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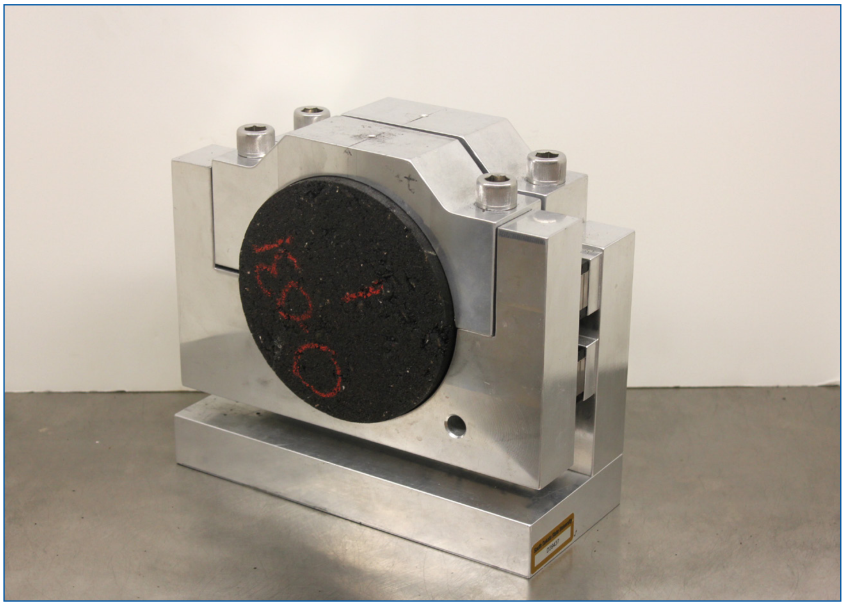
DEVELOPMENT OF A GUIDELINE FOR THE SELECTION OF TACK COATS IN SOUTH DAKOTA



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DEVELOPMENT OF A GUIDELINE FOR THE SELECTION OF TACK COATS IN SOUTH DAKOTA

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ABSTRACT

Several types of tack coats are used in South Dakota for asphalt pavement construction projects. This study was conducted to determine the effects of application rate, surface type, texture, moisture, and freeze-thaw on the early-age performance of three tack coat emulsions applied on four surface types in dry conditions and after moisture-conditioning. The specimens' early-age interlayer shear strength (ISS) was measured and used to study the effectiveness of different tack coat types applied at different rates on each surface texture type. The effects of freeze-thaw cycles on the ISS values were examined on moisture-conditioned specimens. It was found that the samples prepared using tack coats having a harder binder grade exhibited higher early-age ISS values at low application rates compared with those prepared using a polymer-modified tack coat. In addition, it was found that applying tack coats resulted in a reduction in early-age ISS values for specimens prepared by using different textures of HMA surfaces. Moisture conditioning resulted in a considerable reduction in the specimens' ISS values consisting of an HMA layer compacted on a grooved PCC layer using different tack coats. The polymer-modified tack coat was the most effective in reducing moisture's effect on the ISS values.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Several pavement failures have been reported due to inadequate interlayer bond due to the application of insufficient or excessive tack coat and moisture penetration. Inadequate interlayer bond leads to distresses such as half-moon-shaped cracks, delamination followed by longitudinal wheel path cracking, potholes, fatigue cracks, slippage, and rutting. In some cases, the application of an inappropriate amount of tack is due to a lack of a widely accepted specification or error in calculating the application rate. Other factors affecting the bond quality are application methods, equipment type and calibration procedures, asphalt layer surface type (old, milled, or new, Portland cement concrete), surface cleanliness, moisture, and temperature. The tack coat application rate should be adjusted with the pavement surface's conditions to achieve an adequate interface bond. Therefore, determining the type and optimum tack coat application rate are vital to pavement performance and service life. The most critical quantity in tack coat application is the residual amount of asphalt (not the asphalt concentration in the diluted emulsion), which ultimately affects the bond strength. Currently, the selection of tack coat type and application rate in South Dakota is generally made based on experience and engineering judgment. This is primarily due to the lack of specific guidelines for the selection of tack coat type and application rate as a result of the lack of test data. Given the harsh winter conditions in South Dakota and north central states, it is important to evaluate the effectiveness of the selected type and application rate of tack coats in extreme weather conditions, which asphalt pavements experience, specifically at an early age. This will help minimize the maintenance cost in the future due to improved interlayer bond strength. In the current study, a Louisiana Interlayer Shear Strength Tester (LISST) device was used to measure the early-age interlayer shear strength (ISS) of layered samples. It should be noted that tack coat failure is more likely to occur at the early age of the pavement in which the residue in the interlayer is not aged and is softer. The test matrix included two main parts: (1) identify the optimum tack coat application rates and (2) evaluate the effect of moisture conditioning on ISS of the samples prepared at the optimum application rate. The top layer of all the test samples was prepared to simulate a new hot mix asphalt (HMA) overlay. The top layer was compacted on four different bottom layers: new HMA, aged and worn HMA, milled HMA, and grooved Portland cement concrete (PCC). Three types of tack coats, namely CRS-2P, CSS-1h, and SS-h, were evaluated. Tack coats were applied at four application rates, namely 0, 0.140, 0.281, and 0.702 liters per square meter (L/m^2). Results indicated that among the tack coats evaluated in this study, CSS-1h exhibited the highest ISS values on all surface types compared with those measured for surfaces without any tack coat. Also, on all HMA bottom layer types, CSS-1h showed the best performance at low application rates. The CSS-1h was the only tack coat with a higher early-age ISS value than HMA on HMA samples without any tack coat. The SS-h tack coat application on PCC bottom layers also resulted in a higher ISS value than that measured with other tack coats. The highest ISS value measured for the PCC and HMA interlayer was observed when the SS-h tack coat was used. Generally, the CRS-2P tack coat improved the ISS at higher application rates, while CSS-1h was effective when applied at a lower application rates. The highest ISS value was observed when the tack coat was applied on aged and worn HMA bottom layers, followed by new HMA, milled HMA, and grooved PCC. For both new HMA and aged and worn HMA bottom layers, the CSS-1h tack coat applied at a rate of 0.140 L/m^2 showed the best performance. For milled HMA bottom layers, CSS-1h and SS-h tack coats used at a rate of 0.140 L/m^2 exhibited superior effectiveness in improving the ISS value. All the tested tack coats showed increased ISS values for grooved PCC bottom layers than samples prepared without applying any tack coat. Hence, it is essential to use a proper tack coat for any PCC surface overlaid by HMA. Moisture conditioning negatively affected the ISS of the samples with PCC bottom layer regardless of the tack coat type. However, the early-age ISS values of the samples containing tack coats applied at their optimum application rates on other types of HMA bottom layers were not found to be negatively affected due to moisture conditioning in the laboratory setting.

1. INTRODUCTION

1.1 Problem Statement

Asphalt pavement is constructed in multiple layers and should behave as a single coherent structural unit to achieve its design performance goal. Without a proper bond between the pavement layers, when it is subjected to traffic loading and environmental elements, achieving a pavement structure with a monolithic behavior will not be feasible (Al-Qadi et al., 2008). To improve the bond between pavement layers, an asphaltic material, namely tack coat, is applied to the existing pavement surface before the construction of the top layer(s) (Mohammad et al., 2010). Poor structural integrity, reduction in the bearing capacity of the pavement structure, and premature failures such as delamination of the asphalt layer, rutting, and half-moon cracking can occur as a result of inadequate interlayer bond due to the application of insufficient or excessive amounts of tack coat (Ghabchi and Dharmarathna, 2022; Ghabchi and Mihandoust, 2021; Chen, 2010; Ziari et al., 2007; Mohammad et al., 2002). Therefore, applying an optimum amount of tack coat between layers is critical. Over the past decades, several studies have been conducted to determine the optimum tack coat application rate based on tack coat type, surface characteristics, and temperature. Since interlayer failure can occur due to different mechanisms, namely direct shear, torsion (indirect shear), and direct tension, different laboratory and in-situ test methods have been proposed and applied to characterize interlayer bonds with different failure mechanisms. However, the shear failure mechanism at the layers' interface is known to be the most prevalent failure scenario observed in the field. Therefore, it is critical to determine the interlayer shear strength (ISS) of the pavement layers to assess the propensity of the layered pavements to shear failure (Mohammad et al., 2012). Many factors affect the ISS, such as tack coat application rate, tack coat type, layer type and texture, cleanliness, test temperature, curing time, moisture, aging conditions, and confinement pressure, among other factors (Covey et al., 2017; Coleri et al., 2017; Wang et al., 2017; Zhang, 2017; Wilson et al., 2016; Karshenas, 2015; Mohammad et al., 2012; Al-Qadi et al., 2012; Bae et al., 2010, Chen and Huang, 2010; McGhee and Clark, 2009; Al-Qadi et al., 2008; Tashman et al., 2006). The optimum tack coat application rate is the amount of the specific type of tack coat applied using the proper application method on a well-prepared pavement surface at given conditions to maximize the ISS value (Salinas et al., 2013; Mohammad et al., 2010).

In recent years, several pavement failures, specifically in overlay projects, have been reported in Region 8 states, including South Dakota. The primary causes of failures were insufficient or excessive tack coat application and moisture penetration in the interface of two layers, resulting in an inadequate bond between layers. In some cases, applying an insufficient or excessive amount of tack coat occurs due to the lack of a widely accepted specification and error in the calculation of the application rate. Currently, the selection of tack coat types in South Dakota is generally made based on experience or engineering judgment. This is primarily due to the lack of specific guidelines for the selection of tack coat type, application rate, placement, and evaluation. It is also important to evaluate the effectiveness of the selected type and optimum application rate of tack coats in extreme weather conditions, which asphalt pavements experience in South Dakota as a quality control procedure prior to construction. This will help minimize the maintenance cost in the future due to improved interlayer bond strength.

Given the foregoing needs, this study aimed to investigate the effectiveness of different tack coats in improving the early-age interlayer shear strength of asphalt pavements constructed on different surface types. The effects of other parameters, such as tack coat type, application rate, moisture, freeze-thaw cycle, and surface texture, on interlayer shear strength were also studied. Table 1.1 provides a summary of the tests and materials tested in this study in different conditions.

Table 1.1 Test Matrix

Louisiana Interlayer Shear Strength Test				
Surface Type	Tack Coat Type	Application Rates (L/m^2)	Dry Conditioned	Moisture Conditioned
New HMA	No Tack Coat	0	Yes	Yes
	CRS-2P	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
	CSS-1h	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
	SS-h	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
Aged and Worn HMA	No Tack Coat	0	Yes	Yes
	CRS-2P	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
	CSS-1h	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
	SS-h	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
Milled HMA	No Tack Coat	0	Yes	Yes
	CRS-2P	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
	CSS-1h	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
	SS-h	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
Grooved PCC	No Tack Coat	0	Yes	Yes
	CRS-2P	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
	CSS-1h	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes
	SS-h	0.140, 0.281, 0.702	Yes	No
		Optimum Application Rate	Yes	Yes

Percent Residue Test (ASTM D6934)		
CRS-2P	CSS-1h	SS-h
Yes	Yes	Yes

1.2 Objectives

The main objective of this study was to determine the optimum application rates of three types of commonly used tack coats in South Dakota, namely CSS-1h, CRS-2P, and SS-h, applied on different pavement surface textures. Four types of pavement surface textures—new HMA, aged and worn HMA, milled HMA, and grooved PCC—were evaluated. The optimum application rates were determined based on the ISS results obtained from conducting shear tests using a Louisiana Interlayer Shear Strength Tester

(LISST). Laboratory-prepared samples were used to perform the LISST tests. Another important objective was to determine the effect of moisture and freeze-thaw cycles on ISS values. For this purpose, after the determination of optimum application rates of each tack coat type evaluated for each pavement texture, samples were prepared with optimum application rates using each tack coat for all surface types and were tested after moisture conditioning. The ISS values of the moisture-conditioned samples were compared with those from testing dry samples.

The specific objectives of this study were as follows.

1. Determine the optimum application rates of different types of tack coats widely used in South Dakota: CRS-2P, CSS-1h, and SS-h;
2. Study the effects of pavement and environment parameters on early-age ISS of selected tack coats using a LISST device. The following parameters were considered:
    a. Tack coat application rate: 0, 0.140, 0.281, and 0.702 L/m^2
    b. Surface type: new hot-mix asphalt (HMA), aged and worn HMA, milled HMA, and grooved PCC
    c. Effect of the environment: moisture/freeze-thaw conditioned and dry samples
3. Develop a database of tack coat parameters (type and application rate), surface parameters (new HMA, aged and worn HMA, milled HMA, and grooved PCC), optimum application rates, the effect of moisture, and early-age ISS values based on the LISST test results. This database will be used as a guideline for the selection of tack coat types and application rates;
4. Determine the percent binder residue of CRS-2P, CSS-1h, and SS-h tack coat emulsions as the basis of tack coat application rate.

1.3 Research Tasks

This study comprised six major tasks, as follows.

Task 1: Conduct a comprehensive literature review focusing on the characterization of tack coat and its performance in pavement interlayer.

Task 2: Collect different materials, namely tack coat, asphalt binder, asphalt mix, and Portland cement concrete.

Task 3: Prepare cylindrical HMA samples having 50-mm height and 150-mm diameter with 7% ± 0.5% target air voids. Condition the samples so that their surfaces represent new HMA, aged and worn HMA, and milled surface conditions. Mix and prepare grooved PCC samples having 50-mm height and 150-mm diameter. Compact a layer of asphalt overlays with 7% ± 0.5% air voids after treating the prepared samples with a tack coat.

Task 4: Conduct ISS tests on asphalt interlayer treated with tack coat for determination of the optimum tack coat application rates. Tack coats with the residual application rates were applied to cylindrical samples having different surface conditions (new HMA, aged and worn HMA, milled HMA, and grooved PCC) and will be tested using an LISST device. After determining the optimum tack coat application rate for each case, the effect of moisture and freeze-thaw will be evaluated by conducting additional ISS tests.

Task 5: Analyze the data collected from ISS tests conducted on the interlayers containing tack coats. The outcomes will be used to develop a tack coat efficiency database for South Dakota.

Task 6: Submit a final report of the research methodology, findings, and recommendations to MPC.

2. LITERATURE REVIEW

2.1 Tack Coats and their Properties

2.1.1 General

As per the definition given by the American Society for Testing Materials (ASTM), a tack coat is a thin adhesive layer applied at the interface of two pavement layers to create a solid bond between a non-absorptive old surface and a new asphalt layer. Depending on the industry's preparation technique, tack coats are categorized into different types, namely conventional asphalt binders, asphalt emulsions, and cutback asphalt binders. Among all three classes of tack coats, asphalt emulsions have become more popular due to fewer environmental concerns associated with emulsified asphalt, easy applicability, and low energy consumption. Cutback asphalt binders are rarely used due to environmental concerns. In general, conventional asphalt binder tack coats provide a higher shear strength than emulsified tack coats.

An asphalt emulsion consists of an asphalt binder, water, and an emulsifying agent. In recent years, polymer additives have been used to improve tack coats' properties. Depending on the emulsifying agent, three types of tack coats—anionic, cationic, and nonionic—are produced and used in construction (Gierhart and Johnson, 2018). The charge of the emulsifying agent is responsible for the electric charge of the tack coat. Negatively charged emulsifying agents make anionic tack coats, while positively charged emulsifying agents make the cationic ones.

In the terminology of tack coats, the cationic ones are identified with the letter "C" (e.g., CSS-1h, CSS-1, CRS-2P, etc.), and those that lack the letter "C" are the anionic emulsions (e.g., SS-1, SS-1h, SS-h, etc.). The letter "h" in a tack coat label denotes a hard-grade asphalt with low penetration. In the classification of the tack coat emulsion material, number 1 indicates a low viscosity, while number 2 means a high viscosity residue. A highly viscous material will produce a strong bond. For example, tack coat emulsion CRS-1 was shown to have a higher bond strength than CRS-2 emulsion. However, having a highly viscous emulsifying material does not always result in a high-strength bond in the presence of unwanted fine particles.

