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EVALUATION OF THE EFFECT OF TACK COAT TYPE, APPLICATION RATE, AND SURFACE TYPE ON INTERLAYER SHEAR STRENGTH

BY

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CHAMIKA PRASHAN DHARMARATHNA

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Civil Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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This thesis is dedicated to my parents.

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ABBREVIATIONS

SD	South Dakota
SDSU	South Dakota State University
LISST	Louisiana Interlayer Shear Strength Tester
OTAR	Optimum Tack Coat Application Rate
ISS	Interlayer Shear Strength
AV	Air Voids
MTS	Material Testing System
Gal	Gallons
Yd	Yard
Lbs	Pounds
L	Liters
M	Meters
Kg	Kilo-grams

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ABSTRACT

EVALUATION OF THE EFFECT OF TACK COAT TYPE, APPLICATION RATE, AND SURFACE TYPE ON INTERLAYER SHEAR STRENGTH

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Tack coat is an asphaltic material applied between asphalt pavement layers. Since pavement is a multilayered structure, it is highly important to make proper bond between the layers to achieve a monolithic behavior. Hence, inadequate bond due to application of inadequate amount of tack coat may lead to poor structural behavior and premature failure. Also, applying excessive amount of tack coat may lead to layer slippage and binder migration. Therefore, it is highly important to apply an optimum amount of tack coat between layers. Over the past decades several studies have been conducted to determine the optimum tack coat application rate, based on tack coat type, surface preparation, and temperature. In those studies, different types of tests were used to determine the Interlayer Shear Strength (ISS). It was reported that, many factors affect the ISS such as tack coat application rate, tack coat type, layer type and texture, cleanliness, test temperature, and confinement pressure among other factors.

In the current study, a Louisiana Interlayer Shear Strength Tester (LISST) device was used to measure the ISS values of layered samples. The test matrix included 2 main parts, one to identify the optimum tack coat application rate and the other part to study the effect of moisture conditioning on ISS of the samples prepared at optimum application rate. The top layer of all of the test samples were prepared in a way to simulate a new Hot Mix Asphalt (HMA) overlay. The top HMA layer was compacted on four types of bottom layers, namely new HMA, aged and worn HMA, milled HMA, and grooved Portland Cement Concrete (PCC). Three types of tack coats were evaluated: CRS-2P, CSS-1h, and SS-h. Tack coats were applied at four rates: 0, 0.140, 0.281, and 0.702 liters per square meter (L/m^2).

Results indicated that for the tack coat types evaluated in the current study CSS-1h exhibited the highest ISS values on all the surface types compared to those measured for surfaces without any tack coat. Also, on all HMA bottom layer types, CSS-1h showed the best performance at lowest application rate. It was observed that, CSS-1h was the only tack coat which showed higher ISS compared to no tack coat application. On PCC bottom layers, application of the SS-h tack coat resulted in a higher ISS value compared to other tack coats. The highest ISS value measured for the interface of PCC and HMA was observed when the SS-h tack coat was used. Generally, the CRS-2P tack coat was found to be more effective in improving the ISS at higher application rates while CSS-1h was effective when it was applied at a lower application rate.

The highest ISS value was observed when 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, 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 applied at a rate of 0.140 L/m^2 exhibited a higher effectiveness in improving the ISS value. For grooved PCC bottom layers all the tested tack coats exhibited increased ISS values than samples prepared without applying any tack coat. Hence, it is highly important to use any tack coat for an overlay of PCC bottom layer.

Moisture conditioning was found to negatively affect the ISS of the samples with PCC bottom layer regardless of the tack coat type. However, the ISS values of the samples containing tack coats applied at their optimum application rates on other types of HMA bottom layer were not found to be negatively affected due to moisture conditioning.

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Tack coat is an asphaltic material applied between an asphalt pavement layer and an existing pavement surface (The Asphalt Handbook, 1989). It is a common practice to use tack coat before placing a new HMA layer on an existing pavement (Mohammad et al., 2010). Asphalt emulsions, cutback asphalts, and asphalt binders are being used as tack coats. It is highly important to use an adequate amount of tack coat between layers in order to obtain a monolithic system so that it can withstand the traffic loading and environmental impacts and minimize premature failure (Mohammad et al., 2002). Since pavements are multi-layered structures, the bond strength between layers are as important as the strength and the stiffness of individual layers (Al-Qadi et al., 2008). Inadequate tack coat or no tack result in poor bond between layers and a reduction in the bearing capacity and could result in delamination of asphalt layer and premature structural failure (Mohammad et al., 2002). Application of tack coat in excessive amounts, however, can cause slippage between pavement layers and cause distresses such as rutting or half-moon cracking. The highest interlayer bond strength could be achieved by using the appropriate type of tack coat at optimum application rate using the proper application method on a well-prepared surface (Salinas et al., 2013).

Interlayer shear strength (ISS) in the interface of pavement layer varies depending on the type and the application rate of tack coat, as well as layer surface and characteristics. Hence, it is highly imperative to pavement performance to determine the optimum tack coat application rate commonly used in a specific area. Generally, selection of the optimum tack coat application rate is carried out based on experiences, empirical judgements and handling convenience (Mohammad et al., 2012). Different tests are used to evaluate the bond strength of pavement layers where tack coat is applied. Louisiana Interface Shear Strength Test (LISST) is one of the effective methods used for evaluating of the bond strength due to tack coat between pavement layers (Mohammed et al., 2010). Interlayer surface type is a major factor affecting the bond strength of pavement layers (Chen et al., 2010). Different types of pavement surfaces such as new Hot Mix Asphalt (HMA), aged and worn HMA, milled HMA, and grooved Portland Cement Concrete (PCC) require different application rates of tack coat to obtain the adequate interlayer bond strength. Type of tack coat and the application rate is also an important factor affecting ISS (Chen et., 2010). Temperature is another influential factor that contributes to measured bond strength of pavement layers in the presence of tack coat (Bae et al., 2010, Leng et al., 2008). Apart from that, the practices used for preparation of the existing pavement surface, cleaning, tack coat application method, and HMA laying procedures significantly affect the bond strength between layers of the pavement (Coleri et al., 2017). Another important concern during the construction is the removal of the applied tack coat from the pavement surface due to wheel tracking by construction equipment. Hence, a new generation of tack coats, namely trackless tack coats have been introduced which can significantly reduce this problem (Bae et al., 2010). Effect of moisture is another parameter which can negatively affect the bond strength between pavement layers (Al-Qadi et al., 2008). Al-Qadi et al. have concluded that moisture conditioning can negatively affect the interlayer bond strength.

In South Dakota, three types of tack coat emulsions, namely CSS-1h, CRS-2P, and SS-h are widely used in construction of asphalt pavements. Hence, it is highly important to identify the optimum application rate of each tack coat type based on the types of the existing pavement surfaces. Since South Dakota has cold and harsh winters, it is important to determine the effect of moisture and freeze thaw cycle on effectiveness of the abovementioned tack coats.

1.2 RESEARCH OBJECTIVE

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, namely new HMA, aged and worn HMA, milled HMA, and grooved PCC were evaluated. The optimum application rates were determined based on the Interlayer Shear Strength (ISS) results obtained from conducting shear tests using a Louisiana Interlayer Shear Strength Tester (LISST). Laboratory-prepared samples were used to conduct the LISST tests.

Another important objective was to determine the effect of moisture and freeze-thaw cycles on ISS values. For this purpose, after determination of optimum application rates of each tack coat type evaluated for each pavement texture, samples 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.

CHAPTER TWO: 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) tack coat is a thin adhesive layer, providing a solid bond between relatively non-absorptive old surface and a new asphalt layer (ASTM, 2004). Depending on the preparation technique used by the industry, tack coats can be categorized into different types as conventional asphalt binders, asphalt emulsions, and cutback asphalt binders. Among all the three classes of tack coats, asphalt emulsions have become more popular due to less 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 that of emulsified tack coats (Ozer and Rivera-Perez, 2017).

In general, an asphalt emulsion consists of an asphalt binder, water, and an emulsifying agent. In recent years, there is a trend of using some polymer additives to improve tack coats' properties. Depending on the emulsifying agent, two types of tack coats namely, anionic and cationic tack coats are produced. The charge of the emulsifying agent is responsible for the charge of the tack coat. Anionic tack coats are produced by negatively charged emulsifying agents while the cationic ones are produced by positively charged emulsifying agents.

In the nomenclature of tack coats, the cationic ones are identified with the letter "C" (e.g., CSS-1h, CSS-1, CRS-2P, etc.) and ones that lack the letter "C" are the anionic emulsions (e.g., SS-1, SS-1h, SS-h, etc.). The letter “h” in the label of a tack coat denotes a hard grade asphalt having a low penetration. In the classification of the tack coat emulsion material, number 1 indicates a low viscosity while number 2 means a high viscosity material. A highly viscous material will contribute to producing a strong bond (California Department of Transportation, 2009). For example, tack coat emulsion CRS-1 was shown to have a higher bond strength than CRS-2 emulsion (Panda et al., 2013). However, having a highly viscous emulsifying material doesn't always result in a high strength bonds in presence of unwanted fine particles (Kulkarni et al., 2005).

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) (California Department of Transportation, 2009). Commonly-used slow setting tack coats are SS-1, SS-1h, CSS, and CSS-1h. Also, common 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 are QS-1, QS-1h, CQS-1, and CQS-1h (Harder, 2016). Moreover, there are latex-modified (LM) and polymer-modified (PM) tack coat emulsions available in the market. Trackless tack coats as 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 (Rorrer et al. 2012).

Every tack coat emulsion has a certain breaking time and a setting time. The color change of the emulsion from brown to black indicates the breaking of a tack coat emulsion. Breaking of a tack coat is the separation of the water from the tack coat emulsion (Mohammad et al., 2012). Setting time is the time needed for water to entirely evaporate 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 the weather condition including wind speed, solar radiation, temperature, and humidity were factors affecting the breaking time of a tack coat. Regardless of the condition and tack coat type, low application rate was found to result in a short breaking time. Also, low temperature and no solar radiation was found to lead to low workability which highlighted the problems associated with the application tack coats at night.

2.1.2 Effect of Tack Coat Properties on Interlayer Strength

Asphalt rheology is the study of flow and deformation of the asphalt materials (Attoh-Okine et al., 2016). Since the asphalt binders constitute the adhesive agent present in tack coat emulsions, the rheological properties of the asphalt binder present in tack coat has a major effect on its properties. Therefore, the rheology is an important parameter to consider in characterization of tack coats and their mechanical properties (Marcado and Fuentes, 2017). Covey et al. (2017) has suggested the use of non-destructive tests for the evaluation of tack coat materials based on their simple rheological properties. Also, correlations were developed between the rheological properties and the interlayer shear strength (ISS) values due to use of tack coat emulsions (i.e., slow-setting grade emulsion, CSS-1H, new-engineered emulsions). Covey et al. (2017) concluded that linear relationships exist between the rheological properties (i.e., rotational viscosity, penetration, softening point) and the ISS values. Karshenas (2015) and Wilson et al. (2016) concluded that type of tack coat has a significant effect on interlayer bond strength.

Mohammad et al. (2012) reported that an increase in viscosity of the tack coat emulsion resulted in an increase in tensile strength of tack coat. Also, an increase in the binder’s softening point was found to be correlated to the maximum tensile strength. Furthermore, bond strength was found to increase with an increase in the application rate, temperature, and viscosity. An increase of temperature caused a reduction of the shear strength. Tack coat emulsions with low viscosities exhibited a higher bond strength than tack coat emulsions having a 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 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). The tack coat having a harder residue has shown a high bond strength than the those having a soft bitumen (Destrée and Visscher, 2017).

Raab et al. (2015) reported aging to improve the interlayer bond strength with and without 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 the tack coat performance. Also, intrinsic factors such as tack coat type, tack coat application rate, curing time, aging of the asphalt surface, application condition, the effect of temperature, mix type, and surface texture were identified as major factors affecting the ISS values.

Cho et al. (2017) evaluated the possibilities of debonding at the surface of interlayers in asphalt pavements using a computational method. A special computer software, Layered Visco-Elastic Pavement analysis for Critical Distresses (LVECD), was used to understand the critical stresses that lead for debonding of flexible pavement layers. Also, the mechanism that these stresses get affected by the design parameters and environment were revealed from this analysis. Further, a 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. The use of LVECD was found to be an easy, economically efficient, and quick method for the proper selection of tack coat materials.

2.1.3 Effect of Surface Texture on Interlayer Strength

Sometimes pavement construction is an entirely new project which allows the tack coat to bind to two new HMA surfaces. In asphalt overlay projects, tack coat should bind an aged and worn or a milled surface to a new HMA layer. Also, due to its economic feasibility, use of the HMA overlay on PCC surfaces is popular. The pavement surface texture is known to affect the measured ISS values (Covey et al., 2017). Milled HMA surfaces provided the highest ISS values followed by PCC, old HMA, and new HMA surfaces (Mohammad et al., 2012, Raposeiras et al., 2013), concluded that bond strength was increased when the surface roughness was increased. A strong correlation between the surface texture and interlayer shear strength was found to exist (Coleri et al., 2017).

