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DEVELOPMENT OF GUIDELINES FOR SELECTION AND EVALUATION OF TACK COATS IN OKLAHOMA

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Oklahoma Department of Transportation

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16. ABSTRACT

Asphalt pavements are generally constructed by compacting asphalt mixes in multiple lifts to achieve the required density across the layers. Also, depending on pavement preservation and maintenance plan, from time to time, a thin overlay may be constructed over an existing asphalt pavement or a Portland Cement Concrete (PCC) pavement. The quality and integrity of the bond between asphalt layers, especially the bond between the existing surface and an overlay, is crucial to pavement's durability and serviceability. Inadequate interlayer bond may lead to distresses such as half-moon-shaped cracks, delamination, longitudinal wheel path cracking, potholes, fatigue cracks, slippage, and rutting. In order to improve the interlayer bonding of asphalt pavements, and create a moisture barrier at layers' interfaces, tack coats are used. Tack coats improve the interlayer bond strength and help pavement layers behave as a single cohesive system. This improves pavement's resistance to traffic and environmental stresses. The interlayer bond strength is mainly governed by the selection of tack coat product and applying it at an optimum residual application rate (referred to as application rate in this report). The optimum application rate of a tack coat, to a great extent, depends on the existing pavement surface conditions such as new, old, or milled surface, tack coat type, moisture, and temperature. This study evaluated the effectiveness of tack coats used by the Oklahoma Department of Transportation, namely SS-1, CRS-1, CBC-1H, CRS-1S, NTHAP, and NTQS-1HH with respect to their type and application rate, pavement surface conditions, moisture-induced damage, and temperature. Two test methods were used for testing the tack coats: (i) Interlayer Shear Strength (ISS) of tack coat using the Louisiana Interlayer Shear Strength Tester (LISST); and (ii) Room-Temperature Tracking (RTT) test. Also, laboratory-compacted samples and a number of field cores from selected projects were collected and tested selectively to evaluate the tack coat performance. Based on the test results, a database that can be implemented for the selection of tack coat type and application rates was developed. Also, the optimum tack coat application rates, based on their ISS values was developed and presented that can be used for selection of the tack coats depending on pavement surface types. Also, as the removal of the tack coat through tracking by the construction equipment is a concern, setting times of the tack coats were presented that can be immediately implemented. Finally, a draft special provision was developed and included for improving the current practice in using tack coats in construction of the asphalt pavements in Oklahoma.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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1.1 Background

Asphalt pavements are generally constructed by compacting asphalt mixes in multiple lifts in order to achieve the required density across the layers. Also, depending on the pavement preservation and maintenance plan, a thin overlay may be constructed over an existing asphalt pavement or a Portland Cement Concrete (PCC) pavement. The asphalt overlay enhances the pavement's overall service life by increasing its structural number, and often reducing its life cycle cost (Hajj, 2016; Brown and Heitzman, 2013; Newcomb, 2009). The quality and integrity of the bond between the asphalt layers, especially the bond between the existing surface and an overlay, is crucial to a pavement's durability and serviceability (Barman et al., 2017; Hajj, 2016; Brown and Heitzman, 2013). Inadequate interlayer bond may lead to distresses such as half-moon-shaped cracks, delamination, longitudinal wheel path cracking, potholes, fatigue cracks, slippage, and rutting (Mohammad et al., 2011; Hu and Walubita, 2011; Rahman et al., 2009; West et al., 2005; TxDOT, 2001). Slippage usually happens due to high horizontal stresses and insufficient bonding between the asphalt layers at locations of wheel acceleration, deceleration, and turns (West et al., 2005; Hachiya and Sato, 1997). According to Mohammad et al. (2009), delamination occurs at locations where the interface shear stresses exceed the interface shear resistance or fatigue life. In order to improve the interlayer bonding of asphalt pavements and create a moisture barrier at layers' interfaces, tack coats are used (Zhang, 2017; Hu et al., 2017; Song et al., 2015; Johnson et al., 2015; Mohammad et al., 2012; Mohammad et al., 2010; Canestrari and Santagata, 2005; Cross and Shrestha, 2005; Sangiorgi et al., 2002). Tack coats help the pavement layers to behave as a single cohesive system, which in turn improves its resistance to traffic and environmental stresses (Mohammad et al., 2012).

Tack coat involves application of a thin layer of liquid asphalt to promote bonding between the existing pavement and the new layer or between two lifts and to provide a waterproofing barrier. It is generally used in the form of an emulsion diluted with water or cutback (ASTM, 2017). According to Mohammad et al. (2012), emulsified asphalts (or asphalt emulsions or emulsified tack coats) are most commonly used as tack coats. In the emulsified tack coats, the emulsifying agent imparts an electric charge at the asphalt binder and water interface and resists the asphalt binder globules from coalescing (TxDOT, 2006; Roberts et al., 1996). Emulsified tack coats, based on their setting times, are generally classified as Rapid-Setting (RS), Medium Setting (MS), and Slow-Setting (SS). Also, emulsified tack coats are further classified as anionic (negatively charged) and cationic (C) (positively charged) based on their electric charges imparted by the emulsifying agent (Brown et al., 2009). For instance, SS-1 is an anionic slow setting tack coat and CRS-1 is a cationic rapid setting tack coat. Based on the survey results reported by Paul and Scherocaman (1998) and Cross and Shrestha (2004), slow-setting tack coats are the most preferred tack coats by many state Departments of Transportation (DOTs) in the United States. However, there are a number of states that use different types of tack coats. For example, Georgia DOT uses hot asphalt (AC-20 and AC-30) as tack coat. Also, California DOT primarily uses AR-4000, followed by SS-1 and CSS-1 (Cross and Shrestha, 2004). Furthermore, New Mexico and Texas DOTs use Performance-Grade (PG) asphalt binders as tack coat (Mohammad et al., 2012).

The interlayer bond strength is mainly governed by the selection of a tack coat product and applying it at an optimum residual application rate (referred to as application rate) (Nguyen et al., 2016; Mohammad et al., 2002; Paul and Scherocman, 1988). The optimum application rate of a tack coat, to a great extent, depends on the existing pavement surface conditions such as new, old, or milled surface (Mohammad et al., 2012). For instance, according to Paul and Scherocman (1988), residual application rate may vary between 0.01 and 0.06 gal/yd^2 based on asphaltic residue and pavement surface type. According to Chaignon and Roffe (2001), the optimum residual application rate can vary from 0.02 to 0.09 gal/yd^2 for different types of Hot Mix Asphalt (HMA) surfaces. Asphalt Institute (AI) recommends an application rate of a 1:1 diluted tack coat from 0.05 to 0.15 gal/yd^2, which is equivalent to a residual application rate between 0.02 to 0.05 gal/yd^2 (AI, 1989). In the HMA Paving Handbook (USACE, 2000), the recommended residual application rates of tack coats range from 0.04 to 0.06 gal/yd^2. The optimum application rate also depends on tack coat type and temperature. Several studies have indicated that an increase in test temperature results in a decrease in the interlayer bond strength and a larger portion of shear resistance at high temperatures comes from layer surface roughness (Ai et al., 2017; Zhang, 2017; Song et al., 2015; Seo et al., 2015; Leng et al., 2008; Deysarkar and Tandon, 2005; Canestrari et al., 2005; West et al., 2005; Sholar et al., 2002; Uzan, 1978). For instance, in a study conducted by West et al. (2005), the interlayer bond strengths were found to be more than 2 times greater at 10°C compared to 25°C. Also, the interlayer bond strengths at 25°C were found to be about 6 times higher than those at 60°C (West et al., 2005). Hachiya and Sato (1997) found an optimum tack coat application rate of 0.04 gal/yd^2 for rubber-modified asphalt emulsions, namely PK-R80, PK-HR1, and PK-HR2. Mohammad et al. (2002) reported an application rate of 0.02 gal/yd^2 for four tack coats, namely CRS-2P, SS-1, CCS-1, and SS-1h, and two asphalt binders, namely PG 64-22 and PG 76-22M. Leng et al. (2008) studied SS-1hP emulsion and RC-70 cutback considering several parameters such as HMA type, tack coat application rate, PCC surface texture, and temperature. Based on the results, the optimum residual application rate was selected as 0.05 gal/yd^2.

Other factors affecting the interlayer bond quality are application methods, equipment type and calibration procedures, breaking and setting times, asphalt layer surface type (HMA, PCC, old, milled or new), surface cleanliness, moisture, and temperature (Zhang, 2017; Willis and Taylor, 2015; Panda et al., 2014; ASTM D2995, 2014; Chen et al., 2012; West et al., 2005; Sholar et al., 2004; Hachiya and Sato, 1997). Tashman et al. (2006), Sholar et al. (2004), and West et al. (2005) reported that milled surfaces with or without tack coat had interlayer shear strengths significantly higher than those of the non-milled surfaces. Mechanistically, higher roughness in milled surfaces contribute to higher shear strengths (friction-based) than surfaces without milling (e.g., interface between two new layers of asphalt). The cleanliness at the interface resulted in an improved adhesion between layers and consequently, enhanced the interlayer bond strength (Destree and Visscher, 2017). Seo et al. (2015) observed that interlayer bond strength was independent of aggregate type; however, aggregates with smooth surfaces showed slightly higher bonding (adhesion-based) than those with rough surfaces. Zhang (2017) and West et al. (2005) reported that the effect of tack coat on interlayer bond strength was more pronounced when it was applied on fine-graded mixes than that of coarse-graded mixes. The asphalt mixes designed with high air voids or coarse aggregate structure did not exhibit significant changes in the interlayer bond strength due to application of tack coat. An increase in confinement pressure is also known to improve the bond strength, especially at high temperatures (West et al., 2005).

The present study evaluated the effectiveness of tack coats used by the Oklahoma Department of Transportation with respect to their types and application rates, pavement surface conditions, moisture-induced damage, and temperature. Two test methods were used for testing the tack coats: (i) Interlayer Shear Strength (ISS) using the Louisiana Interlayer Shear Strength Tester (LISST), developed by Mohammad et al. (2012); and (ii) Room-Temperature Tracking (RTT) test. Tack coats were applied to laboratory-compacted samples and field cores from selected projects. Their shear strengths were evaluated under different conditions and used as an indicator of the tack coat performance. Although tensile strength is important to tack coat performance, it was not addressed in this study due its limited scope and budget. Also, effect of curing time was not addressed in this study.

1.2 Objectives

The specific objectives of this study are as follows:

1. Determine the optimum tack coat application rates of different types of tack coats widely used in Oklahoma, namely SS-1, CRS-1, CBC-1H, CRS-1S, NTHAP, and NTQS-1HH, using the LISST test with respect to different types of pavement surfaces.
2. Using the LISST test, study the effects of pavement parameters on the bond strength of the selected tack coats. Based on these results, develop a database that can be used in the selection of tack coat type and application rate. The following parameters were included:
   - 2.1 Tack coat application rate (no tack coat and three other rates);
   - 2.2 Asphalt surface age (new or unaged, aged conditions);
   - 2.3 Surface type (milled asphalt layer and PCC layer (core samples from the field));
   - 2.4 Testing temperature (low, intermediate and high);

2.5 Moisture conditioning (moisture-conditioned and dry);

3. Determine the setting time of the selected tack coats using Room-Temperature Tracking test;
4. Help develop guideline(s) for the optimum tack coat application rate based on the pavement surface conditions and identify the effects of temperature and moisture-damage on tack coats' effectiveness.

1.3 Problem Statement

In order to achieve adequate interface bond, the application rate of tack coat should be adjusted based on the surface conditions of the pavement (e.g., new, old, milled, grooved, cracked). Inadequate tack coat coverage or low application rate may result in a weak interlayer bond strength and various types of pavement distresses. Also, an excessive application of tack coat may result in shear slippage at the interface, particularly at a high temperature. Therefore, determining the type of tack coat and optimum application rate is vital to achieving adequate interface bond and limiting associated pavement distresses.

Insufficient or excessive application of tack coat was likely responsible for several pavement failures in Oklahoma. For example, premature pavement failures were observed in Toddle project, Colgate project, and Heritage Park Mall project in Reno, due to absence, insufficient use, and excessive use of tack coat, respectively. In some cases not using the right amount of tack coat resulted from confusion due to different units and calculations used by the design engineers and the construction crew. Currently, four different tack coat rates are used in the technical documents: (i) application rate at application temperature; (ii) rate at 60°F (15.6°C); (iii) original emulsion application rate; and (iv) residual rate. In reality, the most important parameter in tack coat application, which ultimately affects the bond strength, is the residual amount of asphalt (not the asphalt concentration in diluted emulsion). The selection of tack coat type for pavements is generally made based on experience and/or empirical judgment. This is mainly due to lack of sufficient guidelines for selection of tack coat material, application rate, placement, and evaluation. Also, it is important to evaluate the effectiveness of the selected type and application rate of tack coat as a quality-control procedure, prior to construction of the pavement. This would help minimize the maintenance costs in future. Hence, the present study evaluated the effectiveness of the tack coats used in Oklahoma for pavement projects based on tack coat type and application rate, pavement surface conditions, moisture effect, and temperature.

Chapter 2 Literature Review

A comprehensive literature review was conducted in this study with a focus on the characterization of tack coats and their performance under different climatic conditions. Sources of literature included, but not limited to, TRIS, TRB, FHWA, NCHRP, and DOTs. Other sources such as society journals (ASCE), Asphalt Institute (AI), Western Research Institute (WRI), and NCAT were also consulted. Moreover, national and international conferences, symposia and workshops were reviewed. A summary of the literature review is included in this chapter

Ai et al. (2017) used Marshall testing machine with a supplementary fixture to determine the interlayer shear strength (ISS) of a cationic emulsified tack coat. For this purpose, tests were conducted at different application rates, namely 0.09, 0.13, 0.18, 0.22, and 0.27 gal/yd^2, at different temperatures (5°, 20°, 25°, 35°, 40°, and 60°C), and confinement levels varying from 0 to 0.70 MPa. Double-layered asphalt mix samples of 101.6 mm diameter and 76.2 mm height were compacted using a Marshall compactor. It was reported that the shear peak strength of the tack coat was achieved at a rate of 0.18 gal/yd^2 regardless of the confinement level. Also, the magnitude of peak shear strength was found to increase and decrease with an increase in confinement level and temperature, respectively. Based on the statistical observations of the test results using AVONA analysis, temperature was found to be the most influential factor affecting the ISS of a tack coat followed by confinement stress and tack coat application rate.

Das et al. (2017) studied the effects of slow-setting (SS-1 and SS-1H) and trackless (NTSS-1HM and CBC-1H) tack coats applied to interface of asphalt mix overlay and existing pavement layers in the field. For this purpose, 14 different field sections were constructed at three different locations, namely Missouri (0.05 gal/yd^2), Louisiana (0.05 gal/yd^2), and Florida (0.02 and 0.04 gal/yd^2). Effects of pavement surface types and residual application rates on the ISS of tack coat were evaluated. Specifically, ISS tests were conducted on field cores using a LISST device. It was found that the use of trackless tack coats provided higher ISS values than the slow-setting tack coats due to harder base binders used in those products. Also, the ISS values were found to depend on the surface type, surface roughness being an important factor.

The highest ISS value was measured for milled HMA surface, followed by new HMA, non-milled HMA, and PCC. The results also indicated that the ISS values increased over in-service time of the pavement for both slow-setting and trackless tack coats. However, improvement in the ISS with time for the trackless tack coats were comparatively higher than that for slow-setting tack coats.

Destree and Visscher (2017) conducted Shear Bond Test (SBT) at 20°C on field cores having a diameter of 150 mm. The SBT tests were conducted in a displacement-controlled mode at a rate of 50 ± 2 mm/min. The field sections were prepared using cationic bituminous $C_{60}B_3$ emulsions with hard and soft base binders at a residual application rate of 250 g/m^2. Also, the effect of cleanliness of the milled surface on the ISS values was investigated. Milling of existing surface was performed at milling speeds of 10 and 20 m/min and the milled surface was cleaned using a high-pressure suction sweeper at varying vacuum pressures, namely 40, 100 and 150 bars. The results indicated that the use of tack coat with a hard base binder provided greater interface bond strength than with a soft base binder. Also, the cleanliness of the surface was found to be an important parameter affecting the bond strength at the interface. A cleaner interface resulted in an improved adhesion between two layers and consequently, enhanced bond strength. However, a change in surface texture was not found to have any notable effect on the measured ISS values.

Hu et al. (2017) evaluated the ISS of two different emulsified tack coats, namely cationic emulsified asphalt binder (PC-3) and fast-break emulsified asphalt binder with high viscosity (HV). For this purpose, three different residual application rates, namely 0.25, 0.5, and 0.75 kg/m^2 and four different temperatures, namely -10°, 0°, 25°, and 50°C, were selected. A Superpave® Gyratory Compactor (SGC) was used to compact double-layered asphalt samples with tack coat at the interface. The tack coat was allowed to set for 24 hours. It was observed that a decrease in temperature resulted in an increase in the ISS values. As expected, the samples exhibited brittle behavior at low temperature and soft behavior at high temperature. Also, the HV tack coat led to higher ISS values than those observed for the PC-4 tack coats, due to higher viscosity and a lower penetration grade of the base binder. Furthermore, at low temperature, ISS increased with an increase in the application rate. However, at intermediate and high temperatures, ISS decreased with an increase in the application rate.

Mahmoud et al. (2017) developed an in-situ testing equipment to measure the long-term post-construction bond strength of tack coats in pavement sections. This equipment, Oregon Field Torque Tester (OFTT), can measure the in-situ ISS of tack coats. The device works with a software to provide a controlled rotation rate and a controlled movement of the platen relative to the extracted core sample. The effectiveness of the equipment was determined by comparing the OFTT field test results with the laboratory shear strength test results conducted using a LISST device on the cores collected from the field. The shear strength results measured using the OFTT were found to correlate well with the laboratory results.

Ouyang et al. (2017) studied the rheological properties of Cement Asphalt (CA) emulsions with cationic and anionic charges. For this study, a coaxial cylinder rheometer was used at 22˚C and at varying shear rates. The results indicated that the apparent viscosity was highly dependent on the emulsifier type. A cationic CA paste had a higher apparent viscosity than the anionic CA paste at high shear rates. Additionally, it was found that the pH value and emulsifier did not define the yield stress at low shear rates.

Zhang (2017) conducted a review on the parameters affecting the ISS of the asphalt pavement layers with different tack coats applied at their interfaces. It was reported that the most influential parameter affecting the ISS was temperature. An increase in temperature decreased the ISS significantly. Also, the ISS values increased with an increase in traffic loads and confining pressure. Furthermore, cleaned milled surfaces always exhibited the highest ISS values. Moreover, it was reported that the asphalt mixes designed with high air voids or coarse aggregate structure had low ISS values.

Nguyen et al. (2016) investigated the ISS of asphalt mix samples with and without CRS-1 emulsion at their layer interfaces. Modified Leutner shear tests were conducted on samples at four different (non-residual) application rates, namely 0, 0.04, 0.09, and 0.20 gal/yd^2 and five different temperatures ranging from 20° to 60°C at 10°C interval. A displacement rate of 50.8 mm/min was used in conducting these tests. The results indicated that the ISS, in general, decreased with an increase in temperature. At elevated temperatures, specifically 50° and 60°C, the ISS values did not show any noticeable change, at the selected application rate. Also, it was observed that a change in the application rate of emulsion had marginal effect on the ISS values. At 20°C, the optimum application rate was found to be 0.2 gal/yd^2.

Das et al. (2016) determined the ISS values measured between HMA overlay and underlying pavement layers in the field considering different tack coat types, pavement surface types, and application rates. The ISS values were determined using the LISST device. It was observed that the trackless tack coats had higher interface bond strengths because of stiffer base asphalt materials as compared to slow-setting tack coats. The results also indicated that the pavement surface type can significantly affect the interface bond strength. Milled HMA surface provided the highest interface bond strength followed by new HMA, existing HMA, and PCC surfaces. Furthermore, the interface bond strength was found to increase with in-service time irrespective to the surface type. The increase in the interface bond strength was more pronounced for slow-setting tack coats than that for trackless tack coats.

Sufian et al. (2016) studied the optimum application rate of a selected asphalt emulsion for Kansas, when applied on the milled HMA surface in the field. For this purpose, a slow-setting polymer-modified (SS-1hP) asphalt emulsion was applied at four different application rates, namely 50%, 100%, 160%, and 240% of 0.05 gal/yd^2. The rut depth and strain were measured periodically at the interface. It was found that the section with 50% of 0.05 gal/yd^2, i.e. 0.025 gal/yd^2, application rate had the lowest rutting. The other application rates (i.e., 100%, 160%, and 240% of 0.05 gal/yd^2) had negligible changes in rutting. Therefore, an application rate of 0.05 gal/yd^2 was considered optimum for the SS-1hP tack coat in Kansas.

Vrtis and Timm (2016) investigated the interface bond strength of double-layered asphalt mix samples with tack coat applied at the interface. A plant produced HMA mix was used to prepare the test samples. The samples were divided into four groups: unconditioned samples tested after three days of compaction, unconditioned samples tested after 35 days of compaction, long-term aged samples following AASHTO R 30 procedure, and moisture-conditioned samples using a Moisture-Induced

Stress Tester (MIST) and following the ASTM D7870 (ASTM, 2013) procedure for conditioning. The NCAT test sections were also considered to evaluate the interlayer performance of asphalt mixes containing Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) containing tack coats. A trackless tack coat, namely NTSS-1HM, was applied at the interlayer at an undiluted application rate of 0.05 gal/yd^2. High application rates (0.08 - 0.1 gal/yd^2) were used for the reconstructed sections containing a high amount of RAP. The tack coat was allowed to break within 24 hours. The samples were tested using a displacement-controlled mode at a rate of 50.8 mm/min using a Marshall Stability Tester. It was found that the sections containing RAP had the highest overall interlayer bond strength. Also, the bond strength was found to reduce after moisture-conditioning and increase with aging. The samples containing high RAP amounts (>50%) showed the highest reduction in the bond strength due to moisture conditioning.

Rahman et al. (2016) conducted a review of interface bond testing in pavement layers under both shear and tension modes. Based on this review, the general features of an ideal standardized specification test were specified. It was indicated that the standardization of a test procedure should consider multiple factors such as loading modes (shear or tension), repeatability and reproducibility of results, contractors' and agency's needs, researcher's requirement and preference, and interrelations between different factors.

A forensic investigation was performed by Munoz et al. (2016) to determine the cause of slippery (low interface bond strength) Ultra-Thin Bonded Wearing Course (UTBWC) on an asphalt pavement. For this purpose, cores were collected from the field sections constructed with and without tack coats at interfaces. A profile analysis of the field cores indicated a large variation in the asphalt binder content along the depth of the core. The asphalt binder content was minimum at the top and increased with depth. The highest binder content was observed at the interface of UTBWC and the old HMA layer. At some places, the asphalt binder content was in excess of 2% over the JMF values. Similar results were observed using XRF analysis suggesting that the excess applied tack coat was migrating upward toward to the top, which may have been a contributing factor to the loss of skid resistance in the pavement.

Song et al. (2016) measured the fatigue life of asphalt samples compacted with and without tack coats at the interface. For this purpose, both 50% stiffness reduction method and energy approach were used to evaluate the fatigue life. The double-layered asphalt mix samples were compacted in the laboratory. The bottom layer was compacted as a dense layer (named as BM and TLD in Tennessee, respectively) and the upper layer consisted of OGFC. The test (cyclic direct tension) was conducted using a direct shear fatigue test device applying a sinusoidal loading cycle at 10Hz frequency and 20°C temperature. The results showed that the use of tack coat resulted in a decrease in the fatigue life. The higher the application rate, the lower the fatigue life. It was also found that a good correlation exists between the plateau value (calculated based on dissipated energy during cracking) and fatigue life (calculated based on 50% stiffness reduction method). According to the test results, the OGFC-TLD had a higher fatigue life than the OGFC-BM. It was recommended that the plateau value failure criteria be considered to quantify the fatigue life.

Rawl et al. (2016) used a "Tack Lifter" to measure the effective dosage of tack coats in the laboratory and in the field at specified locations along the length of paving. Tack Lifter is a simple 15-kg-weight device that is placed on the top of a super-absorbent foam sheet applied to a paving surface. The amount of emulsion absorbed in the foam sheet, emulsion density, and surface area of foam were used to measure the emulsion application rate. The results indicated that the absorbed amount of emulsion depends on the surface type. A rough surface texture resulted in a lower tack emulsion absorption than a smooth surface. However, the predicted absorption of emulsions into a paving surface was found sensitive to the emulsion viscosity and its type.

Ronald and Luis (2016) discussed the complexity involved in the formulation of asphalt emulsions. The emulsion stability, emulsion viscosity, droplet size and droplet particle distribution, asphalt binder type and content, asphalt binder composition, available surfactant, chemical reagents, emulsification process, agitation speed, and emulsification time were indicated as some of the important parameters to be considered during the emulsification process. For example, increasing the surfactant concentration was found to decrease the droplet size in the emulsifier. It was concluded that the amount of surfactant should not be higher than critical micelle concentration to avoid the generation of micelles in the solution. Also, the droplet size can be reduced by increasing the agitation speed. In this study, it was found that the use of a cationic surfactant results in a better adhesion with aggregate, a better stability, and an increased resistance to moisture-induced damage. Also, it was found that the asphalt binders containing a lower resin to asphaltene ratio are more difficult to emulsify.

Song et al. (2015) conducted direct shear tests to evaluate the ISS between an open-graded friction course (OGFC) layer and the underlying layer. For this purpose, the effects of temperature, tack coat application rate, underlying layer depth and material type on ISS values were studied. For testing, double-layered asphalt mix samples with SS-1 tack coat applied at their interfaces were compacted using a SGC. The tack coat was applied at residual application rates, namely 0, 0.03, 0.07, and 0.11 gal/yd^2 and were allowed to break for 30 minutes. The results indicated that temperature was the most influential factor affecting the ISS values between OFGC and underlying layer, followed by surface texture depth of underlying layer. A decrease in temperature was found to increase the ISS. At 25°C, residual application rate and surface texture had significant effects on the measured ISS values. Also, it was observed that at 50°C, variation in the residual application rate did not significantly affect the ISS values.

In a study conducted by Willis and Taylor (2015), two-layer HMA slabs were prepared in the laboratory using different application rates, different emulsions, and different surface conditions (new HMA and milled surface). A Nano (derived from organosilane)-modified emulsion, which converts a hydrophilic surface to a hydrophobic surface, and a cationic emulsion (CSS) were used in this study. Shear strength tests were conducted to determine the interlayer shear strength of samples cored from the slabs. Results indicated that the bond strength of the cores with modified emulsion and those containing CSS were similar. Moisture-induced damage was observed for the new HMA surface, but not for the milled surface. Also, the new HMA samples with modified and control emulsions had the equivalent resistance to moisture-induced damage.

Seo et al. (2015) conducted Multiple-Stress Creep Recovery (MSCR), X-ray diffraction, and adhesion tests using a Pneumatic Adhesion Tensile Testing Instrument

(PATTI) considering three different aggregates, one trackless tack coat (CQS-1HT) and one asphalt binder (PG 64-22). The results indicated that the resistance to permanent deformation and bonding strength at the interface increased with aging time. Also, the bond strength of tack coat and asphalt binder at the interface was independent of aggregate type. However, in general, the aggregate with smooth surface showed slightly higher bonding than that with rough surface. The results also indicated that the temperature is an important factor for interaction between asphalt binder and aggregate. The pull-off strength, measured using a PATTI device, showed an increase with an increase in preheating temperature of aggregate.

Panda et al. (2014) studied the influence of setting time on the ISS of tack coats, namely CRS-1 and CMS-2 tack coats and VG 10 and VG 30 asphalt binders. For this purpose, double-layered asphalt samples were compacted in the laboratory with 101.5 mm diameter and 100 mm height (60 mm for bottom and 40 mm for upper layers). The testing was performed by applying the load on the upper layer sample at a displacement rate of 50.8 mm/min. It was found that the ISS values were a function of tack coat type, application rate, curing time, and test temperature. Based on the test results, the optimum application rate was recommended to be 0.25 kg/m^2 for CRS-1 tack coat, 0.15 kg/m^2 for CMS-2 tack coat, and 0.2 kg/m^2 for both VG 10 and VG 20 asphalt binders. Additionally, among all the considered tack coats and asphalt binders, CRS-2 exhibited the maximum interlayer shear strength with the minimum application rate. The ISS values were the highest in the absence of a tack coat.

Wang et al. (2013) measured zeta potential of asphalt droplets to evaluate the effect of the pH value on cationic and anionic emulsifiers. The results indicated that an increase in pH value decreases the zeta potential leading to formulation of a flocculated structure and a reduction in the stability of the emulsion. On the other hand, anionic emulsions showed slightly improved performance as a result of an increase in pH value. The increased size of asphalt droplets in the cationic emulsion due to flocculation was visible in the results obtained from laser diffraction and optical microscope tests.

Raposeiras et al. (2013) studied the effectiveness of a newly designed device for controlling the application rate of tack coats, based on the surface macro-texture. The surface macro-texture of a sample was estimated based on its volumetric properties such as air voids. Based on the results, it was concluded that the device could be used to determine the proper amount of tack coat to be applied on site. In this study, the device was basically used to determine the absorbance of the emulsion by a geotextile on its surface macro-texture. The research indicated that geotextiles of low surface macro-texture values absorbed the highest amount of emulsion. Also, an increase in the amount of a tack coat increased the absorption by the geotextiles. This was likely due to the fact that for samples with low surface macro-texture, the applied tack coat accumulated on the samples' surfaces. However, for samples with a high surface macro-texture, the applied tack coat flowed through the sample reducing the emulsion retained on the surface.

