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

Diakhate, M., A. Millien, C. Petit, A. Phelipor-Mardele and B. Pouteau. (2011). *Experimental investigation of tack coat fatigue performance: Towards an improved lifetime assessment of pavement structure interfaces.* Construction and Building Materials, 25, pp. 1123-1133.

Dongré, R., J. D'Angelo and A. Copeland. (2009). *Refinement of Flow Number as Determined by Asphalt Mixture Performance Tester: Use in Routine Quality Control—Quality Assurance Practice*. Transportation Research Record: Journal of the Transportation Research Board, (2127), pp.127-136.

Federal Highway Administration (FHWA). (2016). *Tack coat best practices.* Office of Asset Management, Pavements and Construction, Report No. FHWA-HIF-16-017.

FLIR Systems. (2017).FLIR Ex-Series Cameras. Retrieved from http://www.flir.com/instruments/ex-series/

ForConstructionPros.com. (2018). *How to apply a tack coat.* Retrieved from https://www.forconstructionpros.com/asphalt/article/11576337/how-to-apply-a-tack-coat

Francken, L. (1977). *Pavement Deformation Law of Bituminous Road Mixes in Repeated Load Triaxial Compression.* Presented at Fourth International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor.

Hachiya, Y., S. Umeno and K. Sato. (1997). *Effect of tack coat on bonding characteristics at interface between asphalt concrete layers.* Eighth International Conference on Asphalt Pavements, Seattle, Washington, pp. 349–362.

Hofman, V. and E. Solseng. (2004). *Spray equipment and calibration.* North Dakota State University, Fargo, ND.

Holtrop, W. and S. Patrick. (2014). *Performance Requirements for Bitumen Sprayers.* Austroads Technical Report AP-T262-14, Syndey, Australia.

Hu, X., Y. Lei, H. Wang, P. Jiang, X. Yang and Z. You. (2017*). Effect of tack coat dosage and temperature on the interface shear properties of asphalt layers bonded with emulsified asphalt binders*. Construction and Building Materials, Vol. 141, pp. 86-93.

Johnson, E.N., M.K. Cole and J. Pantelis. (2015). *Tack Coat Testing – Measuring Field Bond Strength*, Final Report 2015- 25, Office of Materials and Road Research, Minnesota Department of Transportation.

King, G. and R. May. (2003). *New Approaches to Tack Application*, Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C.

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

Kruntcheva, M.R., A.C. Collop and N.H. Thom. (2005). *Effect of bond condition on flexible pavement performance*. ASCE 11, pp. 880–888, http://dx.doi.org/10.1061/ (ASCE)0733-947X(2005) 131:11(880).

Landefeld, C.E. (2014). Evaluation of Pave-IR Thermal Imaging for Asphalt Pavement Uniformity. *Ohio Department of Transportation Office of Statewide Planning & Research: Final Report*. April 2014.

Mahmoud, A. (2016). *Development of technologies to evaluate Hot Mix Asphalt layer adhesion through Tack Coat.* Abstract Thesis, Oregon State University, Corvallis, OR.

Mahmoud, A., E. Coleri, J. Batti and D. Covey. (2017a) *Development of A Field Torque Test to Evaluate In-Situ Tack Coat Performance.* Journal of Construction and Building Materials, 135, p.377-385, doi.org/10.1016/j.conbuildmat.2017.01.013.

Mahmoud, A., E. Coleri, J. Batti and D. Covey. (2017b). *Development of a Wireless Field Tack Coat Tester to Evaluate In-Situ Tack Coat Performance.* Journal of Road Materials and Pavement Design, pp.1-19, doi: 10.1080/14680629.2017.1354775.

McLeod, N.W. (1969). *A General Method of Design for Seal Coats and Surface Treatments.* Proceedings of the Association of Asphalt Paving Technologists, Vol. 38, pp. 537–630.

Mohammad, L. and J. Button. (2005). *Optimization of Tack Coat for HMA Placement.* Final Contract Report No. NCHRP Project 9-40, National Cooperative Highway Research Program, Louisiana Transportation Research Center and Texas Transportation Institute.

Mohammad, L.N., A. Bae, M.A. Elseifi, J. Button and J.A. Scherocman. (2009). *Interface shear strength characteristics of emulsified tack coats*. Journal of the Association for Asphalt Paving Technologists, Vol. 78, pp. 249–278.

Mohammad, L.N., A. Bae, M.A. Elseifi, J. Button and N. Patel. (2010). *Effects of Pavement Surface Type and Sample Preparation Method on Tack Coat Interface Shear Strength.* Transportation Research Record: Journal of the Transportation Research Board, No. 2180, Transportation Research Board of the National Academies, Washington, D.C., pp. 93–101. DOI: 10.3141/2180-11

Mohammad, L.N., Elseifi, M.A, Bae, A., Patel, N., Button, J. and Scherocman, J.A. (2012). *Optimization of Tack Coat for HMA Placement.* National Cooperative Highway Research Program, No. NCHRP 712, Washington, D.C.: Transportation Research Board.