Milled surface is one of the most common surface types in overlay projects. However, the effect of presence of the tack coats on the ISS values in the milled sections was found to be insignificant while, it was it was highly significant for non-milled sections (Tashman et al., 2008, McGhee and Clark, 2009).

Raposeiras et al. (2016) reported that the surface macro-texture is one of the influential factors affecting the measured ISS values. It was found that the aggregate particles larger than 8 mm have the highest contribution to shear strength when they were used at a rate between 40 % and 50%. However, it has been reported in other studies that the surface texture is not an influential factor affecting the ISS value (Destrée and Visscher, 2017). Also, it was reported that surfaces with higher macro-texture values showed high potential of absorbing emulsion (Raposeiras et al., 2013).

In a different study, Ziari et al. (2007) showed that interface condition can affect the stresses and strains in the interlayer. Also, it was concluded that absence of tack coat in between binder course and base course resulted in a more negative impact on the strain level than that measured in between two binder courses. Chen (2009) 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. Cored samples from simulated slabs were used for testing. The upper layer and bottom layer of the simulated pavement were constructed using three different layer types, namely Dense Graded Asphalt concrete (DGAC), gap graded asphalt concrete, 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 namely, K-value (interlayer tangential reaction modulus), peak shear, and residual shear were evaluated to find the mechanical behavior of tested samples. 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 are the main factors affecting shear strength. It was concluded that, the surface characteristics and tack coat type are main factors, affecting the optimum application rates.

In a different study Mohammad et al. (2010) found that the use of 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 bond by tack coats in a pavement including few application practices. Factors, namely surface treatment type (milled vs. non-milled), curing time, residual application rates (0.00, 0.018, 0.048, 0.072 gal/m^2), the location of the test (wheel path and middle of the lane) were considered in that study. It was concluded that the milled pavement sections exhibited a higher shear strength compared to non-milled sections. For the milled surfaces, the presence of the tack coat was not an advantage 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 the fact that absence of tack coat could negatively affect the bond strength of non-milled sections. The most important finding from the pull-off test was non-milled section had a higher pull-off strength value than that of the milled section.

The variation of ISS value with time between an HMA overlay and existing pavement layer of was evaluated by Das et al. (2017). The layer type, type of tack coat, and application rate of the tack coat were considered. Interlayer Shear Strength was measured with using Louisiana Interlayer Shear Strength Tester (LISST) test. Short-term performance evaluation was carried out after conducting the tests on the cores extracted from the pavement shortly after construction. The SS-1, SS -1h, NTSS-1hM, and CBC-1h were the evaluated tack coats. Results showed that with an increase in service time interface bond strength increased regardless of the surface type.

In another study, Al-Quadi et al. (2012) showed that for milled surfaces, the optimum residual application rate was 0.06 gal/yd^2; while for new binder SMA layer, the optimum residual application rate was found to be 0.02 gal/yd^2.

2.2 CHARACTERIZATION OF INTERLAYER BOND STRENGTH

Various types of tests are used to evaluate 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 namely, shear strength tests, tensile strength tests, 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 the direct shear devices are the most commonly used method (Zaniewski et al., 2015). A number of test methods used for characterization of the tack coats in pavement interlayers are discussed in this section.

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

Shear Strength	Tensile Strength	Torsion Strength
Louisiana Interlayer Shear Strength Test (LISST)	Layer-Parallel Direct Shear (LPDS)	Torque Bond Test
Leutner Shear Test	Switzerland Pull-Off Test	
Louisiana Transportation Research Center (LTRC) Direct Shear Test	The ATacker™ Test	
Texas Transportation Institute (TTI) Torsional Shear Test	University of Texas at El Paso (UTEP) Pull - Off Test	
Florida Direct Shear 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

Louisiana Interlayer Shear Strength Tester (LISST) was developed in NCHRP Project 9-40 as a direct shear test (Mohammad et al., 2012). This test can be used for measuring the interlayer shear strength (Mohammad et al., 2012). The LISST device consists of a frame with one stationary and a moving part. 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 (0.1 in.) per minute. Specimen should be conditioned for 2 hours at the desired temperature before testing. The load actuator apply normal pressure up to 206.84 kPa (30 psi) on a 150-

mm diameter sample. Generally, a loading frame is used to provide the appropriate displacement to the shearing frame. The graph for interlayer shear stress vs. axial displacement is then developed to identify the ISS value. Figure 2.1 shows the main components of a LISST device (Mohammad et al., 2012).

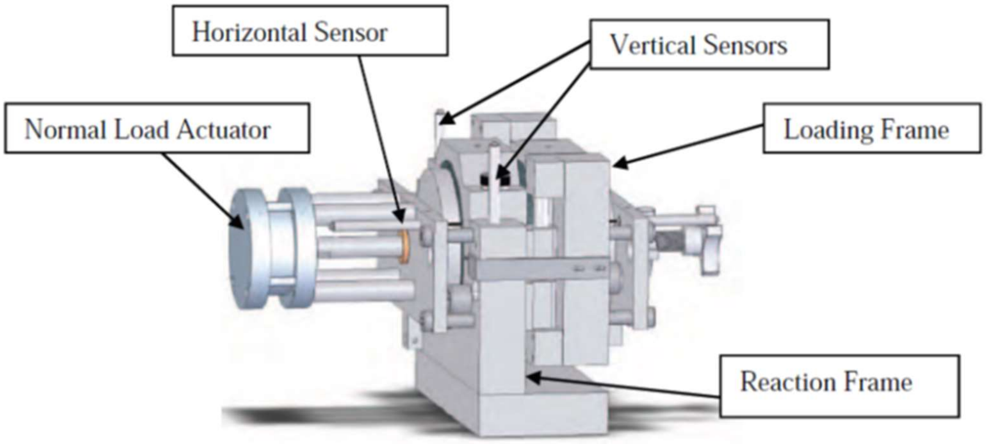


Figure 2.1 Components of Louisiana interlayer shear strength tester (Mohammad et al., 2012)

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 has a capability of applying a vertical load at a controlled deformation rate of (5±0.5 mm (0.2 ± 0.02 inch) per minute. The load cell should have a working range of 90.7 kg to 2268 kg (200 to 5,000 lbs.) with an accuracy of 1%. The sample should be placed inside the environmental chamber to condition at 25±1.1° C (77±2° F) for 2 hours before testing.

2.2.3 Ancona Shear Testing Research and Analysis Test

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 introduced this test (Canestrari and Santagata, 2004). To conduct ASTRA test a horizontal displacements is applied to top layer of the sample (Figure 2.2) while the horizontal displacement is increased at a constant rate. Also, a constant vertical load is applied to provide confinement. The whole setup is placed inside an environmental chamber while testing. Shear resistance is evaluated by measuring the maximum interface shear stress. This resistance is used to assess the tack coat's effectiveness in improving the ISS value. The test can be conducted on both field cores as well as laboratory-prepared samples.

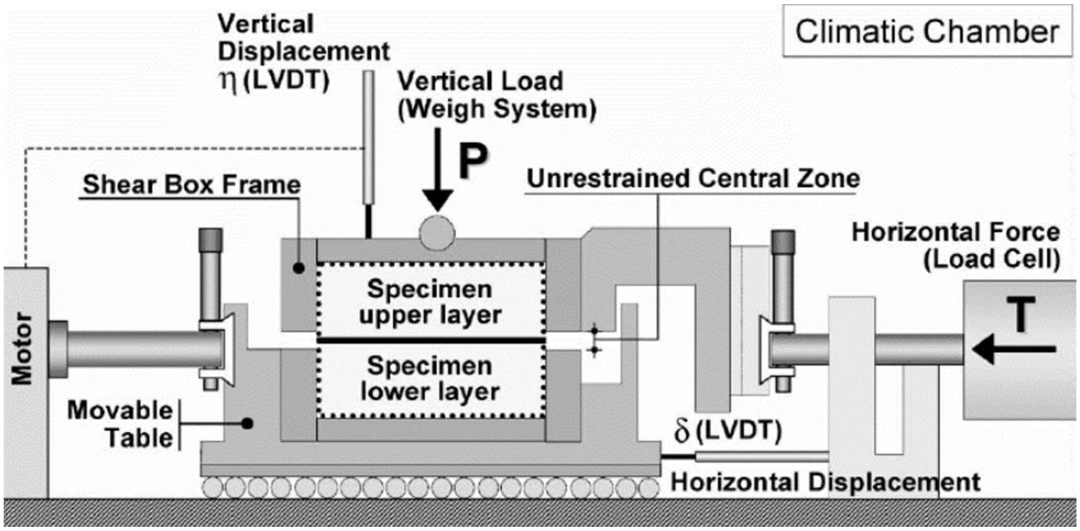


Figure 2.2 Ancona shear testing research and analysis test setup with major components of the device (Canestrari and Santagata, 2004)

2.2.4 University of Texas at El Paso Pull-off Test

UTEP Pull-Off Device (UPOD) was developed at the University of Texas at El Paso to evaluate the tensile strength of the interlayers treated with or without any tack coat. The UPOD has three pivoted feet and a plate which is used as a support. A torque a wrench is used to pull the plate up. The device used for UTEP pull-off test is shown in Figure 2.3 (Tashman et al., 2006).

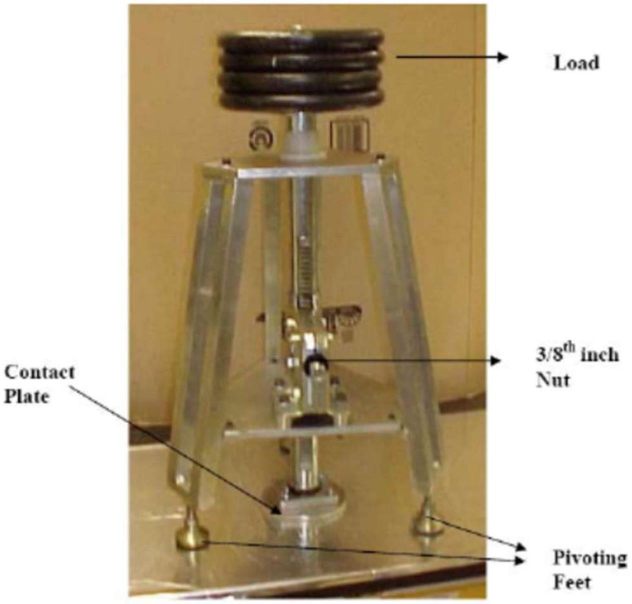
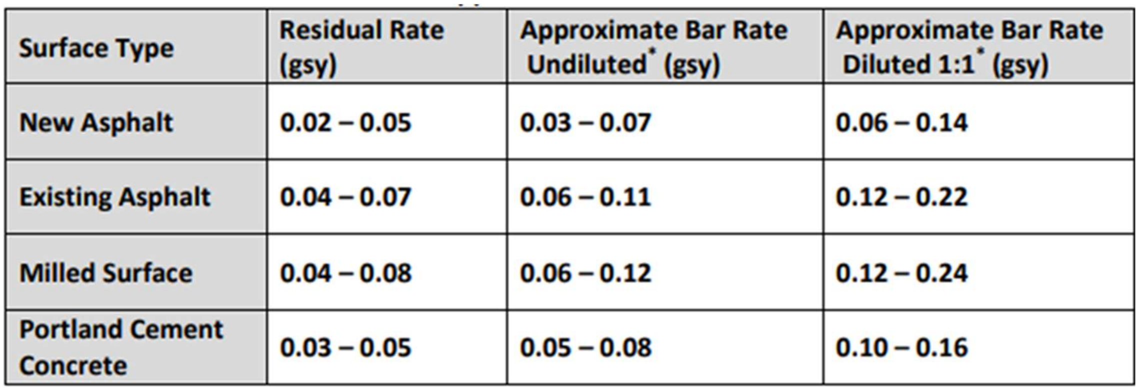


Figure 2.3 Main components of University of Texas at El Paso pull-off device (Tashman et al., 2006)

2.3 TACK COAT APPLICATION RATES

Tack coats are applied in various application rates according to available specifications. Researchers concluded the importance of tack coat application rate and tack coat type on pavement distresses (Ozer et al., 2012). Yet, decisions on application rates are made based on engineering judgements and are quite empirical and experience based. Hence, it is highly important to review typical application rates of different types of tack coat materials used in practice. Table 2.2 shows a number of typical application rates of tack coats according to the surface type (Tech Brief, 2016).

