



CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 08-023
UILU-ENG-2008-2010
ISSN: 0197-9191

TACK COAT OPTIMIZATION FOR HMA OVERLAYS: LABORATORY TESTING

Prepared By

**Imad L. Al-Qadi
Samuel H. Carpenter
Zhen Leng
Hasan Ozer**

University of Illinois at Urbana-Champaign

James S. Trepanier
Illinois Department of Transportation

Research Report FHWA-ICT-08-023

A report of the findings of
ICT-R55
Tack Coat Optimization for HMA Overlays

Illinois Center for Transportation

September 2008

Technical Report Documentation Page

| | | | |
|---|---|---|--|
| 1. Report No. FHWA-ICT-08-023 | 2. Government Accession No. | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle Tack Coat Optimization for HMA Overlays Laboratory Testing | | 5. Report Date | 6. Performing Organization Code |
| 7. Author(s) Imad L. Al-Qadi, Samuel H. Carpenter, Zhen Leng, Hasan Ozer, James S. Trepanier | | 8. Performing Organization Report No. FHWA-ICT-08-023 UILU-ENG-2008-2010 | |
| 9. Performing Organization Name and Address Illinois Center for Transportation Department of Civil and Environmental Engineering University of Illinois at Urbana-Champaign 205 N. Mathews Ave. MC-250 | | 10. Work Unit (TRAIS) | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address Illinois Department of Transportation Bureau of Materials and Physical Research 126 East Ash Street Springfield, IL 62704-9766 | | 13. Type of Report and Period Covered 14. Sponsoring Agency Code | |
| 15. Supplementary Notes | | | |
| 16. Abstract <p>Interface bonding between hot-mix asphalt (HMA) overlays and Portland cement concrete (PCC) pavements can be one of the most significant factors affecting overlay service life. Various factors may affect the bonding condition at the interface, including HMA material, tack coat material, tack coat application rate, PCC surface texture, temperature, and moisture conditions. The objective of this study is to quantify the impact of these parameters on the permanent deformation of the HMA overlay. This study includes three major components to achieve the objective: laboratory testing, numerical modeling, and accelerated pavement testing. This report presents and analyzes the laboratory testing results.</p> <p>A direct shear test device was built and utilized to investigate the characteristics of the HMA-PCC interface and to determine the interface shear strength in the lab. Tests were run in monotonic mode at a constant loading rate of 0.47 in/min (12 mm/min). Test specimens were prepared using field PCC cores, laboratory prepared HMA, and tack coat materials provided by the supplier. Parameters affecting the interface performance that were evaluated include HMA material type (SM-9.5 surface mix and IM-19.5A binder mix), tack coat type (SS-1h and SS-1hP emulsions, and RC-70 cutback), tack coat application rate, PCC surface texture, temperature, and moisture conditions. Test results showed that the asphalt emulsions SS-1h and SS-1hP produced greater interface bonding strength than the cutback asphalt RC-70. The SM-9.5 surface mix was found to have better interface strength than the IM-19.0A binder mix.</p> <p>The HMA tested produced the same trend of interface shear strength with tack coat application rate for various tack coat types. The optimum residual tack coat application rate for the SS-1hP emulsion using IM-19.0A binder mix was 0.04 gal/yd² (0.18 L/m²) in the lab. The direction of tining on the PCC produced no effect on interface shear strength at 20 oC. However, the milled concrete surface provided greater interface shear strength than both tined and smooth PCC surfaces for the same tack coat application rate. At the optimum tack coat application rate, the smooth PCC surface produced higher interface shear strength than the tined surface. As temperature increased, interface bonding strength decreased. Moisture conditioning significantly decreased the interface shear strength. This reduction was more pronounced when a stripping-vulnerable binder mix IM-19.0B was used.</p> | | | |
| 17. Key Words Tack Coat, HMA Overlay, PCC Pavement, Direct Shear Test | | 18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161. | |
| 19. Security Classif. (of this report) Unclassified | 20. Security Classif. (of this page) Unclassified | 21. No. of Pages | 22. Price |

ACKNOWLEDGMENT

This paper is based on the results of ICT-R55, Tack Coat Optimization for HMA Overlays. ICT-R55 is conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation, Division of Highways; and the U.S. Department of Transportation, Federal Highway Administration. The authors would like to acknowledge the assistance of David Lippert, IDOT's Engineer of Materials and Physical Research and the following members of the Technical Review Panel for ICT-R55: James Trepanier (Chair), Amy Schutzbach, Charles Weinrank, Patty Broers, Terry Hoekstra, Derek Parish, and Thomas Winkelman.

DISCLAIMER

The contents of this report reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Center for Transportation, the Illinois Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

EXECUTIVE SUMMARY

Interface bonding between hot-mix asphalt (HMA) overlays and Portland cement concrete (PCC) pavements can be one of the most significant factors affecting overlay service life. Various factors may affect the bonding condition at the interface, including HMA material, tack coat material, tack coat application rate, PCC surface texture, temperature, and moisture conditions. The objective of this study is to quantify the impact of these parameters on the permanent deformation of the HMA overlay. There are three major components included in this study to achieve the objective: laboratory testing, numerical modeling, and accelerated pavement testing. This report presents and analyzes the laboratory testing results.

A direct shear test device was built and utilized to investigate the characteristics of the HMA-PCC interface and to determine the interface shear strength in the lab. Tests were run in monotonic mode at a constant loading rate of 0.47 in/min (12 mm/min). Test specimens were prepared using field PCC cores, laboratory prepared HMA, and tack coat materials provided by the supplier. Parameters affecting the interface performance that were evaluated include HMA material type (SM-9.5 surface mix and IM-19.5A binder mix), tack coat type (SS-1h and SS-1hP emulsions, and RC-70 cutback), tack coat application rate, PCC surface texture, temperature, and moisture conditions. Test results showed that the asphalt emulsions SS-1h and SS-1hP produced greater interface bonding strength than the cutback asphalt RC-70. The SM-9.5 surface mix was found to have better interface strength than the IM-19.0A binder mix.

The HMA tested produced the same trend of interface shear strength with tack coat application rate for various tack coat types. The optimum residual tack coat application rate for the SS-1hP emulsion using IM-19.0A binder mix was 0.04 gal/yd² (0.18 L/m²) in the lab. The direction of tining on the PCC produced no effect on interface shear strength at 68 °F (20 °C). However, the milled concrete surface provided greater interface shear strength than both tined and smooth PCC surfaces for the same tack coat application rate. At the optimum tack coat application rate, the smooth PCC surface produced higher interface shear strength than the tined surface. As temperature increased, interface bonding strength decreased. Moisture conditioning significantly decreased the interface shear strength. This reduction was more pronounced when a stripping-vulnerable binder mix IM-19.0B was used.

TABLE OF CONTENTS

| | |
|--|----|
| ACKNOWLEDGMENT | i |
| EXECUTIVE SUMMARY | ii |
| CHAPTER 1 INTRODUCTION | 1 |
| 1.1 TACK COAT DEFINITIONS | 1 |
| 1.2 EFFECTS OF INTERFACE POOR BONDNG/DEBONDING | 2 |
| CHAPTER 2 LITERATURE REVIEW | 4 |
| 2.1 LABORATORY STUDIES | 4 |
| 2.2 SUMMARY OF LITERATURE FINDINGS..... | 12 |
| CHAPTER 3 TESTING DEVICE AND SPECIMEN PREPARATION | 14 |
| 3.1 TESTING APPARATUS AND MODE | 14 |
| 3.2 SPECIMEN PREPARATION | 14 |
| 3.3 MOISTURE CONDITIONING PROCEDURE | 16 |
| CHAPTER 4 MATERIALS AND TESTING PROGRAM..... | 19 |
| CHAPTER 5 TEST RESULTS AND ANALYSIS..... | 21 |
| 5.1 EFFECTS OF HMA TYPE AND TACK COAT TYPE AND APPLICATION RATE | 21 |
| 5.2 OPTIMUM TACK COAT APPLICATION RATE DETERMINATION | 25 |
| 5.3 PORTLAND CEMENT CONCRETE SURFACE TEXTURE EFFECT | 26 |
| 5.4 TEMPERATURE EFFECT..... | 28 |
| 5.5 MOISTURE EFFECT..... | 29 |
| CHAPTER 6 SUMMARY | 31 |
| REFERENCES | 32 |

CHAPTER 1 INTRODUCTION

The interface bonding condition between a hot-mix asphalt (HMA) overlay and a Portland Cement Concrete (PCC) pavement has long been accepted as being highly influential on the performance of the overlay. Loss of bonding between layers can result in pavement distresses such as slippage cracking (Romanoschi, 1999) as well as increased difficulty in compaction (West et al., 2005). Considerable research has been conducted on the interface bonding between pavement layers (Donovan et al., 2000; Hachiya et al., 1997; Mohammad et al., 2002; Romanoschi, 1999; Tashman et al., 2006; Uzan et al., 1978; West et al., 2005; Woods, 2004; Yildirim et al., 2005). However, most of these research studies focused on the interface between HMA layers, and few have considered PCC pavement as an underlying layer (Yildirim, 2005). The difference in modulus between HMA and PCC layers increases the shear at the interface, making them more likely to fail in a shear mode. Therefore, a higher tack coat application rate might be required for HMA-PCC interfaces than for HMA-HMA interfaces. Given that the use of HMA overlays as a rehabilitation technique for deteriorated PCC pavements is increasing, it is prudent to investigate the effect of HMA-PCC interface characteristics on pavement overlay performance. The characteristics which may affect the bonding condition between HMA overlays and PCC pavements include the HMA material, tack coat material, tack coat application rate, PCC surface texture, temperature, and moisture conditions. The objective of this project is to evaluate the effects of these parameters on the HMA-PCC interface bonding.