In a study conducted by Chen et al. (2012), the ISS and cracking resistance of a trackless tack coat (a polymer-modified hard base asphalt) were evaluated and compared to those of a SS-1 tack coat. For this purpose, the double-layered asphalt samples, were prepared using a SGC. Samples consisted of a dense-graded asphalt mix in the lower layer and an open-graded asphalt mix in the upper layer with the trackless tack coat applied to the contact. The repeated tensile loading cycles were applied to compacted samples and the number of cycles to failure was recorded along with the damage rate. The results indicated that the samples with trackless tack coat exhibited a lower resistance to top-down cracking as compared to samples with SS-1 tack coat. However, the ISS values measured for the samples containing trackless tack coat at their interface were found to be higher than those for samples with SS-1 tack coat. Also, an increase in the residual application rate was found to increase the ISS of the interlayers containing trackless tack coat. It was recommended to consider both shear strength and cracking resistance of the interface for selecting any interface bonding agents.

Mohammad et al. (2010) conducted a full-scale experimental study to investigate the ISS of PG 64-22 asphalt binder and four different tack coats, namely SS-1h, SS-1, CRS-1, and trackless tack coats. For this purpose, four different residual application rates (namely 0, 0.03, 0.06, and 0.15 gal/yd^2), four distinct surface types (existing HMA, new HMA, milled HMA, and existing PCC), two levels of confining pressures (0 and 138 kPa), one test temperature (25°C), and two moisture conditions (wet and dry) were considered. Double-layered asphalt mix samples of 100 mm diameter were compacted in the laboratory using a SGC with tack coat layer applied to the layers' interfaces. Four test lanes were also constructed in the field and 100 mm diameter cores were collected. The samples were tested using the LISST device at a displacement rate of 2.54 mm/min. It was observed that the applied tack coats reduced the moisture-induced damage potential of the samples. Among all tack coats, trackless tack coat exhibited the highest ISS regardless of the application rate and surface type. The results of the LISST tests conducted on the field cores indicated that the ISS values increased with an increase in application rate. Therefore, the optimum application rate was not recommended for any tack coat. Furthermore, the milled HMA surfaces resulted in the maximum ISS values followed by the existing PCC, existing HMA, and new HMA surfaces. The study also reported that the ISS values of laboratory-prepared samples was 2 to 10 times higher than those of field cores.

Leng et al. (2008) studied the effect of HMA type, residual application rate of tack coat, PCC surface texture, and temperature on the ISS of different tack coats. For this purpose, SS-1hP emulsion and RC-70 cutback were used as tack coats. The tack coats were applied at 0.02, 0.05, and 0.09 gal/yd^2 residual application rates. The results indicated that the SS-1hP emulsion tack coat had higher ISS values at different temperatures and application rates than the RC-70 cutback tack coat. Also, tack coats applied to the interface of a surface mix, with a Nominal Maximum Aggregate Size (NMAS) of 9.5 mm, exhibited higher ISS values than the mix with an NMAS of 19 mm. Based on the ISS values measured at different residual application rates and surface types, 0.05 gal/yd^2 was selected as the optimum residual application rate. Furthermore, an increase in temperature resulted in a significant decrease in the ISS values.

Tashman et al. (2006) studied the effect of several factors, namely surface treatment, curing time, residual application rate, and coring locations on the ISS of existing HMA layer and a new HMA overlay. A Florida DOT shear tester was used to measure the ISS values of the CSS-1 tack coat applied at the layers' interfaces. Tack coats were applied at residual application rates of 0.00, 0.018, 0.048, and 0.072 gal/yd^2. It was found that milled sections had significantly higher ISS values at the interface than non-milled sections. Similar results were observed in the absence of tack coat at the interface. For non-milled sections, the absence of tack coat resulted in significantly lower ISS values. The test results indicated that curing time, residual application rate, and coring location had minimal effect on the ISS values.

In a study conducted by Cross and Shrestha (2005) a guideline was developed to for the design engineers and construction crew to ensure adequate and appropriate application of prime and tack coat in construction of asphalt pavements. In this study, a literature review covering the available guidelines, manuals, specifications, and reports was carried out. Also, information from phone surveys was collected. The study summarized the usage, material types, properties and effectiveness of the prime and tack coat, as well as the negative and positive environmental effects on their performance.

Canestrari and Santagata (2005) validated the use of the ASTRA (Ancona Shear Testing Research and Analysis) interface shear test to evaluate the performance of tack coats. The tests were conducted at different temperatures and normal stresses. For this purpose, double-layered asphalt mix samples were prepared using the asphalt mix consisting of 5.8% of 50/70 penetration grade binder. The results were processed to predict the effects of dilatancy, normal stress, tack coat type, and test temperature. The results were also compared with theoretical approach based on the identification of various strength components due to cohesion, pure friction, and dilatancy. It was found that the newest version of the equipment successfully captured the temperature related effects of tack coats on the interlayer bond strength.

Pouliot et al. (2003) studied the effect of using both cationic and anionic asphalt emulsions, namely SS-1 and CSS-1, in the cement slurry. It was observed that the addition of asphalt emulsions (up to 10%) did not influence the hydration process of the cement slurry. Scanning Electron Microscope (SEM) results showed a uniform dispersion of the asphalt droplets in the cement mortar. Also, a decrease in the mechanical strength of the cement paste was observed because of using asphalt emulsion. Also, cement pastes containing a cationic emulsion had higher strengths than the pastes containing an anionic emulsion. Furthermore, it was observed that cement pastes containing asphalt emulsions exihibit a higher peak strain, indicating an increased ductility of the system.

Mohammad et al. (2002) performed simple shear tests at 25˚C and 55˚C to determine the ISS values and optimum application rates of tack coats. For this purpose, four tack coats, namely CRS-2P, SS-1, CSS-1, and SS-1h and two asphalt binders, namely PG 64-22 and PG 76-22, were selected. The residual application rates were 0, 0.02, 0.05, 0.1, and 0.2 gal/yd^2. A total of 156 double-layered asphalt mix samples with tack coat layer applied to interfaces were compacted in the laboratory using a SGC. The tests were conducted at a constant loading rate of 222.4 N/min. The results indicated that an increase in the residual application rate or temperature resulted in a reduction in the ISS values. At high temperatures, a change in the application rate was found to have a negligible effect on the ISS values. When PG 64-22 and PG 76-22 asphalt binders were used as tack coats, the optimum residual application rates for both tack coats were found to be 0.5 gal/yd^2. Similarly, the optimum residual application rate for CSS-1 tack coat was observed to be 0.5 gal/yd^2. The use of SS-1 or SS-1h did not result in any improvement in the ISS values. Also, the results indicated that among all the tested tack coats, use of the CRS-2P resulted in the highest ISS values at both temperatures and at the optimum application rate of 0.2 gal/yd^2.

Paul and Scherocman (1998) conducted a series of field tests to determine the frictional characteristics of asphalt interfaces containing tack coat. Effects of factors such as residual application rate, testing time, and combinations of wet, dry, and flushed surface conditions on ISS values were studied. It was found that at typical residual application rates specified in Louisiana, reduced surface friction condition existed for up to 7 hours after tack coat application. Based on the measured friction numbers, it was suggested that traffic should be maintained only at controlled low speeds if at all. This is due to the friction properties of the tack-coated surface at residual application rates that would allow traffic at moderate speeds. After several days of traffic or weather abrasion, friction numbers returned to the original condition.

Li et al. (1998) conducted the laboratory tests on strength, fatigue life, rigidity, temperature susceptibility on the cement-asphalt emulsion composite (CAEC). In this study, the coarse aggregate was coated with CSS-1h emulsion and then mixed with cement mortar. The results indicated an increase in the fatigue life and ductility of the composite after adding emulsion. Thereby, it was suggested that CAEC be used in the base course of flexible pavements. However, a CAEC system had relatively low strength than cement concrete base due to weak interfacial bond between the asphalt layer and cement mortar.

From the summary of previous studies presented above it is evident that for a given tack coat and application rate, the interlayer shear strength depends on various factors such as curing time, surface roughness, confinement, temperature, scale (laboratory vs field) and loading rate (static vs cyclic). These factors can have different levels of influence on the adhesive and frictional components of the overall interlayer shear strength.

Chapter 3 Materials and Methods

In this chapter, a description of the materials and laboratory methods used for conducting this study is provided. Whenever possible, standard test methods (AASHTO and ASTM) are used. It should be noted that, “interlayer shear strength,” “interface bond strength” and “bond strength” are used interchangeably in this report. Also, the terms “aged HMA surface” and “aged and worn HMA surface” are used interchangeably.

3.1 Material Collection

For this study, an asphalt mix and different types of tack coats were collected from a local asphalt plant and material suppliers. The identification and selection of the materials and their suppliers were carried out in close cooperation with the ODOT Materials Division.

3.1.1 Asphalt Mix

A dense-graded surface course (S4) asphalt mix (NMAS=12.5 mm) without any RAP or RAS was collected from the asphalt plant of Haskell Lemon Construction Co. in Norman, Oklahoma. Figure 3.1 and Figure 3.2 show photographic views of the material collection efforts. The collected mix consisted of 5.2% of PG 64-22 asphalt binder. The details of aggregate types and sources used in this mix are given in Table 3.1. The particle size distribution data of the collected mix is given in Table 3.2 and the gradation curve of combined aggregates is presented in Figure 3.3. The mix ID for the collected mix was S4qc0131302900.

Figure 3.1 Collection of Asphalt Mix from Haskell Lemon Construction Co., Norman, OK

Figure 3.2 Stacking of the Collected Asphalt Mix in the Truck

Table 3.1 Aggregate Type and Source for the Collected Asphalt Mix from Haskell Lemon Construction Co., Norman, OK (Mix-ID: S4qc0131302900)

Bin No.	Aggregate	Supplier	Aggregate Type	Amount of Aggregate (%)
1	5/8" Chips	Martin-Marietta (Snyder, OK) P/S # m002323802	Granite	37
2	Man. Sand	Martin-Marietta (Davis, OK) P/S # m002285005	Limestone	17
3	C-33 Scrns.	Martin-Marietta (Snyder, OK) P/S # m002323802	Granite	11
4	Scrns.	Martin-Marietta (Snyder, OK) P/S # m002323802	Granite	20
5	Sand	General Materials Inc (Oklahoma City, OK) P/S # m009215515	Sand	15

Table 3.2 Aggregate Gradation for the Collected Asphalt Mix from Haskell Lemon Construction Co., Norman, OK

Sieve Size mm (in.)	% Passing Bin No. 1	% Passing Bin No. 2	% Passing Bin No. 3	% Passing Bin No. 4	% Passing Bin No. 5	Combined Gradation (%)
19 (3/4 in.)	100	100	100	100	100	100
12.5 (1/2 in.)	88	100	100	100	100	96
9.5 (3/8 in.)	62	100	100	100	100	86
4.75 (#4)	5	94	90	62	99	61
2.36 (#8)	1	56	65	69	95	45
1.18 (#16)	1	30	43	47	84	32
0.6 (#30)	1	18	26	33	65	23
0.3 (#50)	1	10	13	22	40	14
0.15 (#100)	1	6	6	14	14	7
0.075 (#200)	0.5	3.5	3.5	9.4	1.6	3.3

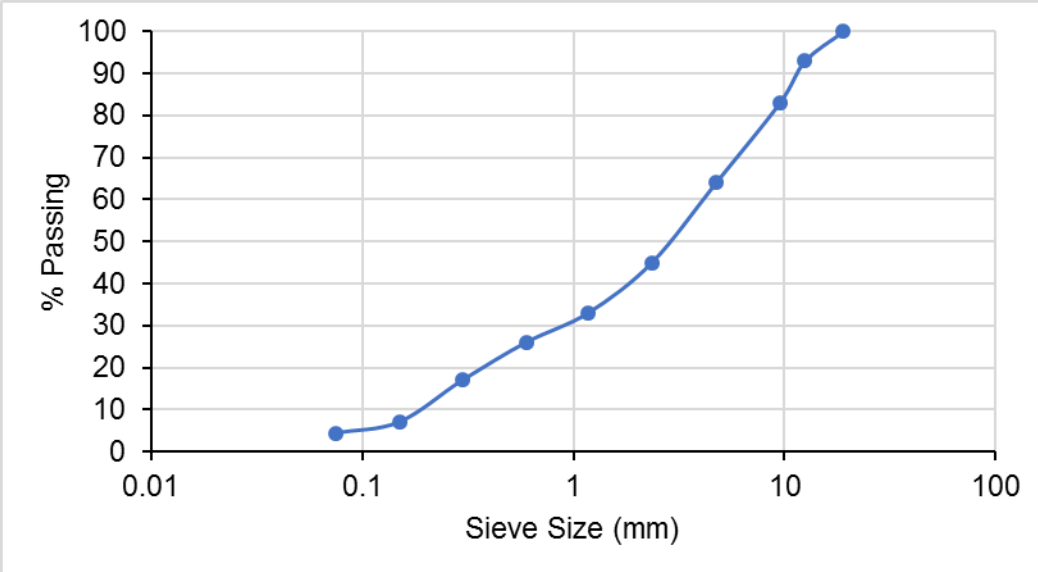


Figure 3.3 Aggregate Gradation Curve of the Mix

3.1.2 Tack Coats

For this study, six different types of tack coats, namely SS-1, CRS-1S, CBC-1H, CRS-1, NTQS-1HH, and NTHAP, were shipped to the University of Oklahoma Broce Asphalt Laboratory. Tack coats are generally classified as Slow Setting (SS), Medium Setting (MS), and Rapid Setting (RS) depending upon the amount and type of emulsifying agent and base binder used during production (Brown et al., 2009). For example, SS-1 is a slow setting tack coat and CRS-1S and CRS-1 tack coats both are rapid setting tack coats. Therefore, the SS-1 tack coat is not recommended for using in cold climate, in night construction, during precipitation, or in rapid construction (CAPA, 2017).

Also, tack coats are classified as anionic (negatively charged) and cationic (positively charged) with letter 'C' based on their electric charge imparted by the emulsifying agent (Brown et al., 2009). For instance, SS-1 is an anionic slow setting tack coat and CRS is a cationic rapid setting tack coat. However, NTHAP and NTQS-1HH tack coats are categorized as trackless tack coats containing polymer-modified hard base asphalt binder. Table 3.3 shows the tack coats collected for this study along with their general classifications.

Table 3.3 Tack Coat Classification

No.	Tack Coat Type*	Anionic	Cationic	Trackless
1	SS-1	✔		
2	CRS-1S		✔	
3	CBC-1H		✔	✔
4	CRS-1		✔	
5	NTQS-1HH	✔		✔
6	NTHAP			✔

**SS: Slow Setting; RS: Rapid Setting; QS: Quick Setting; 1: Low viscosity; NT: Non-Tracking (Trackless); H: Hard Base Binder; S: Soft Base Binder; and P: Polymer-Modified Base Binder.*

As discussed in Chapter 2, the tack coat application rate should be adjusted with respect to the pavements' surface conditions in order to achieve adequate interface bond (Mohammad et al., 2012). Inadequate tack coat coverage or low application rate may lead to a weak interlayer bond strength and resulting pavement distresses. Excessive tack coat application can result in shear-induced slippage at the interface (Mohammad et al., 2012). Therefore, determining the type and optimum amount of tack coat application rate is vital to performance and service life of a pavement. In this study, the LISST tests were conducted at four different residual application rates, namely 0, 0.031, 0.062, and 0.155 gal/yd^2 to determine the optimum application rates of the selected tack coast. For the NTHAP tack coat, three selected application rates of 0.08 gal/yd^2, 0.12 and 0.155 gal/yd^2 were used for sample preparation. Of these selected rates, 0.08 gal/yd^2 is recommended by the manufacturer.

3.1.2.1 Determination of Asphaltic Residue of Tack Coats

Asphaltic residue of tack coats was measured in accordance with the procedure 'A' specified in the ASTM D 6834 "*Standard Test Method for Residue by Evaporation of Emulsified Asphalt*" (ASTM, 2008). This method requires heating up 50 ± 1.0 gm of a tack coat emulsion in an oven at 163° ± 3°C for two hours in three different 1,000 ml glass beakers. During the two-hour-long heating period, tack coat was manually stirred thoroughly using a glass rod. Then, the beakers were placed back in the oven for another hour at the same temperature for the remaining water to evaporate. Finally, the residue in the beakers was cooled at room temperature. The asphaltic residue of the tack coat was then determined in percent using Equation (1).

$$Residue\ (\%) = 2\ (A - B) \qquad (1)$$

where,

A = weight of sample, beaker, and rod after oven aging (gm); and

B = weight of beaker and rod (gm).

The measured asphaltic residue of the tack coats is presented in Table 3.4. It is evident from Table 3.4 that the selected tack coats had different asphaltic residue contents varying from 49.8% for CBC-1H to 100% for NTHAP. The other tack coats, namely SS-1, CRS-1S, CRS-1 and NTQS-1HH had similar asphaltic residue contents. These results indicated that the amount of tack coat required to achieve the same residual application rate are different: maximum for CBC-1H, followed by SS-1, CRS-1S, NTQS-1HH, CRS-1, and NTHAP. From Table 4, the standard deviation of the results was very low, indicating a good repeatability of the test results. According to ASTM D 6934 test standard (ASTM, 2008), the test results having less than 0.4% repeatability in weight difference can be accepted with a 95% confidence level.

Table 3.4 Asphaltic Residue of Tack Coats

No.	Tack Coat Type	Residue (%) Beaker 1	Residue (%) Beaker 2	Residue (%) Beaker 3	Average	Standard Deviation
1	SS-1	63.0	62.8	63.0	62.9	0.1
2	CRS-1S	62.8	63.0	63.2	63.0	0.2
3	CBC-1H	49.8	49.8	49.8	49.8	0.0
4	CRS-1	63.6	63.6	63.8	63.7	0.1
5	NTQS-1HH	63.2	63.2	63.2	63.2	0.0
6	NTHAP	Considered as 100%	Considered as 100%	Considered as 100%	Considered as 100%	Considered as 100%

3.1.3 Milled HMA and PCC Cores

Milled HMA and PCC field cores were collected from different projects with the help of ODOT Materials Division. Photographic views of the milled HMA and PCC cores are shown in Figures 3.4 (a) and 3.4 (b), respectively. A photographic view of the core bit and drill used by ODOT for extracting the field cores is shown in Figure 3.5.

Figure 3.4 Field Cores of (a) Milled HMA; and (b) PCC

Figure 3.5 Core Bit and Drill Used by ODOT for Extracting the Field Cores

3.2 Work Plan for Laboratory Testing

As noted previously, this study evaluated the effectiveness of tack coats used by the Oklahoma Department of Transportation with respect to their types and application rates, pavement surface conditions, moisture-induced damage, and temperature. Two test methods were used for testing the tack coats: (i) Interlayer Shear Strength (ISS) of tack coat using the Louisiana Interlayer Shear Strength Tester (LISST), developed by Mohammad et al. (2012); and (ii) Room-Temperature Tracking (RTT) test. The RTT tests were conducted in the laboratory to determine the amount of time required for a tack coat to become “trackless.” Figure 3.6 presents a flow chart showing the work flow followed for conducting the laboratory tests.

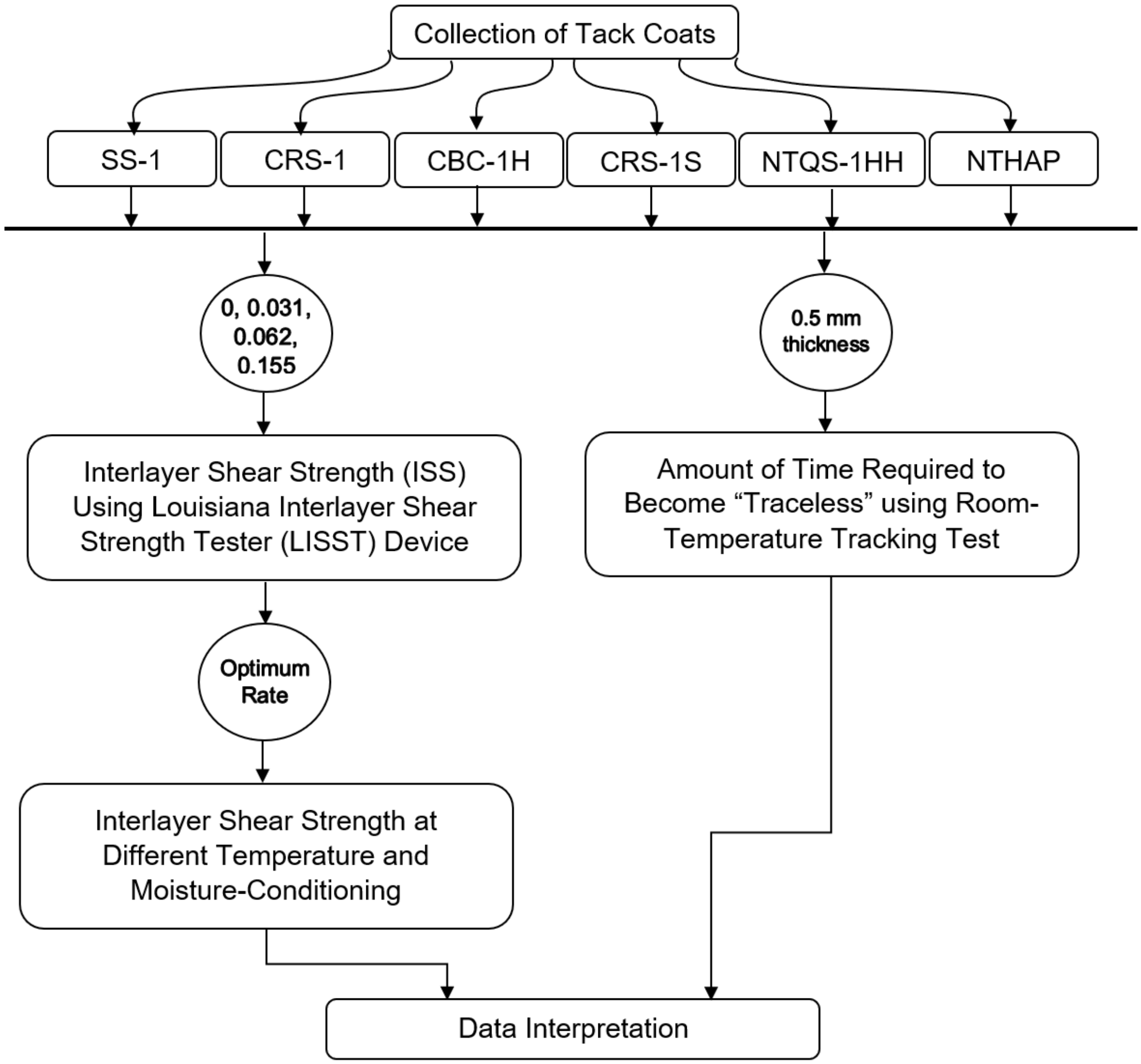


Figure 3.6 Work Flow of Laboratory Tests

3.3 Louisiana Interlayer Shear Strength Test (LISST)

The LISST device, as shown in Figure 3.7, was used to determine the ISS of test samples prepared without or with tack coats at different application rates. The details of the sample preparation for the LISST test are presented in Section 3.5. The measured ISS values were analyzed to determine the optimum application rate of tack coats for different surface types and to evaluate the tack coats' resistance to different environmental conditions. The LISST device consisted of two fixtures. One of these fixtures can move up and down (moving jaw) parallel to the other (stationary jaw). After the double-layered asphalt sample was fixed in the LISST device, the moving jaw was loaded in the vertical direction parallel to the asphalt layers' interface so that shear stresses are developed at the pre-existing interlayer, as depicted in Figure 3.8. Load application was increased until failure at the interlayer was observed.

In this study, a loading frame manufactured by Materials Testing Systems (MTS) was used to apply load on the samples inside the LISST device. The LISST tests were conducted inside an environmental chamber manufactured by GCTS. The chamber was mounted on the MTS loading frame to maintain the test temperatures used in this study. A test procedure or template was developed and programmed using the MTS software in order to apply the load in a displacement rate of 2.54 mm/min (0.1 in./min) until failure. The template was also used to record the axial forces as the displacements were applied. Figure 3.9 shows the variations of the axial force with crosshead displacement in a typical LISST test. The ISS value was calculated by dividing the maximum axial load at failure by the cross-sectional area of the sample, as shown in Equation (2).

$$ISS = \frac{Peak\ Axial\ Load}{Cross-Sectional\ Area} \quad (2)$$

Figure 3.7 Louisiana Interlayer Shear Strength Test (LISST) Setup

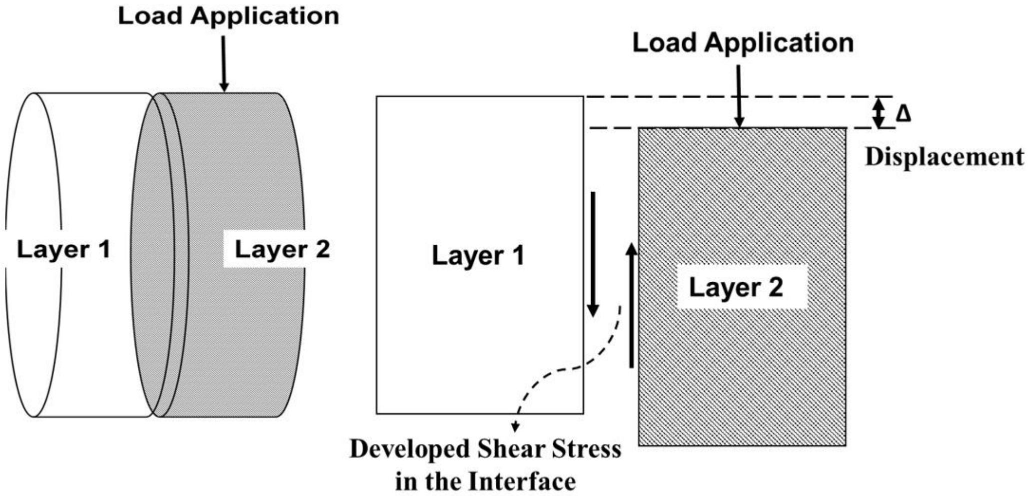


Figure 3.8 Working Mechanism of LISST Device

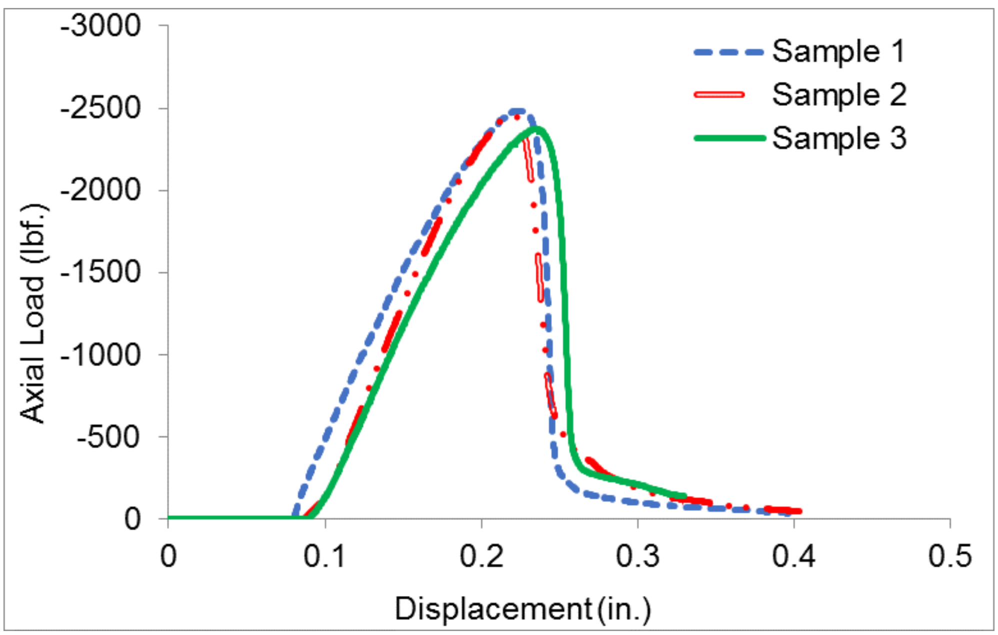


Figure 3.9 Typical Axial Force vs. Displacement Curve Obtained from a LISST Test

To fulfil the objectives of this study, samples for LISST tests were prepared without tack coat and with tack coat at residual application rates of 0, 0.031, 0.062, 0.155 gal/yd^2. Based on the LISST test results, the optimum residual application rate for each tack coat was calculated. The work flow and test matrix used for determining the optimum tack coat application rates are shown in Figure 3.10 and Table 3.5, respectively. From Table 3.5, it is evident that a total of 190 test samples, including those compacted in the laboratory and those collected from the field, were prepared to determine the optimum residual tack coat application rates. Then, the ISS values of each tack coat at its optimum application rate were determined under different temperature (low, intermediate, and high) and moisture conditions.