Table 2.2 Common application rates of tack coat as per surface type (Tech Brief, 2016)



Surface Type	Residual Rate (gsy)	Approximate Bar Rate Undiluted* (gsy)	Approximate Bar Rate Diluted 1:1* (gsy)
New Asphalt	0.02 – 0.05	0.03 – 0.07	0.06 – 0.14
Existing Asphalt	0.04 – 0.07	0.06 – 0.11	0.12 – 0.22
Milled Surface	0.04 – 0.08	0.06 – 0.12	0.12 – 0.24
Portland Cement Concrete	0.03 – 0.05	0.05 – 0.08	0.10 – 0.16

2.4 EFFECT OF ENVIRONMENT ON TACK COAT PERFORMANCE

Impact of the environment is an important factor that affects the performance of a tack coat. Temperature, moisture, freeze-thaw, and solar radiation are the main environmental factors affecting the quality of tack coat. The effect of environment on the performance of a tack coat has been studied by several researchers and temperature has been identified as the most significant factor affecting the interlayer shear strength (Ai et al., 2017; West et al., 2005). It was found that an increase in temperature resulted in a reduction interlayer shear strength for all surface types (Ai et al. 2017; Al-Qadi et al. 2012; Amelian and Kim 2017; Chen et al., 2010; Hu et al., 2016; Mohammad et al., 2012; Zhang 2017).

Also, Hu et al (2016) reported that at a higher temperature, the tack coats with high viscosities showed good shear strengths 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 but for higher temperatures, such possibility was not observed. Similar findings were reported by Mohammad et al. (2002), Recasens et al. (2003), and Canestrari et al. (2005), as well. In a different study, Bae et al. (2010) found that at testing temperatures higher than 40° C, the bond strength of trackless emulsion tack coats were higher than that of CRS-1 tack coat. Graziani et al. (2017), conducted research to identify the effect of test temperature and Interlayer Deformation Rate (IDR) on ISS of two layered-flexible pavements. A range of temperature (5° C to 40° C) was tested along with deformation rates at a range of 1 mm/min to 50 mm/min for both interlayers with and without any tack coat. Both test results revealed that ISS values increased high IDR. It was concluded that this was due to the time dependency behavior of bituminous materials.

Moisture is another major environmental factor affecting the ISS values. Zhang (2017) reported that moisture conditioning 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 factors which were considered as variables in this research. It was found that most of the tested samples showed no statistically significant difference in measured ISS values between the dry and moisture-conditioned samples. Similarly, Zaniewski et al. (2015) reported that moisture conditioning of the samples led to a reduction in bond strength.

2.5 PRACTICES USED FOR APPLICATION OF TACK COAT IN CONSTRUCTION

Zhang (2017) recommended a dry clean surface for applying a tack coat. Mealiff et al. (2017) and Raposeiras et al. (2013) reported that the surface cleanliness of a milled asphalt surface 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 can be achieved with a dusty condition than that in clean condition.

In general, a better compaction is known to result 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 104 to 105 loading cycles. Interlayer bond strength is known to be affected by tack coat setting time (Zaniewski et al., 2015). However, it was reported that overlay exhibited a better tensile bond with the existing pavement layer when it was immediately placed after tack coat application compared to that measured 2 hours after application of tack coat (Hakimzadeh et al., 2012).

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

Salinas et al. (2013) reported that the optimum residual application rates for milled HMA surface and new HMA surface were found as 0.06 gal/yd^2 (0.27 L/m^2) and 0.02 gal/yd^2 (0.09 L/m^2), respectively. SS-1hP tack coat exhibited a better bond compared to that measured for SS-1h. 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 spray paver was found to be a cost-effective method.

Both application methods evaluated yielded similar ISS values. Hence, for a project with a larger scale, SS-1h and SS-1hP were found to be cost-effective when applied using spray method.

2.6 TACK COAT SHEAR FAILURE MODES

Destrée and Visscher (2017) classified the shear failure modes of the interface using a visual assessment method. Failure mode classification is described in Figure 2.4 and Table 2.3.

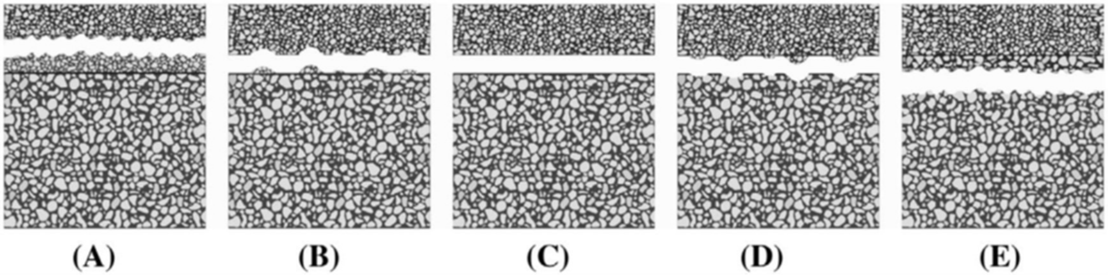


Figure 2.4 Different types of the inter layer failure modes (Destrée and Visscher, 2017)

Table 2.3 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

2.7 IMPORTANT RECENT DEVELOPMENTS AND RELEVANT FINDINGS

Polymer-modified tack coat material is one of the new types of tack coats used by the pavement industry. It was found that the polymer-modified tack coat increased the resistance of the asphalt pavement against cracking and rutting at the same time without changing the friction and noise (Birgisson et al., 2006; Hakimxadeh et al., 2012). However, trackless tack coats have lower resistance to top-down cracking compared to CRS-1 (Chen et al., 2012). In a study where three tack coat types, namely styrene–butadiene–styrene-modified asphalt, emulsified asphalt, and epoxy resin were evaluated it was found that epoxy resin has the highest fatigue performance compared to other two tack coat types (Li and Yu 2013). In another study, Tran et al. (2013) reported that a heavier tack coat performs better than regular tack coat in between Open-Graded Friction Course (OFGC) and underlay.

Hou et al. (2018) evaluated the shear strength, track resistance, pull-off strength, and rheological properties for a new Trackless Tack Coat Material (TTCM). The results revealed that the TTCM tack coat improved the shear strength by 69% compared to that of base asphalt at 20° C and the material became trackless in 1 minute after application. There was no report of tire deterioration upon the contact with TTCM at 60° C. Viscosity of TTCM was found to increase after cooling material, which led to a better bond between layers. The new material exhibited a higher thermal stability compared to base asphalt. Recasens et al. (2003) Reported that polymer-modified emulsions exhibited a better performance than regular tack coat materials. For fewer air voids, the adhesion was found to be higher than the samples with higher air voids.

CHAPTER THREE: MATERIALS AND METHODS

3.1 INTRODUCTION

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 in between the two layers. The top layer of the samples was prepared using one type of an asphalt mix with a Nominal Maximum Aggregate Size (NMAS) of 12.5 mm while three types of the asphalt bottom layers namely, new HMA, aged and worn HMA, and milled HMA were prepared using a mix with a NMAS = 19.0 mm and one type of PCC bottom layer which was 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 LISST test and determine the interlayer shear strength of the samples with different tack coat type, application rate and surface texture; (vi) determine the optimum application rate of each tack coat on all types 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 a 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 surface type was determined by conducting LISST tests in dry condition on samples prepared with each surface type with 3 residual application rates, namely 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	x	x	x	x
	CSS-1h	0.140	x	x	x	x
		0.281	x	x	x	x
		0.702	x	x	x	x
	CRS-2P	0.140	x	x	x	x
		0.281	x	x	x	x
		0.702	x	x	x	x
	SS-h	0.140	x	x	x	x
		0.281	x	x	x	x
		0.702	x	x	x	x
Moisture-Conditioned	No Tack Coat	0	x	x	x	x
	CSS-1h	OTAR	x	x	x	x
	CRS-2P	OTAR	x	x	x	x
	SS-h	OTAR	x	x	x	x

*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 (SDSU)'s 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 Nominal Maximum Aggregate Size (NMAS) of 12.5 mm. The combined aggregate structure and particle size distribution is shown in in Figure 3.2. Approximately, 800 kg of BL-HMA mix was collected. Figure 3.1 shows a photographic view of the research team's efforts for collection of BL-HMA, on October 19. 2017.

Figure 3.1 Research team collecting BL-HMA mix

Asphalt mix required to compact top layer of the samples was collected from “I-90” interstate resurfacing project from Border States Paving Inc. near Brandon, SD. Approximately, 1000 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 a NMAS = 12.5 mm. The combined aggregate structure and particle size distribution of the TL-HMA is shown in in Figure 3.2. The collected mix was classified as a Q5 mix, as per South Dakota DOT’s mix classification system.

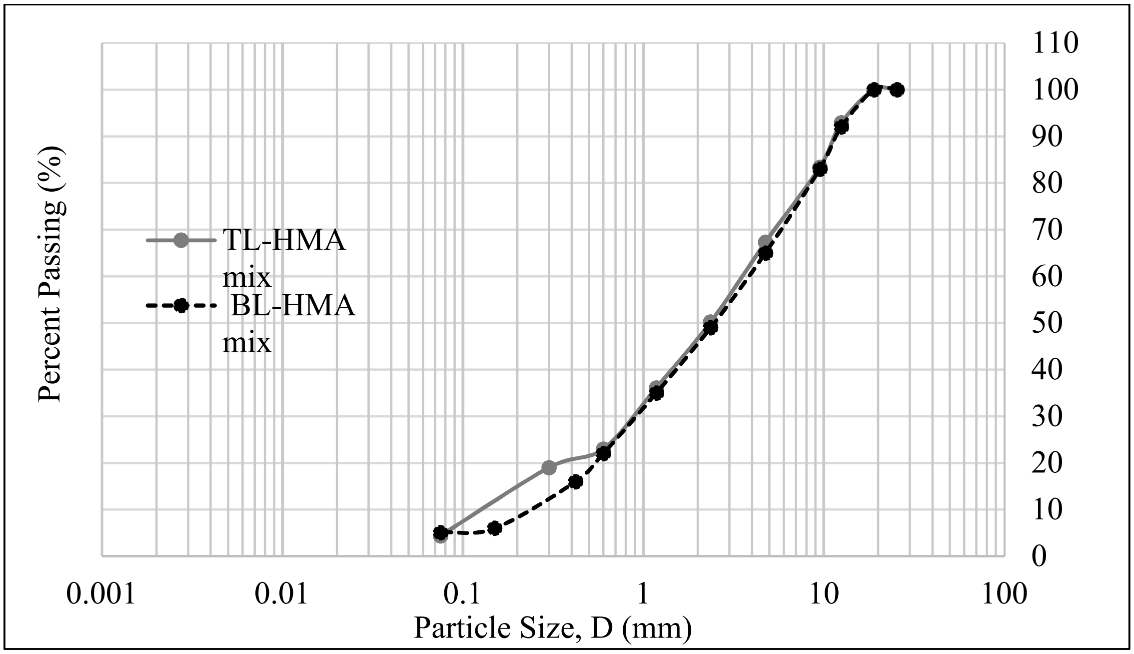


Figure 3.2 Particle size distribution curves for BL-HMA and TL-HMA mixes

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

Material required to prepare grooved PCC bottom layers, as well as concrete mix design sheets used for construction of rigid pavements were collected from GCC ready-mix plant at Brookings, SD. The concrete mixes produced by GCC are commonly used for 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, namely, 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. Effect of each tack coat applied with different application rates on interlayer shear strength was compared with that of the samples prepared without applying tack coats. Each type of the abovementioned tack coats and their properties were discussed in section 2.1.1 of Chapter 2. All of the tack coats were received in asphalt laboratory and kept in airtight solid dark containers for further evaluation.

3.3 DETERMINATION OF THE PERCENT RESIDUE OF TACK COATS

The percent residue of the tack coats was determined in the laboratory in accordance with the ASTM D6934-08 standard test method (ASTM, 2016). For this purpose, tack coat emulsion was shaken and then agitated using a wire rod. Two sets of beakers and mixing rods were selected and carefully weighed. Then, 50 g of the tack coat emulsion was poured in 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 2 hours. Then, the contents of the beakers were mixed using the mixing rod and were returned and kept inside the oven at 163° C for another hour. Finally, the weight of the residue, beaker, and rod 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 beaker, rod and residue and the percent residue was calculated accordingly. Average percent residue value of 2 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 having of 60 mm thickness and 150 mm diameter, each. Prior to compaction of double-layered samples, trial samples were compacted and 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 the weight of each sample to achieve 7.0% ± 0.5 % air voids. The 7.0% ± 0.5% air voids represent the field condition and simulates the air voids after construction and compaction of an actual pavement. To obtain 7.0% ± 0.5% target air voids, 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 a SGC in height mode. Sample height was set to 60 mm and a SGC mold with an inner diameter of 150 mm was used. Theoretically, each sample has a volume of $6 \times \pi \times (15/2)^2 = 1060.29 \text{ cm}^3$. The volume was multiplied by the percent density and the Theoretical Maximum Specific Gravity (G_{mm}) to obtain the trial weight of each sample. The G_{mm} values indicated in each mix design sheet were initially used for calculation of 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 Rice test as per AASHTO T209 test (AASHTO, 2012) 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

To prepare the cylindrical samples, the SGC molds, chute, trays, and scoops were pre-heated at 165° C in an oven. Asphalt mix was heated in the oven at 165° C for 1 hour in a tray as shown in Figure 3.3. After the first 30 minutes asphalt mix was mixed using metal scoops. Then, mix was heated for another 20 minutes while mixed in every 10 minutes to a uniform consistency. The required weight of the heated mix was placed inside SGC chute and was returned inside 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 and transferred on top of a scale and tared, as shown in Figure3.4. Asphalt mix inside the chute was again mixed with using a scoop and was carefully placed inside the mold while adjusting the weight. Then desired asphalt mix weight inside the mold was checked for the second time. Then the top surface of the asphalt mix inside the mold was leveled using a spatula as shown in Figure 3.5. Then, a circular paper disc was placed on top of the leveled surface and the lid of the mold was placed on top of it. Mold was then placed inside the Superpave® gyratory compactor as shown in Figure 3.6 and compaction process was initiated in fixed height mode (60 mm). After compaction was complete, the sample was partially extracted and was kept at room temperature for 15 minutes, before extraction, as shown in Figure 3.7. Then the sample was transferred to a level surface, as shown in Figure 3.8.

