AN ABSTRACT OF THE THESIS OF

David J. Covey for the degree of Master of Science in Civil Engineering presented on August 3, 2016.

Title: Evaluation of Oregon Tack Coat Performance to Reduce Tracking and Increase Interlayer Shear Strength of Asphalt Pavements.

Abstract approved: ____

Erdem Coleri

CSS-1H is the most commonly used slow-setting emulsion grade in Oregon. “New” engineered emulsions were recently developed in Oregon to reduce tracking, the pick-up of tack coats by construction vehicle tires during construction activities, and increase interlayer shear strength (ISS), the amount of adhesive bond present between layers of asphalt pavement. Tracking reduces the amount of tack coat in particular areas and creates a non-uniform tack coat distribution between two pavement layers. The non-uniform tack coat distribution leads to localized distresses and significant reductions in interlayer shear strength, leading to complete failure of the pavement structure. The magnitude of this effect and performance of the tack coat is dependent on tack coat type, residual application rate, temperature, existing surface condition (cracked, milled, overlay), and curing time.

For this reason, reducing tracking and increasing interlayer shear strength between pavement layers becomes vital to the longevity of the pavement structure. The performance (ability to reduce tracking and increase ISS) of these emulsions, most effective application rates, the effects of pavement surface texture and traffic on ISS, and curing times were evaluated in this study.

Results show that lower temperatures and increased application rates lead to longer curing times, while higher wind speeds will reduce curing times. The results indicate that tracking will decrease with increased curing time. Results show that a positive correlation between pavement surface texture and interlayer shear strength exists and that milled surfaces provide significantly higher ISS than non-milled overlay surfaces. The results indicated that there are positive correlations between rheological tests and interlayer shear strengths from field cores. The results also showed significant variances in application rates by distributor trucks. Hence there is a need for unified guidelines on tack coat QC/QA and construction practices.

Evaluation of Oregon Tack Coat Performance to Reduce Tracking and Increase Interlayer Shear Strength of Asphalt Pavements

by
David J. Covey

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented August 3, 2016
Commencement June 2017

Master of Science thesis of David J. Covey presented on August 3, 2016

APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

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

David J. Covey, Author

ACKNOWLEDGEMENTS

I would like to thank and recognize my advisor, Professor Erdem Coleri, for his support and guidance over this last year. Being given the opportunity to pursue this degree was a great blessing and I thank him for bringing me aboard his research team. Through his expertise, I have learned a great deal about my research topic, both in groups and independently. The lessons and knowledge learned from him and through this research will positively affect my career as an engineer.

The members of Coleri Research Group have all contributed in some way to my thesis. Whether it be assistance with field measurements, obtaining core samples, photography, driving to field locations, developing a smartphone app, or general support. I would like to express my appreciation and say thank you to Aiman Mahmoud, Shashwath Sreedhar, Blaine Wruck, Mostafa Estaji, Sogol Haddadi, Yuqi Zhang Jeffery Knowles, Natasha Anisimova, Matt Haynes, and Dylan Kreiger.

This research in this thesis was supported by the Oregon Department of Transportation (ODOT), which is greatly appreciated. Also, a special thank you for the support of all ODOT coring crew members, and the individuals of the Technical Advisory Committee (TAC).

Finally, to my parents, Valerie, Kevin, and Dave, my sister, Felicia, and all of my friends thank you! Without their support and encouragement, this study and my whole college career would have been near impossible.

GO BEAVS!!

CONTRIBUTION OF AUTHORS

Aiman Mahmoud assisted with data collection and interpretation of the data for both manuscripts. Aiman’s assistance with field and laboratory experiments was a huge part of making this a successful project. Natasha Anisimova was responsible for the coding and development of the smartphone app. Natasha helped write section 3.3.3.2 in the second manuscript.

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1.0 CHAPTER 1 – INTRODUCTION

Tack coats are the bituminous materials applied between pavement lifts to provide an adequate bond between the two surfaces. The adhesive bond between the two layers helps the pavement system to behave as a monolithic structure and improves the structural integrity. The absence, inadequacy or failure of this bond, also known as interlayer shear strength (ISS), result in a significant reduction in the shear strength resistance of the pavement structure and make the system more vulnerable to many distress types, such as cracking, rutting, and potholes (Tashman et al., 2008; Ziari & Khabiri, 2007).

Tracking, the pick-up of tack coats by construction vehicle tires during construction activities, reduces the amount of tack coat in particular areas and creates a non-uniform tack coat distribution between the two construction lifts (Flexible Pavements of Ohio (FPO), 2001; WSDOT, 2003). This non-uniform tack coat distribution reduces the quality of the adhesive bond between tack coat and pavement layers. This creates localized failures around the low tack coat locations and reduces the overall structural integrity of the pavement structure. The magnitude of this effect and performance of the tack coat is dependent on tack coat type, residual application rate(the amount of asphalt binder remaining on the surface after water evaporation), temperature, existing surface condition (cracked, milled, overlay), and curing time (Flexible Pavements of Ohio (FPO), 2001). Also, residual application rate, temperature, wind speed, and existing surface condition (cracked, milled, new, old, or grooved) are the other factors that affect the tack coat performance.

For this reason, reducing tracking and increasing interlayer shear strength between pavement layers becomes vital to the longevity of the pavement structure. By considering all these factors, a quality control and quality assurance (QC/QA) process need to be developed to maximize tack coat performance during pavement service life.

King and May (2003) evaluated the effect of bond strength on fatigue life by using BISAR software (De Jong et al. 1973). Simulations were conducted for a range of bonding levels ranging from no slip (100% bonding) to full slip (0% bonding). Results illustrated that fatigue life decreases by up to 50% when the bond is reduced by 10%. Roffe and Chaignon (2002) performed similar experiments using ALIZE, a French pavement design program, and results showed that pavement service life could reduce from 20 to 7 years due to lack of bond between pavement layers.

Using the optimum amount of tack coat is vital to achieving a full bond between two pavement layers. Slippage problems start to arise when an excessive amount of tack coat material is sprayed during construction. On the other hand, inadequate amount of tack coat can result in debonding problems over the design life (especially in the wheel paths) of the pavement structure (Tashman et al., 2008). Thus, optimum residual application rates should be determined by considering surface (texture and age) and environmental (temperature, humidity, and the wind) conditions. Mohammad et al. (2012) recommended to use different residual application rates for i) new or subsequent layers ii) existing relatively smooth, and iii) old, oxidized, cracked, and milled pavement surfaces. Flexible Pavements of Ohio (FPO) (2001) association specified residual application rates for new hot-mix asphalt (HMA), oxidized HMA, milled HMA, milled PCC, and new PCC surfaces. Since surface texture increases with aging and milling, application rates also increase accordingly. Caltrans (2009) also provided recommendations for residual applications.

CSS-1H is most commonly used slow-setting emulsion grade in Oregon. “New” engineered emulsions were recently developed in Oregon to reduce tracking and increase interlayer shear strength. The performance of these emulsions, most effective application rates, the effects that pavement surface texture and traffic have on ISS, and curing times were evaluated in this study.

This thesis is presented in a manuscript format, with Chapter 2 and Chapter 3 being separate papers related to the same topic. Chapter 2 presents and evaluation of Oregon tack coat rheological properties and the effects of these properties and other factors on the interlayer shear strength (ISS). Instead of determining the ISS in a traditional manner by taking field cores and using a direct shear test, correlations between rheological properties and shear strength were used to develop prediction equations. Chapter 3 presents the development of a smartphone app and device to reduce tack coat tracking. Linear regression was used to make a model to be used in the app that calculates in-situ curing times of tack coats. The device was a rolling wheel that simulates a construction vehicle tire and measures the tracking resistance of various tack coats. Development of two new technologies (smartphone app and wheel tracking device), along with recommended prediction equations for ISS, are expected to improve construction practices, reduce tracking, and improve the bond strength between pavement layers.

2.0 CHAPTER 2 – EVALUATION OF TACK COAT RHEOLOGICAL PROPERTIES AND THE EFFECTS ON INTERLAYER SHEAR STRENGTH[4]

David Covey[1]; Erdem Coleri[2]; and Aiman Mahmoud[3]

Abstract: CSS-1H emulsions are the most commonly used slow-setting grades in Oregon. “New” emulsions are the engineered emulsions recently developed in Oregon to reduce tracking and increase interlayer shear strength (ISS). In this study, the performance of these emulsions, most effective application rates, and the effects of pavement surface texture and traffic/environment on ISS were evaluated. Results indicated that there are positive correlations between rheological tests and ISS from field cores, which generated linear equations that can predict in-situ ISS using the results of simple rheological experiments. Results showed variances in application rates and uniformity by distributor trucks. Hence there is a need for unified guidelines on tack coat QC/QA and construction practices.

Keywords: tack coat, interlayer adhesion, interlayer shear strength, rheological properties

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2.1 Introduction

2.1.1 Tack coat application and its importance

Tack coats are the bituminous materials applied between pavement lifts to provide an adequate bond between the two surfaces. The adhesive bond between the two layers helps the pavement system to behave as a monolithic structure and improves the structural integrity. The absence, inadequacy or failure of this bond result in a significant reduction in the shear strength resistance of the pavement structure and make the system more vulnerable to many distress types, such as cracking, rutting, and potholes (Tashman et al., 2008; Ziari & Khabiri, 2007).

Using computational modeling, Hachiya and Sato (Hachiya & Sato, 1997) showed that high tension and shear forces created by truckloads could break the bond between the two layers when the applied stresses exceed the shear and tensile strength of the tack coat. When the bond between the two layers is broken, two layers start to act as independent layers (Canestrari, Ferrotti, Partl, & Santagata, 2005). This change in the pavement structure shifts the critical strain location from the bottom of the asphalt structure to the debonded location (Mohammad et al., 2012).

King and May (King & 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 hot-mix asphalt (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 (Roffe & Chaignon, 2002) conducted similar analysis using the French pavement design program ALIZE and concluded that pavement service life could reduce from 20 years to 7 years due to the lack of bond between two asphalt layers.

Using the optimum amount of tack coat is vital to achieving a full bond between two pavement layers. Slippage problems start to arise when an excessive amount of tack coat material is sprayed during construction. On the other hand, inadequate amount of tack coat can result in debonding problems over the design life (especially in the wheel paths) of the pavement structure (Tashman et al., 2008). Thus, optimum residual application rates should be determined by considering surface properties (texture and age) and environmental (temperature, humidity, and the wind) conditions (CalTrans, 2003; Flexible Pavements of Ohio (FPO), 2001; Mohammad et al., 2012).

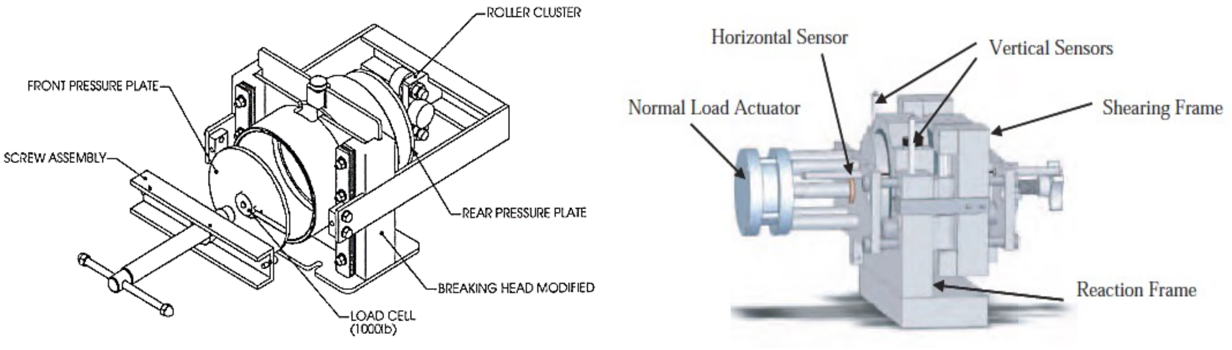
2.1.2 Laboratory evaluation of tack coat performance

2.1.2.1 Interlayer shear strength test devices

It has been shown that peak shear stress required to break the bond between the two layers is the best fundamental parameter to quantify the interlayer shear strength (ISS) between pavement layers (Sholar, Page, Musselman, P, & H, 2004). Although there are several test types for tack coat performance characterization, the common purpose of all tack coat tests is to determine the strength of the bond at the interface under shear or tensile forces. In this research project, peak shear stress measured by a direct shear test is used to quantify ISS between pavement layers. The following devices, National Center for Asphalt Technology (NCAT) bond strength test, and the Louisiana Interlayer Shear Strength Tester (LISST), along with AASHTO TP 114 (AASHTO TP114, 2015), were investigated to develop a general procedure for interlayer shear strength testing. This test procedure was repeated several months after the initial testing to quantify the changes in ISS due to traffic loading and environmental factors.

West et al. (West, Zhang, & Moore, 2005) developed the NCAT bond strength test (**Figure 2.1a**) to determine the best tack coat material and optimum application rates with a loading rate of 50mm/min. Two types of emulsions (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 (also known as confining pressure) were 0, 10, and 20 psi. The major conclusions of the study were normal pressure did not affect the measured ISS while increasing temperatures reduced ISS.

Mohammad et al. (Mohammad et al., 2012) developed the Louisiana Interlayer Shear Strength Test (LISST) **(Figure 2.1b**) to characterize interface bond properties under shear loads. The major difference from the NCAT bond strength test was the reduced loading rate (2.54mm/min) and improved test fixture with less friction. Loading rate was reduced to avoid unrealistically high interlayer shear strengths observed under fast loading rates (Hachiya & Sato, 1997). Experiments were conducted with samples obtained from full-scale test sections under different conditions to investigate the effects of surface type, tack coat type, application rate, cleanliness, water, confinement, and tack coat coverage on interlayer shear strength (ISS). The major conclusions of the LISST experiments were: i) Trackless tacks had higher ISS than conventional tacks; ii) using a confining pressure provided a better estimate of ISS; iii) increasing temperature reduced ISS, and iv) increasing texture increased ISS.



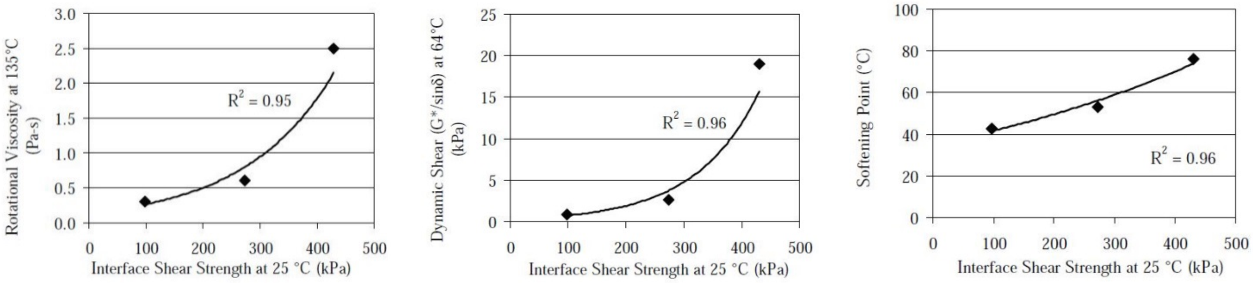
(a) (b)

Figure 2.1. Laboratory shear test devices for interlayer shear strength measurement (a) NCAT device (West et al. 2005) (b) LISST device (Mohammad et al. 2012)

2.1.2.2 Rheological correlations with interlayer shear strength

Peak shear stress has been recognized as the best parameter for quantifying interlayer shear strength (ISS) of pavement layers, but recently several researchers have been investigating rheological test results as a way to characterize tack coat performance. Shear experiments, such as the NCAT and LISST, provide in-situ (ground truth) interlayer shear strength values by testing field cores. Being able to use simple rheological test results to predict ISS results has potential to be very useful to state agencies due to practicality and non-destructive nature of rheological experiments.

Mohammad et al. (2012) evaluated the correlations between the rheological properties of tack coat materials and interlayer shear strength (measured by LISST) by conducting experiments at temperatures ranging from -10 to 60 °C with a 10 °C interval. Rotational viscosity, $G^*/\sin\delta$, and the softening point were the properties used for comparison. Test results showed that rheological properties are correlated with the measured ISS values (**Figure 2.2).** This result suggested that simple rheological tests can provide valuable information about the in-situ performance of tack coats. Results of the consistency tests (penetration, absolute viscosity, rotational viscosity) showed that the trackless material was the stiffest tack coat followed by SS-1h, PG 64-22, and CRS-1.



(a) (b) (c)

Figure 2.2. Relationship between interlayer shear strength and rheological tests (a) rotational viscosity (b) dynamic shear (c) softening point (Mohammad et al. 2012)

2.1.3 Summary

Many studies in the literature have investigated interlayer shear strength (ISS) and the various affecting factors, as well as alternative testing methods to determine the ISS. This study is a comprehensive field investigation consisting of field and laboratory testing, field coring, and construction sampling of tack coats used in Oregon. Within the study, two new tack coat materials from two companies were, for the first time, evaluated for their performance. Field coring was completed at two different periods (3 months and 7 months after construction), as well as two travel lines (wheel-path and center-line for the impact of tack coat tracking), to capture the effect of traffic loading and environmental factors on ISS. Recommendations for the most efficient application rate along with ISS prediction equations based on rheological properties were developed. Results of this evaluation will provide valuable information about correlations between rheological tests and ISS, as well as the effects of texture, traffic loads/environmental factors, and application rate on ISS.