Three components are included in this project: laboratory tests, numerical modeling, and accelerated pavement testing. This report presents laboratory test results, using a custom designed direct shear device. In Chapter 1, definitions of a tack coat and effects of poor interface bond or debonding are introduced. Chapter 2 presents the previous laboratory research work on evaluating pavement interface bonding. Chapter 3 introduces the test device used in the laboratory and testing specimen preparation procedure. In Chapter 4, properties of testing materials and the laboratory testing program are introduced, and Chapter 5 discusses the test results. Laboratory testing findings are summarized in Chapter 6.

1.1 TACK COAT DEFINITIONS

ASTM D8-02 Standard Terminology Relating to Materials for Road and Pavements defines tack coat as “an application of bituminous material to an existing relatively non absorptive surface to provide a thorough bond between old and new surfacing” (ASTM, 2003). The Asphalt Emulsion Manufacturers Association (AEMA) defines tack coat as “a light application of asphalt emulsion between hot-mix asphalt layers designed to create a strong adhesive bond without slippage” (Asphalt Institute, 2000).

According to the United States Army Corps of Engineers (USACE), tack coat is a heated Rapid Curing (RC) liquid asphalt or an emulsified asphalt (normally SS grade), which is applied to the clean existing surface before the new course is constructed to ensure a good bonding between the two layers (USACE, 1991). According to the USACE’s Unified Facilities Criteria (UFC), “tack coat is an application of diluted asphalt emulsion or cutback asphalt placed on an existing HMA or old concrete surface to provide a bonding with a new HMA layer” (USCAE, 2001).

Three types of tack coat are commonly used in pavement construction including asphalt emulsions, cutback asphalts, and asphalt cements. Diluted slow set asphalt emulsions are the most commonly used materials for a tack coat, as they have the following advantages: 1) they provide additional volume needed for the distributor to function at normal speed when lower application rates are used and 2) they flow easily from the distributor at ambient temperatures allowing for a more uniform and safer application

(Asphalt Institute, 2000). Cutback asphalts and asphalt cements are occasionally used. However, both of these have drawbacks which limit their use in some locations. Environmental pollution is the biggest issue for cutback asphalts (TxDOT, 2001). Asphalt cements must be heated sufficiently to allow spray application; otherwise, it will be very difficult to apply asphalt cement binder uniformly on existing pavement surface, especially at low application rates (USACE, 2000).

1.2 EFFECTS OF INTERFACE POOR BONDING/DEBONDING

Pavements are layered structures. The overall strength and stiffness of the pavement depends not only on the strength and stiffness of each individual layer, but also on the bond between them. The function of the tack coat material is to provide the necessary bond between the underlying layer and the new layer. This bond ensures that various pavement layers work together to support the traffic and environmental loading.

The assumption in pavement design is that adjacent layers are fully bonded together without any relative slip. However, in reality, this is not always true. Whether the interface is fully bonded depends on various factors, such as texture of contact surfaces, application rate of tack coat, and distribution of tack coat. At locations where poor interface bonding or debonding occurs, pavement distresses will quickly appear.

One of the most typical distresses caused by poor interface bonding between HMA overlay and the underlying layer is slippage cracking. Slippage cracking, shown in Figure 1-1, is usually crescent or half-moon in shape with both ends pointed into the direction of traffic (Huang, 2003). This occurs most often in areas where braking or turning causes the pavement to slide or deform (e.g., intersection, sharp curve). A study by Shahin et al. (1987) examined the effects of horizontal shearing loads at the top of the overlay. The magnitude of the horizontal loads was assumed to be half of the vertical load. In this case, the maximum tensile strains appear at the edge of the contact area on the top of the overlay, leading to a progressive formation of "crescent cracks," typical for an overlay with debonding at the interface. Under these loads, the surface strains are critical for the case of full bond, but they increase by up to 50% when slippage occurs. Other pavement problems such as difficulty with compaction, premature fatigue, top-down cracking, and surface layer delamination may also be related to poor bond between pavement layers (West et al, 2005).



Figure 1-1. Slippage cracking caused by poor interface bonding.

The redistribution of stresses and strains in the pavement due to inadequate interface conditions has long been considered as a cause of premature failure. Shahin et al. (1987) used the BISAR model (DeJong, 1973) to compute pavement life for a structure with an HMA overlay on top of a flexible pavement. BISAR allows modification of the slippage condition between the layers by considering the relative displacement between layers to be proportional to the shear stress transfer across the interface. This study found that for the full bonding, the maximum tensile strain remained at the bottom of the original existing HMA layer and the overlay was in compression while for the full slip case, the tensile strain at the bottom of the overlay was greater than that at the bottom of the existing HMA layer (see Figure 1-2). The strain distribution was similar for the case of partial slip and full slip. The vertical subgrade strain also increased when the bonding was lost. In the case of HMA overlays on top of PCC pavements, the full bonded condition produces lower failure stresses/strains. Stresses in the PCC slab are lowest with a fully bonded HMA overlay, extending the service life of the pavement. In addition, the overlay also reduces the temperature gradients in the PCC slab and thus the curling phenomenon. If the interface is partially bonded, tensile strains will develop at the bottom of the overlay and shear strains promoting rutting will develop in the upper portion of the overlay as shown by Carpenter and Freeman (1986). The importance of shear with the HMA layer has been recently presented by Al-Qadi et al. (2008) as a major cause of flexible pavement near surface cracking.

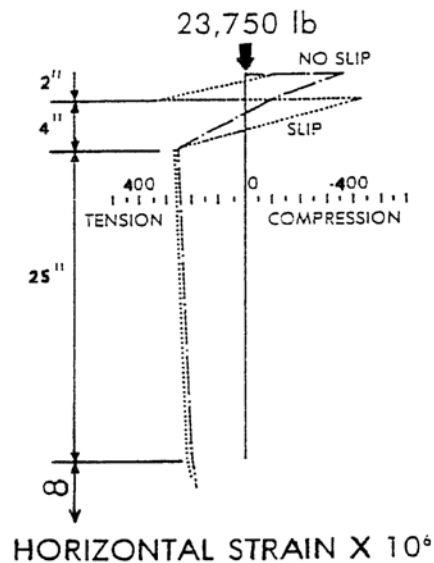


Figure 1-2. Horizontal strain under central line of a single DC-9 wheel (Shahin et al., 1987).

The ultimate result of pavement interface bonding failure is reduced pavement life. As reported by Khweir and Fordyce (2003), bonding failure could lead to a predicted loss of two-fifths to five-sixths of the potential life of the pavement. This study was the only one found that determined a numerical reduction in pavement life caused by poor interface bonding.

CHAPTER 2 LITERATURE REVIEW

Numerous studies have been performed investigating adhesive properties of the interface between layers. These studies have typically developed a unique test method or instrument for analysis of the interface bond strength. The most common test setup used to measure interface shear strength uses a direct shear mechanism, where the load is applied to generate shear failure on a pre-defined interface plane. Pull-off and torsional shear tests are also used to evaluate the interface strength. A number of these laboratory studies have been completed, some of which are summarized herein in chronological order.