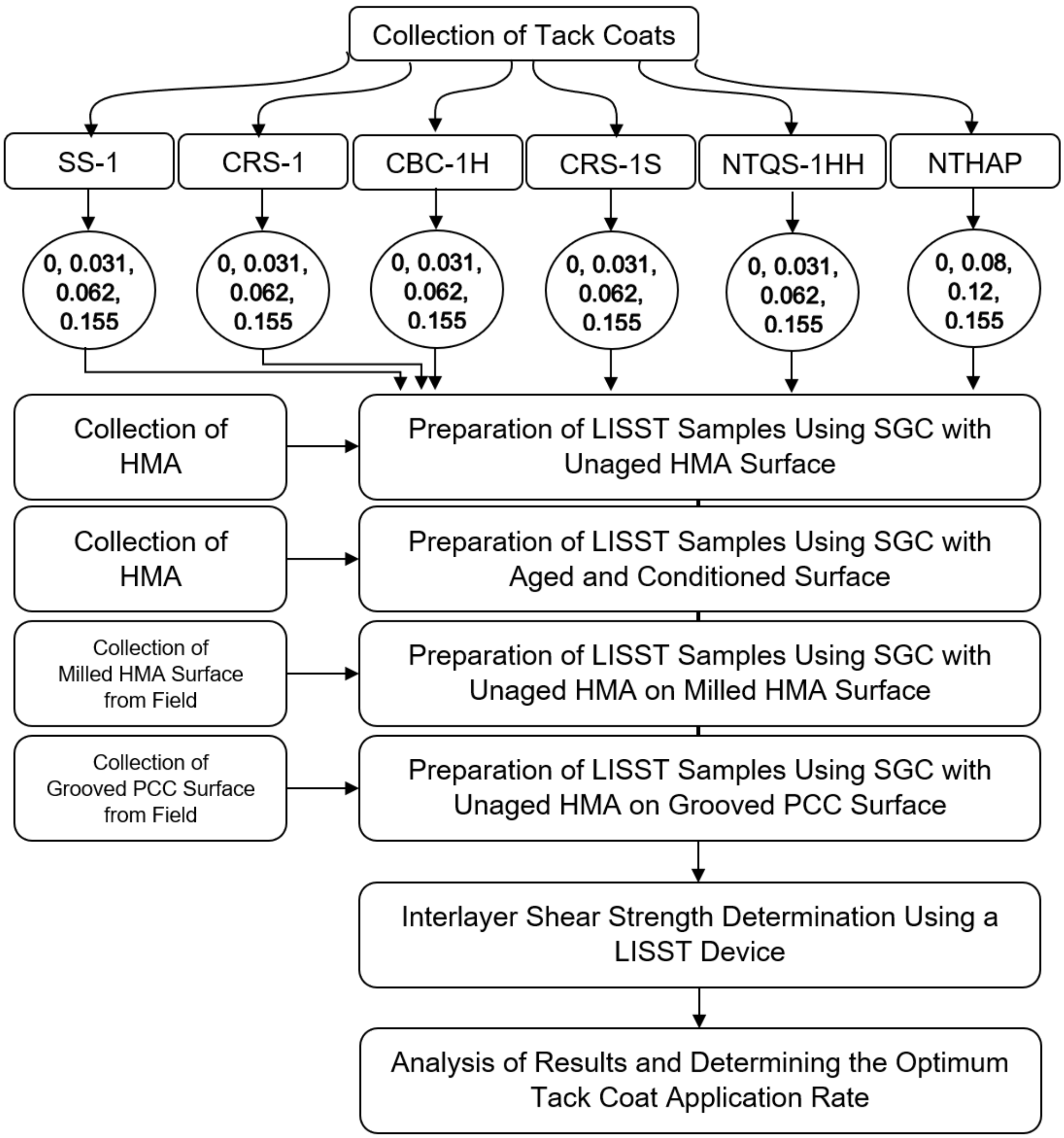


Figure 3.10 Work Flow for Determination of Optimum Tack Coat Application Rate

Table 3.5 Test Matrix for LISST Testing Based on Optimum Tack Coat Application Rate

No.	Tack Coat Type	Residual Application Rate (gal/yd^2)	Unaged HMA	Aged and Worn	Milled HMA Cores from Field	PCC Cores from Field
1	No Tack Coat	0	3	3	2	2
2	SS-1	0.031	3	3	2	2
3	SS-1	0.062	3	3	2	2
4	SS-1	0.155	3	3	2	2
5	CRS-1S	0.031	3	3	2	2
6	CRS-1S	0.062	3	3	2	2
7	CRS-1S	0.155	3	3	2	2
8	CBC-1H	0.031	3	3	2	2
9	CBC-1H	0.062	3	3	2	2
10	CBC-1H	0.155	3	3	2	2
11	CRS-1	0.031	3	3	2	2
12	CRS-1	0.062	3	3	2	2
13	CRS-1	0.155	3	3	2	2
14	NTQS-1HH	0.031	3	3	2	2
15	NTQS-1HH	0.062	3	3	2	2
16	NTQS-1HH	0.155	3	3	2	2
17	NTHAP	0.08	3	3	2	2
18	NTHAP	0.12	3	3	2	2
19	NTHAP	0.155	3	3	2	2
Total	*	*	57	57	38	38

Since temperature plays an important role in the interlayer shear strength (Mohammad et al., 2012), a series of ISS tests were conducted on unaged and aged samples at three selected temperatures (7° (low), 25° (intermediate), and 60°C (high)), as shown in Table 3.6. The results from these tests were used to quantify the effect of temperatures on the ISS values when tack coats were applied at their optimum application rates. For this purpose, the LISST samples were placed in an environmental chamber for at least 6 hours at the desired temperature before testing.

As noted earlier, in addition to providing resistance to interlayer shearing, a tack coat is serves as a moisture barrier at the interface and reduces any moisture-induced damage. For this purpose, the ISS values of the samples prepared with or without tack coats at their optimum application rates were determined before and after moisture-conditioning. In this study, a Moisture-Induced Stress Tester (MIST) was used for moisture-conditioning the samples. Details of moisture-conditioning of the samples using a MIST device are presented in Section 3.4.6. After completion of moisture-conditioning, samples were tested at 25°C, as shown in Table 3.6. According to Table 3.6, 154 samples were tested in total to determine the effect of temperature and moisture on their interlayer shear strengths.

Table 3.6 Test Matrix Used to Determine the Effects of Temperature and Moisture on ISS Values

No.	Tack coat Type	Surface Type	Unconditioned 7°C	Unconditioned 25°C	Unconditioned 60°C	Moisture-Conditioned 25°C
1	No Tack Coat	Unaged HMA	3	3	3	2
2	No Tack Coat	Aged HMA	3	3	3	2
3	SS-1	Unaged HMA	3	3	3	2
4	SS-1	Aged HMA	3	3	3	2
5	CRS-1S	Unaged HMA	3	3	3	2
6	CRS-1S	Aged HMA	3	3	3	2
7	CBC-1H	Unaged HMA	3	3	3	2
8	CBC-1H	Aged HMA	3	3	3	2
9	CRS-1	Unaged HMA	3	3	3	2
10	CRS-1	Aged HMA	3	3	3	2
11	NTQS-1HH	Unaged HMA	3	3	3	2
12	NTQS-1HH	Aged HMA	3	3	3	2
13	NTHAP	Unaged HMA	3	3	3	2
14	NTHAP	Aged HMA	3	3	3	2
Total	*	*	42	42	42	28

3.4 Preparation of Samples for LISST Testing

The LISST tests were conducted on samples consisting of two layers. In this report, the bottom layer is referred to as Layer 1 and the top layer is referred to as Layer 2. The tack coat is applied on the top of Layer 1. The following steps were used to prepare the test samples in the laboratory (Figure 3.11):

1. Preparation of bottom layer;
2. Application of tack coat; and

3. Compaction of top layer on the bottom layer.

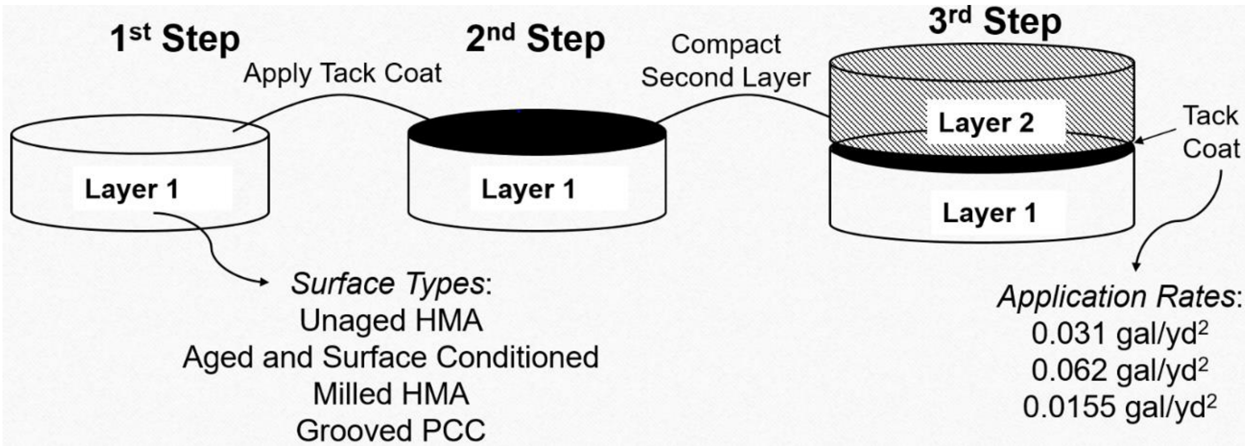


Figure 3.11 Preparation of Test Samples in the Laboratory

3.4.1 Preparation of Bottom Layer Samples

The collected S4 mix was heated to 165 ºC and used to prepare cylindrical samples of 60 mm (2.36 in) height and 150 mm (6 in) diameter using a SGC with 7% ± 0.5% air voids. These samples were used as the bottom layer of the double-layered samples. The calculation of dry weight of a sample corresponding to 7% ± 0.5% air voids is presented in Section 3.5.1.1.

In order to compact top layer, the bottom layer sample had to be placed back in the SGC mold. Therefore, a bottom layer sample was compacted with a diameter slightly smaller than the diameter of the SGC mold. For this purpose, new metal strips and paper board strips were used in the inner surface of the SGC mold, as shown in Figure 3.12 (a) and 3.12 (b). Figure 3.13 shows the metal strips and the paper board strips after being used for compaction. From Figure 3.13 it is evident that the metal and paper strips could not be reused, since they lost their shape after sample compaction. Therefore, new strips were cut and used for compacting each new sample. Figures 3.14 (a) and 3.14 (b) show the samples compacted using both metal strips and paper strips, respectively. It was found that the use of metal strips and cooling the samples inside the mold for 15 to 20 minutes after compaction resulted in the desired sample diameter, making it possible to slide into the mold under its self-weight, as depicted in Figure 3.15.

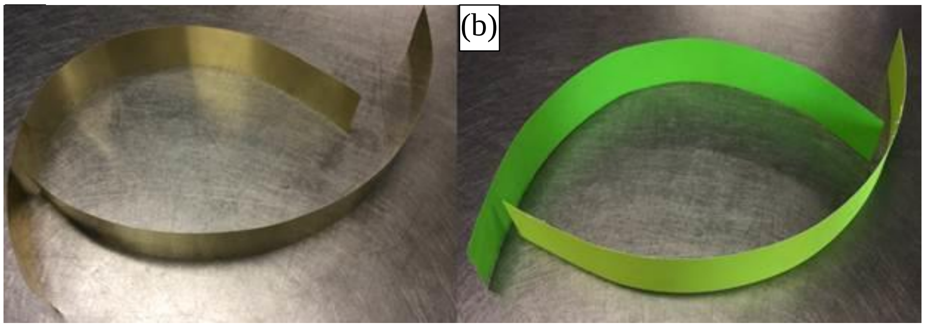


Figure 3.12 New (a) Metal Strips; and (b) Paper Board Strips Used Inside the Molds

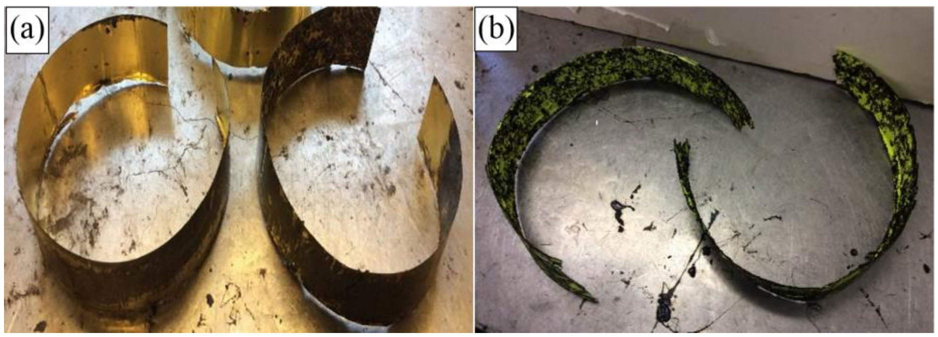


Figure 3.13 Used (a) Metal Strips; and (b) Paper Board Strips Used Inside the Molds

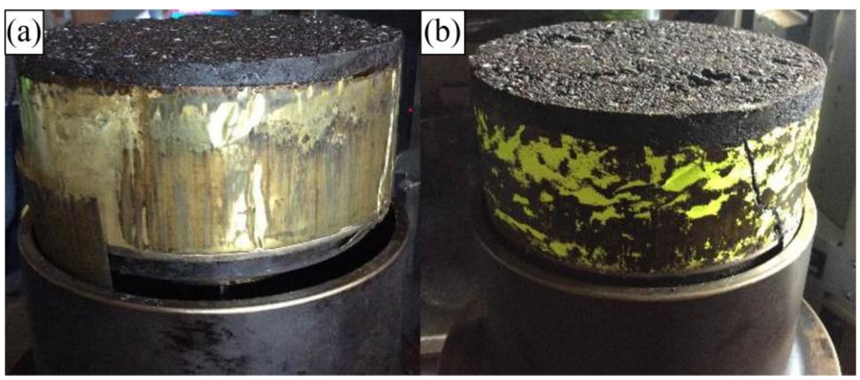


Figure 3.14 Asphalt Mix Samples Compacted using (a) Metal; and (b) Paper Strips

Figure 3.15 Sliding of Bottom Layer Sample into the SGC Mold Under Self-Weight

3.4.2 Preparation of Aged Asphalt Surfaces

In order to examine the effect of surface texture and aging on the interlayer shear strength, a number of bottom layer samples was surface-conditioned by polishing and aging. The surface-conditioning was carried out by polishing and smoothening the top surface using a 100-grit sand paper. After polishing the dusts from the surface were removed using pressurized air. Then, the samples were aged by keeping them inside a mechanical convection oven at 85˚C for 120 hours, as specified by the AASHTO R 30 (AASHTO, 2010) standard. A representative sample after polishing is shown in Figure 3.16. A representative sample after 120 hours of oven-aging is shown in Figure 3.17.

Figure 3.16 Asphalt Mix Sample after Polishing

Figure 3.17 Asphalt Sample Surface after 120 hours of Oven Aging and Polishing

3.4.3 Preparing Field Cores for LISST Testing

The collected milled HMA and PCC field cores were cut to the required height of 60 mm (2.36 in). Then, the samples were dried for 24 hours inside an oven at 45°C to a constant mass. Figures 3.18 (a) through 3.18 (f) show a systematic procedure followed in this study to prepare field cores having the height required for LISST testing. A number of field cores was not properly leveled (i.e., coring axis was not vertical to the top surface). Those samples were leveled by using plaster of Paris. This leveling correction ensured formation of pure shear plane at the interface while conducting the LISST tests. Misaligned interfaces can negatively impact the accuracy of the ISS values measured in LISST tests.

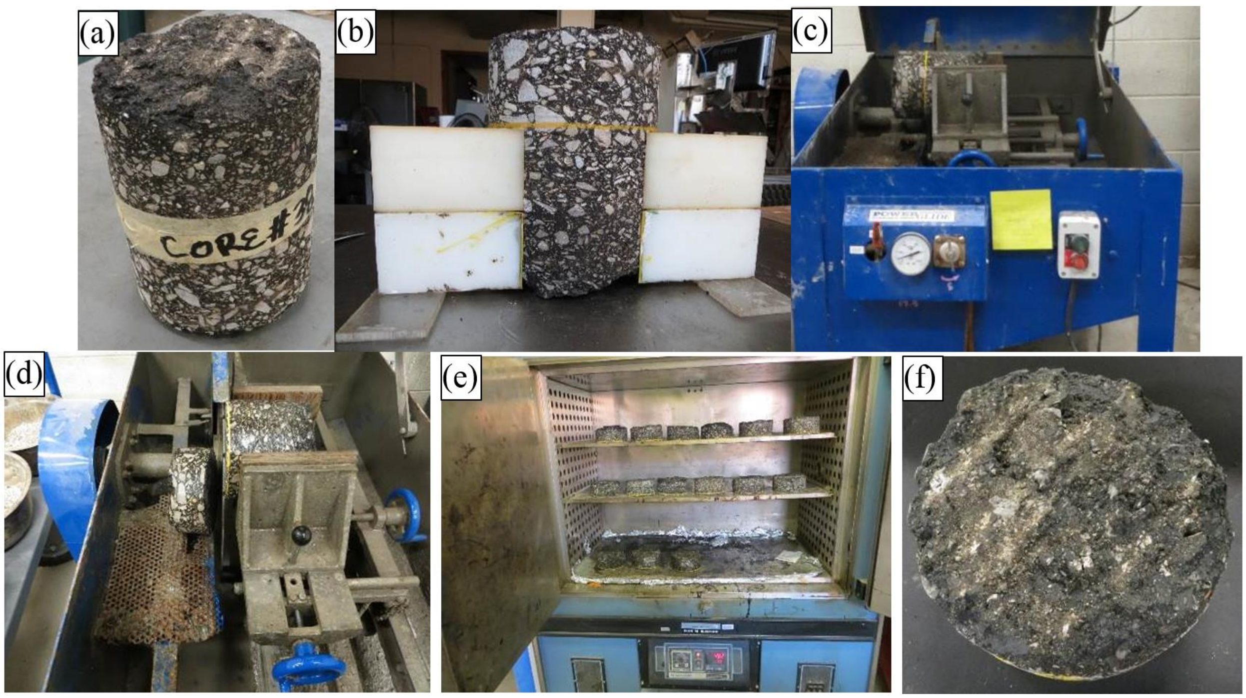


Figure 3.18 Photographic Views of the Procedure Followed for Preparing Field Cores for LISST Tests: (a) Typical Field Core; (b) Marking Sample; (c) Asphalt Saw; (d) Cut Sample, (e) Drying Samples in the Oven; and (f) Final Sample

3.4.1.1 Estimation of Sample Dry Weight Required for 7% ± 0.5% Air Void Content

The collected loose S4 asphalt mix was heated in an oven to 165°C and was compacted into the shape of cylindrical specimens of 60 mm (2.36 in) height and 150 mm (6in) diameter using a SGC to target air voids ranging from 6.0 to 8.5%. Bulk specific gravity (G_{mb}) of all compacted samples were determined in accordance with AASHTO T 166 (AASHTO, 2011) standard test method. The maximum theoretical specific gravity (G_{mm}) of the mix (2.499), from the mix design sheet (ID: S4qc0131302900) and the measured G_{mb} values were used to calculate the %density and air voids of the compacted samples. The measured G_{mb} and the corresponding air voids of a selected number of samples are presented in Table 3.7. The linear regression analysis was used to determine the dry weight of the asphalt mix corresponding to 7.0% air voids content (Figure 3.19). It was found that the dry weight should be 2435.5 g to obtain samples with 7% ± 0.5% target air voids. Additional G_{mb} tests confirmed this finding.

Table 3.7 Bulk Density and % Air Voids Content of Asphalt Mix Sample

Sample Name	**T/10F9**	**T/10F10**	**T/10F12**	**T/10F13**	**T/10F15**	**T/10F16**	**T/10F20**	**T/10F21**
Dry Wt. (g)	2343.6	2371	2387.5	2357.5	2371.2	2380.8	2439.6	2312
Wet Wt. (g)	1317.8	1344	1360.8	1333.2	1341	1354.4	1392.5	1294.9
SSD Wt. (g)	2361.6	2383.8	2400.5	2370	2381.2	2397.4	2445.3	2334.5
G_{mb}	2.245	2.280	2.296	2.274	2.280	2.283	2.317	2.224
% Air Voids	10.2	8.8	8.1	9.0	8.8	8.7	7.3	11.0

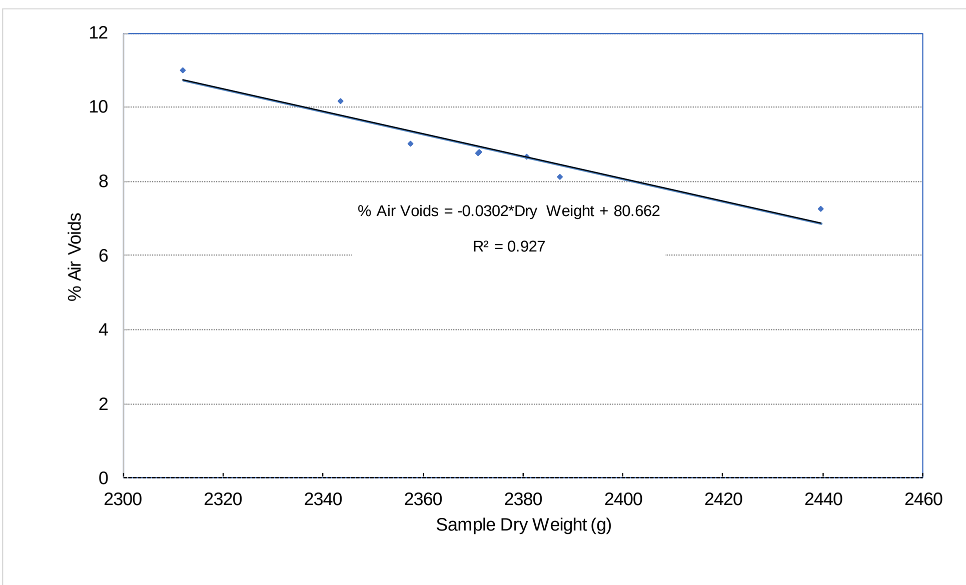


Figure 3.19 Percentage Air Voids of Asphalt Mix Samples at Different Dry Weights

3.4.4 Application of Tack Coat

In order to apply the right amount of tack coat, a bottom sample was placed on an electric scale and tared. Then, the required amount of tack coat was applied using a regular paintbrush, as used by contractors for small patches in the field and other researchers in the laboratory (Leng et al., 2008; Mohammad et al., 2009; Mohammad et al., 2010, Ghaly et al., 2014; Barrett Roofs, 2017). In this study, tack coats were applied at three different residual application rates of 0.031, 0.062, and 0.155 gal/yd^2. The required application weights of tack coats at application rates of 0.031, 0.062, and 0.155 gal/yd^2 were calculated based on the asphaltic residue content of the tack coats presented in Table 3.4. Photographic views of selected laboratory-compacted samples after application of tack coat at different residual application rates are shown in Figure 3.20. Also, photographic views of selected milled HMA cores after application of different amounts of tack coat are shown in Figure 3.21.

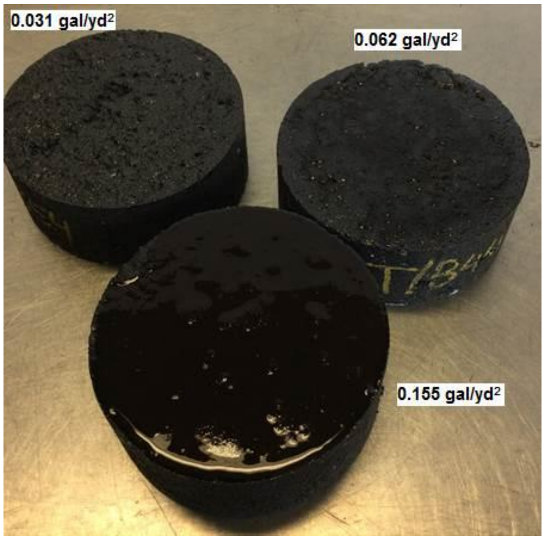


Figure 3. 20 Asphalt Samples after Application of Tack Coat

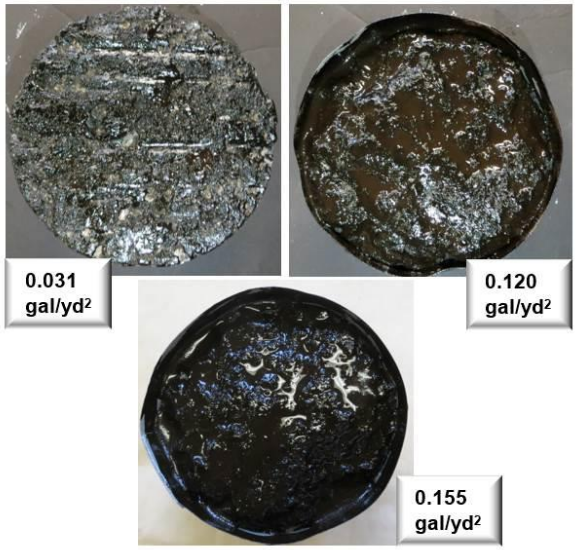


Figure 3.21 Photographic Views of Milled HMA Cores after Application of Tack Coat

3.4.5 Compaction of Double-Layered Test Samples

After reaching the breaking time of the tack coat applied on the surface of bottom layer sample, the process for compacting the top layer was initiated. The breaking of tack coat was ensured by visual changes in tack coat color from brown to black. Then, the bottom layer sample was placed inside an oven for 2 hours at 50˚C to represent a sun-warmed surface. The sample was then removed from the oven and placed inside the SGC mold. Then, a specified amount of loose hot mix asphalt, corresponding to 7.0% air voids, was poured into the mold on the top of the bottom layer sample. The mold was then placed in the SGC and the top layer sample was compacted so as to achieve a height of 60 mm (2.36 in). Thus, the final height of a double-layered sample after compaction was 120 mm (4.72 in). The compacted sample was cooled down to room temperature and extracted from the mold. A photograph of compacted double-layered samples, ready for testing, is shown in Figure 3.22.

Figure 3.22 Compacted Samples for LISST Testing

3.4.6 Moisture-Conditioning of Compacted Samples

In order to simulate the detrimental effects of moisture on interlayer bond strength, the compacted samples were moisture-conditioned in the laboratory using a MIST device. For this purpose, one sample at a time was placed inside the conditioning chamber of the MIST device. Then, the chamber was filled with water and its lid was secured on top by tightening the bolts attached to it. Next, the overflow cups were filled with water to about 2/3 of their capacity. Finally, the automated moisture conditioning process was initiated using the controller unit of the device. The moisture-conditioning process consisted of heating the sample to 60°C and performing 20 hours of adhesion, followed by 3,500 cycles of pressurizing (40 psi) and depressurizing at 60°C. A photographic view of the MIST device used for moisture-conditioning is shown in Figure 3.23.

Figure 3.23 A Photographic View of MIST Device used for Moisture-Conditioning of Samples

3.5 Room-Temperature Tracking (RTT) Test

The purpose of the Room-Temperature Tracking (RTT) test was to determine the amount of time required for a tack coat to become “trackless.” For this purpose, a #30 roofing paper, a steel cylinder (Figure 3.24), a mechanical spreader (Figure 3.25), and letter-size paper sheets were used. The test was conducted in accordance with ASTM D 711 (ASTM, 2010). The procedure followed for conducting the RTT test is listed below:

1. The roofing paper was cut to a width of 610 mm (24 in) and a length of 914 mm (36 in) and was secured to the concrete floor in Broce Laboratory using masking tapes (Figure 3.26);
2. A 203 mm (8 in) by 394 mm (15.5 in) area was marked on the roofing paper for tack coat application (Figure 3.26);
3. Tack coat was applied to the roofing paper inside the marked area using a mechanical spreader (Figure 3.27). In this study, a flexible mechanical spreader,

having a width of 203 mm (8 in) was used to spread a uniform layer of tack coat. The desired thickness of the tack coat was 0.5 mm (0.02 in);

4. A letter-sized white paper was then placed and secured to the floor for securing the impression of tack coat in O-rings and the steel cylinder, as shown in Figure 3.28;
5. The Room-Temperature Tracking device, consisting of a steel cylinder and rubber O-rings, was then set on a ramp having a slope of 1:6, as shown in Figure 3.28;
6. The cylinder was allowed to roll down (Figure 3.29a) the ramp and pass through the roofing paper and the letter-size white paper, as specified by ASTM D711(ASTM, 2010) (Figure 3.29b);
7. The letter-size paper was replaced by a new one each time and the impression of the wheel path was observed and photographed (Figure 3.30);
8. Tack coat residue was removed from O-rings and the steel cylinder;
9. The applied tack coat was allowed to set for 10 minutes before first testing and between subsequent testing;
10. After 10 minutes, the test was repeated till no track was seen on the letter-size paper;
11. The total time (from the application of tack coat and the last rolling with no track) was reported as the setting time.