2.2 Objectives of the study

The objectives of this study are given as follows:

- Develop methods and equations to predict ISS from simple rheological test results;
- Evaluate the effects of pavement surface texture on ISS;
- Assess the effects of traffic/environment on ISS;
- Evaluate the effects of transverse location and impact of tack coat tracking on ISS (wheel-path vs. centerline);
- Determine the most effective application rates and methods to:
    - Maximize ISS
    - Improve current QC/QA for tack coat application

2.3 Materials and Methods

2.3.1 Experimental design for field testing and sampling

The general layout of the experimental design is summarized in **Table 2.1**. In total, testing and sampling were conducted at three locations in the field. Asphalt overlays were constructed with two lifts on Highway 99 between Monmouth and Rickreall Oregon. First lift (2.5 inches) was placed on a milled surface while the second lift (2 inches) was built on the first lift (without any milling) about a month after the construction. Each location had the same tests performed for the milled and overlay surfaces. A test location consisted of three 200-foot sections, each of which contained a different target application rate (**Table 2.1**). Location 1 and Location 2 were operating at normal highway speeds, northbound and southbound lanes respectively. Vehicle speeds on Location 3 were lower because it was located within a turning lane at an intersection. The six tack coat types considered in this study are shown in **Table 2.1**. Generic tack coat type labels are used to conceal the identity of the company providing the material. CSS-1H emulsions are the most commonly used slow-setting grades in Oregon. “New” emulsions are the engineered emulsions recently developed in Oregon to reduce tack coat tracking, the pick-up of tack coats by construction vehicle tires during construction activities, and increase interlayer shear strength.

Table 2.1. Site layout for field testing

Surface	Location	Day	Tack Coat Type	Application Rates (gal/yd^2)
Milled	1	Day 1	CO1_CSS 1H_a	0.08, 0.10, 0.12
	2	Day 2	CO1_New_a	0.08, 0.12, 0.16
	3	Day 3	CO2_New	0.08, 0.12, 0.16
Overlay	1	Day 4	CO1_CSS 1H_b	0.05, 0.07, 0.10
	2	Day 5	CO1_New_b	0.05, 0.07, 0.09
	3	Day 6	CO2_CSS 1H	0.05, 0.07, 0.10

2.3.2 Field and laboratory experiments

Tack coat sampling from the distributor truck was performed during construction before tack coat application (**Figure 2.3a**). Sampling was done according to ASTM D140 (ASTM Standard D140, 2015). On each construction day, three 5-gallon buckets were filled, labeled, and sealed with electrical tape. This extra step to seal the buckets ensured a reduction in bias due to evaporation of water from the emulsion during storage. Buckets of sampled emulsion were then taken to the lab for the rheological experiments to be performed.

Sand patch testing was conducted to measure the macrotexture depth of the pavement surface for both milled and overlay surfaces according to ASTM E965 (ASTM Standard E965, 2015) (**Figure 2.3b)**. Eight tests were performed at random spots within each of the three site locations.

Application rate measurements were taken by placing 1 square foot textile pads end to end in the travel lane in the transverse direction according to ASTM D2995 (ASTM Standard D2995, 2014) (**Figure 2.3c)**. Company distributor trucks (new truck) were used for all milled surface spraying and Location 1 and 2 of overlay surfaces. The contractor's distributor truck (old truck) was used for Location 3 overlay surface spraying to evaluate the truck related variability and bias in application rates.

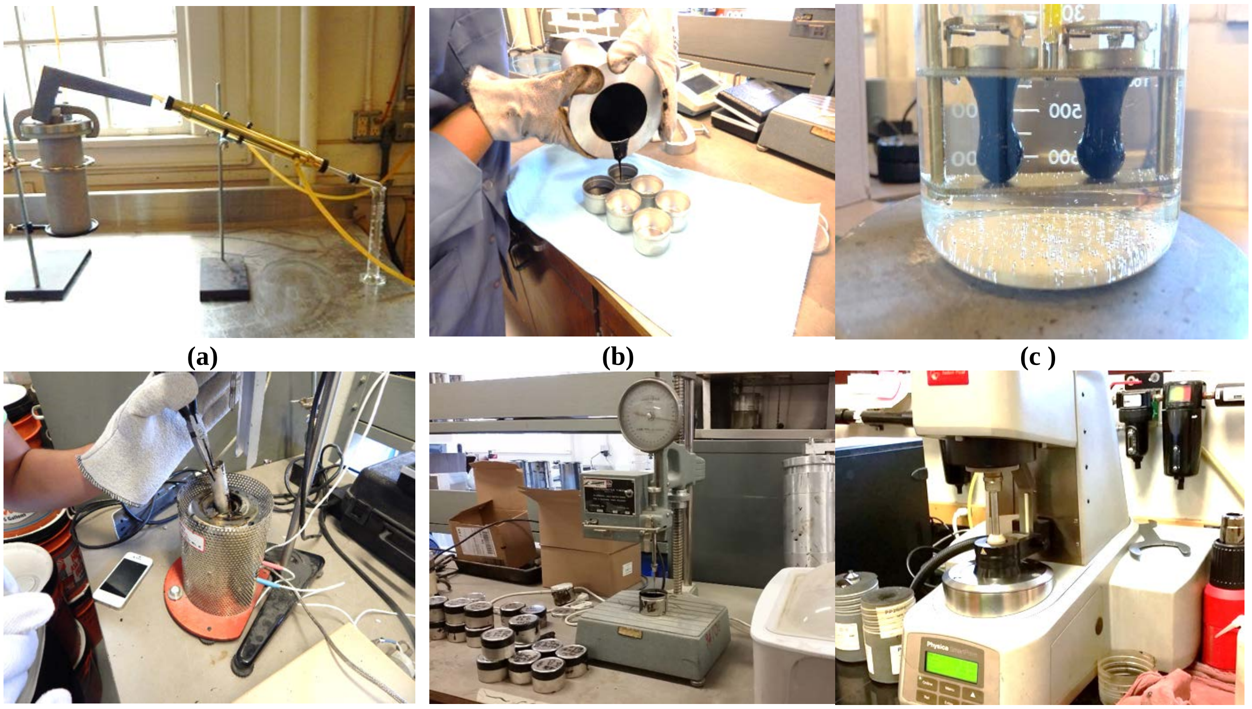

(a) **(b)** **(c)**

Figure 2.3. Experiments conducted to evaluate tack coat application methods and procedures (a) Emulsion sampling for lab testing (b) Sand patch texture measurements (c) Application rate measurement

All binder residues were extracted from sampled emulsions according to ASTM D6997 (ASTM Standard D6997, 2012) (**Figure 2.4a** and **Figure 2.4b**). Measured emulsion densities and water contents are given in **Table 2.2**. Softening point and rotational viscosity tests were performed according to ASTM D36 (ASTM Standard D36, 2014) (**Figure 2.4c**) and ASTM D4402 (ASTM Standard D4402, 2015) (**Figure 2.4d**), respectively. Other tests performed included penetration and dynamic shear rheometer (DSR) according to ASTM D5 (ASTM Standard D5, 2013) (**Figure 2.4e**) and ASTM D7175 (ASTM Standard D7175, 2015) (**Figure 2.4f**), respectively.

Distillation was performed at two temperatures (170 and 260 °C) for several emulsions to determine the impact of distillation temperature on measured performance parameters for all tack coat types. Results of the experiments showed that the correlation between viscosities at different distillation temperatures is significant, which indicates that the distillation temperature had minimal effect on the performance properties (**Figure 2.5**).

Although a lower distillation temperature (170^{o}C) was used to recover binder residue from Day 5, CO1_New_b emulsion, both the standard temperature (260 ^{o}C) and the reduced temperature resulted in the sample burning and massive amounts of water being collected (152 mL or 76%). For this reason, rheological experiments could not be performed on CO1_New_b.



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

(d) **(e)** **(f)**

Figure 2.4. Series of rheological tests performed (a) distillation of emulsified asphalt (b) resulting binder residue from distillation (c) softening point (d) rotational viscometer (e) penetrometer (f) dynamic shear rheometer

Table 2.2. Emulsion densities and water contents

Surface	Location	Day	Tack Coat Type	Density (g/mL)	Water Distilled (mL)	Percent Water (%)
Milled	1	Day 1	CO1_CSS 1H_a	0.930	102	51
	2	Day 2	CO1_New_a	0.928	147	73
	3	Day 3	CO2_New	0.889	123	62
Overlay	1	Day 4	CO1_CSS 1H_b	0.873	94	47
	2	Day 5	CO1_New_b	0.909	152	76
	3	Day 6	CO2_CSS 1H	0.914	110	55

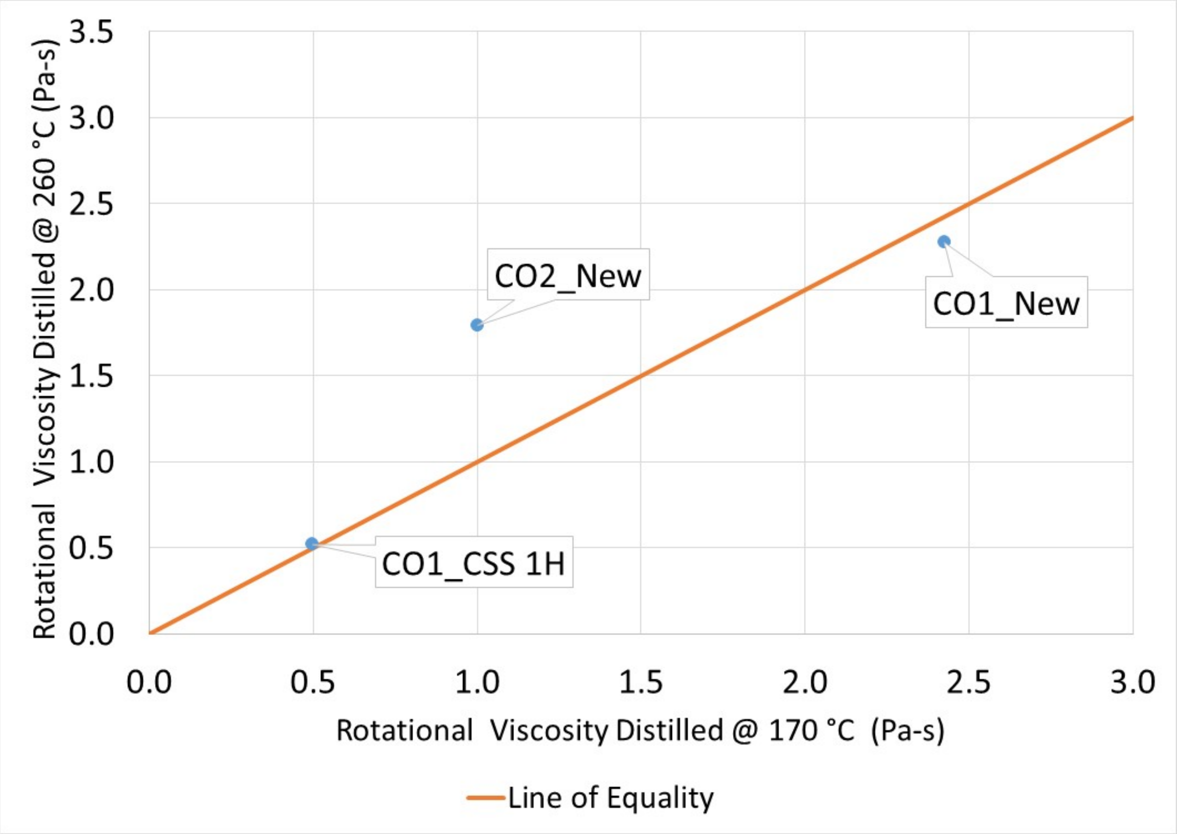


Figure 2.5. The effect of distillation temperature on viscosity of tack coats

2.3.3 Field coring and testing

2.3.3.1 Procedure for obtaining field cores

The first round of coring took ten cores from each section (for a total of 90), with six in the wheel-path nearest the fog line and four in the center of the travel lane (**Figure 2.6**). The reason for having two locations was to evaluate the impact of tack coat tracking on ISS. Wheel-path locations are expected to exhibit more tracking, because the vehicles are directly driving on the applied tack coat. In the second round of coring, 24 cores were taken seven months after construction (four months after taking the initial 90 cores) from similar areas within Locations 1 and 2 only. Of the 24 cores taken, only 16 shear experiments were performed (eight cores were used for another experiment for another study). Within the locations, only Sections 2 and 3 had cores taken from them. The purpose of the second round of field cores was to quantify the changes in interlayer shear strength due to traffic loading and the environment. Only the top layer (overlay surface) interfaces were tested for ISS and then compared to values obtained four months earlier to capture this effect.

The second round of coring deviated from the previous pattern due to top layer separation during coring in Location 1 and coordination of results with another field test happening at the same time. Second round cores for Location 1 were taken from the center of the travel lane for both sections 2 and 3, while Location 2 cores were taken from the wheel path for both sections 2 and 3 (**Table 2.3**).

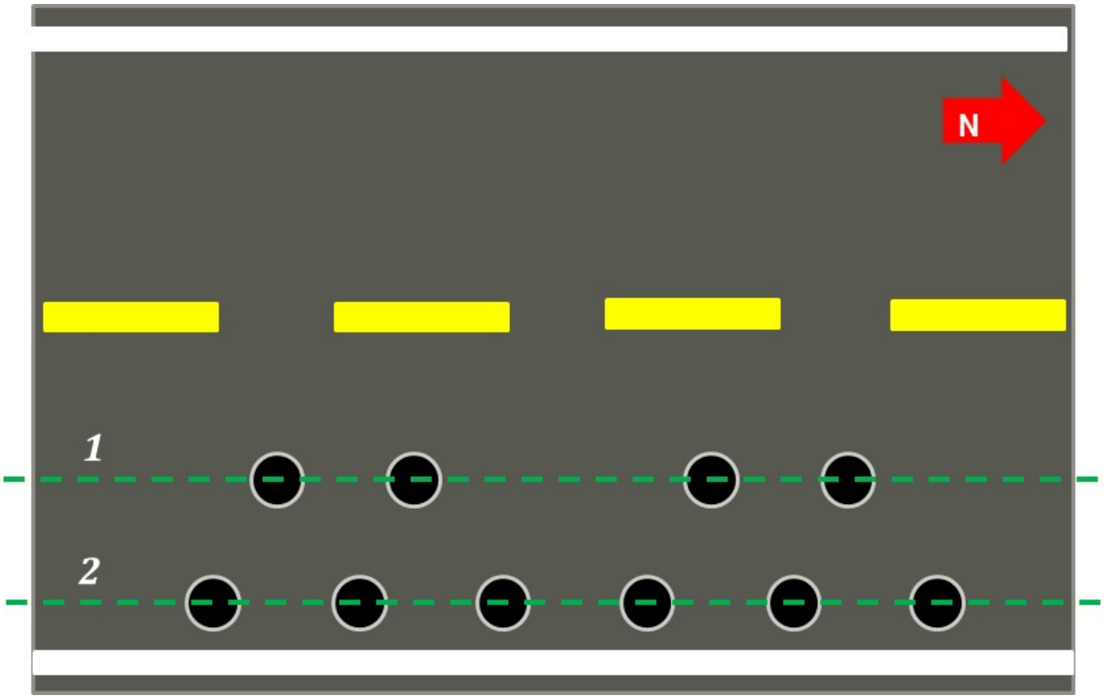


Figure 2.6. Field coring site layout; (1) center-line (2) wheel-path

2.3.3.2 Procedure for determining ISS of field cores

To be able to evaluate the correlations between the parameters from simple rheological experiments and in-situ (ground truth) interlayer shear strengths, field cores were taken from all sections (9) to conduct shear experiments according to AASHTO TP114 (AASHTO TP114, 2015). Field cores were also used to evaluate which application rate and tack coat type provided the maximum ISS.

The general procedure for specimen preparation and ISS testing is illustrated in **Figure 2.7**. Asphalt concrete cores used in this study were taken from three locations (as described in **Table 2.1**) along HWY 99 near Monmouth, Oregon. In total, 114 cores were taken (90 cores three months after construction and 24 cores seven months after construction). The followed steps are as follows:

- Before drilling, the location of each core was marked and arrows were drawn to indicate the direction of traffic within the lane (**Figure 2.7a**). All cores were sheared in the direction of traffic to reduce variability and bias in test results.
- Six-inch field cores were retrieved using a drill rig (**Figure 2.7b**). Specific location labels were applied before cores were transported.
- All cores were left to dry (**Figure 2.7c**).
- Core diameters and lift heights were recorded (**Figure 2.7d**).
- Each core was cut, using a large wet saw, to ensure a proper fit inside the testing apparatus (**Figure 2.7e**).
- A single core was loaded horizontally into the Asphalt Tack Bond Shear Strength Apparatus with the direction of traffic arrow facing down (shearing direction) and the pavement surface on the shearing side (AASHTO TP114, 2015) (**Figure 2.7f**). A confining pressure of 20 psi was used for testing.
- Testing apparatus was placed into the loading frame inside the environmental chamber. Vertical and horizontal displacement sensors (LVDTs) were secured (**Figure 2.7g**), and samples were left to be conditioned at the 25^{o}C test temperature for a minimum of 2 hours (AASHTO TP114, 2015).
- Data was collected via computer software, filtered with MATLAB, and exported into Excel (**Figure 2.7h**).
- **Figure 2.7i** shows a sample successfully sheared at the pavement lift interface. All samples showed a similar failure pattern.