2.1 LABORATORY STUDIES

Uzan et al. (1978) were one of the first researchers working on the pavement interface problem with laboratory tests. They studied the interface adhesion properties of HMA layers based on direct shear test results. A neat binder Pen 60-70 was used as the tack coat. Tests were performed at 77 °F (25 °C) and 131 °F (55 °C) at normal stress levels of 0.7, 7.1, 14.2, 35.5 and 71.1 psi (0.05, 0.5, 1.0, 2.5 and 5.0 kg/cm²). The application rates considered were 0, 0.11, 0.22, 0.32 and 0.43 gal/yd² (0, 0.49, 0.97, 1.46 and 1.94 L/m²). However, it was not clearly stated which type of tack coat application rate was referred to in that study. It was reported that increasing tack coat application rate increased the interface strength. The optimum tack coat application rates yielding the maximum shear strength were found to be 0.22 gal/yd² (0.97 L/m²) at 77 °F (25 °C) and 0.11 gal/yd² (0.49 L/m²) at 131 °F (55 °C).

Figure 2-1 shows the apparatus used by Santagata et al. (1994) to evaluate the strength of tack coat interfaces. The significant feature of this testing apparatus, which is not found in the other test fixtures described herein, is the measurement of displacements in the normal direction as well as the shear direction. This allowed measurement of dilation, also known as volumetric expansions, is at the interface level.

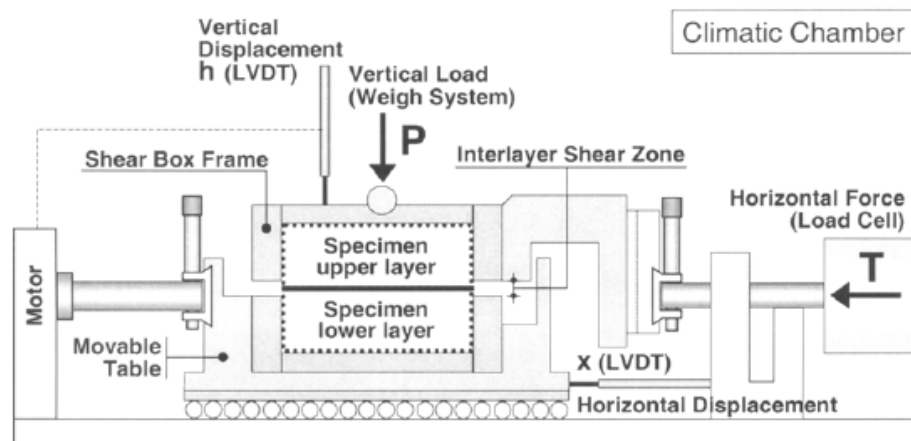


Figure 2-1. Shear strength testing apparatus (ASTRA) (Santagata et al., 1994).

Tschegg et al. (1995) developed a new testing method called the wedge splitting test to characterize the fracture mechanics properties of bonding between various HMA layers. Specimens were prepared with a groove at the interface and were split with a wedge of a specified angle, as shown in Figure 2-2, producing a tensile stress on the interface. Cationic bitumen emulsion (K) and polymer modified bitumen emulsion (P) were applied at the interface. The application rate was not specified by the authors. Vertical and horizontal displacements and vertical loads were measured, which were converted into horizontal loads based on the wedge angle. The load-displacement curve was obtained by plotting the

force, F_H , versus the displacement, δ . The energy to fracture the specimen, fracture energy G , was derived from the area below the load-displacement curve. The specific fracture energy, G_F , which equals the fracture energy per unit fracture area, was obtained to characterize the crack growth resistance of the material. This test was repeated at temperatures of 50.9, 32, 14, and -5.8 °F (10.5, 0, -10.0, and -21.0 °C). Plastic ductile fracture behavior with relatively low maximum horizontal force was apparent at the high temperatures. The response of the interface became brittle with higher maximum horizontal forces at lower temperatures. Specific fracture energy was found to be higher with P specimens at temperatures from -5.8 to 32 °F (-21 to 0 °C) whereas K specimens had higher G_F at 50.9 °F (10.5 °C). The authors indicated that the specific fracture energy was more appropriate to characterize the fracture power than the maximum load. It was reported that the specific fracture energy of a layered specimen was smaller than a homogeneous sample one by a factor of 0.15 to 0.5, which supported the idea of existence of weak planes in the layered systems.

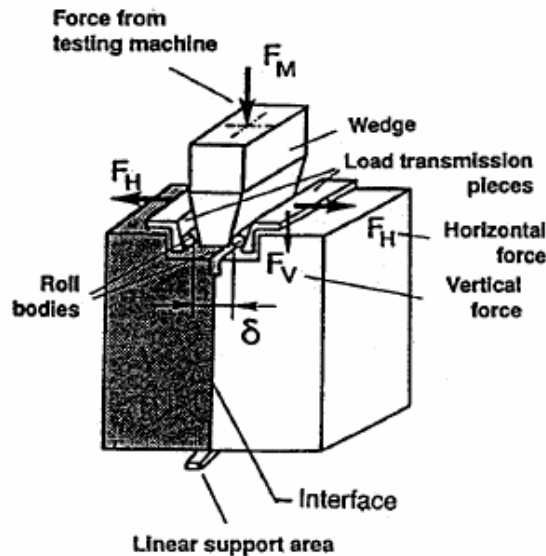


Figure 2-2. Wedge Splitting Test (Tschegg, 1995).

In Japan, Hachiya and Sato (1997) studied the effect of bond between HMA layers using direct shear tests on rectangular blocks and cylinders. Investigated parameters included temperature, surface cleanliness, loading rate, tack coat application rate, and curing period. One typical cationic asphalt emulsion and one rubberized asphalt emulsion were investigated. The results showed that tack coat had relatively small effect at 68 °F (20 °C) but did improve the bond strength at 104 °F (40 °C). Unexpectedly, dirty surfaces were found to have negligible effect on the interface bonding if the tack coat was properly cured. However, if improperly cured, emulsion was ineffective in bonding the layers. The high loading rate of 4 in/mm (100 mm/min) resulted in much higher bonding strengths than 0.04 in/mm (10 mm/min). The highest interface shear strength was obtained at 0.04 gal/yd² (0.2 L/m²) when a newly developed rubberized asphalt emulsion was used, which had higher viscosity.

Mrawira and Demude (1999) evaluated interface shear strength using a test apparatus adapted from ASTM D 143 for testing shear strength of woods. This study compared shear strength of an interface between two freshly paved layers with and without tack coats. The tack coat was an SS-1 asphalt emulsion applied at a rate of 0.04 to 0.07

gal/yd² (0.2 to 0.3 L/m²) of total tack coat. Tests were conducted at a constant rate of 0.04 in/min (1mm/min) and 72 °F (22 °C). Surprisingly, it was found that the maximum shear strength of the tack-coated layers was slightly lower than that of the non-tacked layers. The authors suggested that the tack coat weakened the interface by introducing a slippage plane. Although the range of tack coat application rate may not be sufficient to judge such a conclusion, the results were consistent with the study by Mohammad et al. (2002), which showed the same trend for this particular type of tack coat.

A laboratory testing program was conducted at Virginia Tech to determine the optimum asphalt binder tack coat rate for a geocomposite membrane in roads and overlaid bridge decks (Donovan et al., 2000). To accomplish this, a fixture as shown in Figure 2-3 was designed to allow the application of cyclic shear loading at the geocomposite membrane interface when used as an interlayer simulating one of the two situations: a PCC bridge deck overlaid with the geomembrane and an HMA overlay or a flexible pavement with the geocomposite membrane sandwiched between an HMA base layer and an HMA wearing surface. The parameter examined was the tack coat application rate on both sides of the geocomposite membrane. The optimum tack coat application rate was defined as the amount of tack coat needed to provide the maximum number of cycles to induce failure. It was recommended to use 2.58 lbs/yd² (1.40 kg/m²) when the geocomposite surface was in contact with an HMA base mix, 2.77 lbs/yd² (1.50 kg/m²) when it was in contact with an HMA wearing surface mix, and 3.23 lbs/yd² (1.75 kg/m²) when it was in contact with PCC surfaces. It was also found that use of a polymer modified binder tack coat slightly increased the number of cycles to failure in the laboratory tests. Although this test procedure was designed for obtaining the optimum tack coat rate for geocomposite membrane, the same device and procedure are also applicable to determine the optimum tack coat rates without geocomposite membrane. The significance of this testing device is the ability to apply a normal load on the top of the cores, which allows evaluation of the sensitivity of the interface response to the normal pressure.