Figure 3.3 Heating the asphalt mix inside an oven at 165° C

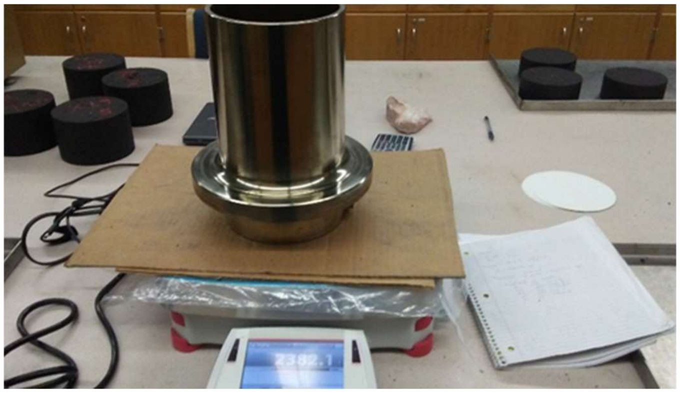


Figure 3.4 Weighing the asphalt mix inside the mold

Figure 3.5 Leveling the surface of asphalt mix inside the mold

Figure 3.6 Compaction of sample using Superpave® gyratory compactor

Figure 3.7 Partially-extruded sample

Figure 3.8 Sample after removing 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 result in cylindrical samples of 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 BL-HMA mix using a SGC operated at height mode (h = 60 mm) following the sample preparation procedure described in section 3.3.1. 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 procedure described in section 3.3.2 were used to prepare the aged and worn bottom layer samples. Aforementioned samples were polished and aged to simulate a worn and aged pavement surface. A circular 80-grit sand paper mounted on a 125 mm random orbital sander disc was used to polish the surface of the sample. The sander was operated at a constant speed for 1 minute to evenly polish the surface of the samples. After the first minute surface was brushed, and dust was cleaned. Additional care was given to polish the surface evenly, and then the sample was polished for another 1 minute. Figure 3.9 shows the surfaces of a polished (right) and an unpolished for comparison purpose. Polished samples were placed inside the oven at a temperature of 85°C for 120 hours (5 days) for aging. This oven aging represents and aging equivalent to 5 to 7 years of in-service oxidative aging of asphalt mix.

Figure 3.9 Unpolished surface on the left and polished surface on the right.

3.4.4 Milled HMA Bottom Layer Sample

Milled HMA surfaces were simulated in the laboratory by creating the milling pattern on the surface of the HMA sample as described by Zaniewski et al. (2015). Unaged HMA bottom layers compacted using BL-HMA mix were used for this purpose. The effect of milling was then simulated first by marking a grid pattern on top of the sample (Figure 3.10) and then cutting through the marked area using a wet rock saw following the method suggested by Zaniewski et al. (2015). Figure 3.11 shows the final simulated milled surface. Samples were dried in an oven at 60° C for 24 hours prior to application of tack coats.

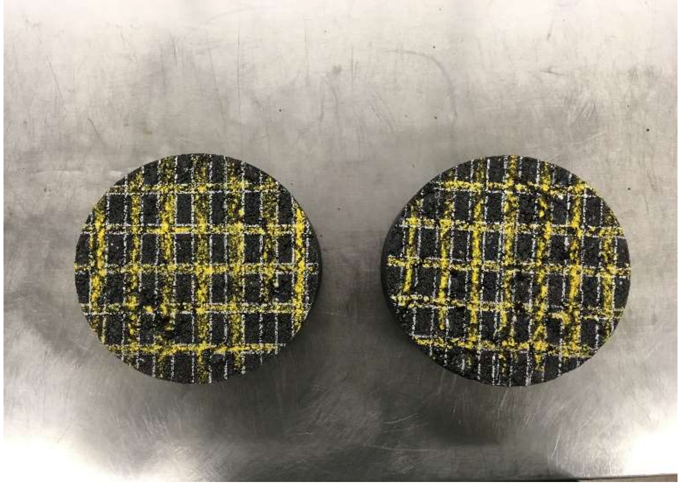


Figure 3.10 Marked milling pattern

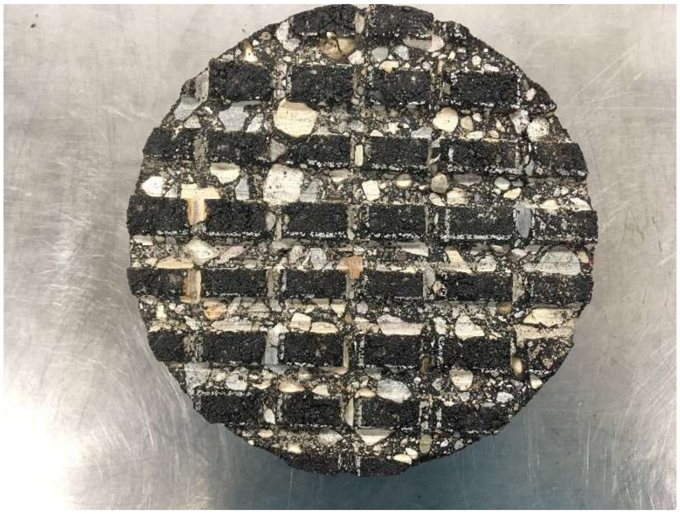


Figure 3.11 Simulated milled surface

3.4.5 PCC Bottom Layer

PCC bottom layers were prepared first by mixing concrete in the laboratory by following the mix design sheet (Table 3.3) using the concrete materials collected from a batch plant. Concrete mixing was conducted by using a concrete mixer in the concrete lab. A standard cylindrical plastic mold having a diameter of 150 mm was modified to have an inner height of 60 mm. Also, the inner diameter of the mold was reduced by 1.5 mm by inserting 2 layers of plastic strips as mold lining. This practice ensured the prepared PCC sample to fit inside the SGC mold. The prepared concrete was poured in 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 concrete was poured and compacted inside the mold, it was left for 3 hours before creating the groove pattern on top of the sample. Grooving was carried out using a device fabricated in the laboratory, consisted of nails having a diameter of 2 mm attached to a wooden straight edge having spacing of 20 mm. Groove depth was 2 - 4mm. Figure 3.12 shows a grooved PCC bottom layer sample. Samples were kept inside the mold overnight and then transferred to environmentally-controlled humidity room and kept for 7 days to cure. Samples were dried in an oven at 60° C for 24 hours prior to application of tack coats.

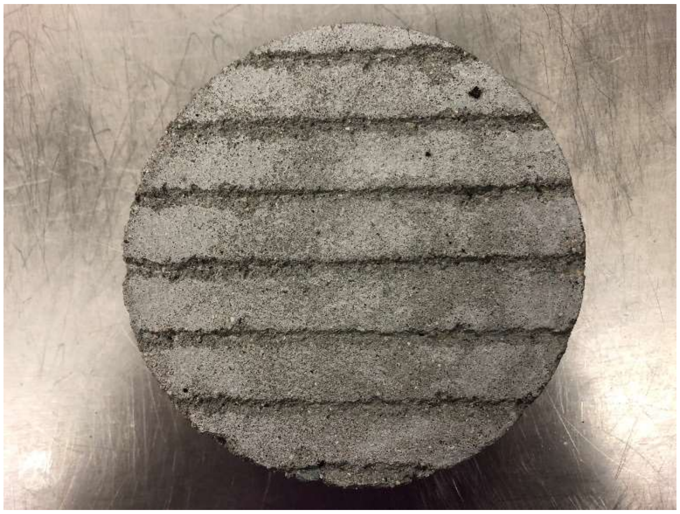


Figure 3.12 Grooved PCC bottom layer sample

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 2 hours before applying tack coat. This period simulated a sun-warmed surface of the pavement. A brush was used for application of tack coat on the sample surface, as shown in Figure 3.13. 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 shook well before applying it to the bottom layer sample. After tack coat was evenly applied, a paint brush 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, namely 0.140, 0.281, and 0.702 L/m^2. Determination of percent residue of a tack coat is described in Section 3.4. Application amount of each tack coat to obtain the residual rates are shown in Table 3.4.

Figure 3.13 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
	0.281	63.5	7.9
	0.702	63.5	19.9

3.4.7 Tack Coat Breaking Time

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

Top layer of the samples were prepared by heating and compacting the TL-HMA mix using a SGC, as described in section 3.3.1. Prior to compaction of the top layer, tack coat applied on the bottom layer sample (if any) was let to break on applied surface. Then, the bottom layer sample was carefully placed inside the heated SGC mold and pushed all the way down in the mold. Then, the mold was placed on top of the scale and scale reading was noted. Asphalt mix with the weight determined in section 3.1.1 was placed inside the mold using a chute. Surface of the loose mix was leveled and a paper disc and top lid of the mold were carefully placed to cover the loose mix. 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 having a height of 120 mm and air vids of 7.0 ± 0.5% was pre-determined after compaction of trial samples.

3.4.9 Moisture Conditioning of the Compacted Samples

To study the effect of moisture on interlayer shear strength of different tack coat types, a number of samples were tested after moisture conditioning. For this purpose, a modified version of the standard moisture conditioning procedure as described in 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 8 minutes. Water level inside the container was adjusted to cover the full height of the specimen. Then, vacuum was released, and sample was kept inside the water for another 7 minutes before drying its surface using a damp towel. Then, it was wrapped and sealed using cling wrap. Wrapped sample along with 10 cc of water were placed inside another plastic bag and sealed after removing the excess air inside the bag. Sealed sample was then placed inside a freezer at -18° C for 16 hours. Then, the sample placed inside a water bath at 25° C, after removing the plastic wrap from the sample. Temperature of the water bath was continuously monitored and maintained at 25° C. Sample was kept inside the water bath for 4 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). Test was conducted as per the proposed standard method of test for determining the interlayer shear strength of asphalt pavement layers described in NCHRP report 712 (Mohammad et al., 2012) under AASHTO TP114 (AASHTO, 2017). The LISST device was fixed in a loading frame from Material Testing System (MTS). Laboratory-prepared double-layered samples were cured for 14 days and tested at 25°C. In order to ensure the sample's shear failure occurs at the interlayer, the boundary of two layers was marked. The marked area was adjusted to locate right in the middle of the gap between moving and stationary jaws of the LISST equipment. Laboratory setup of the LISST device fixed inside a MTS loading frame, and a close-up view of the LISST device and the actuator are shown in Figures 3.14 and 3.15, respectively. As shown in Figures 3.14 and 3.15, the load was applied loading frame's actuator in 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. Test was concluded and the procedure was stopped after the shear failure of the interlayer as shown Figure 3.16. 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 3.14 Test set-up of LISST test

Figure 3.15 Conducting LISST test

Figure 3.16 Failed sample

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 TRIAL SAMPLES

Trial samples were prepared to 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 were determined as per AASHTO T 166 (AASHTO, 2015) 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, variation 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 are also displayed on Figure 4.1 and Figure 4.2. The trend line equations were used to determine the weight of the loose mix needed to obtain a 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** (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
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** (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
AV***(%)	7.0	7.2	7.6	7.3	7.4	7.9	7.8	7.0