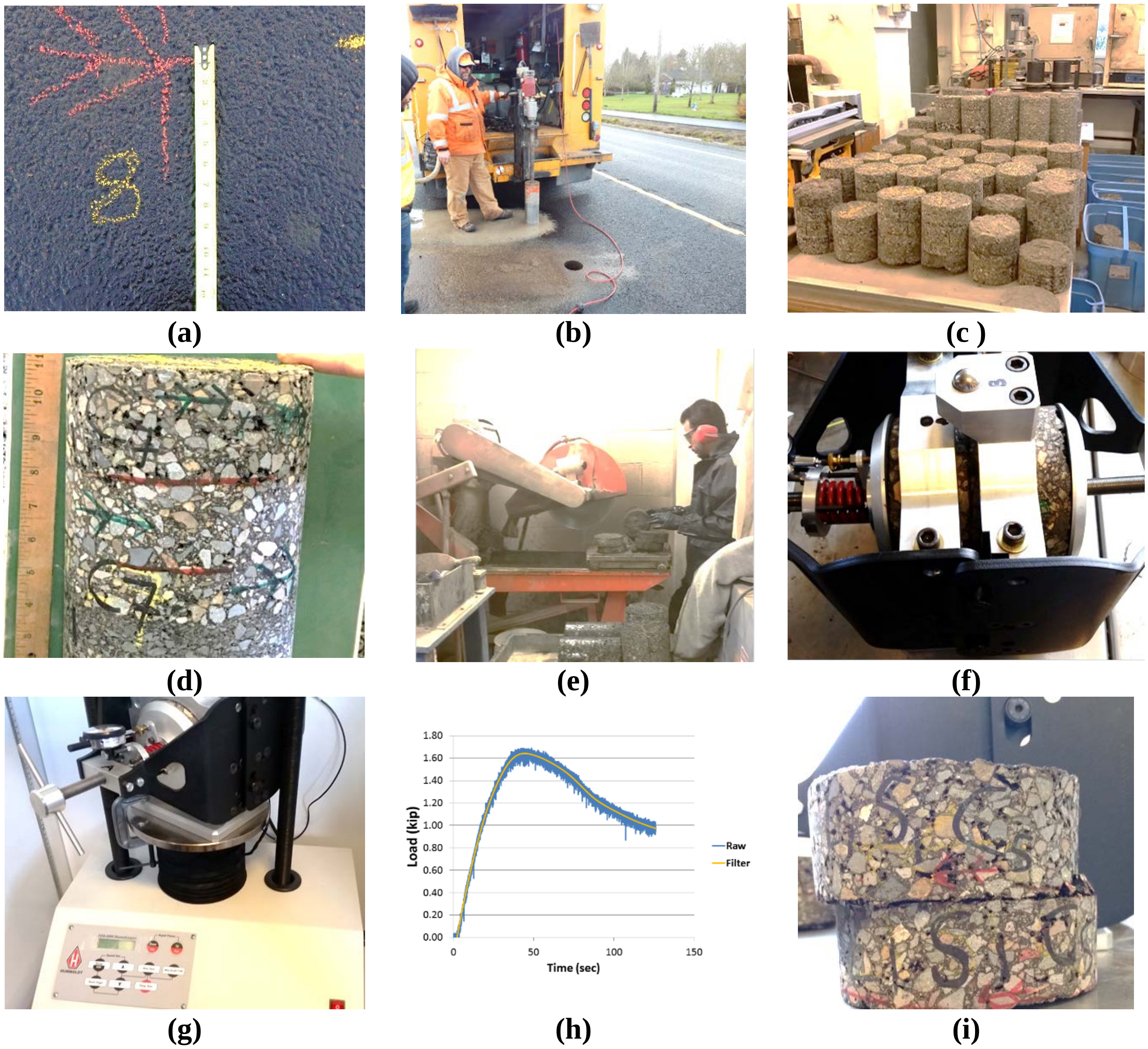


Figure 2.7. General procedure used to determine interlayer shear strength of field cores

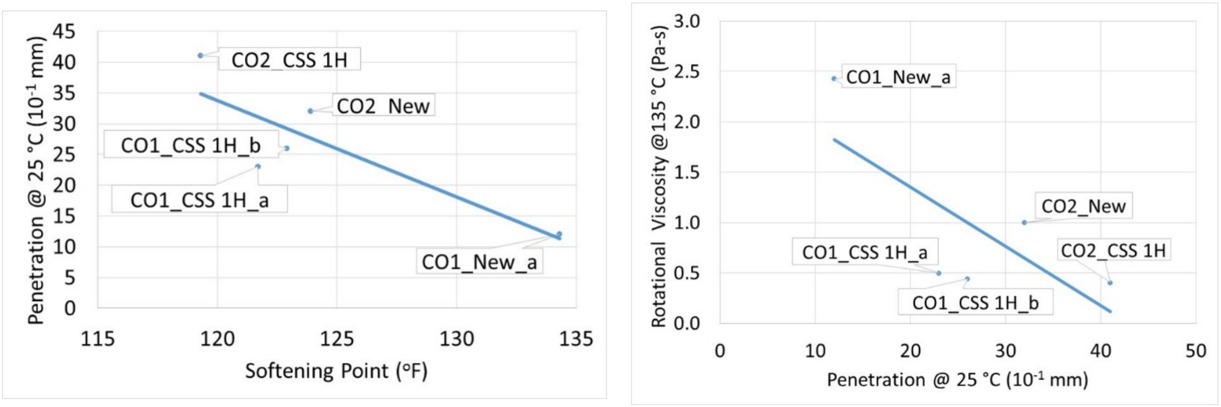
2.4 Results and Discussion

2.4.1 Measured rheological properties and correlations with measured interlayer shear strength

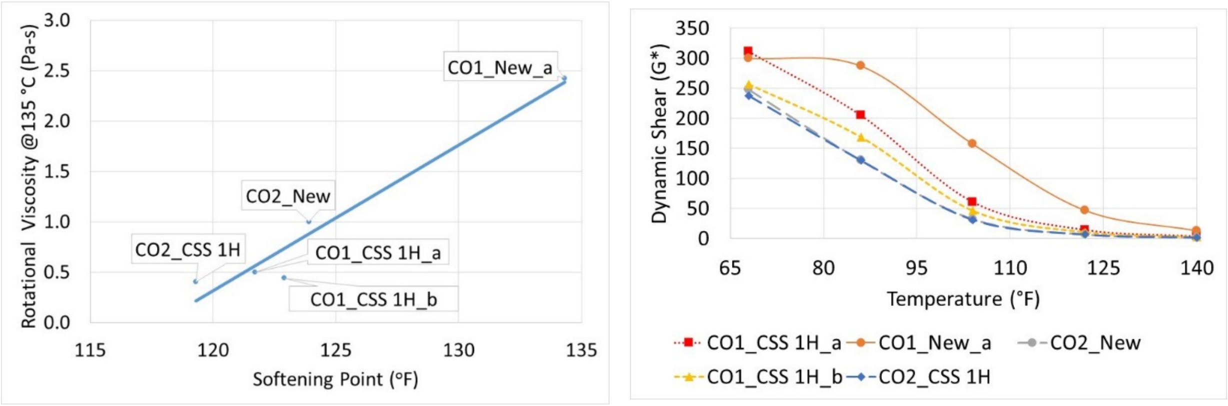
2.4.1.1 Rheological properties of Oregon tack coats

Results of the rheological experiments are shown in **Figure 2.8**. Relationships between measured softening point, rotational viscosity, penetration, and DSR values were investigated. Results of the tests conducted with only five of the six tack coats are presented since CO1_New_b was unable to be distilled. Therefore, rheological tests could not be performed with CO1_New_b. **Figure 2.8a** shows that tack coat materials with higher softening points have less penetration given the testing conditions. **Figure 2.8b** demonstrates the relationship between rotational viscosity and penetration.

Materials with higher viscosities were observed to provide less penetration, as expected. CO1_New_a was the most viscous material followed by CO2_New, CO1_CSS 1H_a and b, and CO2_CSS 1H. **Figure 2.8c** relates rotational viscosity to softening point. It can be observed that tack coats with higher viscosities exhibit higher softening point temperatures. The ranking of materials from the stiffest to softest was CO1_New_a, CO2_new, CO1_CSS 1H_a and b, and CO2_CSS 1H (**Figure 2.8b**). Results of DSR experiments also align with the relationships described above (**Figure 2.8d**).



(a) **(b)**



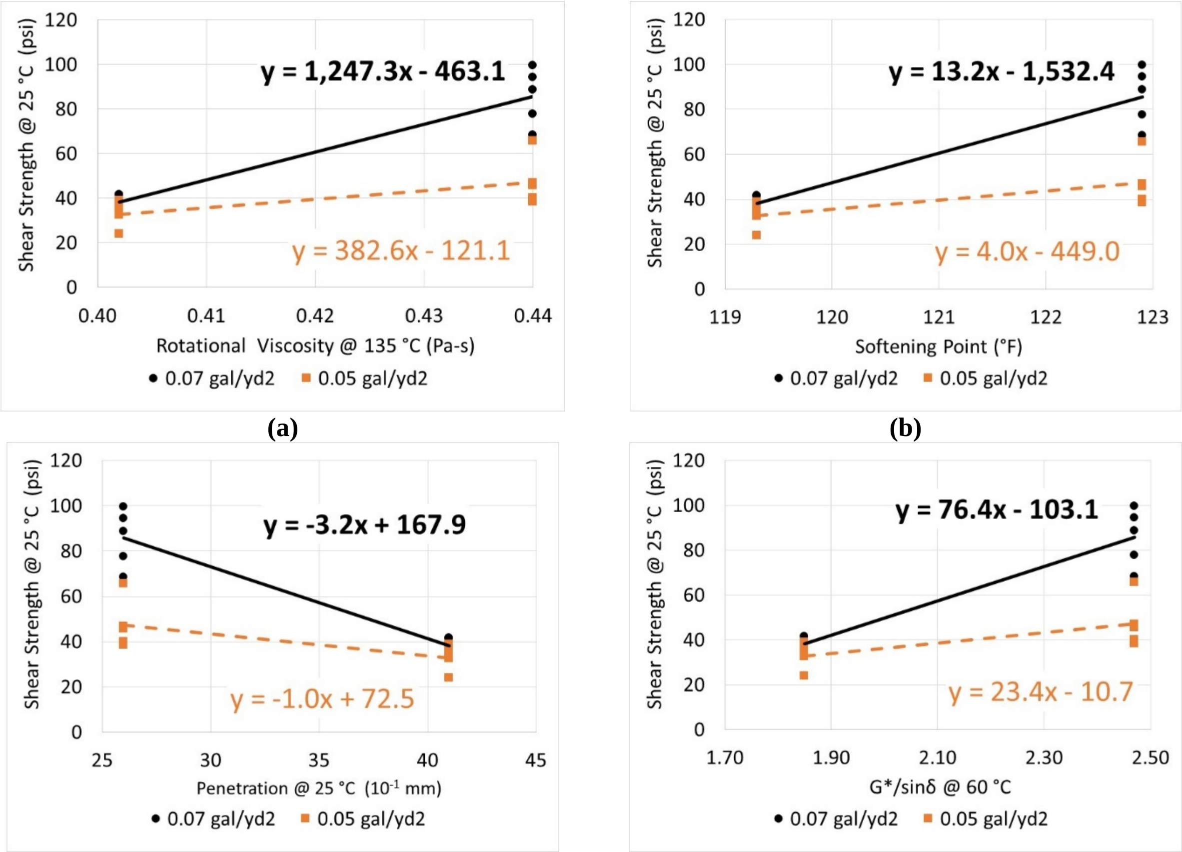
(c) **(d)**

Figure 2.8. Average rheological test results and relationships

2.4.2.2 Effects of rheological properties on ISS of overlay surfaces

Effects of rheological properties of tack coats on interlayer shear strength (ISS) were investigated by comparing rheological test results with the results obtained from overlay surface ISS tests. These tests were conducted with samples taken three months after construction. ISS values measured for milled surfaces were not used due to the significant texture effect on ISS (**Figure 2.11**). The purpose was to develop methods and equations to predict in-situ interlayer shear strengths from simple rheological test results. **Figure 2.9** shows relationships between rotational viscosity, G*/sinδ at 60°C, penetration, and the softening point of residue asphalt binder with ISS at application rates of 0.05 gal/yd^2 and 0.07 gal/yd^2 represented by the dashed and solid lines, respectively. Each grouping of data points, in the vertical direction (along the y-axis), accounts for a different location and respective tack coat material.

For example, in **Figure 2.9a** there is a grouping of points at a viscosity of 0.402 Pa-s and a grouping at 0.440 Pa-s. The first grouping (0.402) represents Location 3-CO2_CSS 1H, while the second grouping (0.440) represents Location 2-CO1_CSS 1H. Location 1 is not presented due to failed attempts to extract binder residue from CO1_New_b. Equations to predict the ISS using rheological properties are also given in **Figure 2.9**. Location 2 and Location 3 both consisted of sections sprayed with 0.05 gal/yd^2 and 0.07 gal/yd^2 rates. Therefore two equations are provided. Overall, positive correlations were observed between the tack coat properties and the ISS results. The strength at the interface increased as the tack coat rotational viscosity, softening point, and DSR stiffness parameter (G*/sinδ) increased, as expected. Similar results (correlations) were observed at both application rates. For penetration, as ISS increased, values decreased, which is expected given the trends of other rheological tests.



(a) (b)

(c) (d)

Figure 2.9. Relationship between overlay surface interlayer shear strength and average rheological test results three months after construction (a) rotational viscosity (b) softening point (c) penetration (d) dynamic shear

2.4.2 Effects of surface texture on ISS

Effects of pavement surface texture on interlayer shear strength were investigated by determining the surface texture using the sand-patch test method according to ASTM E965 (ASTM Standard E965, 2015) and investigating the correlations between the measured surface texture and measured interlayer shear strength. Sand patch test method was adopted for its ease of use in the field and for its production of results that are highly correlated with the results from less economical laser texture scanners. A 2004 report by Hanson and Prowell (Hanson & Prowell, 2004) of the NCAT evaluated the Circular Texture Meter (CT Meter) and compared this laser-based device to the simple volumetric method known as the "sand-patch" method. CT Meter and Sand Patch measurements were taken at five random locations on 45 different asphalt pavement sections at the NCAT test track. The high coefficient of determination ($R^2 = 0.95$) indicated a strong relationship between values obtained from the two different test methods (Hanson & Prowell, 2004).

Mean texture depths (MTD) for the field sections measured by following the sand-patch method are given in **Figure 2.10**. Results showed that milled surfaces had a significantly higher MTD than the overlay surfaces that were not exposed to milling during construction (**Figure 2.10**). Each box plot represents the spread of texture values obtained from the eight tests performed at each location. Average surface texture values were recorded as the mean of these eight tests for each location for milled and overlay surface types. The overlay surfaces had a considerably smaller (82% less) mean texture depth (MTD) than the milled surfaces. The milled surface exhibited higher variance in MTD values across the three locations when compared to the overlay surface MTD variance.

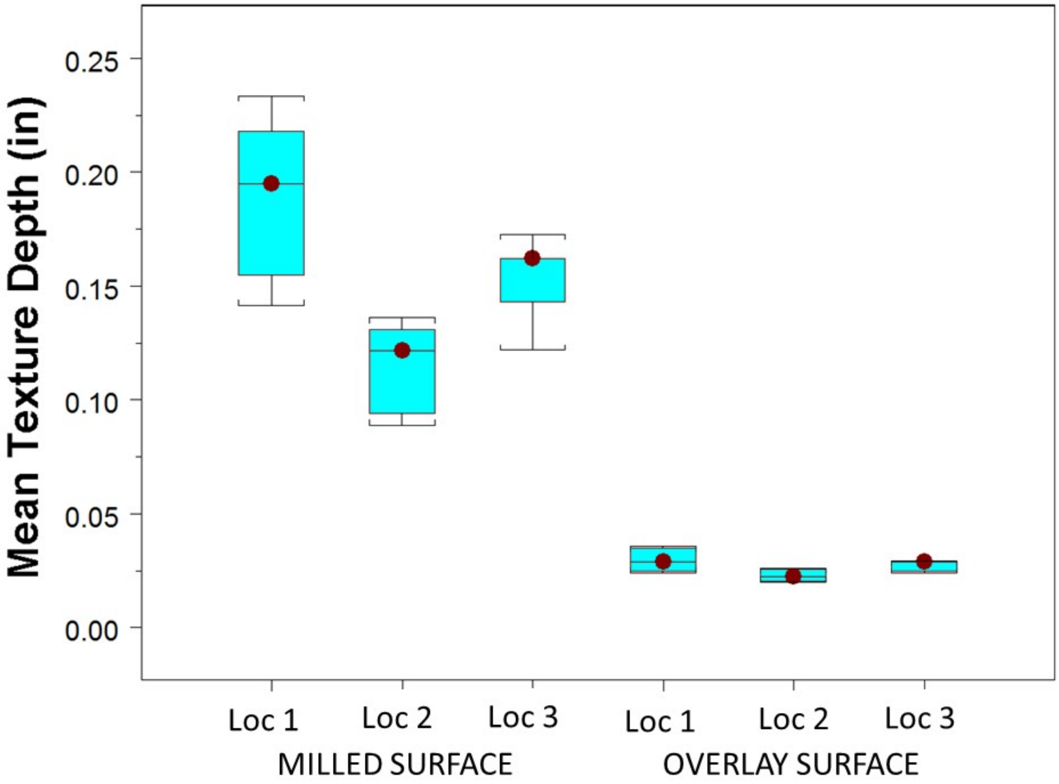


Figure 2.10. MTD results from Sand Patch tests

The purpose of determining the surface texture was to compare the measured texture to the measured interlayer shear strength (ISS) values to determine the impact of texture on ISS. **Figure 2.11** shows the relationships between surface texture values and the interlayer shear strengths of field cores. Results show a strong positive correlation between texture and ISS. Each point in **Figure 11** represents the average ISS for an entire test location as described in **Table 2.1** and the average MTD for the corresponding location. Independently, milled surface test results also showed a positive relationship, as texture increases so do interlayer shear strength. Because of the strong correlation between texture and ISS, conclusions about tack coat materials and application rates derived from results involving the overlay surface can be expected to be more reliable than the conclusions made from milled surfaces. Texture has too much influence on the interlayer shear strength results for milled surfaces to extract clear relationships and milled surfaces exhibit higher variance in texture values.