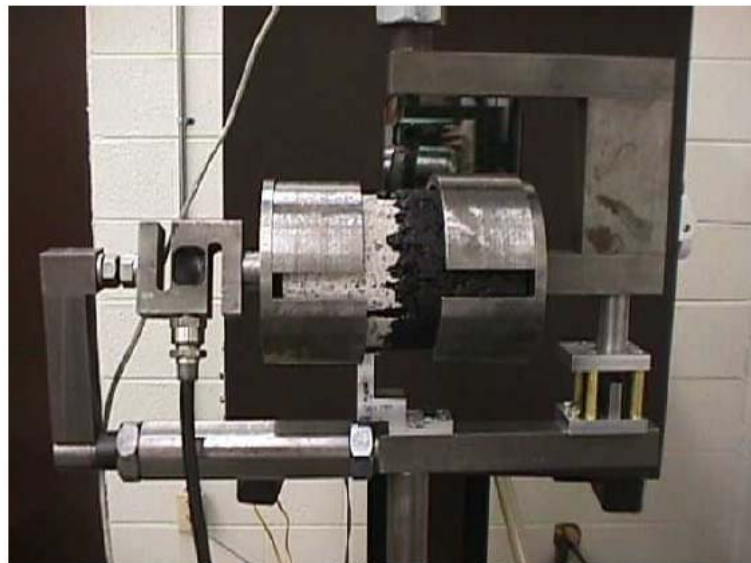


Figure 2-3. A fixture developed at Virginia Tech (Donovan et al., 2000).

Mohammad et al. (2002) used the SuperPave™ Shear Tester (SST) as shown in Figure 2-4 to investigate the shear strength of interfaces between two HMA layers. The applied tack coats included two performance graded binders (PG64-22 and PG76-22M) and four emulsions (CRS-2P, SS-1, CSS-1 and SS-1h). Tack coat materials were characterized

by complex shear modulus, phase angle, and rotational viscosity. A constant rate of shear of 50 lb/min (222.5 N/min) was applied, and materials were tested at 77 °F (25 °C) and 131°F (55 °C). The researchers found that the CRS-2P emulsion provided the highest interface shear strength at the residual application rate of 0.02 gal/yd² (0.09 L/m²). For other tack coats, no distinctive optimum rate was observed. It was also reported that at lower test temperatures (77 °F (25 °C)), an increase in tack coat application rate resulted in a decrease in interface shear strength. However, at higher test temperatures (131 °F (55 °C)), shear strength was not sensitive to application rate. As shown in Table 2-1, application of tack coat does not necessarily increase the interface shear strength.

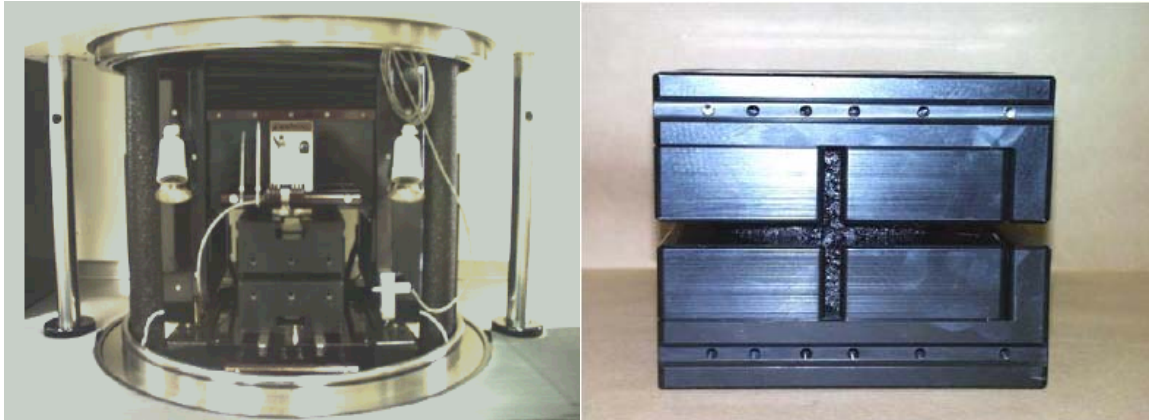


Figure 2-4. SuperPave™ shear tester (Mohammad et al., 2002).

Table 2-1. Interface Shear Strength Change with Tack Coat Application

| Tack Coat | Max Interface Shear Strength with Tack Coat (psi) | Strength gain* (%) |
|-----------|---|--------------------|
| PG 64-22 | 44.3 | 14.6 |
| PG 76-22M | 41.9 | 8.5 |
| CRS-2P | 51.0 | 31.0 |
| SS-1 | 38.6 | No gain |
| CSS-1 | 39.5 | 2.3 |
| SS-1h | 34.0 | No gain |

*Strength gain = [(Max. Interface Shear Strength with tack coat) - (Interface Shear Strength without tack coat)] / (Interface Shear Strength without tack coat)

Interface Shear Strength without tack coat = 266.6kPa

1kPa = 0.145psi

Woods (2004) used a Tack Coat Evaluation Device (TCED) developed by InstroTeck Inc. to determine adhesive strength of tack coat applications. The TCED, as shown in Figure 2-5, determines tensile and torque-shear strength by compressing a smooth, circular, aluminum contact plate onto a prepared tack coat. The testing sequence is depicted in the inserted schematics in Figure 2-6, beginning with the application of a standard normal force (a) and then recording the force required to remove the contact plate from the testing surface by either tension (b) or torque-shear (c). A second device, the Laboratory Bond Interface Strength Device (LBISD), as shown in Figure 2-7 was developed to determine interface shear strength of cylindrical laboratory specimens. This device determines interface shear strength in direct shear using the standard Marshall loading device. During testing, specimens are loaded parallel to the interface plane at a constant displacement rate of 2.0 in/min (5.08 cm/min) with no normal load. Three emulsions (SS-1, CSS-1, and CRS-2) and one asphalt binder (PG 67-22) were evaluated at various application rates, dilutions, and set times. Study results indicated that application rate, tack coat, and emulsion set time

significantly affected TCED strength of the interface. It was also shown that the prototype TCED could distinguish between different types of tack coat applications. For the four tack coats tested, PG 67-22 yielded the highest strengths and CRS-2 yielded the highest strength among the emulsions. In the study, tack coat application rates were the rates by the amount of applied tack coat. According to the provided emulsion certificate sheets, the asphalt residue rates for SS-1, CSS-1, and CRS-2 were 66.0%, 62.5%, and 66.9%, respectively. When emulsions were not fully broken, tensile and torque-shear strengths gave the highest values at the low application rate of 0.05 gal/yd² (0.23 L/m²). When emulsions were fully broken, the application rate of 0.09 gal/yd² (0.41 L/m²) yielded the highest tensile and torque-shear strength. In the LBISD tests, interface specimens were prepared with four tack coats: SS-1, CSS-1, CRS-2 and PG67-22 asphalt binder. Emulsions were applied at rates of 0.05, 0.09, and 0.13 gal/yd² (0.23, 0.41, and 0.59 L/m²) and the asphalt binder was applied at rates of 0.04, 0.07 and 0.10 gal/yd² (0.18, 0.32 and 0.46 L/m²). Specimens were also prepared with a coarse and fine base layer. A reaction index was introduced to approximate the slope of the load-displacement diagram from each test. It was reported that tack coat type significantly affected maximum shear strength and reaction index. The PG 67-22 produced both the highest maximum shear strength and the highest reaction index. Emulsion type did not significantly influence maximum shear strength or reaction index. The base mix gradation had a significant effect on reaction index, but not maximum shear strength. Finally, the tack coat application rate had no significant effect on maximum shear strength or reaction index. The author indicated a possible reason for this was that deformation of the base specimen caused by heating introduced excessive aggregate interlock, negatively affecting results.

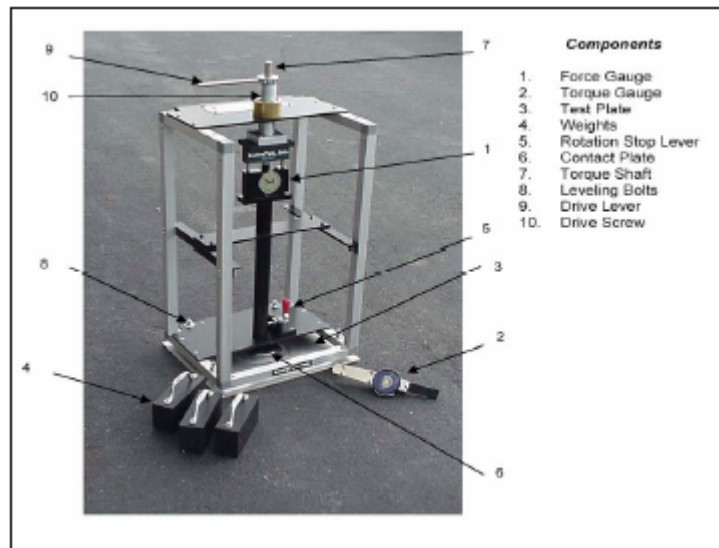


Figure 2-5. Tack coat evaluation device (TCED) (Woods, 2004).