Mohammad, L.N., M.A. Elseifi, A. Bae and N. Patel. (2012). *Optimization of Tack Coat for HMA Placement.* NHCRP Report 712. Louisiana Transportation Research Center, Louisiana State University, Baton Rouge, Louisiana.

Mokarem, D.W. (2006). *Hot-Mix Asphalt Placement: Virginia's Move to a Two-Inch Drop-Off.* Virginia Transportation Research Council, Report No. VTRC 06-R19.

Oregon Department of Transportation (ODOT) (2014). *ODOT Hydraulics Manual.* Oregon Department of Transportation, Salem, Oregon.

Oregon Department of Transportation (ODOT) (2015). *Oregon Standard Specifications for Construction.* Oregon Department of Transportation, Salem, Oregon.

ProVal. (2018). http://www.roadprofile.com

Raposeiras, A.C., A. Vega-Zamanillo, M.A. Calzada-Perez and D. Castro-Fresno. (2012). *Influence of surface macro-texture and binder dosage on the adhesion between bituminous pavement layers.* Construction and Building Materials, Vol. 28, pp. 187-192.

Rawls, M., J.H. Im and C. Castorena. (2016). *Tack Lifter for In Situ Measurement of Effective Emulsion Application Rates.* Transportation Research Record: Journal of the Transportation Research Board, No. 2550, Transportation Research Board, Washington, D.C., pp. 80–88. DOI: 10.3141/2550-11

Roffe, J.C. and F. Chaignon. (2002). *Characterization Tests on Bond Coats: Worldwide Study, Impact, Tests, Recommendations.* 3rd International Conference on Bituminous Mixtures and Pavements, Thessaloniki, Greece.

Romanoschi, S.A. and J.B. Metcalf. (2001). *Characterization of Asphalt Concrete Layer Interfaces.* Transportation Research Record, pp. 132-138.

Salinas, A., I.L. Al-Qadi, K.I. Hasiba, H. Ozer, Z. Leng and D.C. Parish. (2013). *Interface layer tack coat optimization.* Transportation Research Record, 2372 (1), pp. 53–60.

Shiells, D.P. (2015). *Uniform Paving Platform Regional Asphalt Seminar.* Blacksburg, VA. Obtained from http://slideplayer.com/slide/3925239/

Sholar, G., G. Page, J. Musselman, P. Upshaw and H. Moseley. (2004). *Preliminary Investigation of a Test Method to Evaluate Bond Strength of Bituminous Tack Coats.* Journal of the Association of Asphalt Paving Technologists. Vol. 73, pp. 771–801.

Song, W., X. Shu, B. Huang and M. Woods. (2015). *Factors affecting shear strength between open-graded friction course and underlying layer.* Construction and Building Materials, Vol. 101, pp. 527-535.

Tashman, L, K. Nam, T. Papagiannakis, K. Willoughby, L. Pierce and T. Baker. (2008). *Evaluation of Construction Practices That Influence the Bond Strength at the Interface between Pavement Layers.* Journal of Performance of Constructed Facilities, Vol. 22, No. 3, pp. 154–161.

Tashman, L., K. Nam and T. Papagiannakis. (2006). *Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength between Pavement Layers.* Report No. WCAT 06- 002. Report prepared for Washington State Department of Transportation.

Tayebali, A. A., Rahman, M. S., Kulkarni, M. B. and Xu, Q. (2004). A mechanistic approach to evaluate contribution of prime and tack coat in composite asphalt pavements. No. FHWA/NC/2004-05.

Tozzo, C., N. Fiore and A. D'Andrea. (2014). Dynamic shear tests for the evaluation of the effect of the normal load on the interface fatigue resistance. Construction and Building Materials, 61, pp. 200-205.

Trulson, F.J., A.F. Scarpelli and G.L. Sarosy. (1991). *Ultrasonic Multilayer Paint Thickness Measurement.* United States Patent.

Tschegg, E.K. (1997). *An efficient fracture test method for bituminous materials and layer bonds.* Proceedings of the Fifth Intern. RILEM Symposium on Mechanical Tests for Bituminous Materials, Lyon, pp. 405–411.

Walsh, I.D., and J.T. Williams. HAPAS Certificates for Procurement of Thin Surfacing (2001). Highways and Transportation, Vol. 48, Nos. 7-8, 2001, pp. 12–14. Retrieved from https://trid.trb.org/view.aspx?id=715783

Wang, J., F. Xiao, Z. Chen, X. Li and S. Amirkhanian. (2017). *Application of tack coat in pavement engineering.* Construction and Building Materials, Vol. 152, pp. 856-871.

West, R.C. (2010). *Reclaimed asphalt pavement management: Best practices.* NCAT Draft Report. National Center for Asphalt Technology, Auburn, AL.

West, R.C., J. Zhang and J. Moore. (2005). *Evaluation of Bond Strength between Pavement Layers.* NCAT Report 05-08, National Center for Asphalt Technology, Auburn University.

Willis, J. and D. Timm. (2006). *Forensic Investigation of Debonding in Rich-bottom Pavement.* National Center for Asphalt Technology Report 06-04, Auburn, AL.