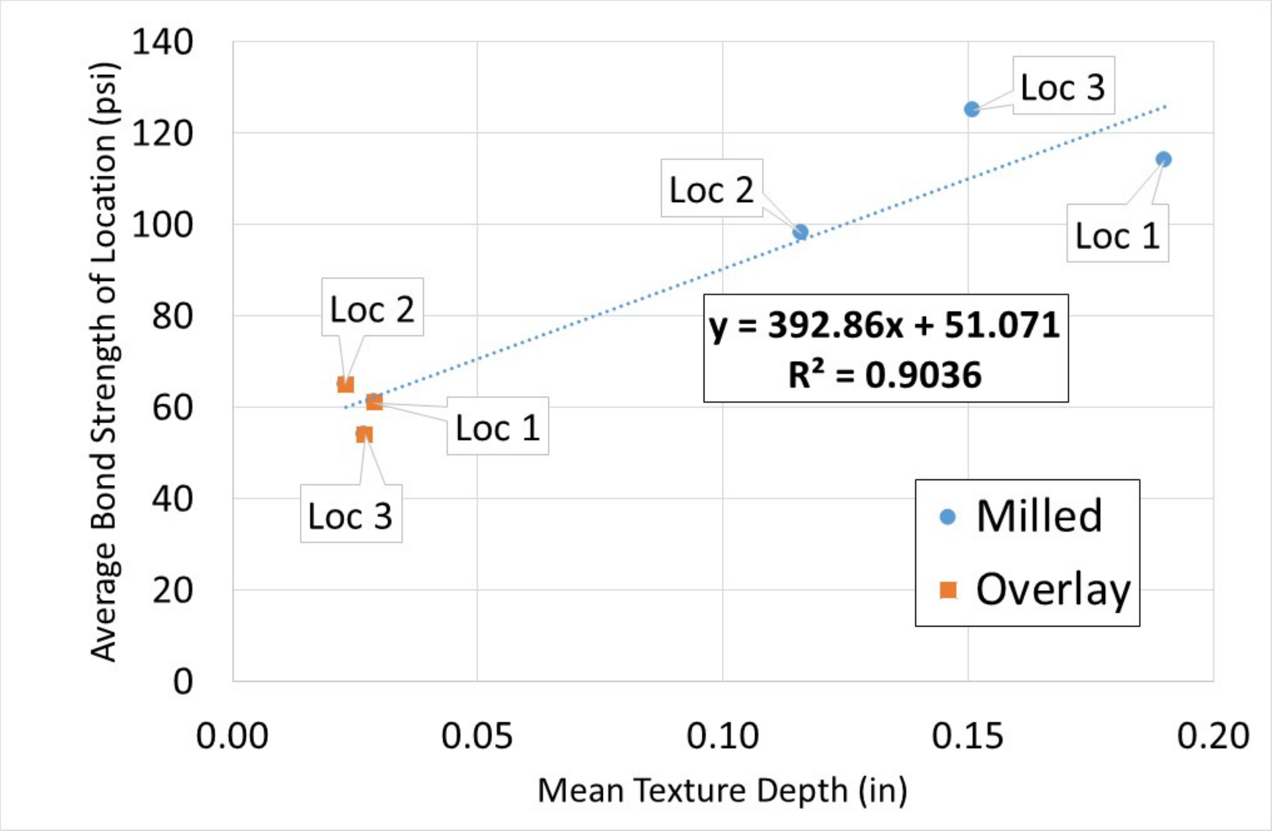


Figure 2.11. Effects of pavement surface texture on interlayer shear strength

2.4.3 Effects of traffic and environmental factors on ISS

Effects of traffic loading and environmental factors on the interlayer shear strength of pavement layers were investigated by taking field cores four months after the first round of cores were taken (seven months after initial construction) and comparing the measured strength values from the two sets of samples collected. The purpose was to see how the interlayer shear strength between layers would change over time with traffic loading and the environment. **Figure 2.12** illustrates the reduction in average ISS of field cores taken at three months and seven months after construction for one of the tack coat types and one application rate (Location 1, Section 3). Tabulated values for all sections and the corresponding strength reductions are summarized in **Table 2.3**.

In total 16 shear experiments were performed with the cores taken seven months after construction. Results for Location 1, sections 2 and 3 and Location 2, sections 2 and 3 are tabulated in **Table 2.3**. Only the bond between overlay surfaces was tested and compared. Of the results obtained, reduction in average interlayer shear strength varied from 0 to 39%, with larger reductions seen in Section 3 than in Section 2 (**Table 2.3**). These results illustrate the need for monitoring bond strengths of asphalt pavements. In a period of four months, the bond strengths were reduced a maximum of 39%, which over several years could be increased significantly leading to a structural failure.

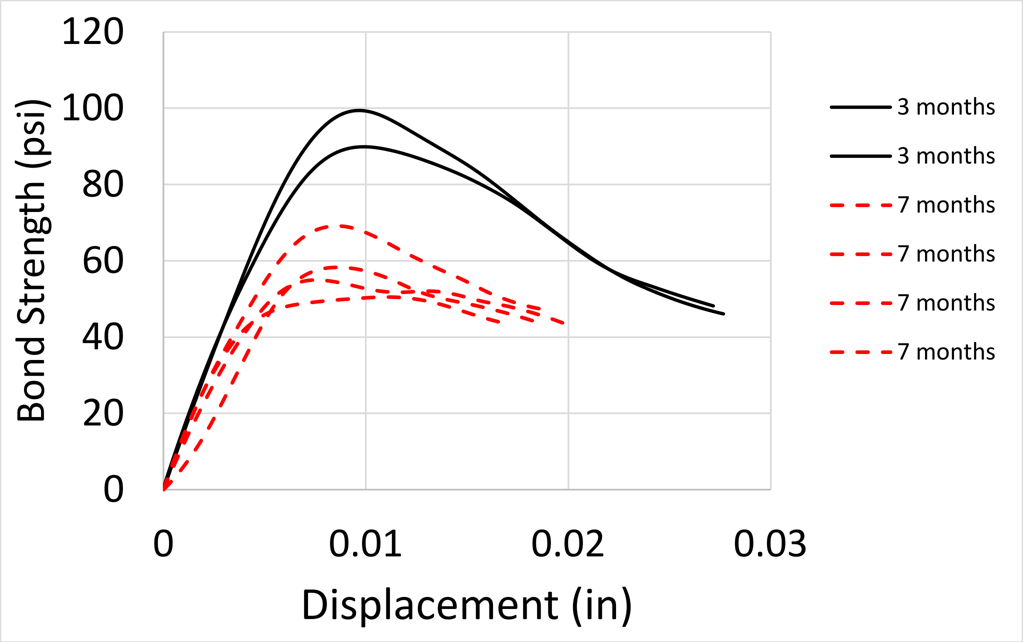


Figure 2.12. Effects of traffic on average interlayer shear strength with 0.10 gal/yd2 application rate and CO1_New tack coat

Table 2.3. Reductions in average interlayer shear strength due to traffic loading

Location	Date	Tack Coat	Line	0.07 gal/yd^2	0.10 gal/yd^2
L1	3 mo.	CO1_New	CL[1]	69	95
	7 mo.	CO1_New	CL	69	58
	Reduction (%)			***0***	***39***
Location	**Date**	**Tack Coat**	**Line**	**0.07 gal/yd^2**	**0.09 gal/yd^2**
L2	3 mo.	CO1_CSS 1H	WP[2]	94	45
	7 mo.	CO1_CSS 1H	WP	76	38
	Reduction (%)			***19***	***16***

Note: [1] CL: Centerline – center of the lane, [2] WP: Wheel path – south side of lane, near fog line

2.4.4 Effects of location in transverse direction and impact of tracking on ISS

Effects of transverse location on interlayer shear strength were evaluated by taking cores from two different lines within the travel lane (centerline of the lane and right wheel path). Using two locations allowed this study to evaluate the impact of tracking on ISS. Wheel-path locations are expected to exhibit more tracking and therefore should exhibit reductions in ISS. The removal of the tack coat (tracking) from the surface creates a non-uniform distribution of tack coat, which leads to localized pavement distresses and bond failures.

The results of statistical analysis of travel lines (wheel-path and center of travel lane) show that there is no difference in ISS between the two transverse locations for an initial set of cores taken three months after construction (**Table 2.4**). For the sections that were tested in this study, tracking did not reduce tack coat performance, because there were no observed differences in ISS of the cores taken from the two transverse locations. On the other hand, the difference in interlayer shear strength for the milled and overlay (bottom and top respectively) interfaces was statistically significant (**Figure 2.13** and **Table 2.4**).

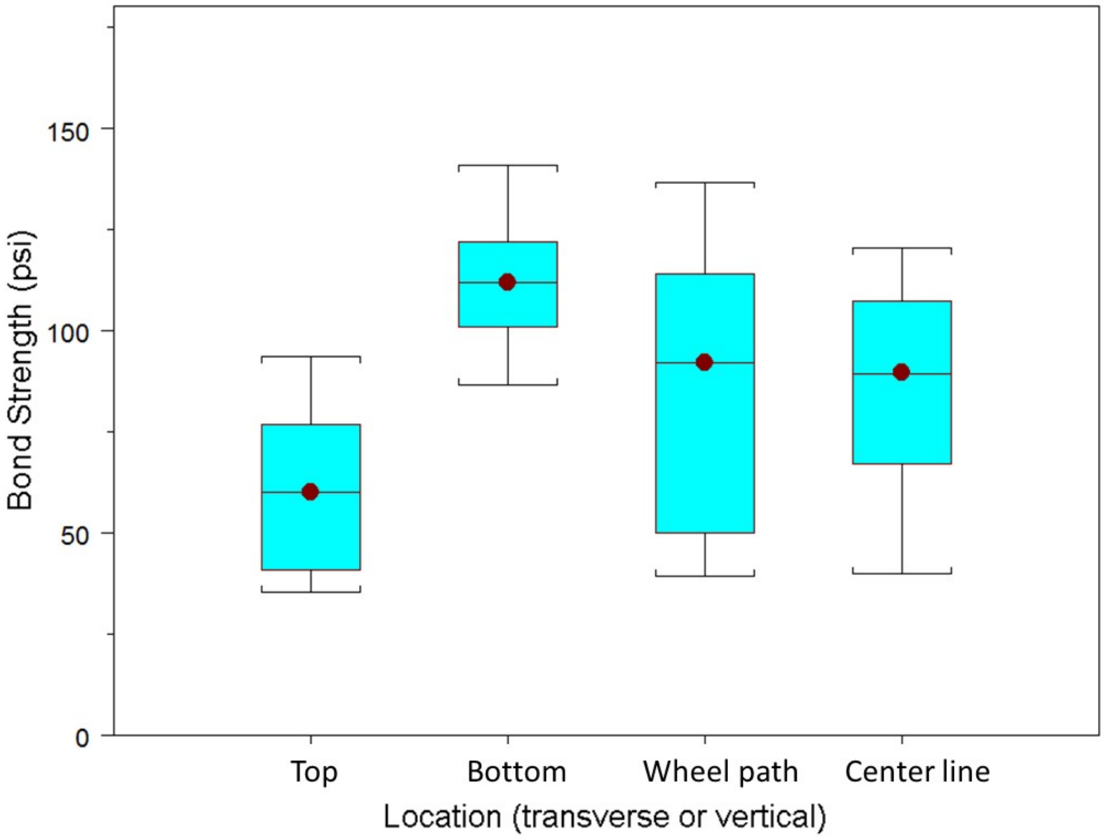


Figure 2.13. Differences in interlayer shear strength for various locations

Table 2.4. Summary statistics for transverse location and texture on ISS

Sample	Test 1		Test 2	
	Top	Bottom	Centerline	Wheel path
Min	24.0	59.0	24.0	31.0
Mean	60.2	112.3	84.9	87.1
Median	60.0	112.0	89.0	92.0
Max	104.0	166.0	132.0	166.0
Total N	54.0	54.0	54.0	54.0
Std Dev.	22.1	23.1	29.4	37.8
t	10.959		-0.305	
df	87.840		85.855	
p-value	0.000		0.761	

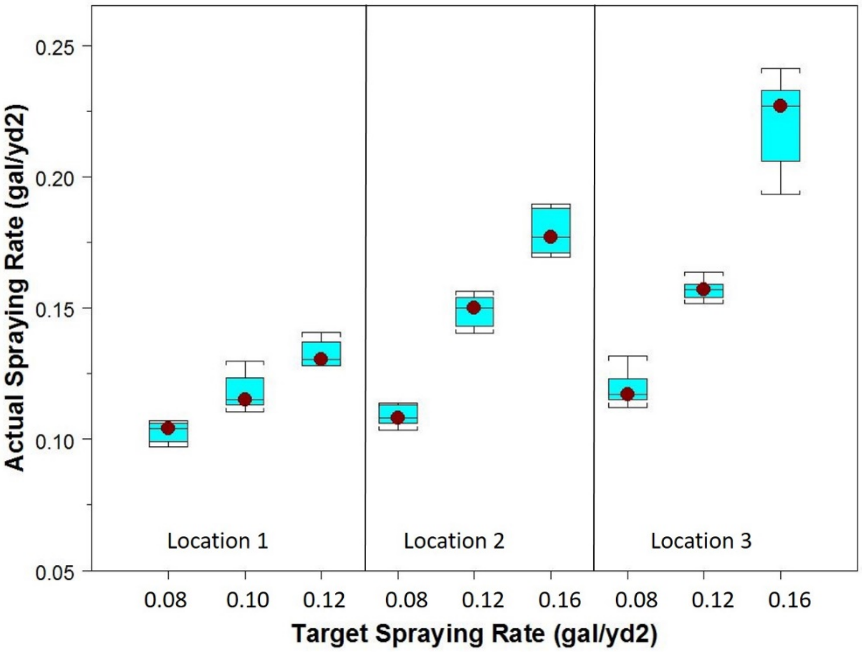
2.4.3 Most effective application rate to maximize ISS

To determine the most effective application rate to maximize ISS, application rate measurements were performed according to ASTM D2995 (2014) first to determine the accuracy of the distributor trucks during tack coat application. As expected, large differences in the target (specified rates) and the actual application rates exist, as shown in **Figure 2.14**. Each boxplot represents the variance of application rates captured by the line of textile pad squares placed in the transverse direction (**Figure 2.3c**) for each of three sections within each test location.

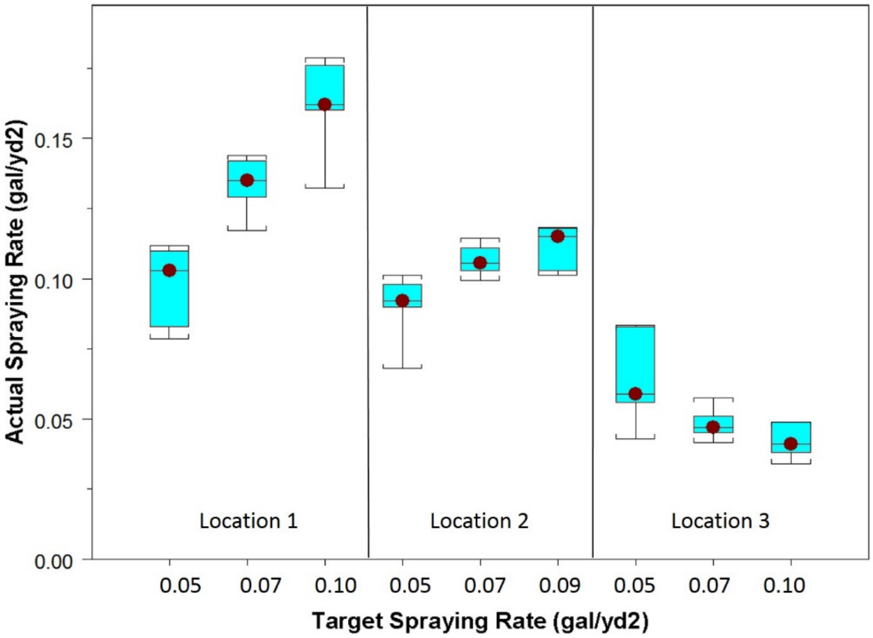
Results show that there is a significant lack of control in tack coat application rates. Actual tack coat application rates for milled surfaces were consistently above the target values (**Figure 2.14a**) and showed an increasing trend from one rate to the next. Overlay surface spraying exhibited this same pattern at Location 1 and Location 2. Overlay surface spraying at Location 3 showed that application rates were consistently above the target values, but a decreasing trend was observed (**Figure 2.14b**). An increasing trend from one rate to the next, similar to Location 1 of the milled surface, is expected. Observable differences in actual application rates can be seen from the boxplots in all the milled surface location and the overlay surfaces at Locations 1 and 2. These significant differences in target application rates allow the effects of application rate on interlayer shear strength to be observed. Overlay surface results at Location 3 exhibit no increasing trend from one rate to the next, which is unexpected. Results related to the effects of application rate on interlayer shear strength at Location 3-Overlay were inconclusive due to inaccurate tack application. Inconclusive results may be attributed to the use of the contractor’s distributor truck (old truck) for this location only.