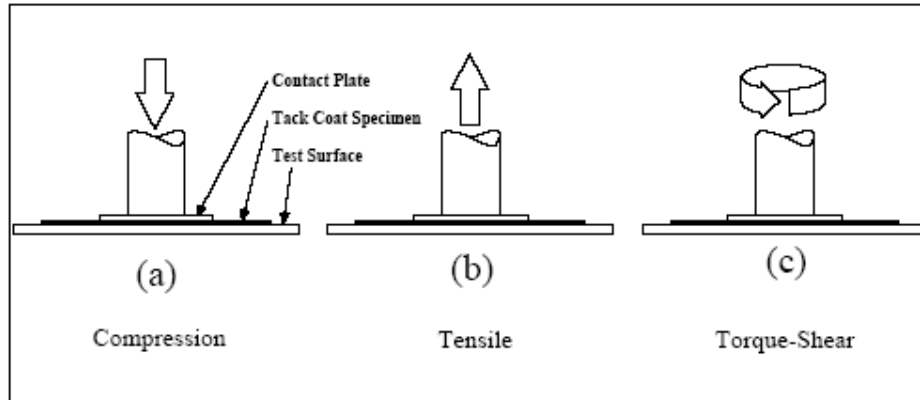


Figure 2-6. TCED testing (Woods, 2004).



Figure 2-7. Laboratory bond interface strength device, LBISD (Woods, 2004).

Yildirim et al. (2005) determined tack coat related performance results from the Hamburg wheel tracking and simple shear tests on laboratory prepared specimens. The performance of thin HMA overlays on PCC pavements was evaluated. Four influence factors were investigated including mix type, tack coat type, tack coat application rate and trafficking. Hamburg wheel tracking tests and a modified Marshall press were used to evaluate the bond strength. Asphalt mixes with Type D and open Coarse Matrix High Binder (CMHB) gradations with limestone aggregate were used. Tack coat types included SS1 and CSS-1H emulsions. Tests were conducted at residual application rates of 0.025 and 0.05 gal/yd² (0.11 and 0.23 L/m²). Rheological properties of the tack coat materials were also determined in this study. The temperatures for Hamburg tracking tests and simple shear testing were 122 and 68 °F (50 and 20 °C), respectively. It was reported that mix type, tack coat application rate, and Hamburg trafficking were the significant factors; while tack coat type did not have a significant influence. The area beneath the stress-displacement curve was found to be a better discriminating factor to determine the significance of main effects and interactions. The results also showed that tack coat performance was generally better at the higher application rate. However, in contrast to expectations, it was found that Hamburg trafficking improved the shear strength response. Since the Hamburg tracking tests were conducted for only 5000 cycles, it was concluded that expected tack coat failure didn't happen at this number of cycles. The authors suggested that Hamburg tests be done at a lower temperature (25 °C) and that more cycles (20,000) be applied to investigate the influence of trafficking.

West et al. (2005) evaluated the bond strength between pavement layers and developed a testing procedure in the first phase of their study sponsored by the Alabama

Department of Transportation. Direct shear tests were conducted to evaluate the interface bond strength. CRS-2, CSS-1 and PG64-22 were utilized as bonding agent between HMA samples prepared with various mix designs. Application rates were 0.02, 0.05, and 0.08 gal/yd² (0.09, 0.23, and 0.36 L/m²) based on asphalt residue. Normal pressures applied to the specimens were 0, 10 and 20 psi (0, 68.9, and 137.9 kPa). The tests were conducted at three temperatures: 50, 77, and 140 °F (10, 25, and 60 °C). Static shear testing was conducted at a displacement rate of 2 in/min (50.8 mm/min). The authors concluded that interface bond strength was sensitive to normal pressure only at high temperature. Low application rates usually yielded higher interface bond strength than high application rates for fine graded mixes. The PG 64-22 provided the highest bond strength among the three bonding agents tested.

Mohammad et al. (2005) studied optimization of tack coat for HMA placement within the scope of an NCHRP project. The project's objectives were to determine optimum application methods, equipment type and calibration procedures, application rates, and asphalt binder materials for the various uses of tack coats and to recommend revisions to relevant AASHTO methods and practices related to tack coats. Tasks 1 and 2 of the project have now been completed, which are literature review and design of a comprehensive laboratory and field experiment. Some of the key findings from their literature review included: more high float emulsions are used than the non-high float emulsion on existing un-ground PCC or diamond ground PCC pavements. There is no agreement concerning how long a tack coat should remain uncovered before placing the HMA layer; the most commonly used method to check the application and residual tack coat rates is to measure the change in the amount of material in the distributor tank over a given section, and there is no standard laboratory or field test method to determine the interface bond strength between pavement layers. It is generally accepted that shear tests are the best way to simulate pavement interface failure among all of the different laboratory and field test methods, which could be grouped into shear test, tension test, and torque test. Numerous variables including temperature, normal pressure, surface condition, application rate, setting time, mixture type, and pavement composition have been found to be factors affecting the interface bond strength. However, literature does not show agreement on the effects of these factors. For example, literature agrees that the normal stress will increase the interface bond strength. However, there is no agreement in the literature concerning whether the tack coat type and application rate affect the interface bond strength significantly. Based on the findings from task 1, the study selected a direct shear test and a tensile test. In task 2, partial factorial designs for both laboratory and field testing have been performed to evaluate the effects of various parameters including four pavement types, two pavement surface coverages by tack coat, two surface textures, two permeability levels, two levels of surface cleanliness, two tack coat material types, three grades, three application methods, two levels of traffic loading, four climate zones, three placement seasons, and three replicates of each test.

A two phase study including both laboratory and field work was performed by West et al. (2005) in Alabama to develop a test for measuring the bond strength between HMA pavement layers. The factors that were investigated in the lab included tack coat type, tack coat application rate, mixture type, testing temperature, and normal pressure. It was found that all the factors considered in the test plan were significant to the bond strength. With an increase in temperature, bond strength decreased significantly. Paving grade asphalt binder provided higher bond strength than emulsions; especially for the fine-graded mixtures tested at high temperature. For the fine-graded mixture, low application rates of tack coat generally provided high bond strength; while for the coarse-graded mixture, tack coat application rate was an insignificant factor. An outcome of the laboratory work was a draft procedure for determining the bond strength between pavement layers. A simple shear device developed by NCAT was selected, and the test is run at 77 °F (25 °C) and a loading rate of 2.0 in/min

(50 mm/min). The draft procedure was validated in the field phase of the study. A key finding of the field study was that milled surfaces provided significantly higher bond strength between pavement layers. Both emulsion and paving grade asphalt tack coat applications could provide good bond strengths in the field.

A recent study was performed by Tashman et al. (2006) at Washington State to investigate the factors that affect bond strength between HMA layers and to quantify the effectiveness of the tack coat. The factors investigated included the surface treatment, curing time, residual application rate, and coring location. Three test methods were utilized including the laboratory Florida DOT shear test (Figure 2-8), the laboratory bond torque test (Figure 2-9), and the field UTEP Pull-off test (Figure 2-10). The study indicated that milling the existing surface improved bonding, while tack coat curing time and coring locations were insignificant factors. The study also suggested that tack coat application was not needed for milled surfaces. Based on this study, it appeared that the bond torque test could be a feasible test.

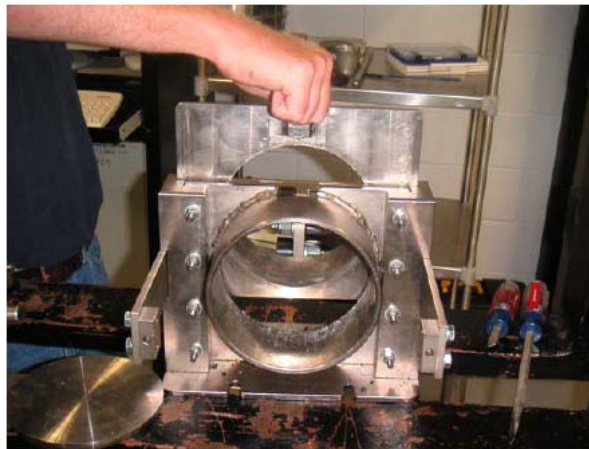


Figure 2-8. Shear test attachments used in FDOT shear tester (Tashman et al. 2006).



Figure 2-9. Torque bond test (Tashman et al. 2006).

