AN ABSTRACT OF THE THESIS OF

Blaine M. Wruck for the degree of Master of Science in Civil Engineering on November 27, 2018.

Title: Improving Interlayer Bond Quality with Engineered Tack Coats under Adverse Construction Conditions: A Laboratory and Field Investigation

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Erdem Coleri

Tack coat emulsion, comprised of asphalt binder, water and emulsifying agents, is an interlayer membrane applied before asphalt pavement construction, which helps pavement layers bond together and permeate stresses and strains induced by heavy wheel loads through the entire thickness of the pavement structure. Proper interlayer bonding aids in preventing localization of stresses and strains at the surface asphalt layer, where premature fatigue cracking can develop causing early pavement failure. In Oregon, CSS-1H tack coats have been used conventionally; however, newly engineered tack coats are purported to improve interlayer bond quality. Proprietary blends of polymer modifiers used in engineered tack coats are used to improve interlayer bond characteristics. Engineered tack coats are often specific to overlay surfaces with low macrotexture or milled pavement surfaces with high surface macrotexture. However, they are not yet widely adopted due to their increased cost.

Pavement construction can inherently produce adverse conditions that can compromise tack coat bond quality and exacerbate failure mechanisms that stem from poor interlayer bonding. These conditions are prevalent in Oregon pavement construction. Milling of existing aged pavements creates high amounts of dust, some of which is retained on the pavement surface after cleaning. Tack coats readily bond to dust particles instead of the pavement layers, resulting in reduced bond quality. Problems with tack coat distributor equipment can create nonuniform tack coat application due to clogged applicator nozzles, often termed “streaking”, effectively reducing the
pavement surface area covered by tack coat. Rainfall during construction can wash away the applied tack coat and reduce the ability of the two asphalt layers to bond together.

In this study, engineered tack coats were evaluated against conventional tack coats under different application rates, pavement surface types (overlay and milled) and in the presence of adverse conditions commonly experienced during Oregon pavement construction. A novel laboratory sample preparation method was developed using a hydraulic laboratory roller compactor and laboratory milling to closely mimic field conditions. Monotonic Direct Shear Testing (DST) was employed for laboratory evaluation of tack coat performance. The Oregon Field Torque Tester (OFTT), developed at Oregon State University, was used to evaluate tack coat bond quality in the laboratory and in the field. Statistical analyses were performed to compare tack coat performance. Comparisons between monotonic DST and OFTT results were also made to identify the suitability of the OFTT for evaluating tack coat bond quality in the field. Field OFTT results were compared to laboratory tests to highlight bond quality issues that exist with pavements in Oregon.

Results showed that engineered tack coats perform better than conventional tack coats in general. Adverse conditions such as dust, nonuniform coverage/streaking and rainfall significantly affected tack coat performance. Comparisons showed that OFTT tests were generally well-correlated with laboratory monotonic DST results, indicating that OFTT testing captures the interlayer bond quality of both engineered and conventional tack coats. Field performance of tack coats as measured by the OFTT were inferior when compared to laboratory results, due to lack of control over extraneous factors during construction. This disparity proves that better control over construction practices needs to be sought in order to obtain proper tack coat bond quality in the field.
Improving Interlayer Bond Quality with Engineered Tack Coats under Adverse Construction Conditions: A Laboratory and Field Investigation

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APPROVED:

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Blaine M. Wruck, Author
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CHAPTER 1 - INTRODUCTION

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

The tack coat bond is known to dictate the longevity of asphalt pavements. Proper interlayer bonding prevents successive pavement layers from acting independently of one another and creating nonuniform stress and strain profiles in the pavement structure (FHWA 2016). Current structural pavement design methodologies assume that the pavement structure behaves monolithically (100% bonding between all pavement layers), which testifies to the importance of proper interlayer bonding using tack coat (FHWA 2016). Poor bonding between pavement layers can result in various pavement failures such as slippage cracking, debonding and early fatigue cracking, all of which contribute to a reduced pavement fatigue life (Al-Qadi et al. 2012b). King and May (2003) purport that a 50% reduction in pavement fatigue life can be expected when tack coat bond strength is reduced by 10%. Debonding is more prone to occur at high temperatures and/or high traffic loads, especially when there are problems with interlayer bonding due to inadequacy of tack coat materials or application rates (Celaya et al. 2010).

A multitude of adverse conditions encountered during construction can govern the quality of the tack coat application and resulting bond strength. Factors such as pavement surface condition, presence of contaminants (dust or moisture), aging, temperature and nonuniform tack coat coverage all have significant bearing on the quality of the resulting tack coat bond and pavement structure. The two principal asphalt resurfacing strategies also bring about different bonding characteristics. Overlays, where a new layer is constructed directly atop a smooth asphalt surface, are constructed on an underlying pavement surface with significantly less macrotexture than an inlay or “mill and fill”, where a new asphalt layer is constructed on a highly-texturized pavement
surface that is left behind after an aged asphalt layer is milled/removed from the pavement structure. A milled surface and overlay surface will exhibit different interlayer shear strength (ISS) characteristics, as milled surfaces tend to facilitate higher interface friction and hence higher ISS (Al-Qadi et al. 2012b). Milled surfaces also tend to require higher application rates due higher surface area because of the increased macrotexture (FHWA 2016).

Various types of tack coat materials exist that cater to different requirements. There are three principal types of tack coat materials that have been commonly used: paving grade asphalt binder, asphalt emulsions and cutback asphalts. Asphalt emulsions are by far the most widely used tack coat material and are employed by several developed countries and most United States paving agencies. Asphalt tack coat emulsions are comprised of asphalt binder and water mixed with emulsifying agents. They are less viscous than paving-grade asphalt binder and can easily be sprayed. They allow contractors to have greater control over factors such as application rate and coverage uniformity (Coleri et al. 2017; FHWA 2016).

Use of tack coats is commonly employed by many states, but its use is dependent on site-specific conditions such as pavement surface condition, environmental conditions and location (Amelian and Kim 2017). Also, since tack coat emulsions require additional time for the water to separate and evaporate from the residual asphalt, they can create a logistical complication during paving operations and cause problems during construction such as “tracking”, where tack coat is picked up by construction vehicle tires. This can directly impact the quality of the tack coat bond by removing the tack coat from the pavement surface that would otherwise be available to facilitate interlayer bonding. Special newly engineered tack coats exist that are purported to reduce set times and also reduce tracking. These tack coats have proprietary blends of stiff binders and/or chemical/polymer modifications which are meant to combat tracking issues and improve bond quality.

Tack coats have historically been investigated in both laboratory and field settings. A notable test that is commonly used to characterize the tack coat interlayer bond in the laboratory is Direct Shear Testing (DST). DST can either be Monotonic, where a load is applied at a constant displacement rate to extract peak strength and energy parameters, or Cyclic, where a repeated load is applied to
the interlayer bond to closely replicate cyclic truck loading experienced by in-service pavements. Monotonic DST is discussed in detail within the first two manuscripts of this document. Additionally, field characterization of tack coat bond quality in-situ can be accomplished by using the Oregon Field Torque Tester (OFTT), which was developed by Coleri et al. (2017). This novel device quantifies the tack coat bond quality of newly constructed pavements and has the ability to extract peak strength and energy parameters, similar to monotonic DST. This device is used extensively in the third manuscript of this document, where correlations between results of OFTT tests and monotonic DST tests are investigated.

The following manuscripts presented in this document investigate engineered tack coats in laboratory and field settings in order to determine their benefits when compared to tack coats traditionally used in Oregon under a variety of conditions. Tack coats from three different companies were evaluated using different testing protocols (Monotonic DST, OFTT testing) under the consideration of factors such as tack coat type (conventional versus engineered), application rate, surface type (overlay and milled) and presence of contaminants/adverse construction conditions. These studies aim to advance the knowledge of engineered tack coat performance and ultimately identify if they are suitable for regular use in Oregon based on comparisons to conventional tack coats. Additionally, their performance under adverse conditions such as presence of dust on the pavement surface, nonuniform tack coat coverage and rainfall is investigated against conventional tack coats used in Oregon. These manuscripts are meant to highlight situations where engineered tack coats are more beneficial than conventional tack coats, with the overarching goal of promoting pavement structures that meet or exceed their structural design lives, thereby promoting sustainability in the asphalt pavement industry by reducing the need for expenditures of funds and natural resources on costly premature maintenance and rehabilitation of pavements in Oregon.
2.0 CHAPTER 2 – THE IMPACT OF EMULSION TYPE, APPLICATION RATE & ADVERSE CONDITIONS ON TACK COAT PERFORMANCE

Blaine Wruck¹, Erdem Coleri² and Shashwath Sreedhar³

Abstract: Tack coats are used in asphalt pavement construction as a bonding agent between new and existing pavement layers, with their primary function being to create a monolithic pavement structure that meets or exceeds its structural design life. Highway construction operations inherently introduce adverse conditions such as varying application rates, contaminants on the pavement surface (dust) and nonuniform coverage (streaking) which directly impact tack coat bond quality. Oregon’s climatic conditions can also create issues late in the construction season due to heavy rainfall. Newly engineered tack coat emulsions have been developed that are purported to improve bonding characteristics at the asphalt pavement interlayer and reduce the propensity of early fatigue cracking and pavement failure to occur. This study evaluates new engineered tack coats from three companies against tack coats conventionally used in Oregon in a laboratory setting to identify their benefits under varying pavement surface types, application rates and adverse construction conditions commonly experienced during highway pavement construction. Monotonic Direct Shear Testing was employed to characterize the tack coat bond using two response parameters, Interlayer Shear Strength (ISS) and Interlayer Bond Energy (IBE). This study serves as an incremental advance in the knowledge of engineered tack coat performance under real-world conditions and also employs a laboratory sample preparation methodology that is more representative of pavement construction in the field.

Keywords: Tack Coat; Emulsion; Polymers; Interlayer Shear Strength; Interlayer Bond Energy; Milled Surface; Overlay Surface; Roller Compactor; Dust; Streaking; Coverage; Rainfall; Construction.

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2.1 INTRODUCTION & LITERATURE REVIEW

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

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

In recent research, there has been a significant disconnect in the relation of laboratory sample preparation processes to real-world construction practices. Some research has attempted to replicate field conditions in laboratory tack coat testing but has been unable to achieve results comparable to field performance. A disparity is present in the shear strength of laboratory-produced samples versus field-extracted core samples in previous studies (Mohammad et al. 2012; Mohammad et al. 2010). In these studies, the Superpave Gyratory Compactor (SGC) was used to procure samples for laboratory tests, which differs significantly from roller-compacted pavements in the field in terms of the compaction mechanism. In general, the laboratory-prepared samples overestimated the shear strength of the tack coat bond at the layer interface by a factor ranging from 2 to 10 for a given application rate. This is due to the difference in compaction methods and tack coat application methods between laboratory-prepared samples and field-cored samples.

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

A variety of laboratory tests exist to quantify the quality of the interlayer bond. Direct shear testing (DST) is a common method of measuring bond strength between pavement layers in a laboratory setting and has been utilized by many researchers. Monotonic DST refers to measurement of peak shear strength and energy of the interlayer bond using a load applied at a constant displacement rate (Amelian and Kim 2017). This test yields several useful parameters that aid in characterizing the tack coat bond. Cyclic DST is a novel method of bond strength measurement and is more representative of loading experienced by the interlayer in the field.
In this study, several types of tack coats which are used in Oregon are evaluated in a laboratory setting under a diverse set of conditions. New engineered tack coats are paired against tack coats that are conventionally used in Oregon in order to identify the benefits of engineered tack coats in light of variables such as pavement surface type (overlay versus milled), application rate and adverse construction conditions such as presence of dust on the pavement surface, nonuniform coverage/streaking and rainfall. A robust experimental factorial encompasses these variables. This study prescribes monotonic DST as a means for evaluating the performance of each tack coat under each of these conditions.

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

From the load-displacement curves obtained for each laboratory shear test, IBE was extracted to characterize the tack coat bond performance. IBE is calculated as the area under the load-displacement curve up to the peak load. IBE takes into account the peak strength of the tack coat bond, as well as the associated displacement endured before bond failure. This parameter has been shown to be highly correlated ($R^2 = 0.8$) with fatigue failure criteria for tack coat interlayer bonds and is highly indicative of the fatigue-related shear resistance of tack coats (Amelian and Kim 2017). Figure 2.1 shows a graphical representation of interlayer bond energy.
An auxiliary component of this study was to examine the performance of tack coats used in Oregon, both conventional and engineered, under special scenarios that emulate real-world construction conditions. In Oregon, there are three prevalent construction issues that plague tack coat performance and pavement longevity, which are termed in this study as adverse construction conditions.

Firstly, the presence of dust on milled surfaces during construction is a significant problem that directly impacts the quality of highway pavements in Oregon. Milling/grinding of existing pavements, where existing aged or fatigued pavement is removed from the pavement structure, is often performed as a precursor to overlay or inlay (“mill and fill”) projects in Oregon. This process creates large amounts of dust and particulate matter resulting from the crushing of aggregates by the diamond cutting heads of milling machines. A considerable amount of dust is left behind on the pavement surface after milling, which is then removed using sweeper trucks after milling occurs (FHWA 2016). However, the sweepers often do not remove all dust particles. Retained dust particles effectively act as a contaminant on the pavement surface, as tack coats applied to a dusty surface will readily stick to high surface area dust particles instead of the underlying pavement, which reduces the tack coat’s ability to bond the new and existing pavement layers (FHWA 2016).
Two principal methods of removing dust from the pavement surface currently exist. As it stands, contractors typically clean the pavement surface using one of two methods: sweeping/vacuuming and air blasting (Al-Qadi et al. 2012). Figure 2.2 shows these two methods being employed in the field during paving operations.

![Figure 2.2. Common field cleaning methods: (a) Sweeping and vacuuming and (b) air blasting (Al-Qadi et al. 2012).](image)

Air blast cleaning was suggested by Salinas et al. (2013) as an effective measure for removing dust from the pavement surface prior to construction. This suggestion was based on results from a field study that compared the pavement surface cleanliness of sweeping and air blasting against the effect on tack coat bond strength and required application rate. However, although this study suggests that air blasting can improve bond performance at lower residual application rates (below 0.04 gal/yd² for a SS-1H tack coat), it is also time-consuming and can cause health and safety hazards in urban environments due to dust particulate clouds. Air blasting also resulted in inferior bond performance when compared to sweeping at higher application rates.

The effect of surface cleanliness on bond performance was evaluated by Mohammad et al. (2012). The authors used uniformly graded sand to simulate dust on the pavement surface and found that ISS was enhanced by the presence of dust. This result was attributed to the effect of dust combining with residual asphalt and creating a mastic with a viscosity exceeding that of the residual asphalt alone, which provided greater shear resistance. This, combined with grittiness of sand particles providing extra frictional resistance, yielded a higher ISS. However, due to the use of a uniformly graded sand to simulate dust effects, actual field conditions may not be represented by these results. In any case, the authors suggested that cleaning and sweeping of the pavement surface prior to construction is worthwhile to avoid any problems related to the presence of dust.
Additionally, the effect of dust on the pavement surface can contribute to increased tracking of tack coats during construction, whereby tack coat sticks to construction vehicle tires and is removed from the underlying pavement surface to which it is applied. This phenomenon effectively reduces the amount of tack coat on the pavement surface that is available for interlayer bonding. Tracking is exacerbated by dust particles on the pavement surface, since vehicle tires will pick up tack coats stuck to dust particles much more readily than if the tack coat was properly adhered to the underlying pavement surface (Mohammad et al. 2012). The tracked debris accumulates and falls off construction vehicle tires, creating inconsistencies and additional debris on the milled pavement surface prior to paving. Since the issue of dust is highly prevalent in Oregon, this study evaluates the impact of dust on interlayer bond quality. Figure 2.3 shows an example of tracking by a paver during construction due to excess dust on the pavement surface.

Figure 2.3. Tracking on paver wheels due to excess dust (Mohammad et al. 2012).