Other than the production technique, tack coats are also categorized based on their setting time as slow setting (SS), rapid setting (RS), and quick setting (QS). Commonly used slow-setting tack coats are SS-1, SS-1h, CSS, and CSS-1h. Also, typical rapid-setting tack coat emulsions are RS-1, RS-2, CRS-2, PMRS-2, PMRS-2h, PMCRS-2, and PMCRS-2h. Furthermore, ordinary quick setting tack coat emulsion is QS-1, QS-1h, CQS-1, and CQS-1h. Moreover, there are latex-modified (LM) and polymer-modified (PM) tack coat emulsions available in the market. Trackless tack coats are another type of modern tack coat that eliminates the tracking problem due to construction equipment used in pavement construction projects. Trackless tack coats are shown to have several advantages over conventional tack coat emulsions.

Every tack coat emulsion has a specific breaking time and a set time. The color change of the emulsion from brown to black indicates the breaking of a tack coat emulsion. Tack coat break is the separation of the water from the tack coat emulsion (Mohammad et al., 2012). Setting time is the time needed for water to evaporate entirely from the emulsion and leave the tack coat as a thin film on the pavement/road surface (Mohammad et al., 2012). Yaacob et al. (2014) reported that weather conditions, including wind speed, solar radiation, temperature, and humidity, affect the tack coat's breaking time. Regardless of the condition and tack coat type, a low application rate was found to result in a short breaking time. Also, low temperature and no solar radiation were found to lead to low workability, highlighting the problems associated with the application of tack coats at night.

2.1.2 Effect of Tack Coat Properties on Interlayer Strength Characteristics

Asphalt binder constitutes the adhesive agent present in a tack coat emulsion; therefore, the rheological properties of the asphalt binder present in a tack coat have a significant effect on the interlayer's mechanical properties. Hence, rheology is a vital parameter to consider in the characterization of tack coats and their mechanical properties. Covey et al. (2017) suggested using non-destructive tests to evaluate tack coat materials based on their simple rheological properties. Also, correlations were developed between the rheological properties and the ISS values measured for the layered pavements containing tack coats. Covey et al. (2017) concluded that linear relationships exist between the rheological properties, such as rotational viscosity, penetration, and binder softening point, and the measured ISS values. Karshenas (2015) and Wilson et al. (2016) concluded that the type of tack coat has a significant effect on interlayer bond strength.

Mohammad et al. (2012) reported an increase in tack coat emulsion viscosity increased a tack coat's tensile strength. Also, an increase in the binder's softening point was correlated to the maximum tensile strength. Furthermore, bond strength was found to increase with an increase in application rate to a certain extent. An increase in temperature caused a reduction in the shear strength. Tack coat emulsions with low viscosities exhibited a higher bond strength than tack coat emulsions with high viscosity (Ghaly et al., 2013).

As conducting the Superpave® binder tests on tack coats is practical and relatively simple, the relationship between asphalt binder rheological parameter ($G^*/\sin\delta$) and ISS in different application rates can be readily used as a parameter for the selection of tack coat emulsions (Bae et al., 2010). NCHRP report 712 established a relationship between the bonding characteristics of tack coats and the rheology of the materials (Mohammad et al., 2012). A tack coat having a harder residue has been shown to have a high bond strength than those having a softer residue (Destrée and Visscher, 2017).

Raab et al. (2015) reported that aging improves the interlayer bond strength with and without a tack coat. However, this improvement was more significant when a tack coat was used. Long-term oven aging and site aging both were found to have a similar effect on ISS values. Wang et al. (2017) conducted a comprehensive study to investigate the factors affecting tack coat performance. Also, intrinsic factors such as tack coat type, tack coat application rate, curing time, aging of the asphalt surface, application condition, temperature, mix type, and surface texture were identified as significant factors affecting the ISS values.

Cho et al. (2017) evaluated the possibilities of debonding at the interlayer surface in asphalt pavements using a computational method. A special computer software, Layered Visco-Elastic Pavement analysis for Critical Distresses (LVECD) program, was used to understand the critical stresses that lead to debonding flexible pavement layers. Also, this analysis revealed the mechanism that the critical stresses get affected by the design parameters and environment. Further, the prediction model was developed for determining interlayer shear bond strength with different tack coats and temperatures along with various loading rates and normal confining stresses. Using LVECD was proven to be a feasible, economically efficient, and quick method for the proper selection of tack coat materials.

2.1.3 Effect of Surface Texture on Interlayer Strength Characteristics

In new constructions or an asphalt overlay project, a tack coat should bind a new HMA, an aged and worn HMA, a milled HMA, or a PCC surface to a new HMA layer. Due to its economic feasibility, the use of the HMA overlay on PCC surfaces is widespread. The pavement surface texture affects the measured ISS values (Covey et al., 2017). Milled HMA surfaces were found to provide the highest ISS values, followed by PCC, aged HMA, and new HMA surfaces (Mohammad et al., 2012, Raposeiras et al., 2013).

Additionally, it was concluded that an increase in the surface roughness leads to an increase in the bond strength. A strong correlation between the surface texture and interlayer shear strength was also reported to exist (Coleri et al., 2017).

Milled HMA surface is one of the most common surface types in overlay projects. However, the effect of the tack coat on the ISS values in the milled sections was found to be insignificant while highly significant for non-milled sections (Tashman et al., 2008; McGhee and Clark, 2009). Raposeiras et al. (2016) reported that surface macro-texture is one of the influential factors affecting the measured ISS values. It was established that the aggregate particles larger than 8 mm had the highest contribution to shear strength when they were used at a rate between 40% and 50%. However, other studies reported surface texture not to be an influential factor affecting the ISS value (Destrée and Visscher, 2017). The surfaces with higher macro-texture values were found to have a high potential for absorbing emulsion (Raposeiras et al., 2013). In a different study, Ziari et al. (2007) showed that interface conditions could affect the interlayer's stresses and strains. Also, it was concluded that the absence of tack coat in between the binder course and base course resulted in a more negative impact on the strain level than that measured in between two binder courses. Chen (2010) found that slippage crack failure mode in asphalt pavement occurs mainly due to insufficient bonding between two layers due to inadequate or poor-quality of tack coat application. Chen et al. (2010) evaluated the effect of surface features on interlayer shear strength in the presence of a tack coat. The direct shear test was used to evaluate the interlayer shear strength with a constant displacement rate of 2.5 mm/min. Tests were conducted on cored samples from simulated slabs. The simulated pavement's upper and bottom layers were constructed using three different layer types: dense graded asphalt concrete (DGAC), gap-graded asphalt concrete, and open-graded asphalt concrete. In addition, three test temperatures (25°C, 35°C, 50°C), two types of tack coats (CRS emulsion, MAE emulsion) and four residual application rates (0.06, 0.12, 0.18, 0.24, 0.3 L/m^2) were evaluated. Three parameters, K-value (interlayer tangential reaction modulus), peak shear, and residual shear, were evaluated to find tested samples' mechanical behavior. It was found that both shear strength and K values decreased with an increase in mean texture depth (MTD) and film thickness (FT). Out of all the surface types, DGAC-DGAC exhibited the highest shear strength values. Also, it was found that the MTD and FT were the main factors affecting shear strength. It was concluded that the surface characteristics and tack coat type are the main factors affecting the optimum application rates. In another study, Mohammad et al. (2010) found that milled HMA resulted in the highest interlayer shear strength, followed by PCC surface, aged HMA surface, and new HMA. Tashman et al. (2006) conducted a study on the parameters affecting interlayer bonds in the pavement containing tack coats, including a few application practices. A number of factors, namely surface treatment type (milled and non-milled), curing time, residual application rates (0.00, 0.0815, 0.2173, 0.3260 L/m^2), and test location (wheel path and middle of the lane), were considered in that study. The study revealed that the milled pavement sections exhibited a higher shear strength compared with non-milled sections. The tack coat's presence was not an advantage for the milled surfaces, whereas, for non-milled surfaces, it improved the interlayer shear strength. Similarly, from the torque bond test, it was found that milled surfaces had the highest shear strength. This test also confirmed that the absence of a tack coat could negatively affect the bond strength of non-milled sections. The most important finding from the pull-off test was that the non-milled section had a higher pull-off strength value than that of the milled one. The variation of ISS values with the age of the pavement after construction was evaluated by Das et al. (2017). Surface type, tack coat type (SS-1, SS-1h, NTSS-1hM, and CBC-1h), and application rate of the tack coats were examined. The ISS values were measured using an LISST device. A short-term performance evaluation was carried out after conducting the tests on the cores extracted from the pavement shortly after construction. Results showed that an increase in service time resulted in an increase in interface bond strength regardless of the surface type. A study by Al-Quadi et al. (2012) showed that the optimum residual application rate for milled surfaces was 0.2716 L/m^2. For the new binder SMA layer, the optimum residual application rate was found to be 0.0905 L/m^2.

2.2 Characterization of Interlayer Bond Strength

Various types of tests are developed and applied for the evaluation of the interlayer bond strength. These tests are used to evaluate the effectiveness of the tack coat in different failure scenarios. Interlayer bond strength tests can be listed under three main categories: shear strength, tensile strength, and torsion tests (Raposeiras et al., 2013; West et al., 2005). Some of these tests are conducted in the laboratory, while others can be performed as in-situ tests. Table 2.1 shows prevailing bond strength evaluation tests used by the asphalt industry. Among these tests, direct shear devices are the most commonly used method (Zaniewski et al., 2015). A number of test methods used for the characterization of the tack coats in pavement interlayers are discussed in this section.

Table 2.1 Test methods used for the evaluation of interlayer bond strength

Shear Tests	Tensile Tests	Torsion Tests
Louisiana Interlayer Shear Strength Test (LISST)	Layer-Parallel Direct Shear (LPDS)	Torque Bond Test
Leutner Shear Test	Switzerland Pull-Off Test	Texas Transportation Institute (TTI) Torsional Shear Test
Louisiana Transportation Research Center (LTRC) Direct Shear Test	The ATacker™ Test	
Florida Direct Shear Test	University of Texas at El Paso (UTEP) Pull - Off Test	
Virginia Shear Fatigue Test		
Ancona Shear Testing Research and Analysis (ASTRA) Test		
Loboratorio de Caminos de Barcelona Shear Test (LCB)		

2.2.1 Louisiana Interlayer Shear Strength Tester

The Louisiana Interlayer Shear Strength Tester (LISST) was developed as a part of NCHRP Project 9-40 as a direct shear test (Mohammad et al., 2012). This test can measure the interlayer shear strength (Mohammad et al., 2012). The LISST device consists of a frame with one stationary and a moving jaw. The moving element is also known as the shearing frame, while the fixed part is known as a reaction frame. The LISST device can test a cylindrical specimen having a diameter of 150 mm or 100 mm. Total specimen thickness must be below 150 mm, and the loading rate should be 2.54 mm per minute. The specimen should be conditioned for two hours at the desired temperature before testing. The load actuator applies normal pressure up to 206.84 kPa on a 150-mm diameter sample. Generally, a loading frame is used to shear the sample. The variations of interlayer shear stress with axial displacement are plotted to determine the ISS value. Figure 2.1 shows the main components of an LISST device (Mohammad et al., 2012).

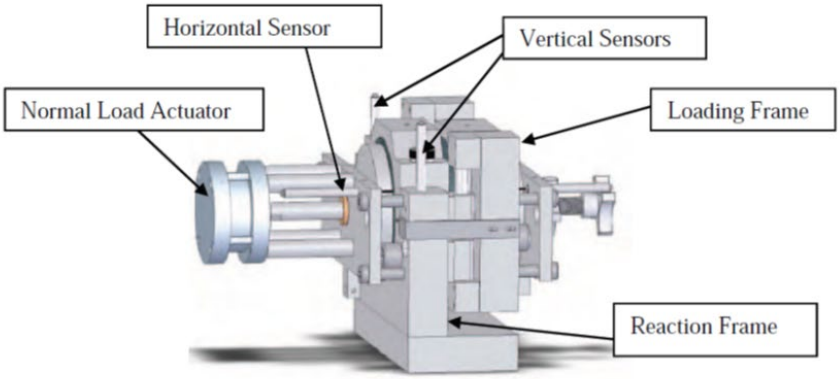

Figure 2.1 Components of Louisiana Interlayer Shear Strength Tester (Mohammad et al., 2012)

2.2.2 Texas Shear Bond Strength Test

This test has a setup similar to that of LISST. The loading frame used for conducting this test can apply a vertical load at a controlled deformation rate of 5±0.5 mm per minute. The load cell should have a working range of 90.7 kgf to 2268 kgf with 1% accuracy. The sample should be placed inside an environmental chamber to condition at 25 ± 1° C for two hours before testing.

2.2.3 Ancona Shear Testing Research and Analysis Test

The Ancona Shear Testing Research and Analysis (ASTRA) test is another direct shear test method used for measuring the interlayer shear strength. An Italian research team developed and introduced this test (Canestrari and Santagata, 2005). To conduct the ASTRA test, horizontal displacements are applied to the top layer of the sample (Figure 2.2), while it is increased at a constant rate. Also, a constant vertical load is used to provide confinement. The whole setup is placed inside an environmental chamber during the testing. The shear resistance is then evaluated by measuring the maximum interface shear stress used to assess the tack coat's effectiveness in improving the ISS value. The test is conducted on both field cores as well as laboratory-prepared samples.

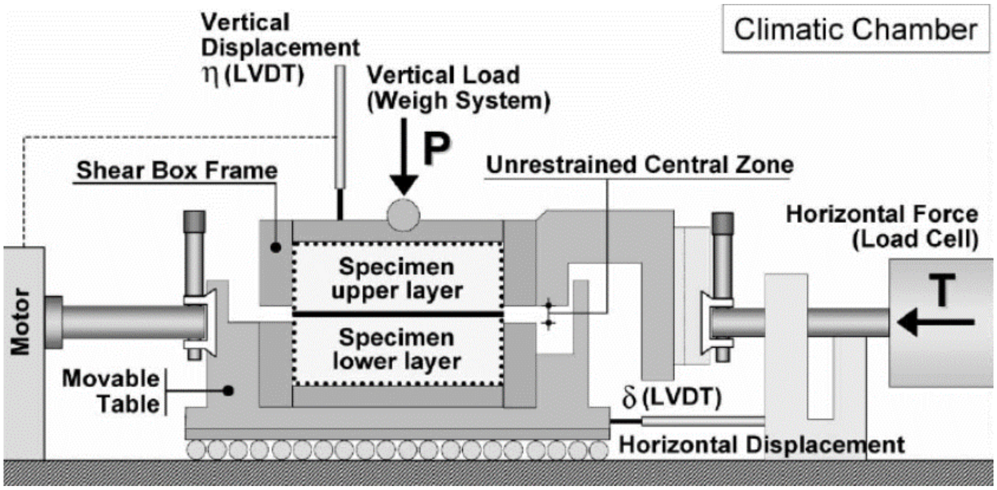

Figure 2.2 Ancona Shear Testing Research and Analysis Test Setup with Major Components of the Device (Canestrari and Santagata, 2005)

Destrée and Visscher (2017) classified the shear failure modes of the interface using a visual assessment method. Failure mode classification is described in Figure 2.3 and Table 2.2.

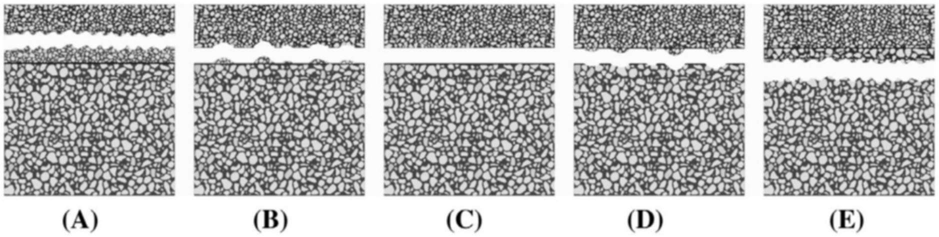

Figure 2.3 Different Types of Interlayer Failure Modes (Destrée and Visscher, 2017)

Table 2.2 Interlayer failure mode classification (Destrée and Visscher,2017)

Classification	Visual Assessment	Mode of Failure
A	Within the top layer	Cohesion
B	Partly at the interface, partly in the top layer	Mixed
C	At the interface	Adhesion
D	Partly in the bottom layer, partly at the interface	Mixed
E	In the bottom layer	Cohesion

2.2.4 University of Texas at El Paso Pull-off Test

The UTEP Pull-Off Device (UPOD) was developed at the University of Texas at El Paso to evaluate the interlayers' tensile strength treated with or without any tack coat. The UPOD has three pivoted feet and a plate that is used as support. A torque wrench is used to pull the plate up. The UTEP pull-off test device is shown in Figure 2.4 (Tashman et al., 2006).