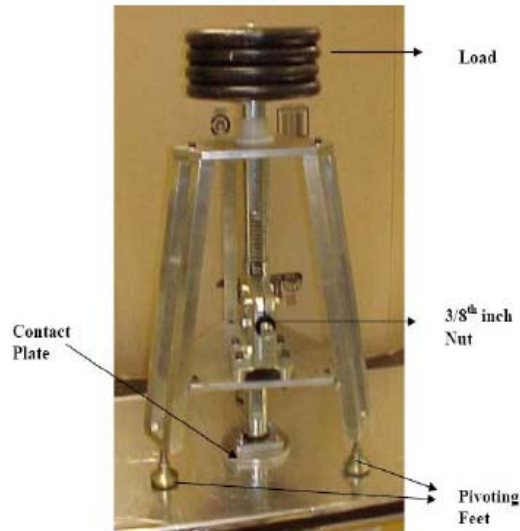
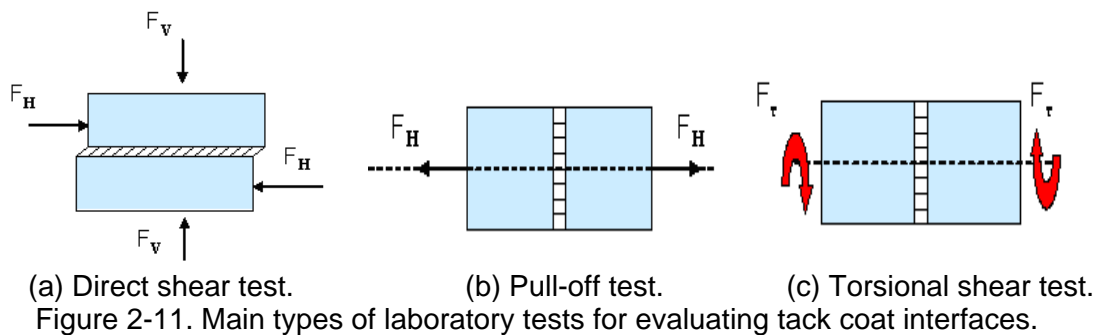


Figure 2-10. Pull-off test device (Tashman et al. 2006).

2.2 SUMMARY OF LITERATURE FINDINGS

Generally, three different loading mechanisms shown in Figure 2-11 have been developed as a laboratory test to investigate tack coat performance. Those are direct shear test, pull-off test, and torsional shear test. Direct shear testing has been most commonly used. The wedge splitting testing conducted by Tschegg et al. (1995) is essentially a pull-off test. Woods (2004) applied both the pull-off tests and torsional tests to obtain the tensile and torsional shear strength of the tack coats. It is important to note that some of those tests included normal load component and some did not, relying on the fact that the tack coat interface is not sensitive to normal pressure. Shearing displacement was the only deformation parameter recorded in most of the studies. The relevance of measuring normal deformation might be of particular interest in developing numerical models for tack coat interface behavior.



The major concern with these types of shear tests is the difficulty of producing pure shear at the interface (type a and c). Shear stresses derived from these tests are idealizations assuming that the shearing force can generate uniform shear stresses at the interface. Strain localizations are inevitable no matter how sophisticated the loading mechanism. However, the use of shorter cores with smaller moment arms can minimize the effect of strain localizations to a certain extent in direct shear test mechanisms. A testing fixture which can hold cylindrical specimens is preferred to evaluate the field extracted

specimens. Apart from the mechanical limitations, another concern about these tests relates to the restrictions in simulating the field loading conditions. Each test (type a, b, and c) can represent only one stress state that occurs in the field, which may not be the critical condition. Given this, it is only possible to characterize interface behavior and optimize tack coat application rate with any validity for that stress state. Testing mechanism type (a) provides the ability to rotate the principal axes so that it can represent different stress states in one test fixture. The principal axes are not necessarily the vertical and horizontal axes as in the case of field stress states away from the wheel loading. In reality, an interface is subjected to different stress states depending on its relative location with respect to loading and environmental conditions. However, none of these considerations of stress state will be as critical as direct shear or uniaxial tension in terms of interface strength. Recognizing the importance of optimizing the tack coat application rate, direct shear and uniaxial tension tests will be sufficient. However, complete characterization of interface response may require more than this.

Some of the findings from the literature on tack coat applications indicate that the major factors affecting laboratory interface shear strength are rate of shear, magnitude of normal force, HMA type, tack coat type, tack coat application rate, surface cleanliness, and temperature. Generally, increased shear rate or normal force magnitude results in increased shear strength, especially at higher temperatures such as 140 °F (60 °C). At lower temperatures, most of the laboratory studies revealed an insensitivity of tack coat interface to normal pressures. Emulsion type used in the tack coat was found to be a factor affecting the maximum shear strength at the interface. Mrawira et al. (1999) reported that the maximum shear strength of tack-coated layers was slightly lower than that of the non-tacked layers for the SS-1 tack coat. Mohammad et al. (2002) verified the loss of interface shear strength with use of SS-1 and even extended this to another emulsion: SS-1h. West et al. (2005) reported the superiority of PG 64-22 over CRS-2 and CSS-1. Hachiya et al. (1997) reported an optimum tack coat application rate for PG-based or rubberized emulsified asphalt tack coats, CRS-2P, CSS-1 etc., which maximized shear stress or number of cycles to induce interface failure. For similar interface conditions, increased temperature resulted in reduced shear strength as reported by almost all of the studies cited herein.

Two criteria have been used to determine the optimum tack coat application rate: maximum shear stress or maximum number of cycles to induce failure. The first criterion is more commonly used because of the simple operation and control during testing. However, the second criterion better simulates the real pavement situation if the proper loading scheme can be applied. Research results also indicated that the area beneath the stress-displacement curve or the fracture energy was a better discriminating factor to characterize the crack growth resistance of the material.

CHAPTER 3 TESTING DEVICE AND SPECIMEN PREPARATION

3.1 TESTING APPARATUS AND MODE

In this study, a modified version of a direct shear apparatus developed by Al-Qadi et al. has been used (Donovan et al., 2000). This device was designed to apply shear force in the vertical direction and normal force in the horizontal direction. The effects of bending moment induced by the eccentricity of the shear force were eliminated by the U-shaped loading arm shown in Figure 3-1. The testing apparatus houses, in specially designed steel chambers, 3.87-in diameter (98.4-mm diameter) PCC and 3.94-in-diameter (100-mm diameter) HMA specimens. The apparatus is attached in a Universal Testing Machine 5P by IPC Ltd.

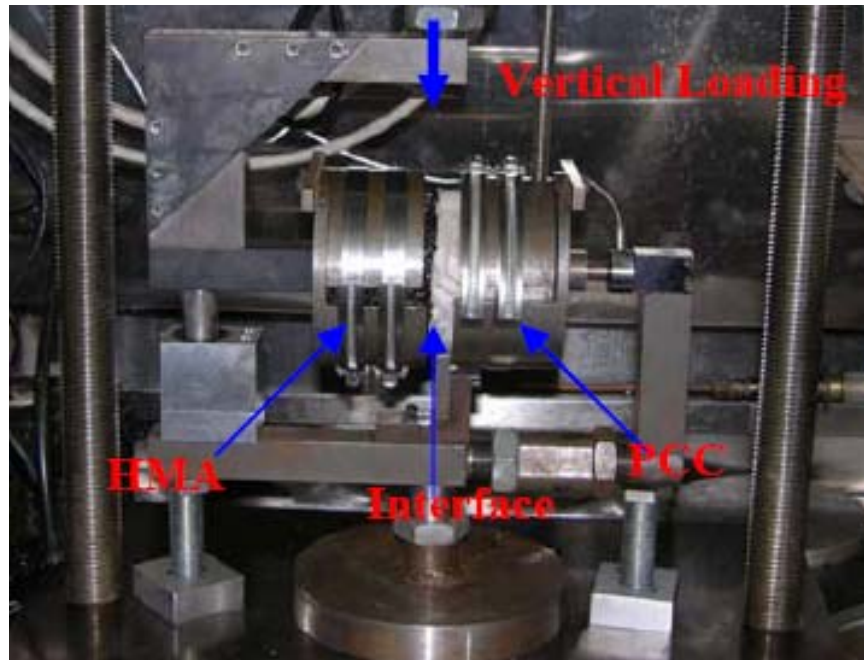


Figure 3-1. Direct shear test apparatus.

During testing, the vertical load is applied to the HMA while the PCC is held stationary. Load and displacement are recorded by the data acquisition system of the loading machine.

Both cyclic and monotonic tests can be performed by this test machine. Two criteria have been used in the literature to determine the optimum tack coat application rate: maximum shear stress for monotonic tests or maximum number of failure cycles for cyclic tests. The first criterion is more commonly used because of its simple operation and control during testing. However, the second criterion better simulates the real pavement situation.