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

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

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

A lack of adequate tack coat coverage can have direct implications on the quality of the tack coat bond. Mohammad and Button (2005) note that the maximum bond strength between layers occurred when 90-95% coverage was achieved at the optimum application rate. Mohammad et al. (2012) found that when tack coat coverage was reduced to 50% of the subject area, the interface shear strength (ISS) at the tack coat bond was reduced between 50% to 70%. Coverage is an important consideration for quality assurance (QA) since it is the most visually apparent factor for monitoring tack coat quality during construction. Visual acceptance of coverage is the primary means for tack coat quality assurance during construction in Oregon. Coverage that is nonuniform can give rise to high variability in interlayer bonding characteristics. According to FHWA (2016), it is important that application of tack coat materials is uniform in all directions (transverse and longitudinal). In light of the ramifications of nonuniform tack coat coverage/streaking, it was of specific interest in this study to evaluate this phenomenon in the laboratory. Figure 2.4 shows acceptable and unacceptable uniformity in tack coat application.
Finally, the effect of rainfall on tack coat bond quality was investigated in this study. This is an issue during highway construction in Oregon during the spring and fall months when rainfall is common. Water on the pavement surface during construction can be caused by rainy weather or tack coats that have not had sufficient time to set. Excess moisture on the pavement surface after tack coat application can complicate paving operations temporally by impacting the break and set times of applied tack coat emulsions. More importantly, the applied tack coat can be washed away from the pavement surface by a rainfall event due to the flow of runoff on the roadway profile slope, effectively removing tack coat that would otherwise be available to facilitate interlayer bonding. Some research suggests that if moisture remains on the existing pavement surface as paving occurs that bond quality could be reduced (Wang et al. 2017; Sholar et al. 2004). Other research suggests that moisture on the pavement surface does not impact bond quality, as excess moisture is readily evaporated during HMA placement (Mohammad et al. 2012). However, the question of a significant rainfall event’s impact on tack coat bond quality is largely unanswered. In this study, a rainfall event occurring after tack coat application was replicated in the laboratory on a milled surface texture and the resulting bond quality was quantified and compared to results with no rainfall.

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

2.1.1 Objectives

The major outcomes of this study are as follows:

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

2.2 MATERIALS AND METHODS

2.2.1 Experimental Design

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

In order to evaluate the performance of each tack coat, a comprehensive experimental factorial was designed, which took into account different tack coat types from three different companies, two application rates and two pavement surface textures (overlay and milled surface textures). Table 2.1 shows the experimental design for this study. Under tack coat type, “O” designates tack coats designed specifically for overlay surfaces and “M” designates tack coats designed for milled surfaces.

**Table 2.1. Experimental design for tack coat type & application rate tests.**

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

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

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

It should be noted that not all companies provided the same tack coats for laboratory shear testing. Company 1 and Company 2 provided engineered tack coats that were specific to milled surfaces. Company 1 also provided an engineered tack coat that was designated for use on overlay surfaces. Company 3 provided an engineered tack coat designed for use on both overlay and milled surfaces. Additionally, Company 3 requested that the residual rates of Company 1 be matched. The residual rate for Company 1’s CSS-1H tack coat was used for Company 3’s CSS-1 tack coat. Residual rates for Company 1 tack coats were back-calculated using the water content of the emulsion and Equation (2.1) shown below. Average water contents and densities of the tack coat emulsions were measured in this study and are shown in Table 2.2.

Residual Rate = Application Rate * (1 – Water Content)  \hspace{1cm} (2.1)

### Table 2.2. Summary of tack coat emulsion water contents and densities

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

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

To examine the impact of adverse conditions (dust, streaking/reduced coverage, rainfall/moisture), a separate experimental factorial was developed. Results from the experimental factorial proposed in Table 2.1 were used as reference (control) cases for testing each of these adverse conditions.
Table 2.3 below shows the experimental plan for evaluating the adverse construction conditions cases outlined previously.

**Table 2.3. Experimental design for adverse conditions evaluation.**

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Tack Type</th>
<th>Company</th>
<th>Application Rate</th>
<th>Surface Type</th>
<th>Dust Level</th>
<th>Coverage Level</th>
<th>Rainfall</th>
<th>Replicates</th>
<th>Total Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage/</td>
<td>CSS1H,</td>
<td>CO1</td>
<td>1Low, High</td>
<td>Milled</td>
<td>None</td>
<td>100%, 50%</td>
<td>None</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>Streaking</td>
<td>ENGR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust</td>
<td>CSS1H,</td>
<td>CO1</td>
<td>Low, High</td>
<td>Milled</td>
<td>None, 15g Dust</td>
<td>100%</td>
<td>None</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>ENGR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall</td>
<td>CSS1H,</td>
<td>CO1</td>
<td>Low, High</td>
<td>Milled</td>
<td>None</td>
<td>100%</td>
<td>None, 2hr</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>ENGR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: 1 Low rate: 0.09 gal/yd²; High rate: 0.15 gal/yd²

For this portion of the study, tack coats from Company 1 were chosen to evaluate each of the cases described above. Both conventional and engineered tack coats were used to evaluate the effect of nonuniform coverage/streaking, presence of dust and rainfall to identify any advantages that engineered tack coats had over conventional tack coats in the adverse conditions of interest. Low/high application rates for adverse conditions tests were the same as those used in Table 2.1. Sample preparation methodology for adverse construction conditions cases is shown in Chapter 2.2.3.

In order to replicate field conditions, this study employed a hydraulic laboratory roller compactor to create two-layer (two-lift) pavement structures in the laboratory. In this way, nuances of roller compaction in the field could be better represented in the resulting cylindrical core samples than is possible using a Superpave Gyratory Compactor (SGC). A research study by Mohammad et al. (2012) revealed that the bond strength of two layered asphalt specimens prepared with SGC can be artificially amplified by 2 to 10 times when compared to field-extracted cores. In this study, asphalt samples for shear testing prepared by a laboratory roller compactor was determined to provide interlayer shear strength (ISS) results that are better correlated with field core samples as compared to SGC-prepared samples. Furthermore, the equipment cost for the roller compactor was slightly lower than the SGC, offering another reason why the roller compactor was a more practical choice for sample preparation.
This study focused on monotonic direct shear testing (DST) for evaluation of new engineered tack coats against tack coats conventionally used in Oregon. Milling of laboratory-produced samples was performed in order to closely replicate the actual texture of milled surfaces in the field. Milling texture was quantified using the Sand Patch Test (ASTM 2015a).

2.2.2 Laboratory Shear Test Sample Preparation

This section details the sample preparation and shear test procedure for producing and testing two-layer asphalt core samples. Figure 2.5 shows photos of the sample preparation and shear testing processes. Each step is described in detail below.
Figure 2.5. General sample preparation process for laboratory-produced shear test samples.

2.2.2.1 Asphalt Sampling and Preparation

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

Prior to compaction, the production mix pails were heated in the oven at 110 °C (230 °F) for four hours and put through a mechanical splitter in order to obtain uniform sampling of the mixture. Figure 2.5a shows mechanical splitting of the production mixture.
The theoretical maximum specific gravity ($G_{mm}$) of the mixture was measured in the lab using a CoreLok device according to AASHTO T 209 (AASHTO 2012). Three replicate $G_{mm}$ measurements (2.520, 2.494, and 2.515) were taken and the average (2.510) was used as the asphalt mixture $G_{mm}$. Required amounts for first and second lift compactions were then weighed out based on the measured average $G_{mm}$ of the mixture and the selected 7% air void content. The 7% air void content was chosen since it is commonly specified during construction in Oregon. Weighed amounts were split equally into two pans to facilitate homogeneous heating of the mixture to compaction temperature.

### 2.2.2.2 First Lift Compaction of Block Samples

Pavement structures consisting of two lifts (layers) were compacted in custom 260 mm x 400 mm x 100 mm (10.2 in x 15.7 in x 3.93 in) compaction molds. A custom spacer 50.8 mm (2.0 in) in height was used in the mold to compact the first lift. Figure 2.5b shows the custom mold with spacer.

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

Parchment paper was placed between the roller surface and the asphalt mixture to avoid any contamination of the first lift asphalt surface with grease or oils that may have been present on the roller surface. Mold dimensions were input to the roller compactor. A target number of passes was selected to facilitate full compaction of the mixture to the target air void content. The compaction was performed by applying pressure to the asphalt using an adjustable dial on the roller compactor until the sample was compacted to the specified height. Figure 2.5c shows compaction taking place using the laboratory roller compactor.
Once compacted, the mold was removed from the roller compactor and allowed to cool until the internal temperature of the sample fell below the softening point of the asphalt binder used in the mixture. This was done to ensure that the sample would not unravel when removed from the mold. Before removing the sample from the mold, a rubber wheel was rolled across the entire area of the first lift surface eight times to remove any fresh asphalt from the pavement surface. This simulated traffic on the pavement surface between lifts, as is commonly seen in the field. The choice of the target number of passes with the rubber-tire roller wheel was developed out of trial and error and visual comparison of surface tackiness to field conditions. This step was particularly important for tack coats applied to an overlay surface, since additional residual asphalt could amplify bond strength. Figure 2.5d shows the rubber wheel being applied to the first lift samples. The mold was disassembled after the sample had cooled sufficiently (below 40 °C (104 °F)). Completed samples were placed aside for milling (when appropriate) and tack coat application.

2.2.2.3 Milling of First Lift Block Samples

Milling was performed on first lift samples accordingly. Milling was only performed on those samples which were intended for milled surface tests. A milled surface texture with a mean texture depth (MTD) of 0.07 in - 0.09 in (1.78 mm - 2.29 mm) was targeted in order to closely replicate actual milled surface textures in the field (Coleri et al. 2017). Milling was performed using a 4.5 in (114.3 mm) angle grinder with a concrete cutting wheel. The grinder was held at a 45° angle to produce straight grooves on the samples, similar to the pattern of milled surfaces in the field. Figure 2.5e shows milling taking place on first lift samples. Figure 2.6 below shows a comparison of laboratory milled surface samples to an actual milled surface in the field.
After milling, the sample was cleaned with a coarse wire brush to simulate sweeping in the field. Sand patch testing, according to ASTM E965 (ASTM 2015a), was performed after milling in order to quantify the MTD of each sample. Although milling of the samples increased the volume of the second lift in the compaction mold, no adjustments were made to the amount of HMA in the second lift. It was assumed that a similar phenomenon would result in the field as a result of milling.

2.2.2.4 Tack Coat Application and Second Lift Compaction of Block Samples

Before tack coat application, duct tape was placed around the perimeter of the first lift sample to avoid dripping of tack coat which would cause the first lift sample to stick in the mold (Al-Qadi et al. 2008). Tack coats sampled from the manufacturer were agitated for five minutes prior to tack coat application to facilitate homogeneous mixing of the water, residual asphalt and emulsifying agents. Densities of each tack coat were measured using a 100-mL graduated cylinder and a high-accuracy scale. Three replicate densities were obtained for each tack coat. Average densities for each tack coat can be found in Table 2.2.

The required amount of tack coat by weight was then calculated based on the densities of the tack coats, target application rates and the known sample area. Application rates chosen for this study were for undiluted tack coat solution and were not residual application rates. Tack coats were then applied to the first lift block samples using a foam art roller. Using a high-accuracy scale, the
amount of tack coat applied to each sample was carefully tracked until the required amount had been applied to achieve the target application rate. Figure 2.5f shows a tack coat being applied to a first lift block sample. Tack coat application for overlay surface samples followed the same process as for milled surface samples.

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

2.2.2.5 Coring of Block Samples

Completed two-lift block samples were allowed to rest at room temperature for two weeks prior to coring. The direction of traffic was marked on each block sample prior to coring to allow for consistency in shear testing (ALDOT 2008). Block samples were cored on a stationary core drill using a six-inch (152.4 mm) core drill bit. In order to fit the blocks into the core drill jig, the block samples were cut in half along the midpoint of the sample. Six-inch cores were then taken from the block samples using the core drill. Core samples were then allowed to dry at room temperature for at least three days prior to testing. Figure 2.5g shows coring taking place on a block sample.

2.2.3 Sample Preparation for Adverse Conditions Cases

This section outlines the special steps taken during the sample preparation stage for each of the adverse conditions cases evaluated in this study. First/second lift compaction and coring processes remained the same for these samples as they were described in Section 2.2.2.

2.2.3.1 Dust Sample Preparation

Dust is a problematic byproduct of milling during pavement construction and is therefore of specific interest in this study. In order to realistically simulate a dusty pavement surface, dust was
collected and reserved from laboratory milling operations in order to capture a dust type that was representative of what is seen under field conditions. The reserved dust was sieved and the portion passing the #200 sieve was used for dust simulation. A 15g quantity of dust was chosen to apply to the milled pavement surface samples. The choice to use 15g of dust was borne out of trial and error and visual comparison to field conditions. Dust was spread around the pavement surface uniformly using a dry paint brush. Figure 2.7 shows dust being applied to milled surface samples. Tack coats were then applied atop of the dust using the same procedures outlined in Section 2.2.2.4.

![Figure 2.7. Dust being applied to pavement surface.](image)

### 2.2.3.2 Streaking Sample Preparation

Streaking reduces the effective pavement surface area that is coated with tack coat, thereby reducing the propensity for proper interlayer bonding from tack coat. In this study, streaking was simulated in the laboratory during tack coat application. A condiment bottle was used to apply tack coat in streak-like patterns to mimic clogged tack coat applicator nozzles in the field. Figure 2.8 below shows tack coat application using the condiment bottle for streaking samples. For streaking samples, the amount of tack coat applied was the same as was used for samples with standard tack coat application (full coverage). Since a clogged nozzle should not impact the
volumetric flow rate of the tack coat, it was assumed that the amount of tack coat applied to the surface would be the same under streaking conditions.

![Image](image1.png)

Figure 2.8. Application of tack coat using condiment bottle for coverage/streaking samples.

2.2.3.3 Rainfall/Moisture Sample Preparation

Because rainfall is prevalent at the beginning and end of the construction season in Oregon, it was of interest in this study to identify how rainfall on the pavement surface after tack coat application would impact tack coat bond quality of the finished pavement. To investigate this effect, first lift samples were placed in a rainfall simulator five minutes after tack coat was applied to the pavement surface. Rainfall simulation was allowed to run for 2hrs prior to compaction at a rainfall intensity similar to what is observed in the Portland, Oregon climate (0.48 in/hr). A 2hr rainfall duration was selected in order to replicate a rainfall event duration that would commonly be observed in this region late in the construction season during the fall months. The rainfall intensity in the simulator was measured and adjusted to match the intensity of a 25-year precipitation event in Portland, OR for the selected rainfall duration by adjusting the pump system of the rainfall simulator (ODOT 2014). The 25-year rainfall intensity was selected to simulate an extreme rainfall event in order to highlight the impact of rainfall on tack coat bond quality in a severe circumstance. Also, the rainfall simulator platform was oriented at a 2% slope to simulate a common roadway profile slope which would facilitate the action of rainfall runoff. After rainfall ensued, the sample was removed from the rainfall simulator and compaction took place immediately. Figure 2.9 shows first lift samples being conditioned in the rainfall simulator after tack coat application.
2.2.4 Laboratory Shear Testing

Before testing, the diameter of each sample was measured and recorded for the purpose of calculating interlayer shear strength (ISS). The location of the interlayer was then marked on each sample using a permanent marker. Samples were then conditioned at 25 °C (77 °F) for 24 hours in an environmental chamber. On the day of testing, each sample was loaded into the testing jig with the direction of traffic positioned downward and the wearing course positioned on the shearing side (ALDOT 2008). Figure 2.10 shows the sample loading configuration for shear testing.
Confining pressure was applied to the sample using the spring actuator and calibrated dial on the testing jig. The sample was then placed back in the environmental chamber for one hour prior to testing to allow the sample’s temperature to re-equilibrate to 25 °C (77 °F). Figure 2.5h shows the shear test jig used for testing.

Shear tests were then performed using a Universal Testing Machine (UTM) at a strain-controlled constant displacement rate of 2.54 mm/min (0.1 in/min) according to AASHTO TP 114 (AASHTO 2016). The peak load, as well as the load-displacement curve, were captured and recorded for each sample. Tests were terminated before the loading plate made contact with the bottom of the jig to avoid damaging the jig or the UTM. Following completion of the test, the sheared sample was removed and another sample was loaded, following the same procedures described above. Figure 2.5i shows shear testing taking place in the UTM environmental chamber.