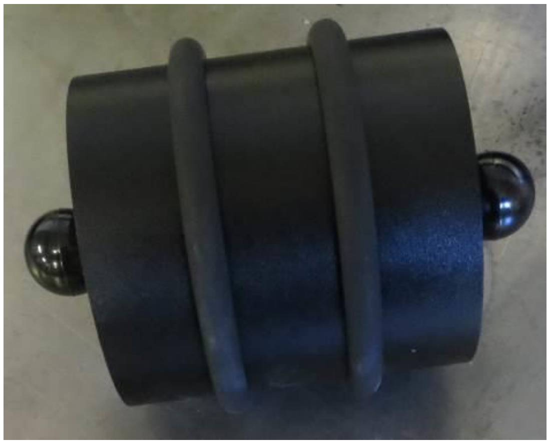


Figure 3.24 Steel Cylinder and Rubber O-rings Used for RTT Test

Figure 3.25 Mechanical Spreader Used for Spreading Tack Coat

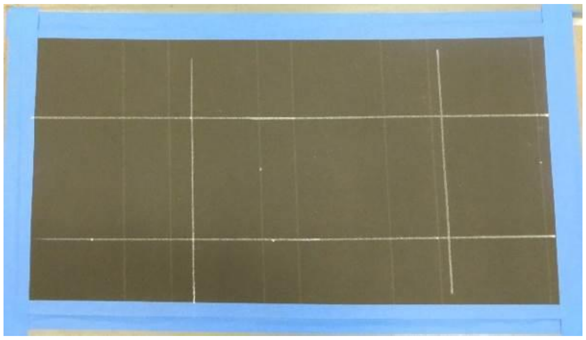


Figure 3.26 A Photographic View of the Marked and Secured Roofing Paper

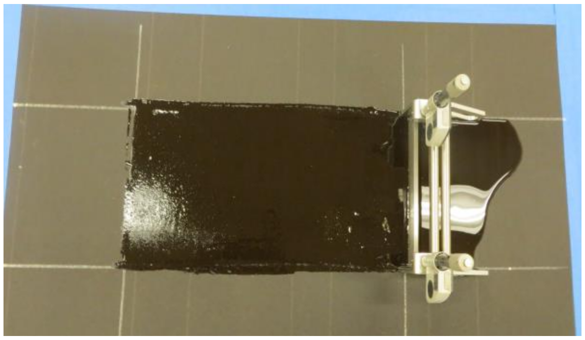


Figure 3.27 Spreading of Tack Coat on Roofing Paper Using a Mechanical Spreader

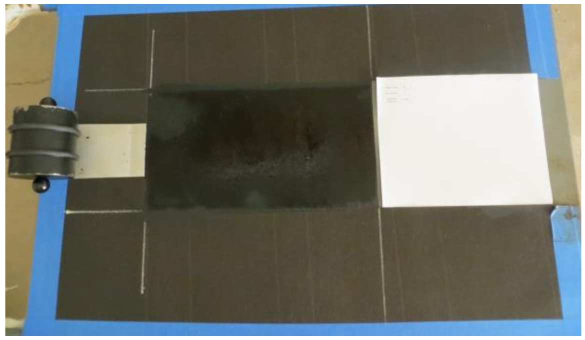


Figure 3.28 A Photographic View of the RTT Test Setup

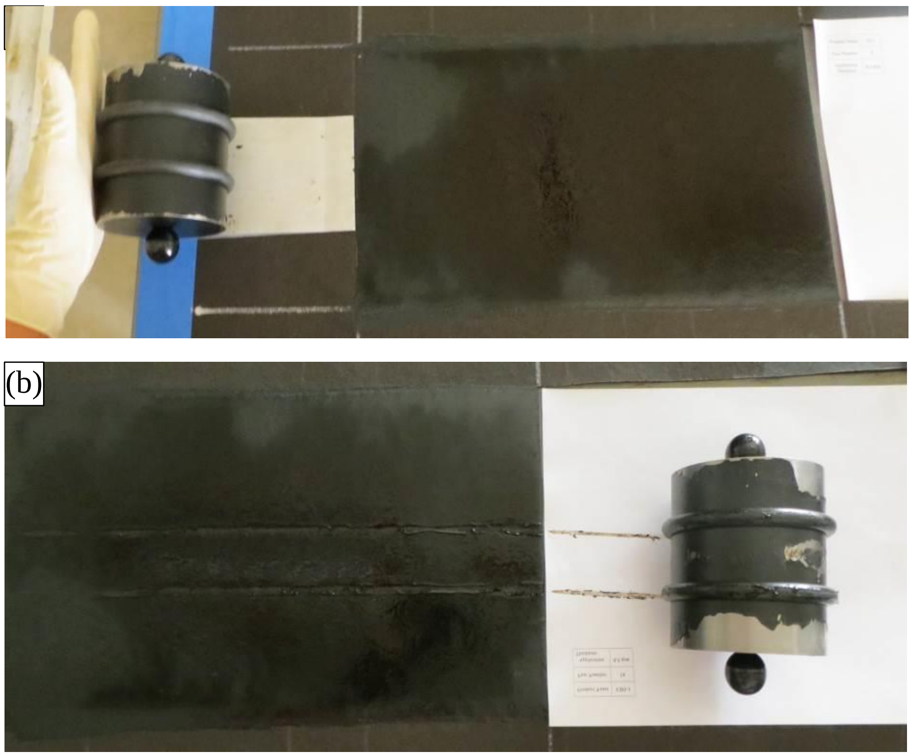


Figure 3. 29 Photographic Views of the RTT Cylinder (a) About to be Rolled; and (b) After Passing over Tack Coat and Letter-Sized Paper

Figure 3.30 Photographic View of the Tracking Mark on Letter-Sized Paper

Chapter 4 Results and Discussions

This chapter presents the ISS values obtained from the LISST tests involving different amounts tack coat type, amount, temperature, and surface and moisture conditions. Also, the setting times of tack coats measured using the RTT tests are discussed in this chapter.

4.1 Interlayer Shear Strength of Tack Coats

As discussed in Chapter 3, the interlayer shear strength of the double-layered test samples was measured using a LISST device placed inside an environmental chamber mounted. An MTS loading frame was used for testing these samples in shear (in a displacement-controlled mode) along a predefined surface, as discussed in Section 3.4. No confinement was considered in this study. The ISS values of the selected tack coats, namely SS-1, CRS-1S, CBC-1H, CRS-1, NTQS-1HH, and NTHAP, under different surface, temperature and moisture conditions, are presented in this section.

4.1.1 Effect of Residual Application Rates and Different Surface Types

4.1.1.1 Unaged HMA Surface

Figure 4.1 and Table 4.1 present the ISS values of tack coats for different residual application rates, namely 0, 0.031, 0.062 and 0.155 gal/yd^2 and unaged HMA samples tested at 25°C. To demonstrate repeatability of test results, important statistical parameters, namely Standard Deviation (St. Dev.) and Coefficient of Variation (COV), are presented in Table 4.1 and the corresponding error bars are shown in Figure 4.1. From Table 4.1, the COV values are found to be less than 6%, an indicator of good repeatability of test results. From Figure 4.1 and Table 4.1 it is evident that an increase in residual application rate from 0 to 0.031, 0.062 and 0.155 gal/yd^2 of SS-1 and CRS-1 tack coats resulted in a steady decrease in their ISS values. This decrease was found to be more notable for the CRS-1 tack coat. Application of 0.031, 0.062 and 0.155 gal/yd^2 of CRS-1 tack coat resulted in ISS values of 69.9, 65.3 and 45.4 psi, indicating 25, 30, and 51% reduction in the ISS values, respectively, compared to those of samples with no tack coat (93.1 psi). The ISS values for the SS-1 tack coat with application rates of 0.031, 0.062 and 0.155 gal/yd^2 were found to be 74.5, 70.1 and 58.5 psi, respectively, representing 20, 25 and 37% decrease in compared to the ISS values for samples with no tack coat (93.1 psi). For CBC-1H and CRS-1S tack coats it was also observed that an increase in tack coat application rate resulted in a decrease in the ISS values but to a lesser extent than those measured for SS-1 and CRS-1 tack coats. For example, application of 0.031, 0.062 and 0.155 gal/yd^2 of CBC-1H tack coat resulted in the ISS values of 78.9, 79.7 and 77.8 psi, representing 15, 14 and 16% reduction, respectively, compared to samples with no tack coat. Similarly, the ISS values of the CRS-1S tack coat with 0.031, 0.062 and 0.155 gal/yd^2 application rates were found to be 79.5, 75.8 and 75.2 psi, indicating a reduction of 15, 19 and 19%, respectively, compared to the ISS values of samples with no tack coat. A different trend in variation of ISS values with tack coat application rates was observed for the trackless tack coats. In general, an increase in ISS values was observed with an increase in tack coat application rates for the trackless tack coats. For example, application of 0.031, 0.062 and 0.155 gal/yd^2 of the NTQS-1HH tack coat resulted in ISS values of 89.3, 103.1 and 104.7 psi, representing 4% decrease and 11 and 12% increase in ISS values, respectively, compared to samples without any tack coat. Increase in ISS values with tack coat application rate was more pronounced for the NTHAP trackless tack coat: 0.031, 0.062 and 0.155 gal/yd^2 application rates of NTHAP resulted in ISS values of 110.0, 112.2 and 115.9 psi, indicating 18, 21 and 24% increase in the ISS values, respectively, compared to samples without any tack coat.

As reported by previous researchers, the ISS values are influenced by various factors including tack coat type, application rate, temperature, surface type, surface condition, confinement, curing time, and loading type and rate (Ai et al., 2017; Destree and Visscher, 2017; Zhang, 2017; Nguyen et al., 2016; Song et al., 2015; Willis and Taylor, 2015; Seo et al., 2015; Leng et al., 2008; Mohammad et al., 2012). Failure mechanism wise, the overall shear strength of interfaces is governed by the adhesive and cohesive strength and the frictional strength. Although the cohesive component of ISS is expected to increase with increasing application rate (up to some rate), the frictional component can decrease, the level of reduction depending upon the application rate. Such reductions in frictional component can be significant under no confinement, which is a likely parameter in the decrease of ISS with increasing application rate. Also, temperature is another influential parameter as both cohesive and frictional strengths are impacted negatively (i.e., reduced ISS) by increasing temperature. The type of base binder in a tack coat also plays an important role in the variations in the ISS values due to application rates. A hard base binder, representing the trackless tack coats in this study, can have significantly higher shear strengths than a soft base binder. Influence of the base binder type is likely to reduce with increasing test temperature. Curing time is another important influencing parameter. Previous studies show that the ISS values increase with increased curing time. In the present study, a selected curing time of one day was used for all specimens. The selection of one day as curing time was due to the fact that the time and traffic are known to contribute to development of sufficient bond between the old and the new asphalt pavement layers (Mohammad et al., 2012). According to Mohammad et al. (2012) use of slow-setting emulsions as tack coat in overlay projects may result in premature pavement failure due to slippage during the early life of the pavement. The premature slippage becomes a more serious concern if the pavement experiences heavy traffic immediately after construction. Failure mode (shear vs tensile) is another extremely important parameter in tack coat performance. In the present project, only shear failure was studied. Incorporation of tensile failure in a future study would significantly enrich the application guidelines of tack coats.

As noted earlier in this section, the trackless tack coats (NTQS-1HH and NTHAP) exhibited an increase in the ISS values with an increase in residual application rates, likely due to hard base binder used in manufacturing these tack coats. Among the two trackless tack coats studied here, NTHAP was found to improve the interlayer shear strength more profoundly than the other trackless tack coat (NTQSD-1HH). It exhibited the highest ISS value at all application rates. Anionic slow-setting (SS-1) and cationic rapid setting (CRS-1, CRS-1S, and CBC-1H) tack coats were found to reduce the ISS of the unaged HMA samples with an increase in application rates for possible reasons outlined above. Similar findings reported in other studies indicate that an increase in tack coat application rate resulted in lower ISS values compared to the samples without any tack coat (Song et al., 2015; Zaniewski et al., 2015; Panda et al., 2014; Mohammad et al, 2012; Mohammad et al., 2002; Hachiya et al., 1997). Mohammad et al. (2002) reported that an increase in application rates of SS-1, SS-1h, CSS-1 and PG 64-22 resulted in lower ISS values compared to samples without any tack coat. However, this was not the case for polymer-modified binder and tack coat (CRS-2P and PG 76-22). It should be noted that in this study, SS-1, CRS-1, CRS-1S, and CBC-1H are all non-polymer-modified tack coats, and similar trend is observed. Hachiya et al. (1997) reported that an increase in asphalt emulsion's thickness resulted in lower shear strength values. Song et al. (2015) also reported that an increase in application rate of the SS-1 tack coat tested at 25ºC resulted in a reduction in ISS values. Similarly, Zaniewski et al. (2015) reported lower ISS values of the samples containing SS-1h tack coat compared to those without any tack coat. In this study one day was used as the curing time, resulting in low ISS values. The low ISS values as a result of short curing period was also reported by Hachiya et al. (1997). It was observed that increasing the tack coat curing time from 1 hour to 24 hours resulted in an increase in ISS value (Hachiya et al., 1997). This is another observation that verifies the findings of this study in which a short curing time was used. In a different study, Mohammad et al. (2012) reported that the sample preparation method (laboratory vs. field) directly affects the ISS values measured after tack coat application. It was found that for the samples prepared in the laboratory, an increase in tack coat application rates resulted in a decrease in their measured ISS values.

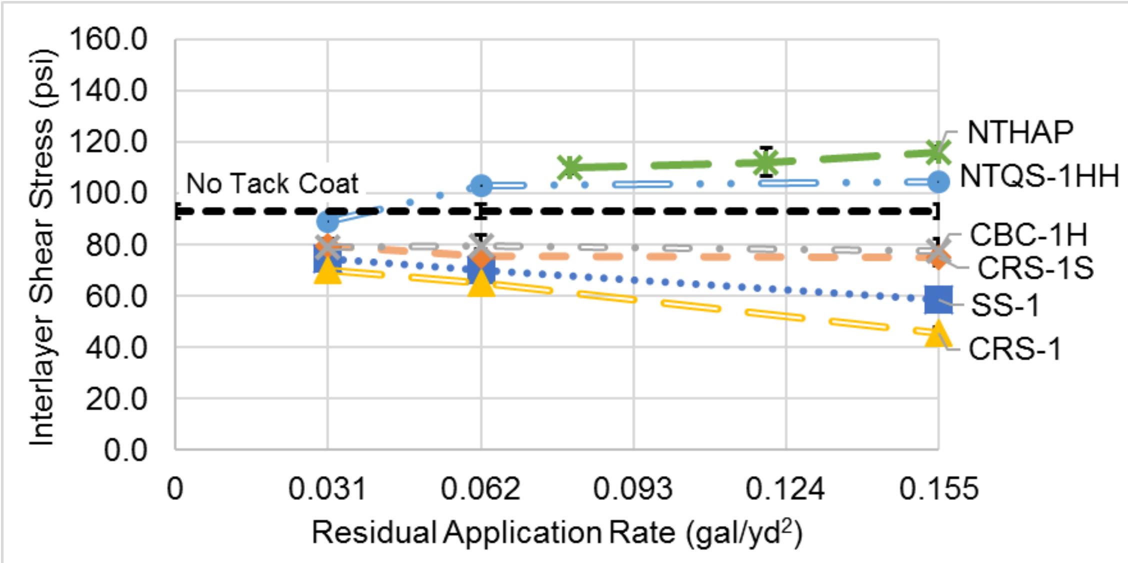


Figure 4.1 Effect of Residual Application Rates on ISS: Unaged HMA Layer

Table 4.1Effect of Residual Application Rates on ISS: Unaged HMA Layer

No.	Tack coat Type	Residual Application Rate (gal/yd^2)	Test Temperature (°C)	Average ISS (psi)	ISS Standard Deviation (psi)	ISS Coefficient of Variation (%)
1	No Tack Coat	0	25	93.1	2.7	2.9
2	SS-1	0.031	25	74.5	2.5	3.4
3	SS-1	0.062	25	70.1	1.5	2.2
4	SS-1	0.155	25	58.5	2.9	4.9
5	CRS-1S	0.031	25	79.5	1.1	1.4
6	CRS-1S	0.062	25	75.8	2.5	3.3
7	CRS-1S	0.155	25	75.2	3.2	4.3
8	CBC-1H	0.031	25	78.9	3.6	4.5
9	CBC-1H	0.062	25	79.7	4.3	5.4
10	CBC-1H	0.155	25	77.8	4.4	5.6
11	CRS-1	0.031	25	69.9	1.8	2.6
12	CRS-1	0.062	25	65.3	1.5	2.3
13	CRS-1	0.155	25	45.4	2.6	5.8
14	NTQS-1HH	0.031	25	89.3	0.4	0.5
15	NTQS-1HH	0.062	25	103.1	1.5	1.5
16	NTQS-1HH	0.155	25	104.7	1.5	1.4
17	NTHAP	0.08	25	110.0	2.0	1.8
18	NTHAP	0.12	25	112.2	5.4	4.8
19	NTHAP	0.155	25	115.9	2.3	2.0

4.1.1.2 Aged HMA Layers

Figure 4.2 and Table 4.2 present the ISS values for tack coats applied at different residual application rates, namely 0, 0.031, 0.062 and 0.155 gal/yd^2 on aged HMA layers tested at 25°C. To show the repeatability of the test results, Standard Deviation and COV values calculated for the measured ISS values are presented in Table 4.2 and the corresponding error bars are displayed on Figure 4.2. From Table 4.2, the calculated COV values were found to be less than 11.1%, an indicator of an acceptable repeatability of the LISST tests conducted on aged HMA layers. From Figure 4.2 and Table 4.2 it is evident that an increase in residual application rate of CRS-1, SS-1 and CBC-1H tack coats resulted in a consistent decrease in their ISS values. This reduction was found to be more pronounced for the SS-1 tack coat. For example, application of 0.031, 0.062 and 0.155 gal/yd^2 of SS-1 resulted in ISS values of 79, 75.4 and 61.5 psi, indicating 8, 13, and 29% reduction in the ISS values, respectively, compared to those of samples without any tack coat (86.3 psi). The ISS values for the CRS-1 tack coat with 0.031, 0.062 and 0.155 gal/yd^2 application rates were found to be 75.8, 72.0 and 63.3 psi, respectively, representing 12, 17 and 27% reductions compared to those for samples with no tack . Similarly, application of 0.031, 0.062 and 0.155 gal/yd^2 of CRS-1S tack coat resulted in ISS values of 77.9, 74.5 and 70.2 psi, exhibiting 10, 14, and 19% reductions, respectively, compared to those of samples containing no tack coat. For the CBC-1H tack coat it was observed that an increase in tack coat application rates up to 0.062 gal/yd^2 resulted in a slight increase in the ISS values and then a decrease at a higher application rate. Similar findings reported in other studies indicate that an increase in tack coat application rate resulted in lower ISS values compared to the samples without any tack coat (Song et al., 2015; Zaniewski et al., 2015; Panda et al., 2014; Mohammad et al, 2012; Mohammad et al., 2002; Hachiya et al., 1997). More specifically, application of 0.031, 0.062 and 0.155 gal/yd^2 CBC-1H tack coat resulted in ISS values of 88.4, 90.4 and 73.6 psi, which represent 2 and 5% increase and 15% decrease in the ISS values, respectively, compared to samples with no tack coat. This observation suggests that moderate application of CBC-1H is effective in increasing the interlayer shear strength for aged HMA surfaces. Unlike the anionic slow-setting (SS-1) and cationic rapid setting (CRS-1, CRS-1S, and CBC-1H) tack coats, trackless tack coats exhibited higher ISS values with increased application rate, compared to samples containing no tack coat. For example, application of 0.031, 0.062 and 0.155 gal/yd^2 NTHAP tack coat resulted in ISS values of 99.2, 95.2 and 94.5 psi, representing 20, 24 and 28% increase in ISS values, respectively, compared to samples with no tack coat. The increase in ISS values with tack coat application rate was more pronounced for the NTQS-1HH trackless tack coat: 0.031, 0.062 and 0.155 gal/yd^2 application rates resulted in ISS values of 103.4, 106.8, 110.1psi, which correspond to 20, 24 and 28% increase, respectively, compared to samples with no tack coat.

In general, among all tack coats, the trackless tack coats (NTQS-1HH and NTHAP) exhibited significant increase (up to 28%) in the ISS values with an increase in residual application rates, when applied to worn and aged HMA surfaces. The CBC-1H tack coat was also found to slightly improve the ISS (up to 5%) when applied in moderate rates (0.062 gal/yd^2). Among the two tested trackless tack coats, NTQS-1HH was found to improve the interlayer shear strength more effectively (up to 28%) than the other trackless tack coat (NTHAP). It exhibited the highest ISS value at all application rates. Other anionic slow-setting (SS-1) and cationic rapid setting (CRS-1 and CRS-1S) tack coats exhibited a reduction in bonding strength with increased application rates, when applied at the interface of aged HMA layers.

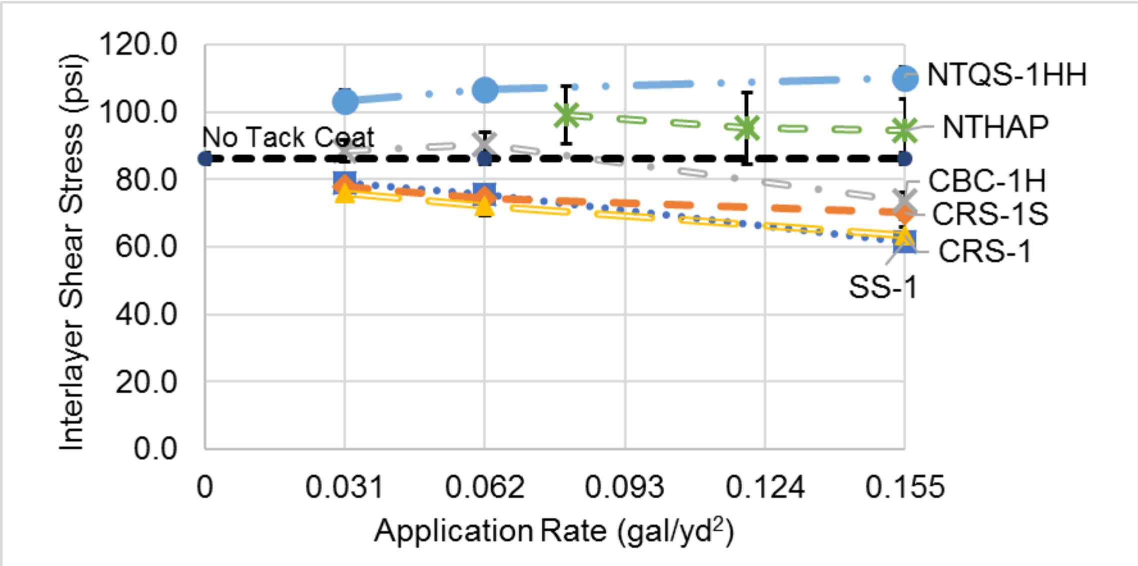


Figure 4.2 Effect of Application Rate on ISS for Aged HMA Surface

Table 4.2 Effect of Application Rate on ISS for Aged HMA Surface

No.	Tack coat Type	Residual Application Rate (gal/yd^2)	Test Temperature (°C)	Average ISS (psi)	ISS Standard Deviation (psi)	ISS Coefficient of Variation (%)
1	No Tack Coat	0	25	86.3	1.7	1.9
2	SS-1	0.031	25	79.0	1.8	2.3
3	SS-1	0.062	25	75.4	2.2	3.0
4	SS-1	0.155	25	61.5	1.5	2.4
5	CRS-1S	0.031	25	77.9	4.1	5.3
6	CRS-1S	0.062	25	74.5	1.5	2.0
7	CRS-1S	0.155	25	70.2	2.0	2.8
8	CBC-1H	0.031	25	88.4	3.2	3.6
9	CBC-1H	0.062	25	90.4	3.4	3.8
10	CBC-1H	0.155	25	73.6	2.6	3.5
11	CRS-1	0.031	25	75.8	2.0	2.6
12	CRS-1	0.062	25	72.0	2.7	3.8
13	CRS-1	0.155	25	63.3	2.7	4.2
14	NTQS-1HH	0.031	25	103.4	3.2	3.1
15	NTQS-1HH	0.062	25	106.8	1.7	1.6
16	NTQS-1HH	0.155	25	110.1	3.2	2.9
17	NTHAP	0.08	25	99.2	8.5	8.6
18	NTHAP	0.12	25	95.2	10.6	11.1
19	NTHAP	0.155	25	94.5	9.4	9.9

4.1.1.3 Milled HMA Layer (Field Cores)

Figure 4.3 and Table 4.3 present the ISS values for tack coats applied at different residual application rates, namely 0, 0.031, 0.062 and 0.155 gal/yd2 on field cores from milled pavements and tested at 25°C. To verify repeatability of the test results, Standard Deviation and COV calculated for the measured ISS values are shown in Table 4.3 and the corresponding error bars are shown in Figure 4.3. From Table 4.3 it was observed that the calculated COV values varied between 0.5 and 28.4%, an indicator of a high variability in ISS values compared to those for laboratory compacted samples (both layers). The increased variability in measured ISS values was attributed to texture inconsistencies of the field cores due to milling. Different surface texture is known to result in different interlayer shear strengths (Mohammad et al., 2012).

From Figure 4.3 and Table 4.3 it is evident that an increase in residual application rate of CRS-1, CRS-1S and SS-1 tack coats from 0 to 0.031 gal/yd^2 resulted in an increase in ISS values by 19, 8 and 35%, respectively. Higher application rates, however, led to a consistent decrease in ISS values compared to those measured for samples without any tack coat. This reduction was found to be more pronounced for the CRS-1S tack coat. The ISS values for the CRS-1S tack coat with 0.031, 0.062 and 0.155 gal/yd^2 application rates were found to be 92.1, 71.1 and 66.0 psi, respectively, representing 8% increase and 17 and 23% reduction in ISS values, respectively, compared to those for samples with no tack coats (85.3 psi). Similarly, application of 0.031, 0.062 and 0.155 gal/yd^2 of CRS-1 tack coat resulted in ISS values of 101.6, 83.5 and 81.4 psi, indicating a 19% increase and 2 and 5% reductions in ISS values, respectively, compared to those of samples with no tack coat. Also, it was observed that application of 0.031, 0.062 and 0.155 gal/yd^2 of SS-1 tack coat resulted in ISS values of 115.2, 80.5 and 79.2 psi, indicating an initial increase of 35% and then 6 and 7% reductions, respectively, compared to those of samples with no tack coat. The ISS values measured for the CBC-1H tack coat applied at rates of 0.031, 0.062 and 0.155 gal/yd^2 exhibited an initial reduction (74.1 psi), an increase (92.1 psi) and another reduction (82.6 psi), respectively, compared to those of samples without any tack coat (85.3 psi). These results suggest that a moderate application rate (0.062 gal/yd^2) of CBC-1H is effective in increasing the interlayer shear strength for milled HMA surfaces. Unlike the anionic slow-setting (SS-1) and cationic rapid setting (CRS-1, CRS-1S, and CBC-1H) tack coats, trackless tack coats exhibited higher ISS values with application of tack coat, compared to those of samples containing no tack coat in their interlayers. For example, application of 0.031, 0.062 and 0.155 gal/yd^2 NTQS-1HH resulted in ISS values of 103.8, 105.3 and 93.1 psi, indicating 22, 23 and 9% increase in ISS values, respectively, compared to those of samples with no tack coat. The increase in ISS values with tack coat application rates was more pronounced for the NTHAP trackless tack coat: application of 0.031, 0.062 and 0.155 gal/yd^2 resulted in ISS values of 105.1, 126.8 and 1.6 psi, representing 23, 49 and 33% increase in ISS values, respectively, compared to those of samples with no tack coat.

In general, the test results presented in this section suggest that among all tack coats applied on milled HMA surfaces, the trackless tack coats (NTQS-1HH and NTHAP) exhibited significant increase in the ISS values with an increase in residual application rates compared to those of samples with no tack coat. More specifically, NTQS-1HH and NTHAP tack coats exhibited maximum effectiveness when they were applied at intermediate rates, namely 0.062 and 0.12 gal/yd^2, respectively. Among the two tested trackless tack coats, NTHAP was found to exhibit the highest ISS values at all application rates and improve the interlayer shear strength more effectively (up to 49%) than the NTQS-1HH tack coat. The CBC-1H tack coat was found to improve the ISS values up to 8% compared to samples without any tack coat, when applied in moderation (0.062 gal/yd^2). Other anionic slow-setting (SS-1) and cationic rapid setting (CRS-1 and CRS-1S) tack coats applied at a rate of 0.031 gal/yd^2 were found to more effectively improve the interlayer bond strength by increasing the ISS values by 35, 19 and 8%, respectively, compared to samples without any tack coat.