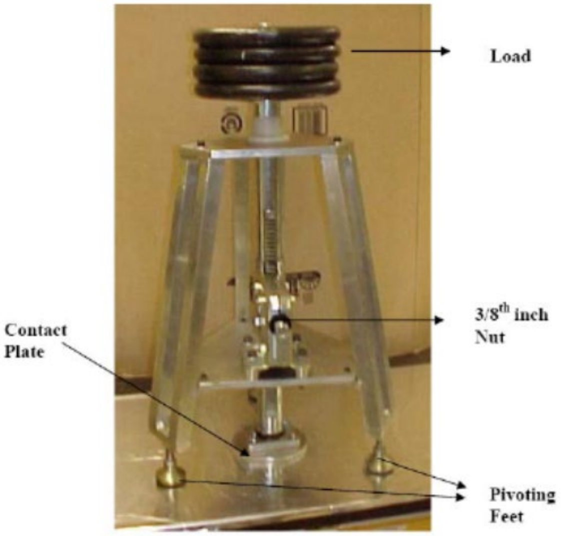

Figure 2.4 Main Components of the University of Texas at El Paso Pull-off Device (Tashman et al., 2006)

2.3 Optimum Tack Coat Application Rates

Tack coats are applied at various application rates according to available specifications. It was reported that tack coat application rate and tack coat type have an effect on pavement distresses (Ozer et al., 2012). Yet, decisions on application rates are generally made based on engineering judgments and are entirely empirical and experience-based. Hence, it is essential to determine the optimum typical application rates of different types of tack coats used on different surfaces. Table 2.3 shows several standard application rates of tack coats according to the surface type (Mohammad et al., 2012).

Table 2.3 Optimum tack coat application rates for different surface types (Mohammad et al., 2012)

Surface Type	Residual Application Rate (gallons per square yards)	Residual Application Rate (L/m^2)
New asphalt mixture	0.035	0.158
Old asphalt mixture	0.055	0.249
Milled asphalt mixture	0.055	0.249
Portland cement concrete	0.045	0.204

2.4 Effect of Environment on Tack Coat Performance

The impact of the environment is a critical factor that affects the performance of a tack coat. Temperature, moisture, freeze-thaw, and solar radiation are the main environmental factors affecting the tack coat's quality. Several researchers have studied the effect of the environment on a tack coat's performance, and the temperature has been identified as the most influential factor affecting the interlayer shear strength (Ai et al., 2017; West et al., 2005). It was reported that an increase in temperature resulted in a reduction in interlayer shear strength for all surface types (Ai et al., 2017; Al-Qadi et al., 2012; Amelian and Kim, 2017; Hu et al., 2017; Mohammad et al., 2012; Zhang 2017).

Hu et al. (2017) reported that tack coats with high viscosities showed high shear strength at a higher temperature while low-viscosity tack coats showed low shear strength values. It was concluded that the ISS values improved at lower temperatures by increasing the tack coat application rate. At higher temperatures, this was not the case. Similar findings were reported by Mohammad et al. (2002) and Canestrari et al. (2005) as well. A study by Bae et al. (2010) found that at testing temperatures higher than 40°C, the bond strength of trackless tack coat emulsions was higher than that of the CRS-1 tack coat. Graziani et al. (2017) investigated the effect of test temperature and interlayer deformation rate (IDR) on the ISS of two-layered-flexible pavements. Interlayers containing tack coats and those without any tack coat were tested at temperatures ranging from 5°C to 40°C and deformation rates ranging from 1 mm/min to 50 mm/min. Test results revealed that ISS values increased with increasing the IDR values. It was concluded that this was due to the time dependency behavior of bituminous materials.

Zhang (2017) reported that moisture conditioning of layered specimens reduced the ISS values. Zhao et al. (2017) studied the factors affecting the interlayer shear strength between the concrete slab and an asphalt overlay. Surface texture, tack coat type, tack coat application rate, moisture effect, temperature, and overlay mix type were considered in that study. It was found that most of the samples tested after moisture-conditioning and those tested without any moisture conditioning did not exhibit a statistically significant difference in their measured ISS values. However, Zaniewski et al. (2015) reported that moisture conditioning reduced the ISS values.

2.5 Practices Used for Application of Tack Coat in Construction

Zhang (2017) recommended a dry and clean surface for applying a tack coat. Mealiff et al. (2017) and Raposeiras et al. (2013) reported that a milled asphalt surface's cleanliness could affect bond strength between two layers. Similarly, McGee and Clark (2009) recommended paying additional care to clean the surface before placing the new HMA overlay on a milled HMA surface. However, Mohammad et al. (2012) concluded that a higher ISS value could be achieved by applying the tack coat on a dusty surface than by applying it on a clean surface condition.

In general, better compaction results in a higher ISS value (Raab et al., 2004). However, with the continuous application of loads, the interlayer bond may fail due to fatigue. Diakhate et al. (2006) showed that fatigue failure occurred with 10^4 to 10^5 loading cycles. Interlayer bond strength is affected by the tack coat setting time (Zaniewski et al., 2015). However, the overlay exhibited a better tensile bond with the existing pavement layer when it was immediately placed after the tack coat application compared with values measured for the surfaces on which the overlay was placed two hours after the application of the tack coat (Hakimzadeh et al., 2012).

Amelian and Kim (2017) reported that while breaking time was not different for the studied tack coats, high application rates required a longer braking time. The CRS-2P was identified as the material with the shortest braking time. The CSS-1h at 30% dilution was found to have the longest breaking time. CFS-1 and CRS-2P at an application rate of 0.72 L/m^2 (0.16 gal/yd^2) and CFS-1 applied at a rate of 0.36 L/m^2 (0.08 gal/yd^2) showed the best performance.

Salinas et al. (2013) reported that the optimum residual application rates for milled HMA surfaces and new HMA surfaces were found as 0.27 L/m^2 (0.06 gal/yd^2) and 0.09 L/m^2 (0.02 gal/yd^2), respectively. SS-1hP tack coat exhibited a higher ISS value compared with that measured for SS-1h. The air blast cleaning technique was found to reduce the optimum application rate while maintaining a high ISS value. According to the cost analysis, applying a tack coat using a spray paver was a cost-effective method. Both evaluated application methods yielded similar ISS values.

2.6 Important Recent Developments and Relevant Findings

The polymer-modified tack emulsions are among the new types of tack coats used by the pavement industry. The polymer-modified tack coat increases the resistance of the asphalt pavement to cracking and rutting at the same time without changing the friction and noise (Hakimzadeh et al., 2012). However, trackless tack coats have lower resistance to top-down cracking compared with CRS-1 (Chen et al., 2012). In a study evaluating three tack coat types—styrene-butadiene–styrene-modified asphalt, emulsified asphalt, and epoxy resin—epoxy resin was found to have the highest fatigue performance compared with the other two tack coat types (Li and Yu, 2013). A study by Tran et al. (2013) reported that a heavier tack coat performs better than a regular tack coat between the open-graded friction course (OGFC) and underlay.

Hou et al. (2018) evaluated the shear strength, track resistance, pull-off strength, and rheological properties of a new trackless tack coat material (TTCM). The results revealed that the TTCM tack coat improved the shear strength by 69% compared with base asphalt at 20°C, and the material became trackless one minute after application. There was no report of tire deterioration upon contact with TTCM at 60°C. Viscosity of TTCM was found to increase after cooling, which led to a better bond between layers. The new material exhibited higher thermal stability compared with base asphalt.

3. MATERIALS AND METHODS

3.1 Overview

This chapter provides an overview of material selection and collection processes, procedures used for sample preparation, and test methods. The test matrix included testing three types of tack coats on four types of pavement surfaces. Each sample consisted of two layers representing an existing pavement surface (bottom layer) and an asphalt overlay on top of that (top layer). The tack coat was applied between the two layers. The sample's top layer was prepared using one type of asphalt mix with a nominal maximum aggregate size (NMAS) of 12.5 mm. The three types of the asphalt bottom layer, new HMA, aged and worn HMA, and milled HMA, were prepared using a mix with an NMAS = 19.0 mm, and one type of PCC bottom layer grooved. The main tasks of this project were to (i) collect two types of asphalt mixes commonly used in South Dakota; (ii) collect aggregate and Portland cement to prepare PCC bottom layer samples; (iii) collect tack coats widely used in South Dakota; (iv) prepare samples consisting of two layers with different tack coats in their interlayers; (v) conduct an LISST test and determine the interlayer shear strength of the samples with other tack coat types, application rate, and surface texture; (vi) determine the optimum application rate of each tack coat on all kinds of surfaces, and (vii) evaluate the effect of moisture on the ISS of the samples prepared using optimum tack coat application rate. A test matrix summarizing the sample surface types, tack coat types, tack coat application rates, and moisture-conditioning states of the samples tested in LISST equipment is shown in Table 3.1. As shown in Table 3.1, the optimum tack coat application rate (OTAR) for each tack coat and the surface type was determined by conducting LISST tests. These tests were performed in dry conditions on samples prepared with each surface type with three residual application rates: 0.140, 0.281, and 0.702 L/m^2. After the samples were tested and their ISS values were measured, the OTAR values for each tack coat type and surface type were determined. Then, samples prepared at their OTAR values were tested to measure their ISS values after moisture conditioning

Table 3.1 Test matrix of the project

Sample Conditioning	Tack Coat Type	Residual Tack Coat Application Rate (L/m^2)	Type of the Tested Samples			
			Unaged HMA	Aged and Worn HMA	Milled HMA	Grooved PCC
Dry	No Tack Coat	0	✓	✓	✓	✓
	CSS-1h	0.140	✓	✓	✓	✓
		0.281	✓	✓	✓	✓
		0.702	✓	✓	✓	✓
	CRS-2P	0.140	✓	✓	✓	✓
		0.281	✓	✓	✓	✓
		0.702	✓	✓	✓	✓
	SS-h	0.140	✓	✓	✓	✓
		0.281	✓	✓	✓	✓
		0.702	✓	✓	✓	✓
Moisture-Conditioned	No Tack Coat	0	✓	✓	✓	✓
	CSS-1h	OTAR	✓	✓	✓	✓
	CRS-2P	OTAR	✓	✓	✓	✓
	SS-h	OTAR	✓	✓	✓	✓

*OTAR: optimum tack coat application rate

3.2 Material Collection

3.2.1 Collection of Asphalt Mixes

Material required to prepare the bottom layer samples with unaged, aged, and worn, and milled HMA surfaces was collected from a parking lot construction project carried out by Bowes Construction Inc. at South Dakota State University's (SDSU) main campus located at Brookings, SD. Since this mix was used to compact bottom layer samples, it will be referred to as "BL-HMA" in the current document. This mix consisted of 20% reclaimed asphalt pavement (RAP), a PG 58-28 asphalt binder, and aggregates with a nominal maximum aggregate size (NMAS) of 12.5 mm. The combined aggregate structure and particle size distribution are shown in Figure 3.2. Approximately 800 kg of the BL-HMA mix was collected. Figure 3.1 shows a photographic view of the research team's efforts to collect BL-HMA on October 19. 2017.

Figure 3.1 Research Team Collecting BL-HMA Mix

The asphalt mix required to compact the top layer of the samples was collected from the I-90 interstate resurfacing project from Border States Paving Inc. near Brandon, SD. An approximately 1,000-kg mix was collected right after the mix was dumped from the truck in front of the paver. Since this mix was used to compact top layer samples, it will be referred to as "TL-HMA" in the current document. The TL-HMA mix consisted of a PG 64-34 asphalt binder and aggregates with an NMAS = 12.5 mm. The combined aggregate structure and particle size distribution of the TL-HMA are shown in Figure 3.2. The collected mix was classified as a Q5 mix, as per South Dakota DOT's mixed classification system.

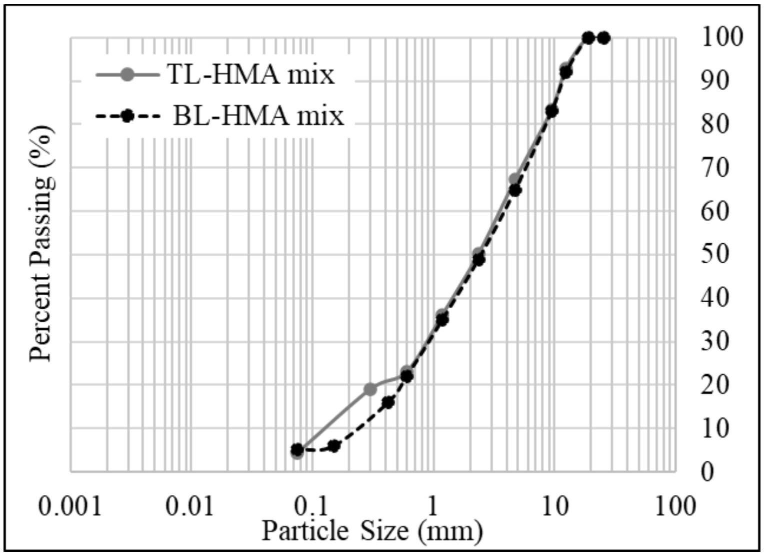

Figure 3.2 Particle Size Distribution Curves for BL-HMA and TL-HMA Mixes

3.2.2 Material Collection for Production of Portland Cement Concrete (PCC)

Material required to prepare grooved PCC bottom layers and concrete mix design sheets used to construct rigid pavements were collected from the GCC ready mix plant at Brookings, SD. GCC's concrete mixes are commonly used for the construction of rigid pavements and other construction projects. The collected materials were mixed in the laboratory according to the mix design sheet (Table 3.2) and used for preparing cylindrical grooved PCC samples.

Table 3.2 Mix design for preparing 1665 kg of ready-mix concrete

Material	Unit	Quantity
Cement	Kg	247.6
Fly-ash	Kg	43.5
Rock	Kg	790.1
Sand	Kg	514.3
Water	Kg	54.9
Water-reducing admixture	Kg	12.3
Air entraining agent	Kg	1.7
Total concrete weight	Kg	1664.9

3.2.3 Collection of Tack Coats

Three types of emulsified tack coats widely used in South Dakota, CSS-1h, CRS-2P, and SS-h, were evaluated. Both CSS-1h and CRS-2P tack coats were collected from Jebro Inc., while the SS-h tack coat was collected from Flint Hills Resources, LLC. The ISS values obtained from each tack coat applied with different application rates were determined and compared with those of the samples prepared without applying tack coats. The types of the above-mentioned tack coats and their properties were discussed in section 2.1.1. All tack coats were received in the asphalt laboratory and kept in airtight solid dark containers for further evaluation.

3.3 Determination of Tack Coats' Percent Residue

The percent residue of the tack coats was determined in the laboratory following the ASTM D6934-08 standard test method (ASTM, 2016). For this purpose, tack coat emulsion was shaken and then agitated. Two sets of beakers and mixing rods were selected and carefully weighed. Then, 50 g of the tack coat emulsion was poured into each set of glass beakers containing a mixing rod inside each. The beakers, rods, and emulsions inside them were kept inside the oven at 163°C for two hours. Then, the beakers' contents were mixed using the mixing rod and were returned and kept inside the oven at 163°C for another hour. Finally, the residue, beaker, and rod weight for each set apparatus were measured using the scale. Each residual weight was obtained by deducting the correspondent beaker and rod weights from the total weight of the beaker, rod, and residue, and the percent residue was calculated accordingly. The average percent residue value of two samples was recorded as the percent residue of each tack coat.

3.4 Sample Preparation

Asphalt samples were compacted in the laboratory using a Superpave® gyratory compactor (SGC). Each sample consisted of two layers of cylindrical samples with 60-mm thickness and 150-mm diameter each. Before compaction of double-layered samples, trial samples were compacted. The required amount of asphalt mix was determined to result in target air voids of 7.0% ± 0.5% for each layer after SGC compaction.