2.3 RESULTS

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

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

2.3.1 Company-wise Comparisons of ISS & IBE

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

2.3.1.1 Tack Coats Applied to an Overlay Surface

Figure 2.11 shows the ISS and IBE response for all tack coats applied to overlay surfaces at two application rates (low rate of 0.05 gal/yd² and high rate of 0.09 gal/yd²). Error bars indicate ± 1 standard deviation. The “-O” designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to an overlay surface, and does not depict the intended design surface type of these tack coats. The “-O1” and “-O2” designations on CO2 tack coats indicate the two different engineered tack coats for overlay surfaces.
Figure 2.11. Overlay surface tack coat response for (a) ISS and (b) IBE at two application rates with error bars indicating ±1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N-m = 8.85 in-lbs).

From Figure 2.11 above, it is readily apparent that engineered tack coats are performing markedly better than conventional tack coats on overlay surfaces. The performance of the CO1-ENGR-O is
noticeably better than the CO1-CSS1H tack coat. It is also clear that the CO3-ENGR-O tack coat showed the best performance for the overlay surface. CO2-ENGR-O2 exhibited slightly better IBE performance than CO2-ENGR-O1, and was also nearly equivalent to CO1-ENGR-O in terms of ISS and IBE. A peculiar ISS result is exhibited with CO1-ENGR-O1; the high application rate performed worse than the low application rate. This trend is not consistent with what is seen in the IBE results, suggesting that IBE may be a better indicator of bond quality than ISS. Most tack coats tended toward improved ISS/IBE at a higher application rate, except the ISS response of CO2-ENGR-O1 and the IBE response for CO1-CSS1H-O, where the high application rate slightly diminished the result. This observation lends itself to the conclusion that the low rate (0.05 gal/yd$^2$), although within the range of specifications for construction in Oregon (ODOT 2015), is not adequate and should be increased. The optimum application rates for most tack coats in this study are likely much higher than the low rate (0.05 gal/yd$^2$) selected for use in this study. Optimum application rates should be sought for each of the tack coat types tested in this study. Further research is needed to determine optimum application rates for each tack coat.

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

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

$$H_0: F_1(x) = F_2(x)$$
$$H_A: F_1(x) \neq F_2(x)$$

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

- Reject $H_0$ if $p < 0.05$
- Fail to reject $H_0$ if $p \geq 0.05$

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

Table 2.4 and Table 2.5 below show correlation matrices for the ISS and IBE of all tack coats tested on an overlay surface at a low application rate (0.05 gal/yd$^2$). The “-O” designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to an overlay surface, and does not depict the intended design surface type of these tack coats. A p-value of less than 0.05 indicates a significant difference between the two tack coats under comparison.
Table 2.4. Correlation matrix for ISS of all overlay surface tack coats at a low application rate.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-O-Low</th>
<th>CO1-ENGR-O-Low</th>
<th>CO2-ENGR-O1-Low</th>
<th>CO2-ENGR-O2-Low</th>
<th>CO3-CSS1-O-Low</th>
<th>CO3-CSS1H-O-Low</th>
<th>CO3-ENGR-O-Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-O-Low</td>
<td>1.000</td>
<td>0.6667</td>
<td>0.0683</td>
<td>0.3869</td>
<td>0.0222</td>
<td>0.3868</td>
<td>0.0023</td>
</tr>
<tr>
<td>CO1-ENGR-O-Low</td>
<td>0.6667</td>
<td>1.000</td>
<td>0.1263</td>
<td>0.7724</td>
<td>0.0116</td>
<td>0.3002</td>
<td>0.0118</td>
</tr>
<tr>
<td>CO2-ENGR-O1-Low</td>
<td>0.0683</td>
<td>0.1263</td>
<td>1.000</td>
<td>0.1538</td>
<td>0.0031</td>
<td>0.0528</td>
<td>0.2564</td>
</tr>
<tr>
<td>CO2-ENGR-O2-Low</td>
<td>0.3869</td>
<td>0.7724</td>
<td>0.1538</td>
<td>1.000</td>
<td>0.0102</td>
<td>0.2220</td>
<td>0.0064</td>
</tr>
<tr>
<td>CO3-CSS1-O-Low</td>
<td>0.0222</td>
<td>0.0116</td>
<td>0.0031</td>
<td>0.0102</td>
<td>1.000</td>
<td>0.1055</td>
<td>0.0045</td>
</tr>
<tr>
<td>CO3-CSS1H-O-Low</td>
<td>0.3868</td>
<td>0.3002</td>
<td>0.0528</td>
<td>0.2220</td>
<td>0.1055</td>
<td>1.000</td>
<td>0.0211</td>
</tr>
<tr>
<td>CO3-ENGR-O-Low</td>
<td>0.0023</td>
<td>0.0118</td>
<td>0.2564</td>
<td>0.0064</td>
<td>0.0045</td>
<td>0.0211</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 2.5. Correlation matrix for IBE of all overlay surface tack coats at a low application rate.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-O-Low</th>
<th>CO1-ENGR-O-Low</th>
<th>CO2-ENGR-O1-Low</th>
<th>CO2-ENGR-O2-Low</th>
<th>CO3-CSS1-O-Low</th>
<th>CO3-CSS1H-O-Low</th>
<th>CO3-ENGR-O-Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-O-Low</td>
<td>1.000</td>
<td>0.1806</td>
<td>0.1654</td>
<td>0.1366</td>
<td>0.0251</td>
<td>0.8512</td>
<td>0.0207</td>
</tr>
<tr>
<td>CO1-ENGR-O-Low</td>
<td>0.1806</td>
<td>1.000</td>
<td>0.8065</td>
<td>0.9189</td>
<td>0.0044</td>
<td>0.1939</td>
<td>0.1060</td>
</tr>
<tr>
<td>CO2-ENGR-O1-Low</td>
<td>0.1654</td>
<td>0.8065</td>
<td>1.000</td>
<td>0.7953</td>
<td>0.0031</td>
<td>0.2158</td>
<td>0.0739</td>
</tr>
<tr>
<td>CO2-ENGR-O2-Low</td>
<td>0.1366</td>
<td>0.9189</td>
<td>0.7953</td>
<td>1.000</td>
<td>0.0033</td>
<td>0.1927</td>
<td>0.0840</td>
</tr>
<tr>
<td>CO3-CSS1-O-Low</td>
<td>0.0251</td>
<td>0.0044</td>
<td>0.0031</td>
<td>0.0033</td>
<td>1.000</td>
<td>0.0836</td>
<td>0.0027</td>
</tr>
<tr>
<td>CO3-CSS1H-O-Low</td>
<td>0.8512</td>
<td>0.1939</td>
<td>0.2158</td>
<td>0.1927</td>
<td>0.0836</td>
<td>1.000</td>
<td>0.0274</td>
</tr>
<tr>
<td>CO3-ENGR-O-Low</td>
<td>0.0207</td>
<td>0.1060</td>
<td>0.0739</td>
<td>0.0840</td>
<td>0.0027</td>
<td>0.0274</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The correlation matrix above yields some interesting conclusions about the performance of each overlay tack coat at a low application rate. It is notable that in Table 2.4, CO3-ENGR-O had significantly better ISS performance than all tack coats (p-value less than 0.05), other than CO2-ENGR-O1, at a 95% confidence level. Interestingly enough, CO1-ENGR-O did not exceed the
performance of CO1-CSS1H-O based on the p-value of 0.6667 for ISS (Table 2.4) and 0.1806 for IBE (Table 2.5) at 95% confidence. Also, CO1-CSS1H-O had equivalent performance to CO2-ENGR-O2 in terms of both ISS and IBE based on the high p-values shown in Table 2.4 and Table 2.5 at a 95% confidence level, which is consistent with the observation made in Figure 2.11. CO2 engineered tack coats were also not significantly different from each other at a 95% confidence level. Additionally, it can be said with 95% confidence that CO3-CSS1-O had inferior ISS and IBE performance when compared to all other tack coats other than CO3-CSS1H-O, based on p-values shown in Table 2.4 and Table 2.5. From the correlations presented in Table 2.4 and Table 2.5 above, it was discerned that engineered tack coats do not significantly improve interlayer bond performance on overlay surfaces, although at face value they appeared to improve ISS and IBE (Figure 2.11).

Table 2.6 and Table 2.7 below show correlation matrices for the ISS and IBE of all tack coats tested on an overlay surface at a high application rate (0.09 gal/yd²). The “-O” designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to an overlay surface, and does not depict the intended design surface type of these tack coats. A p-value of less than 0.05 indicates a significant difference between the two tack coats under comparison.
Table 2.6. Correlation matrix for ISS of all overlay surface tack coats at a high application rate.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-O-High</th>
<th>CO1-ENGR-O-High</th>
<th>CO2-ENGR-O1-High</th>
<th>CO2-ENGR-O2-High</th>
<th>CO3-CSS1-O-High</th>
<th>CO3-CSS1H-O-High</th>
<th>CO3-ENGR-O-High</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-O-High</td>
<td>1.000</td>
<td>0.1913</td>
<td><strong>0.5547</strong></td>
<td>0.1581</td>
<td>0.0625</td>
<td>0.3321</td>
<td>0.0966</td>
</tr>
<tr>
<td>CO1-ENGR-O-High</td>
<td>0.1913</td>
<td><strong>1.000</strong></td>
<td>0.0589</td>
<td><strong>0.8470</strong></td>
<td><strong>0.0015</strong></td>
<td>0.0119</td>
<td>0.4525</td>
</tr>
<tr>
<td>CO2-ENGR-O1-High</td>
<td>0.5547</td>
<td>0.0589</td>
<td><strong>1.000</strong></td>
<td>0.0507</td>
<td>0.0825</td>
<td><strong>0.6649</strong></td>
<td>0.0355</td>
</tr>
<tr>
<td>CO2-ENGR-O2-High</td>
<td>0.1581</td>
<td>0.8470</td>
<td>0.0507</td>
<td><strong>1.000</strong></td>
<td><strong>0.0019</strong></td>
<td>0.0107</td>
<td>0.5336</td>
</tr>
<tr>
<td>CO3-CSS1-O-High</td>
<td>0.0625</td>
<td>0.0015</td>
<td>0.0825</td>
<td>0.0019</td>
<td><strong>1.000</strong></td>
<td><strong>0.0402</strong></td>
<td><strong>0.0052</strong></td>
</tr>
<tr>
<td>CO3-CSS1H-O-High</td>
<td>0.3321</td>
<td>0.0119</td>
<td>0.6649</td>
<td>0.0107</td>
<td>0.0402</td>
<td><strong>1.000</strong></td>
<td><strong>0.0180</strong></td>
</tr>
<tr>
<td>CO3-ENGR-O-High</td>
<td>0.0966</td>
<td>0.4525</td>
<td>0.0355</td>
<td>0.5336</td>
<td>0.0052</td>
<td>0.0180</td>
<td><strong>1.000</strong></td>
</tr>
</tbody>
</table>

Table 2.7. Correlation matrix for IBE of all overlay surface tack coats at a high application rate.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-O-High</th>
<th>CO1-ENGR-O-High</th>
<th>CO2-ENGR-O1-High</th>
<th>CO2-ENGR-O2-High</th>
<th>CO3-CSS1-O-High</th>
<th>CO3-CSS1H-O-High</th>
<th>CO3-ENGR-O-High</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-O-High</td>
<td>1.000</td>
<td><strong>0.0159</strong></td>
<td>0.0504</td>
<td><strong>0.0212</strong></td>
<td>0.1947</td>
<td>0.0777</td>
<td><strong>0.0052</strong></td>
</tr>
<tr>
<td>CO1-ENGR-O-High</td>
<td>0.0159</td>
<td><strong>1.000</strong></td>
<td><strong>0.0272</strong></td>
<td><strong>0.9693</strong></td>
<td>0.0001</td>
<td><strong>0.0132</strong></td>
<td>0.1445</td>
</tr>
<tr>
<td>CO2-ENGR-O1-High</td>
<td>0.0504</td>
<td>0.0272</td>
<td><strong>1.000</strong></td>
<td>0.1741</td>
<td>0.0008</td>
<td><strong>0.5761</strong></td>
<td><strong>0.0310</strong></td>
</tr>
<tr>
<td>CO2-ENGR-O2-High</td>
<td>0.0212</td>
<td>0.9693</td>
<td>0.1741</td>
<td><strong>1.000</strong></td>
<td>0.0132</td>
<td>0.1170</td>
<td>0.1775</td>
</tr>
<tr>
<td>CO3-CSS1-O-High</td>
<td>0.1947</td>
<td>0.0001</td>
<td>0.0008</td>
<td>0.0132</td>
<td><strong>1.000</strong></td>
<td><strong>0.0013</strong></td>
<td><strong>0.0038</strong></td>
</tr>
<tr>
<td>CO3-CSS1H-O-High</td>
<td>0.0777</td>
<td>0.0132</td>
<td>0.5761</td>
<td>0.1170</td>
<td>0.0013</td>
<td><strong>1.000</strong></td>
<td><strong>0.0230</strong></td>
</tr>
<tr>
<td>CO3-ENGR-O-High</td>
<td>0.0052</td>
<td>0.1445</td>
<td>0.0310</td>
<td>0.1775</td>
<td>0.0038</td>
<td>0.0230</td>
<td><strong>1.000</strong></td>
</tr>
</tbody>
</table>

In Table 2.6 and Table 2.7 above, it is evident that engineered tack coats generally demonstrated improved performance over conventional tack coats at a high application rate on overlay surfaces. Notably, CO1-ENGR-O and CO3-ENGR-O tack coats improved bond quality over conventional tack coats when IBE was used as the response parameter. These statistically significant differences
are highlighted by the p-values of less than 0.05 in Table 2.7 at a 95% confidence level. Additionally, the above tables show that CO2-ENGR-O1 produced bond quality that was essentially the same as CSS-1H tack coats provided by Company 1 and Company 3, based on the high p-values for both ISS and IBE at the 95% confidence level. CO1-ENGR-O and CO2-ENGR-O2 were noted to have equivalent performance as well, with p-values of 0.8470 for ISS and 0.9693 for IBE at the 95% confidence level. This result confirms observations made in Table 2.4, Table 2.5 and Figure 2.11.

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

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

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

2.3.1.2 Tack Coats Applied to a Milled Surface

Figure 2.12 shows the ISS and IBE response for all tack coats tested applied to milled surfaces at two application rates (low rate of 0.09 gal/yd² and high rate of 0.15 gal/yd²). The “-M” designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of these tack coats. Error bars indicate ± 1 standard deviation.
Figure 2.12. Milled surface tack coat response for (a) ISS and (b) IBE at two application rates with error bars indicating ±1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N·m = 8.85 in-lbs).

As can be seen in Figure 2.12, CO2-ENGR-M1 did not have performance that was congruent with the other two companies’ engineered tack coats. This tack coat yielded ISS/IBE results that were
within the range of conventional tack coats (CSS-1 and CSS-1H) provided by other companies. This contradicts the expected result, as milled surfaces typically exhibit better bond quality due to aggregate interlock of the new pavement layer with the coarse milled surface texture (Coleri et al. 2017; FHWA 2016; Mohammad et al. 2010). This result is attributed to the tack coat’s low residual asphalt content. This tack coat was observed to have a very high water content in comparison to other engineered tack coats, which translates into a low amount of residual asphalt binder that is available to facilitate interlayer bonding once the tack coat sets. Additionally, it was noted during sample preparation that the CO2-ENGR-M1 tack coat permeated through the voids of the first lift samples during tack coat application, causing some of the tack coat to soak through to the bottom of the sample instead of being retained on the pavement surface. This may have reduced the effective amount of residual asphalt available for bonding at the interlayer, since some of the residual asphalt soaked through the voids of the underlying asphalt layer. This phenomenon is likely due to the high water content of this tack coat. The tack coat flowed much more readily through the voids of the first lift samples since it had a lower viscosity than other tack coats used on milled surfaces.