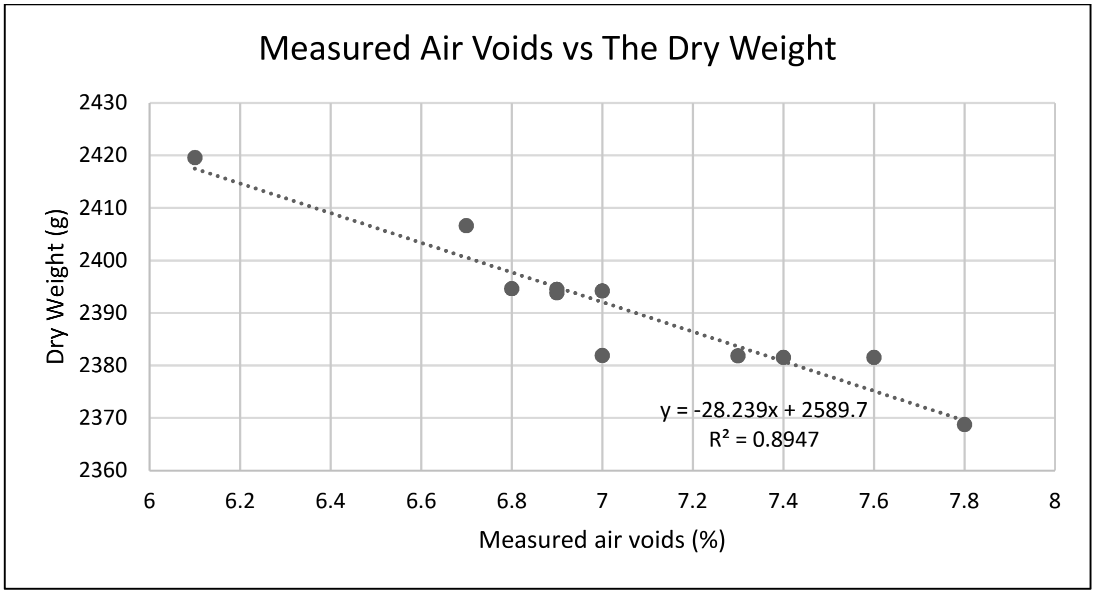


Figure 4.1 Measured air voids vs. dry weights for TL-HMA mix

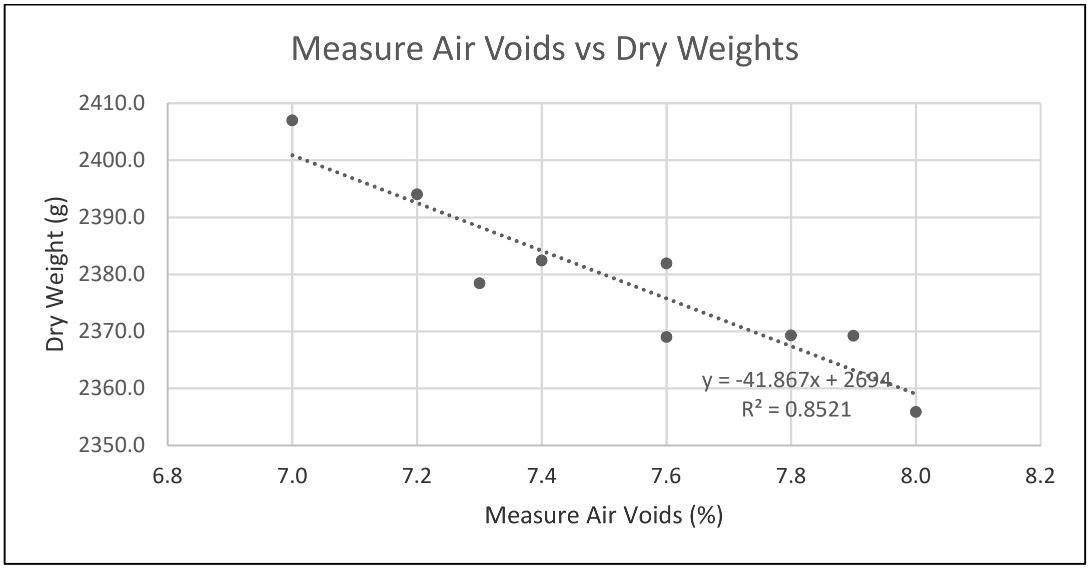


Figure 4.2 Measured air voids vs. dry weights for BL-HMA mix

4.2 PERCENT RESIDUE OF TACK COAT EMULSIONS

The percent residue of tack coat emulsions were 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, percent residue of tack coats CSS-1h, CRS-2P, and SS-h were 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 coats are less than 1% and 5%, respectively, indicating an acceptable test repeatability. From the percent residue values, the weight of tack coat emulsions needed to achieve 0.140, 0.281, 0.702 L/m^2 residue application rates on a sample of 150 mm diameter were calculated for all tack coats (CSS-1h, CRS-2P, and SS-h) and were presented in Table 3.4.

Table 4.3 Test results for the percent residue of tack coats

Set No.	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 LISST RESULTS

A typical graph showing the variations of the measured interlayer shear stress vs. axial displacements for a 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 up 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.

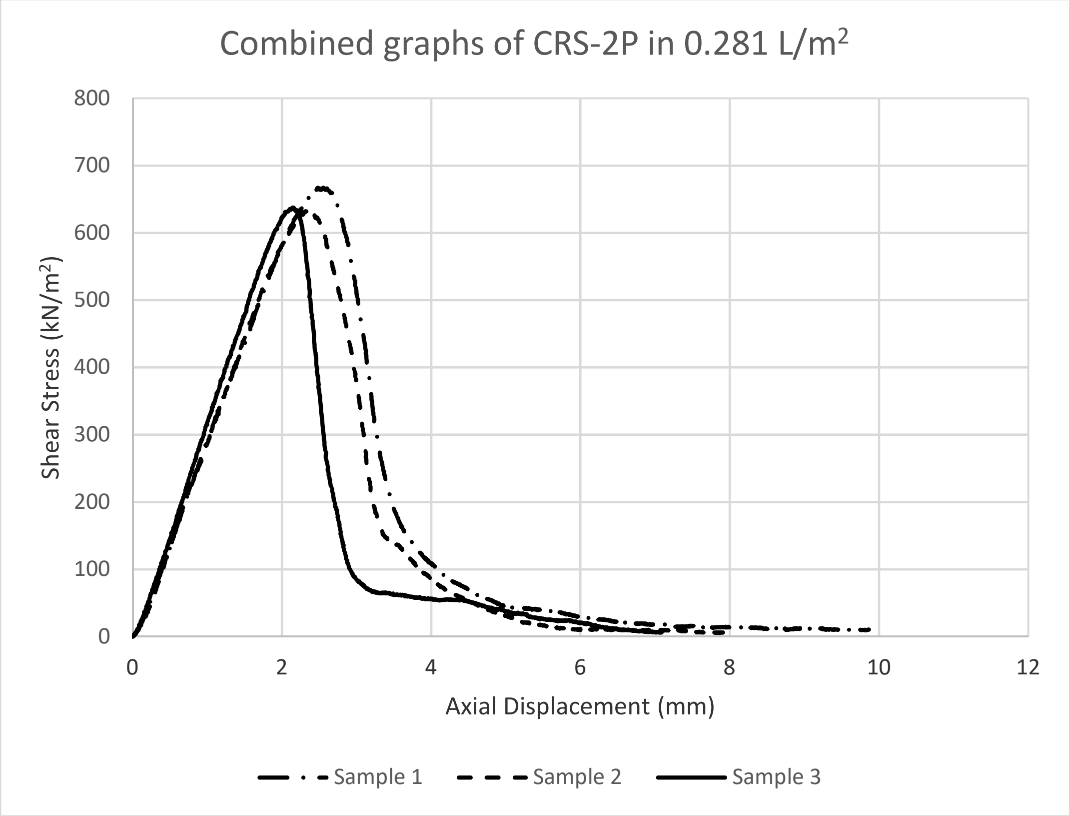


Figure 4.3 Typical LISST test results conducted on three replicate samples

Important statistical parameters, namely 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 repeatability of the LISST test recommend a maximum COV of 15% for measured ISS values (Al-Qadi et al., 2012 and 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. Interlayer shear strength values, a COV greater than 12% was considered maximum COV 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 INTERLAYER SHEAR STRENGTH VALUES

Effect of using 3 tack coat types, namely CRS-2P, CSS-1h, and SS-h applied at different rates, namely 0.140, 0.281, and 0.702 L/m^2 on different pavement surfaces were evaluated in this study. Also, samples prepared without application of tack coats were tested.

4.4.1 Samples Prepared with No Tack Coat

Interlayer shear strength (ISS) values obtained by conducting the LISST test on specimens prepared using four different types of bottom layer surfaces, namely new HMA, aged and worn HMA, milled HMA, and grooved PCC, without applying any tack coat, are shown in Figure 4.4. As shown in Figure 4.4, the highest ISS value for no tack coat application was observed in samples 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 to field cores. Specially, 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 milled HMA bottom surface. However, similar to the findings of the current study, Mohammad et al. (2012) reported that that the ISS values measured for laboratory-prepared specimens without applying any tack coat were, significantly higher than zero.

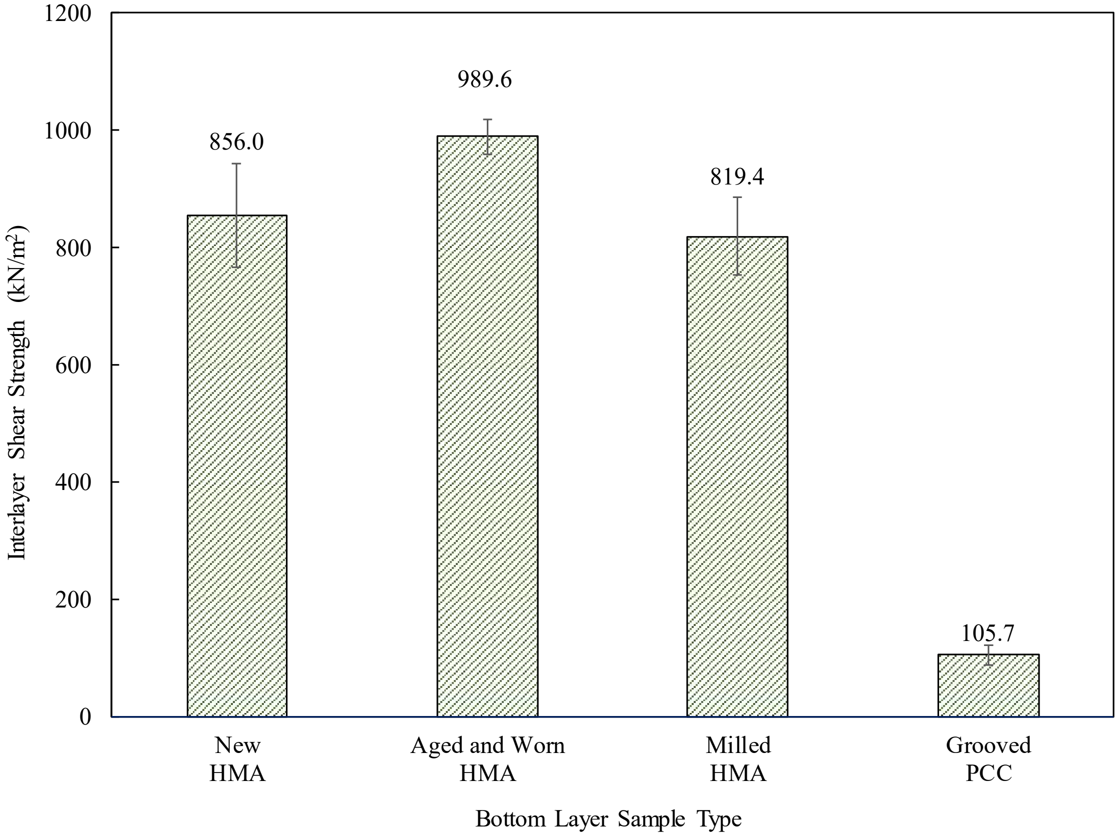


Figure 4.4 Interlayer shear strength of samples prepared by using different bottom layers without any tack coat

4.4.2 Samples Prepared with CRS-2P Tack Coat

Figure 4.5 presents the ISS values measured for samples prepared using CRS-2P 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 4.5, 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 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 having new HMA bottom layer and containing 0.140, 0.281, and 0.702 L/m^2 of CRS-2P tack coat in their interlayers were found to decrease by 27%, 30%, and 13%, respectively, compared to that 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 CRS-2P tack coat in their interlayers were found to decrease by 38%, 35%, and 7% compared to that of samples prepared without any tack coat in their interlayer. Likewise, the ISS values of the samples having milled HMA bottom layer and containing 0.140, 0.281, and 0.702 L/m^2 of CRS-2P tack coat in their interlayers were found to decrease by 6%, 11%, and 22% compared to that of samples prepared without any tack coat in their interlayer. All of these observations suggest that application of CRS-2P tack coat may result in a reduction in ISS values compared to that of samples containing no tack coat having HMA bottom layer with different surface textures. This overestimation of the ISS values in laboratory-prepared samples containing no tack coat compared to those compacted in the field was also reported by Mohammad et al. (2010). Although the application of tack coat was found to reduce the ISS values, different trends in ISS variations were observed for samples having new HMA, aged and worn HMA, and milled HMA as their bottom layers. In samples having new HMA and aged and worn HMA bottom layers, application of 0.140 and 0.281 L/m^2 of CRS-2P tack coat resulted in a reduction in ISS values. While the ISS values showed an improvement with further increasing the application rate (0.702 L/m^2). This was attributed to the fact that the binding agent was absorbed by the surface at low application rats and emulsifier and/or other ingredients of the tack coat interacted with interlayer, resulting a lubricating effect. However further increasing the tack coat application rate made more bonding agent available for adhesion even after absorption of a part of it by the sample surfaces. A similar observation was also reported by Amelian et al. (2017). It was found 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 (on polished textures) the measured ISS values were more sensitive to increase of CRS-2P tack coat application rate than that for samples having 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 layer were tested. This is an indication of the effect of the surface type on the ISS values measured for HMA samples. Mohammad et al. (2012) reported that, when the surface gets filled with any tack coat, surface texture or roughness has less contribution to ISS value.