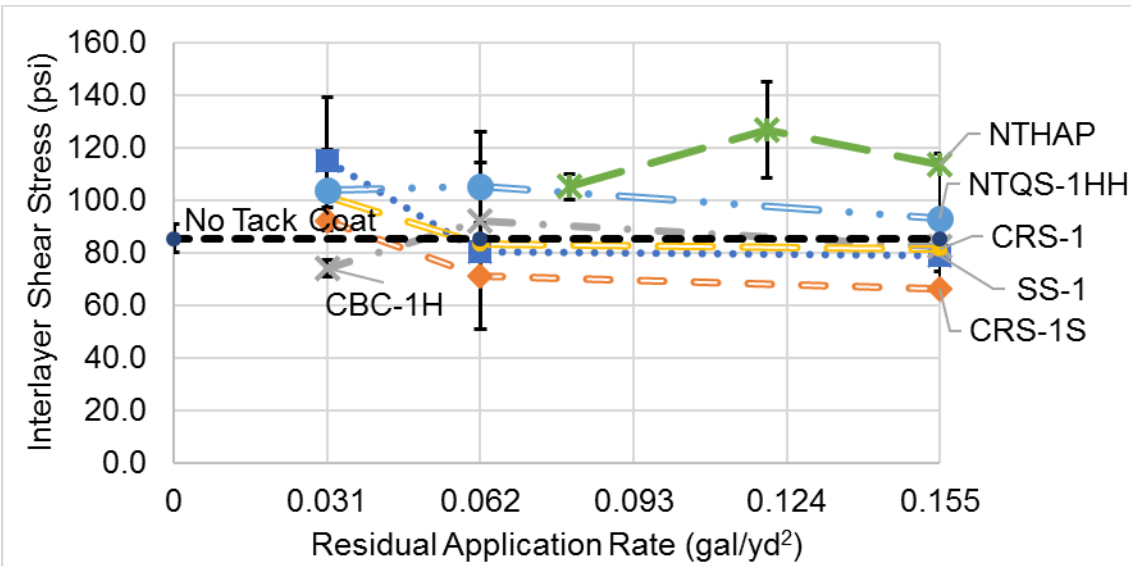


Figure 4.3 Effect of Application Rate on ISS for Milled Field HMA Core

Table 4.3 Effect of Application Rate on ISS for Milled Field Cores

No.	Tack coat Type	Residual Application Rate (gal/yd^2)	Test Temperature (°C)	Average ISS (psi)	ISS Standard Deviation (psi)	ISS Coefficient of Variation (%)
1	No Tack Coat	0	25	85.3	5.3	6.3
2	SS-1	0.031	25	115.2	23.9	20.7
3	SS-1	0.062	25	80.5	0.4	0.5
4	SS-1	0.155	25	79.2	11.1	14.0
5	CRS-1S	0.031	25	92.1	0.4	0.5
6	CRS-1S	0.062	25	71.1	20.2	28.4
7	CRS-1S	0.155	25	66.0	1.0	1.5
8	CBC-1H	0.031	25	74.1	3.4	4.6
9	CBC-1H	0.062	25	92.1	22.1	24.0
10	CBC-1H	0.155	25	82.6	1.9	2.3
11	CRS-1	0.031	25	101.6	4.4	4.4
12	CRS-1	0.062	25	83.5	2.9	3.5
13	CRS-1	0.155	25	81.4	8.4	10.4
14	NTQS-1HH	0.031	25	103.8	15.3	14.7
15	NTQS-1HH	0.062	25	105.3	20.6	19.5
16	NTQS-1HH	0.155	25	93.1	24.8	26.6
17	NTHAP	0.08	25	105.1	4.8	4.6
18	NTHAP	0.12	25	126.8	18.4	14.5
19	NTHAP	0.155	25	113.6	1.5	1.4

4.1.1.4 PCC Layer

Figure 4.4 and Table 4.4 present the ISS values for tack coats applied at different residual application rates, namely 0, 0.031, 0.062 and 0.155 gal/yd^2 on field PCC cores, and tested at 25°C. To show the repeatability of the test results, Standard Deviation and COV calculated for the measured ISS values are shown in Table 4.4 and the corresponding error bars are shown on Figure 4.4. From Table 4.4 it was observed that the COVs calculated for measured ISS values were between 0 and 14.2%, an indicator of a good repeatability of ISS values obtained from the LISST tests on double-layered samples with PCC cores as the bottom layer. From Figure 4.4 and Table 4.4 it is evident that an increase in residual application rate of CRS-1, CRS-1S and SS-1 tack coats resulted in a steady reduction in ISS values, compared to those of samples with no tack coat (43.5 psi). The ISS values for SS-1 tack coat with 0.031, 0.062 and 0.155 gal/yd^2 application rates were found to be 37, 39.5 and 21.6 psi, respectively, representing 15, 32 and 50% reductions, respectively, compared to those for samples with no tack coat (43.5 psi). Similarly, application of 0.031, 0.062 and 0.155 gal/yd^2 of CRS-1 tack coat resulted in ISS values of 34.1, 30.5 and 20.2 psi, indicating 22, 30 and 54% reductions, respectively, compared to those of samples with no tack coat. Also, it was observed that application of 0.031, 0.062 and 0.155 gal/yd^2 of CRS-1S tack coat resulted in ISS values of 32.6, 33.7 and 24.6 psi, which correspond to 25, 23 and 43% reductions, respectively, compared to samples with no tack coat. The ISS values for the CBC-1H tack coat applied at rates of 0.031, 0.062 and 0.155 gal/yd^2 were found to be 54.2, 53.0 and 47.0 psi , respectively, which represent 25, 22 and 8% increase compared to those for samples without any tack coat. These results suggests that application of CBC-1H at a rate of 0.031 gal/yd^2 increased the interlayer shear strength more effectively, as evident by increased ISS value by 25%, compared to those of samples with no tack coat. Trackless tack coats were found to improve the ISS values more effectively than anionic and cationic tack coats or no tack coat. For example, application of 0.031, 0.062 and 0.155 gal/yd^2 NTQS-1HH resulted in ISS values of 88.1, 104.8 and 107.8 psi, which indicate 103, 141 and 148% increase, respectively, compared to samples with no tack coat. The increase in ISS values with tack coat application rates was more pronounced for the NTHAP trackless tack coat: application of 0.08, 0.12 and 0.155 gal/yd^2 NTHAP tack coat resulted in ISS values of 105.1, 117.6 and 132.1 psi, which reflect 142, 170 and 204% increase in ISS values, respectively, compared to samples without any tack coat.

In general, among all tack coats applied on PCC surfaces, the trackless tack coats (NTQS-1HH and NTHAP) exhibited significant increase in the ISS values with an increase in residual application rates compared to samples containing no tack coat in their interfaces. More specifically, NTQS-1HH and NTHAP tack coats exhibited maximum effectiveness when they were applied at their maximum application rates, namely 0.155 gal/yd^2. Among two tested trackless tack coats, NTHAP was found to improve the interlayer shear strength more effectively (up to 204%) than the other trackless tack coat (NTQS-1HH). It exhibited the highest ISS values at all application rates. The CBC-1H tack coat was found to improve the ISS values up to 25% compared to samples without any tack coat, when applied in moderation (0.062 gal/yd^2). Also, the other anionic slow-setting (SS-1) and cationic rapid setting (CRS-1 and CRS-1S) tack coats were found to reduce the interlayer bond at all application rates, compared to those of samples without any tack coat. It should be noted that the ISS values herein were obtained for double-layered samples tested one week after compaction. Mohammad et al. (2012) observed an increase in ISS values with curing time. Based on their results, the ISS would increase with time after construction. Also, it is observed that the PCC surface has the lowest ISS value when no tack coat was applied, compared to other surface types (unaged HMA, aged HMA and milled HMA). Therefore, it is important to apply right type and amount of tack coat for the PCC layer and the HMA overlay to act as a coherent system.

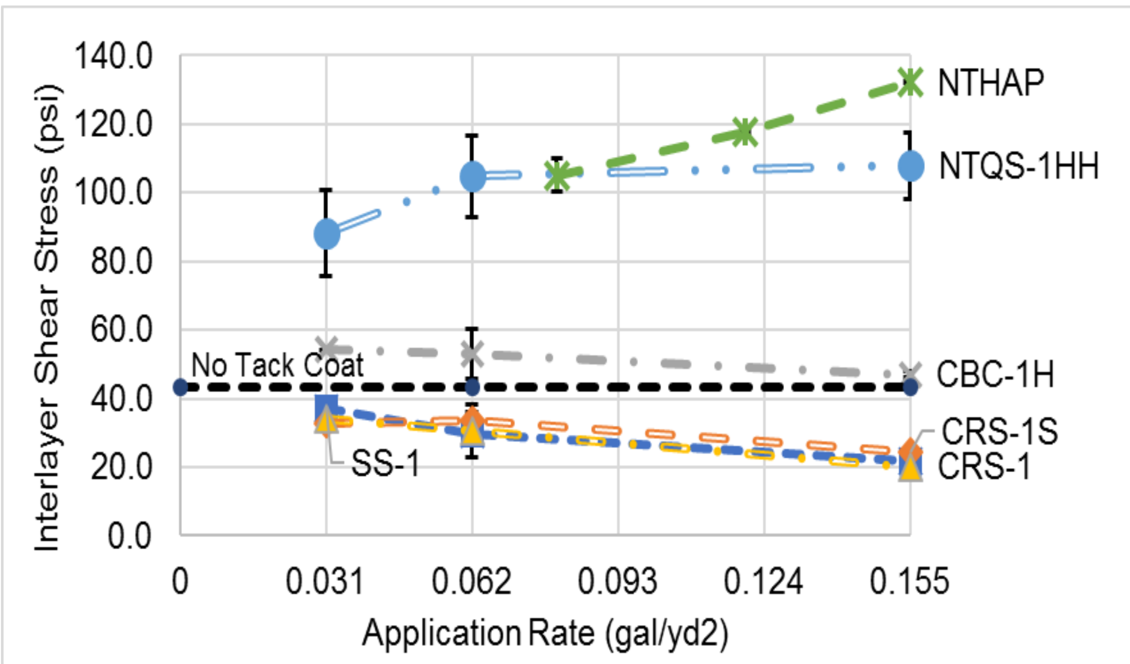


Figure 4.4 Effect of Application Rate on ISS of PCC Surface

Table 4.4 Effect of Application Rate on ISS of PCC Surface

No.	Tack coat Type	Residual Application Rate (gal/yd^2)	Test Temperature (°C)	Average ISS (psi)	ISS Standard Deviation (psi)	ISS Coefficient of Variation (%)
1	No Tack Coat	0	25	43.5	0.4	0.9
2	SS-1	0.031	25	37.0	1.5	4.1
3	SS-1	0.062	25	29.5	0.4	1.2
4	SS-1	0.155	25	21.6	1.1	5.1
5	CRS-1S	0.031	25	32.6	0.0	0.0
6	CRS-1S	0.062	25	33.7	2.4	7.2
7	CRS-1S	0.155	25	24.6	0.5	2.1
8	CBC-1H	0.031	25	54.2	0.0	0.0
9	CBC-1H	0.062	25	53.0	7.3	13.7
10	CBC-1H	0.155	25	47.0	1.0	2.2
11	CRS-1	0.031	25	34.1	1.6	4.7
12	CRS-1	0.062	25	30.5	7.6	24.9
13	CRS-1	0.155	25	20.2	0.1	0.6
14	NTQS-1HH	0.031	25	88.1	12.5	14.2
15	NTQS-1HH	0.062	25	104.8	11.9	11.3
16	NTQS-1HH	0.155	25	107.8	9.8	9.1
17	NTHAP	0.08	25	105.1	4.8	4.6
18	NTHAP	0.12	25	117.6	0.8	0.7
19	NTHAP	0.155	25	132.1	0.3	0.2

4.1.2 Effect of Tack Coat Type

4.1.2.1 No Tack Coat

Figure 4.5 presents the ISS values for samples with different surface types, namely unaged HMA, aged HMA, milled HMA, and PCC, when no tack coat was applied to their interfaces. Also, error bars are shown in Figure 4.5 an an indicator of repeatability of the test results. As shown in Figure 4.5, the ISS values for samples without any tack coat were 93.1, 86.3, 85.3 and 43.5 psi for interfaces with unaged HMA, aged HMA, milled HMA and PCC, respectively. It was observed that all types of HMA lower layers (unaged HMA, aged HMA and milled HMA) exhibited similar ISS values (85.3 to 93.1 psi). The ISS value of PCC samples were about 50% lower (43.5 psi) than those for the HMA samples (all three surface types). According to these test results, placing a new HMA layer over an existing HMA with any surface conditions (unaged, aged and milled) would result in similar bonding strength and resistance to shear failure. However, construction of a new HMA layer over an existing PCC layer without any tack coat has the risk of shear failure or slippage at the interface.

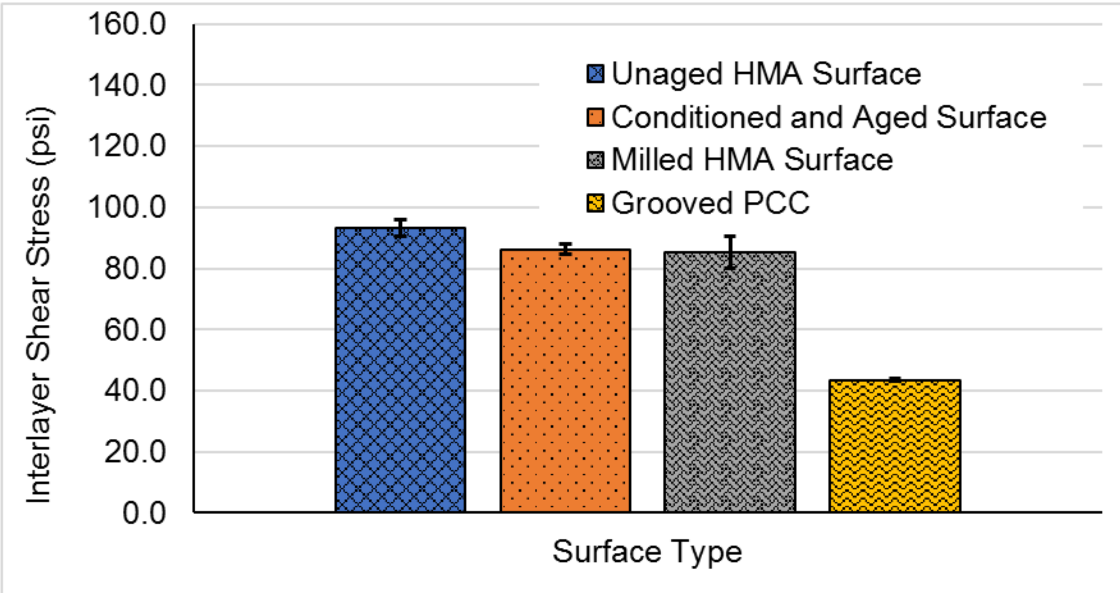


Figure 4.5 Effect of Surface Types on ISS without any Tack Coat at Interface

4.1.2.2 SS-1 Tack Coat

The ISS values of samples with different application rates of SS-1 tack coat and different surface types are shown in Figure 4.6. From Figure 4.6 it is evident that the SS-1 tack coat exhibited the maximum ISS at an application rate of 0.031 gal/yd^2 for all four surface types. An increase in residual application rate decreased the ISS values regardless of surface type. This is consistent with the observations reported in other studies (Song et al., 2015; Zaniewski et al., 2015; Panda et al., 2014; Mohammad et al, 2012; Mohammad et al., 2002; Hachiya et al., 1997). It is also believed that an increase in tack coat application rate results in a thicker tack coat material in interlayer. A thicker tack coat acts as a lubricant and results in less friction which in turn translates into lower ISS values. In other words, an adhesive failure in the case of low application rate becomes a cohesive failure in the case of high residual application rate at the early stage of the pavement life. It should be noted that time and traffic can improve the bond strength (Mohammad et al., 2012). While the ISS values for unaged HMA and aged interlayers were close (approximately 6% difference), those for the PCC samples were the lowest. From Table 4.3 and Figure 4.6 it is evident that 0.031 gal/yd^2 of SS-1 tack coat produces a relatively high ISS value (115.2 psi) for HMA surfaces (unaged or aged) For PCC surface, the corresponding ISS value (31.7 psi) is significantly lower (211.8% and 113.9% lower than those for milled HMA and aged HMA, respectively). Thus, the SS-1 tack coat would likely be more effective in improving bond strength in milled HMA pavements than in PCC pavements.

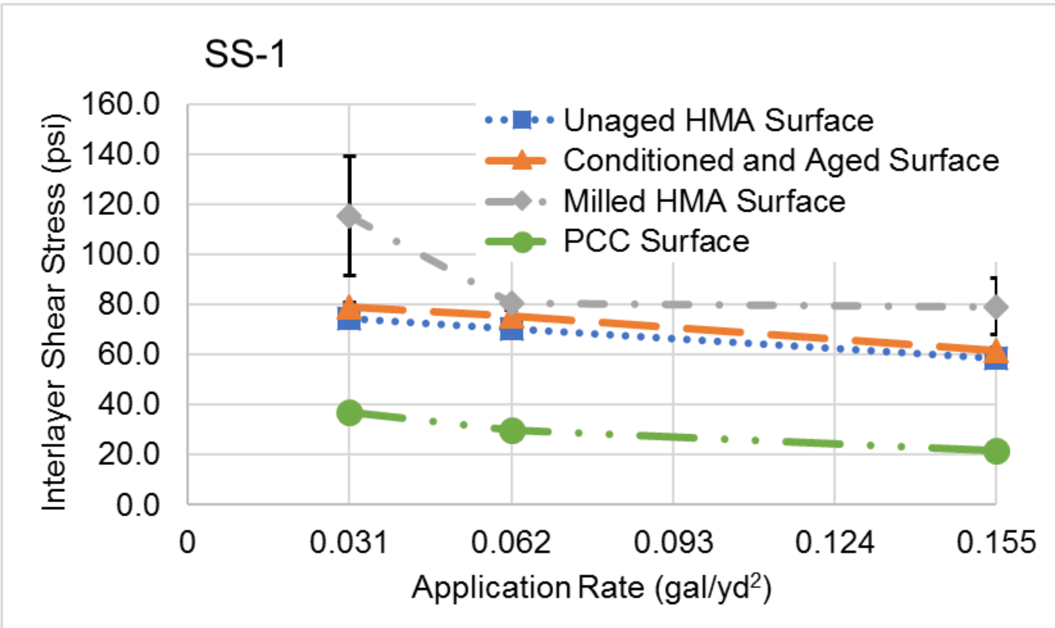


Figure 4.6 Effect of Surface Types on ISS for SS-1 Tack Coat

4.1.2.3 CRS-1S Tack Coat

The ISS values for samples with different surface types and different application rates of CRS-1S tack coat are shown in Figure 4.7. From Figure 4.7 it is evident that for milled HMA, unaged HMA, and aged HMA surfaces, the ISS values were the highest at a rate of 0.031 gal/yd^2. For PCC surface, however, the highest ISS value was attained at a rate of 0.062 gal/yd^2. Among all surface types, the milled HMA surface exhibited the highest ISS of 92.1 psi at a rate of 0.031 gal/yd^2. From Figure 4.7, at 0.062 and 0.155 gal/yd^2, the milled HMA, unaged HMA, and aged HMA surfaces had similar ISS values. A thicker tack coat could result in reduced frictional component of shear strength of the interface, particularly during early ages (1 week in this study). An increase in ISS may be expected with increased curing time, as reported in previous studies (Mohammad et al., 2012). From Figure 4.7, PCC interlayer containing CRS-1S tack coat is found more effective in improving bond strengths in asphalt surfaces than in PCC surfaces.

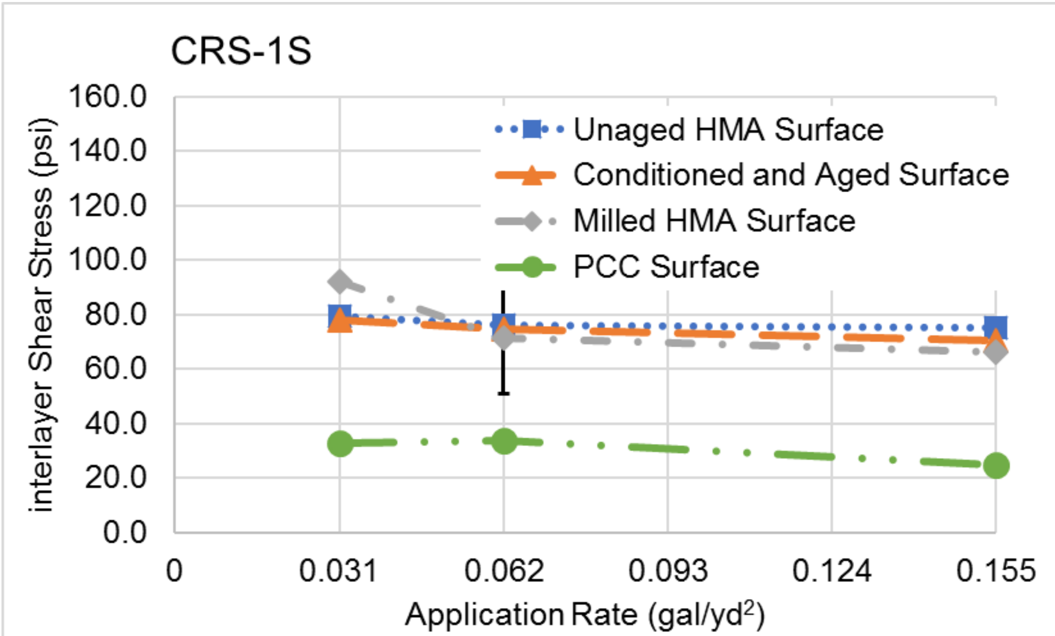


Figure 4.7 Effect of Surface Types on ISS for CRS-1S Tack Coat

4.1.2.4 CBC-1H Tack Coat

The ISS values for samples having surface types and application rates are summarized in Figure 4.8. It is evident from Figure 4.8 that PCC surface exhibited the lowest ISS at all selected rates. The highest ISS of 92.1 psi was observed when the CBC-1H tack coat was applied on the milled HMA surface at 0.062 gal/yd^2. The aged HMA surface also exhibited a similar ISS value (90.4 psi) at 0.062 gal/yd^2. At other rates (0.031 gal/yd^2 and 0.155 gal/yd^2), the CBC-1H tack coat had a lower ISS for all surface types than that of 0.062 gal/yd^2. These results indicated that application of CBC-1H tack coat at very low or very high application rates could result in reduced shear strengths for all surface types. This is consistent with the observations reported in other studies (Song et al., 2015; Zaniewski et al., 2015; Panda et al., 2014; Mohammad et al, 2012; Mohammad et al., 2002; Hachiya et al., 1997).

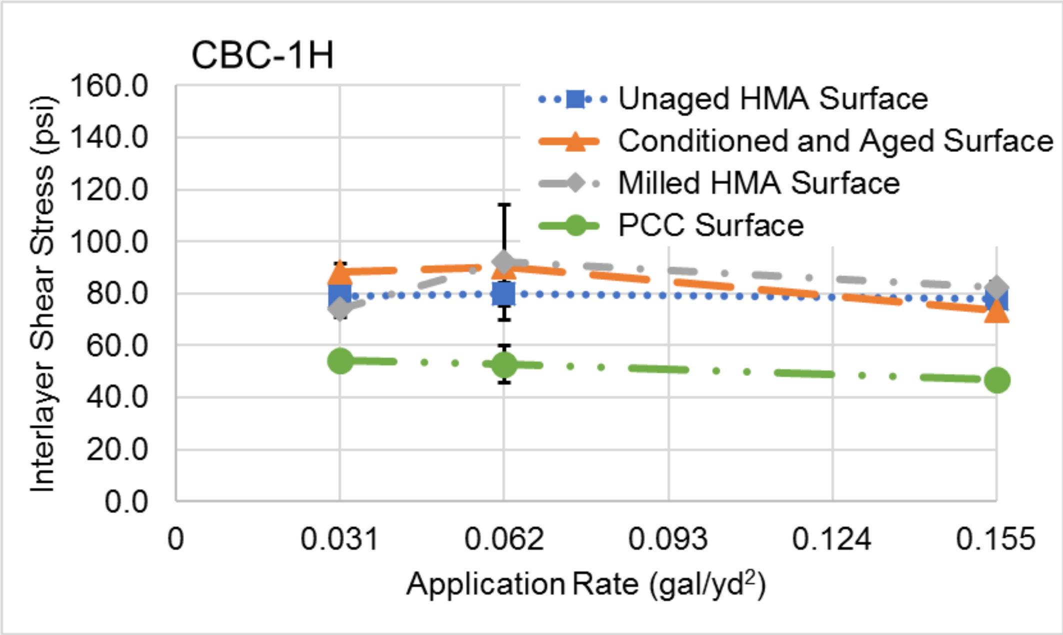


Figure 4.8 Effect of Surface Types on ISS for CBC-1H Tack Coat

4.1.2.5 CRS-1 Tack Coat

The ISS values for samples with different application rates and surface types are shown in Figure 4.9 for CRS-1 tack coat. Similar to SS-1, CRS-1S, and CBC-1H tack coats, the lowest ISS values of CRS-1 tack coat were observed for PCC surface at all application rates. The highest ISS values were observed for milled HMA surface when the CRS-1 tack coat was applied at a rate of 0.031 gal/yd^2. Similarly, for other surface types, the ISS values were maximum when applied rate was 0.031 gal/yd^2 . Figure 4.9 also indicates that an increase in residual application rate beyond 0.031 gal/yd^2, would likely result in a decrease in ISS values for all surfaces. Therefore, for CRS-1S tack coat 0.031 gal/yd^2 was considered optimum for all surface types.

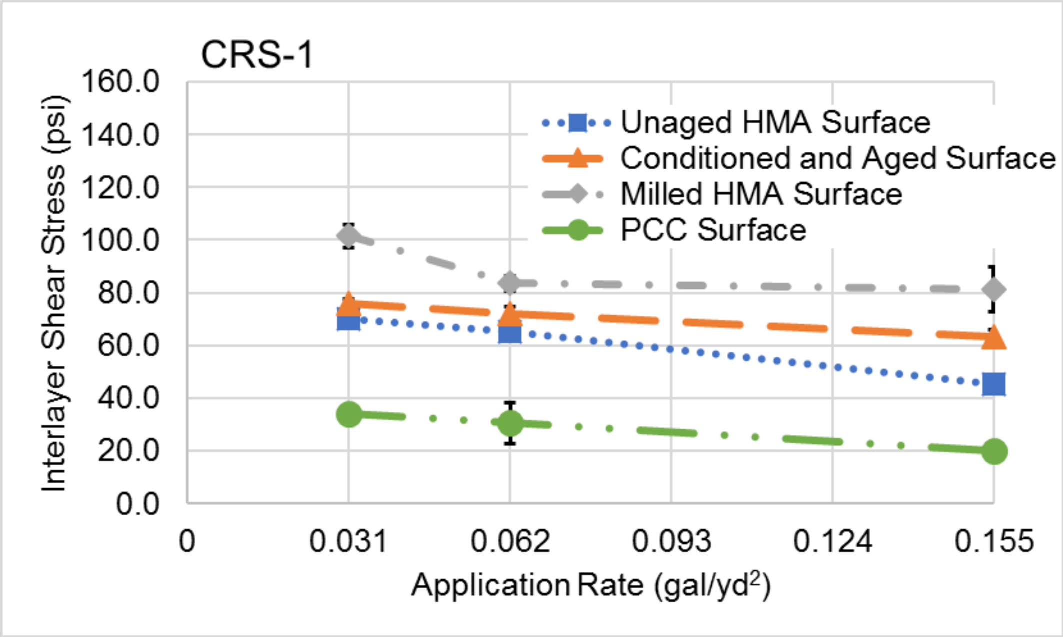


Figure 4.9 Effect of Surface Types on ISS for CRS-1 Tack Coat

4.1.2.6 NTQS-1HH Tack Coat

The ISS values for samples with different surface types and applications rates of NTQS-1HH trackless tack coat are shown in Figure 4.10. From Figure 4.10, application of NTQS-1HH tack coat is found to have similar ISS values for unaged HMA surface and PCC surface at all selected application rates. Also, it was observed that, unlike other cationic and anionic tack coats, application of the NTQS-1HH tack coat improves the ISS value for PCC interlayer as effectively as for other surfaces. Based on these results, application of NTQS-1HH is considered very effective in improving interlayer bond strengths for all types of interfaces considered in this study.

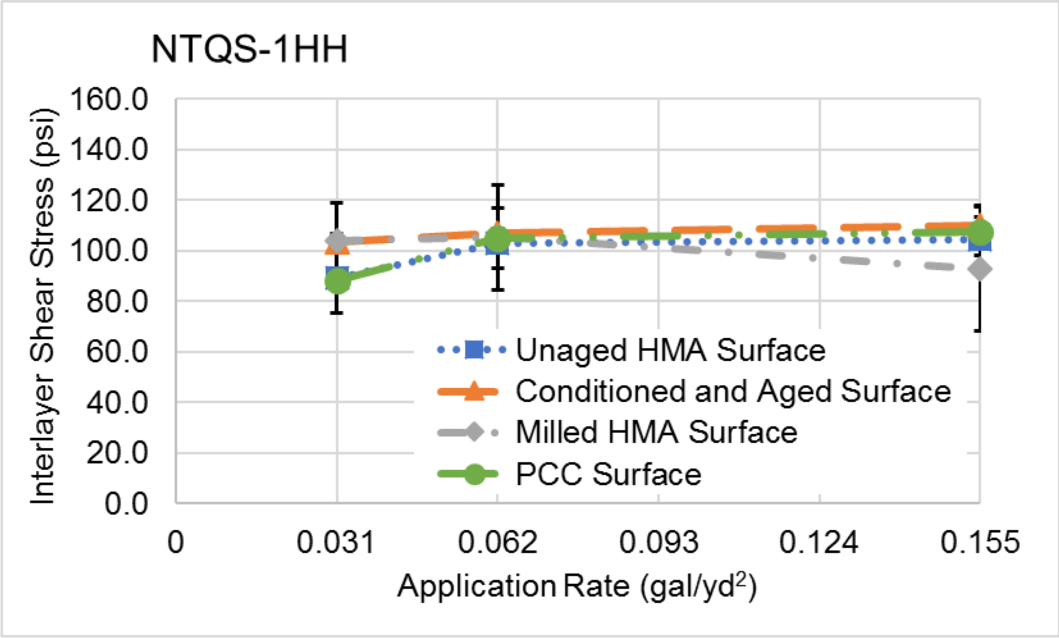


Figure 4.10 Effect of Surface Types on ISS for NTQS-1HH Tack Coat

4.1.2.7 NTHAP Tack Coat

The ISS values for samples with different surface types and application rates of NTHAP trackless tack coat are shown in Figure 4.11. From Figure 4.11 it is evident that the NTHAP tack coat, similar to NTQS1-HH, was very effective in improving the ISS values. This improvement in ISS values was more pronounced for samples with PCC surface. It was also observed that an increase in application rate resulted in an increase in ISS values for samples with unaged HMA and milled HMA surfaces. However, the ISS values for aged HMA interfaces, exhibited a decrease with an increase in application rate. These results indicated that while the NTHAP tack coat was very effective in improving the interlayer shear strength of all types of surfaces, the improvement was more pronounced for unaged HMA, milled HMA and PCC surfaces.