3.4.1 Trial Sample Preparation

Trial sample preparation was carried out for both TL-HMA and BL-HMA mixes to determine each sample's weight to achieve 7.0% ± 0.5 % air voids. The 7.0% ± 0.5% air voids represent the field condition and simulate the air voids after construction and compaction of an actual pavement. The amounts of asphalt mix to achieve theoretical target air voids of 7.0%, 7.5%, 8.0%, 8.5%, and 9.0% were calculated and compacted using an SGC in height mode. This step was conducted to obtain 7.0% ± 0.5% target air voids. The sample height was set to 60 mm, and an SGC mold with an inner diameter of 150 mm was used. Theoretically, each sample has a volume of $6 \times \pi \times (15/2)^2 = 1060.29$ cm^3. The volume was multiplied by the percent density and the theoretical maximum specific gravity (G_{mm}) to obtain each sample's trail weight. The G_{mm} values indicated in each mix design sheet were initially used to calculate required trail weights (%density x G_{mm} x volume). Calculated trail weights for BL-HMA are shown in Table 3.3. However, the actual G_{mm} was determined by conducting the Rice test as per the AASHTO T209 test (AASHTO, 2019) standard method in the laboratory. The actual air voids of the trial samples were calculated based on the measured G_{mm} value.

Table 3.3 Calculated trial weights for BL-HMA to obtain theoretical target air voids

Target Air Voids (%)	Target Density (%)	Weight (g)
7.0	93.0	2420.8
7.5	92.5	2407.8
8.0	92.0	2394.8
8.5	91.5	2381.7
9.0	91.0	2368.7

The SGC molds, chute, trays, and scoops were pre-heated at 165°C in an oven to prepare the cylindrical samples. The asphalt mix was heated in the oven at 165°C for one hour in a tray, as shown in Figure 3.3. After the first 30 minutes, the asphalt mix was mixed using metal scoops. The mixture was then heated for another 20 minutes while mixed every 10 minutes to a uniform consistency. The heated mix's required weight was placed inside the SGC chute and was returned to the oven at 165°C and kept for another 10 minutes. A circular paper disc was placed at the bottom of the pre-heated mold. This paper disc was then transferred on top of a scale and tared, as shown in Figure 3.4. Asphalt mix inside the chute was mixed with a scoop and carefully placed inside the mold while adjusting the weight. The desired mixed asphalt weight inside the mold was then checked for the second time. Then the top surface of the asphalt mix inside the mold was leveled using a spatula, and a circular paper disc was placed on top of the leveled surface. The lid of the mold was placed on top of it. The mold was then placed inside the Superpave® gyratory compactor, as shown in Figure 3.5, and the compaction process was initiated in fixed height mode (60 mm). After compaction was complete, the sample was partially extracted and kept at room temperature for 15 minutes before extraction, as shown in Figure 3.6. The sample was then transferred to a level surface, as shown in Figure 3.7.

Figure 3.3 Heating the Asphalt Mix Inside an Oven at 165°C

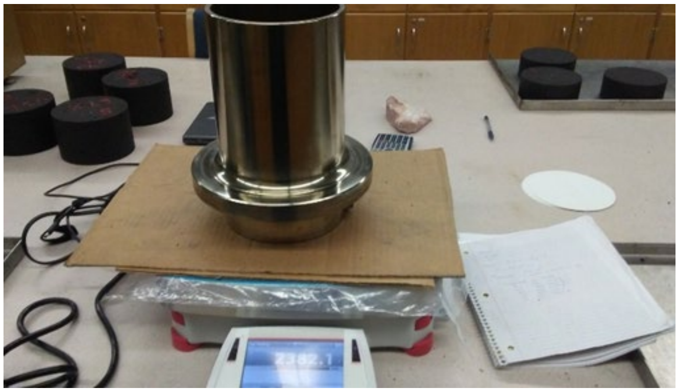

Figure 3.4 Weighing the Asphalt Mix Inside an SGC Mold

Figure 3.5 Preparation and Compaction of HMA Sample Using Superpave® Gyratory Compactor

Figure 3.6 Partially-Extruded HMA Sample

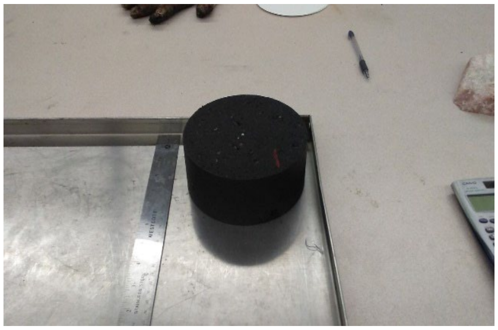

Figure 3.7 HMA Sample Removed from the Mold

The bulk specific gravity (G_{mb}) values of the compacted samples were determined according to the AASHTO T 166 standard test method (AASHTO, 2016). It was found that using 2392.0 g of TL-HMA and 2401.0 g of BL-HMA mixes for compacting cylindrical samples having a diameter of 150 mm and a thickness of 60 mm resulted in 7.0% ± 0.5% air voids.

3.4.2 Preparation of Unaged HMA Bottom Layer Samples

Unaged HMA bottom layer samples were prepared by compacting the BL-HMA mix using an SGC operated at height mode (h = 60 mm) following the sample preparation procedure described in section 3.3.1. An asphalt mix weight of 2401.0 g was used for compacting samples to achieve 7.0% ± 0.5% air voids.

3.4.3 Aged and Worn HMA Bottom Layer Sample

Unaged HMA bottom layer samples prepared according to the procedure described in section 3.3.2 were used to prepare the aged and worn bottom layer samples. The samples mentioned above were polished and aged to simulate a worn and aged pavement surface. Circular 80-grit sandpaper mounted on a 125-mm random orbital sander disc was used to polish the sample's surface. The sander was operated at a constant speed for one minute to evenly polish the samples' surface. After the first-minute surface was brushed, the dust was cleaned. Additional care was given to polish the surface evenly, and then the sample was polished for another one minute. Figure 3.8 shows the surfaces of a polished (right) and an unpolished sample. Polished samples were placed inside the oven at a temperature of 85°C for 120 hours (five days) for lab-simulated long-term oven aging in accordance with AASHTO R 30 standard practice (AASHTO, 2019). This oven aging represents an aging equivalent of five to seven years of in-service oxidative aging of asphalt mix.

Figure 3.8 Unpolished Surface (Left) and Polished Surface (Right)

3.4.4 Milled HMA Bottom Layer Sample

Milled HMA surfaces were simulated in the laboratory by creating the milling pattern on the HMA sample's surface, as described by Zaniewski et al. (2015). Unaged HMA bottom layers compacted using the BL-HMA mix were used for this purpose. The milling effect was then simulated first by marking a grid pattern on top of the sample (Figure 3.9) and then cutting through the marked area using a wet rock saw, following the method suggested by Zaniewski et al. (2015). Figure 3.10 shows the final simulated milled surface. Samples were dried in an oven at 60°C for 24 hours before the application of tack coats.

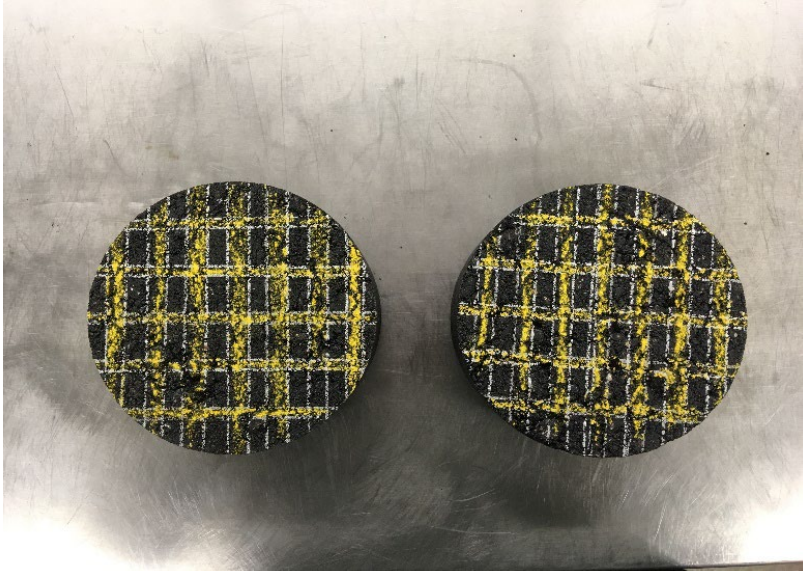

Figure 3.9 Marked Milling Pattern

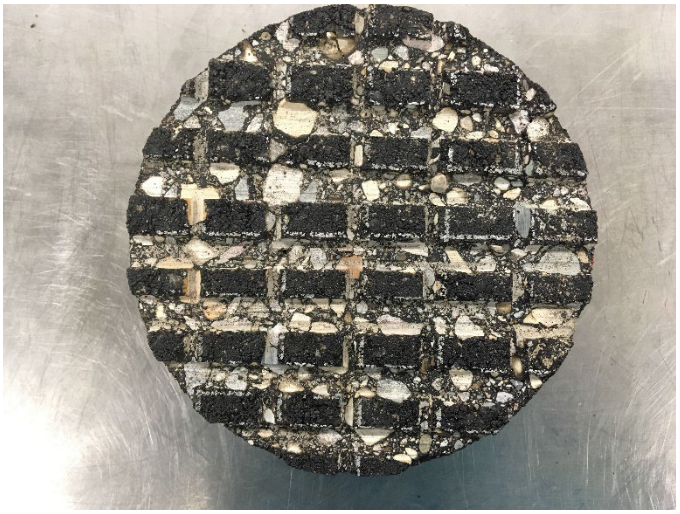

Figure 3.10 Lab-Simulated Milled Surface

3.4.5 PCC Bottom Layer

PCC bottom layers were prepared first by mixing concrete in the laboratory by following the mixed design sheet (Table 3.3) using the batch plant's concrete materials. Concrete mixing was conducted by using a concrete mixer in the concrete laboratory. A standard cylindrical plastic mold with a 150-mm diameter was modified to have an inner height of 60 mm. The mold's inner diameter was reduced by 1.5 mm by inserting two layers of plastic strips as mold lining. This practice ensured the prepared PCC sample fit inside the SGC mold. The prepared concrete was poured into the mold, and a rubber mallet was used to tap around the mold to achieve a honeycomb-free, well-compacted PCC bottom layer sample. After the concrete was poured and compacted, it was left for three hours. After this step, the groove pattern on top of the sample was created. Grooving was carried out using a device fabricated in the laboratory, which consisted of nails having a diameter of 2 mm attached to a straight wooden edge having a spacing of 20 mm. Groove depth was between 2 and 4 mm. Figure 3.11 shows a grooved PCC bottom layer sample. Samples were kept inside the mold overnight and then transferred to an environmentally controlled humidity room and kept for seven days to cure. Samples were dried in an oven at 60°C for 24 hours before the application of tack coats.

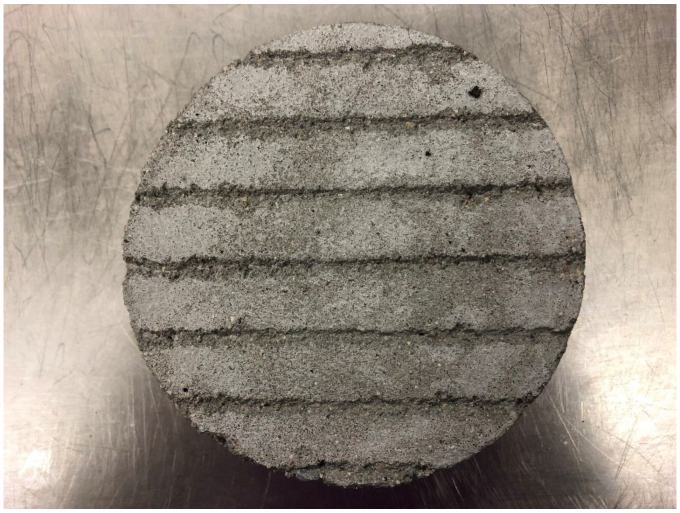

Figure 3.11 Grooved PCC Bottom Layer Sample

3.4.6 Tack Coat Application

Bottom layer samples (unaged HMA, aged and worn HMA, and grooved PCC) were kept inside an oven at 54°C for two hours before applying the tack coat. This period simulated a sun-warmed surface of the pavement. A brush was used to apply the tack coat on the sample surface, as shown in Figure 3.12. For this purpose, the preheated sample was placed on top of the scale, and the reading was zeroed. Tack coat emulsion kept inside a capped plastic dispenser was shaken well before applying it to the bottom layer sample. After the tack coat was evenly applied, a paintbrush was used to spread the tack coat material evenly on the bottom layer sample. The weight reading on the scale was controlled to achieve three residual application rates: 0.140, 0.281, and 0.702 L/m^2. The determination of the percent residue of a tack coat is described in Section 3.4. The application amounts of each tack coat to obtain the residual rates are shown in Table 3.4.

Figure 3.12 Applying Tack Coat on Bottom Layer Sample

Table 3.4 Tack coats residual application amounts

Tack Coat Type	Residual Application Rate (L/m²)	Percent Residue (%)	Application Weight of Tack Coat (g)
CRS-2P	0.140	69.2	3.7
	0.281	69.2	7.3
	0.702	69.2	18.2
CSS-1h	0.140	60.8	4.1
	0.281	60.8	8.3
	0.702	60.8	20.8
SS-h	0.140	63.5	4.0
	0.281	63.5	7.9
	0.702	63.5	19.9

3.4.7 Tack Coat Breaking Time

As described in Chapter 2, the tack coat breaking time is known as the time needed for a tack coat to change its color from brown to black. The breaking time of each tack coat in the laboratory depends on the tack coat's properties, application rate, ventilation, and surface type (Yaacob et al., 2014). Visual inspection of color change was performed to determine each tack coat's breaking time at different application rates. The breaking time of each tack coat on other surfaces is shown in Table 3.5.

Table 3.5 Breaking times of tack coats in different application rates

Tack Coat Type	Residual Application Rate (L/m²)	Breaking Time (Hours)			
		New HMA	Aged and Worn HMA	Milled HMA	Grooved PCC
CRS-2P	0.140	0.5	0.5	0.5	0.5
	0.281	0.5	0.5	0.5	1.0
	0.702	1.0	1.0	1.0	3.0
CSS-1h	0.140	0.5	0.5	0.5	0.5
	0.281	0.5	0.5	0.5	1.0
	0.702	1.0	1.0	1.0	3.0
SS-h	0.140	0.5	0.5	0.5	0.5
	0.281	0.5	0.5	0.5	1.0
	0.702	1.0	1.0	1.0	3.0

3.4.8 Top Layer Compaction

The top layer of the samples was prepared by heating and compacting the TL-HMA mix using an SGC, as described in section 3.3.1. Before compaction of the top layer, the tack coat applied on the bottom layer sample (if any) was left to break on the applied surface. The bottom layer sample was then carefully placed inside the heated SGC mold and pushed all the way down in the mold. The mold was placed on top of the scale, and a scale reading was noted. The asphalt mix with the weight determined in section 3.1.1 was placed inside the mold using a chute. The loose mix's surface was leveled, and a paper disc and top lid of the mold were carefully placed to cover the loose blend. The mold was transferred inside the SGC, and the asphalt mix was compacted. The SGC was operated in gyration mode with the number of gyrations set to 42. The number of gyrations required to compact a double-layer sample with a height of 120 mm and air vids of 7.0 ± 0.5% was pre-determined after trial samples' compaction.

3.4.9 Moisture Conditioning of the Compacted Samples

Several samples were tested after moisture conditioning to study moisture's effect on the interlayer shear strength of different tack coat types. For this purpose, a modified version of the standard moisture conditioning procedure, as described in the AASHTO T283-02 standard test method (AASHTO, 2014), was used. The specimen was first vacuum-saturated by placing it inside the vacuum flask at 1.9-9.7 psi (13-67 kPa) absolute pressure (10-26 in Hg partial pressure) for eight minutes. The water level inside the container was adjusted to cover the full height of the specimen. The vacuum was then released, and the sample was kept inside the water for another seven minutes before drying its surface using a damp towel. It was then wrapped and sealed using cling wrap. Wrapped samples and 10 ccs of water were placed inside another plastic bag and sealed after removing the excess airbag. The sealed sample was then placed inside a freezer at -18° C for 16 hours. The sample was then placed inside a water bath at 25°C after removing the plastic wrap from the sample. The temperature of the water bath was continuously monitored and maintained at 25°C. The sample was kept inside the water bath for four hours. Then, the abovementioned freezing-thaw process was repeated for another cycle. After completing the second freeze-thaw cycle, the sample was ready for conducting the LISST test.