From Figure 2.12 above, a clear advantage is exhibited for engineered tack coats from Company 1 and Company 3, in terms of both ISS and IBE. It is also clear to see in Figure 2.11 and Figure 2.12 that the CO3 engineered tack coat had superior performance as compared to conventional CSS-1 and CSS-1H tack coats, both in terms of ISS and IBE. The CSS-1 tack coat did not achieve the performance of the CSS-1H or engineered tack coats. CSS-1H tack coats also exhibited similar performance on both milled and overlay surfaces, whereas the engineered tack coats tended towards slightly higher ISS/IBE on milled surfaces.

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

Table 2.8 and Table 2.9 below show correlation matrices for the ISS and IBE of all tack coats tested on milled surfaces at a low application rate (0.09 gal/yd\(^2\)). The “-M” designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of these tack coats. A p-value of less than 0.05 indicates a significant difference between the two tack coats under comparison. The decision rule for significance was the same as was used for comparisons for overlay tack coats.

### Table 2.8. Correlation matrix for ISS of all milled surface tack coats at a low application rate.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-M-Low</th>
<th>CO1-ENG-R-M-Low</th>
<th>CO2-ENG-R-M-Low</th>
<th>CO3-CSS1-M-Low</th>
<th>CO3-CSS1H-M-Low</th>
<th>CO3-ENG-R-M-Low</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO1-CSS1H-M-Low</strong></td>
<td>1.000</td>
<td>0.0393</td>
<td>0.2517</td>
<td>0.0455</td>
<td>0.0278</td>
<td>0.0230</td>
</tr>
<tr>
<td><strong>CO1-ENG-R-M-Low</strong></td>
<td>0.0393</td>
<td>1.000</td>
<td>0.0386</td>
<td>0.0038</td>
<td><strong>0.0066</strong></td>
<td>0.1704</td>
</tr>
<tr>
<td><strong>CO2-ENG-R-M1-Low</strong></td>
<td>0.2517</td>
<td>0.0386</td>
<td>1.000</td>
<td><strong>0.9344</strong></td>
<td>0.8217</td>
<td>0.0106</td>
</tr>
<tr>
<td><strong>CO3-CSS1-M-Low</strong></td>
<td>0.0455</td>
<td>0.0038</td>
<td>0.9344</td>
<td>1.000</td>
<td>0.7507</td>
<td>0.0043</td>
</tr>
<tr>
<td><strong>CO3-CSS1H-M-Low</strong></td>
<td>0.0278</td>
<td>0.0066</td>
<td>0.8217</td>
<td>0.7507</td>
<td>1.000</td>
<td>0.0077</td>
</tr>
<tr>
<td><strong>CO3-ENG-R-M-Low</strong></td>
<td>0.0230</td>
<td>0.1704</td>
<td>0.0106</td>
<td>0.0043</td>
<td>0.0077</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Table 2.9. Correlation matrix for IBE of all milled surface tack coats at a low application rate.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-M-Low</th>
<th>CO1-ENGR-M-Low</th>
<th>CO2-ENGR-M1-Low</th>
<th>CO3-CSS1-M-Low</th>
<th>CO3-CSS1H-M-Low</th>
<th>CO3-ENGR-M-Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-M-Low</td>
<td>1.000</td>
<td>0.0036</td>
<td>0.2877</td>
<td>0.0687</td>
<td>0.0461</td>
<td>0.0009</td>
</tr>
<tr>
<td>CO1-ENGR-M-Low</td>
<td>0.0036</td>
<td>1.000</td>
<td>0.0244</td>
<td>0.0008</td>
<td>0.0007</td>
<td>0.0362</td>
</tr>
<tr>
<td>CO2-ENGR-M1-Low</td>
<td>0.2877</td>
<td>0.0244</td>
<td>1.000</td>
<td>0.9754</td>
<td>0.9251</td>
<td>0.0069</td>
</tr>
<tr>
<td>CO3-CSS1-M-Low</td>
<td>0.0687</td>
<td>0.0008</td>
<td>0.9754</td>
<td>1.000</td>
<td>0.8044</td>
<td>0.0003</td>
</tr>
<tr>
<td>CO3-CSS1H-M-Low</td>
<td>0.0461</td>
<td>0.0007</td>
<td>0.9251</td>
<td>0.8044</td>
<td>1.000</td>
<td>0.0009</td>
</tr>
<tr>
<td>CO3-ENGR-M-Low</td>
<td>0.0009</td>
<td>0.0362</td>
<td>0.0069</td>
<td>0.0003</td>
<td>0.0009</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Correlations between milled surface tack coats showed that CO3-ENGR-M had superior ISS and IBE performance as compared to all other tack coats applied on milled surfaces at a 95% confidence level, based on the p-values below 0.05 shown in Table 2.8 and Table 2.9. The only exception to this was the ISS of CO1-ENGR-M, which was not statistically different from CO3-ENGR-M at the 95% confidence level based on the p-value of 0.1704. Another notable conclusion is that CO1’s ENGR-M tack coat performed significantly better than all other CSS-1 and CSS-1H tack coat at the 95% confidence level based on the p-values less than 0.05 in Table 2.8 and Table 2.9. This result indicates that Company 1’s engineered tack coat for milled surfaces will improve bond quality over conventional tack coats. Also, an important conclusion is that CO2-ENGR-M1 did not exhibit improved performance like engineered tack coats of Company 1 and Company 3. This tack coat did not have significantly different performance from CO1-CSS1H-M, CO3-CSS1-M or CO3-CSS1H at the 95% confidence level, as can be seen from the high p-values shown in Table 2.8 and Table 2.9. These statistical comparisons also reaffirm the conclusion suggested earlier that the low application rate (0.09 gal/yd^2) must be close to the optimum rate for tack coats applied to milled surfaces, since all of the expected trends in tack coat performance are represented in these comparisons. However, it is still a worthwhile endeavor in future research to determine the optimum application rates for each tack coat tested in this study.
Comparisons of ISS/IBE performance of tack coats applied at high application rates on milled surfaces were not made since the trends exhibited in the comparisons for the low application rate were representative of the expected results and the low application rate was deemed appropriate for milled surfaces.

2.3.2 Effect of Dust on Tack Coat Bond Quality

Figure 2.13 shows the average ISS/IBE responses for CO1 tack coats on milled surfaces in the presence of dust and without dust at two application rates (low rate of 0.09 gal/yd$^2$ and high rate of 0.15 gal/yd$^2$). The “-M” designation on the CSS-1H tack coat is merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of this tack coat. Error bars indicate ±1 standard deviation. Percentage differences for dust/no dust cases are shown above the columns.
From Figure 2.13, it can be deduced that dust does impact tack coat bond quality. There is no discernable difference in ISS/IBE reduction between engineered and conventional tack coats,
indicating that engineered tack coats are not helping to improve bond quality when the underlying pavement surface is dusty prior to paving and compaction. This result may indicate that engineered tack coats have the same propensity as conventional tack coats to stick to dust particles on the pavement surface, perhaps due to electrochemical properties of the polymer modifiers in the engineered tack coats.

Additionally, the reduction in ISS is benign for low application rates. This is true for both engineered and conventional tack coats. This result could be due to the tack coat blending with the dust particles and forming a mastic, which is suggested to increase bond strength (Mohammad et al. 2012). At higher application rates, there was a more pronounced reduction in both ISS and IBE. This observation can also be attributed to the earlier conclusion that an application rate of 0.09 gal/yd² is likely close to the optimum application rate for tack coats tested in this study. In general, the presence of dust seems to be more problematic at higher application rates, as greater reductions in ISS and IBE can be seen for tack coats applied at high application rates in the presence of dust. This result allows the inference that tack coats applied at high rates lead to a portion of the tack coat membrane that is not actively bonding the two pavement layers.

In general, dust did not significantly impact the bond quality of tack coats. The reduced impact of dust on ISS for low application rates is illustrated by the low percentage differences shown in Figure 2.13. Percentage differences are generally higher for high application rates. Percentage differences for IBE were slightly higher for low application rates, indicating that IBE may be better representing the difference in performance for dust/no dust cases.

Table 2.10 and Table 2.11 below show correlation matrices for the ISS and IBE of Company 1 tack coats tested on milled surfaces with and without dust present at a low application rate (0.05 gal/yd²). A p-value of less than 0.05 indicates a significant difference between the two cases under comparison. The decision rule for significance was the same as was used for comparisons shown in Section 2.3.1.1.
Table 2.10. Correlation matrix for ISS of all tack coats tested with dusty surface.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-NoDust-Low</th>
<th>CO1-CSS1H-Dust-Low</th>
<th>CO1-ENGR-M-NoDust-Low</th>
<th>CO1-ENGR-M-Dust-Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-NoDust-Low</td>
<td>1.000</td>
<td>0.5925</td>
<td>0.0393</td>
<td>0.1001</td>
</tr>
<tr>
<td>CO1-CSS1H-Dust-Low</td>
<td>0.5925</td>
<td>1.000</td>
<td>0.0358</td>
<td>0.0928</td>
</tr>
<tr>
<td>CO1-ENGR-M-NoDust-Low</td>
<td>0.0393</td>
<td>0.0358</td>
<td>1.000</td>
<td>0.7960</td>
</tr>
<tr>
<td>CO1-ENGR-M-Dust-Low</td>
<td>0.1001</td>
<td>0.0928</td>
<td>0.7960</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 2.11. Correlation matrix for IBE of all tack coats tested with dusty surface.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-NoDust-Low</th>
<th>CO1-CSS1H-Dust-Low</th>
<th>CO1-ENGR-M-NoDust-Low</th>
<th>CO1-ENGR-M-Dust-Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-NoDust-Low</td>
<td>1.000</td>
<td>0.1203</td>
<td>0.0036</td>
<td>0.1355</td>
</tr>
<tr>
<td>CO1-CSS1H-Dust-Low</td>
<td>0.1203</td>
<td>1.000</td>
<td>0.0013</td>
<td>0.0627</td>
</tr>
<tr>
<td>CO1-ENGR-M-NoDust-Low</td>
<td>0.0036</td>
<td>0.0013</td>
<td>1.000</td>
<td>0.2508</td>
</tr>
<tr>
<td>CO1-ENGR-M-Dust-Low</td>
<td>0.1355</td>
<td>0.0627</td>
<td>0.2508</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Based on the correlation matrices for ISS and IBE of tack coats applied at a low application rate with and without dust, the impact of dust on bond quality is further explained. Interestingly, the impact of dust on ISS and IBE for CO1-CSS1H was not statistically significant at a 95% confidence level, based on p-values of 0.5925 for ISS and 0.1203 for IBE. Similarly, dust did not have a statistically significant effect on ISS/IBE performance of CO1-ENGR-M based on p-values of 0.7960 and 0.2508, respectively. Another interesting conclusion pointed out in these correlation matrices was the change of correlation between CO1-CSS1H and CO1-ENGR-M when dust was present. Recall from in Table 2.8 and Table 2.9 that there was strong statistical evidence to show that CO1-CSS1H-M and CO1-ENGR-M had significantly different ISS and IBE from one another based on the p-values that were less than 0.05 for both ISS and IBE. However, when dust is present for both of these tack coats, the statistical significance is nullified at a 95% confidence level, based on the p-values of 0.0928 for ISS and 0.0627 for IBE. This result may give credence to the conclusion suggested by Mohammad et al. (2012) about dust forming a mastic with tack coat and enhancing bond strength.
2.3.3 Effect of Streaking/Nonuniform Coverage on Tack Coat Bond Quality

Figure 2.14 shows the average ISS/IBE responses for CO1 tack coats on milled surfaces under streaking and no streaking conditions at two application rates (low rate of 0.09 gal/yd$^2$ and high rate of 0.15 gal/yd$^2$). Again, the “-M” designation on the CSS-1H tack coat is merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of this tack coat. Error bars indicate ±1 standard deviation. Percentage differences for streaking/no streaking cases are shown above the columns.
Figure 2.14. Milled surface tack coat response for (a) ISS and (b) IBE with and without streaking at two application rates, with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N-m = 8.85 in-lbs).

Figure 2.14 clearly shows that streaking of tack coats is significantly reducing the interlayer bond quality on milled surfaces, both in terms of ISS and IBE. It also appears that the engineered tack
coat (ENGR-M) experienced greater reductions in ISS/IBE than did the conventional tack coat (CSS-1H). This is represented by the higher percentage differences for engineered tack coats at both low and high application rates. Reductions in IBE are more pronounced than ISS, but in general, there are undeniable negative ramifications of tack coat streaking in both parameters based on these results. These results testify to the importance of ensuring proper spray nozzle function on distributor trucks. Reductions in bond quality of this magnitude will undoubtedly impact the longevity of pavements in the field if streaking occurs.

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

Table 2.12 and Table 2.13 below show correlation matrices for the ISS and IBE of Company 1 tack coats tested on milled surfaces with and without streaking at a low application rate (0.05 gal/yd²). A p-value of less than 0.05 indicates a significant difference between the two cases under comparison. The decision rule for significance was the same as was used for comparisons shown in Chapter 2.3.1.1.

**Table 2.12. Correlation matrix for ISS of tack coats with and without streaking at a low application rate.**

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-NoStreaking</th>
<th>CO1-CSS1H-Streaking</th>
<th>CO1-ENGR-M-NoStreaking</th>
<th>CO1-ENGR-M-Streaking</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-NoStreaking</td>
<td>1.000</td>
<td>0.0234</td>
<td>0.0393</td>
<td>0.0348</td>
</tr>
<tr>
<td>CO1-CSS1H-Streaking</td>
<td>0.0234</td>
<td>1.000</td>
<td>0.0021</td>
<td>0.1278</td>
</tr>
<tr>
<td>CO1-ENGR-M-NoStreaking</td>
<td>0.0393</td>
<td>0.0021</td>
<td>1.000</td>
<td>0.0025</td>
</tr>
<tr>
<td>CO1-ENGR-M-Streaking</td>
<td>0.0348</td>
<td>0.1278</td>
<td>0.0025</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Table 2.13. Correlation matrix for IBE of tack coats with and without streaking at a low application rate.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H-NoStreaking</th>
<th>CO1-CSS1H-Streaking</th>
<th>CO1-ENGR-M-NoStreaking</th>
<th>CO1-ENGR-M-Streaking</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H-NoStreaking</td>
<td>1.000</td>
<td>0.0031</td>
<td>0.0036</td>
<td>0.0031</td>
</tr>
<tr>
<td>CO1-CSS1H-Streaking</td>
<td>0.0031</td>
<td>1.000</td>
<td>0.0005</td>
<td>0.3701</td>
</tr>
<tr>
<td>CO1-ENGR-M-NoStreaking</td>
<td>0.0036</td>
<td>0.0005</td>
<td>1.000</td>
<td>0.0004</td>
</tr>
<tr>
<td>CO1-ENGR-M-Streaking</td>
<td>0.0031</td>
<td>0.3701</td>
<td>0.0004</td>
<td>1.000</td>
</tr>
</tbody>
</table>

These results shown in the correlation matrices for tack coats subject to streaking and no streaking conditions illustrates a definite and discernable decrease in bond quality as measured by ISS and IBE. For CO1-CSS1H, there is strong evidence to suggest that streaking is reducing the resulting ISS and IBE, based on p-values of 0.0234 for ISS and 0.0031 for IBE at a 95% confidence level. It can also be said with 95% confidence that there is overwhelming evidence of a significant decrease in ISS and IBE under streaking conditions for CO1-ENGR-M, based on p-values of 0.0025 for ISS and 0.0004 for IBE. These results confirm the observations made in Figure 2.14. It also reaffirms the importance of preventing streaking during construction of pavements in the field through more thorough inspection of tack coat distributor truck equipment and finding ways to avoid tracking.

2.3.4 Effect of Rainfall on Tack Coat Bond Quality

Figure 2.15 shows the average ISS/IBE responses for Company 1 tack coats on milled surfaces under 2hr rainfall and no rainfall conditions at two application rates (low rate of 0.09 gal/yd² and high rate of 0.15 gal/yd²). Again, the “-M” designation on the CSS-1H tack coat is merely meant to indicate it was applied to a milled surface, and does not depict the intended design surface type of this tack coat. Error bars indicate ±1 standard deviation. Percentage differences for rainfall/no rainfall cases are shown above the columns.
Figure 2.15. Milled surface tack coat response for (a) ISS and (b) IBE with 2hr rainfall after tack coat application and no rainfall at two application rates, with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa; 1.0 N-m = 8.85 in-lbs).