In contrary, application of CRS-2P on the samples having grooved PCC bottom layers was found to effectively increase the ISS values compared to that of the samples prepared without any tack coat in their interlayer. From Figure 4.5 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 CRS-2P tack coat in their interlayers were found to increase by more than 3 times compared to that of samples prepared without any tack coat in their interlayer. Also, as shown in Figure 4.5, ISS values were not significantly affected by increasing the residual application rate of CRS-2P tack coat on specimens prepared with using grooved PCC bottom layers.

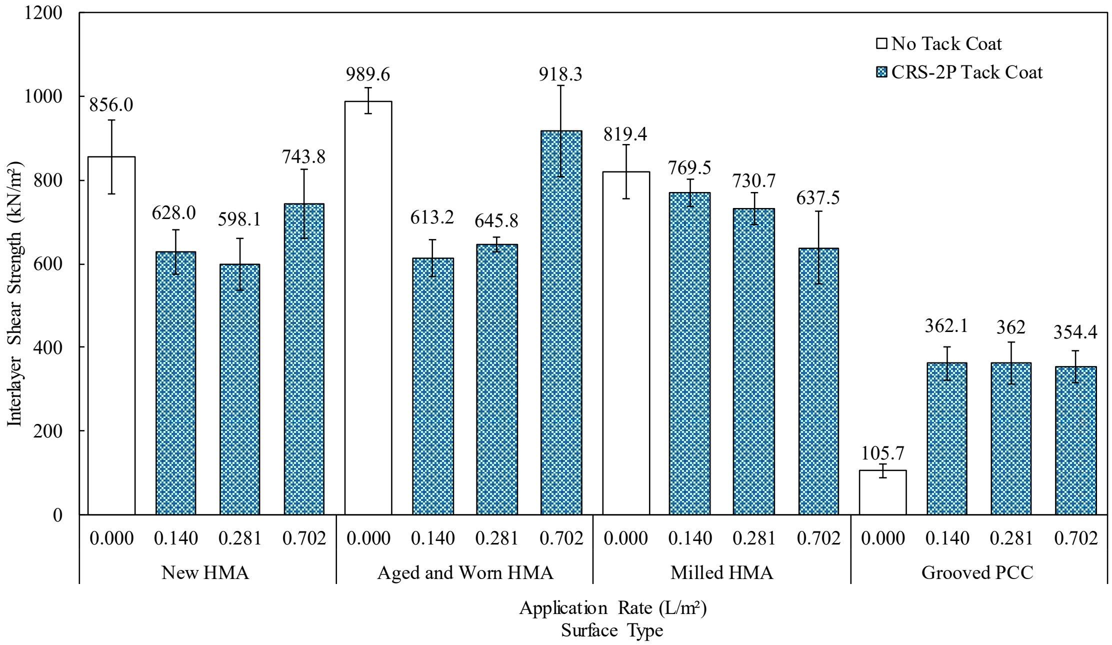


Figure 4.5 Interlayer shear strength values measured for samples having different bottom layers containing CRS-2P tack coat with different application rates

4.4.3 Samples Prepared with CSS-1h Tack Coat

Figure 4.6 presents the ISS values measured for samples prepared using CSS-1h 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 4.6, 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 new 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 1% and decrease by 5%, and 17%, respectively, compared to that 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 CSS-1h tack coat in their interlayers were found to increase by 3% and decrease by 8%, and 47%, respectively, compared to that of samples prepared without any tack coat in their interlayer. Likewise, the ISS values of the samples having milled 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 9%, and 6%, and decrease by 9%, respectively, compared to that of samples prepared without any tack coat in their interlayer. All of these observations suggest that 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 to that of samples containing no tack coat having 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 the fact that the CSS-1h was a cationic tack coat with a stiff base binder which has a less tendency to be absorbed by the surface. Therefore, the base binder can be present in interlayer and contribute to adhesion even at low and intermediate application rates. However, further increasing the application rate resulted in oversaturation of the interlayer with binder and emulsifier which resulted in lubricating effect and a reduced ISS value. This finding is consistent with those reported by Mohammad et al. (2012). Also, it is evident that for samples having aged and worn HMA as their bottom layers (on polished textures) the measured ISS values were more sensitive to excessive application of CSS-1h tack coat than that for samples having new HMA and milled HMA as their bottom layers (application of 0.702 L/m^2 tack coat resulted in a 47% reduction in ISS value compared to that of samples without any tack coat).

Unlike samples having HMA bottom layers, application of CSS-1h tack coat on the samples having grooved PCC bottom layers was found to effectively increase the ISS values compared to that of the samples prepared without any tack coat in their interlayer. 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 tack coat in their interlayers were found to increase by more than 3.4, 4.6 and 3.8 times compared to that of samples prepared without any tack coat in their interlayer. Also, as shown in Figure 4.6, the highest ISS value was measured (488.4 kPa) when the CSS-1h tack coat was applied on grooved PCC bottom sample at an application rate of 0.281 L/m^2.

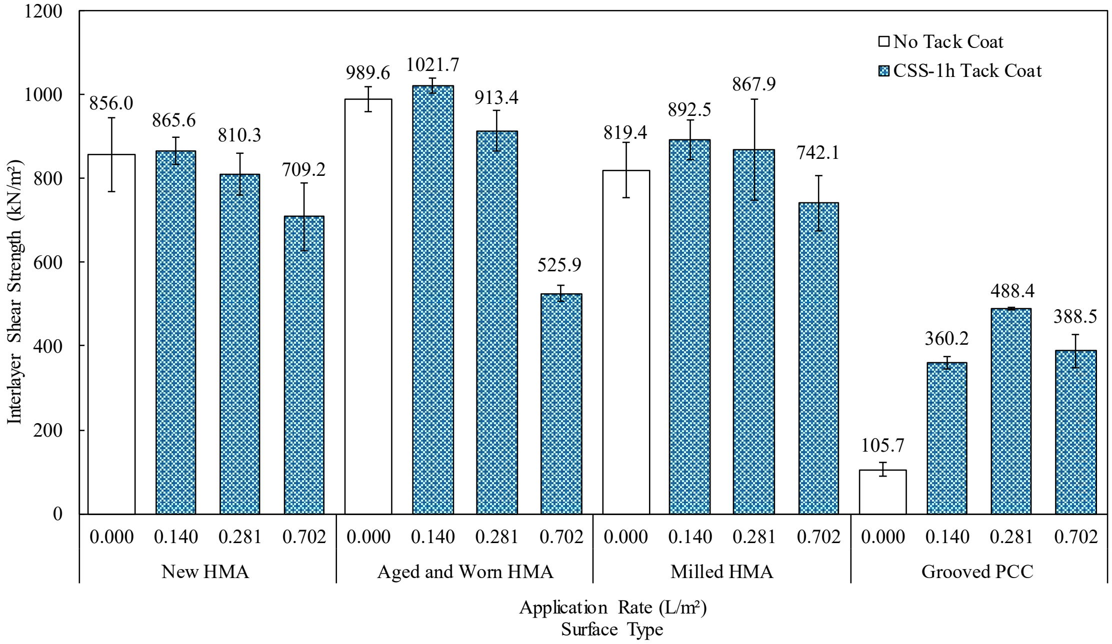


Figure 4. 6 Interlayer shear strength values measured for samples having different bottom layers containing CSS-1h tack coat with different application rates

4.4.4 Samples Prepared with 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 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 to that 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 to that 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 to that of samples 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 better ISS values compared to those 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 to 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 to that 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 to that 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 on grooved PCC bottom sample at an application rate of 0.140 L/m^2.

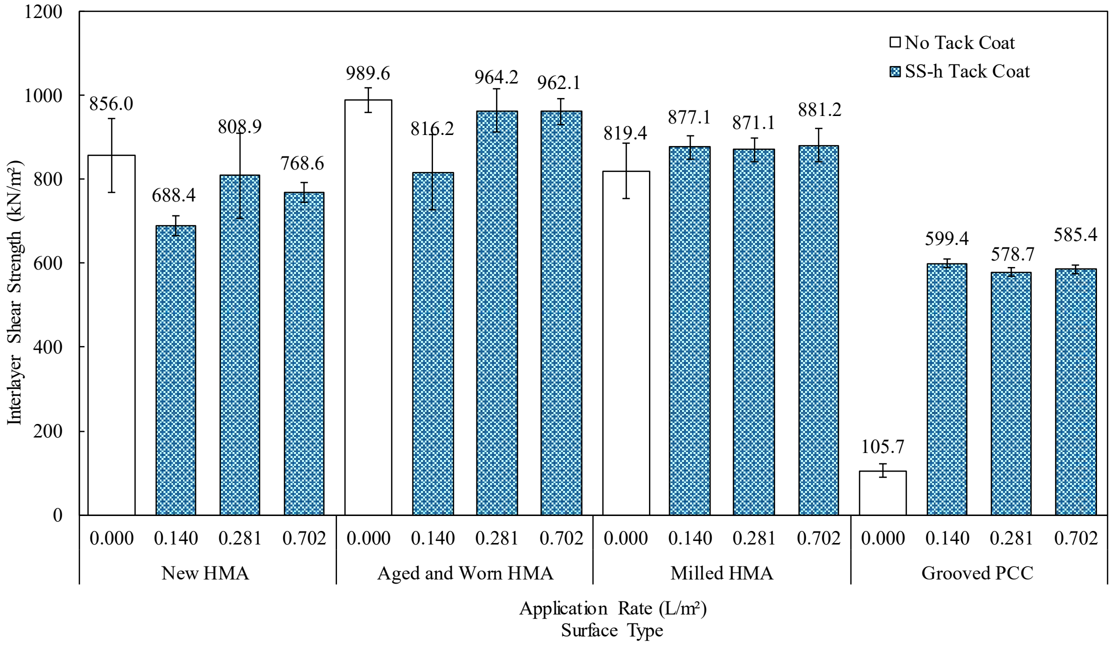


Figure 4.7 Interlayer shear strength values measured for samples having different bottom layers containing SS-h tack coat with different application rates

4.4.5 Summary

Among all the types of tack coats evaluated based on ISS values, CSS-1h tack coat showed the best general 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 with using PCC bottom layers, tack coat SS-h worked better compared to other tack coats. Highest ISS between PCC and HMA was observed when SS-h tack coat was used followed by CSS-1h, and CRS-2P. In general, it was observed that CRS-2P gives 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 is possible to conclude that CSS-1h tack coat can be successfully used on all types of the 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 which is more attracted to positively charged surfaces. It was interesting to see that SS-h tack coat showed higher performance on grooved PCC surfaces. Also, both cationic emulsions showed nearly similar performances on grooved PCC surface. This was attributed to polar attraction between SS-h tack coat emulsion and the surface of the PCC.

4.5 EFFECT OF BOTTOM LAYER SURFACE TYPE ON MEASURED INTERLAYER SHEAR STRENGTH VALUES

Depending on the type and the texture of the bottom layer sample, the ISS between two layers can vary. This is mainly due to friction and interlocking effects present in the interlayer and the tack coat absorption. In this section, a discussion based on the effect of the bottom layer type on the ISS values measured for different tack coats was presented.

4.5.1 Samples Prepared using New HMA Bottom Layer

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

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 medium (0.281 L/m^2) rates is recommended, respectively.