3.5 LISST Test

The interlayer shear strength (ISS) values of the double-layered samples were determined using a Louisiana Interlayer Shear Strength Tester (LISST). The test was conducted as per the proposed standard method of test for determining the interlayer shear strength of asphalt pavement layers described in the NCHRP report 712 (Mohammad et al., 2012) under AASHTO TP114 (AASHTO, 2021). The LISST device was fixed in a loading frame from MTS. Laboratory-prepared double-layered samples were cured for 14 days and tested at 25°C. The marked area was adjusted to locate right in the middle of the gap between the moving and stationary jaws of the LISST equipment to ensure the sample's shear failure occurs at the interlayer. The laboratory setup of the LISST device fixed inside the MTS loading frame and a close-up view of the LISST device and the actuator are shown in Figures 3.13 and 3.14, respectively. As shown in those figures, the load was applied loading the frame's actuator in the vertical direction to the moving jaw of the LISST at a rate of 0.1 inches per minute. The load and axial displacement readings were recorded using a data acquisition system. The test was concluded and the procedure was stopped after the interlayer's shear failure, as shown in Figure 3.15. After the failure, specimens were removed from the LISST device and were visually assessed to identify their failure modes using the interface failure classification introduced by Destrée and Visscher (2017). Details of the failure mode classification used in this study are described in Section 2.7.

Figure 3.13 LISST Test Setup

Figure 3.14 LISST Test in Progress

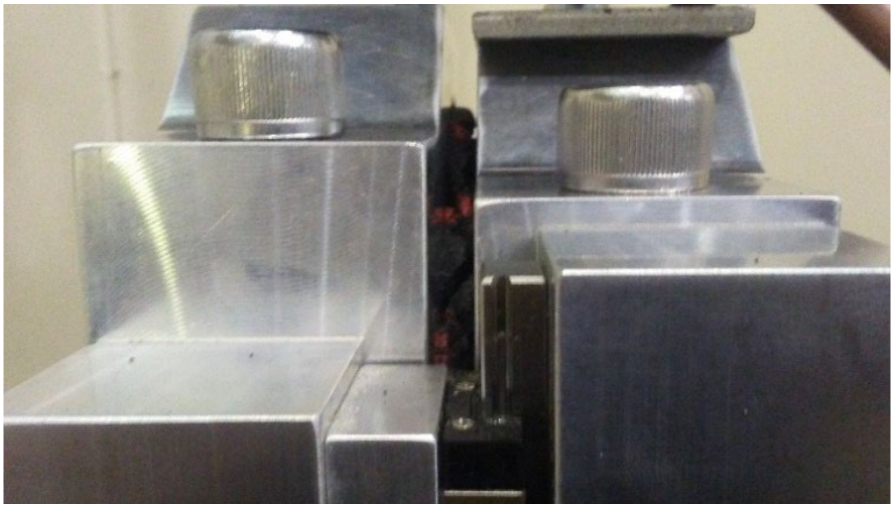

Figure 3.15 Interlayer Shear Failure in a Double-Layer Specimen

4. RESULTS AND DISCUSSION

This study aimed to evaluate the effect of using three tack coat types applied at different rates and on different pavement surfaces on laboratory-measured ISS values. The three tack coat types were CRS-2P, CSS-1h, and SS-h. Different rates of application considered for this study were 0, 0.140, 0.281, and 0.702 L/m^2. Four different pavement surfaces were new HMA, aged and worn HMA, milled HMA, and grooved PCC. The effects of the parameters above on the measured ISS values are discussed in this section.

4.1 Achieving the Target Air Voids of Double-Layer Samples

As discussed in Chapter 3, the trial samples were prepared in order to achieve 7.0±0.5% air voids in cylindrical samples. After preparing the trial samples, the bulk specific gravity values of (G_{mb}) of the SGC-compacted samples were determined as per AASHTO T 166 (AASHTO, 2016) standard test method. Air voids were calculated based on the G_{mb} and G_{mm} values for mixes. The volumetric parameters of the samples prepared using TL-HMA and BL-HMA are presented in Table 4.1 and Table 4.2, respectively.

Also, variations of the calculated air voids with compaction weight for TL-HMA and BL-HMA are graphically presented in Figure 4.1 and Figure 4.2, respectively. A linear trend line was added to each figure, and the regression equation for each mix is also displayed in Figures 4.1 and 4.2. The trend line equations were used to determine the weight of the loose mix needed to obtain an SGC sample having 7.0 ± 0.5% air voids. The calculated weights of the loose TL-HMA and BL-HMA mixes to obtain 7.0 ± 0.5% air voids in compacted samples were found to be 2392.0 and 2401.0 g, respectively.

Table 4.1 Volumetric test results of trial samples compacted using TL-HMA mix

Specimen ID	A	B	C	D	E	F	G	H
Wt.* in Air (g)	2419.6	2406.6	2393.8	2381.5	2368.7	2394.5	2394.6	2394.2
Wt. in Water (g)	1373.4	1361.0	1350.3	1336.7	1327.5	1351.7	1354.5	1350.8
SSD** weight (g)	2420.9	2408.6	2395.8	2383.7	2371.1	2397.5	2398.5	2396.7
G_{mm}	2.461	2.461	2.461	2.461	2.461	2.461	2.461	2.461
G_{mb}	2.31	2.29	2.29	2.27	2.27	2.29	2.29	2.28
Achieved AV$^+$(%)	6.1	6.7	6.9	7.6	7.8	6.9	6.8	7.0

Note: *Weight of the sample **Saturated surface dry weight + air voids

Table 4.2 Volumetric test results of trial samples compacted using BL-HMA mix

Specimen ID	A	B	C	D	E	F	G	H
Wt.* in Air (g)	2407.0	2394.0	2381.9	2378.4	2382.4	2369.2	2369.3	2407.0
Wt. in Water (g)	1370.7	1361.0	1352.1	1353.4	1355.3	1341.3	1344.8	1370.7
SSD** weight (g)	2410.9	2397.4	2387.5	2384.8	2389.3	2375.1	2377.1	2410.9
G_{mm}	2.488	2.488	2.488	2.488	2.488	2.488	2.488	2.488
G_{mb}	2.314	2.31	2.3	2.306	2.304	2.292	2.295	2.314
Achieved AV$^+$(%)	7.0	7.2	7.6	7.3	7.4	7.9	7.8	7.0

Note: *Weight of the sample **Saturated surface dry weight + air voids

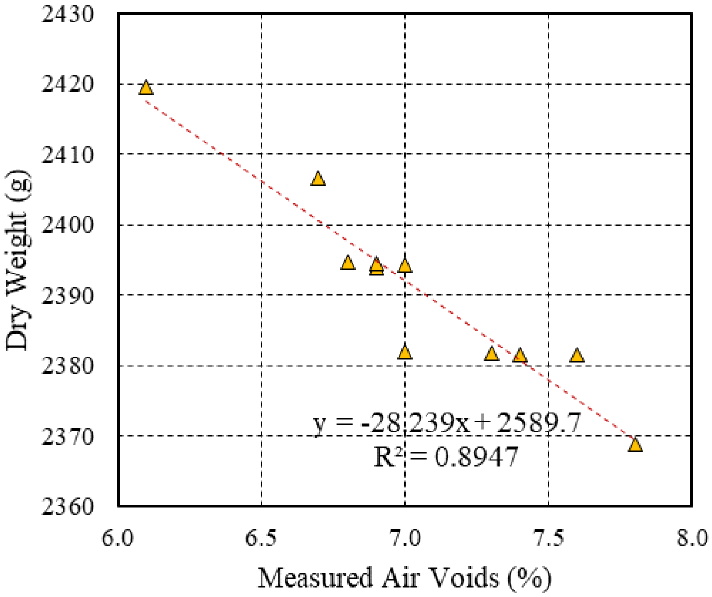

Figure 4.1 Variation of the Measured Air Voids with Dry Weights for TL-HMA Trial Specimens

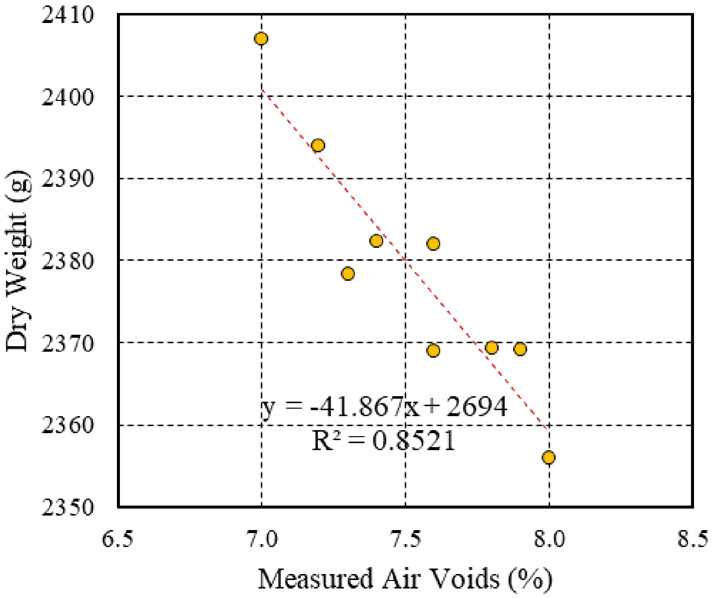

Figure 4.2 Variation of the Measured Air Voids with Dry Weights for BL-HMA Trial Specimens

4.2 Percent Residue of Tack Coat Emulsions

The percent residue of tack coat emulsions was determined according to the ASTM D6934-08 standard test methods (ASTM, 2016). The test procedure is described in Section 3.4. Percent residue values determined CSS-1h, CRS-2P, and SS-h tack coats are summarized in Table 4.3. According to Table 4.3, the percent residue of tack coats CSS-1h, CRS-2P, and SS-h was found to be 60.8%, 69.2%, and 63.5%, respectively. According to Table 4.3, standard deviations and coefficient of variations calculated for the percent residue values of each tack coat are less than 1% and 5%, respectively, indicating acceptable test repeatability. From the percent residue values, the weight of tack coat emulsions needed to achieve 0.140, 0.281, and 0.702 L/m^2 residue application rates on a 150-mm diameter sample were calculated for all tack coats (CSS-1h, CRS-2P, and SS-h) and were presented in Table 3.4.

Table 4.3 Percent residue of tack coat emulsions

Set ID	Description	Tack Coat Type		
		CRS-2P	CSS-1h	SS-h
A	Weight of Beaker + Rod (g)	310.2	310.3	405.8
	Wight of Beaker + Rod + Residue (g)	344.7	340.7	437.4
	Emulsion weight (g)	50.1	50.1	49.9
	Residue weight (g)	34.5	30.4	31.8
	Residue (%)	69.0	60.8	63.6
B	Weight of Beaker + Rod (g)	405.7	405.6	310.4
	Wight of Beaker + Rod + Residue (g)	440.4	436.0	342.1
	Emulsion weight (g)	50.1	49.9	50.0
	Residue weight (g)	34.7	30.4	31.7
	Residue (%)	69.4	60.8	63.4
	Average residue percentage (%)	**69.2**	**60.8**	**63.5**
	Standard deviation (%)	0.282	0	0.141
	Coefficient of variation (%)	4.087	0	2.227

4.3 Interlayer Shear Strength of Double-Layer Samples

A typical graph showing the variations of the measured interlayer shear stress vs. axial displacements for an LISST test conducted on a test sample is shown in Figure 4.3. From Figure 4.3, it is evident that interlayer shear stress gradually increased to a peak value, namely interlayer shear stress (ISS), and decreased after the peak point. Three replicate samples of each type of interlayer, tack coat type, and application rate were produced and tested, and the ISS values were averaged and reported.

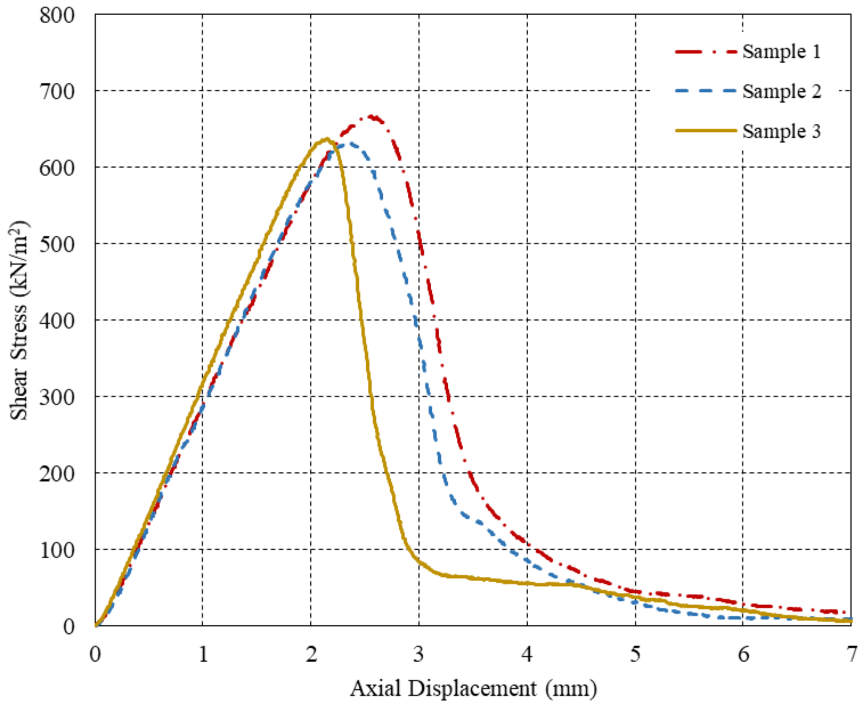

Figure 4.3 Typical Variation of Shear Stress with Axial Displacement in an LISST Test

Important statistical parameters—standard deviation and the coefficient of variation (COV) of the ISS values of three replicas—were also reported for each sample type. Other studies conducted on the repeatability of the LISST test recommend a maximum COV of 15% for measured ISS values (Al-Qadi et al., 2012; Mohammad et al., 2012). In order to increase the accuracy of the results in the current study, three samples were tested; if the COV of the measured ISS values was greater than 12%, more samples were tested. ISS values, a COV greater than 12%, were considered the maximum COV in the current study. After ISS values were determined for all samples, tack coat type, application rate, ISS values, mean ISS, and COV and standard deviation of ISS were summarized and prepared for further analysis.

4.4 Effect of Tack Coat Type and Application Rate on Measured ISS Values

The effect of using three tack coat types, CRS-2P, CSS-1h, and SS-h, applied at rates of 0.140, 0.281, and 0.702 L/m^2 on different pavement surfaces was evaluated in this study. Also, samples prepared without the application of tack coats were tested.

4.4.1 Interlayers with No Tack Coat

ISS values were obtained by conducting the LISST test on specimens prepared using four different types of bottom layer surfaces, new HMA, aged and worn HMA, milled HMA, and grooved PCC without applying any tack coat, are shown in Figure 4.4. From Figure 4.4, the highest ISS value for samples compacted without application of any tack coat was observed in those prepared using aged and worn HMA bottom layer (989.6 kPa), followed by the samples prepared by using new HMA (856.0 kPa), milled HMA (819.43 kPa), and grooved PCC (105.7 kPa), respectively. Mohammad et al. (2012) reported that laboratory-prepared samples always overestimated the ISS values compared with field cores. Mainly, when specimens were obtained from the projects where the overlay was constructed without applying a tack coat, no interlayer shear strength was observed for all the types of bottom surfaces (new HMA, existing HMA, and PCC) except for the milled HMA bottom layer. Similar to the findings presented in Figure 4.4, Mohammad et al. (2012) reported that the ISS values measured for laboratory-prepared specimens without applying any tack coat were significantly higher than zero.