Figure 2.15 shows that, in general, ISS and IBE are reduced when rainfall occurs after tack coat application. The only exception to this is the ISS of CO1-ENGR-M-Low, which remained
essentially the same for the 2hr rainfall case as for the no rainfall case. However, the IBE results for this case paint a different picture, indicating that bond quality was indeed diminished. This contradiction in results seems to suggest that IBE is a better indicator of bond performance than ISS, since the IBE response was able to capture the expected result.

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

It is very important to make one distinction about the impact of rainfall on engineered tack coat performance. From the plots in Figure 2.15 above, it was observed that the reductions in ISS and IBE for the engineered tack coats were of much less magnitude than that of the conventional tack coats. This interesting result can be attributed to the presence of polymer modifiers in the engineered tack coats. The polymers had a higher propensity of sticking to the aggregates on the milled pavement surface, indicating that engineered tack coats are less susceptible to bond quality issues in the presence of rainfall. Although it appeared that the tack coat was washing off the pavement surface during the rainfall simulation, it is clear that some of the polymer residue remained on the pavement surface after rainfall, indicating that engineered tack coats were more difficult to wash away with rainfall, likely due to the electrochemical properties of the polymers and their propensity to stick to aggregates. This result is extremely important in the context of highway pavement construction in Oregon. Since engineered tack coats are performing better under post-rainfall conditions after tack coat application, it can have significant implications for the productivity of the asphalt paving industry in Oregon. Since the industry wants to maximize their available time with which to perform pavement construction, the use of engineered tack coats
could aid in extending the construction window in Oregon into seasons with more inclement weather, effectively increasing productivity and profitability of the asphalt pavement industry in Oregon. However, the possibility of extending the construction season only applies to tack coats. The performance of hot mix asphalt (HMA) constructed in rainfall conditions may be negatively impacted and is not investigated in this study.

Table 2.14 and Table 2.15 below show correlation matrices for the ISS and IBE of Company 1 tack coats tested on milled surfaces under the 2hr rainfall case and the no rainfall case at a low application rate (0.05 gal/yd²). A p-value of less than 0.05 indicates a significant difference between the two cases under comparison. The decision rule for significance was the same as was used for comparisons shown in Chapter 2.3.1.1.

Table 2.14. Correlation matrix for ISS of tack coats with and without rainfall.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H- NoRainfall</th>
<th>CO1-CSS1H- Rainfall</th>
<th>CO1-ENGR-M- NoRainfall</th>
<th>CO1-ENGR-M- Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H- NoRainfall</td>
<td>1.000</td>
<td>0.1143</td>
<td>0.0393</td>
<td>0.1714</td>
</tr>
<tr>
<td>CO1-CSS1H- Rainfall</td>
<td>0.1143</td>
<td>1.000</td>
<td>0.0077</td>
<td>0.0531</td>
</tr>
<tr>
<td>CO1-ENGR-M- NoRainfall</td>
<td>0.0393</td>
<td>0.0077</td>
<td>1.000</td>
<td>0.8774</td>
</tr>
<tr>
<td>CO1-ENGR-M- Rainfall</td>
<td>0.1714</td>
<td>0.0531</td>
<td>0.8774</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 2.15. Correlation matrix for IBE of tack coats with and without rainfall.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H- NoRainfall</th>
<th>CO1-CSS1H- Rainfall</th>
<th>CO1-ENGR-M- NoRainfall</th>
<th>CO1-ENGR-M- Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H- NoRainfall</td>
<td>1.000</td>
<td>0.0039</td>
<td>0.0036</td>
<td>0.4014</td>
</tr>
<tr>
<td>CO1-CSS1H- Rainfall</td>
<td>0.0039</td>
<td>1.000</td>
<td>0.0002</td>
<td>0.0752</td>
</tr>
<tr>
<td>CO1-ENGR-M- NoRainfall</td>
<td>0.0036</td>
<td>0.0002</td>
<td>1.000</td>
<td>0.3220</td>
</tr>
<tr>
<td>CO1-ENGR-M- Rainfall</td>
<td>0.4014</td>
<td>0.0752</td>
<td>0.3220</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The correlation matrices above show that rainfall did not produce statistically significant differences in ISS for CO1-CSS1H or CO1-ENGR-M, based on p-values of 0.1143 and 0.8774 at
a 95% confidence level. The IBE response of CO1-CSS1H was indeed statistically different from the reference case, however, which is confirmed by the p-value of 0.0039 at a 95% confidence level. Another notable observation is that the p-values for the comparison of rainfall to no rainfall cases for CO1-ENGR-M were much higher than for CO1-CSS1H. This result affirms the conclusion from Figure 2.15, that engineered tack coats are affected less by rainfall than are conventional tack coats due to the presence of polymers which are sticking to the aggregates better than conventional tack coats under rainfall conditions.

2.4 SUMMARY AND CONCLUSIONS

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

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

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

The major conclusions of this study are as follows:

1. The ISS and IBE of engineered tack coats was found to be higher than that of conventional tack coats, in general.
2. Engineered tack coats provided by Company 1 and Company 3 exhibited the best performance for both overlay and milled surfaces.
3. Increased application rates significantly improved the bond quality of tack coats applied to overlay surfaces, indicating that the optimum tack coat application rate for overlay surfaces must be much higher than the low rate (0.05 gal/yd^2) selected for use in this study. More research is needed to determine optimum application rates for each of the tack coats tested in this study.
4. Increased application rates did not necessarily result in improved bond performance in all cases. This was especially true for milled surfaces, where the higher application rate provided diminishing returns in bond quality. Higher application rates actually decreased ISS/IBE in some cases for milled surfaces, suggesting that the optimum application rate for milled surface tack coats must be close to the low rate (0.09 gal/yd^2) chosen in this study. More research is required to determine optimum application rates for each of the tack coats tested in this study.
5. IBE was noted to be a better indicator of bond performance/bond quality, as IBE better represented the expected trends in the results for several tack coats.
6. The Company 2 milled surface tack coat stood out from general trends exhibited by Company 1 and Company 3 milled surface tack coats. Company 2’s milled surface tack coat did not achieve better performance than their overlay tack coats or tack coats provided by the other two companies. This result may be attributed to the high water content/low residual asphalt content of Company 2’s milled surface tack coat and the possible need to increase the suggested application rate for this tack coat. Additionally, this tack coat was noted to penetrate through the voids of the first list during tack coat application due to its high water content/low viscosity. More research is needed to determine the optimum application rate for this particular tack coat.

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

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

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

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

11. Rainfall on the freshly tacked pavement surface was noted to rinse away the tack coat, effectively reducing the amount of tack coat available for bonding. However, engineered tack coats were noted to be more difficult to wash away than were conventional tack coats. This observation may suggest that use of engineered tack coats when rainfall is prevalent could help to extend the construction window into seasons with more inclement weather.
12. Engineered tack coats were less susceptible to reductions in ISS and IBE under rainfall conditions than were conventional tack coats, indicating that engineered tack coats are more suitable for pavement construction during inclement weather.

2.5 ACKNOWLEDGMENTS

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). (2012). *Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt.* AASHTO T 209-12.


3.0 CHAPTER 3 - EVALUATION OF MILLED SURFACE TACK COAT PERFORMANCE AT MANUFACTURER-RECOMMENDED APPLICATION RATES

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**Abstract:** Tack coats are bituminous materials applied between asphalt pavement layers to facilitate interlayer bonding, allowing pavement layers to adhere together and behave monolithically. This minimizes tensile strains at the top and bottom of the asphalt layer, which can cause premature fatigue cracking and early pavement failure. New engineered tack coat emulsions are purported to improve bonding and improve resistance to these failures. Using monotonic direct shear testing (DST), this study quantifies the impact of engineered tack coats on bond quality by comparing them to tack coats traditionally used in Oregon on a milled surface texture using manufacturer-recommended application rates. Bond quality in this study is quantified using interlayer shear strength (ISS) and interlayer bond energy (IBE) parameters, which highlight the peak stresses and strains endured by the tack coat bond before failure. Core samples were prepared using a laboratory roller compactor in order to closely simulate nuances of roller compaction in the field and produce correlations with results from field cores. This study advances the knowledge of engineered emulsion performance and promotes sustainability by creating asphalt pavement structures that meet or exceed their structural design lives through optimal interlayer bond quality.

**Keywords:** Tack Coat; Emulsion; Interlayer Shear Strength; Bond Energy; Milled Surface; Roller Compactor.

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3.1 INTRODUCTION & LITERATURE REVIEW

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

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

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

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

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

3.1.1 Objectives

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

- Develop a laboratory sample preparation methodology using a hydraulic laboratory roller compactor and laboratory milling that closely replicates field conditions,
- Characterize the performance of engineered tack coats on milled surfaces using monotonic direct shear testing (DST),
- Compare the performance of engineered tack coats to tack coats conventionally used in Oregon, and
- Identify the adequacy of tack coat application rates suggested by manufacturers.

3.2 EXPERIMENTAL DESIGN

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

<table>
<thead>
<tr>
<th>Company</th>
<th>Tack Types and Application Rates (gal/yd²)</th>
<th>Surface Type</th>
<th>Replicates</th>
<th># of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1</td>
<td>0.060 - CSS1H 0.065 - ENGR-M</td>
<td>Milled</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>CO2</td>
<td>0.080 - ENGR-M1/2</td>
<td>Milled</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>CO3</td>
<td>0.058 - CSS1H 0.059 - CSS1 0.061 - ENGR-OM</td>
<td>Milled</td>
<td>6</td>
<td>18</td>
</tr>
</tbody>
</table>

It should be noted that not all companies provided the same number of tack coats for laboratory ISS testing. This is represented in the above table. Company 1 and Company 2 provided engineered tack coats that were specific to milled surfaces (designated as ENGR-M in the above table). Company 2 provided two different engineered tack coats for milled surfaces. These tack coats had the same binder type as one another and only differed in their water contents. As was suggested by the manufacturer, CO2-ENGR-M1 utilized a low application rate whereas CO2-ENGR-M2 was applied at a higher application rate. Company 3 provided an engineered tack coat designed for use on both overlay and milled surfaces (designated as ENGR-OM in the above table). Additionally, Company 3 requested that the residual rates of Company 1 be matched. The residual rate for CSS-1H for company 1 was used for Company 3’s CSS-1 tack coat. Residual rates for Company 1 tack coats were back-calculated using the water content of the emulsion and Equation (3.1) shown below. Average water contents and densities of the tack coat emulsions were measured in this study and are shown in Table 3.2.

\[
\text{Residual Rate} = \text{Application Rate} \times (1 - \text{Water Content})
\]  

(3.1)
### Table 3.2. Summary of tack coat emulsion water contents and densities

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

\(^a\) 1.0 g = 2.20 \times 10^{-3} \text{ lbs}

### 3.3 MATERIALS AND METHODS

#### 3.3.1 Laboratory Shear Test Sample Preparation

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

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

Prior to compaction, the production mix pails were heated in the oven at 110 °C (230 °F) for four hours and put through a mechanical splitter in order to obtain uniform sampling of the mixture. Figure 3.1a shows mechanical splitting of the production mixture.
The theoretical maximum specific gravity ($G_{mm}$) of the mixture was measured in the lab using a CoreLok device according to AASHTO T 209 (AASHTO 2012). Three replicate $G_{mm}$ measurements (2.520, 2.494, and 2.515) were taken and the average (2.510) was used as the asphalt mixture $G_{mm}$. Required amounts for first and second lift compactions were then weighed out based on the measured average $G_{mm}$ of the mixture and the selected 7% air void content. The 7% air void content was chosen since it is commonly specified during construction in Oregon. Weighed amounts were split equally into two pans to facilitate homogeneous heating of the mixture to compaction temperature.

3.3.1.2 First Lift Compaction of Block Samples

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

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

Parchment paper was placed between the roller surface and the asphalt mixture to avoid any contamination of the first lift asphalt surface with grease or oils that may have been present on the roller compactor. Mold dimensions were input to the roller compactor. A target number of passes was selected to facilitate full compaction of the mixture to the target air void content. The compaction was performed by applying pressure to the asphalt using an adjustable dial on the roller compactor until the sample was compacted to the specified height. Figure 3.1c shows compaction taking place using the laboratory roller compactor.
Once compacted, the mold was removed from the roller compactor and allowed to cool until the internal temperature of the sample fell below the softening point of the asphalt binder used in the mixture. This was done to ensure that the sample would not unravel when removed from the mold. Before removing the sample from the mold, a rubber wheel was rolled across the entire area of the first lift surface eight times to remove any fresh asphalt from the pavement surface. This simulated traffic on the pavement surface between lifts, as is commonly seen in the field. This step was particularly important for tack coats applied to an overlay surface, since additional residual asphalt could amplify bond strength. Figure 3.1d shows the rubber wheel being applied to the first lift samples. The mold was disassembled after the sample had cooled sufficiently (below 40 °C (104 °F)). Completed samples were placed aside for milling (when appropriate) and tack coat application.

3.3.1.3 Milling of First Lift Block Samples

Milling was performed on first lift samples accordingly. Milling was only performed on those samples which were intended for milled surface tests. A milled surface texture with a mean texture depth (MTD) of 0.07 in - 0.09 in (1.78 mm - 2.29 mm) was targeted in order to closely replicate actual milled surface textures in the field (Coleri et al. 2017). Milling was performed using a 4.5 in (114.3 mm) angle grinder with a concrete cutting wheel. The grinder was held at a 45° angle to produce straight grooves on the samples, similar to the pattern of milled surfaces in the field. Figure 3.1e shows milling taking place on first lift samples. Figure 3.2 below shows a comparison of laboratory milled surface samples to an actual milled surface in the field.
After milling, the sample was cleaned with a coarse wire brush to simulate sweeping in the field. Sand patch testing, according to ASTM E965 (ASTM 2015a), was performed after milling in order to quantify the MTD of each sample for later use. Although milling of the samples increased the volume of the second lift in the compaction mold, no adjustments were made to the amount of HMA in the second lift. It was assumed that a similar phenomenon would result in the field as a result of milling.

3.3.1.4 Tack Coat Application and Second Lift Compaction of Block Samples

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

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

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

3.3.1.5 Coring of Block Samples

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

3.3.2 Laboratory Shear Testing

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

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

As a result of monotonic direct shear testing (DST), the shear strength of the tack coat bond was obtained for each sample tested. Figure 3.4 shows the average peak shear strength results for all tack coats tested. The colored bars represent the average strength from six replicate experiments while the length of the error bar on each bar represents the variability of the measured strength for each tack coat type (error bar length = two standard deviations).

![Figure 3.4. Average ISS results for all tack coats with error bars indicating ± 1 standard deviation (1.0 psi = 6.89 kPa)](image)

As can be seen in Figure 3.4 above, the engineered tack coats for Company 1 and Company 3 had ISS values higher than all other tack coats tested, with Company 3 having a slightly higher ISS than Company 1. The standard deviation of ISS for the six Company 3 replicates was also less than that of Company 1. The engineered tack coats provided by Company 2 did not have measured ISS values as high as the engineered or CSS1H tack coats from Company 1 and Company 3. This result is attributed to the high water content of the Company 2 engineered tack coats and the
possible need to increase the residual application rates. Additional research is required to determine the optimum application rates for Company 2’s engineered tack coats.

The mean texture depth (MTD) of each sample, as measured by the Sand Patch Test (ASTM 2015a), was recorded before second lift compactions took place. MTD measurements were compared with the ISS of each sample to identify any relationships between the two variables. The MTD results are compared with peak shear strengths of each sample below in Figure 3.5.