Figure 2.15 summarizes the interlayer shear strength values obtained from field cores taken three months after construction for the various application rates and tack coat materials used in this study. A significant difference in interlayer shear strengths can be seen in those tack coats used on the milled (bottom lift) and overlay surfaces (top lift) (**Figure 2.15a**). The interlayer shear strength of the tack coats used on the milled surface was on average 112 psi, while those used on the overlay surface was on average 60 psi. The most effective application rate maximizing the interlayer shear strength of pavement layers was selected by finding the largest strength value along the y-axis and the corresponding application rate along the x-axis. In cases where differences in interlayer shear strength were minimal (for example CO1_New_b), the most effective rate was selected as the lowest rate to provide a more economical choice. Table 5 lists the recommended application rates that are the most effective to maximize the interlayer shear strength of pavement layers for selected Oregon tack coat materials.

Figure 2.15b also shows the relationship between ISS and target application, but after being normalized to include the effect of texture using the equation from **Figure 2.11**. A calculated ISS was determined using this equation and used as a reduction factor for each measured ISS. Normalizing the interface strength values in this way gives a more realistic comparison between bond strengths of the bottom (first lift) and top (second lift) interfaces. After normalizing the ISS for each tack coat material, CO2_CSS1H exhibits lower values for two of the three application rates than all other materials. CO1_CSS_1H_a, CO1_New_a, and CO1_New_b exhibit more similar ISS values (grouped closer together on the plot) after normalizing. CO1_CSS_1H_b and CO2_New exhibit similar ISS values (approximately 70 psi) for different application rates (**Figure 14b**).

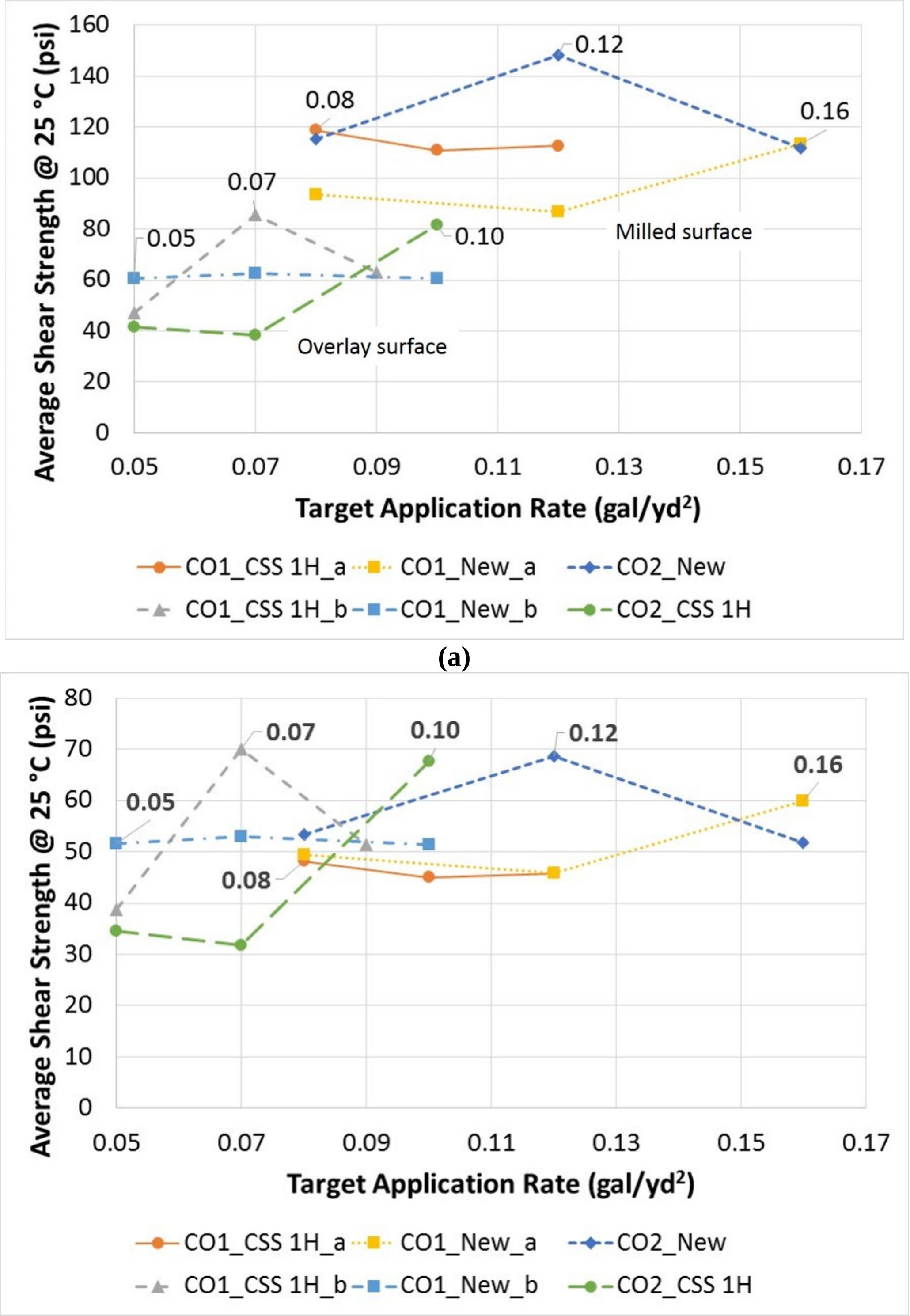


(a)



(b)

Figure 2.14. Differences in target application rate vs. actual application rate in the field (a) milled surface (b) overlay surface



(a)

(b)

Figure 2.15. Relationship between application rate and average ISS (a) measured values without texture effect (b) normalized to include texture effect

Table 2.5. Most effective application rates for tack Oregon materials on milled and overlay surfaces

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.

2.5 Summary and Conclusions

In this study, Oregon’s most commonly used slow-setting grade emulsions, CSS 1H, and “New” engineered emulsions from two companies were investigated for their performance. The performance of these emulsions, most effective application rates, and the effects of pavement surface texture, transverse location, and traffic on interlayer shear strength were evaluated in this study. Results were used to develop equations to predict bond shear strengths from simple rheological test results. The conclusions drawn from the results of this study are:

1. A positive correlation between pavement surface texture and interlayer shear strength exists. The influence of surface texture on measured ISS limited results to be confined to overlay pavement surfaces only when comparisons of tack coat materials were to be made regarding performance.
2. The results of statistical analysis of travel lines (wheel-path and center of travel lane) show that there is no difference in ISS between the two transverse locations for an initial set of cores taken three months after construction. For the sections that were tested in this study, tracking did not reduce tack coat performance. On the other hand, the difference in ISS for the milled and overlay (bottom and top interfaces respectively) interfaces is statistically significant.

3. Tack coat materials with higher viscosities exhibit higher softening point temperatures and lower penetration values. For overlay pavement surfaces in this study, positive correlations between rheological test results and interlayer shear strength of field cores taken three months after construction exist.
4. Traffic and environmental loading can relate to significant loss in interlayer shear strength between pavement layers in just a four-month period. Therefore, bond strength should be periodically monitored to avoid larger reductions in a longer period (over several years), which could lead to structural failures.
5. Large consistency issues (accuracy of application rate and uniformity of application) due to improper maintenance of the distributor truck are present in tack coat application, which leads to low ISS values of cores in this study. It is recommended that application rates and distributor trucks should be calibrated before construction begins

2.6 Future Study

In this study, of the six tack coat materials used, only three were used on overlay surface and three on milled surface. For a complete analysis, all tack coat materials should be utilized on both milled and overlay surfaces to make direct comparisons. It is recommended to take field cores from other sites with similar characteristics and measure the ISS using the *Asphalt Tack Bond Shear Strength Apparatus*. These results should then be compared by using the proposed equations to predict interlayer shear strength from simple rheological properties for validation and calibration. This will complement the conclusions from this study and help improve the predictability of the equations.

2.7 Acknowledgments

This study was supported by the Oregon Department of Transportation (ODOT). The contents of this paper reflect the views of the authors and do not reflect the official views or policies of the State of Oregon or Federal Highway Administration. The authors would like to thank Shashwath Sreedhar, Blaine Wruck, Sogol Haddadi, Yuqi Zhang, Jeffrey Knowles and Mostafa Estaji for their assistance with field measurements, obtaining core samples, and photography of events. A special thank you to the support of all ODOT coring crew members, Wayne Brown at the Materials lab, and all the members of the Technical Advisory Committee (TAC).

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3.0 CHAPTER 3 – DEVELOPMENT OF A SMARTPHONE APP AND DEVICE TO REDUCE TACK COAT TRACKING[2]

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Abstract: Oregon slow-setting grade and "New" engineered emulsions were investigated to evaluate their tracking, the pick-up of tack coats by construction vehicle tires during construction activities, resistance. Tracking reduces the amount of tack coat in particular areas and creates a non-uniform tack coat distribution between the two construction lifts. This non-uniform tack coat distribution leads to localized distresses and even complete failure of the bond between lifts. Oregon tack coat curing times, tracking resistance, and the factors that influence them were determined and evaluated in this study. Tracking resistance was also evaluated by developing a wheel tracking device that can be used in the field as a visual tool or by collecting weight data via the removable rubber "tires". Weight evaporation tests were used to create a linear regression model to predict in-situ curing times and develop a smartphone app using the created model. Prediction of in-situ curing times, along with the wheel tracking device, will reduce tracking and improve current tack coat QC/QA procedures.

Keywords: Curing time, emulsion, tack coat, smartphone app, tracking

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[2] Paper submitted to ASCE Journal of Materials

3.1 Introduction

Tack coats are bituminous materials applied between pavement lifts to create a bond forcing the structure to move as a single cohesive unit, ultimately mitigating early service life distresses (Asphalt Institute, 2000; ASTM Standard D8, 2015; Mohammad et al., 2012; USACE, 2001). While costs of tack coats are small in scale compared to the overall pavement material costs, the firm bond between layers can significantly increase the pavement service life (Johnson, 2015).Inadequate tack coat application practices during construction can result in poor bonding of pavement layers and failure of the pavement structure.

King and May (2003) evaluated the effect of bond strength on fatigue life by using BISAR software (De Jong et al. 1973). Simulations were conducted for a range of bonding levels ranging from no slip (100% bonding) to full slip (0% bonding). Results illustrated that fatigue life decreases by up to 50% when the bond is reduced by 10%. Roffe and Chaignon (2002) performed similar experiments using ALIZE, a French pavement design program, and results showed that pavement service life could reduce from 20 to 7 years due to lack of bond between pavement layers. Bond characteristics depend on several factors such as tack coat type, curing time, and application method and rate.

Tracking, the pick-up of tack coats by construction vehicle tires during construction, reduces the amount of tack coat in particular areas (especially in the wheel paths) and creates a non-uniform tack coat distribution between the two construction lifts (Flexible Pavements of Ohio (FPO), 2001; WSDOT, 2003). This non-uniform tack coat distribution creates localized failures around the low tack coat locations and reduces the overall structural integrity of the pavement structure. The magnitude of the effect of tracking is dependent on the tack coat type and the allotted time for tack coat curing before construction vehicles have access (Flexible Pavements of Ohio

(FPO), 2001). In addition, residual application rate, climate, and existing surface condition (cracked, milled, new, old, or grooved) are the other factors that affect the tack coat performance. By considering all these factors, a quality control and quality assurance (QC/QA) process needs to be developed to maximize tack coat performance during the service life.

3.1.1 Tack coat types

Emulsions, paving grade asphalt binders, and cutback asphalts are the materials used as tack coats. Due to environmental concerns, cutback asphalts (asphalts dissolved in solvents such as kerosene) are not allowed to be used as tack coats by many states. Paving grade asphalt binders are also not commonly used since excessive heating of the asphalt cement is required to achieve proper viscosity for spraying (Leng et al., 2008). According to a survey conducted by Mohammad and Button (2005), all of the responding agencies were using asphalt emulsions as tack coats. 26% used asphalt binders, and cutbacks were used by 21% of the responding states. Rapid setting (RS), medium setting (MS), and slow setting (SS) are the three overall grades used to classify asphalt emulsions (CalTrans, 2009). The type and amount of emulsifying agent control the curing time. Dilution is used to reduce the viscosity of slow-setting emulsions so that they can easily be sprayed using a distributor truck. In this project, the properties of only asphalt emulsions are investigated since they are the most commonly used tack coat types in Oregon.

Mohammad et al. (2012) compared the performance of a trackless tack coat (a polymer-modified emulsion with a hard base asphalt cement, NTSS-1HM) to SS-1h, SS-1, CRS-1, and a paving grade asphalt binder (PG64-22). It was concluded that the "trackless" tack coat exhibited the highest shear strength while CRS-1 resulted in the lowest strength. Cortina (2012) also reported higher shear strength for trackless tack coat materials. In Oregon, the “New” grade emulsions used in this study are expected to show properties similar to that of the “trackless” materials.

Clark et al. (2012) also evaluated non-tracking tack coat materials. The purpose of this study was to create a field validation and lab evaluation procedure for tack coat materials, specifically for the multiple newly created “trackless” tacks used within the state of Virginia. Testing was conducted using five trackless and two conventional (CRS-1 and CRS-2) tack coat materials by following a procedure similar to that described in ASTM D711, Standard Test Method for No-Pick-Up Time of Traffic Paint. This test method was modified to evaluate the tracking properties of tack coat materials. Results showed that the trackless tack materials outperformed conventional tack materials in all tests (shear strength, tensile strength, and tracking) under both laboratory testing temperatures and oven dried conditions. It was recommended to adopt the testing procedures described within the report to qualify candidate non-tracking tack materials for field verification. Wilson et al. (2015) conducted similar tests with trackless materials in the state of Texas, where like Virginia, initially there was only one supplier of trackless tack coats. The purpose of the study was to develop a test to evaluate multiple newly created trackless tacks and measure their tracking resistance. Like Clark et al., Wilson et al. (2015) also adopted a modified ASTM D711 procedure to measure tracking resistance. The wheel tracking device developed by Oregon State University in this study would further modify the procedure used in the previous two studies.

3.1.2 Tack coat application methods

Uniformity and amount of application are two elements required to achieve proper bond strength (Cortina, 2012). The factors that are critical to reaching the necessary application rates and uniformity are summarized as follows (ASTM Standard D2995, 2014; Hachiya & Sato, 1997; Mohammad et al., 2012):

- Nozzle spray patterns should be identical to one another.
- The height of spray bar should be properly set and remain constant during application.
- The distributor should be capable of forcing the tack coat out of the nozzles at all temperatures.
- The distributor should be capable of maintaining the required temperature to ensure adequate flow.
- The size of the nozzles should be sufficient to achieve target spraying pressures for different tack coat types and at different temperatures.

3.1.3 Tack coat curing time

There is no consensus on the importance of tack coat curing time. Several research studies (Flexible Pavements of Ohio (FPO), 2001; TxDOT, 2001) suggested having a cured tack coat layer before constructing the overlay to achieve high bond strengths. Scholar et al. (2004) evaluated the impact of curing on tack coat shear strength and observed a considerable increase in shear resistance with curing time. On the other hand, several other research studies (Lavin, 2003; USACE, 2000) indicated that since water in the emulsion will immediately evaporate and escape as steam after placing the overlay material on the tacked asphalt surface, there is no need to wait several hours for the tack coat to cure. Although, if the water does not escape (use of warm or coldmix) the water will remain in the pavement and can create moisture damage. Under most circumstances, an emulsion is expected to set in 1 to 2 hours (USACE, 2000). Thus, slow-setting emulsions are more vulnerable to slippage during their early lives (USACE, 2008).

Curing time and the impact of curing time on tracking should be investigated for different tack coat types to develop a standard for tack coat type selection and application procedures. Alaska DOT specified a maximum curing time of 2 hours for CSS-1, while Arkansas DOT specified a maximum time of 72 hours for SS-1. Texas DOT specified a maximum curing time of 45 minutes for SS-1 (Mohammad et al. 2012). It should be noted that in Europe, asphalt emulsions are applied underneath the paver (Spray pavers) just before the asphalt concrete (AC) construction to minimize tracking problems (Mohammed et al. 2012).

3.1.4 Summary

This study is an investigation of the performance of Oregon tack coats. Tack coat materials are evaluated for their curing time and tracking resistance. In the literature, there were limited studies focused on tracking, and none were conducted with tack coats used in Oregon. This study developed a wheel tracking device for use in the field to measure tracking and aid in determining the in-situ curing time of tack coats. Laboratory weight evaporation experiments were also performed to determine curing times of selected Oregon tack coats. Those results were used to create a linear regression model for the development of a smartphone app that can be utilized during construction of asphalt pavements. The purpose of the app is to predict tack coat curing times in the field to mitigate tracking by avoiding any construction vehicles driving on the applied tack before the tack coat cures.