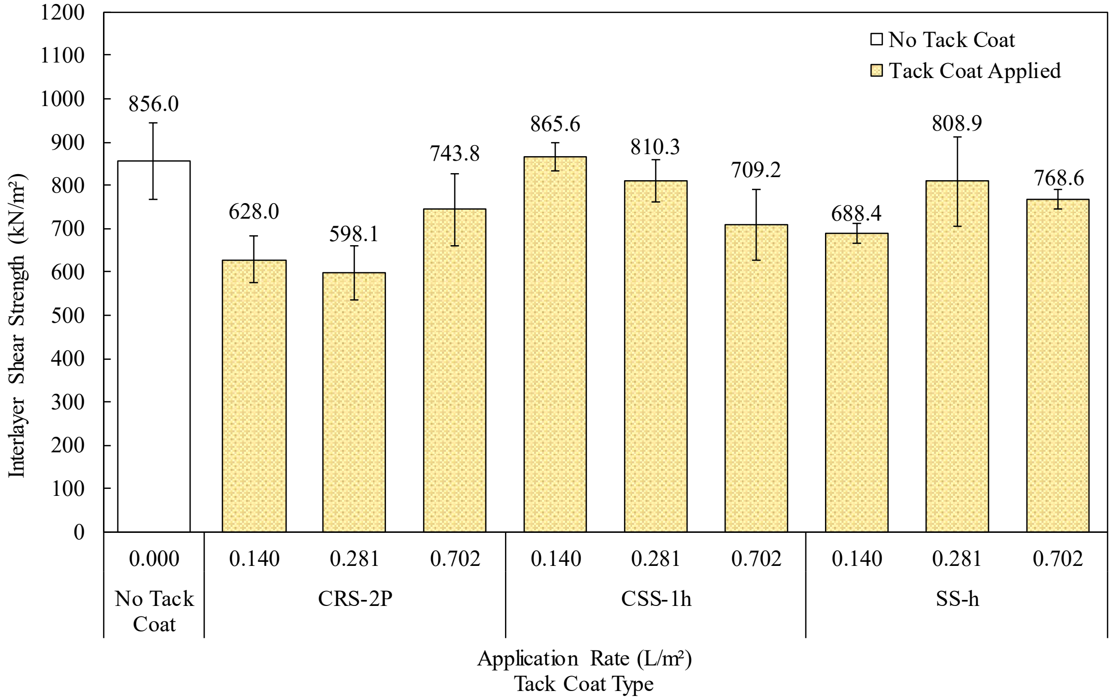


Figure 4.8 Interlayer shear strength values measured for samples having new HMA bottom layers containing CRS-2P, CSS-1h, and SS-h tack coats with different application rates

4.5.2 Samples Prepared using Aged and Worn HMA Bottom Layer

Aged and worn HMA bottom layers had the most polished and the smoothest surface texture among all of the tested surfaces. Figure 4.9 presents the ISS values measured for samples prepared using aged and worn HMA bottom layer containing no tack coat, CRS-2P, CSS-1h, and SS-h tack coats applied at 0.140, 0.281, and 0.702 L/m^2. From Figure 4.9 it is evident that, the samples prepared using aged and worn HMA bottom layers containing tack coat, in general exhibited lower ISS values compared to that of the sample containing no tack coat in its interlayer. Also, it was found that application of the CRS-2P, CSS-1h, and SS-h tack coats were 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 found to be the most effective tack coat in improving the ISS values compared to the specimens prepared without any tack coat. Hence 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 4.8 and Figure 4.9 reveals that, application of tack coat was more effective in improving the ISS values in specimens prepared using the aged and worn HMA bottom layer than that of the specimens prepared using new HMA bottom layer samples. This was attributed to the fact that aged and worn HMA bottom layers provide more surface available to bonding agent and than that of the new HMA bottom layer, which contributes to a higher ISS value. 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.

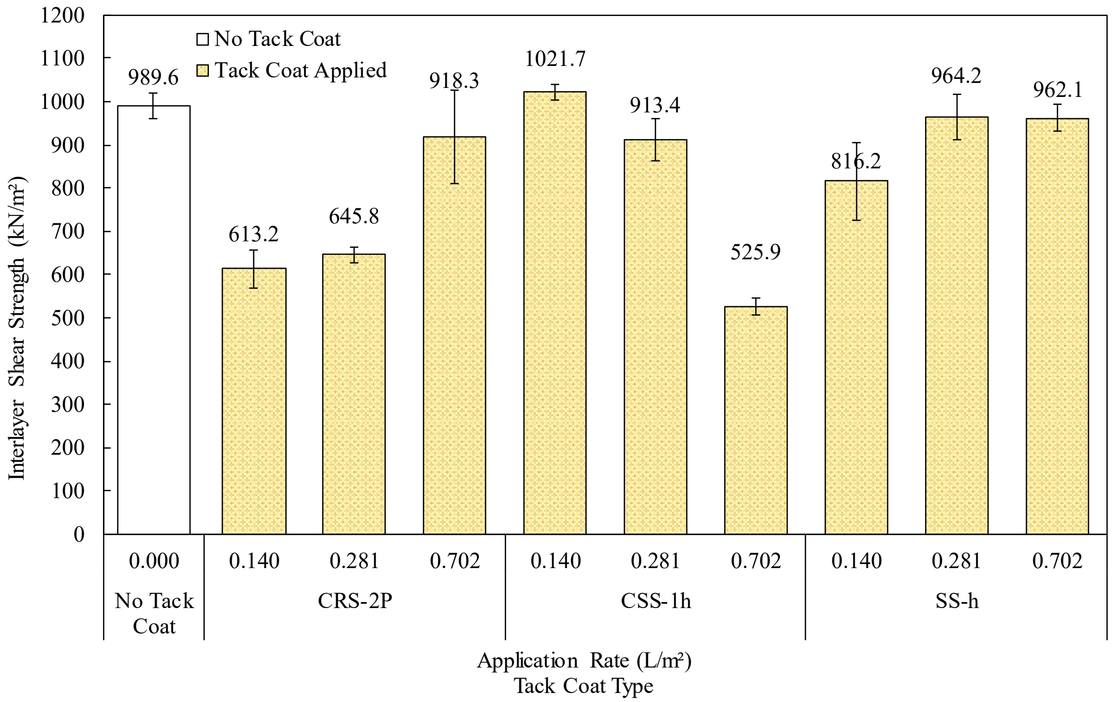


Figure 4.9 Interlayer shear strength values measured for samples having aged and worn HMA bottom layers containing CRS-2P, CSS-1h, and SS-h tack coats with different application rates

4.5.3 Samples Prepared using Milled HMA Bottom Layer

Specimens prepared using milled HMA bottom layers had the roughest texture of HMA bottom layer type among pavement surfaces tested in this study. Figure 4.10 presents the ISS values measured for samples prepared using milled HMA bottom layer containing no tack coat, and CRS-2P, CSS-1h, and SS-h tack coats applied at 0.140, 0.281, and 0.702 L/m^2. As shown in Figure 4.10, samples prepared using milled HMA bottom layer containing tack coat, in general, exhibited higher ISS values compared to that of the sample containing no tack coat in its interlayer (except for CRS-2P). Also, it was found that application of the CRS-2P, CSS-1h, and SS-h tack coats were 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 low application rate (0.140 L/m^2) effectively improved the interlayer shear strength by 9% and 7%, respectively, compared to that of samples without any tack coat. Also, it was observed that different application rates of SS-h tack coat did not have a significant effect on ISS values. Hence, one may recommend using CSS-1h and SS-h tack coats at 0.140 L/m^2 application rate.

Also, Figure 4.10 shows that the ISS values, in general, decreased with an increase in the application rate for samples containing CRS-2P and CSS-1h tack coats. Mainly, when the interlayer becomes saturated and excessive amount of tack coat is present, tack coat acts as a lubricant, resulting in a reduction in the ISS value. Mohammad et al. (2012) reported similar findings.

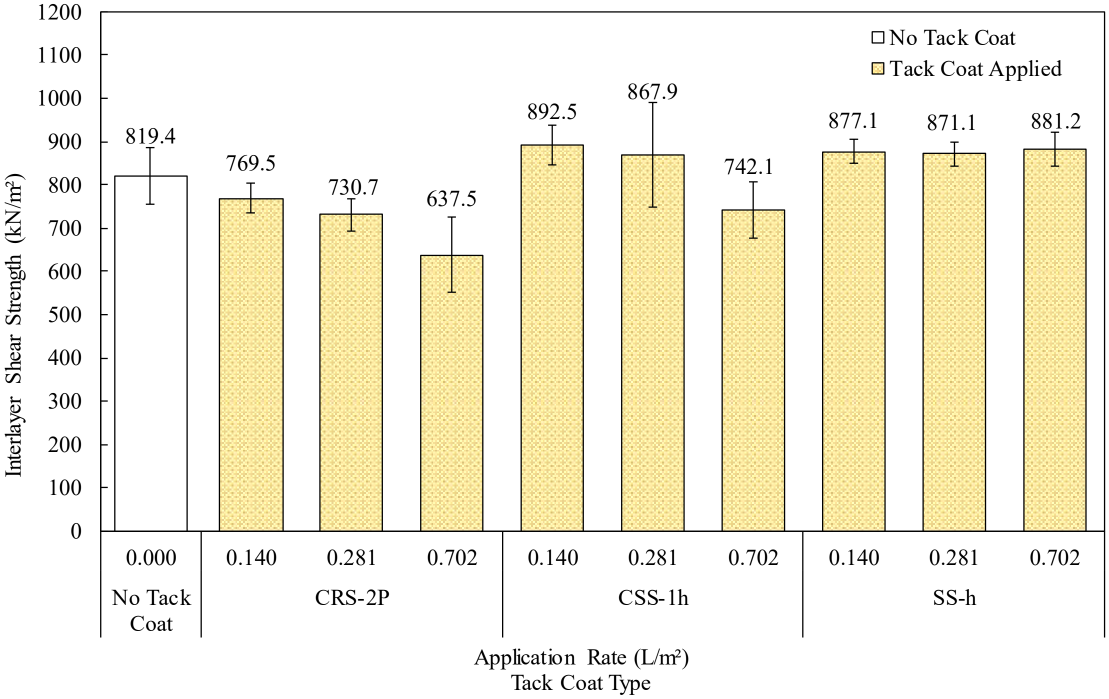


Figure 4.10 Interlayer shear strength values measured for samples having milled HMA bottom layers containing CRS-2P, CSS-1h, and SS-h tack coats with different application rates

4.5.4 Samples Prepared using Grooved PCC Bottom Layer

Figure 4.11 presents the ISS values measured for samples prepared using grooved PCC bottom layer containing no tack coat, and CRS-2P, CSS-1h, and SS-h tack coats applied at 0.140, 0.281, and 0.702 L/m^2. According to Figure 4.11, application of all three types of tack coats, namely CRS-2P, CSS-1h, and SS-h at any application rate (0.140, 0.281, and 0.702 L/m^2) on grooved PCC bottom layer was found to significantly improve the interlayer shear strength of the samples compared to that of the samples without any tack coat. According to Figure 4.11 application of CRS-2P, CSS-1h, and SS-h tack coats applied at all three rates for on specimens prepared using grooved PCC bottom layers increased the average ISS values approximately by approximately, 3.4, 3.9, and 5.6 times, respectively, compared to that of the specimens prepared without applying any tack coat. As shown in Figure 4.11, the measured ISS values were not significantly affected by the application rate of the CRS-2P and SS-h tack coats. Also, the highest ISS values for samples prepared by applying CRS-2P and SS-h tack coats, were measured when they were applied at low application rate (0.140 L/m^2). Similar finding was reported by Al-Quadi (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, 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 to that of samples prepared without any tack coat. This indicates that, the measured ISS values are sensitive to application rate when CSS-1h was used and the maximum ISS value was observed at an application rate of 0.281 L/m^2.

Depending on the preparation method of grooved PCC bottom layer samples in the laboratory, the surface texture is to some extent different than those of the filed cores. Considering the fact that the ISS value of the samples prepared using grooved PCC bottom layers without any tack coat are significantly lower than those measured for asphalt pavements, application of tack coat on PCC layer is of crucial importance to pavement durability and performance.