![Figure 3.5. Peak shear strength versus MTD for each tack coat type (1.0 psi = 6.89 kPa; 1.0 in = 2.54 cm)](image)

As can be seen in Figure 3.5 above, ISS was not highly correlated with MTD for any of the tack coat types tested. This indicates that MTD is not controlling bond strength and that laboratory milling practices did not create any bias in the results.
In order to assess the significance of peak shear strength for each tack coat tested, a Welch modified two-sample t-test was performed between each tack coat type to determine significant differences, if any, between the shear strengths for different tack coat types. Suppose that the two peak shear strength distributions for the tack coat types under comparison (suppose $F_1$ and $F_2$ are two distributions) can be represented by the following null and alternative hypotheses:

\[
H_0: F_1(x) = F_2(x) \\
H_A: F_1(x) \neq F_2(x)
\]

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

- Reject $H_0$ if $p < 0.05$
- Fail to reject $H_0$ if $p \geq 0.05$

In the case where the null hypothesis was rejected, it was concluded that the peak shear strengths of the tack coats under comparison were significantly different from one another. Table 3.3 shows the p-values returned for the two-sample t-test for each tack coat type at a 95% significance level.

Table 3.3. P-values from two-sample t-test comparing peak shear strength of each tack coat type.

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H</th>
<th>CO1-ENGR-M</th>
<th>CO2-ENGR-M1</th>
<th>CO2-ENGR-M2</th>
<th>CO3-CSS1H</th>
<th>CO3-ENGR-M2</th>
<th>CO3-CSS1H</th>
<th>CO3-ENGR-OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H</td>
<td>1.000</td>
<td><strong>0.012</strong></td>
<td>0.297</td>
<td>0.134</td>
<td>0.048</td>
<td><strong>0.297</strong></td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>CO1-ENGR-M</td>
<td>0.012</td>
<td>1.000</td>
<td>0.003</td>
<td>0.010</td>
<td>0.001</td>
<td>0.065</td>
<td><strong>0.600</strong></td>
<td></td>
</tr>
<tr>
<td>CO2-ENGR-M1</td>
<td>0.297</td>
<td>0.003</td>
<td>1.000</td>
<td>0.360</td>
<td>0.390</td>
<td>0.060</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>CO2-ENGR-M2</td>
<td>0.134</td>
<td>0.010</td>
<td>0.360</td>
<td>1.000</td>
<td><strong>0.663</strong></td>
<td>0.055</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>CO3-CSS1H</td>
<td>0.048</td>
<td>0.001</td>
<td>0.390</td>
<td>0.663</td>
<td>1.000</td>
<td>0.007</td>
<td><strong>0.000</strong></td>
<td></td>
</tr>
<tr>
<td>CO3-CSS1H</td>
<td>0.297</td>
<td>0.065</td>
<td>0.060</td>
<td>0.055</td>
<td>0.007</td>
<td>1.000</td>
<td><strong>0.010</strong></td>
<td></td>
</tr>
<tr>
<td>CO3-ENGR-OM</td>
<td>0.001</td>
<td>0.600</td>
<td>0.001</td>
<td>0.011</td>
<td>0.000</td>
<td>0.010</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>

As can be seen in Table 3.3, the engineered tack coat provided by Company 1 had significantly superior ISS when compared to their CSS-1H tack coat since the p-value returned from the two-sample t-test was less than 0.05. It can be said with 95% confidence that Company 1’s engineered tack coat had better shear strength performance than their CSS-1H tack coat.
When comparing Company 1’s engineered tack coat to that of Company 3, Figure 3.4 showed that Company 3’s tack coat had slightly better performance. However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.600 from a two-sample t-test at a 95% confidence level.

When comparing Company 1’s CSS-1H tack coat to that of Company 3, Figure 3.4 showed that Company 3’s tack coat had slightly better performance. However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.297 from a two-sample t-test at a 95% confidence level. Tack coat binder tests conducted with CSS-1H tack coats from Company 1 and 3 also showed that these two tack coats have almost identical properties.

Company 3’s engineered tack coat was found to have significantly better performance as compared to their CSS1 and CSS-1H tack coats. Based on the p-values reported in Table 3.3 from a two-sample t-test, there was a significant difference in peak shear strengths between the Company 3 engineered tack coat and the CSS1/CSS-1H tack coats at a 95% confidence level.

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

### 3.4.2 Interlayer Bond Energy Results

From the load-displacement curves obtained for each laboratory shear test, another useful parameter, interlayer bond energy, was extracted to characterize the tack coat bond performance. Interlayer bond energy takes into account the peak strength of the tack coat bond, as well as the associated displacement endured before bond failure. This parameter has been shown to be highly correlated ($R^2 = 0.8$) with fatigue failure criteria for tack coat interlayer bonds and is highly indicative of the fatigue-related shear resistance of tack coats (Amelian and Kim 2017). The interlayer bond energy is calculated as the area under the load-displacement curve up to the peak load.
Figure 3.6 shows the average interlayer bond energy results for all tack coats tested. The columns represent the average interlayer bond energy from six replicate experiments while the length of the error bar on each column represents the variability of the measured energy for each tack coat type (error bar length = two standard deviations).

Interlayer bond energy was also compared with MTD results from the Sand Patch Test (ASTM 2015a). This was done to identify any relationships between interlayer bond energy and MTD for the samples tested. Figure 3.7 shows the relationship between interlayer bond energy and MTD for each tack coat type.
Similar to ISS, IBE was not highly correlated with MTD for any of the tack coat types tested. This indicates that MTD was not influential on the interlayer bond energy of the tack coats.

Two-sample t-tests were also performed for interlayer bond energy results for each of the tack coat types. The same decision rule was adopted for these comparisons as was used in Section 3.4.1. Table 3.4 shows the p-values returned for the two-sample t-tests at a 95% confidence level.
Table 3.4. P-values from two-sample t-tests of interlayer bond energy for all tack coat types

<table>
<thead>
<tr>
<th>Tack Coat Type</th>
<th>CO1-CSS1H</th>
<th>CO1-ENGR-M</th>
<th>CO2-ENGR-M1</th>
<th>CO2-ENGR-M2</th>
<th>CO3-CSS1</th>
<th>CO3-CSS1H</th>
<th>CO3-ENGR-OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1-CSS1H</td>
<td>1.000</td>
<td>0.002</td>
<td>0.244</td>
<td>0.537</td>
<td>0.703</td>
<td>0.016</td>
<td>0.003</td>
</tr>
<tr>
<td>CO1-ENGR-M</td>
<td>0.002</td>
<td>1.000</td>
<td>0.028</td>
<td>0.006</td>
<td>0.001</td>
<td>0.030</td>
<td>0.646</td>
</tr>
<tr>
<td>CO2-ENGR-M1</td>
<td>0.244</td>
<td>0.028</td>
<td>1.000</td>
<td>0.205</td>
<td>0.169</td>
<td>0.530</td>
<td>0.020</td>
</tr>
<tr>
<td>CO2-ENGR-M2</td>
<td>0.537</td>
<td>0.006</td>
<td>0.205</td>
<td>1.000</td>
<td>0.734</td>
<td>0.070</td>
<td>0.004</td>
</tr>
<tr>
<td>CO3-CSS1</td>
<td>0.703</td>
<td>0.001</td>
<td>0.169</td>
<td>0.734</td>
<td>1.000</td>
<td>0.016</td>
<td>0.002</td>
</tr>
<tr>
<td>CO3-CSS1H</td>
<td>0.016</td>
<td>0.030</td>
<td>0.530</td>
<td>0.070</td>
<td>0.016</td>
<td>1.000</td>
<td>0.028</td>
</tr>
<tr>
<td>CO3-ENGR-OM</td>
<td>0.003</td>
<td>0.646</td>
<td>0.020</td>
<td>0.004</td>
<td>0.002</td>
<td>0.028</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 3.4 shows that the engineered tack coat provided by Company 1 exhibited significantly better interlayer bond energy performance as compared to the CSS-1H tack coat. The two-sample t-test p-value of this comparison was well below 0.05. Thus, the interlayer bond energy of the Company 1 engineered tack coat is different from the CSS-1H bond energy at a 95% confidence level.

The engineered tack coat provided by Company 3 appeared to have superior bond energy performance when compared to that of Company 1 based on Figure 3.6. However, a two-sample t-test confirms that the difference in interlayer bond energy of these two tack coats is not statistically significant at a 95% confidence level. This is illustrated by the high p-value (0.646) shown in Table 3.4.

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

3.4.3 Comparison of Laboratory Peak Shear Strength with Field Results

A research study by Mohammad et al. (2012) revealed that testing bond strength of two layered asphalt specimens prepared with SGC can artificially amplify bond strength by 2 to 10 times when compared to field-extracted cores. In order to assess the viability of the laboratory sample
preparation procedures (using a hydraulic roller compactor) for predicting field performance of tack coats, the peak interlayer shear strength results obtained in this study were compared with interlayer shear strengths of field-cored samples from Coleri et al. (2017). The field cores were taken from a construction project in Oregon where a new overlay was constructed on a milled surface. For the field construction project, Company 1 provided a CSS-1H tack coat and an engineered tack coat (shown as CO1_New_Field in Figure 3.8). Company 2 provided an engineered tack coat only (shown as CO2_New_Field in Figure 3.8). Different application rates were used for each tack coat and are represented in this comparison. The field-cored samples from Coleri et al. (2017) were tested in the same jig under the same loading rate and temperature as the laboratory-produced samples. Figure 3.8 shows a plot of peak shear strength versus application rate for field-cored samples from Coleri et al. (2017) and laboratory-produced samples from this study.

![Figure 3.8. Peak shear strength versus application rate for field-cored samples and laboratory-produced samples (25 °C = 77 °F; 1.0 psi = 6.89 kPa; 1.0 gal/yd² = 4.53 L/m²)](image)

As can be seen in Figure 3.8 above, the ISS of the laboratory-produced samples were not dissimilar to that of the field-cored samples. The laboratory-produced samples had shear strengths that were...
well within the domain of shear strengths yielded from the field-cored samples. This indicates that the sample procurement procedures of this study (using a laboratory roller compactor and laboratory milling procedures) produced shear strength results that are similar to what is observed under field conditions. It should be noted that the figure above shows ISS values that were not corrected for MTD. However, normalization of shear strength by MTD is not expected to change the findings of this comparison.

Additionally, Figure 3.8 does not illustrate a discernable trend between ISS and application rate. For laboratory-produced samples, the ISS responses of CO2-ENGR-M1 and CO2-ENGR-M2, which were applied at higher rates, were low in comparison to the ISS of tack coats applied at lower rates. This was due to the poor performance of CO2 engineered tack coats on laboratory-produced samples, which exhibited low ISS due to their low residual asphalt content/high water content. ISS responses of field samples were highly variable, since there is less control over construction issues such as nonuniform tack coat coverage and dust on the pavement surface prior to tack coat application. Field-cored samples were also obtained from different pavement construction projects in Oregon where construction conditions may have varied significantly between each project.

### 3.5 SUMMARY AND CONCLUSIONS

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

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

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

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

3. When comparing Company 1’s CSS-1H tack coat to that of Company 3 based on laboratory shear test results, Company 3’s tack coat had slightly better performance. However, it was found that there was no statistically significant difference in the peak shear strengths, based on a p-value of 0.297 from a two-sample t-test at a 95% confidence level.

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

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

6. The engineered tack coat provided by Company 1 had significantly superior peak shear strength when compared to their CSS-1H tack coat.
7. Company 3’s engineered tack coat was found to have significantly better performance as compared to their CSS-1 and CSS-1H tack coats.

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

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

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

3.6 ACKNOWLEDGMENTS

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American Association of State Highway and Transportation Officials (AASHTO). (2012). *Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt*. AASHTO T 209-12.


Mohammad, L.N., A. Bae, M.A. Elseifi, J. Button and N. Patel. (2010). *Effects of Pavement Surface Type and Sample Preparation Method on Tack Coat Interface Shear Strength*. 


4.0 CHAPTER 4 - QUANTIFYING IN-SITU TACK COAT PERFORMANCE USING THE OREGON FIELD TORQUE TESTER (OFTT)

Blaine Wruck¹, Erdem Coleri² and James Batti³

Abstract: Substandard tack coat bond quality can lead to premature fatigue cracking and early pavement failure due to the non-uniform distribution of heavy truck load-induced stresses and strains in the pavement structure. In the scheme of current inspection practices, tack coat acceptance is a voluntary and visually-based metric. Quantifying tack coat bond quality after construction is a worthwhile venture for ensuring pavements will perform as designed for their intended service lives. The Oregon Field Torque Tester (OFTT), developed at Oregon State University, is a useful and practical alternative to current inspection protocols and has previously demonstrated its utility for determining tack coat bond strength on overlay surfaces in the field immediately after construction. In this study, the OFTT was improved for practicality and portability and was utilized for testing tack coat bond quality on overlay and milled pavement surfaces both in the field and in the laboratory. Newly engineered tack coats and conventional tack coats were tested. Interlayer Shear Strength (ISS) was used as a response parameter to characterize tack coat bond quality. ISS results from field tests and lab tests were correlated with monotonic direct shear tests to determine the suitability of the OFTT for accurately predicting tack coat bond quality. The goal of this study was to validate the viability of using the OFTT as a QA/QC tool for predicting tack coat performance after construction and to evaluate the quality of tack coats in the field.

Keywords: Oregon Field Torque Tester; OFTT; Shear Strength; Bond Strength; Torque; Tack Coat; Bond Quality; Interlayer Shear Strength; Quality Control; Quality Assurance; Construction; Inspection.

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INTRODUCTION & LITERATURE REVIEW

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

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

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

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

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

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

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

A similar system could be implemented to evaluate tack coat quality after construction using the Oregon Field Torque Tester (OFTT) device, developed by Coleri et al. (2017). The OFTT device was previously shown to have a strong correlation with laboratory-measured interlayer shear strength (ISS) of field pavement cores (Coleri et al. 2017; Mahmoud et al. 2017). Figure 4.1 shows the OFTT device developed by Coleri et al. (2017).

![First generation OFTT device developed by Coleri et al. (2017).](image)

This device could be easily implemented as a QC/QA tool following construction, in order to evaluate if tack coat application was performed adequately. A similar contractor accountability system could be implemented for this device in Oregon, following the same premise as the
intelligent compaction and smoothness bonus systems. For instance, if a desired level of ISS is chosen in advance, the contactor will be rewarded or penalized depending on the ISS measured by the OFTT immediately after construction. If the ISS is extraordinarily low, the contractor should then be responsible for repairing or reconstructing the pavement in order to attain an acceptable bond strength. If the ISS is well-above the predefined threshold, then the contractor would be rewarded with a bonus. These criteria could easily be implemented into ODOT’s existing PWL specification.

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

4.1.1 Improvements to the OFTT

The Oregon Field Torque Tester (OFTT) is a novel device which facilitates testing of the tack coat interlayer bond shortly after highway pavement construction. This device addresses the need for quantification of tack coat bond quality in the field. The OFTT developed by Coleri et al. (2017) at Oregon State University was updated in this study to improve its practicality and utility for bond strength measurement in the field under various conditions, such as different pavement surface types. The second rendition of the OFTT was designed with portability and practicality in mind. The device was fitted to a portable chassis for ease of movement and setup in the field. The device also was affixed with a higher capacity adjustable torque sensor that is better suited for typical bond strengths exhibited by both overlay and milled surface textures and also allows for a simpler test setup. Additionally, the device is now capable of applying a normal load, or confining pressure, to core samples in the field. In this way, the device can capture the interlayer bond behavior in its most critical state, which is under the presence of a truck axle load. A new control module cabinet, motor control software and data acquisition system complement all of these improvements. No external components are needed for operation of the OFTT other than a power supply and a laptop computer for data collection. Figure 4.2 shows the newly updated OFTT device.
A challenge with the first iteration of the OFTT in Coleri et al. (2017) was the matching of the OFTT torque unit with the metal platen glued on the pavement surface. The hex-shaped platen requires that the torque unit be perfectly lowered onto the platen in a particular orientation such that the male hex pattern of the platen lines up with the female hex pattern of the torque unit. Failure to perform this action properly can result in poor test results.