In this study, preliminary tests were performed to compare the two testing modes, and it was found that monotonic testing more precisely quantified the effect of interface characteristics than cyclic testing. Therefore, a monotonic testing mode was selected. The testing was conducted in a displacement control mode at a constant shear rate of 0.47 in/min (12 mm/min). This rate is consistent with other studies (Romanoschi, 1999).

3.2 SPECIMEN PREPARATION

Test specimens were prepared using field PCC cores, laboratory prepared HMA, and tack coats obtained from tack coat supplier. Portland cement concrete cores, 3.87 in (98.4

mm) in diameter, were obtained from PCC pavement at the Advanced Transportation Engineering and Research Laboratory (ATREL) of the University of Illinois at Urbana-Champaign. The HMA was compacted in a gyratory compactor at 3.97-in-diameter (100-mm-diameter) on top of the PCC cores and after placing the tack coat, if applicable.

Initial tests clearly showed that any interface skew in the vertical direction affected repeatability. Hence, it was critical to check the PCC core alignment before applying tack coat and HMA compaction. This concern was resolved by rotating the core to place the skewed surface in the horizontal plane during testing, i.e. no skew in vertical loading/vertical direction.

After the PCC core was cut to the specified height (2.36 in (60 mm)), it was placed inside the steel chamber and rotated until the level bubble indicated that the diameter of the PCC surface was purely vertical (Figure 3-2). This position was marked, so the same position could be used during testing. For oriented surfaces such as those containing transverse or longitudinal tining, cores that did not meet the vertical orientation while maintaining the proper tining alignment were not used in the testing process.

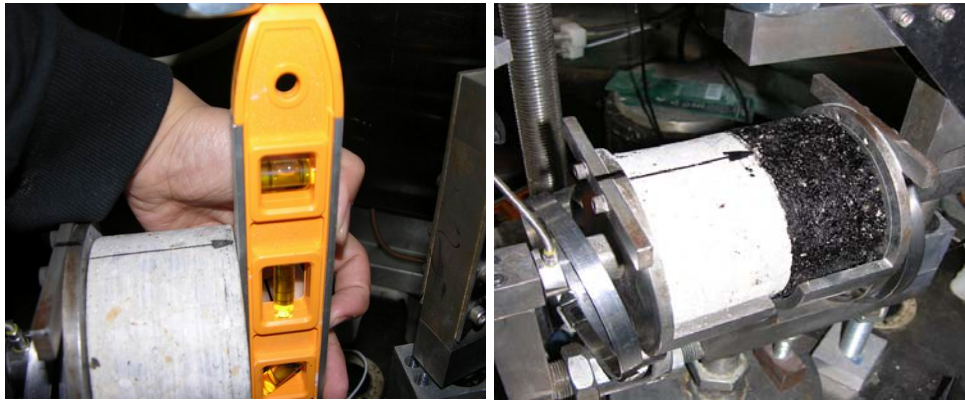


Figure 3-2. PCC surface skew check.

The next step involved tack coat application. The tack coat must be applied uniformly on a clean PCC core surface. All the PCC core surfaces were cleaned by water flushing and brush wiping, followed by drying at room temperature overnight before testing. As shown in Figure 3-3, a plastic bottle with a sponge roller head and paint brushes were used to distribute the tack coat uniformly. The function of the roller head is to roll the tack coat completely over the PCC surface to avoid missing tack coat or applying too much tack coat in any one area. To ensure accurate tack coat application rate, tack coat spillage down the sides of the core was prevented by wrapping duct tape around the wall of the PCC core. The tack coat application rates were monitored by weighing the PCC cores before and after tack coat application. After the tack coat was applied, the core was left at room temperature for 15 min or till visibly broken for setting/ curing.



Figure 3-3. Tools for applying tack coat.

The final step of specimen preparation was HMA compaction on top of the PCC cores upon which tack coat had been applied. Three HMA designs, one for a surface course and two for binder courses, were evaluated. Using a gyratory compactor, specimens were compacted to a total height of 4.53 in (115 mm): 2.36 in (60 mm) PCC + 2.17 in (55 mm) HMA. The target air void of the HMA was set at 7%, which is representative of initial field densities. The required HMA mass to achieve the target air voids was determined through trial and error. Except for tests evaluating moisture effect, prepared specimens were conditioned in an environmental chamber at the specified temperature under dry conditions for at least 4hrs before being tested.

3.3 MOISTURE CONDITIONING PROCEDURE

One of the important tasks of this study was to evaluate the effect of moisture on the interface shear strength. The standard conditioning procedure described in AASHTO Designation T283-02 was modified to be used for conditioning the HMA-PCC specimens (ASTM, 2003). The interface shear strength was determined before and after the moisture conditioning. Two subsets (I and II) of HMA-PCC specimens were tested, each with three replicates. Subset I was tested dry, and subset II was partially vacuum-saturated and soaked in warm water before testing. Subset II was conditioned according to the following procedure.

As shown in Figure 3-4, the specimen was first placed in the vacuum container at 1.9-9.7 psi (13-67 kPa) absolute pressure (10-26 in Hg partial pressure) for a short time (approximately 5 to 10 min). The vacuum was removed and the specimen was submerged in the 68 °F (20 °C) water for a short time (approximately 5 to 10 min). The degree of saturation (S) was then determined using the following equation:

$$S=100J/Va \quad (3-1)$$

where,

S = degree of saturation, percent, %;
 J = volume of absorbed water, in³; and
 Va = volume of air voids, in³.

If the degree of saturation was less than 70%, the procedure was repeated using more vacuum and/or longer time. If the degree of saturation was more than 80%, the specimen has been damaged and must be discarded. In that case, the procedure would be repeated on the next specimen using less vacuum and/or shorter time.



Figure 3-4. HMA-PCC specimen in vacuum container.

If the degree of saturation was between 70% to 80%, the specimens were placed in a bath containing potable water at 140 ± 34 °F (60 ± 1 °C) for 24 hrs (Figure 3-5). After 24 hrs in the 140 °F (60 °C) water bath, the specimens would be placed in a water bath at 68 °F (20 °C) for 2 hrs.



Figure 3-5. Partially vacuumed HMA-PCC specimens in a 140 °F (60 °C) water bath.

The final step was to remove the specimens from the water bath, and test them in the environmental chamber at 68 °F (20 °C). The interface shear strength ratio was then calculated using equation (3-2). Figure 3-6 shows the moisture-conditioned specimen during testing and after failure.

$$SR = S2/S1 \quad (3-2)$$

Where,

SR = interface shear strength ratio, %;

S2 = interface shear strength of moisture-conditioned specimen, psi; and

S1 = interface shear strength of dry specimen, psi.



Figure 3-6. Moisture conditioned HMA-PCC specimen during testing and after failure.

CHAPTER 4 MATERIALS AND TESTING PROGRAM

In this study, six variables were evaluated including HMA type, tack coat type, tack coat application rate, PCC surface texture, testing temperature, and moisture conditioning. The levels for each variable are listed in Table 4-1. Each test was conducted in triplicate. Three HMA types evaluated in this study include: SM-9.5 surface mix, IM-19.0A standard binder mix, and IM-19.0B stripping-vulnerable binder mix. The HMA properties are presented in Table 4-2. Two asphalt emulsions, SS-1hP, SS-1h, and one cutback asphalt, RC-70, used in this study, represent the three tack coat types most widely used in Illinois. Some properties of the three tack coats are presented in Table 4-3. It should be noted that the tack coat application rate used in this report is the residual tack coat application rate. Other tack coat application rates can be calculated according to the residue rate of the tack coat presented in Table 4-3 as well as the amount of the water for dilution.