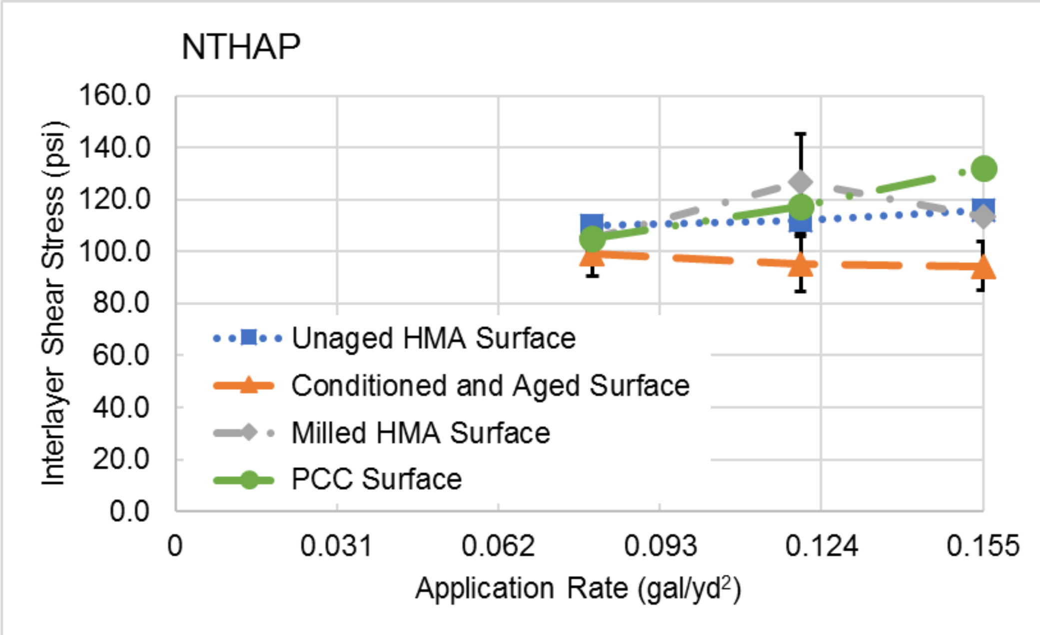


Figure 4.11 Effect of Surface Types on ISS for NTHAP Tack Coat

4.2 Optimum Residual Application Rate

Determination of optimum residual application rate for a tack coat is imperative to selection of right amount of tack coat in the field. In many cases, a low or excessive application rate could result in insufficient bonding between consecutive layers of pavement structure. Insufficient bonding can lead to pavement distresses such as delamination, fatigue cracking, half-moon cracking and slippage at interfaces (Mohammad et al., 2002; FHWA, 2016; Gierhart and Dietz, 2017). In this study, the optimum residual application rate for each tack coat and surface type was determined based on their ISS values presented and discussed in Section 4.1. The suggested optimum residual application rates are summarized in Table 4.5. From Table 4.5, the optimum residual application rate of SS-1, CRS-1S, and CRS-1 tack coats was found to be 0.031 gal/yd^2 (the lowest amount applied) for all surface types. From Figures 4.5, 4.6, and 4.8, the highest ISS values for SS-1, CRS-1S, and CRS-1 tack coats were found at 0.031 gal/yd^2. For CBC-1H tack coat, although the maximum ISS value was observed at 0.062 gal/yd^2 for unaged HMA and aged HMA surfaces, 0.031 gal/yd^2 was selected as the optimum residual application rate. This was due to a relatively small increase of 0.8 psi for the unaged HMA surface and 2.0 psi for the aged HMA surface, due to increased application rate from 0.031 to 0.062 gal/yd^2 (Table 4.1 and Figure 4.2).

Also, CBC-1H tack coat exhibited the highest ISS value at 0.062 and 0.031gal/yd^2 for milled HMA and PCC surfaces, respectively. Therefore, 0.062 and 0.031gal/yd^2 were selected as the optimum rates for milled HMA and PCC surfaces. Furthermore, from Table 4.5 and Figure 4.10, trackless NTQS-1HH tack coat exhibited the maximum interlayer shear strength at a residual application rate of 0.062 gal/yd^2 for unaged HMA, aged HMA and PCC surfaces. For milled HMA surface, however, 0.031 gal/yd^2 of NTQS resulted in the highest ISS value. Therefore, those rates were selected as the optimum residual application rates for NTQS-1HH tack coat. The other trackless tack coat, NTHAP, exhibited the highest ISS values at application rates of 0.08, 0.12 0.155 gal/yd^2 for aged HMA, milled HMA, and PCC surfaces, respectively (Figure 4.11). Therefore, these rates were selected as the optimum residual application rates for NTHAP tack coat. For unaged HMA surface in Table 4.1, NTHAP tack coat exhibited a marginal increase (5.9 psi) in ISS due to increasing the application rate from 0.031 to 0.155 gal/yd^2. Therefore, the optimum residual application rate of NTHAP tack coat was selected as 0.08 gal/yd^2 for unaged HMA surface. As noted earlier, among all tack coats, the NTHAP tack coat exhibited the largest variability in the optimum residual application rates depending on the surface type.

The ISS values of tack coats at their optimum residual application rates are presented in Figure 4.12 for all surface types. From Table 4.5 and Figure 4.12, it is evident that different tack coats at their optimum application rate exhibit different ISS values. Thus, surface type is a major influencing factor. For SS-1, CRS-1, CBC-1H, and CRS-1 tack coats, the highest ISS was observed for milled HMA surface and the lowest for PCC surface. The NTHAP tack coat had the maximum ISS when applied to the PCC surface. Only NTQS-1HH tack coat showed similar ISS values ranging from 103 psi to 110 psi for all surface types at the selected optimum rates. Furthermore, trackless tack coats, namely NTQS-1HH and NTHAP, exhibited significantly higher ISS values than other tack coats for all surface types, when applied at their optimum residual application rates.

Table 4.5 Optimum Residual Application Rates of Tack Coats

No.	Tack coat Type	Test Temperature (˚C)	Unaged HMA Surface	Aged and Worn HMA Surface	Milled HMA cores from field	PCC cores from field
1	SS1	25	0.031	0.031	0.031	0.031
2	CRS-1S	25	0.031	0.031	0.031	0.031
3	CBC-1H	25	0.031	0.031	0.062	0.031
4	CRS-1	25	0.031	0.031	0.031	0.031
5	NTQS-1HH	25	0.062	0.062	0.031	0.062
6	NTHAP	25	0.08	0.08	0.12	0.155

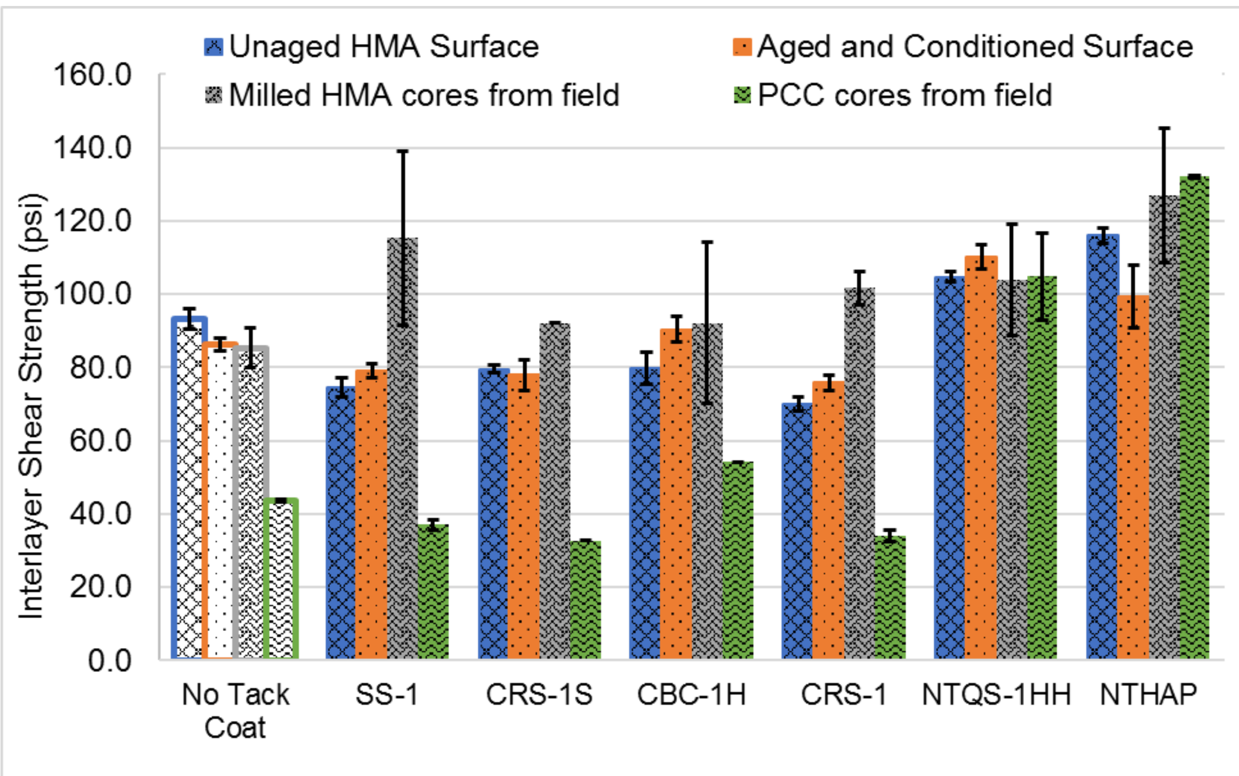


Figure 4.12 ISS Values for Different Surface Types and Optimum Residual Application Rates of Tack Coats

4.3 Interlayer Shear Strength at Different Environmental Conditions

4.3.1 Effect of Test Temperature

After determining the optimum application rates for different tack coats for different interfaces (Table 4.5), effect of test temperature was investigated. The optiumum residual application rates were used in preparing samples for this segment of the study. Also, only laboratory compacted HMA samples with unaged and aged surfaces were tested. The tests were conducted at low (7°C), intermediate (25°C) and high (60°C) temperatures. For tests conducted at 7°C, 4 in. diameter samples were cored from 6 in. diameter samples using a core bit. Reducing sample diameter to 4 in. was was necessary because of very high ISS values of 6 in. diameter samples, exceeding the loading capacity of the LISST device. Reducing the diameters to 4 in. mitigated this problem. After samples were prepared, they were conditioned in an environmental chamber at test temperature for at least 6 hours before testing.

4.3.1.1 Unaged HMA Surface

Figure 4.13 and Table 4.6 present the ISS values of different tack coats and unaged HMA samples tested at 7°, 25° and 60°C. From Figure 4.13 and Table 4.6, the highest ISS values for different surface types and tack coats were observed at 7°C, in the presence or absence of tack coat (i.e., no tack coat). An increase in temperature resulted in a significant decrease in the ISS values for all tack coat types. For example, from Table 4.6 it is evident that the ISS value of unaged HMA samples without any tack coat was found to be 93.1 psi at 25°C. An increase in temperature from 25° to 60°C decreased the ISS value by 84% to 14.9 psi. Also, it was found that a reduction in test temperature from 25° to 7°C increased the ISS value by 114% to 199.3 psi. From Table 4.6, it was also observed that the ISS values for SS-1 tack coat were 176.4 psi at 7°C, 74.5 psi at 25°C, and 11.6 psi at 60°C. Thus, the test temperature is a very influential parameter.

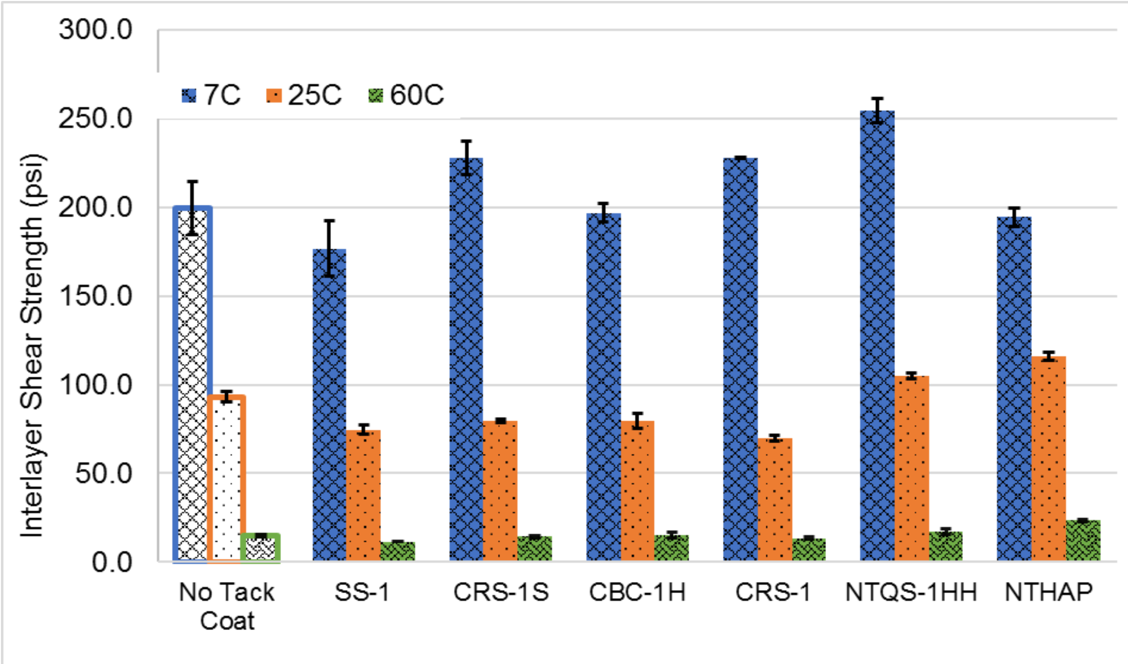


Figure 4.13 Effect of Test Temperature on ISS for Unaged HMA Surface and Optimum Application Rates

Table 4.6 Effect of Test Temperature on ISS for Unaged HMA Surface and Optimum Application Rates

No.	Tack coat Type	Residual Application Rate (gal/yd^2)	Test Temperature (°C)	Average ISS (psi)	ISS Standard Deviation (psi)	ISS Coefficient of Variation (%)
1	No Tack Coat	0	7	199.3	15.1	7.6
2	No Tack Coat	0	25	93.1	2.7	2.9
3	No Tack Coat	0	60	14.9	0.8	5.0
4	SS-1	0.031	7	176.4	15.6	8.9
5	SS-1	0.031	25	74.5	2.5	3.4
6	SS-1	0.031	60	11.6	0.2	1.8
7	CRS-1S	0.031	7	227.6	9.2	4.0
8	CRS-1S	0.031	25	79.5	1.1	1.4
9	CRS-1S	0.031	60	14.3	0.6	4.5
10	CBC-1H	0.031	7	196.7	5.0	2.5
11	CBC-1H	0.031	25	79.7	4.3	5.4
12	CBC-1H	0.031	60	15.3	1.4	9.4
13	CRS-1	0.031	7	227.6	0.4	0.2
14	CRS-1	0.031	25	69.9	1.8	2.6
15	CRS-1	0.031	60	13.3	0.6	4.9
16	NTQS-1HH	0.062	7	254.3	7.0	2.7
17	NTQS-1HH	0.062	25	104.7	1.5	1.4
18	NTQS-1HH	0.062	60	17.0	1.5	8.7
19	NTHAP	0.08	7	194.3	5.0	2.6
20	NTHAP	0.08	25	115.9	2.3	2.0
21	NTHAP	0.08	60	23.4	0.9	3.8

Also, from Figure 4.13 and Table 4.6 it was observed that due to high ISS values , the interlayer shear strength is not a concern at low temperature. However, as the ISS values reduced with an increase in test temperature, providing adequate ISS becomes critical to pavement performance. From Figure 4.13 and Table 4.6 it was found that only for trackless tack coats (NTQH-1HH and NTHAP) and unaged HMA surface, the ISS values increased with increasing test temperature from intermediate (25°C) to high (60°C), compared to those of specimens without any tack coat. For example, use of NTQS-1HH tack coat on unaged HMA surface increased the ISS by 27.6% at 7°C, 12.4% at 25°C, and 14.0% at 60°C, compared to those for the same surface type but without any tack coat. Similarly, the ISS values for NTQS-1HH tack coat and unaged HMA surface, increased by 2.5 % at 7°C, by 56.3% at 25°C, and 14.0% at 60°C, compared to samples with same surface type but without any tack coat.

Among all tack coats at 7°C, NTQS-1HH exhibited the highest ISS value (254.3 psi) compared to other tack coats. At 25° and 60°C, the NTHAP tack coat exhibited the highest ISS values (115.9 psi and 23.4 psi, respectively).

4.3.1.2 Aged HMA Surface

Figure 4.14 and Table 4.7 present the ISS values for different tack coats and aged HMA surface tested at 7°, 25° and 60°C. From Figure 4.14, similar to unaged HMA surface, an increase in temperature significantly decreased the ISS values. From Figure 4.13, the use of SS-1 tack coat on aged HMA surface decreased the ISS values significantly at all testing temperatures, compared to the ISS values without any tack coat. For instance, from Table 4.7 it was found that the ISS values of SS-1 tack coat were 150.7 psi, 79.0 psi, and 20.6 psi, at 7°, 25°, and 60°C, respectively, which indicates 37.4%, 9.1%, and 26.9% reductions compared to those for samples without any tack coat. A similar observation could be made for CRS-1 tack coat where CRS-1 tack coat applied to aged HMA interface resulted in a decrease of 8.9% (from 207.0 psi to 188.5 psi), 12.2% (from 86.3 psi to 75.8 psi), and 58.0% (from 26.1 psi to 11.0 psi) in the ISS values at 7°, 25°, and 60°C, respectively, as compared to those for samples without any tack coat. The use of CRS-1S tack coat, however, increased the ISS values by 8.2% (from 207.0 psi to 223.9 psi) at 7°C and then decreased by 9.7% (86.3 psi to 77.9 psi) at 25°C and 28.0% (from 26.1 psi to 18.8 psi), compared to those for samples without any tack coat. For CBC-1H tack coat, the ISS values reduced by 17.3% (from 207.0 psi to 171.1 psi) at 25°C and 35.8% (from 26.1 psi to 11.0 psi) at 60°C, compared to those for samples without any tack coat. However, a 4.8% increase in ISS was observed due to application of CBC-1H tack coat and tested at 25°C, compared to those for samples without any tack coat.

Application of both trackless tack coats (NTQS-1HH and NTHAP) resulted in an increase in ISS values at 7° and 25°C, and then decrease in at 60°C, compared to those for samples without any tack coat. Among all tack coats, at 7°C, the NTHAP tack coat exhibited the highest ISS value (238.6 psi). At 25°C, the NTQS-1HH tack coat exhibited the highest ISS value (110.1 psi). Finally, at 60°C, the highest ISS value (26.1 psi) was observed when no tack coat was applied. A decrease in ISS values with an increase in testing temperature, was also reported by Mohammad et al. (2012).

From Figures 4.13 and 4.14, comparing the ISS values of tack coats applied to unaged HMA surface with those for aged HMA surface, indicates that the ISS values are highly dependent on surface type, tack coat type, and temperature.

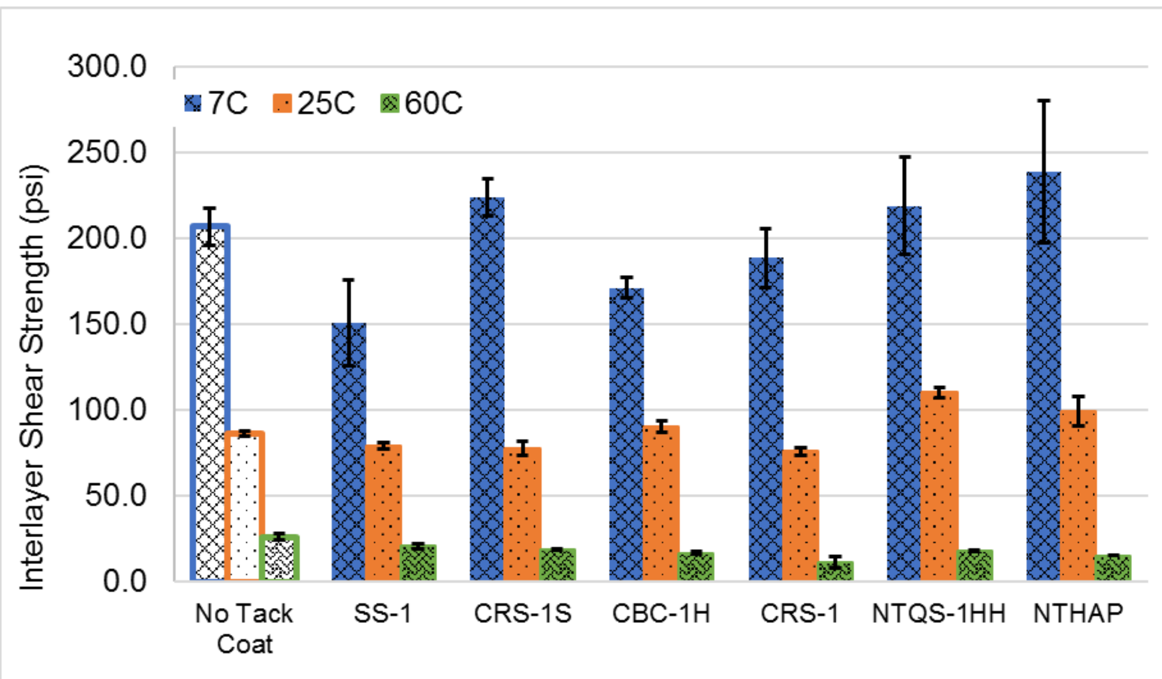


Figure 4.14 Effect of Test Temperature on ISS of Different Tack Coats (Optimum Application Rates) and Aged HMA Surface

Table 4.7 Effect of Test Temperature on ISS of Different Tack Coats (Optimum Application Rates) and Aged HMA Surface

No.	Tack coat Type	Residual Application Rate (gal/yd^2)	Test Temperature (°C)	Average ISS (psi)	ISS Standard Deviation (psi)	ISS Coefficient of Variation (%)
1	No Tack Coat	0	7	207.0	10.8	5.2
2	No Tack Coat	0	25	86.3	1.7	1.9
3	No Tack Coat	0	60	26.1	1.7	6.6
4	SS-1	0.031	7	150.7	25.0	16.6
5	SS-1	0.031	25	79.0	1.8	2.3
6	SS-1	0.031	60	20.6	1.5	7.4
7	CRS-1S	0.031	7	223.9	11.1	5.0
8	CRS-1S	0.031	25	77.9	4.1	5.3
9	CRS-1S	0.031	60	18.8	0.5	2.8
10	CBC-1H	0.031	7	171.1	5.9	3.5
11	CBC-1H	0.031	25	90.4	3.4	3.8
12	CBC-1H	0.031	60	16.8	0.6	3.7
13	CRS-1	0.031	7	188.5	17.4	9.2
14	CRS-1	0.031	25	75.8	2.0	2.6
15	CRS-1	0.031	60	11.0	3.3	30.5
16	NTQS-1HH	0.062	7	218.9	28.0	12.8
17	NTQS-1HH	0.062	25	110.1	3.2	2.9
18	NTQS-1HH	0.062	60	17.8	0.4	2.0
19	NTHAP	0.08	7	238.6	41.5	17.4
20	NTHAP	0.08	25	99.2	8.5	8.6
21	NTHAP	0.08	60	15.3	0.2	1.2

4.3.2 Effect of Moisture

After determining the optimum tack coat application rates (Table 4.5), samples containing tack coats applied at their optimum application rates were tested to evaluate the effect of moisture on ISS. For this purpose, the samples were moisture-conditioned using a MIST equipment, as discussed in Section 3.3.1. The, moisture-conditioned samples were then tested in the LISST device at intermediate temperature (25°C) and their ISS values were determined. In this study, the effect of moisture on the ISS values was investigated only for laboratory compacted HMA samples with unaged HMA and aged HMA surfaces.

4.3.2.1 Unaged HMA Surface

Figure 4.15 and Table 4.8 present the ISS values for unconditioned (dry) and moisture-conditioned samples containing different types of tack coats applied to unaged HMA interface at their optimum application rates. Important statistical parameters, namely Standard Deviation and COV, were also calculated for the ISS values (dry and moisture-conditioned) and presented in Table 4.8. From Table 4.8 it is evident that, COV values were below 6% indicating a good repeatability of test results.

From Figure 4.15 and Table 4.8, the ISS values for samples with unaged HMA surface and without any tack coat were found to be 93.1 and 88.8 psi, respectively, for dry and moisture-conditioned samples. This indicates a 4.6% reduction in ISS value due to moisture-conditioning. Application of any tack coat improved the resistance to moisture-induced damage through increase in ISS values after moisture-conditioning. However, effect of moisture-conditioning depended on tack coat type. For example,, use of CRS-1 tack coat resulted in the highest increase in resistance to moisture-induced damage. Comparatively, NTHAP, a trackless tack coat, exhibited the highest ISS values for both dry and moisture-conditioned samples, followed by the other trackless tack coat, NTQS-1HH.

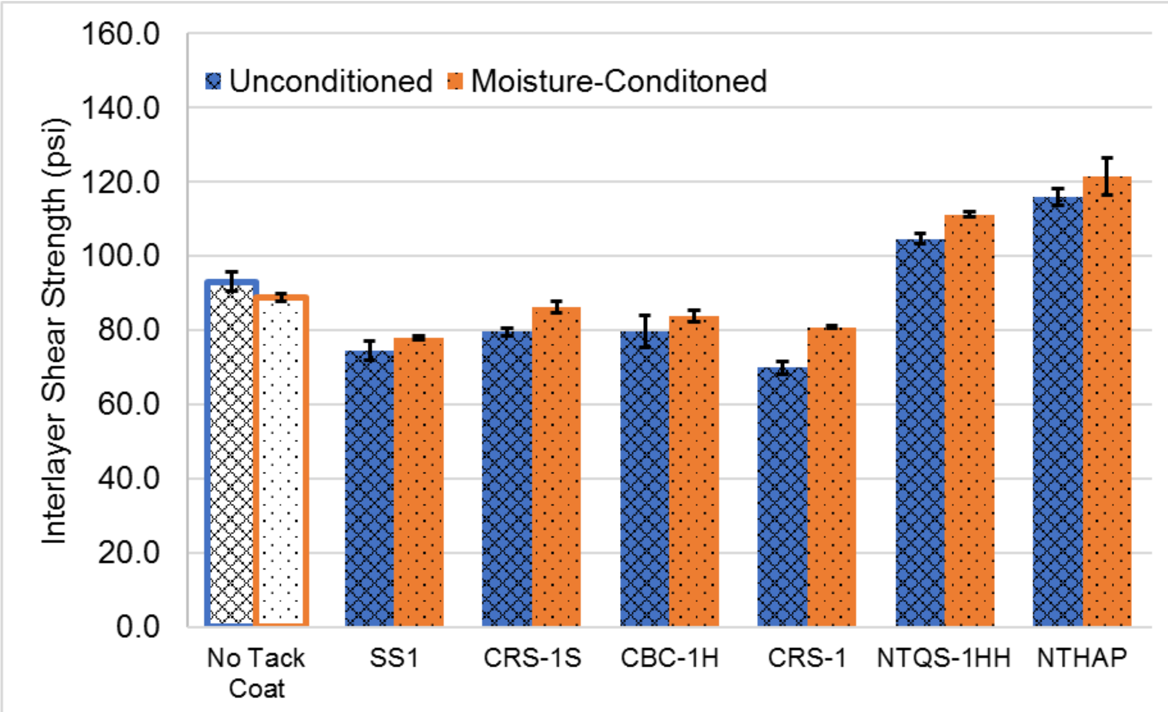


Figure 4.15 Effect of Moisture Conditioning on ISS for Unaged HMA Samples and Different Tack Coats (Optimum Application Rates)

Table 4.8 Effect of Moisture Conditioning on ISS for Unaged HMA Samples and Different Tack Coats (Optimum Application Rates)

No.	Tack coat Type	Optimum Residual Application Rate (gal/yd^2)	Test Temperature (°C)	ISS Dry Average (psi)	ISS Dry Std. Dev. (psi)	Dry ISS COV (%)	Moisture-Conditioned ISS Average (psi)	Moisture-Conditioned ISS Std. Dev. (psi)	Moisture-Conditioned ISS COV (%)
1	No Tack Coat	0	25	93.1	2.7	2.9	88.8	1.0	1.2
2	SS-1	0.031	25	74.5	2.5	3.4	78.0	0.5	0.6
3	CRS-1S	0.031	25	79.5	1.1	1.4	86.4	1.5	1.8
4	CBC-1H	0.031	25	79.7	4.3	5.4	83.9	1.5	1.7
5	CRS-1	0.031	25	69.9	1.8	2.6	80.8	0.3	0.4
6	NTQS-1HH	0.062	25	104.7	1.5	1.4	111.3	0.8	0.7
7	NTHAP	0.08	25	115.9	2.3	2.0	121.3	5.0	4.1

4.3.2.2 Aged HMA Surface

Figure 4.16 and Table 4.9 present the ISS values for dry and moisture-conditioned aged HMA samples containing different types of tack coats applied at their optimum rates. Important statistical parameters, namely Standard Deviation and COV, were also calculated for the ISS values (dry and moisture-conditioned) and presented in Table 4.8. From Table 4.8, the COV values were below 9%, indicating a good repeatability of test results. According to Figure 4.16 and Table 4.9, use of SS-1, CRS-1S, CBC-1H, and CRS-1 tack coats increased the resistance to moisture-induced damage through increasing ISS values. However, moisture conditioning of samples containing NTHAP and NTQS-1HH tack coats resulted in 1.2% and 17.4% reductions in ISS values, compared to those for dry samples. These results indicated that trackless tack coats, namely NTQS-1HH and NTHAP, were slightly susceptible to moisture-induced damage, so far as aged HMA surfaces were concerned.