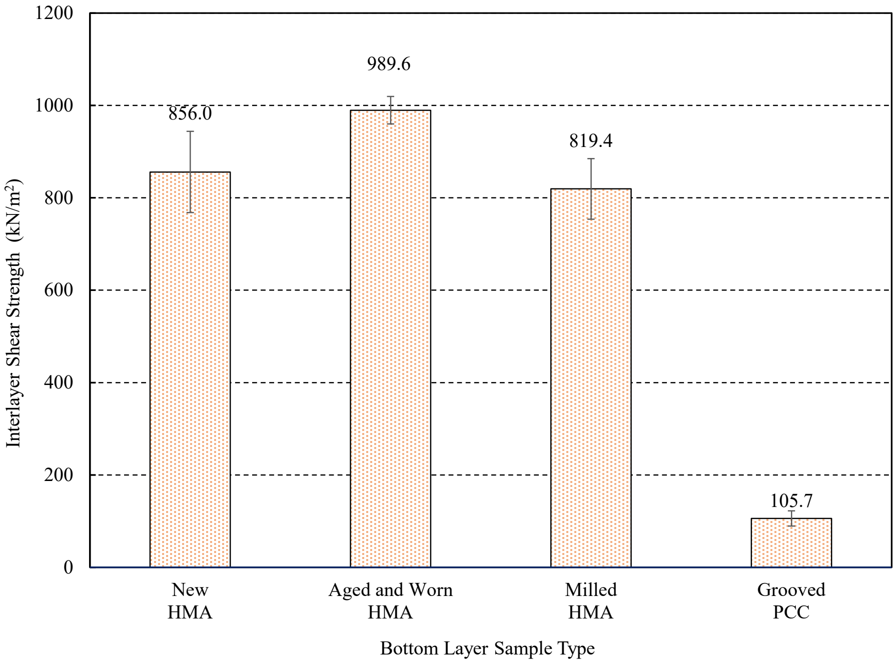

Figure 4.4 Interlayer Shear Strength of Samples with Different Bottom Layers and No Tack Coat

Aged and worn HMA surfaces contain an oxidized asphalt binder with a higher shear modulus and strength than the unaged binder. Therefore, the high ISS value observed for the sample with aged and worn HMA was attributed to the fact that aged asphalt binder film coating the bottom layer's aggregate at the surface created a strong bond at the interlayer, resulting in the highest ISS value. The new HMA, due to unaged binder film on its aggregates at the surface of the sample, did not result in a bond in the interlayer as strong as that observed in the case of aged and worn HMA bottom layer. Among the bottom layers, the grooved PCC surface yielded the lowest ISS value (105.7 kPa), which was 87% lower than the minimum ISS recorded for the HMA bottom layers (819.4 kPa recorded for the milled HMA bottom layer). This was mainly because the PCC bottom layer's texture was considerably smoother than the other samples with the HMA bottom layer. Additionally, the grooved PCC samples did not have the aggregates coated with asphalt binder on their surface, which improved the interlayer shear strength and bond between the bottom and overlay layers.

4.4.2 CRS-2P Tack Coat

Figure 4.5 presents the ISS values measured for samples prepared using the CRS-2P tack coat applied at 0, 0.140, 0.281, and 0.702 L/m2 on the surface of the new HMA, aged and worn HMA, milled HMA, and grooved PCC samples. The early-age ISS values measured for samples with all types of HMA bottom layers containing CRS-2P tack coat were lower than those prepared without applying any tack coat. However, the CRS-2P tack coat on grooved PCC was significantly effective in improving the interlayer shear strength.

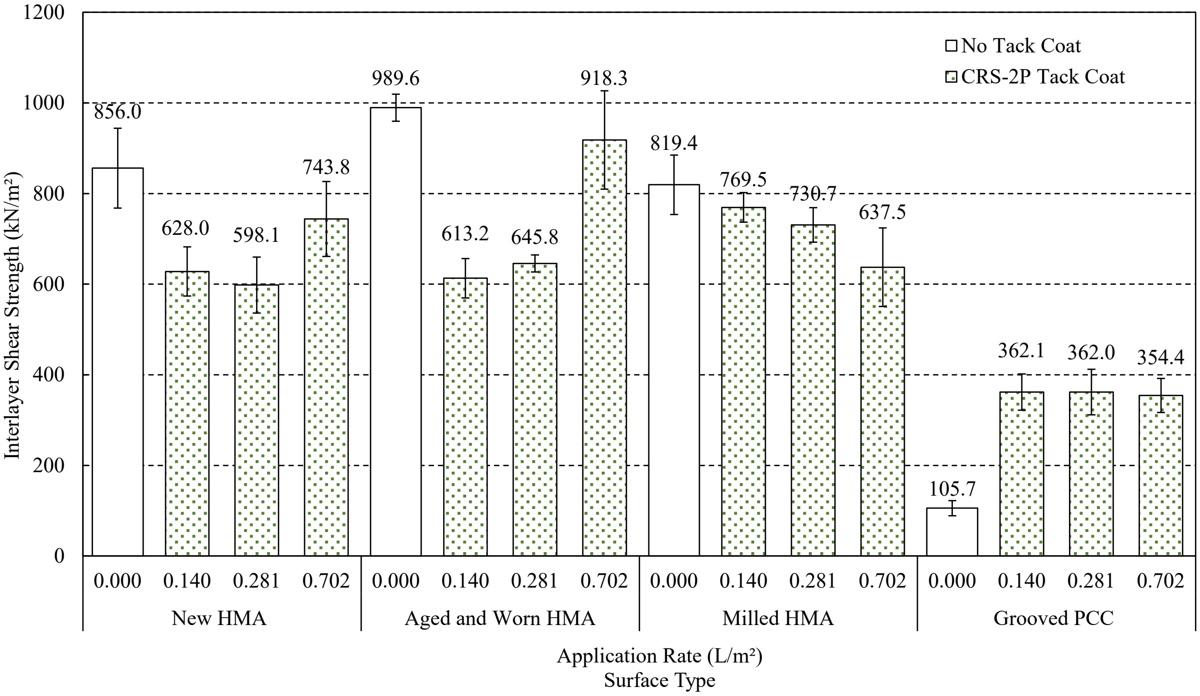

Figure 4.5 Interlayer Shear Strength of Samples with Different Bottom Layers and CRS-2P Tack Coat

As shown in Figure 4.5, the ISS values measured for the samples prepared using new HMA at their bottom layer and containing 0, 0.140, 0.281, and 0.702 L/m2 of CRS-2P tack coat in their interlayers were found to be 856.0, 628.0, 598.0, and 743.8 kPa, respectively. In other words, the ISS values of the samples containing 0.140, 0.281, and 0.702 L/m2 of the CRS-2P tack coat were found to be 27%, 30%, and 13%, respectively, less than those measured for samples prepared without any tack coat. Similarly, the samples' ISS values with the aged and worn HMA bottom layer containing 0.140, 0.281, and 0.702 L/m2 of CRS-2P were 38%, 35%, and 7% less than the ISS values of the samples prepared without any tack coat. Likewise, the ISS values measured for samples with the milled HMA bottom layer and 0.140, 0.281, and 0.702 L/m2 of CRS-2P were found to be 6%, 11%, and 22% less than those measured for samples prepared without any tack coat, respectively. Initial observations suggest that applying the CRS-2P tack coat may reduce ISS values of samples with HMA bottom layers compared with those with no tack coat. This overestimation of the ISS values measured for laboratory-prepared samples containing no tack coat was also reported by Mohammad et al. (2010). Although the tack coat application was found to reduce the early-age ISS values, different ISS variations with tack coat application rates were observed.

In samples having new HMA and aged and worn HMA bottom layers, applications of 0.140 and 0.281 L/m2 of CRS-2P tack coat resulted in a reduction in ISS values. However, the ISS values improved with further increasing the application rate (0.702 L/m2). This improvement was attributed to the fact that the surface absorbed the binding agent at low application rates, and no sufficient bonding agent was available to improve the interlayer bond. However, a further increase in the tack coat application rate made more bonding agent available for adhesion even after absorption of a part of it by the surface texture. A similar observation reported by Amelian and Kim (2017) suggests that in samples with similar surface textures, a higher tack coat application rate results in an increased ISS value. Also, it is evident that for samples having aged and worn HMA as their bottom layers with polished textures, the measured ISS values were more sensitive to an increase in the CRS-2P tack coat application rate than for samples with new HMA bottom layers. However, the ISS values were found to show a steady trend of reduction with increasing the tack coat application rate when samples with milled HMA bottom layers were tested. This indicates the effect of the surface type on the ISS values measured for HMA samples. Mohammad et al. (2012) reported that the surface's saturation with any tack coat leaves less role for surface texture or roughness to contribute to shear strength at the interlayer. Another important finding from Figure 4.5 is the adverse effect of tack coat application when samples are tested at an early age. This is important for adjusting the time between construction and opening of the newly constructed pavement to heavy traffic. At the same time, due to an early age, the tack coat may reduce interlayer shear strength.

On the contrary, the application of CRS-2P on the samples having grooved PCC bottom layers was found to effectively increase the ISS values compared with those of the samples prepared without any tack coat in their interlayer. As shown in Figure 4.5, the ISS values of the samples having grooved PCC bottom layers and containing 0.140, 0.281, and 0.702 L/m2 of CRS-2P tack coat in their interlayers were found to increase by more than three times compared with those of samples prepared without any tack coat in their interlayer. The ISS values were not significantly affected by increasing the residual application rate of the CRS-2P tack coat on specimens prepared using grooved PCC bottom layers.

4.4.3 CSS-1h Tack Coat

Figure 4.6 presents the ISS values measured for samples prepared using CSS-1h tack coat applied with rates of 0, 0.140, 0.281, and 0.702 L/m^2 on new HMA, aged and worn HMA, milled HMA, and grooved PCC surfaces. As shown in Figure 4.6, the ISS values measured for the samples having new HMA at their bottom layer and containing 0, 0.140, 0.281, and 0.702 L/m^2 of CSS-1h tack coat in their interlayers were found to be 856.0, 865.6, 810.3, and 709.2 kPa, respectively. In other words, the ISS values of the samples having a new HMA bottom layer and containing 0.140, 0.281, and 0.702 L/m^2 of CSS-1h were found to increase by 1% and decrease by 5% and 17%, respectively, compared with those of samples without any tack coat. Similarly, the ISS values of the samples having aged and worn HMA bottom layer and containing 0.140, 0.281, and 0.702 L/m^2 of CSS-1h tack coat in their interlayers were found to increase by 3% and decrease by 8% and 47%, respectively, compared with samples with no tack coat. Likewise, the samples' ISS values having a milled HMA bottom layer containing 0.140, 0.281, and 0.702 L/m^2 of CSS-1h were found to increase by 9% and 6% and decrease by 9%, respectively, compared with those of samples without any tack coat in their interlayer. All of these observations suggest that the application of CSS-1h tack coat at low and intermediate application rates (0.140 and 0.281 L/m^2) may result in an improvement in ISS values compared with those of samples containing no tack coat having an HMA bottom layer with different surface textures. However, the ISS values showed a decline with further increasing the application rate to a higher value (0.702 L/m^2). This was attributed to CSS-1h being a cationic tack coat with a stiff base binder, which has a low tendency to be absorbed by the surface. Therefore, the base binder can be present in the interlayer and contribute to adhesion even at low and intermediate application rates due to low absorption. However, further increasing the application rate results in the interlayer's oversaturation with binder residue and emulsifier and forming a thick film of asphalt residue. A thick layer of asphalt binder leads to a reduction in interlocking in the interlayer and lower friction, resulting in a lower ISS value. This finding is consistent with those reported by Mohammad et al. (2012). Also, the ISS values measured for samples with aged and worn HMA bottom layers were more sensitive to excessive application of CSS-1h tack coat than that for samples with new HMA and milled HMA as their bottom layers. For example, the application of a 0.702 L/m^2 tack coat resulted in a 47% reduction in ISS value compared with those without any tack coat. Observations mentioned above clearly indicate that excessive use of tack coats with a hard asphalt binder residue may reduce early-age interlayer shear strength due to the lubrication effect of excessive residue present in the interlayer.

Application of CSS-1h tack coat on the samples having grooved PCC bottom layers was found to effectively increase the ISS values compared with those of the samples prepared without any tack coat. From Figure 4.6, it is evident that the ISS values of the samples having grooved PCC bottom layers and containing 0.140, 0.281, and 0.702 L/m^2 of CSS-1h were found to increase by more than 3.4, 4.6, and 3.8 times compared with those of samples prepared without any tack coat in their interlayer. The highest ISS value was measured (488.4 kPa) when the CSS-1h tack coat was applied on a grooved PCC bottom sample at an application rate of 0.281 L/m^2.

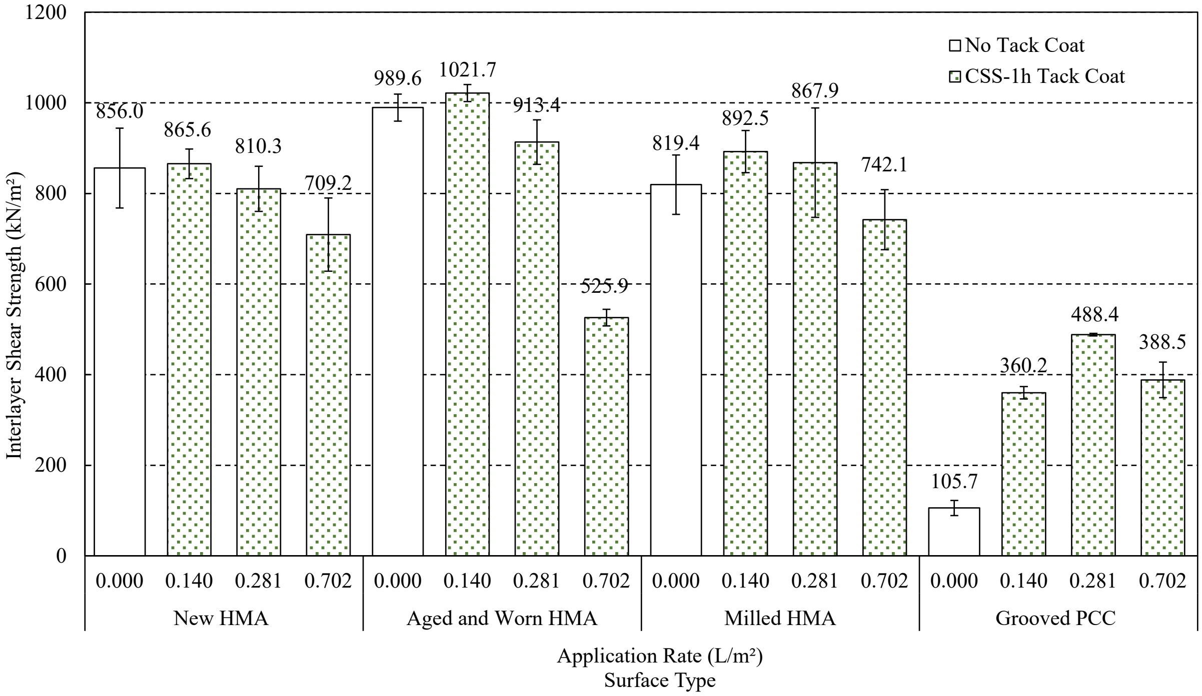

Figure 4.6 Interlayer Shear Strength of Samples with Different Bottom Layers and CSS-1h Tack Coat

4.4.4 SS-h Tack Coat

Figure 4.7 presents the ISS values measured for samples prepared using SS-h tack coat applied at 0, 0.140, 0.281, and 0.702 L/m^2 on new HMA, aged and worn HMA, milled HMA, and grooved PCC surfaces. As shown in Figure 4.7, the ISS values measured for the samples having new HMA at their bottom layer and containing 0, 0.140, 0.281, and 0.702 L/m^2 of SS-h tack coat in their interlayers were found to be 856.0, 688.4, 808.9, and 768.6 kPa, respectively. In other words, the ISS values of the samples having a new HMA bottom layer and containing 0.140, 0.281, and 0.702 L/m^2 of SS-h tack coat in their interlayers were found to decrease by 20%, 5%, and 17%, respectively, compared with those of samples prepared without any tack coat in their interlayer. Similarly, the ISS values of the samples having aged and worn HMA bottom layer and containing 0.140, 0.281, and 0.702 L/m^2 of SS-h tack coat in their interlayers were found to decrease by 18%, 3%, and 3%, respectively, compared with those of samples prepared without any tack coat in their interlayer. However, the ISS values of the samples having milled HMA bottom layer and containing 0.140, 0.281, and 0.702 L/m^2 of SS-h tack coat in their interlayers were found to increase by 7%, 6%, and 8%, respectively, compared with those of milled HMA samples prepared without any tack coat in their interlayer. All of these observations suggest that application of SS-h tack coat on new HMA and aged and worn HMA surfaces at intermediate and high application rates (0.281 and 0.702 L/m^2) may result in a higher ISS value compared with that of the samples prepared by applying tack coats with low application rate (0.140 L/m^2). Also, it was found that the application of the SS-h tack coat on milled HMA all application rates improved the interlayer shear strength compared with samples prepared without any tack coat.