The newly refined OFTT now allows for biaxial adjustment of the torque unit to line up the male and female hex patterns in the plane of the pavement surface. An adjustable torque unit allows rotation of the torque sensor to line up the hex patterns perfectly once roughly centered above the platen. Additionally, the normal load actuator allows the torque sensor to be easily lowered down onto the platen once all components are aligned properly. Figure 4.3 shows the metal platens used for OFTT testing.
In this study, the newly improved OFTT is employed to test tack coats in laboratory and field settings. Both newly engineered tack coats and tack coats traditionally used in Oregon were sampled from three companies and tested on both milled and overlay surfaces at manufacturer-recommended application rates. In laboratory tests, two-layer pavement structures were procured in the laboratory and tested in a temperature-controlled environment to quantify tack coat bond quality using an interlayer shear strength (ISS) response parameter. Results of laboratory OFTT tests were then compared with corresponding laboratory monotonic direct shear test (DST) results to highlight the suitability of the OFTT for accurately quantifying bond quality in the field. Additionally, several field paving projects were visited, where in-situ interlayer bond tests were conducted with the OFTT to determine the tack coat bond quality in each case. The results obtained from field tests were then compared against laboratory OFTT and monotonic DST test results to identify any bond quality issues that were prevalent on each of the projects.

4.1.2 Objectives

The objectives of this study are as follows:

- Implement improvements to the first-generation OFTT device to improve its mobility, practicality and function under different pavement surface conditions,
- Quantify tack coat bond quality using the OFTT in a laboratory setting,
• Compare results of laboratory OFTT tests to monotonic DST laboratory tests to determine
  the effectiveness of OFTT in predicting interlayer bond strength in the field,
• Test bond quality of tack coats in-situ on various field paving projects in Oregon and
  compare these results to laboratory tests, and
• Identify tack coat bond quality issues that were prevalent at each of the field projects.

4.2 MATERIALS AND METHODS FOR OFTT TESTING

4.2.1 Laboratory OFTT testing

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

4.2.1.1 Experimental Design for Laboratory OFTT Testing

In this study, it was of specific interest to test a variety of tack coats, both conventional and
engineered, in a laboratory setting using the OFTT to identify the aptitude of this device to
accurately predict tack coat bond quality. Testing using the updated 2nd generation OFTT device was performed in the laboratory in order to determine the correlation between OFTT and monotonic direct shear test results. Monotonic direct shear testing (DST) provides a peak shear strength parameter from which to make meaningful comparisons to bond strength obtained from OFTT testing. Table 4.1 below shows the experimental plan set forth for this study.

Table 4.1. Experimental plan for laboratory OFTT testing.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Company &amp; Tack Coat Type</th>
<th>Surface Type</th>
<th>Application Rate (gal/yd²)</th>
<th>Replicates</th>
<th># of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFTT</td>
<td>CO1-CSS1H</td>
<td>Overlay, Milled</td>
<td>Overlay: 0.05</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>CO1-ENGR-O/M</td>
<td></td>
<td>Milled: Manufacturer-Suggested Rate (Table 4.2)</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>Monotonic DST</td>
<td>CO2-ENGR-O1/M2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO3-CSS1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO3-ENGR-OM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

The application rate selected for overlay surfaces was chosen based on experiences from Coleri et al. (2017) and was also based on the range of application specified by the Oregon Standard Specifications for Construction (ODOT 2015). Milled surface application rates followed manufacturer-recommended rates. Application rates used were for undiluted tack coat and do not represent residual application rates. Manufacturer-recommended application rates for milled surfaces are shown below in Table 4.2.
### Table 4.2. Manufacturer-recommended application rates for milled surfaces.

<table>
<thead>
<tr>
<th>Company</th>
<th>Tack Coat Types</th>
<th>Application Rate (gal/yd²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1</td>
<td>CSS1H ENGR-M</td>
<td>0.060 0.065</td>
</tr>
<tr>
<td>CO2</td>
<td>ENGR-M2</td>
<td>0.080</td>
</tr>
<tr>
<td>CO3</td>
<td>CSS1 ENGR-OM</td>
<td>0.059 0.061</td>
</tr>
</tbody>
</table>

Additionally, Company 3 requested that the residual rates of Company 1 be matched. The residual rate for CSS-1H for company 1 was used for Company 3’s CSS-1 tack coat. Residual rates for Company 1 tack coats were back-calculated using the water content of the emulsion and Equation (4.1) shown below. Average water contents and densities of the tack coat emulsions were measured in this study and are shown in Table 4.3.

\[
\text{Residual Rate} = \text{Application Rate} \times (1 - \text{Water Content})
\]  

(4.1)

### Table 4.3. Summary of tack coat emulsion water contents and densities

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

\(^a\) 1.0 g = 2.20x10\(^{-3}\) lbs

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

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

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

4.2.2.1 Experimental Design for Field OFTT Testing

Field OFTT testing was performed on three different highway paving projects in multiple regions of Oregon with different climates. OFTT field testing was performed on both milled and overlay surfaces, which was project-dependent based on the type of maintenance or rehabilitation strategy used on each project. Three engineered tack coats were used that were provided by three different
companies. The use of each company’s emulsion was also project-dependent. Table 4.4 below summarizes the experimental plan for OFTT field testing for each paving project.

**Table 4.4. Experimental plan for OFTT field testing.**

<table>
<thead>
<tr>
<th>Project Location</th>
<th>ODOT Region</th>
<th>Company</th>
<th>Tack Coat Type</th>
<th>Application Rate (gal/yd²)</th>
<th>Surface Type</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>I5: Grants Pass</td>
<td>3</td>
<td>CO1</td>
<td>ENGR-M</td>
<td>-</td>
<td>Milled</td>
<td>5</td>
</tr>
<tr>
<td>OR38: Reedsport</td>
<td>3</td>
<td>CO2</td>
<td>ENGR-M</td>
<td>0.06</td>
<td>Milled</td>
<td>5</td>
</tr>
<tr>
<td>OR11: Athena</td>
<td>5</td>
<td>CO3</td>
<td>ENGR-O</td>
<td>0.066</td>
<td>Overlay</td>
<td>5</td>
</tr>
</tbody>
</table>

Application rates were measured in the field using procedures outlined in ASTM D2995 (ASTM 2015b). No application rate measurement was obtained for the I5: Grants Pass project due to complications during construction, however it is expected that application rates for this project would be similar to that of OR38: Reedsport since the pavement surface types were the same (milled surface).

To characterize tack coat bond quality from field OFTT tests, an interlayer shear strength (ISS) response parameter was considered. The OFTT field results were compared against monotonic direct shear test (DST) results and OFTT results obtained in laboratory testing for corresponding tack coat types and surface types. Monotonic DST and laboratory OFTT samples had engineered tack coats that were applied at manufacturer-recommended application rates (Table 4.2). Field application rates are summarized in Table 4.4.

The mean texture depth (MTD) of milled surfaces in the field were also quantified as part of OFTT field testing. MTD measurements were made by Sand Patch testing according to ASTM E965 (ASTM 2015a). Six replicate measurements were collected and averaged. Table 4.5 shows average MTD measurements collected for each construction project where OFTT testing took place. MTD measurements for I5: Grants Pass were not able to be gathered due to complications during construction.
Table 4.5. MTD measurements for field construction projects.

<table>
<thead>
<tr>
<th>Project</th>
<th>I5: Grants Pass</th>
<th>OR38: Reedsport</th>
<th>OR11: Athena</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tack Coat Type</td>
<td>CO1-ENGR-M</td>
<td>CO2-ENGR-M2</td>
<td>CO3-ENGR-O</td>
</tr>
<tr>
<td>Surface Type</td>
<td>Milled</td>
<td>Milled</td>
<td>Overlay</td>
</tr>
<tr>
<td>MTD (in)</td>
<td>-</td>
<td>0.137</td>
<td>0.018</td>
</tr>
</tbody>
</table>

4.2.3 OFTT Sample Preparation & Testing Methodology

The OFTT is versatile in the sense that it can be applied to laboratory-produced samples or pavements in the field. Since it only requires shallow-depth 2.5-inch pavement cores, the test is considered to have a low damage impact in comparison to more conventional pavement testing methodologies that require full-depth 6-inch diameter pavement cores. To quantify tack coat bond quality, the OFTT uses a torsional force applied at a constant angular displacement rate to target failure at the pavement layer interface where tack coat is applied. In this way, the shear resistance of the tack coat bond can be quantified using an algorithm to convert the torsional resistance to an interlayer shear strength (ISS) (Equation (4.2)). The only prerequisite information required for this test is the thickness of the surface course pavement layer.

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

4.2.3.1 Sample Preparation for OFTT Lab Tests

OFTT testing in the lab was performed on two-layer asphalt pavement samples with both milled and overlay surfaces. This section details the sample preparation and test procedure for producing and testing two-layer asphalt pavement structures in the laboratory. Figure 4.4 shows photos of the sample preparation and OFTT testing processes. Each step is described in detail below.
Figure 4.4. General sample preparation and testing procedure for OFTT tests in the laboratory and field.
4.2.3.2 Asphalt Sampling and Preparation

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

Prior to compaction, the production mix pails were heated in the oven at 110 °C (230 °F) for four hours and put through a mechanical splitter in order to obtain uniform sampling of the mixture. Figure 4.4a shows mechanical splitting of the production mixture.

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

4.2.3.3 First Lift Compaction of Block Samples

Pavement structures consisting of two lifts (layers) were compacted in custom 260 mm x 400 mm x 100 mm (10.2 in x 15.7 in x 3.93 in) compaction molds. A custom spacer 50.8 mm (2.0 in) in height was used in the mold to compact the first lift. Figure 4.4b shows the custom mold with spacer.

Prior to compaction, the pre-weighed pans of mixture were placed in the oven at compaction temperature for 2.5 hours along with the compaction mold. The mold was removed from the oven and grease was applied to all interior surfaces of the mold to prevent the asphalt from sticking inside the mold. The heated asphalt mixture was then loaded into the mold and spread evenly throughout the mold. The loaded mold was then placed into the roller compactor and secured.
Parchment paper was placed between the roller surface and the asphalt mixture to avoid any contamination of the first lift asphalt surface with grease or oils that may have been present on the roller compactor. Mold dimensions were input to the roller compactor. A target number of passes was selected to facilitate full compaction of the mixture to the target air void content. The compaction was performed by applying pressure to the asphalt using an adjustable dial on the roller compactor until the sample was compacted to the specified height. Figure 4.4c shows compaction taking place using the laboratory roller compactor.

Once compacted, the mold was removed from the roller compactor and allowed to cool until the internal temperature of the sample fell below the softening point of the asphalt binder used in the mixture. This was done to ensure that the sample would not unravel when removed from the mold. Before removing the sample from the mold, a rubber wheel was rolled across the entire area of the first lift surface eight times to remove any fresh asphalt from the pavement surface. This simulated traffic on the pavement surface between lifts, as is commonly seen in the field. This step was particularly important for tack coats applied to an overlay surface, since additional residual asphalt could amplify bond strength. Figure 4.4d shows the rubber wheel being applied to the first lift samples. The mold was disassembled after the sample had cooled sufficiently (below 40 °C (104 °F)). Completed samples were placed aside for milling (when appropriate) and tack coat application.

4.2.3.4 Milling of First Lift Block Samples

Milling was performed on first lift samples accordingly. Milling was only performed on those samples which were intended for milled surface tests. A milled surface texture with a mean texture depth (MTD) of 0.07 in - 0.09 in (1.78 mm - 2.29 mm) was targeted in order to closely replicate actual milled surface textures in the field (Coleri et al. 2017). Milling was performed using a 4.5 in (114.3 mm) angle grinder with a concrete cutting wheel. The grinder was held at a 45° angle to produce straight grooves on the samples, similar to the pattern of milled surfaces in the field. Figure 4.4e shows milling taking place on first lift samples. Figure 4.5 below shows a comparison of laboratory milled surface samples to an actual milled surface in the field.
After milling, the sample was cleaned with a coarse wire brush to simulate sweeping in the field. Sand patch testing, according to ASTM E965 (ASTM 2015a), was performed after milling in order to quantify the MTD of each sample.

4.2.3.5 Tack Coat Application and Second Lift Compaction of Block Samples

Before tack coat application, duct tape was placed around the perimeter of the first lift sample to avoid dripping of tack coat which would cause the first lift sample to stick in the mold (Al-Qadi et al. 2008). Tack coats sampled from the manufacturer were agitated for five minutes prior to tack coat application to facilitate homogeneous mixing of the water, residual asphalt and emulsifying agents. Densities of each tack coat were measured using a 100-mL graduated cylinder and a high-accuracy scale. Three replicate densities were obtained for each tack coat. Average densities for each tack coat can be found in Table 4.3.

The required amount of tack coat by weight was then calculated based on the densities of the tack coats, target application rates and the known sample area. Application rates chosen for this study were for undiluted tack coat solution and were not residual application rates. Tack coats were then applied to the first lift block samples using a foam art roller. Using a high-accuracy scale, the amount of tack coat applied to each sample was carefully tracked until the required amount had been applied to achieve the target application rate. Figure 4.4f shows a tack coat being applied to
a first lift block sample. Tack coat application for overlay surface samples followed the same process as for milled surface samples.

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

4.2.3.6 Coring & Gluing of Platens

To test the shallow-depth pavement core, custom metal platens (Figure 4.3) are glued to the surface of the pavement core using high-strength epoxy, such that the applied torsional force will translate through the pavement core to the tack coat bond. First, the pavement is cored to a depth that is 0.25 inches below the location of the pavement layer interface using a 2.5-inch diameter core drill bit. Since the core is not full-depth, the core is retained in the pavement. The core and tack coat bond are checked for damage before cleaning the core thoroughly of sediment and debris. The core is also dried thoroughly using a blower. Figure 4.4g shows coring of shallow-depth OFTT samples taking place.

Once the core was clean and dry, the metal platens were glued to the pavement surface. To avoid torsional failure at the interface between the platen and the epoxy, a specific amount of epoxy was used for gluing that were discovered by trial and error. The sides of the core were encased in 20g of epoxy and the platen/core interface was bonded by 15g of epoxy. The sample was encased in epoxy around the circumference of the core to avoid failure from the asphalt layer, which commonly occurred in newly placed pavements during the development of this research. This was done very carefully to avoid any contact of the epoxy between the core and the pavement. In this way, failure is forced to occur at the tack coat bond. Epoxy was allowed to cure for the manufacturer-recommended curing time of one hour. Figure 4.4h shows the OFTT platen being glued to the pavement core surface.
4.2.3.7 Temperature Conditioning of OFTT Samples

The target temperature for OFTT testing was 25°C. Temperature conditioning was performed as needed for OFTT samples. In the laboratory, samples were stored and tested in a temperature-controlled environment, so additional conditioning was not necessary. In the field, temperature and climatic conditions were much more variable, so conditioning was necessary in some cases. Cooling of the pavement was performed using block ice. Trials in the laboratory with cubed ice, block ice and dry ice showed that block ice produced the optimal rate of cooling and was selected for use in the field. Heating of the pavement surface was done using a custom chamber and an adjustable heat gun. Figure 4.4i shows the temperature conditioning apparatus. A testing temperature tolerance of ± 1°C was adopted, consistent with laboratory shear testing specifications (ALDOT 2008).

4.2.3.8 OFTT Setup and Testing

Once the epoxy was fully cured and testing temperature was reached, the OFTT was roughly positioned over the hex shaft of the platen. The biaxial adjustment of the OFTT was utilized to position the torque sensor directly over the platen shaft. The torque sensor was lowered onto the platen shaft after rotating the torque sensor to align the male and female hex patterns. Although the OFTT is capable of applying controlled vertical confining pressure on the platen using a calibrated spring system, no confining pressure was used for OFTT lab tests. Figure 4.4j shows the setup of the OFTT in the field.

Torsional displacement at a constant rate was applied to the pavement core until failure was reached. Custom data acquisition and motor control software was used to perform the test. Torque testing was performed at a constant angular displacement rate of 2 deg/sec. Trial and error led to this decision, as the displacement rate of 3 deg/sec used previously in Coleri et al. (2017) and Collop et al. (2011) was not suitable for milled surfaces. This higher angular displacement rate was causing failure from the asphalt layer instead of the tack coat bond. Reducing the displacement rate in this study was found to eliminate this problem and was adequate for both milled and overlay surfaces. The test was allowed to run long enough to capture the full torque-
displacement curve. Figure 4.6 shows an example of the raw torque-displacement data obtained in the OFTT software.