3.2 Objectives of study

The objectives of this study are to:

- Provide recommendations to improve the current practice for tack coat application (accuracy of application rate and uniformity of application), proper curing time, and tracking resistance
- Measure and evaluate the curing times of Oregon tack coat materials and evaluate the effects of surface texture on curing time
- Develop a smartphone application for tack coat curing time prediction to be used during construction.
- Assess the effects of surface texture (milled vs. overlay) and application rate on tracking resistance;
- Determine the tracking resistance of “New” tack coat technologies developed in Oregon;
- Develop a device to measure tack coat tracking and determine in-situ curing time.

3.3 Materials and Methods

3.3.1 Tack coat materials and curing time test plan

Four different types of emulsions (CO1_CSS 1H, CO1_New, CO2_CSS 1, and CO2_New) are tested in this study to determine the curing time. Generic tack coat type labels are used to conceal the identity of the company providing the material. CSS 1H emulsions are the most commonly used slow-setting grades in Oregon. “New” emulsions are the engineered emulsions recently developed in Oregon to reduce tracking and increase bond strengths.

Tack coat curing time was evaluated in the laboratory through evaporation experiments in a temperature controlled chamber using three application (spraying) rates and two testing temperatures (**Table 3.1**). Experiments were conducted with steel plates (no texture), open-graded (OG) (high texture) asphalt cores, and dense graded (DG) (medium texture) asphalt cores to determine the impact of texture on measured curing time. A summary of the experimental plan is shown in **Table 3.1**. A total of 48 steel plate tests were conducted, along with 48 asphalt concrete core (AC) tests (24 each of OG and DG), for a total of 96 experiments.

As part of the test plan, tack coat densities were determined by measuring out a predetermined volume (100 mL) and using a high accuracy scale to determine the emulsion weight for the measured volume. These densities, along with application rates from **Table 3.1**, were then used to determine the emulsion weight to be applied to the samples during testing for a specific surface area. Calculated application weights for the various application rates are listed in **Table 3.2** and were calculated by using Eq. **(3-1)**:

$$\textit{Target weight} = \textit{Application rate} \times \textit{Sample surface area} \times \textit{Density of tack coat} \qquad \textbf{(3-1)}$$

AC core surface texture, mean texture depth (MTD), was measured for all samples before testing to use as a variable in the regression analysis to evaluate the effect of texture on tack coat curing time. Texture experiments followed a modified procedure from ASTM E965 (2015). Fine sand was lightly applied to each sample to cover the surface completely. By using the before and after the weight of the core sample, the mass of sand applied was determined. The mass of the sand was converted to a volume with the known density using Eq. **(3-2)**

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

where;

MTD = mean texture depth of pavement surface (in.)

V = sample volume (in^3) and

D = average diameter of the area covered by the spreading of the sand (in.) (ASTM Standard E965, 2015).

Table 3.1. Summary of test plan for tack coat curing time determination

Parameter	Emulsion	Temperature (°F)	Application Rate (gal/yd^2)	Texture
Experimental Setting	CO1_CSS 1H CO1_New CO2_CSS1 CO2_New	59 (L) 95 (H)	0.0.45 (L) 0.105 (M) 0.164 (H)	Open grade (OG) Dense grade (DG) Steel plate (SP)

Table 3.2. Summary of target application weights for samples used in tack coat curing time tests (in grams)

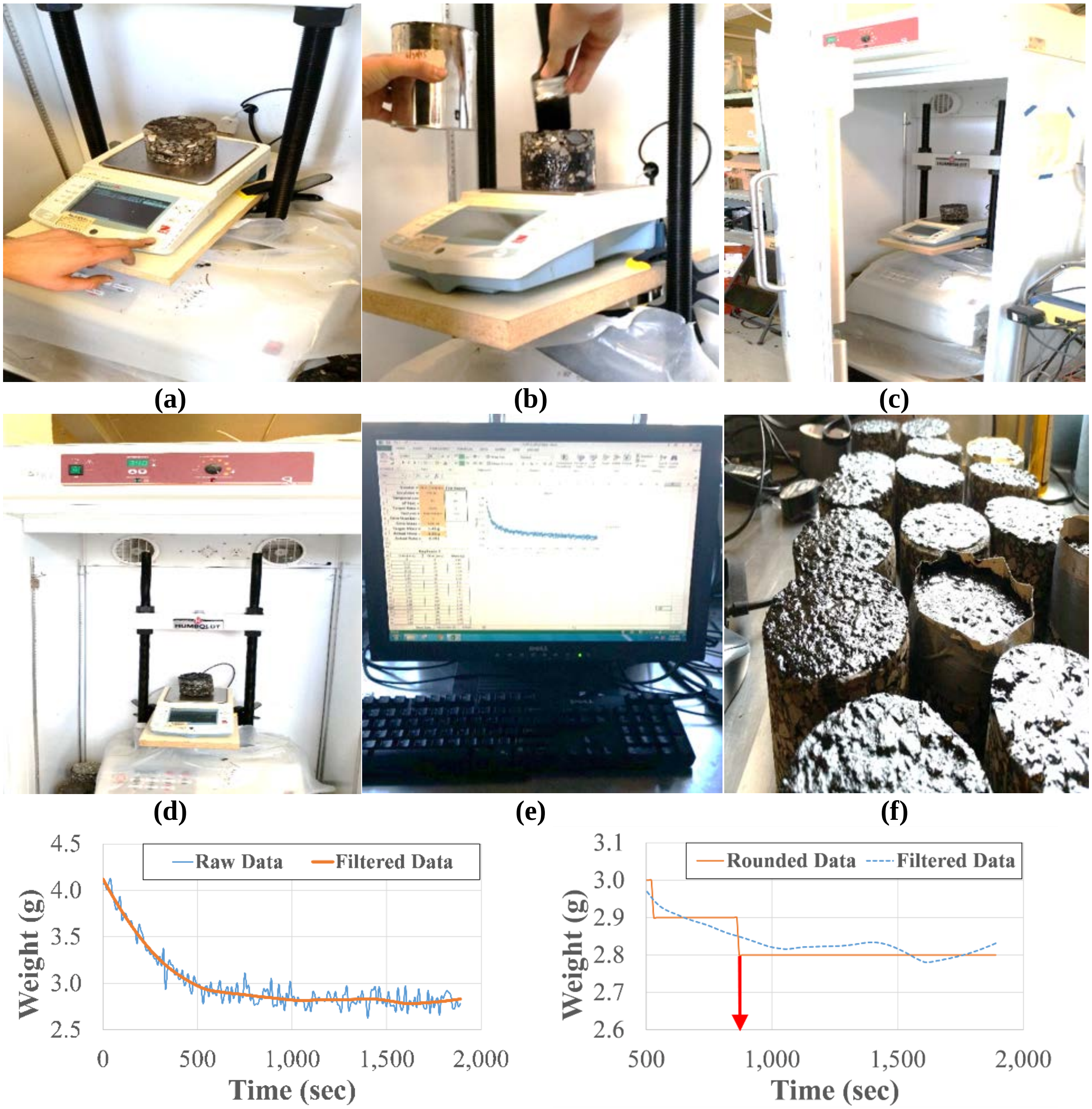
Texture	0.045 gal/yd^2		0.105 gal/yd^2		0.164 gal/yd^2	
	Steel Plate	AC Cores	Steel Plate	AC Cores	Steel Plate	AC Cores
CO2_CSS 1	3.80	1.33	8.88	3.10	13.86	4.84
CO2_New	4.04	1.41	9.42	3.29	14.71	5.13
CO1_CSS 1H	4.17	1.46	9.73	3.40	15.20	5.30
CO1_New	4.52	1.58	10.53	3.68	16.45	5.74

3.3.2 Procedure for determining tack coat curing time

The general procedure followed for tack coat curing time measurement, and data analysis is illustrated in **Figure 3.1**. Steel plate and asphalt cores were cleaned for excess debris and left to dry before testing. The steps for determination of curing time are as follows:

- Samples were placed on a high accuracy scale (capable of measuring the 0.01g change in weight) inside of an environmental chamber **(Figure 3.1a**). After calibrating the scale for the chamber temperature, the scale was initialized to zero.
- An application weight, calculated by converting a specified application rate to grams using the calculated density, was applied via paintbrush to the surface of the sample (**Figure 3.1b**)
- Samples were left on the scale, inside the closed chamber, while data was collected via computer connection **(Figure 3.1c**)
- Tests were conducted at low (59°F) and high temperatures (95 °F) while the temperature was controlled by the chamber (**Figure 3.1d**).
- An excel template was created to collect data at 10-second intervals from the scale using a software package **(Figure 3.1e**).
- Data was collected continuously at 10-second intervals as the weight of the applied tack coat decreased due to evaporation of water. Termination of the test was conducted once a visible horizontal line was present in the data collection plot (**Figure 3.1e**). After the completion of the test, the surface color of the tack coat appears black in color (the weight will be constant) (**Figure 3.1f**).
- Due to the ambient vibrations, the data had a certain level of high-frequency noise. To filter out high-frequency noise, a low-pass filter available in MATLAB R2015b is used (**Figure 3.1g**).
- The filtered signal is then rounded to a single decimal point and plotted. The rounded data reflects reduced accuracy that may be experienced in the field when the curing time is measured by a lower accuracy scale (capable of measuring the 0.1g change in weight). The

curing time is then determined by locating the first time stamp that the rounded data curve has reached the lowest recorded weight (shown with a red arrow in **Figure 3.1h**).



(a) (b) (c)

(d) (e) (f)

(g) (h)

Figure 3.1: General photographic steps used in tack coat curing time determination

3.3.3 Development of a smartphone app

3.3.3.1 Linear regression model for app

This portion of the study focused on the development of regression equations to determine emulsion curing time in the field. By avoiding construction vehicle traffic before the calculated curing time, tracking can be minimized. In addition, moisture damage from the evaporation of water in the emulsion and not escaping as steam after AC overlay construction can be minimized by allowing the tack coat to completely cure. Ultimately, accurately predicting the emulsion curing time will reduce tracking, decrease delays seen in construction, and improve bond strength by minimizing moisture damage. The equations developed in this study will also serve as the beginnings of a quality-assurance and quality-control process to maximize tack coat performance throughout the pavement design life. A field tack coat curing time measurement tool (a smartphone app) was developed using test results and the regression equations.

Simple linear regression analysis was conducted to generate the models. The model selection procedure included the following steps:

- Prepare a scatter (pairs) plot matrix to inspect possible relationships amongst predictor variables;
- Construct a correlation matrix of all variables to assess relationships further;
- Develop an Analysis of Variance (ANOVA) table to identify significant variables;
- Apply regression analysis to develop linear equations;
- Plot the residuals to determine if regression model is suitable for the data being used.

Regression models were developed for three different scenarios:

1. All AC cores (dense and open grade)
2. Steel plates:

   a. Using two replicates
   b. Using a single replicate
3. Combined dataset: AC cores and steel plates.

Steel plate experiments were performed to determine whether texture has an effect on the curing time. Two separate steel plate regression models (all steel plate replicates vs. replicate one only) were developed to determine if performing replicate experiments, having more data, increased the accuracy of the model. The results provided an indication as to whether replicate tests for AC cores were necessary or not.

Monte Carlo simulations were conducted with several of the model equations (AC Core w/ no texture and AC core plus Steel plate w/ no texture) developed to generate a distribution of curing times and determine which model produced more reliable results. Tests were also conducted to determine the effect of the wind on the curing time to improve the accuracy of the linear model. It was determined that increasing the wind reduced the curing time. Therefore the model was adjusted with a Wind Adjustment Factor. Several experiments were also conducted using the procedure given in **Figure 3.1** at a test temperature of 0 °C to see how well the model worked outside of the test temperatures used for model development (15°C and 35°C). It was determined that the relationship between curing time and temperature was linear. Therefore no adjustments were needed for low temperatures.

3.3.3.2 Summary of procedure to develop app

The mobile application linked to this project has Android and iOS versions. The Android version was developed using Android Studio, while the iOS version was developed using Swift. Both were developed by using a C++ program that was created for testing purposes only. The C++ program was set up to keep both versions as similar as possible in concept. During this process, the bounds for the regression equation changed as well as the minimum time that could be calculated. The temperature was given a range appropriate to Oregon weather.

The wind was automatically set to 4 mph for cases when the wind speed is anything higher than 4 mph since the maximum wind speed simulated in the lab was limited. The application rate was set to the same range used in the lab experiments (**Table 3.1**). Even with the bounds set, some predicted curing time values were five minutes or less based on the environmental inputs, although the cases were rare. These results were unexpected when compared to the field data that was collected. For this reason, the code for the application was fixed to give a curing time of 25 minutes for any calculated value that was under 25 minutes. This serves as a factor of safety and ensures that tack coats have adequate time to cure in the field.

After the initial layout and icon design had been created for the mobile application, it was then handed over for testing to the research group as well as other mobile application developers. According to the feedback from the research group and other app developers, both applications were revised and finalized.

3.3.4 Development of a device to measure tack coat tracking

In this part of the study, the goal was to develop a small-scale device to measure and evaluate tack coat tracking in the field. Initial design parameters were based on ASTM D711, *Standard Test Method for No-Pick-Up Time of Traffic Paint* (2010). The modified wheel device developed by Clark et al. (2010) and Wilson et al. (2015) to test trackless tack coats in Virginia and Texas was further developed at Oregon State University.

Different from previous studies, the device in this study was designed to match the tire pressure of a full-size construction truck, assumed to be 720 kPa. The footprint of the tire was assumed to be square. A scaled load was determined by using the tire pressure and contact area (cross section of the O-rings used as tires = 9.5mm). A factor of safety was used to increase the applied load by 50% to a value of 20 kg. The load was converted into a volume using the density of steel (7.5 g/cm^3), the load was transformed into a volume. The device had a fixed diameter of 130 mm. Thus the height of the cylinder was determined to be 190 mm. Two rubber O-rings (tires) were placed 50 mm from each end and 90 mm from each other (**Figure 3.2a**). Each tire has the capability to be removed after use with the purpose of taking weight measurements to record the amount of tack coat picked up (**Figure 3.2b**). Testing is performed by placing the wheel on the sprayed tack coat and rolling the wheel using the handle to complete one revolution (**Figure 3.2c**).

Similar to ASTM D711 testing procedure, the time at which no tack coat is picked up (visually or based on measured weight) is indicated as the curing time of the tack coat. This value serves as an indicator of the in-situ curing time of various tack coat materials within this study.

(a) (b) (c)

Figure 3.2: Tack coat tracking wheel (a) schematic (b) removing O-rings in field (c) use of wheel device during a field test

3.4 Results and Discussion

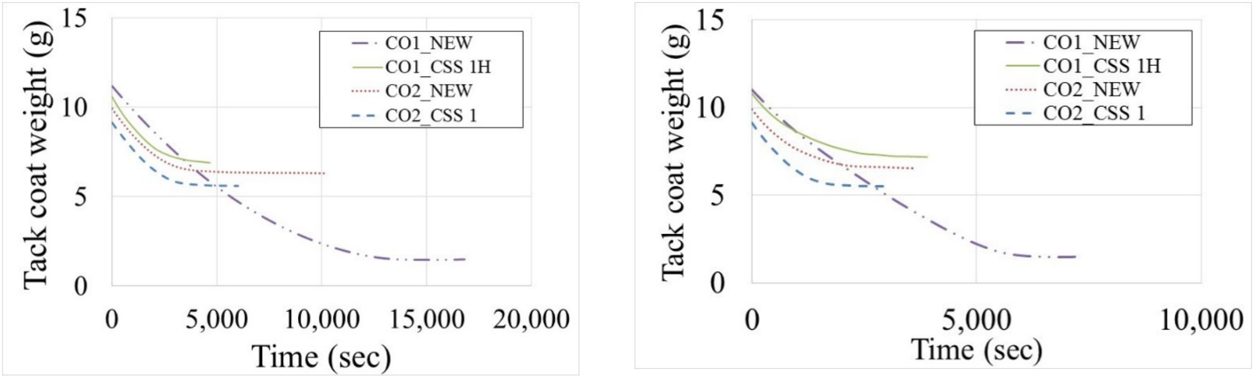
3.4.1 Evaluation of tack coat curing time

<u>3.4.1.1 Laboratory curing time determination</u>

Tack coat curing time was determined by conducting laboratory evaporation tests inside a temperature-controlled chamber using a high-accuracy scale. Testing followed the procedure shown in **Figure 3.1**. Steel plate samples were flat, smooth squares with an area of 36 square inches. AC core samples had a diameter of 4 inches with open and dense-graded surface types. The purpose was to obtain the curing time of various tack coats to aid in the development of linear regression models embedded in the smartphone apps that would predict in-situ curing times.

Figure 3.3 shows general results of the filtered data collected during the curing time experiments for steel plate samples at two different temperatures for the tack coats used for testing. Filtered data (**Figure 3.1g** and **Figure 3.1h**) was used to determine the curing time for each material. Curing times were then tabulated and averaged to make comparisons between tack coat types. For steel plate experiments, CO1_New had a significantly longer curing time than all other emulsions regardless of the testing conditions (different application rate, low or high temperature) (**Table 3.1**). **Figure 3.4** and **Figure 3.5** also show that CO1_New exhibited the longest curing time of all the materials tested regardless of temperature and application rate. A summary of curing times for all steel plates (no-texture surface) experiments are listed in **Table 3.3**.