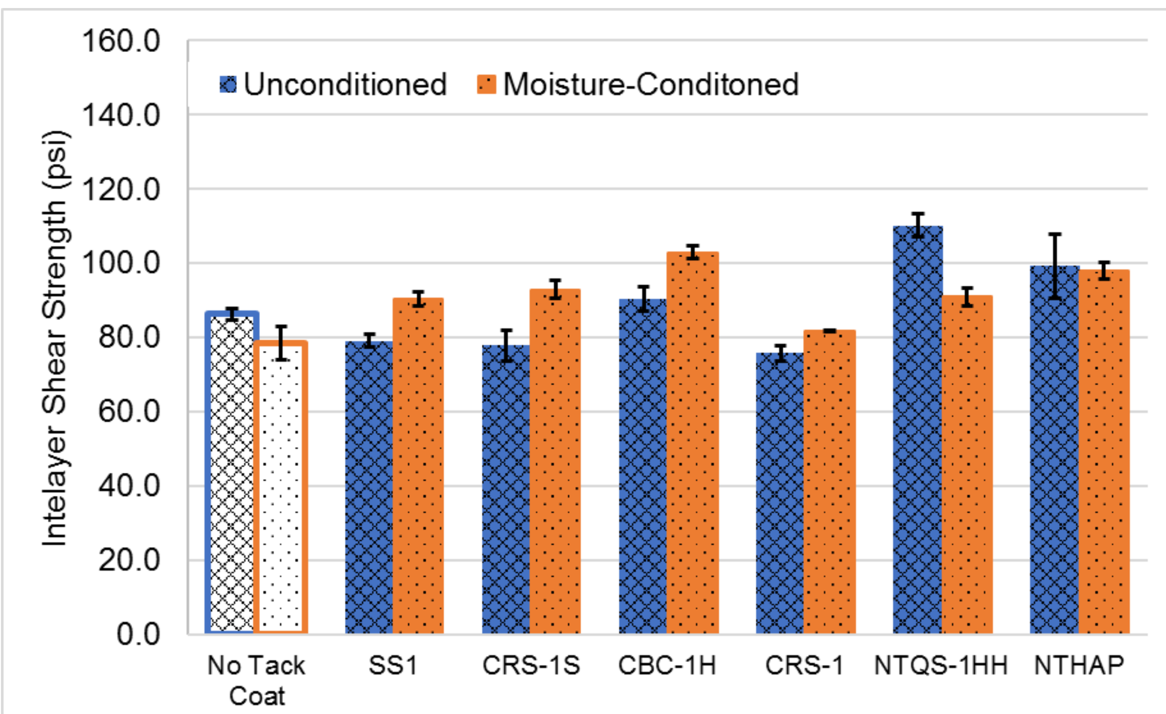


Figure 4.16 Effect of Moisture Conditioning on ISS for Aged HMA Samples and Different Tack Coats (Optimum Application Rates)

Table 4.9 Effect of Moisture Conditioning on Aged Samples and Different Tack Coats (Optimum Application Rates)

No.	Tack coat Type	Optimum Residual Application Rate (gal/yd^2)	Test Temperature (°C)	ISS Dry Average (psi)	ISS Dry Std. Dev. (psi)	Dry ISS COV (%)	Moisture-Conditioned ISS Average (psi)	Moisture-Conditioned ISS Std. Dev. (psi)	Moisture-Conditioned ISS COV (%)
1	No Tack Coat	0	25	86.3	1.7	1.9	78.5	4.5	5.7
2	SS-1	0.031	25	79.0	1.8	2.3	90.3	1.8	2.0
3	CRS-1S	0.031	25	77.9	4.1	5.3	92.9	2.3	2.5
4	CBC-1H	0.031	25	90.4	3.4	3.8	102.9	1.8	1.7
5	CRS-1	0.031	25	75.8	2.0	2.6	81.8	0.1	0.1
6	NTQS-1HH	0.062	25	110.1	3.2	2.9	90.9	2.5	2.8
7	NTHAP	0.08	25	99.2	8.5	8.6	98.0	2.3	2.3

4.4 Setting Time of Tack Coats

The setting times of tack coats were determined by conducting Room-Temperature Tracking (RTT) Test, as described in Section 3.5. A complete summary of the setting times measured for different tack coats is presented in Table 4.10 and the average setting times of tack coats are presented in Figure 4.17. Tables 4.11 through 4.15 present the RTT marks observed for SS-1, CRS-1S, CBC-1H, CRS-1, and NTQS-1HH tack coats, respectively. As shown in Tables 4.11 through 4.15, the test was repeated three time to ensure repeatability. No test was performed on NTHAP tack coat because it could not be applied at room-temperature (around 25°C). This was due to fact that NTHAP tack coat, according to the manufacturer, needed to be heated up at 180˚C to liquefy and to allow uniform application. Therefore, 15 to 20 seconds, as suggested by the manufacturer, is reported as its setting time, in this study.

From Table 4.10 and Figure 4.17, CRS-1S and NTQS-1HH tack coats had the shortest setting time (50-60 minutes), followed by CBC-1H (70-90 minutes) and CRS-1 tack coat (80-90 minutes). Among all tack coats, SS-1 tack coat took the longest time to set (100-120 minutes). After comparing the setting time with percentage asphaltic residue of tack coat, as given in Table 3.2, one can conclude that the setting time did not depend on the percentage asphaltic residue of tack coats. Other parameters such as environmental conditions, applied amount of tack coat, base binder grade, and emulsifying agent are important parameters that largely affect the setting time of a tack coat.

Table 4.10 Setting Times of Tack Coats Applied at 0.5 mm Thickness

No.	Tack coat Type	Asphaltic* Residue (%)	Setting Time Test #1 (Minutes)	Setting Time Test #2 (Minutes)	Setting Time Test #3 (Minutes)	Setting Time Range (Minutes)
1	SS-1	62.9	100	120	120	100-120
2	CRS-1S	62.8	60	60	50	50-60
3	CBC-1H	49.8	70	80	90	70-90
4	CRS-1	63.6	80	80	90	80-90
5	NTQS-1HH	63.2	60	60	50	50-60
6	NTHAP	100	-	-	-	0.25-0.33

* See Section 3.2.2.1 for determination of asphaltic residue (%) for tack coats

** Not applicable at room-temperature. Setting time reported as per manufacturer's data.

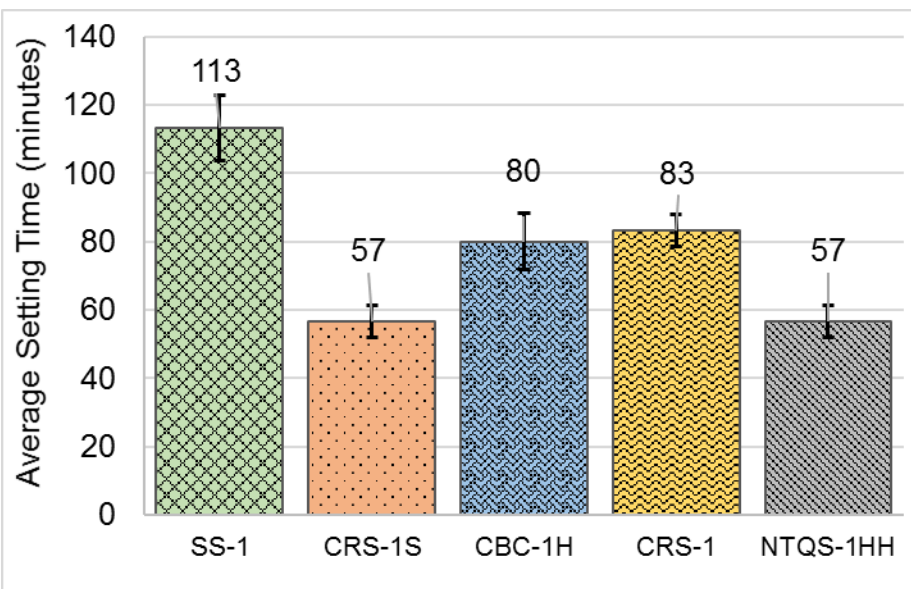


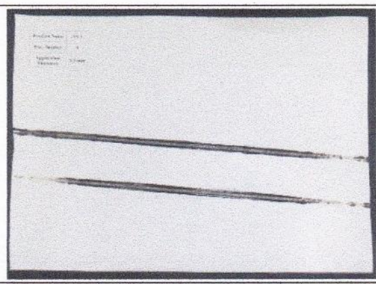
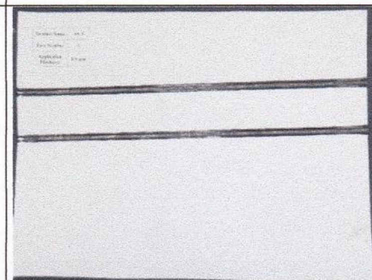
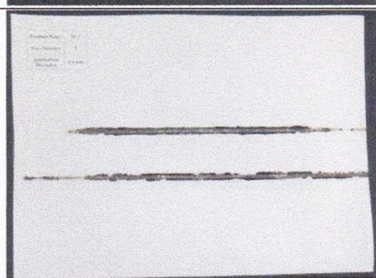
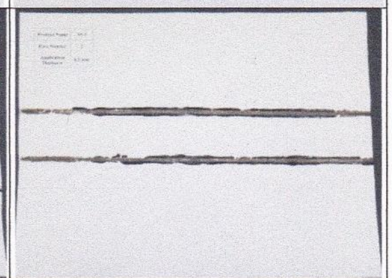
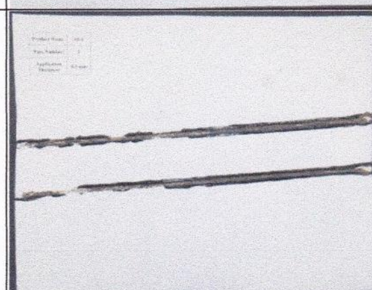
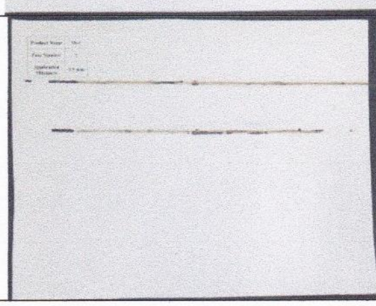
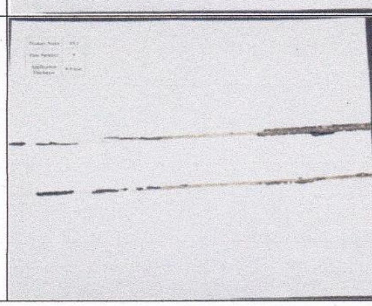
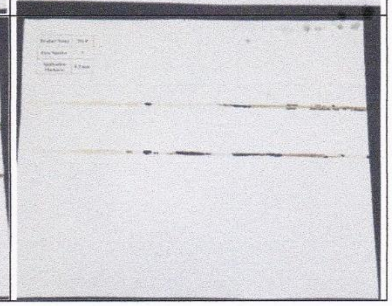
Figure 4. 17 Average Setting Time of Tack Coats Applied at 0.5 mm Thickness

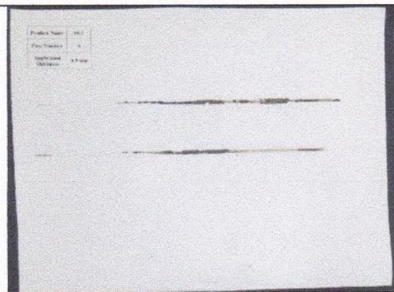
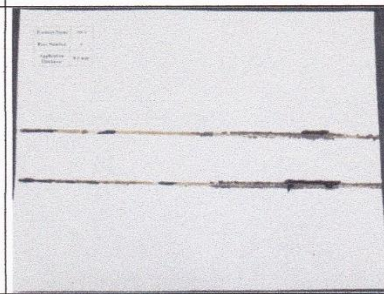
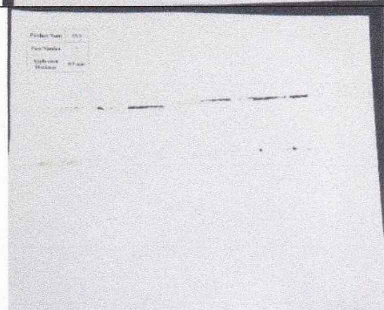
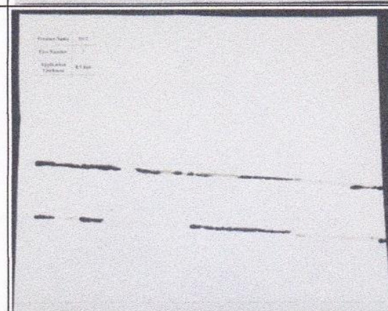
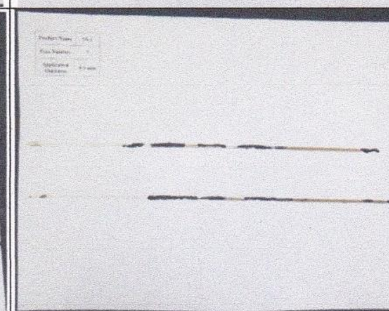
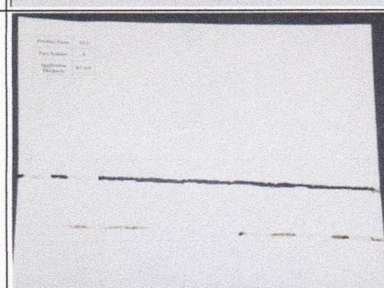
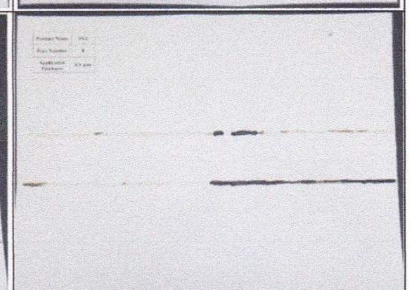
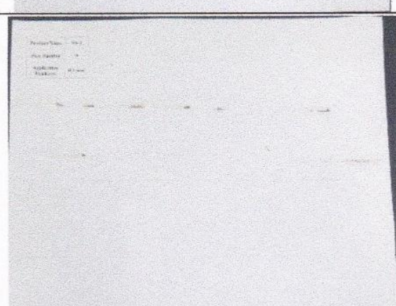
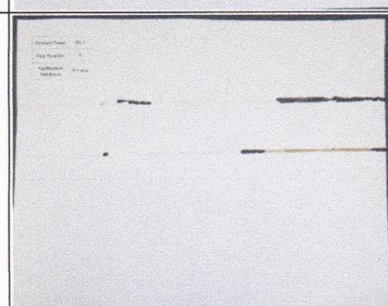
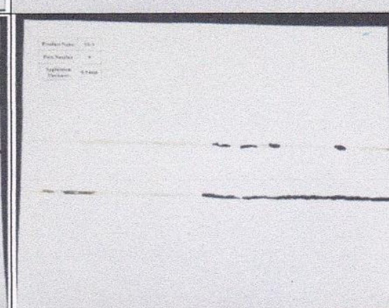
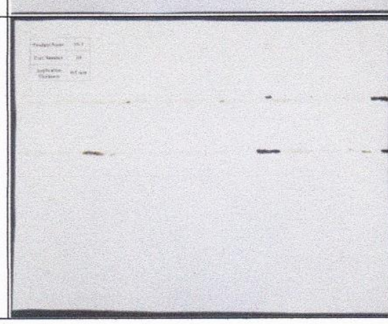
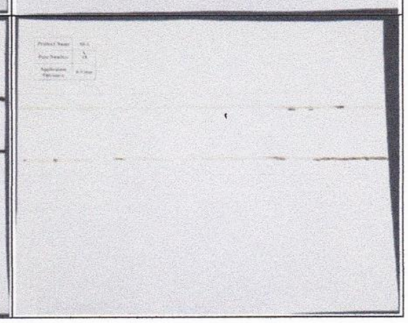
As presented in Table 4.11, the first tracking mark of SS-1 tack coat conducted after 10 minutes of application was too thick. Thicknesses of the tracking marks were similar for the next three passes. At the 5th pass, the thickness of tracking mark started to reduce significantly. In total, for SS-1 tack coat, it took 10-12 passes (100-120 minutes) to become trackless. These results indicated that SS-1 tack coat started breaking after 30-40 minutes of application and took another 70-80 minutes to set.

The CRS-1S tack coat, as shown in Table 4.12, had a very thin tracking mark in the initial passes as compared to other tack coats. Tracking marks of CRS-1S tack coat started to lighten with time (Table 4.12). It took about 50 to 60 minutes for CRS-1S tack coat took to become trackless. The tracking passes for CBC-1H tack coat are shown in Table 4.13. The CBC-1H tack coat took 70-90 minutes to become trackless. Comparing the tracking passes of CBC-1H tack coat with those for SS-1 tack coat, the CBC-1H tack coat sets at least 10 minutes faster than the SS-1 tack coat.

The CRS-1 tack coat, as shown in Table 4.14, had relatively thin tracking mark in the initial passes as compared to other tack coats. Tracking marks of CRS-1 tack coat started to lighten with time. It took about 80 to 90 minutes for CRS-1 tack coat took to become trackless. The NTQS-1HH tack coat required 50-60 minutes to become trackless (Table 4.15).

Table 4.11 Room-Temperature Tracking Test Results for SS-1 Tack Coat

Pass No.	Test #1	Test #2	Test #3
1			
2			
3			
4			
5			

Pass No.	Test #1	Test #2	Test #3
6			
7			
8			
9			
10			

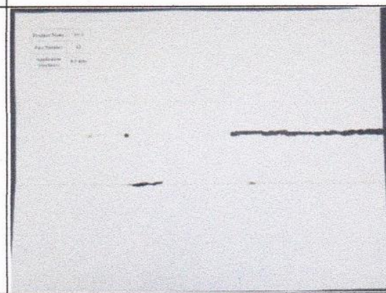
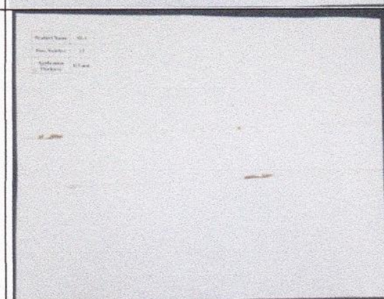
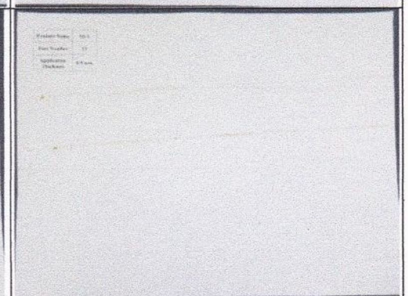
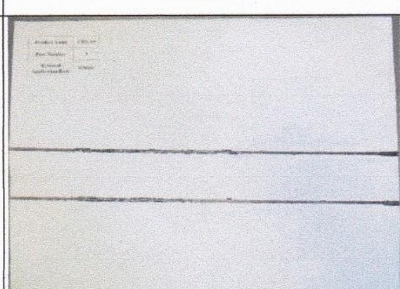
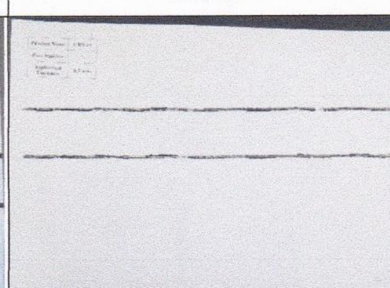
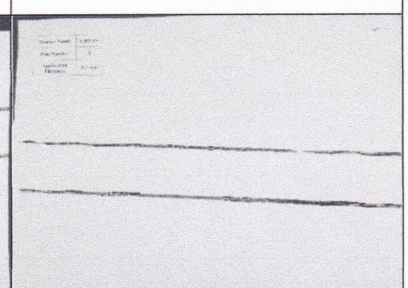
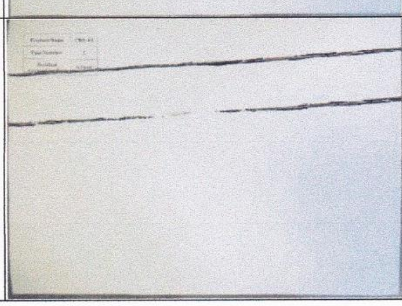
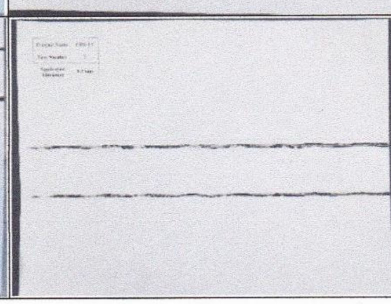
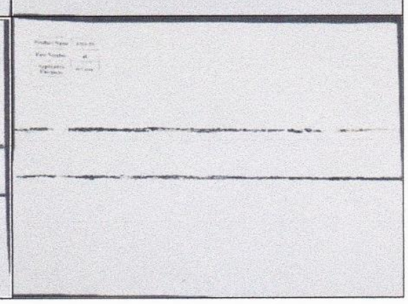
Pass No.	Test #1	Test #2	Test #3
11			
12			
Total Time	**100 minutes**	**120 minutes**	**120 minutes**

Table 4.12 Room-Temperature Tracking Test Results for CRS-1S Tack Coat

Pass No.	Test #1	Test #2	Test #3
1			
2			

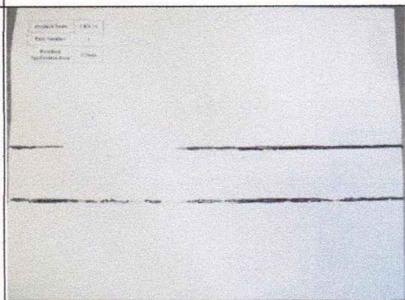
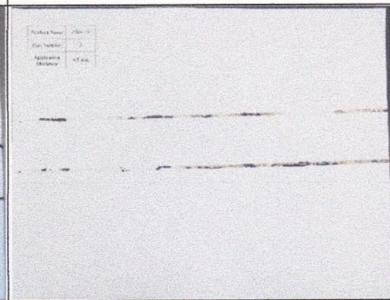
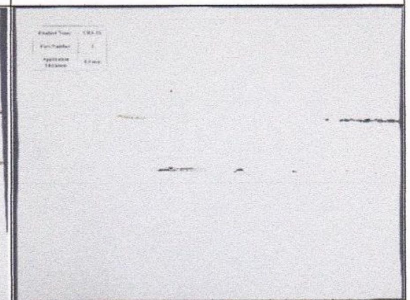
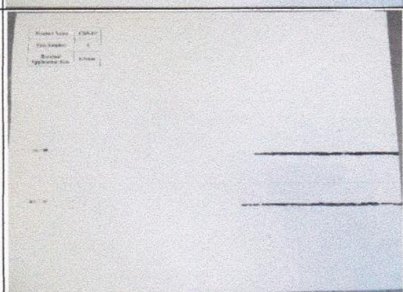
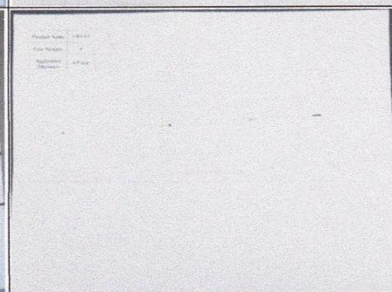
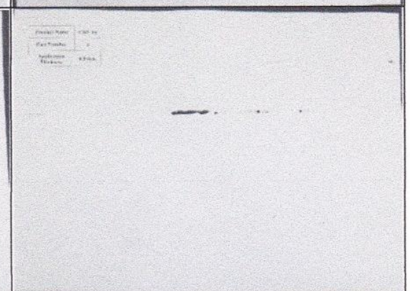
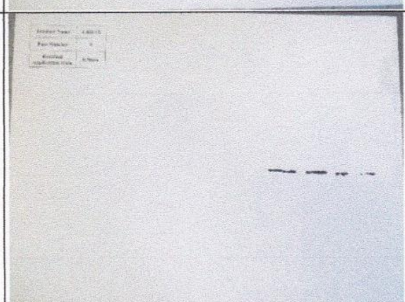
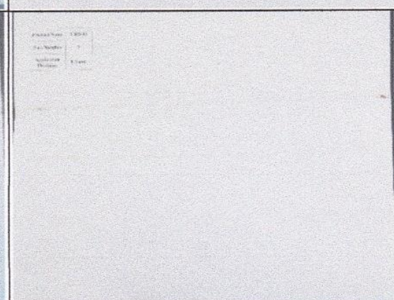
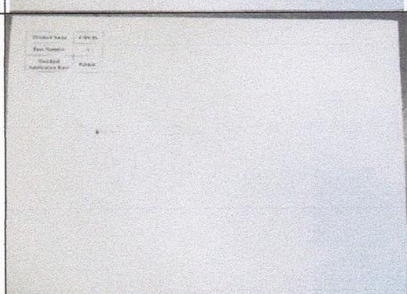
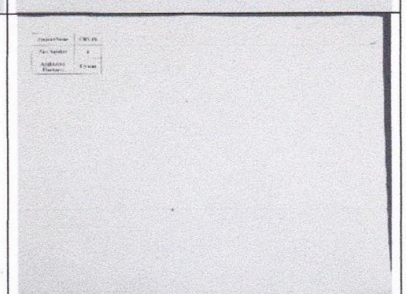
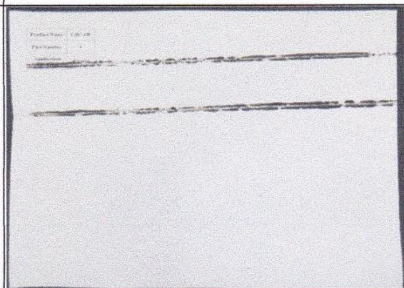
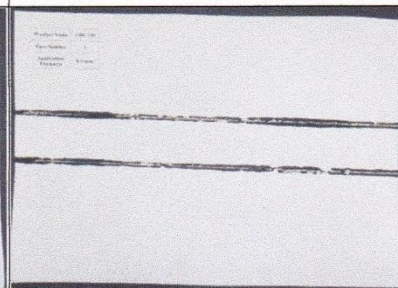
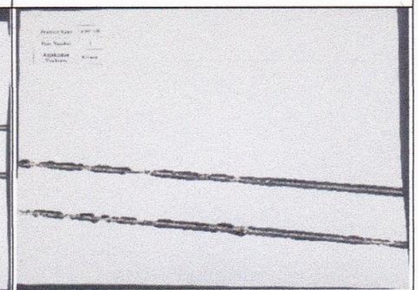
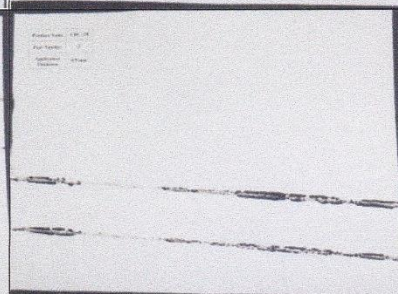
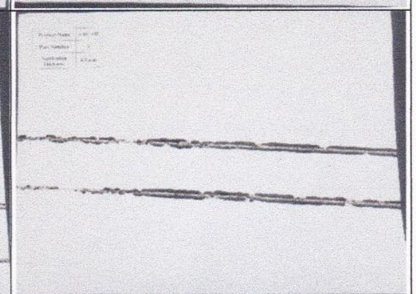
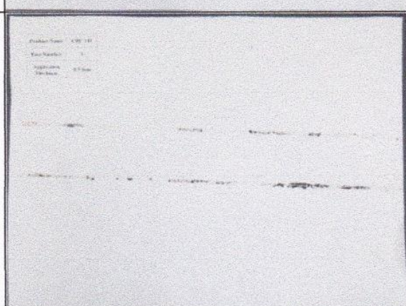
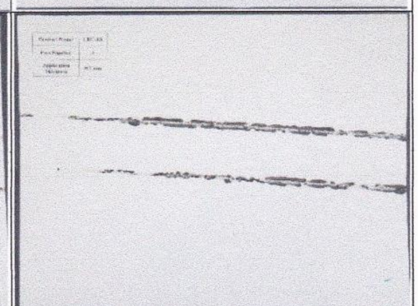
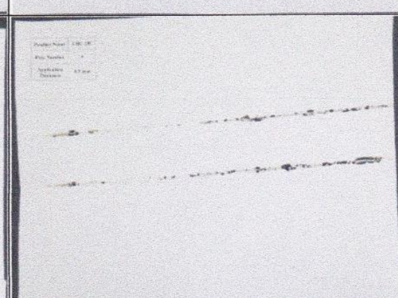
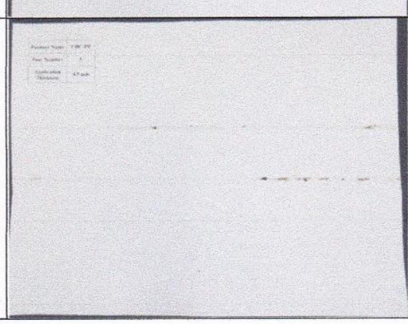
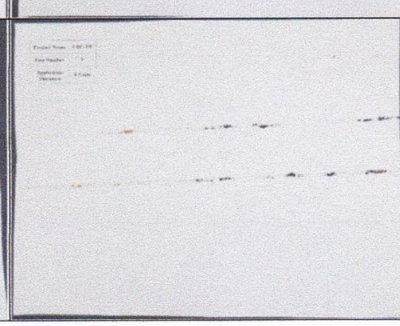
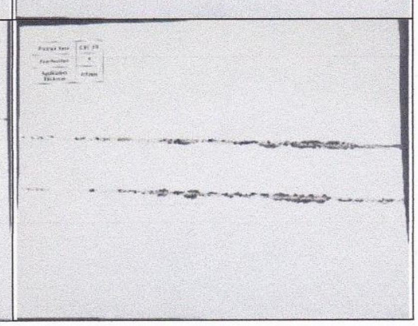
Pass No.	Test #1	Test #2	Test #3
3			
4			
5			
6			
Total Time	**60 minutes**	**50 minutes**	**60 minutes**