Unlike samples having HMA bottom layers, application of SS-h tack coat on the samples having grooved PCC bottom layers was found to effectively increase the ISS values compared with those of the samples prepared without any tack coat in their interlayer. From Figure 4.7, it is evident that the ISS values of the samples having grooved PCC bottom layers and containing 0.140, 0.281, and 0.702 L/m^2 of SS-h tack coat in their interlayers were found to increase by more than 5.6, 5.4, and 5.5 times compared with those of samples prepared without any tack coat in their interlayer. Also, as shown in Figure 4.7, the highest ISS value was measured (599.4 kPa) when the SS-h tack coat was applied to the grooved PCC bottom sample at an application rate of 0.140 L/m^2.

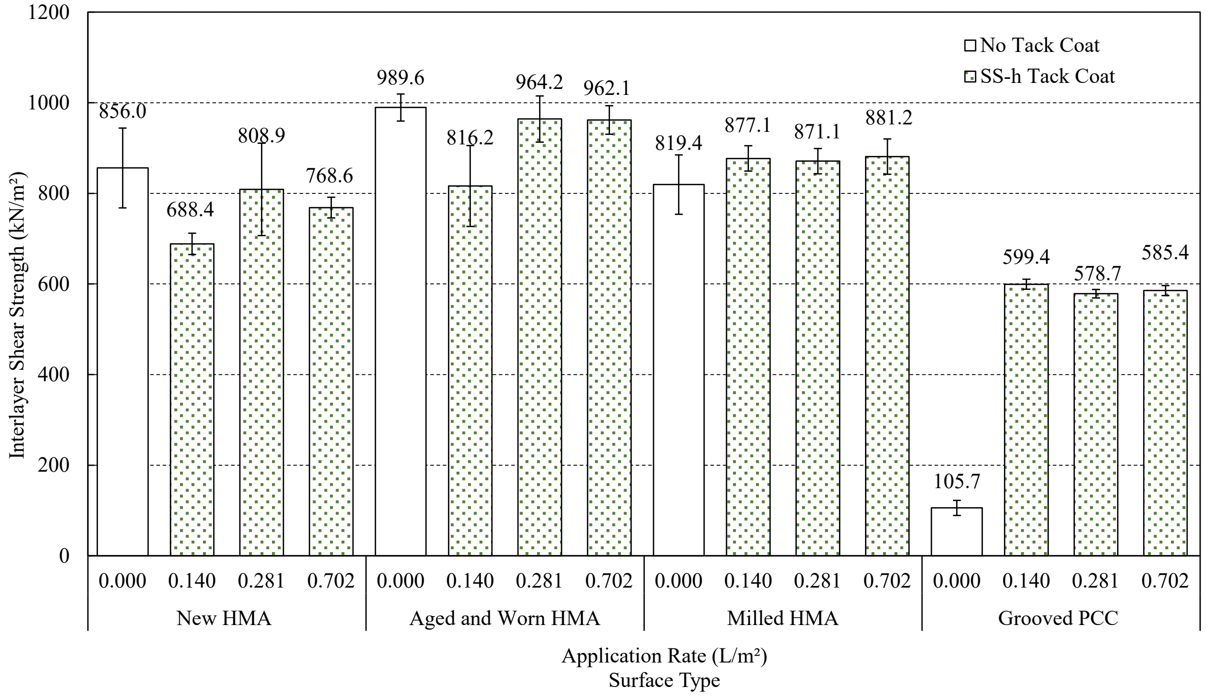

Figure 4.7 Interlayer Shear Strength of Samples with Different Bottom Layers and SS-h Tack Coat

4.4.5 Summary

Among all types of tack coats evaluated by determining the ISS values, in general, the CSS-1h tack coat showed the best overall performance on all the bottom layer types. Also, on all HMA bottom layer types, CSS-1h showed the best performance at the lowest application rate (0.140 L/m^2). On specimens prepared by using PCC bottom layers, SS-h worked better compared with other tack coats. The highest ISS between PCC and HMA was observed when the SS-h tack coat was used, followed by CSS-1h and CRS-2P. Comparatively, it was observed that CRS-2P provides higher ISS values in higher application rates (0.702 L/m^2) while CSS-1h provides a higher ISS value in a lower application rate (0.140 L/m^2). As a result, it may be concluded that CSS-1h tack coat can be successfully used on all types of surfaces.

Among the tested tack coats, both CRS-2P and CSS-1h are cationic tack coats. Cationic asphalt emulsions contain positive charges and are more attracted to negatively charged surfaces. SS-h is an anionic emulsion that is more attracted to positively charged surfaces. It was interesting to see that the SS-h tack coat showed higher performance on grooved PCC surfaces. Also, both cationic emulsions showed nearly similar performances on grooved PCC surfaces. This was attributed to the polar attraction between SS-h tack coat emulsion and the surface of the PCC.

4.5 Effect of Surface Type, Preparation, and Texture on ISS Values

Depending on the type and the texture of the bottom layer sample, the measured interlayer shear strength can vary. This is mainly due to different friction, interlocking, adhesion between layers and tack coat, and tack coat absorption. The effect of the bottom layer type and texture on the measured ISS values is discussed in this section.

4.5.1 New HMA Bottom Layer

Figure 4.8 presents the ISS values measured for samples prepared using the new HMA bottom layer and CRS-2P, CSS-1h, and SS-h tack coats applied at 0 (no tack coat), 0.140, 0.281, and 0.702 L/m^2. Figure 4.8 shows that the specimens prepared using a new HMA bottom layer with a tack coat generally exhibited a lower ISS value than the samples prepared without applying any tack coat. Based on the presented ISS values, the application of CRS-2P on new HMA surfaces resulted in a higher ISS value (743.8 kPa) in the high application rate (0.702 L/m^2). In comparison, the application of CSS-1h at a low rate (0.140 L/m^2) resulted in a high ISS value (856.6 kPa). Also, the application of SS-h in a moderate application rate (0.281 L/m^2) resulted in a high ISS value (808.9 kPa). Figure 4.8 shows that the highest ISS values in both types of specimens with CRS-2P and SS-h tack coats were not higher than those of specimens prepared without applying any tack coat. Yet, specimens with CSS-1h tack coat samples prepared using the lowest application rate (0.140 L/m2) exhibited a higher ISS value than that of specimens prepared without applying any tack coat. Hence, for an asphalt pavement to be constructed on a new HMA layer, CSS-1h used at a rate of 0.140 L/m^2 may be recommended.

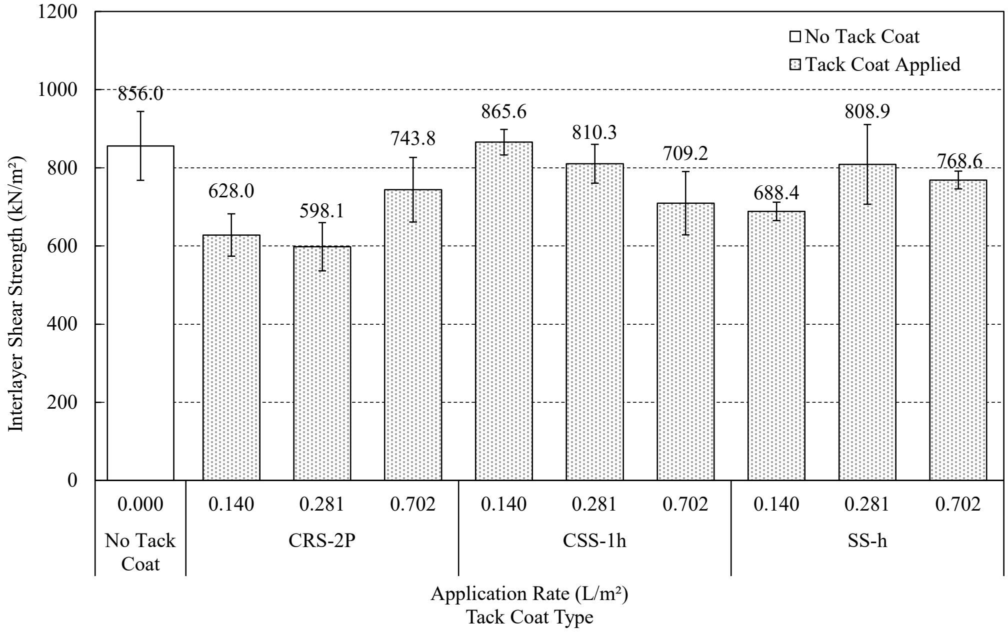

Figure 4.8 Interlayer Shear Strength of Samples with New HMA Bottom Layer and Different Tack Coats

According to Figure 4.8, if CRS-2P and SS-h tack coats are to be used, their application at high (0.702 L/m^2) and intermediate (0.281 L/m^2) rates, respectively, is recommended. Overall, using a slow-setting asphalt emulsion, either anionic or cationic, with a harder base binder grade at moderation on a new HMA surface was more effective than other tack coat types in improving the ISS values.

4.5.2 Aged and Worn HMA Bottom Layer

The HMA bottom layers were oven-aged and polished to simulate the change in the binder chemistry and surface texture due to subjecting an asphalt pavement to environmental elements and traffic during its service life. Figure 4.9 presents the ISS values measured for samples prepared using aged and worn HMA bottom layers containing different types and amounts of tack coat. Figure 4.9 shows that the samples prepared using aged and worn HMA bottom layers containing tack coat generally exhibited lower ISS values than samples containing no tack coat in their interlayer. Also, it was found that the application of the CRS-2P, CSS-1h, and SS-h tack coats was more effective in improving the ISS values when they were used at 0.702, 0.140, and 0.281 L/m^2 application rates, respectively. The CSS-1h tack coat applied at a rate of 0.140 L/m^2 was the most effective in improving the ISS values than the specimens prepared without any tack coat. Hence, the CSS-1h tack coat applied at a rate of 0.140 L/m^2 may be recommended to be used with aged and worn HMA pavement surfaces. Comparing Figure 4.9 and Figure 4.8 reveals that the application of tack coat was more effective in improving the ISS values in specimens prepared using the aged and worn HMA than those prepared using new HMA bottom layer samples. This observation was attributed to the fact that aged and worn HMA bottom layers provide more in-contact surface with the top layer and bonding agent than the new HMA, contributing to a higher ISS value. A similar finding was also reported by Mohammad et al. (2010), indicating that average ISS values for specimens prepared with aged and worn HMA bottom layers were higher than those measured for the specimens prepared using the new HMA bottom layers. Also, Ghabchi et al. (2018) reported that the aged asphalt, compared with the virgin binder, provides better adhesion to the virgin asphalt binder. This can also contribute to better adhesion of the emulsified asphalt to the aged surface than the new HMA surface, leading to higher ISS values for the samples with aged and worn bottom layers.

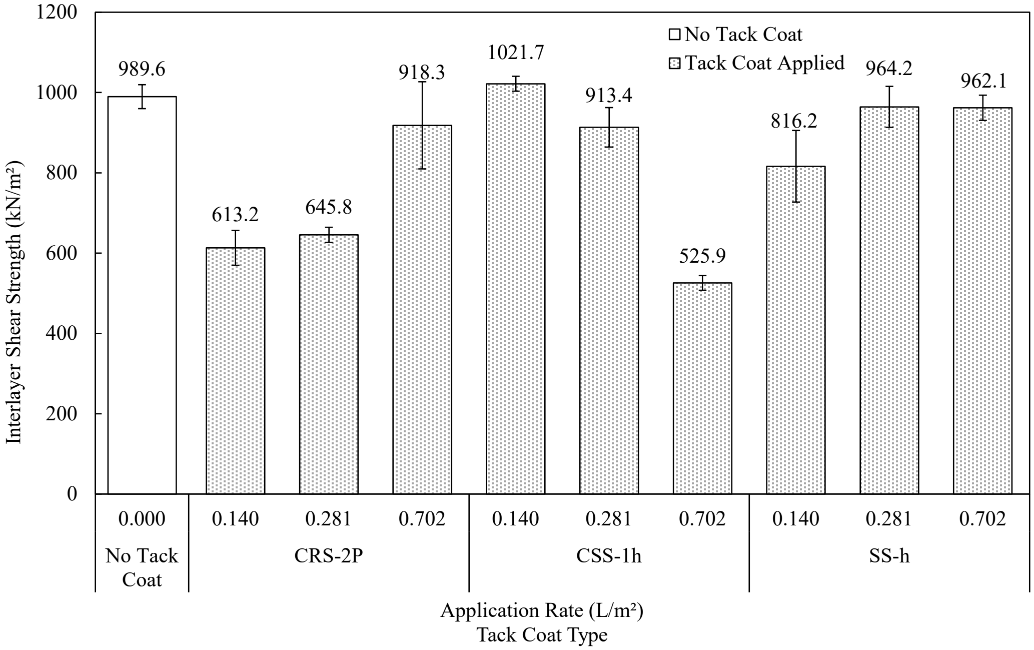

Figure 4.9 Interlayer Shear Strength of Samples with Aged and Worn HMA Bottom Layer and Different Tack Coats

4.5.3 Milled HMA Bottom Layer

Specimens prepared using milled HMA provided the roughest interlayer texture among surfaces tested in this study. Figure 4.10 presents the ISS values measured for samples prepared using milled HMA bottom layer without any tack coat and those containing CRS-2P, CSS-1h, and SS-h each applied at 0.140, 0.281, and 0.702 L/m^2. As shown in Figure 4.10, the application of CSS-1h and SS-h to milled HMA resulted in higher ISS values compared with those of the samples containing no tack coat. Also, it was found that the application of the CRS-2P, CSS-1h, and SS-h tack coats was more effective in improving the ISS values when they were used at 0.140, 0.140, and 0.702 L/m^2 application rates, respectively. It is important to note that both CSS-1h and SS-h applied to milled HMA at a low application rate (0.140 L/m^2) improved the interlayer shear strength by 9% and 7%, respectively, compared with samples without any tack coat. Therefore, using CSS-1h and SS-h tack coats having a hard asphalt binder residue at a 0.140 L/m^2 application rate may be recommended for milled HMA. Also, it was observed that the ISS values, in general, decreased with an increase in the application rate for samples containing CRS-2P and CSS-1h tack coats. When the interlayer becomes saturated, and an excessive amount of tack coat is present, the tack coat acts as a lubricant, resulting in a reduction in measured ISS value (Mohammad et al., 2012).