Filtered data collected during the curing time experiments for asphalt concrete (AC) cores were initially evaluated separately as open and dense graded AC core data. After using the filtered data to determine the curing time for each texture type, the results were combined and averaged to make comparisons between the tested tack coat types. AC core test results were combined because the texture was determined by linear regression (section 3.4.1.2) to not significantly impact the curing time. Similar to the steel plate experiments, CO1_New had the longest curing time amongst all the materials tested (**Table 3.4**). CO2_New was revealed to have the shortest curing time. **Figure 3.4** and **Figure 3.5** also show the ranking of curing times depending on temperature and application rate, respectively. These results suggest that texture does not have a significant impact on the curing time of these particular tack coat types. Analysis of Variance (ANOVA) results showing the insignificant effect of texture on curing time is given in section 3.4.1.2. A summary of curing times for all AC core experiments are listed in **Table 3.4**.



(a) **(b)**

Figure 3.3: Steel plate emulsion evaporation curves with medium rate (0.105gal/yd^2) (a) 59 °F (b) 95 °F

Table 3.3: Average laboratory curing time of tack coats on steel plates

Tack Coat Type	Avg. LT[1] Curing time (min)	Avg. HT[2] Curing time (min)	Avg. LR[3] Curing time (min)	Avg. MR[4] Curing time (min)	Avg. HR[5] Curing time (min)
CO2_CSS 1	72.53	52.31	37.46	58.79	91.00
CO2_New	74.53	39.83	25.04	66.38	80.13
CO1_CSS 1H	73.44	50.14	31.33	62.96	91.08
CO1_New	188.75	95.64	86.42	157.71	164.63

Note: LT[1]: Low temperature – 59 °F, HT[2]: High temperature – 95 °F, LR[3]: Low application rate – 0.045 gal/yd^2, MR[4]: Medium application rate – 0.105 gal/yd^2, HR[5]: High application rate – 0.164 gal/yd^2

Table 3.4: Average laboratory curing times of tack coats on AC cores (dense and open grade)

Tack Coat Type	Avg. LT[1] Curing time (min)	Avg. HT[2] Curing time (min)	Avg. LR[3] Curing time (min)	Avg. MR[4] Curing time (min)	Avg. HR[5] Curing time (min)
CO2_CSS 1	66.56	64.58	44.00	62.96	89.75
CO2_New	58.17	59.94	27.42	44.50	105.25
CO1_CSS 1H	78.75	66.03	33.42	87.83	95.92
CO1_New	183.43	134.72	74.29	144.42	258.53

Note: LT[1]: Low temperature – 59 °F, HT[2]: High temperature – 95 °F, LR[3]: Low application rate – 0.045 gal/yd^2, MR[4]: Medium application rate – 0.105 gal/yd^2, HR[5]: High application rate – 0.164 gal/yd^2

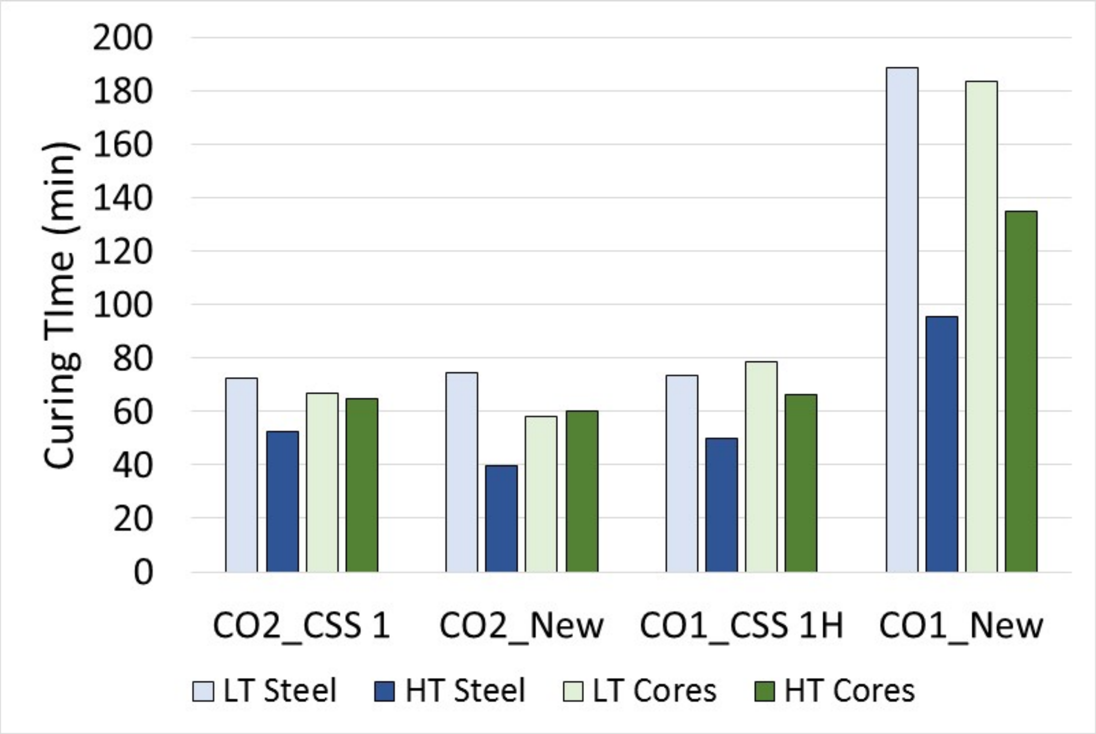


Figure 3.4. Average laboratory curing times of tack coats for low temperatures (LT) and high temperatures (HT) on steel plates and AC cores

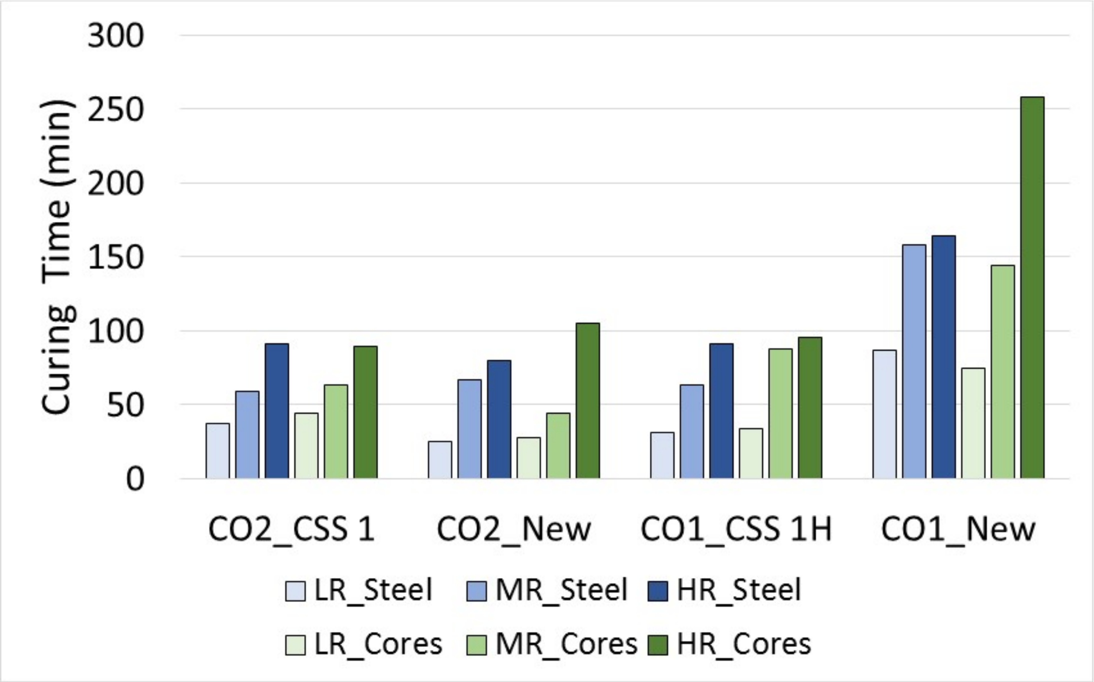


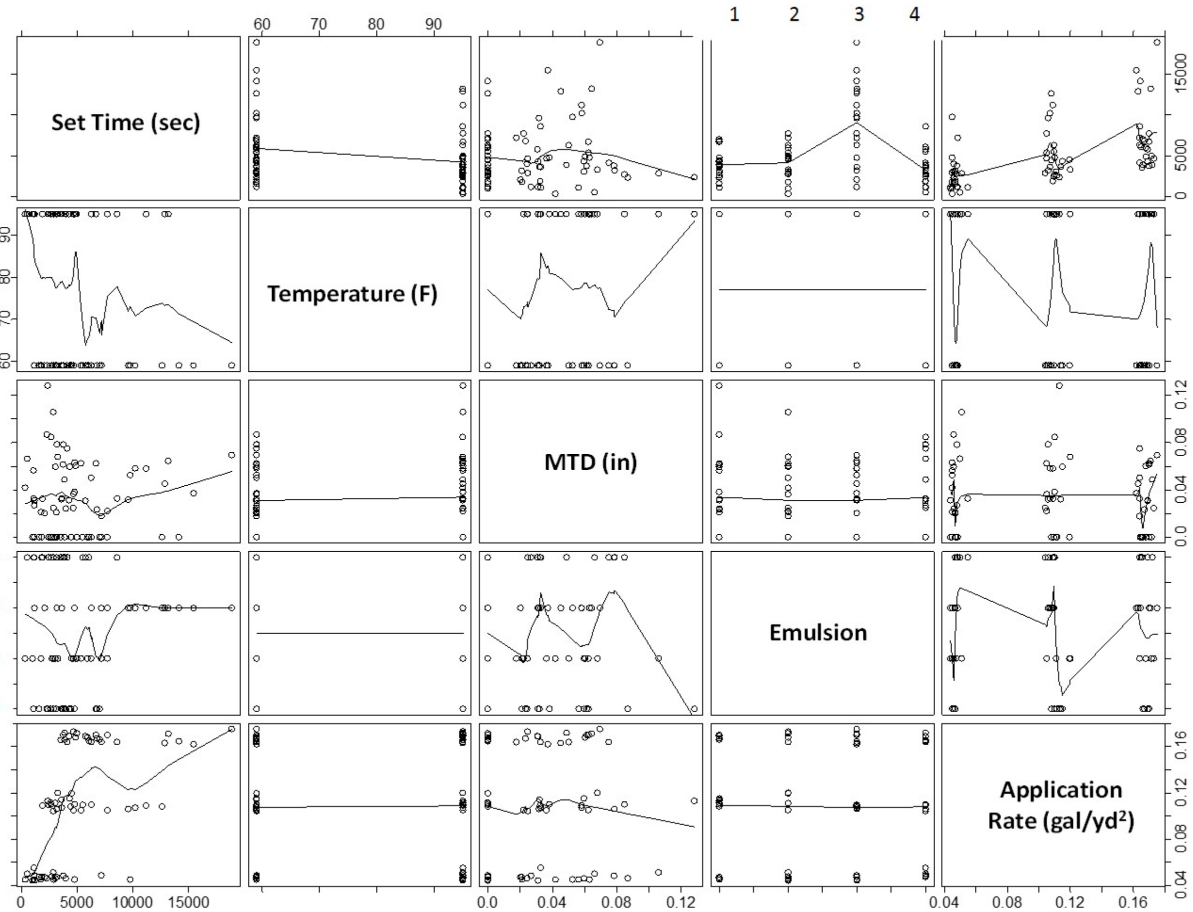
Figure 3.5. Average laboratory curing times of tack coats for various application rates on steel plates and AC cores; low-rate (LR), medium-rate (MR), and high rate (HR)

3.4.1.2 Linear regression model

In this study, the dependent variable used for model development is the emulsion (tack coat) curing time (SET) measured in seconds, and the independent variables are temperature (TEMPF), texture (MTD), emulsion type (EMUL), and the application rate applied (ACTR) (Table 3.1**)**. A correction factor for wind speed was later incorporated into the model.

For the first scenario described in section **3.3.3.1**, only results from AC core curing time experiments were utilized for model development to extract possible relationships between the emulsion curing time and the independent variables considered. Analysis of Variance (ANOVA) of all AC cores model (scenario 1) indicated that texture (MTD) did not have a significant effect on curing time (p-value = 0.9711), while temperature, emulsion type, and application rate were significant. As for the steel plate models, the next scenario, the similarities in regression model coefficients of the two models with (R^2= 0.85) and without steel plate replicates (R^2= 0.84) demonstrate that the models are relatively similar to each other. Overall, using a replicate test did not improve the accuracy and precision of the regression models. Therefore, replicate experiments were not conducted for testing AC cores. The analysis of scenarios one and two led to the development of the final model (scenario three), which was a combined dataset of AC cores and steel plates since the texture was not a significant factor and the final model did not include texture (MTD) as a variable.

Figure 3.6 is a matrix of scatter plots, which depict the interactions between the dependent and independent variables that were used in model development Several trends are illustrated in **Figure 3.6,** for example, higher temperatures result in shorter curing times, emulsion CO2_New has the largest range of curing times, and higher application rates yield longer curing times. It can also be observed that independent variables are not correlated and can be used for regression model development.



Note: 1: CO2_CSS 1, 2: CO1_CSS 1H, 3: CO1_New, 4: CO2_New
Figure 3.6: Scatter plot matrix for AC core and Steel plate test results

The developed equation that excludes the texture variable (MTD) can be considered to be more practical since it may not be practical to conduct sand patch tests during the construction to measure surface texture. The resulting equation used for the smartphone app development is given in Eq. **(3-3)**.

$$\begin{gathered}\text{SET}=3{,}054.59 - 45.79\times\text{TEMPF} + 266.94\times\text{CO1\_CSS 1H} \\ + 5{,}305.85\times\text{CO1\_New} - 499.74\times\text{CO2\_New} + 39{,}970.96\times\text{ACTR} \\ \boldsymbol{R^2 = 0.71}\end{gathered} \tag{3-3}$$

As seen from the equation, terms with negative signs indicate that an increase in this variable will decrease the curing time (SET). For example, higher temperatures and using emulsion CO2_New will decrease the curing time. Since each emulsion type has a corresponding coefficient and term within the equation, not all of the terms are used when a specific emulsion type is selected. For example, to find the curing time of emulsion type CO1_CSS 1H, simply insert a one (1) into the equation where CO1_CSS 1H appears and zeros (0) for the other emulsion types, eliminating the unused coefficients and leaving the one of interest. Similarly, to find the curing time for CO2_CSS 1, insert zeros (0) for all the emulsion terms. The calculated R^2 value, which gives an estimate of the strength of the relationship between the independent variables of the linear regression model and the curing time, was 71%. Although this value gives an indication of a good fitting model, residual plots were assessed to determine any bias, overfitting issues, and outliers.

3.4.1.3 Adjustments to regression model

Effects of the wind on tack coat curing time were investigated by conducted several additional curing time experiments with a target application rate of 0.105 gal/yd^2 using CO1_CSS 1H. The tack coat was applied via paintbrush (approximately 7.64 grams) to a 6-inch diameter asphalt core measuring two inches thick and placed in front of a box fan. The distance from the core and power of the fan were adjusted until the target wind speed was measured via a hand-held anemometer. Tests were conducted at speeds of 0, 2, 4, 6, and 8 mph. Weight measurements were recorded at every five minutes until no significant change in weight occurred. Curing time was determined as the time at which the weight readings remained constant. Results were plotted to show how wind speed affects the curing time of tack coats (**Figure 3.7**).