Table 4.13 Room-Temperature Tracking Test Results for CBC-1H Tack Coat

Pass No.	Test #1	Test #2	Test #3
1			
2			
3			
4			
5			

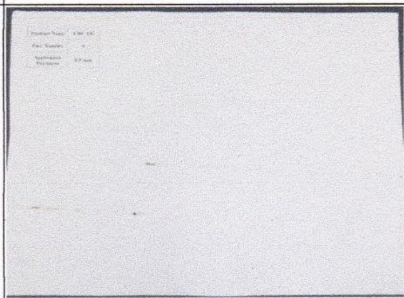
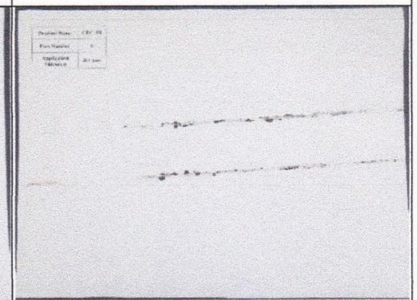
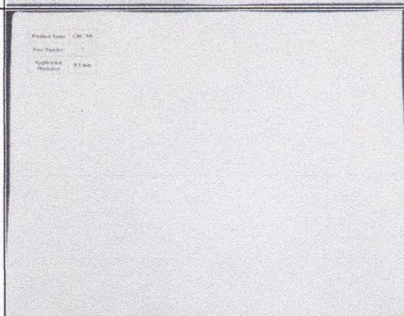
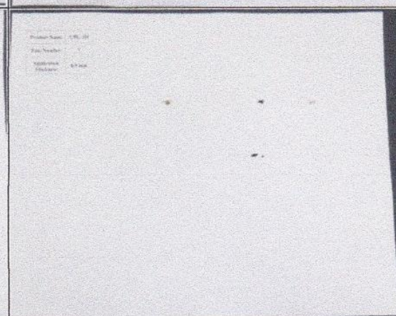
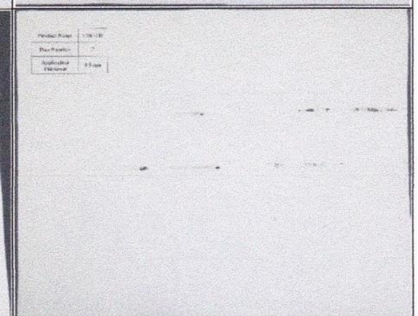
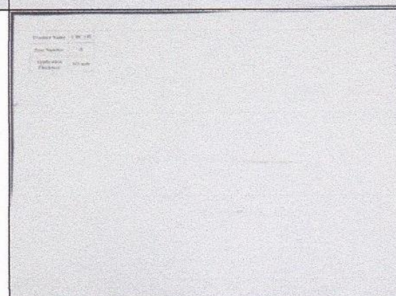
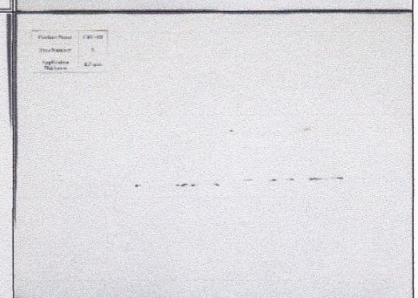
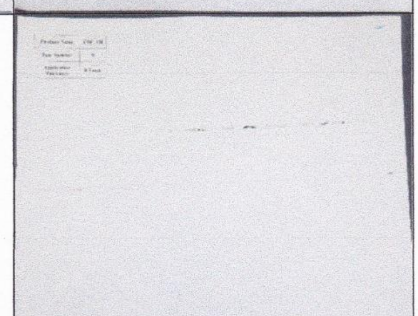
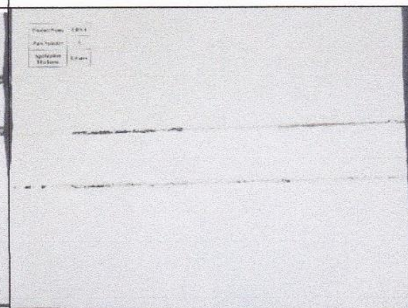
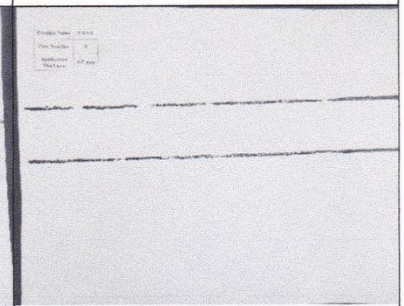
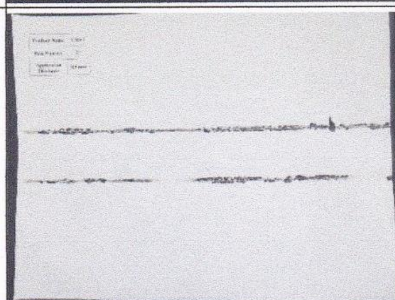
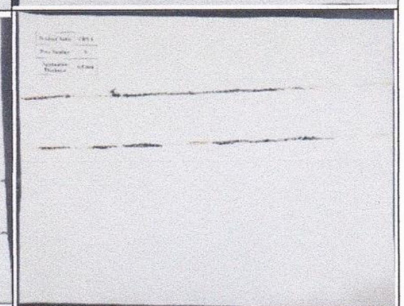
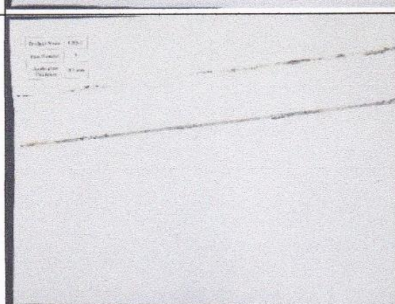
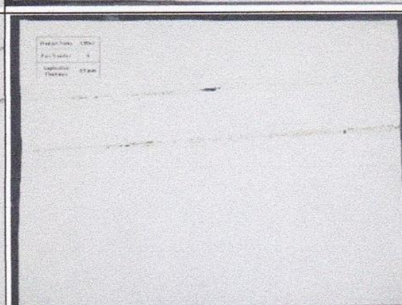
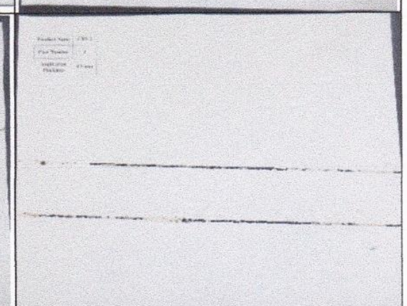
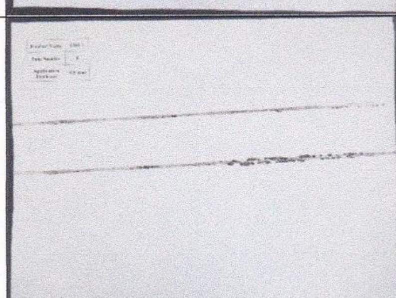
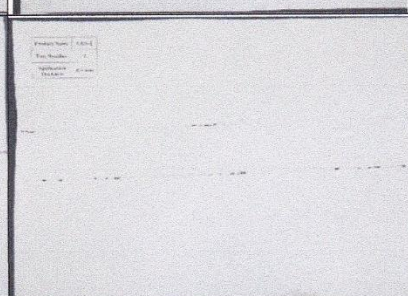
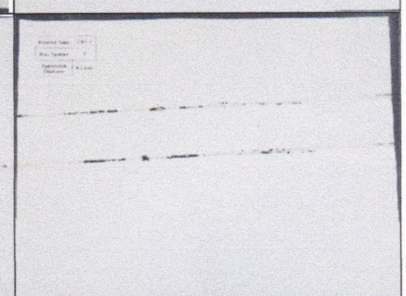
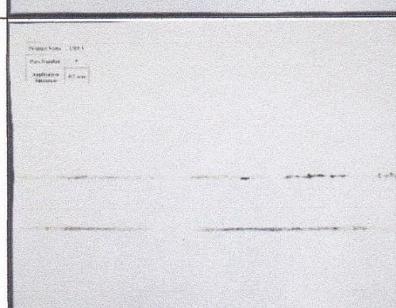
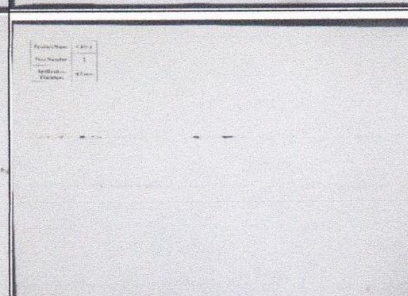
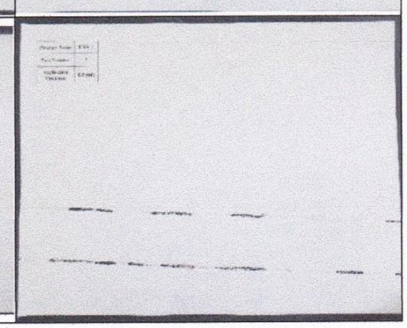
Pass No.	Test #1	Test #2	Test #3
6			
7			
8			
9			
Total Time	**70 minutes**	**80 minutes**	**90 minutes**

Table 4.14 Room-Temperature Tracking Test Results for CRS-1 Tack Coat

Pass No.	Test #1	Test #2	Test #3
1			
2			
3			
4			
5			

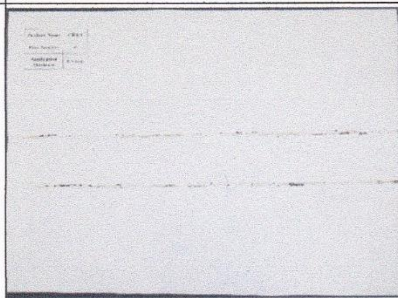
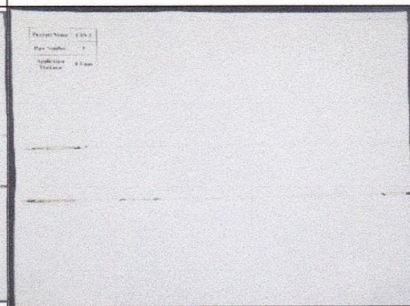
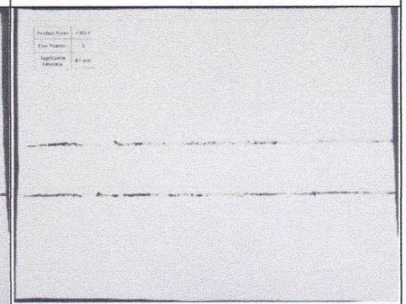
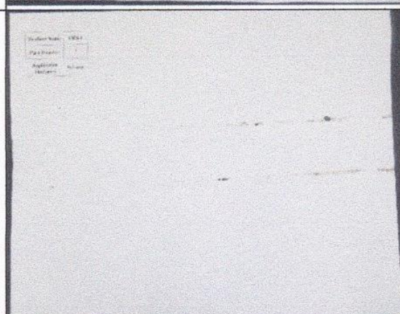
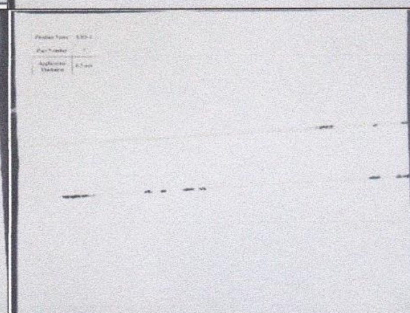
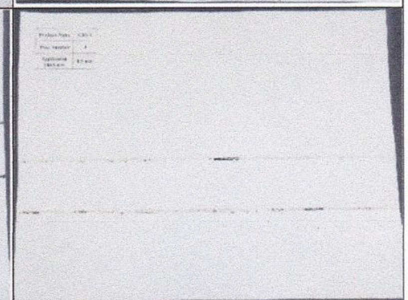
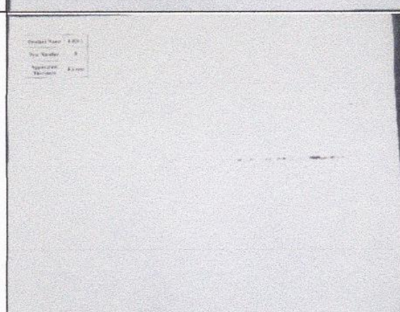
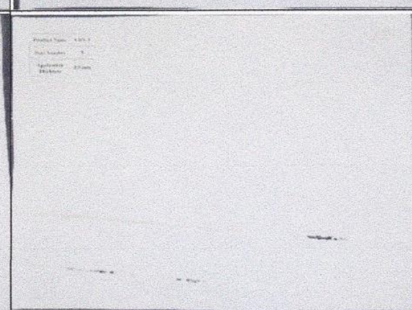
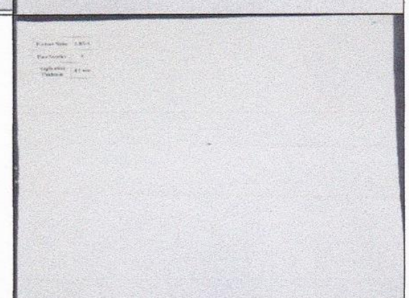
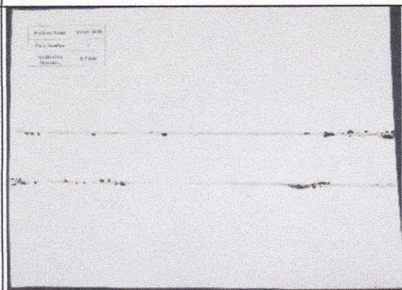
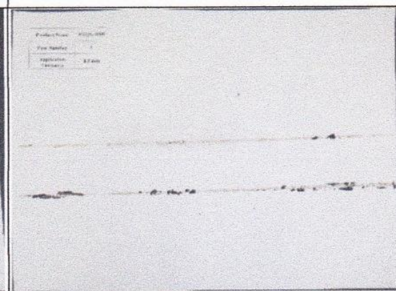
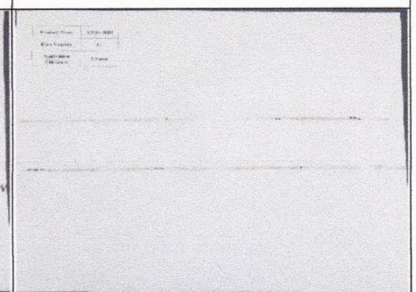
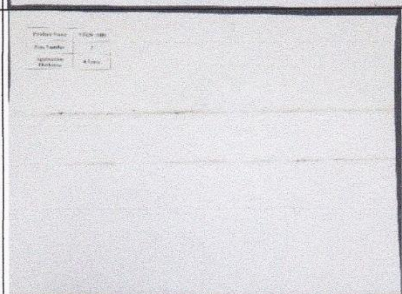
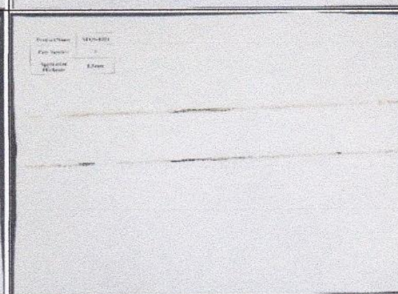
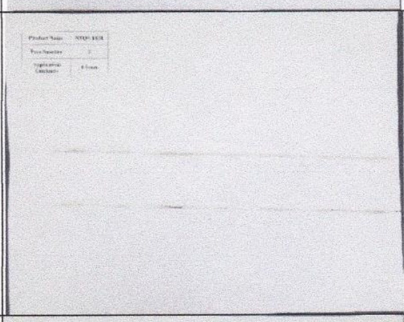
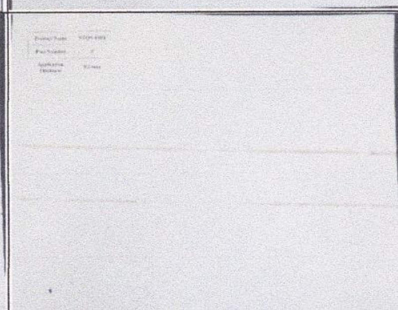
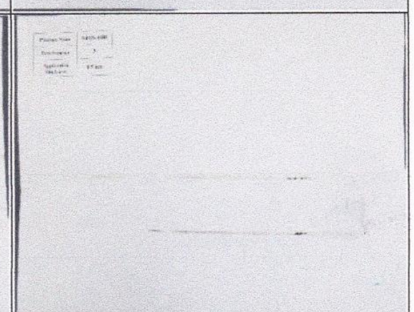
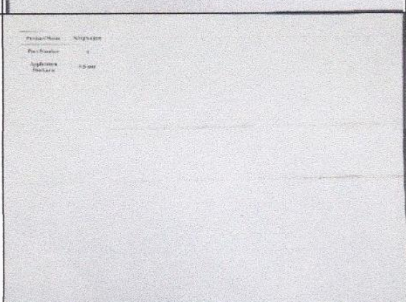
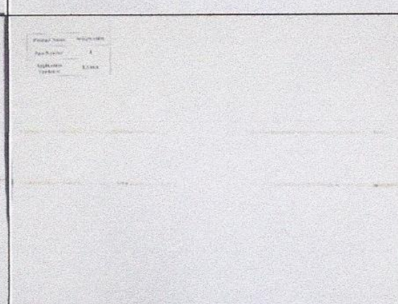
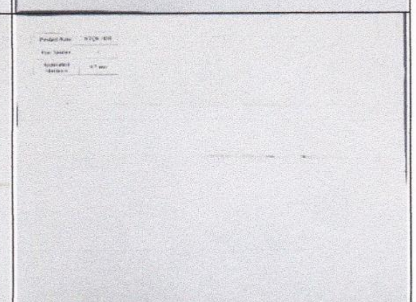
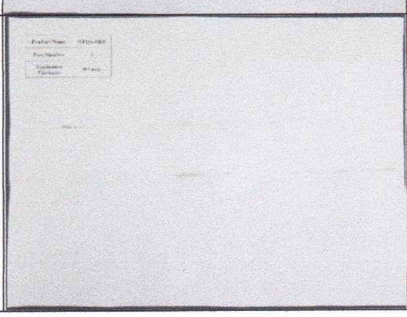
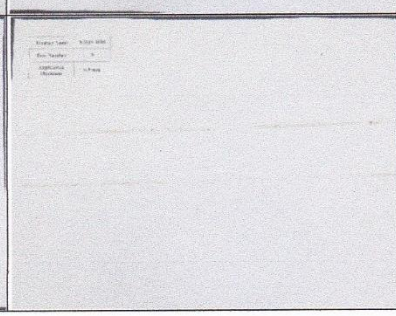
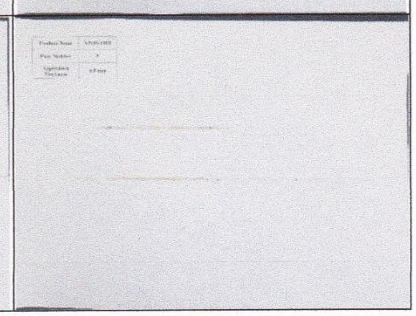
Pass No.	Test #1	Test #2	Test #3
6			
7			
8			
9			
Total Time	**80 minutes**	**80 minutes**	**90 minutes**

Table 4.15 Room-Temperature Tracking Test Results for NTQS-1HH Tack Coat

Pass No.	Test #1	Test #2	Test #3
1			
2			
3			
4			
5			

Pass No.	Test #1	Test #2	Test #3
6			
Total Time	**60 minutes**	**60 minutes**	**50 minutes**

4.5 Technology Transfer Workshop

To promote ODOT’s outreach and technology transfer goals, a technology transfer workshop was organized by the University of Oklahoma team on December 1, 2017 on the SPR (2273) Project: “Selection and Evaluation of Tack Coats in Oklahoma.” The primary objective was to share the findings of this project with the participants. This event also provided opportunity for discussions and networking. This workshop was organized at ODOT headquarter to allow broader participation by ODOT employees, OAPA members and others. A total of 31 people from ODOT, industry and academia attended this workshop. The presentation was followed by question and answer and technical discussions (Figure 4.18).

4.6 Development of a Draft Special Provision

The test results and the database were used to make recommendations on the optimum application rate for different tack coats and surface conditions. Based on the test results and the observations made during this project, a draft special provision for incorporation of emulsified asphalt binders as tack coat materials was developed. Specifically, this contributes to adding the tack coat requirements to Section 407 (Fog Seal and Tack Coat) of ODOT Standard Specification (ODOT, 2009). The details of the draft special provision are included in APPENDIX I. It is important to note that the draft special provision should be reviewed and approved by ODOT before implementation.

Figure 4.18 Technology Transfer Workshop at ODOT Headquarter

Chapter 5 Conclusions

In this study, the effects of tack coat type, application rate, surface type, temperature, and moisture conditioning on the Interlayer Shear Strength (ISS) of laboratory prepared samples were evaluated using a Louisiana Interlayer Shear Strength Tester (LISST). For this purpose, six different tack coats, namely SS-1, CRS-1S, CBC-1H, CRS-1, NTQS-1HH, and NTHAP, were collected from different suppliers in Oklahoma and Louisiana. A surface course asphalt mix (NMAS = 12.5 mm) was collected from an asphalt plant in Oklahoma. The LISST tests were conducted on double-layered (2 – 60 mm each) samples containing tack coats (SS-1, CRS-1S, CBC-1H, CRS-1 and NTQS-1HH). Tack coats were applied at different residual application rates: 0, 0.031, 0.062, and 0.155 gal/yd^2 on four different surface types: unaged HMA, aged HMA, milled HMA, and PCC. The NTHAP tack coat was applied at residual application rates: 0, 0.08, 0.12, and 0.155 gal/yd^2. The rate 0.08 gal/yd^2 was recommended by the manufacturer. Milled HMA and PCC field cores were collected with the help from ODOT. Double-layered asphalt mix samples (unaged and aged) of 150 mm diameter were compacted and prepared in the laboratory, using a SGC. The lower layers of milled HMA and PCC samples were obtained from field cores, and the top HMA layers were compacted in the SGC. The optimum residual application rate of each tack coat was determined for each surface type from the ISS values obtained from the LISST tests conducted at 25ºC. Other factors were also taken into account. Samples were prepared using optimum residual application rates of different tack coats and tested under varying temperature conditions, from 7°C (low) to 60°C (high). Effect of moisture conditioning on the ISS values was evaluated for selected tack coats and surface types. A MIST device was used for moisture conditioning and the LISST tests were conducted at 25°C.

Room-temperature tracking tests were conducted to determine the time required by a tack coat to become “trackless,” also called setting time. A mechanical spreader was used to apply the tack coat at a uniform thickness of 0.5 mm on No. 30 roofing papers. From the test results presented in preceding chapter(s), the following conclusions were drawn.

1. **Interlayer shear strength (ISS):** ISS depended on tack coat type, residual application rate, surface type, temperature, and moisture. Field conditions add additional factors not considered in this study. e.g. Humidity, radiation, wind, dust, traffic consolidation, aging, testing direction (along or against grooves) etc.
2. **Effect of Tack Coat Type**: The use of SS-1, CRS-1, and CRS-1S tack coats was found to reduce the bond strength for all surface types, except when applied on milled HMA surface at a rate of 0.031 gal/yd^2. CBC-1H tack coat exhibited a slight or no improvement in the ISS values depending on its residual application rate and surface type. CBC-1H tack coat was found most effective when applied between PCC and new HMA layers at a rate of 0.031 gal/yd^2. NTQS-1HH and NTHAP, trackless tack coats, exhibited the highest ISS among all tack coats on all surface types.
3. **Effect of Residual Application Rate**: As found in various other research, laboratory prepared specimens showed that an increase in the residual application rates of SS-1, CRS-1, CBC-1H, and CRS-1S tack coats resulted in a decrease in the ISS values for all surface types. Trackless tack coats (NTQS-1HH and NTHAP), however, were found to increase the ISS values, compared to those of for samples without any tack coat.
4. **Effect of Surface Type**: Milled HMA surface, in general, exhibited the highest ISS values. PCC surface exhibited the lowest ISS values indicating poor bonding between PCC and HMA layers (overlay). The application of CBC-1H, NTQS-1HH, and NTHAP tack coats resulted in an increase in the bond strength between PCC and HMA layers.
5. **Optimum Residual Application Rate**: The optimum residual application rates were found to depend on both surface and tack coat types. For SS-1, CRS-1S, CBC-1H, and CRS-1 tack coats, the optimum residual application rate was found to be 0.031 gal/yd^2 for all surface types tested. For trackless tack coats: NTQS-1HH and NTHAP, the optimum residual application rates were found to be 0.062 and 0.08 gal/yd^2, respectively.

6. **Surface Type:** The surface type was found to be an important factor in the selection of the most effective tack coat. Although the optimum residual application rates were found to be very similar for two surface types (HMA and PCC), the ISS values were significantly different.
7. **Effect of Temperature**: Temperature was found to be an influential factor. An increase in temperature decreased the ISS values significantly. At high temperature (60°C), all tack coats had relatively similar ISS values. The use of trackless tack coats: NTQS-1HH and NTHAP, was found to increase the ISS values at all selected temperatures for unaged HMA surface. However, those tack coats were not able to effectively improve the ISS values at 60°C for aged HMA surfaces.
8. **Effect of Moisture**: It was observed that moisture-conditioning reduced the ISS values when no tack coat was applied. The use of tack coat was found to improve the resistance to moisture-induced damage when applied at optimum residual application rates. As a result, it was found that tack coats can significantly reduce the effect of moisture-induced damage by acting as a moisture-barrier. Only NTQS-1HH tack coat exhibited a reduction in the ISS value due to moisture-conditioning for aged HMA surfaces. Also, NTHAP, a trackless tack coat, exhibited the highest ISS values in both unconditioned and moisture-conditioned situations, followed by NTQS-1HH for unaged HMA surface.
9. **Setting Time of Tack Coats**: The setting time of tack coats, excluding NTHAP tack coat, varied from 50 to 120 minutes (2 hours) depending upon their types. The shortest setting time of 50-60 minutes was observed for CRS-1S and NTQS-1HH tack coats. SS-1 and CRS-1 tack coats exhibited the longest setting time of 100-120 minutes. The setting time of CBC-1H tack coat was found to be 70-90 minutes.
10. Setting time was found to be independent of the percentage asphaltic residue of tack coats.

Based on the observations made in this study, the following recommendations were made:

1. For new HMA, aged HMA, and PCC layers, trackless tack coats (NTQS-1HH and NTHAP) improved ISS the most. Of the tack coats tested, PCC overlays would have the strongest bonds using a trackless tack coat.
2. While aggregate interlock and surface friction add shear strength, minimal amount of tack coat is needed to add a moisture barrier.
3. Tack coats do not add shear strength at high temperatures as shown by tests at 60˚C.
4. All tack coats tested improved the moisture resistance at the interface of two pavement layers.
5. ISS tests with no confinement pressure can be used to evaluate new tack coat products for various pavement types.
6. The results presented in this study are based on conducting the LISST tests on asphalt samples at their early age (one day after compaction). As a result, the measured ISS values were comparatively low. Therefore, one can say that opening the pavement to heavy traffic immediately after construction with any emulsion other than trackless tack coat is not recommended. It is also recommended to investigate the effect of aging on ISS values in future studies.
7. A field study is recommended to explore various in-situ factors beyond the scope of this study. Those factors would include: distributor calibration, product application rate, sample location, magnitude of field ISS versus laboratory ISS, specifications, aging, and field guide to name a few.

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APPENDIX I

Draft Special Provision

OKLAHOMA DEPARTMENT OF TRANSPORTATION
RECOMMENDED DRAFT SPECIAL PROVISION
FOR
TACK COAT

These Special Provisions revise, amend, and where in conflict, supersede applicable sections of the 2009 Standard Specifications for Highway Construction, English and Metric.

407.04 CONSTRUCTION METHODS

C. Tack Coat *(Add the following:)*

Apply the tack coat or NT tack material as shown in Table 407:1, unless otherwise required by the Contract. Alter the application rate as directed by the Resident Engineer (based on weather and surface type or layer). In the table, use the highest rate for the surface type or layer (top or bottom).

Table 407:1
Tack Application Rates

Surface Type	Original Emulsion gal/yd^2 [L/m^2]	Residual gal/yd^2 [L/m^2]
New, Old, Milled Asphalt	0.05 [0.23]	0.03 [0.14]
New, Old, Milled Asphalt, Milled PCC (NTQS-1HH, NTSS-1HM)	0.10 [0.46]	0.06 [0.27]
New, Old Asphalt (NTHAP)	--	0.08 [0.36]
Milled Asphalt (NTHAP)	--	0.12 [0.55]
Milled PCC (NTHAP)	--	0.16 [0.73]

Ensure that the tack breaks before the application of the next surfacing layer.

If the tack loses its adhesive properties or is exposed to traffic before being covered by the next surfacing layer, reapply the tack coat at a rate that ensures proper adhesion, as directed by the Resident Engineer, at no additional cost to the Department.

407.06 BASIS OF PAYMENT *(Add the following:)*

The Department will pay for each pay item at the contract unit price per the specified pay unit as follows:

Pay Item:	**Pay Unit:**
(E) NT TACK COAT	Gallon [Liter]

The Department considers the cost of water for dilution of emulsions to be included in the contract unit price for *NT Tack Coat*.