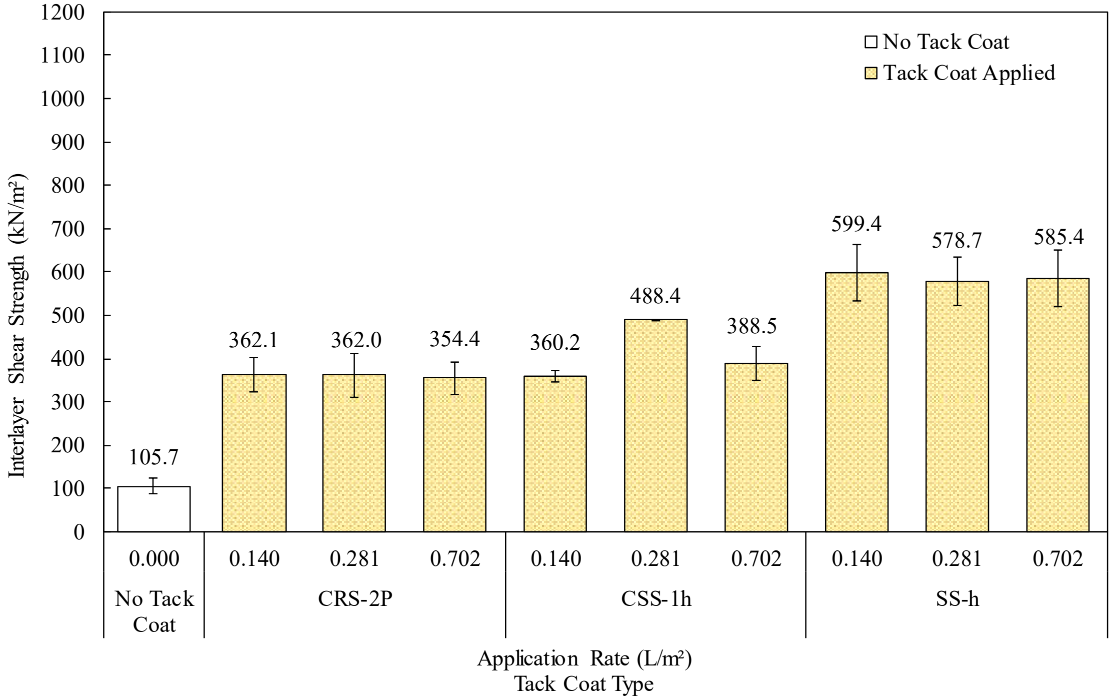


Figure 4.11 Interlayer shear strength values measured for samples having grooved PCC bottom layers containing CRS-2P, CSS-1h, and SS-h tack coats with different application rates

4.5.5 Summary

Comparing Figures 4.8, 4.9, 4.10, and 4.11 revealed 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 best 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, namely CRS-2P, CSS-1h, and SS-h used on grooved PCC bottom layers at 0.140, 0.281, and 0.140 L/m^2 application 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 RATE

Tack coats are asphaltic materials applied in larger scales on road surfaces. Hence, optimum residual application rate of tack coats should be selected based on the lowest application rate which yields the highest ISS values to be economically efficient. It should be noted that, in the cases which the difference between two ISS values at different application rates was not statistically significant the lower application rate was selected as the optimum value.

A summary of optimum residual application rates for all the tested tack coats on all the types of bottom layers is shown in Table 4.4. According to Table 4.4, in general it is possible to conclude that CSS-1h is the best type of tack coat to be used on any type of bottom 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 medium application rate (0.281 L/m^2). Table 4.4 showed that optimum tack coat application rate on milled HMA bottom layer is 0.140 L/m^2 for all of the tested tack coats. In other words, the surface texture has the dominating effect on the interlayer shear strength. Al-Qadi et al. (2012) also, reported that on trafficked and non-trafficked aged HMA bottom layer the optimum residual application rate for the tested tack coats is 0.04 L/m^2 (low application rate). Also, from Table 4.4 it is evident 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 reported by Mohammad et al. 2012.

Table 4.4 Optimum tack coat residual application rates used on different bottom layers

No.	Tack Coat Type	New HMA bottom layer (L/m^2)	Aged and worn HMA bottom layer (L/m^2)	Milled HMA bottom layer (L/m^2)	Grooved PCC bottom layer (L/m^2)
1	CRS-2P	0.702	0.702	0.140	0.140
2	CSS-1h	0.140	0.140	0.140	0.281
3	SS-h	0.281	0.281	0.140	0.140

4.7 EFFECT OF MOISTURE ON INTERLAYER SHEAR STRENGTH

As described in Chapter 3 the effect of moisture due to harsh weather conditions of the northcentral states 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 those of unconditioned samples prepared at optimum application rates. Comparison summary of the ISS values measured for conditioned and unconditioned samples prepared at optimum application rates are shown in Table 4.5 and Figure 4.12. Interestingly, it was observed that most of the moisture-conditioned samples prepared with using HMA bottom layers exhibited higher ISS values compared to those tested in dry condition. However, the difference between the ISS values measured for the conditioned and unconditioned samples were not found to be significant. Since the samples were tested after vacuum saturation, increase in ISS value as a result of moisture conditioning was attributed to the matric suction effect and therefore, better interlocking of two asphalt layers. In order to mitigate this issue, it is recommended to dry the samples before testing. This observation recommends that moisture did not have a detrimental effect on the interlayer shear strength of the samples prepared using HMA bottom layers with optimum tack coat application rates. Among all of the tack coats tested, SS-h tack coat was found to be most effectively capable of increasing the ISS values after moisture conditioning.

Table 4.5 Moisture conditioned and unconditioned ISS test results comparison

Bottom Layer Sample	Tack Coat Type	Optimum Residual Application Rate	Dry-Conditioned ISS (kPa)	Moisture-Conditioned ISS (kPa)
New HMA	No Tack Coat	0.000	856.0	882.7
	CRS-2P	0.702	743.8	571.4
	CSS-1h	0.140	865.6	870.0
	SS-h	0.281	808.9	1018.8
Aged and Worn HMA	No Tack Coat	0.000	989.6	941.5
	CRS-2P	0.702	918.4	954.8
	CSS-1h	0.140	1021.7	1133.1
	SS-h	0.281	964.2	1140.3
Milled HMA	No Tack Coat	0.000	819.4	910.5
	CRS-2P	0.140	769.5	928.5
	CSS-1h	0.140	892.5	981.5
	SS-h	0.140	877.1	997.0
Grooved PCC	No Tack Coat	0.000	105.7	77.4
	CRS-2P	0.140	362.1	355.3
	CSS-1h	0.281	488.4	425.4
	SS-h	0.140	599.4	450.6

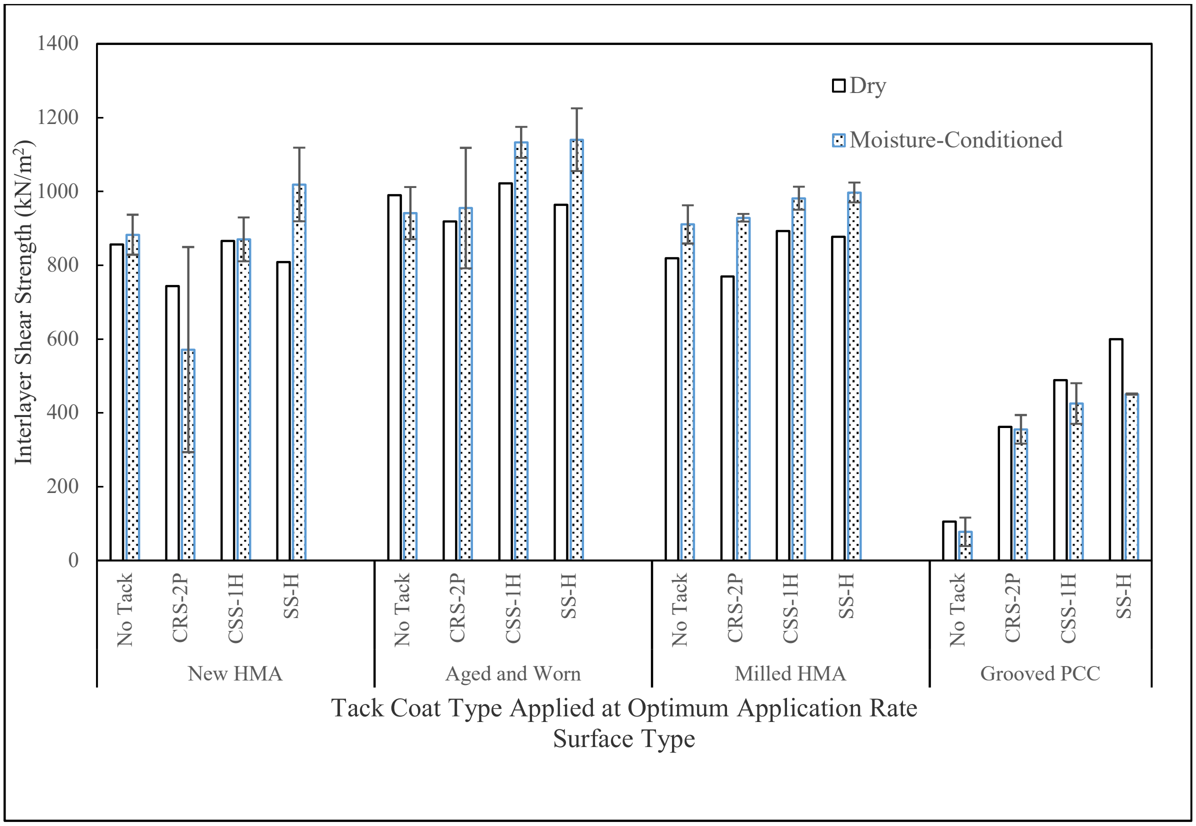


Figure 4.12 ISS test results comparison of moisture conditioned and unconditioned samples

From Figure 4.12 it was observed that, the moisture-conditioned specimens prepared at optimum residual tack coat application rate using grooved PCC bottom layers exhibited lower ISS values compared to those of unconditioned samples. Similar results were reported by Al-Qadi et al. (2008). Also, from Figure 4.12 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 that of the samples prepared without any tack coat, respectively. This shows that application of tack coat on grooved PCC surfaces before construction of an asphalt overlay is of crucial importance to durability and longevity of the pavement structure with and without moisture conditioning.

CHAPTER FIVE: CONCLUSION

5.1 CONCLUSIONS

The effect of three types of commonly used tack coats in South Dakota, their application rate, and existing pavement's surface type and texture on ISS values of laboratory-prepared double-layered specimens was evaluated. Also, optimum tack coat application rates for different tack coat types and surface textures were determined. Furthermore, the effect of moisture and freeze-thaw cycles on the ISS values was investigated. The experimental plan included finding the percent residue of the evaluated tack coats, conducting the LISST test on samples prepared using 4 types of bottom layers in 4 tack coat application rates, in dry and moisture-conditioned states. Effect of tack coat type and application rate on measured ISS values were evaluated for CRS-2P, CSS-1h, and SS-h tack coats. Each of these tack coats were applied at 0.140, 0.281, and 0.702 L/m^2 application rates. Also, samples prepared without applying any tack coat were tested. Furthermore, effect of surface type was evaluated by preparing samples having bottom layer textures namely, new HMA, aged and worn HMA, milled HMA, and grooved PCC. The high performer type of tack coat for each type of bottom layer was identified after conducting the LISST tests. In addition, the optimum application rate of each type of tack coat on different types of bottom layers were also identified. The effect of moisture conditioning on ISS values for samples prepared with optimum tack coat application rate were also evaluated. Based on the results, discussions, and observations made in this study conclusions can be drawn as follows.

1) In general, application of CRS-2P tack coat may result in a reduction in ISS values compared to that of samples containing no tack coat having HMA bottom

layer with different surface textures. Yet, for PCC bottom layers CRS-2P could increase the ISS value significantly at all application rates.

2) All of the observations suggested that 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 to that of samples containing no tack coat having HMA bottom layer with different surface textures. The highest ISS value was measured (488.4 kPa) when the CSS-1h tack coat was applied on grooved PCC bottom sample at medium application rate of 0.281 L/m^2.

3) 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 to those of the samples prepared by applying tack coats with low application rate (0.140 L/m^2). For grooved PCC bottom layers lowest application rate of SS-h resulted in the highest ISS value. For milled HMA change of application rate did not have a significant effect on measured ISS values.

4) Among all tack coats evaluated in this study, 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/m2). On specimens prepared by using PCC bottom layers, SS-h tack coat worked better compared to other tack coats. The highest ISS between PCC and HMA was observed when SS-h tack coat was used followed by CSS-1h, and CRS-2P. In general, it was observed that CRS-2P resulted in higher ISS values when applied at a high rate (0.702 L/m2). However, CSS-1h provided a high ISS value at a lower application rate (0.140 L/m2). As a result, it is possible to

conclude that CSS-1h tack coat can be successfully used on all types of the surfaces.

5) It is possible to conclude that CSS-1h is the best type of tack coat to be used on any type of bottom surface, as it showed the highest ISS values at the lowest application rate (0.140 L/m^2) for specimens with all types of HMA. Also, it showed high ISS values on grooved PCC bottom layers at medium application rate (0.281 L/m^2). Furthermore, 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.

6) For both new HMA and aged and worn HMA bottom layers, CSS-1h tack coat applied at a rate of 0.140 L/m^2 worked better than other tack coats. For milled HMA bottom layers CSS-1h and SS-h tack coats applied at a rate of 0.140 L/m^2 are more effective option compared to other tested materials. For grooved PCC bottom layers all the 3 types of evaluated tack coats (CRS-2P, CSS-1h, and SS-h) are effective options when used in their optimum application rates.

7) Moisture conditioning was not found to have a detrimental effect on the interlayer shear strength of the samples prepared using all types of HMA bottom layers with optimum tack coat application rates. Among all of the tack coats tested, SS-h tack coat was found to be 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 with grooved PCC bottom layers.

5.2 RECOMMENDATIONS

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

1) Since the moisture conditioned samples were tested after vacuum saturation, increase in ISS value as a result of moisture conditioning was attributed effect of suction resulting in a better interlocking of top and bottom layers. In order to mitigate this issue, it is recommended to dry the samples before testing.
2) The LISST was conducted only in room temperature. Therefore, it is recommended to conduct the LISST at different temperatures to evaluate the effect of temperature on ISS values.
3) 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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