Because the regression model was developed without considering the wind, an equation was developed to calculate an adjustment factor to incorporate the impact of wind into the predictions of the developed linear regression equation. Each curing time value from the developed linear regression equation should be modified using Eq. (**3-4**) and Eq. (**3-5**):

$$Set\ Time\ Final = Set\ Time * Wind\ Factor \qquad \textbf{(3-4)}$$

where;

$$Wind\ Factor = \frac{-9.75 * Wind\ speed\ (mph) + 129}{129} \qquad \textbf{(3-5)}$$

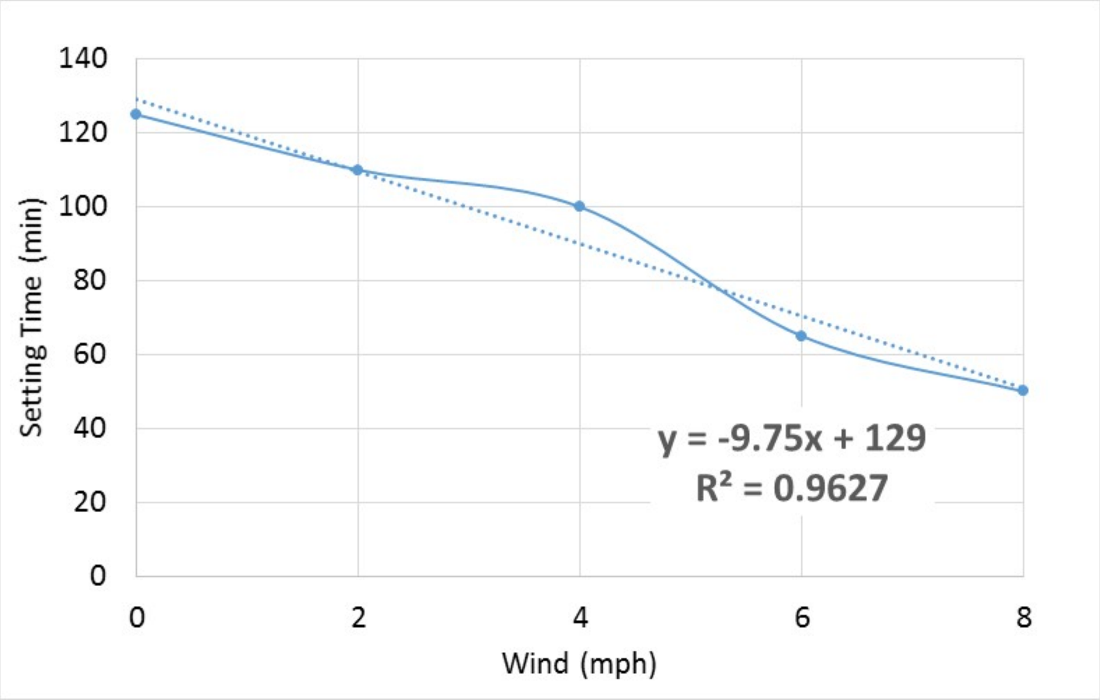
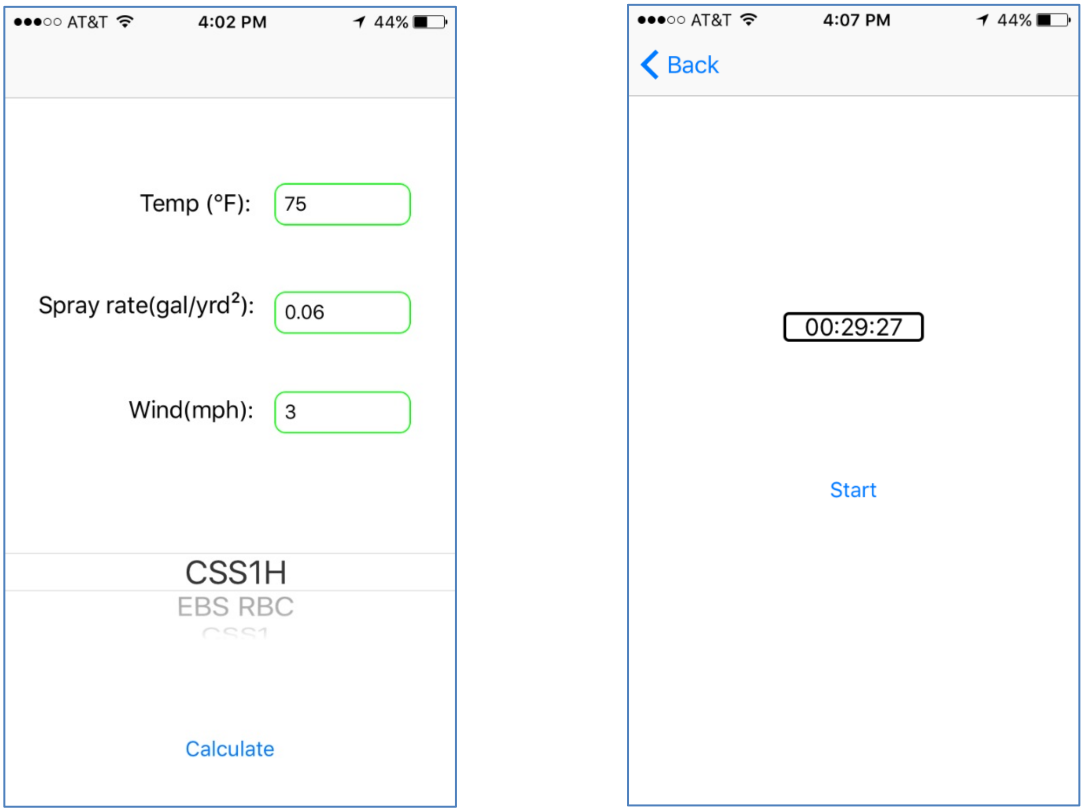


Figure 3.7: Effect of the wind on tack coat curing time

3.4.1.4 Smartphone app

IOS and Android apps were developed to calculate tack coat set time in the field. The IOS app screenshot in **Figure 3.8** is showing the input screen and the output screen with the timer. After entering the input parameters and tapping on “Calculate”, the app calculates the required time for the tack coat to set (**Figure 3.8b).** The timer can be started by tapping on the start icon on the output screen. The app sends a notification (with vibration) to the contractor saying “Tack coat is set” when the timer reaches zero. Both IOS and Android apps will be available in app stores.



Temp (°F): 75

Spray rate(gal/yrd^2): 0.06

Wind(mph): 3

CSS1H

00:29:27

(a) **(b)**

Figure 3.8: Screenshot is taken from smartphone app developed for tack coat curing time (a) user input (b) countdown timer

3.4.2 Evaluation of tack coat tracking

Tack coat tracking was also investigated by using a wheel device developed for this study in a parking lot experiment on an asphalt surface and in a field experiment on milled and overlay surfaces. Each experiment consisted of placing the wheel on the applied tack coat some known amount of time after spraying and making one pass of the wheel (one revolution of the wheel). The purpose was to measure tack coat tracking using this device to determine the in-situ curing time and provide recommendations to reduce tracking during construction. **Figure 3.9** depicts the average amount of tack coat tracked by the developed wheel device over time for several tack coat types for the parking lot tests (non-milled surfaces) conducted with an application rate of 0.07 gal/yd^2.

Tack coat tracking also serves as an indicator of the actual curing time of that specific tack coat material. As the amount being tracked decreases, the tack coat approaches a cured state ready for haul vehicles to drive on. The amount tracked decreased as time increased. This result suggests that wheel tracking device can be a useful tool to determine tack coat curing time in the field and can be used to reduce tracking by not allowing construction vehicle traffic on the applied tack before an appropriate amount of time has passed. Tack coat CO2_New showed the highest initial amount of tracking while CO1_CSS 1H showed the lowest amount of tracking (**Figure 3.9)**.

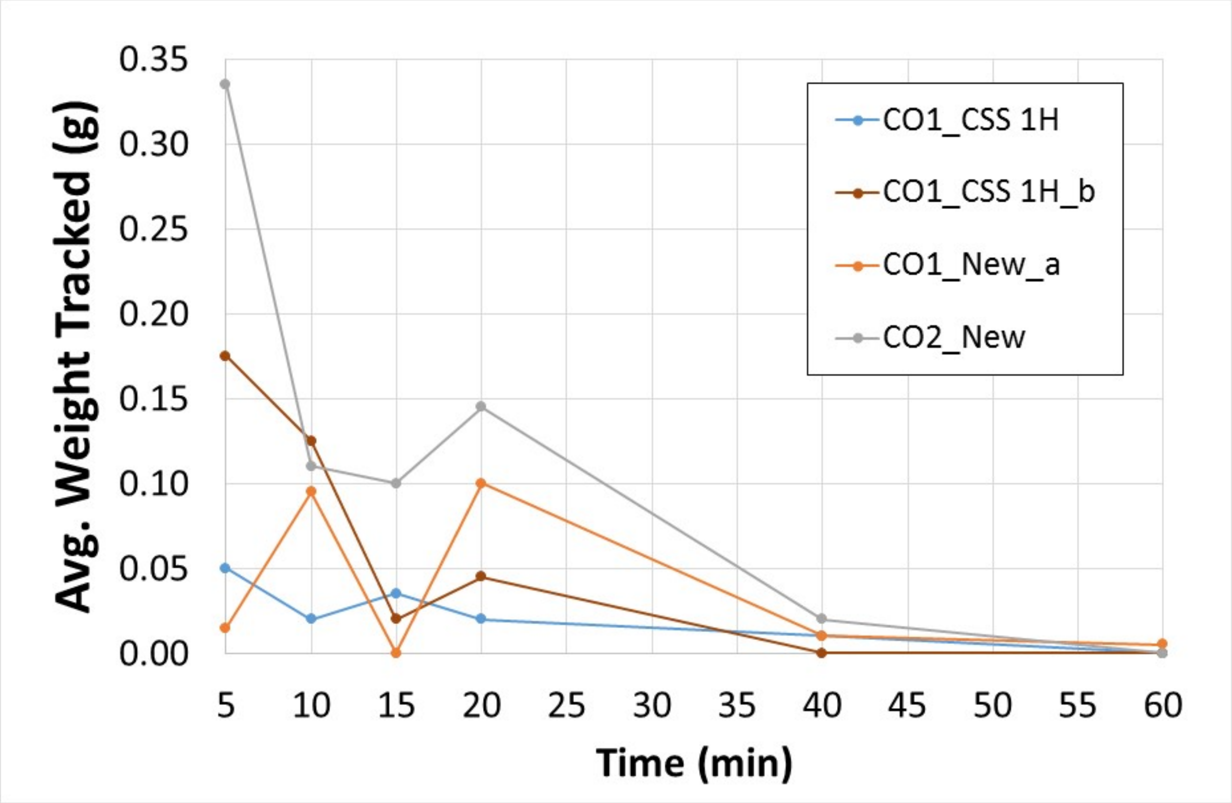
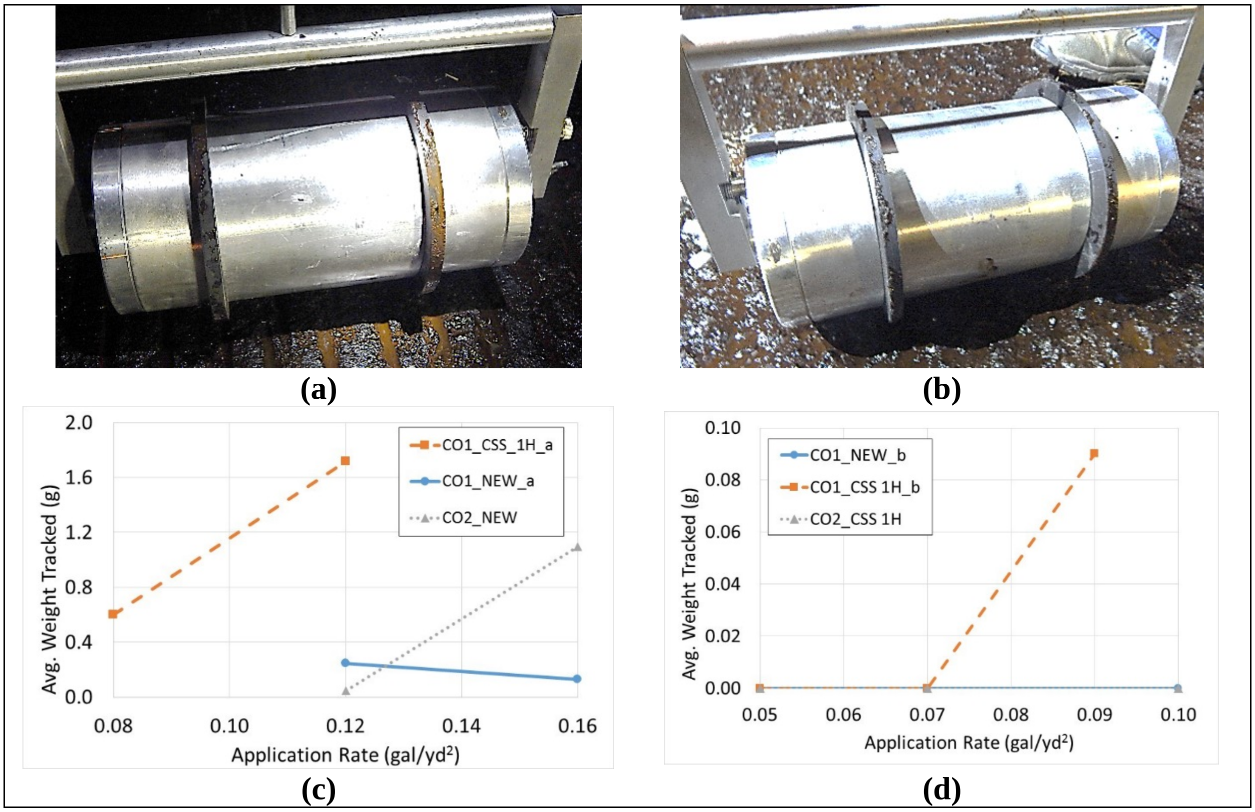


Figure 3.9: Parking lot tracking of tack coats over time with 0.07 gal/yd^2

Field experiments were also conducted on a highway construction of new HMA. Milled and overlay surfaces were evaluated at various application rates at approximately the same time after spraying occurred. **Figure 3.10** shows the relationship of tack coat tracking for different application rates at approximately 50 minutes after spraying for the two surface types considered**.** **Figure 3.10a** and **Figure 3.10b** also show tack coat tracking of milled and overlay surfaces, respectively, by a visual inspection. Visual inspection (without weighing the tires with a high accuracy scale) can be performed to give an indication of whether or not the tack coat is cured. Less tracking measured by tire weighing or less material on the tires of the wheel device (observed by visual inspection) indicates that the tack coat is approaching the curing time. Milled surfaces tracked significantly more than overlay surfaces both in visual inspection and by tire weighing (**Figure 3.10c** and **Figure 3.10d**). CO1_CSS 1H_a tracked the most on the milled surface, followed by CO1_New_a and CO2_New. “New” engineered emulsions appear to be tracking less than the traditional tack coat materials (**Figure 3.10**).



(a) (b)

(c) (d)

Figure 3.10: Tack coat tracking relationship with application rate (a) visual inspection on milled surface (b) visual inspection on overlay surface (c) measured tracking on milled surface (d) measured tracking on overlay surface

3.5 Summary and Conclusions

The tracking potential of Oregon’s CSS 1H and “New” engineering emulsions from two companies were investigated with regards to curing time and tracking. Curing time was evaluated by performing weight evaporation tests in a laboratory. Data from evaporation tests were used to develop a linear regression model to predict curing times and develop a smartphone application. Tack coat tracking evaluation of selected tack coats was completed by using a wheel tracking device developed in this study. Tests were conducted in the parking lot and field on milled and overlay surfaces. Development of two new technologies (smartphone app and wheel device) is expected to improve construction practices, reduce tracking, and improve the bond strength between pavement layers.

The conclusions and recommendations of this study are:

1. CO1_New illustrated the longest curing time in laboratory experiments, followed by CO1_CSS 1H, CO2_CSS 1, and CO2_New for all testing conditions (temperatures and application rates);
2. Regardless of the texture of the surface (steel plate vs. AC core), increasing the application rate lead to increased curing times.
3. Regression analysis revealed that mean texture depth (MTD) did not have a significant effect on curing time
4. Tack coat tracking, the amount picked up, will decrease over time after application. “New” engineered emulsions in Oregon are tracking less than CSS_1H materials. Their use in the field can help reduce tracking.
5. Milled surfaces exhibit more tracking, due to tack coat accumulating in grooves of texture, when compared to overlay surfaces (almost no tracking). For this study, tracking does not appear to be an issue for overlay surfaces.
6. The wheel tracking device can be effectively used to determine tack coat curing time during construction. Construction traffic and paving should resume only after the tack coat has cured to avoid tracking and moisture damage from evaporation of water within tack coats.

3.6 Future Study

Future studies should measure in-situ tracking by using the wheel device. Tack coat curing time measured by the wheel device should be compared with the smartphone app predictions to validate/calibrate the regression models used to develop the app. Also, the smartphone app should be used alongside the wheel tracking device in the field and the parking lot to see if curing time results for similar environmental conditions are similar.

In this study, of the six tack coat materials used during field testing, only three were used on overlay surface and three on milled surface. For a complete analysis, all tack coat materials should be utilized on both milled and overlay surfaces to determine the effectiveness of the wheel device at measuring tracking. More wheel tracking tests are needed to prove the effectiveness.

3.7 Acknowledgements

This study was supported by the Oregon Department of Transportation (ODOT). The contents of this paper reflect the views of the authors and do not reflect the official views or policies of the State of Oregon or Federal Highway Administration. The authors would like to thank Natasha Anisimova, Shashwath Sreedhar, Blaine Wruck, Sogol Haddadi, Yuqi Zhang, Jeffery Knowles, and Mostafa Estaji for their assistance with field measurements, obtaining core samples, and photography of events. A special thank you to the support of all ODOT coring crew members and all the members of the Technical Advisory Committee (TAC).

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4.0 CHAPTER 4 – CONCLUSION

The performance (ability to reduce tracking and increase ISS) of these emulsions, most effective application rates, the effects of pavement surface texture and traffic on ISS, and curing times were evaluated in this study. In the literature, limited studies were focused on tracking, and none were conducted with tack coats used in Oregon. On the other hand, many studies in the literature have investigated the interlayer shear strength and the various affecting factors, as well as alternative testing methods to determine the ISS.

This study was a comprehensive field investigation consisting of field and laboratory testing, field coring, and construction sampling of tack coats used in Oregon. Within the study, two new tack coat materials from two companies were, for the first time, evaluated for their performance. Field coring was completed at two different time increments, as well as two travel lines (wheel path and center of the lane), to capture the effect of traffic loading on interlayer shear strength (Chapter 2).

Chapter 2 focused on recommendations for the most efficient application rate along with interlayer shear strength (ISS) prediction equations based on rheological properties. Chapter 3 developed a wheel tracking device for use in the field to measure tracking and aid in determining the in-situ curing time of tack coats. The wheel tracking device can be utilized in the field as a visual tool or by collecting weight data via the removable rubber “tires”. Data from weight evaporation tests were used to create a linear regression model to predict in-situ curing times and develop a smartphone app using the created model (Chapter 3). Prediction of in-situ curing times will reduce tracking and improve the current practice.

Development of two new technologies (smartphone app and wheel device), along with recommended prediction equations for ISS, for the state of Oregon, are expected to improve construction practices, reduce tracking, and improve the bond strength between pavement layers.

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