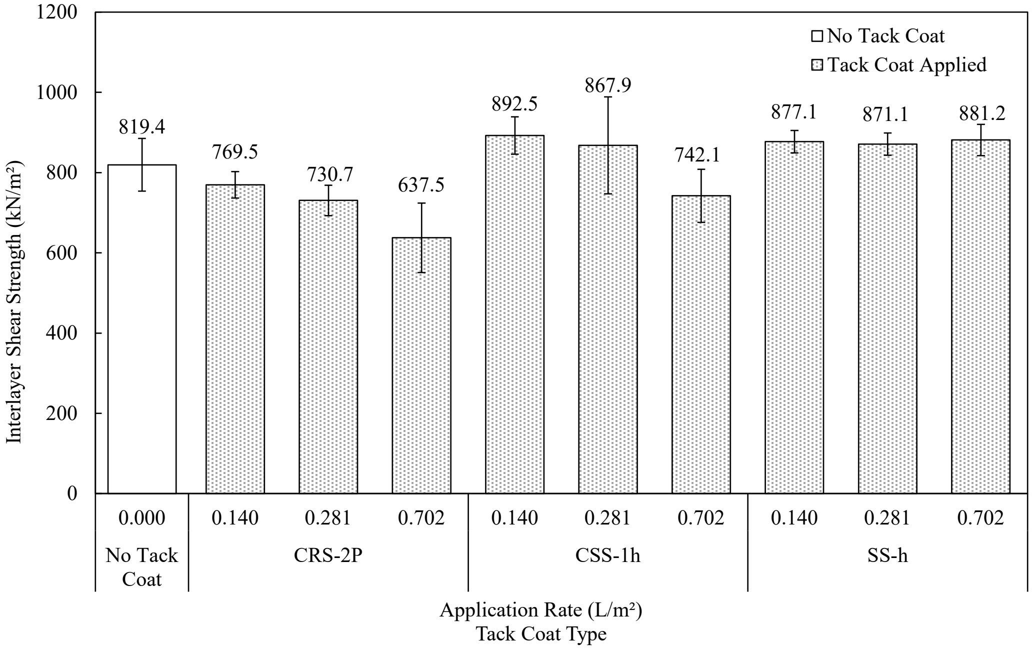

Figure 4.10 Interlayer Shear Strength of Samples with Milled HMA Bottom Layer and Different Tack Coats

4.5.4 Grooved PCC Bottom Layer

Figure 4.11 presents the ISS values measured for samples prepared using the grooved PCC bottom layer containing no tack coat, CRS-2P, CSS-1h, and SS-h, each applied at 0.140, 0.281, 0.702 L/m^2 application rates. According to Figure 4.11, the application of all three types of tack coats at all rates on grooved PCC bottom layers resulted in a significant improvement in the interlayer shear strength values compared with interlayers without any tack coat. For example, samples prepared using grooved PCC bottom layers containing CRS-2P, CSS-1h, and SS-h tack coats had ISS values that were 3.4, 3.9, and 5.6 times higher than those measured for grooved PCC specimens prepared without any tack coat, respectively. In other words, the SS-h tack coat was found to be the most effective in improving the interlayer shear strength of specimens prepared with grooved PCC bottom layer. It is noteworthy that, in general, a PCC surface has a negative electric charge (Elakneswaran et al., 2010), which facilitates the dispersion of the SS-h, an anionic tack coat with a negative electric charge. A better tack coat dispersion on the interlayer results in a uniform coating, leading to the formation of a stronger interlayer bond. This can explain higher ISS values measured for PCC bottom layers coated with SS-h tack coat. Also, from Figure 4.11, it is evident that the ISS values measured for the specimens with grooved PCC bottom layers were not significantly affected by the application rate of the SS-h tack coat. Furthermore, the highest ISS values for samples prepared by applying CRS-2P and SS-h tack coats were measured when they were used at a low rate (0.140 L/m^2). A similar finding was reported by Al-Qadi et al. (2008), indicating that the optimum tack coat application rate for samples prepared using PCC bottom layers was found to be 0.140 L/m^2. Also, from Figure 4.11, it was observed that the use of CSS-1h tack coat at application rates of 0.140, 0.281, and 0.702 L/m^2 resulted in an increase in measured ISS values by 3.4, 4.6, and 3.7 times, respectively, compared with those of samples prepared without any tack coat. This indicates that the measured ISS values were sensitive to the application rate when CSS-1h was used, and the maximum ISS value was observed at an application rate of 0.281 L/m^2.

The ISS values of the samples prepared using grooved PCC bottom layers without any tack coat are significantly lower than the minimum recommended ISS value of 276 kN/m^2 (Mohammad et al., 2012) and those measured for asphalt pavements. Therefore, applying a tack coat on the PCC layer is crucial to the pavement's durability and field performance.

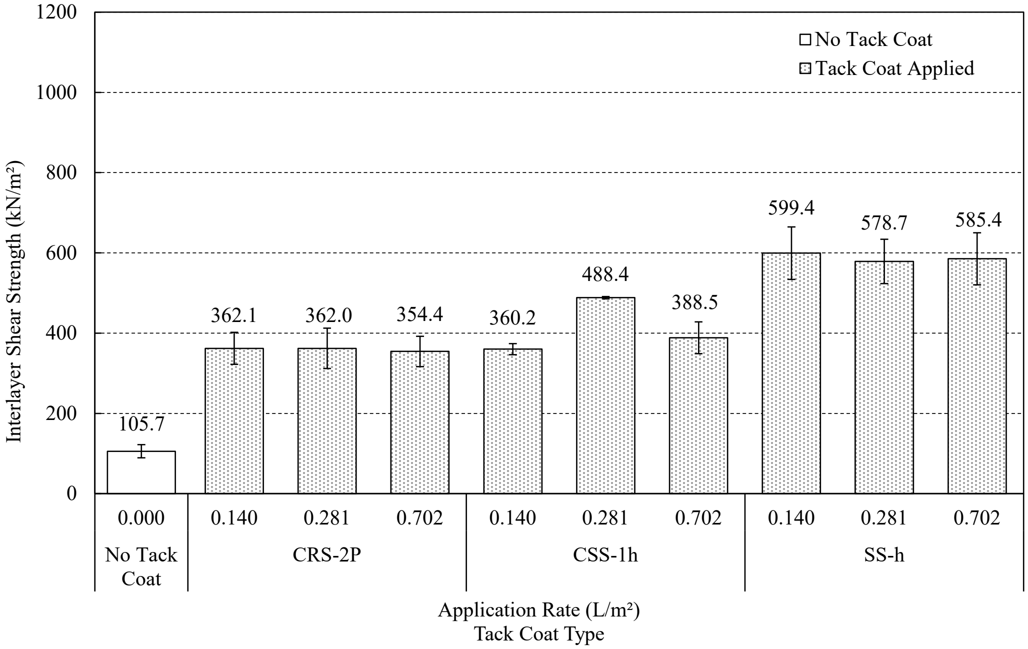

Figure 4.11 Interlayer Shear Strength of Samples with Grooved PCC Bottom Layer and Different Tack Coats

4.5.5 Summary

From comparing Figures 4.8, 4.9, 4.10, and 4.11, it was concluded that the highest ISS values were observed in specimens prepared using aged and worn HMA, followed by new HMA, milled HMA, and grooved PCC bottom layers. For both specimens prepared using new HMA and aged and worn HMA bottom layers, CSS-1h tack coat with an application rate of 0.140 L/m^2 was found to result in the greatest improvement in ISS values. For specimens prepared using milled HMA bottom layers based on the ISS values, both CSS-1h and SS-h tack coats applied at a rate of 0.140 L/m^2 were found to be the most effective tack coats in improving the ISS values. All three types of tack coats, CRS-2P, CSS-1h, and SS-h, on grooved PCC bottom layers applied at 0.140, 0.281, and 0.140 L/m^2 rates, respectively, were found to be effective in improving the ISS values. Among the evaluated tack coat types for specimens with grooved PCC bottom layers, SS-h was found to be the most effective one in improving the ISS values.

4.6 Optimum Tack Coat Residual Application Rates

A summary of optimum residual application rates for all the tested tack coats on all types of bottom layers is shown in Table 4.4. According to Table 4.4, in general, one may conclude that the CSS-1h can be used effectively on any surface, as it showed the highest ISS values in the lowest application rate (0.140 L/m^2) for specimens with all types of HMA bottom layers. Also, it showed the highest ISS values for specimens prepared using grooved PCC bottom layers at a medium application rate (0.281 L/m^2). Table 4.1 showed that the optimum tack coat application rate on the milled HMA bottom layer is 0.140 L/m^2 for all the tested tack coats. In other words, the surface texture has a dominating effect on the interlayer shear strength. Also, from Table 4.4, it can be concluded that the optimum application rates of CSS-1h and SS-h tack coats used on the specimens prepared using new HMA and aged and worn HMA bottom layers were determined as 0.140 and 0.281 L/m^2, respectively. Similar findings were also reported by Mohammad et al. 2012.

Table 4.4 Optimum asphalt residue application rates for different bottom layers

Tack Coat Type	Optimum Residual Application Rate (L/m^2)			
	New HMA	Aged and worn HMA	Milled HMA	Grooved PCC
CRS-2P	0.702	0.702	0.140	0.140
CSS-1h	0.140	0.140	0.140	0.281
SS-h	0.281	0.281	0.140	0.140

4.7 Effect of Moisture and Freeze-Thaw Cycles on Interlayer Shear Strength

The effect of moisture on interlayers was simulated for samples prepared with optimum residual application rates and tested using LISST equipment. The ISS values obtained for moisture-conditioned samples were compared with unconditioned samples prepared at optimum application rates. A summary of the ISS values measured for moisture-conditioned and dry samples prepared at optimum application rates is presented in Table 4.5. From Table 4.5, it was observed that most of the moisture-conditioned samples prepared using HMA bottom layers exhibited higher ISS values than those tested in dry conditions. However, the difference between the ISS values measured for the conditioned and unconditioned samples was not found to be significant. Since the samples were tested after vacuum saturation, an increase in ISS value resulting from moisture conditioning was attributed to the negative capillary pressure effect. This negative pressure (suction), in turn, led to a better interlocking and improved friction between two asphalt layers. This observation recommends that, in the laboratory setting, moisture did not have a measurable detrimental effect on the early-age interlayer shear strength of the samples prepared using HMA bottom layers with optimum tack coat application rates. Among all the tack coats tested, the SS-h tack coat was the most effective in increasing the early-age ISS values after moisture conditioning.

Additionally, it was found that specimens prepared using grooved PCC bottom layers after moisture-conditioning and freeze-thaw cycles exhibited lower ISS values compared with those of unconditioned samples. Similar results were reported by Al-Qadi et al. (2008). Also, from Table 4.5, it was observed that the ISS values of the moisture-conditioned samples with grooved PCC bottom layers containing CRS-2P, CSS-1h, and SS-h tack coats applied at their optimum application rates were 4.6, 5.5, and 5.8 times higher than those of the samples prepared without any tack coat, respectively. Therefore, applying tack coat on grooved PCC surfaces before constructing an asphalt overlay is crucial to the pavement structure's durability and longevity.

Table 4.5 Interlayer shear strength values measured for dry and moisture-conditioned samples with different surface types containing tack coats applied at their optimum rates

Bottom Layer Type	Tack Coat Type	Optimum Residual Application Rate (L/m^2)	Dry		Moisture-Conditioned	
			ISS (kPa)	Standard Deviation (kPa)	ISS (kPa)	Standard Deviation (kPa)
New HMA	No Tack Coat	-	856.0	88.1	882.7	54.2
	CRS-2P	0.702	743.8	82.7	571.4	277.9
	CSS-1h	0.140	865.6	32.6	870.0	59.3
	SS-h	0.281	808.9	101.9	1018.8	99.8
Aged and Worn HMA	No Tack Coat	-	989.6	29.8	941.5	70.8
	CRS-2P	0.702	918.4	108.6	954.8	163.3
	CSS-1h	0.140	1021.7	18.6	1133.1	42.1
	SS-h	0.281	964.2	51.0	1140.3	84.9
Milled HMA	No Tack Coat	-	819.4	65.7	910.5	51.8
	CRS-2P	0.140	769.5	32.8	928.5	10.5
	CSS-1h	0.140	892.5	46.6	981.5	31.0
	SS-h	0.140	877.1	27.9	997.0	26.9
Grooved PCC	No Tack Coat	-	105.7	16.6	77.4	38.7
	CRS-2P	0.140	362.1	40.0	355.3	38.6
	CSS-1h	0.281	488.4	3.0	425.4	55.0
	SS-h	0.140	599.4	10.9	450.6	1.7

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Inadequate or excessive amounts of tack coat can result in premature failures in asphalt pavements due to poor interlayer bonding, slippage, or binder migration. Several studies have been conducted to determine the optimum tack coat application rate. Different parameters, namely tack coat emulsion type, surface material, texture, application practice, curing time, and moisture, affect the interlayer shear strength and the determined optimum application rates. Since tack coat binder is much softer shortly after construction compared with that after aging during the in-service life of the pavement, the likelihood of the asphalt pavement's interlayers undergoing shear failure in their early age is considerably high. Therefore, this study was undertaken to determine the effects of application rate, surface type, and moisture on the early-age performance of three types of tack coat emulsions applied on four surface types in dry conditions and after moisture-conditioning.

For this purpose, a layer of hot-mix asphalt (HMA) was compacted on different surfaces. These surfaces were new HMA, aged and worn HMA, milled HMA, and grooved Portland cement concrete (PCC). Three types of tack coats widely used in upper Midwest states, CRS-2P, CSS-1h, and SS-h, were applied at residual rates of 0, 0.140, 0.281, and 0.702 liters per square meter (L/m^2).

The early-aged interlayer shear strength (ISS) of the specimens were measured and used to study the effectiveness of different combinations of tack coat type applied at different rates on each surface texture type. Additionally, to determine the effects of moisture and freeze-thaw cycles on the ISS values, moisture-conditioned specimens prepared using all tack coat types applied on different surface textures were tested. It was found that the specimens prepared using tack coats having a harder binder grade (CSS-1h and SS-h) exhibited higher early-age ISS values at low application rates compared with those prepared using a polymer-modified tack coat (CRS-2P). Also, it was found that in general, applying tack coat resulted in a reduction in early-age ISS values for specimens prepared by using different textures of HMA surfaces (new HMA, aged and worn HMA, and milled HMA). However, applying all three types of tack coats at all application rates increased the ISS values of specimens consisting of an HMA layer compacted on a grooved PCC layer. Moisture conditioning was not found to substantially affect the early-age ISS values of the specimens having HMA bottom layer with various surface types and textures. However, moisture conditioning resulted in a considerable reduction in the specimens' ISS values consisting of an HMA layer compacted on a grooved PCC layer using different tack coats. Among evaluated tack coats, the polymer-modified tack coat was the most effective in reducing moisture's effect on the ISS values.

5.2 Conclusions

Based on the results, discussions, and observations made in this study, conclusions as follows can be drawn.

- In general, the early-age ISS values of the specimens containing tack coat prepared by using HMA as their interlayers, regardless of the surface type, were found to be less than those prepared without any tack coat. In both cases (interlayers with and without tack coat), the ISS values were found to be higher than the minimum recommended ISS value (276 kN/m^2).
- The early-age ISS values of samples with grooved PCC bottom layer without any tack coat were notably lower than the minimum recommended ISS value (276 kN/m^2). Application of all types of tack coats at all rates effectively improved the early-age ISS of those samples.
- Surface type and texture were found to have a significant effect on the ISS values. The highest ISS values were measured for specimens prepared using aged and worn HMA, followed by new HMA, milled HMA, and grooved PCC bottom layers.

- In all cases, including different surface types and textures, the application of both anionic and cationic tack coats with a hard binder grade was more effective in improving the ISS values than using a polymer-modified tack coat.
- The application of CSS-1h tack coat at low and intermediate application rates (0.140 and 0.281 L/m^2) resulted in an improvement in ISS values compared to that of samples containing no tack coat with an HMA bottom layer and different surface textures.
- Application of SS-h tack coat on new HMA and aged and worn HMA surfaces at intermediate and high application rates (0.281 and 0.702 L/m^2) showed higher ISS values compared with those of the samples prepared by applying tack coats at low application rate (0.140 L/m^2). For milled HMA, change of application rate did not have a significant effect on measured ISS values.
- CRS-2P, CSS-1h, and SS-h tack coats applied on grooved PCC surfaces at 0.140, 0.281, and 0.140 L/m^2 application rates were highly effective in improving the ISS values. Among the evaluated tack coats, SS-h was the most effective in enhancing the ISS values on grooved PCC surfaces.
- In general, CRS-2P resulted in higher ISS values when applied at a high rate (0.702 L/m^2). However, CSS-1h provided a high ISS value at a lower application rate (0.140 L/m^2). As a result, it is possible to conclude that the CSS-1h tack coat can be successfully used on all types of surfaces.
- Moisture and freeze-thaw cycles were not found to have a detrimental effect on the measured early-age interlayer shear strength of the samples prepared using all types of HMA bottom layers with optimum tack coat application rates. Among all tested tack coats, the SS-h tack coat was most effectively capable of increasing the ISS values after moisture conditioning. Moisture conditioning showed a negative impact on the ISS values measured for the samples prepared using grooved PCC bottom layers. However, ISS values measured for moisture-conditioned samples containing tack coats were consistently higher than the minimum recommended ISS value (276 kN/m^2).

5.3 Recommendations

The following recommendations were made based on the limitations and the scope of the present study.

- Since the moisture-conditioned samples were tested after vacuum saturation, an increase in ISS value resulting from moisture conditioning was attributed to suction, resulting in a better interlocking of top and bottom layers. To mitigate this issue, it is recommended to dry the samples before testing.
- The LISST was conducted only at room temperature. Therefore, it is recommended to perform the LISST at different temperatures to evaluate the effect of temperature on ISS values.
- The LISST tests were conducted on laboratory-prepared samples. It is recommended to conduct additional LISST tests on field cores prepared using the same tack coat types tested in this study.

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