![Graph showing torque vs. time](image)

**Figure 4.6.** Raw torque-displacement data obtained from OFTT testing in custom software.

After completion of the test, the failed pavement core was removed and inspected to ensure that failure indeed occurred at the tack coat bond and not in the asphalt layer. Figure 4.4k shows inspection of OFTT samples after testing. Figure 4.4l shows an example of the torque-displacement curve output by the OFTT data collection software.

Results from OFTT tests were interpreted using a custom algorithm to convert the torsional resistance curve of the tack coat bond to a stress-displacement curve. Equation (4.2) below shows the expression used to convert torque to shear strength. The curve was filtered for noise using a Matlab code which employed a loess smoothing function with a smoothing coefficient of 0.08. It was found through trial and error that this function and smoothing coefficient provided adequate noise filtering while still fitting the curve well. From the smoothed curve, peak shear strength and interlayer bond energy parameters were extracted.

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

(4.2)
4.3 RESULTS OF OFTT TESTING

4.3.1 ISS Results from OFTT Lab Testing

The response parameter used for quantifying tack coat bond quality in OFTT testing was interlayer shear strength (ISS). Figure 4.7 shows the average ISS response for each tack coat tested on both milled and overlay surfaces. The “-O” designation on the CSS-1, CSS-1H and CO3-ENGR tack coats are merely meant to indicate it was applied to an overlay surface, and does not depict the intended design surface type of these tack coats. Error bars indicate ±1 standard deviation.

As can be observed in Figure 4.7 above, tack coats applied to milled surfaces exhibited considerably better ISS and did tack coats applied to overlay surfaces. This is expected, since the increased surface texture of milled surfaces serves to improve the tack coat bond strength due to aggregate interlock (Coleri et al. 2017; FHWA 2016; Mohammad et al. 2010). Also, considering the nature of the torque test, where the cylindrical core sample is rotated about its central axis to target torsional failure of the tack coat bond, the impact of aggregate interlock becomes more dominant, as the grooves of the milled surface provide additional resistance against the rotating core.
Also evident from Figure 4.7 is the improved bond quality of engineered tack coats. Engineered tack coats generally hold an advantage over conventional tack coats in terms of ISS. This conclusion was also made from the results of monotonic DST which are discussed later. One exception to this is CO2-ENGR-M2, which has a slightly lower ISS than CO3-CSS1-M. This result suggests that this particular tack coat is not improving bond quality beyond what is seen with conventional tack coats. This tack coat had a very high water content, which translated into a low amount of residual asphalt available for interlayer bonding at the manufacturer-recommended application rate. This result indicates that an optimum application rate should be determined for this tack coat. More research is needed to determine optimum application rates for tack coats tested in this study.

4.3.1.1 Comparison of OFTT ISS with Monotonic DST

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

Figure 4.8 shows correlation plots for ISS of OFTT and monotonic DST for all tack coats tested on all surface types, tack coats tested on overlay surfaces only, and tack coats tested on milled surfaces only. Coefficients of determination are displayed on each plot to gauge the strength of the correlation between the two test types. Error bars indicate ± 1 coefficient of variation (COV).
Figure 4.8. Correlation plots for ISS of OFTT and monotonic DST for (a) all tack coats tested on all surface types, (b) tack coats tested on overlay surfaces only, and (c) tack coats tested on milled surfaces only (1.0 psi = 6.89 kPa).
As can be seen in Figure 4.8 above, ISS results obtained from OFTT testing were well correlated ($R^2 = 0.89$) with monotonic DST ISS results for overlay surfaces. This is not unreasonable to believe, as overlay surfaces typically have lower variation in macrotexture, so the contribution of surface texture to ISS is minimal.

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

Finally, the OFTT ISS results did not have an excellent with monotonic DST ISS ($R^2 = 0.41$) when considering all tack coats applied to both milled and overlay surfaces. While surface texture may be an influential factor in this correlation, there is also something to be said about the calibration of the OFTT device for milled versus overlay surfaces. Since these two surface types exhibit different ranges of average ISS values, it may be the case that the OFTT results should have a calibration factor applied to them in order to make the results more comparable. However, since the monotonic DST and OFTT ISS results were generally well-correlated when considering pavement surface types separately, using the OFTT ISS results directly and incorporating this test
into an inspection protocol is also reasonable. It is not necessary to equate OFTT results to monotonic DST results in field pavement testing. This was done only to highlight how well the OFTT is replicating monotonic DST results.

In light of the ISS correlations for overlay and milled surfaces, it was worthwhile to investigate how each surface type impacted the OFTT results. To investigate this, average ISS values from laboratory OFTT tests for both milled and overlay surfaces were multiplied by a calibration factor. An Excel Solver algorithm was employed to perform a least squares adjustment on the differences between the average OFTT and monotonic DST ISS results for each tack coat applied to overlay and milled surfaces to see if different calibration factors could be yielded for each surface type. It was found that multiplication of average laboratory OFTT ISS values by calibration factors of 0.514 for overlay surfaces and 0.587 for milled surfaces produced average laboratory OFTT ISS values that were better aligned with the monotonic DST ISS values. Correlation plots using the calibrated averages are shown in Figure 4.9.

Figure 4.9 shows correlation plots for calibrated average OFTT ISS results against monotonic DST results for all tack coats tested on all surface types, tack coats tested on overlay surfaces only, and tack coats tested on milled surfaces only. Coefficients of determination are displayed on each plot to gauge the strength of the correlation between the two test types. Error bars indicate ± 1 coefficient of variation (COV). A line of equality (red) is also shown on the plots.
Figure 4.9. Correlation plots for calibrated OFTT ISS results against monotonic DST results for (a) all tack coats tested on all surface types, (b) tack coats tested on overlay surfaces only, and (c) tack coats tested on milled surfaces only (1.0 psi = 6.89 kPa).
Upon observing Figure 4.9 with cognizance of the ISS correlations shown in Figure 4.8, it is clear that applying the calibration factor to the average ISS results brought the OFTT ISS results within a reasonable range of the monotonic DST results. This indicates that the relationship between monotonic DST results and OFTT results changes between milled and overlay surface types. In Figure 4.9a, the coefficient of determination changed from that shown in Figure 4.8 when the calibration factors were applied. This was due to separately calibrated results for both overlay and milled surfaces being shown on the same chart. The correlation between OFTT and monotonic DST test results actually improved when the calibration factor was applied ($R^2 = 0.41$ in Figure 4.8 to $R^2 = 0.66$ in Figure 4.9), which indicates that the application of a calibration factor to the OFTT results is making the results more comparable. Note that the coefficients of determination for Figure 4.9b/c did not change. Furthermore, the difference between the uncalibrated OFTT results and the monotonic DST results can be attributed to the lack of confining pressure on OFTT tests. In monotonic DST, a confining pressure of 20psi was used. Due to complications with applying confining pressure during OFTT field tests, it was foregone during OFTT tests in this study.

### 4.3.2 OFTT Field Tests versus Monotonic Lab Tests and OFTT Lab Tests

Results from OFTT testing were obtained from three paving projects in Oregon. Engineered tack coats from three companies were used on each of the three projects. OFTT field results were compared with monotonic DST and OFTT laboratory test results to determine, in general, if field OFTT tests were capturing the expected response from each tack coat type and also identify if tack coat bond quality in the field is adequate.

Figure 4.10 below shows the average ISS and IBE response for OFTT field tests, OFTT laboratory tests and monotonic DST laboratory tests on engineered tack coats. Calibration factors used for laboratory OFTT results were also applied to field OFTT results. Error bars indicate ±1 standard deviation.
Figure 4.10: Average ISS response of OFTT field tests versus monotonic DST and OFTT lab tests, with error bars indicating ±1 standard deviation (1.0 psi = 6.89 kPa).

As can be seen in Figure 4.10 above, the calibrated average ISS of field-tested OFTT samples was less than that of OFTT lab tests and significantly less than that of monotonic DST lab tests. This disparity is due to the ideal conditions in which laboratory sample preparation and testing took place. Field conditions are much more variable (presence of dust on pavement surface, nonuniform tack coat coverage, environmental conditions) and hence interlayer bond quality is likely to be diminished in field-measured results. Calibration factors were applied to lab and field OFTT ISS results to improve their comparability to monotonic DST results in this study, however calibration of OFTT ISS results would not be necessary if the OFTT were implemented as a QC/QA tool for evaluating tack coat field performance and acceptable ISS thresholds for OFTT field tests were developed. Also, application rates for CO2-ENGR-M2 and CO3-ENGR-O were fairly close to the application rates used for monotonic DST and OFTT lab testing, so a disparity in application rates is likely not the cause of the difference in average ISS for these tack coats.

Also captured in these results is the reduced bond quality of the CO2-ENGR-M2 tack coat. This result was expected, since this tack coat had a water content that was much higher than other tack coats tested in this study. Monotonic DST test results also showed that this particular tack coat
had inferior performance to other tack coats. This result suggests the possible need to increase the application rate for this tack coat. More research is needed to determine optimum application rates for tack coats tested in this study. Additionally, the fact that the OFTT was able to capture the response of this low-quality tack coat material testifies to the ability of the OFTT device to accurately depict tack coat performance in-situ.

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

4.4 SUMMARY & CONCLUSIONS

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

The major conclusions of this study are as follows:

1. The newly updated OFTT was confirmed to successfully capture tack coat bond quality on both milled and overlay surfaces in the laboratory and in the field.
2. Engineered tack coats were noted to perform better than tack coats conventionally used in Oregon.
3. ISS results extracted from OFTT laboratory tests were found to capture the expected trends in tack coat performance on both milled and overlay surfaces.
4. Calibration of OFTT laboratory ISS results for milled and overlay surfaces was found to enhance the comparability of these results to that of monotonic DST.
5. ISS results from OFTT field tests were significantly diminished from results of OFTT tests and monotonic DST tests performed on laboratory-produced samples, indicating that problems with tack coat application in the field are hindering performance of in-service pavements in Oregon.

4.5 PLANNED FUTURE WORK

In future research, it is planned to further refine the OFTT testing protocol to make it suitable as a QC/QA device in the field within the existing highway construction inspection framework. Additional field tests will be conducted in the state of Oregon during the next construction season that will help to give the OFTT testing protocol additional data to build a strong foundation from which to build specifications. Different types of tack coat materials, surface types and construction projects will be sought in order to complete more field tests and gather a greater breadth of data. From these additional results, acceptable thresholds for bond quality for different tack coat materials will be determined and incorporated into a proposed inspection protocol. The ultimate
goal with this device is to render it reliable enough to implement as a QC/QA tool for contractors and agencies to verify tack coat interlayer bond quality in-situ and create a reward/penalization system for contractors that will fit into the current ODOT PWL pay factor specifications.

4.6 ACKNOWLEDGMENTS

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4.7 REFERENCES


5.0 SUMMARY AND CONCLUSIONS

In this thesis, three manuscripts present findings pertaining to engineered tack coat performance, impact of construction issues on pavement interlayer bond quality, and development of a quality control/quality assurance device for monitoring construction quality and field performance of tack coats. In the first manuscript, the performance of engineered tack coats were compared to tack coats conventionally used in Oregon under different application rates, different underlying pavement surface types (overlay and milled) and adverse construction conditions. A sample preparation method was employed which uses a hydraulic laboratory roller compactor and laboratory milling in order to closely replicate field conditions and avoid artificial amplification of bond performance that would have otherwise occurred if using a Superpave Gyratory Compactor (SGC). Two principal response parameters which are highly correlated with tack coat interlayer bond quality were extracted from results of monotonic direct shear tests (DST) on laboratory-produced samples. These two parameters, interlayer shear strength (ISS) and interlayer bond energy (IBE), were utilized as a primary means of evaluating the performance of each tack coat. A variety of adverse conditions that commonly occur during highway pavement construction were replicated in a laboratory setting to determine their impact on tack coat interlayer bond quality, namely presence of dust on a milled pavement surface, nonuniform tack coat coverage/streaking and rainfall after tack coat application. Each adverse condition case was compared to a reference (control) case to identify how the conditions impacted tack coat interlayer bond quality. To identify variations in performance between each tack coat type, surface type, application rate and adverse condition case, correlation matrices were developed to highlight statistically significant differences between each case using two-sample t-tests.

The second manuscript evaluated the performance of engineered tack coats applied to milled surfaces using manufacturer-recommended application rates. Newly engineered tack coats sampled from three companies were compared to conventional tack coats used in Oregon using monotonic DST of laboratory-produced samples. Sample preparation methodology that mimicked the characteristics of field pavement construction through use of laboratory milling and laboratory roller compaction was developed in this study. ISS and IBE of each tack coat was compared and statistical comparisons were drawn between each tack coat to identify statistically significant differences in performance. ISS and IBE response parameters were compared to the MTD of each
sample to identify if laboratory milling procedures created any bias in the results. Finally, ISS results from laboratory-produced samples were compared to that of core samples obtained in the field to identify if the laboratory sample preparation methodology developed in this study was producing results that were comparable to field conditions.

The final manuscript focused on the use of the Oregon Field Torque Tester (OFTT) developed at Oregon State University to quantify the bond quality of engineered and conventional tack coats on both overlay and milled surface types. OFTT testing on laboratory-produced samples was conducted to obtain an ISS response parameter for each tack coat type and surface type, which were cross-correlated with corresponding results from laboratory monotonic DST to identify the suitability of the OFTT for accurately capturing the expected bond quality of each tack coat type. Calibration factors for OFTT results on overlay and milled surfaces were proposed which helped to make laboratory OFTT results more comparable to monotonic DST results and also address the sensitivity of the OFTT to inherent differences in overlay and milled surface types. OFTT tests were also conducted on three highway construction projects in Oregon which utilized engineered tack coats on different surface types. Comparisons between results of OFTT field tests, OFTT lab tests and monotonic DST tests were made in order to identify how tack coat bond quality in the field differs from the laboratory scenario and also to identify areas for improvement in tack coat practices during field construction.

The following important conclusions were obtained from these three bodies of research:

- Performance of engineered tack coats generally exceeds that of tack coats conventionally used in Oregon.
- The laboratory sample preparation methodology developed in these studies (using a hydraulic laboratory roller compactor and laboratory milling) replicates field conditions very well and produced excellent correlations with results from pavement cores obtained in the field.
- IBE is a useful parameter for quantifying the quality of tack coat interlayer bonding when monotonic DST is employed.
- The impact of adverse conditions commonly experienced during construction affect tack coat bond quality in the following ways:
Presence of dust on the pavement surface prior to tack coat application reduces the ISS and IBE of the resulting tack coat bond for both conventional and engineered tack coats. However, this reduction is not statistically significant for low application rates.

Nonuniform coverage/streaking caused by poor maintenance of tack coat applicator equipment was shown with statistical significance to have negative ramifications for tack coat bond quality and, consequentially, pavement longevity.

Rainfall after tack coat application was shown to reduce tack coat bond quality moreso for conventional tack coats than for engineered tack coats due to the presence of polymers in engineered tack coats which actively stick to the pavement surface. However, these reductions were not statistically significant in all cases.

- Manufacturer-recommended application rates for engineered tack coats were found to be adequate in most cases, but optimum application rates for each tack coat tested in these studies should be sought.

- The engineered tack coat designed for milled surfaces provided by Company 2 did not exhibit good performance in these studies. It had performance that was comparable to conventional CSS-1/CSS-1H tack coats. The high water content and low application rate of this tack coat are believed to be the culprit of the poor results.

- The newly improved OFTT device was found to accurately quantify the bond strength of conventional and engineered tack coats on both milled and overlay surfaces, suggesting that it is a useful and practical tool for verifying tack coat bond quality immediately after construction.

- Field performance of tack coats in Oregon is noticeably inferior to performance of tack coats on laboratory-produced samples, suggesting that poor inspection and QC/QA measures during field pavement construction are hindering the performance of tack coats and affecting the longevity of pavements in Oregon.
6.0 BIBLIOGRAPHY

American Association of State Highway and Transportation Officials (AASHTO). (2012). *Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt*. AASHTO T 209-12.