Table 4-1. Experimental Variables and Levels

| Variables | Levels (No. of Levels) |
|-------------------------------------|---|
| HMA Type | SM-9.5, IM-19.0A, IM-19.0B (3) |
| Tack Coat Type | SS-1hP, SS-1h, RC-70 (3) |
| Residual Tack Coat Application Rate | 0, 0.02, 0.05, 0.09 gal/yd ² (4) * |
| Concrete Surface Texture | Smooth, Transverse Tining, Longitudinal Tining, milling (4) |
| Temperature | 50, 68, 86 °F (3) ** |
| Moisture Condition | Dry, Saturated (2) |

1 L/m² = 0.22 gal/yd²; ** Corresponding to 10, 20, 30 °C

Table 4-2. HMA Job Mix Formula

| Property | | | Passing Ratio (%) | | |
|--------------------------|----------------------|------|-------------------|----------|----------|
| | Sieve Size | | SM-9.5 | IM-19.0A | IM-19.0B |
| | (mm) | (in) | | | |
| Aggregate Gradation | 25.4 | 1.0" | 100 | 100 | 100 |
| | 19.0 | 3/4" | 100 | 98.4 | 98.4 |
| | 12.5 | 1/2" | 100 | 75.0 | 74.2 |
| | 9.5 | 3/8" | 97.0 | 64.2 | 63.2 |
| | 4.75 | # 4 | 57.3 | 38.8 | 36.4 |
| | 2.36 | # 8 | 34.3 | 22.2 | 20.3 |
| | 1.18 | # 16 | 22.7 | 13.3 | 12.2 |
| | 0.6 | # 30 | 15.0 | 6.5 | 8 |
| | 0.3 | # 50 | 8.9 | 5.9 | 5.6 |
| | 0.15 | #100 | 6.3 | 4.4 | 4.3 |
| | 0.075 | #200 | 6.1 | 3.8 | 3.5 |
| | Asphalt Cement Grade | | | PG 70-22 | PG 64-22 |
| Asphalt Content (%) | | | 5.4 | 4.5 | 5.0 |
| Maximum Specific Gravity | | | 2.501 | 2.446 | 2.492 |

Table 4-3. Tack Coat Properties

| Tack Coat Property | SS-1hP | SS-1h | RC-70 |
|--|--------|-------|-------|
| Tack Coat Specific Gravity @ 60 °F (15.6 °C) | 1.006 | 1.009 | 0.943 |
| Tack Coat Asphalt Residue Rate by Volume (%) | 62 | 64 | 66 |

As shown in Table 4-1, the complete factorial experiment results in 2592 tests ($3 \times 3 \times 4 \times 4 \times 3 \times 2 \times 3$). Considering resource and time limitations, performing this number of tests is not possible. Therefore, a partial factorial experimental design was performed in four steps to minimize the total number of tests. In the first step, the effects of HMA type, tack coat type, and the application rate were evaluated. Specimens were prepared with two HMA types (SM-9.5 and IM-19.5A), three tack coat types (SS-1hP, SS-1h and RC-70), and four residual application rates (0, 0.02, 0.05, and 0.09 gal/yd² (0, 0.09, 0.23, and 0.41 L/m²)). The PCC core surface was smooth and the test was conducted at 68 °F (20 °C).

The second step evaluated the effect of PCC surface texture. The following textures were considered: smooth, transverse tining, longitudinal tining, and milling. All test specimens were prepared with standard binder mix and SS-1hP tack coat at several residual application rates varying from 0.02 to 0.09 gal/yd² (0.09 to 0.4 L/m²) at 68 °F (20 °C).

The third step examined the temperature effect on the interface shear strength. All specimens in this step were prepared with SM-9.5 surface mix, SS-1hP tack coat at a residual application rate of 0.05 gal/yd² (0.23 L/m²), and smooth PCC surfaced cores. Tests were conducted at three temperatures: 50, 68 and 86 °F (10, 20 and 30 °C).

The fourth step assessed the moisture conditioning effect on the interface shear strength. Two HMA designs were considered, one was a standard binder mix, IM-19.0A, and the other a stripping-vulnerable binder mix, IM-19.0B. The aggregate gradations of the two mixes are similar. However, an anti-stripping agent is required in IM-19.0B. A modified approach to the standard conditioning procedure, AASHTO T283-02, as described in Chapter 3, was used for conditioning the HMA-PCC specimens. All the specimens in this step were prepared with SS-1hP at 0.05 gal/yd² (0.23 L/m²) and smooth PCC surfaced cores.

CHAPTER 5 TEST RESULTS AND ANALYSIS

Interface shear strength is considered the critical parameter to quantify the influence of each test variable on the interface bonding. It is calculated as the measured peak shear load divided by the area of the interface. A typical interface shear stress-shear displacement plot is shown in Figure 5-1. The effect of each testing variable on the interface shear strength is discussed in the following sections.

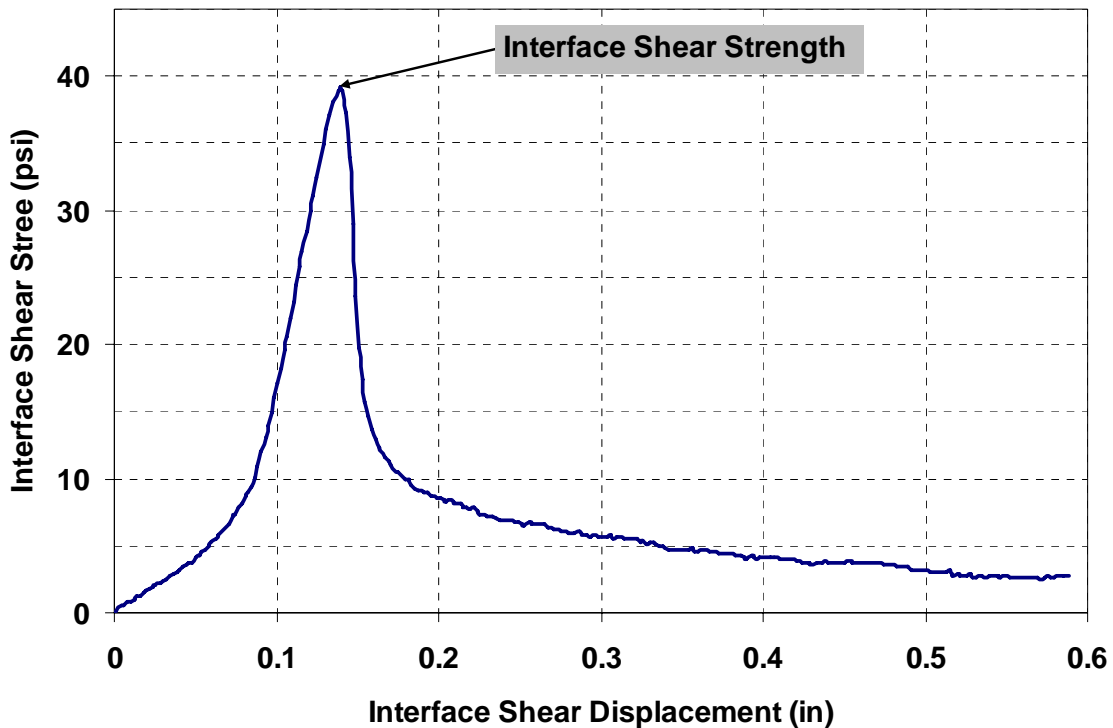


Figure 5-1. Interface shear stress–displacement curve.

5.1 EFFECTS OF HMA TYPE AND TACK COAT TYPE AND APPLICATION RATE

The shear strengths for the two HMA and three tack coat types at four application rates are presented in Table 5-1. From Figure 5-2, the following observations can be made:

- It is evident that asphalt emulsions (SS-1h and SS-1hP) provide better interface shear strength than cutback asphalt (RC-70) at various tack coat application rates for both surface and binder mixes. No obvious difference is found in the interface shear strength between the two asphalt emulsions.
- In general, surface mix shows better interface shear strength than the standard binder mix for the same tack coat material type except for RC-70 at 0.02 gal/yd² (0.09 L/m²).
- The application rate of 0.05 gal/yd² (0.23 L/m²) provides the highest interface shear strength among the four application rates considered.

Table 5-1. Interface Shear Strength (psi)

| HMA | Tack Coat | Residual Tack Coat Application Rate (gal/yd ²) | | | |
|---------------------|-----------|--|-------------|-------------|-------------|
| | | 0.00 | 0.02 | 0.05 | 0.09 |
| Surface Mix | RC-70 | 9.1 (15.8) | 10.0 (12.5) | 44.3 (13.1) | 43.8 (6.4) |
| | SS-1h | 9.1 (15.8) | 40.4 (7.5) | 64.0 (13.5) | 59.0 (16.4) |
| | SS-1hP | 9.1 (15.8) | 37.7 (2.1) | 63.4 (10.0) | 59.1 (7.5) |
| Standard Binder Mix | RC-70 | 8.4 (4.8) | 10.5 (10.9) | 34.0 (1.6) | 26.4 (12.2) |
| | SS-1h | 8.4 (4.8) | 20.7 (24.1) | 64.0 (13.5) | 51.5 (16.5) |
| | SS-1hP | 8.4 (4.8) | 49.0 (23.1) | 77.2 (4.6) | 76.6 (17.9) |

Notes: 1 kPa = 0.145 psi

1 L/m² = 0.22 gal/yd²

The values in the table are the average from three individual specimens;

The values in the parentheses represent the coefficient of variation (%).

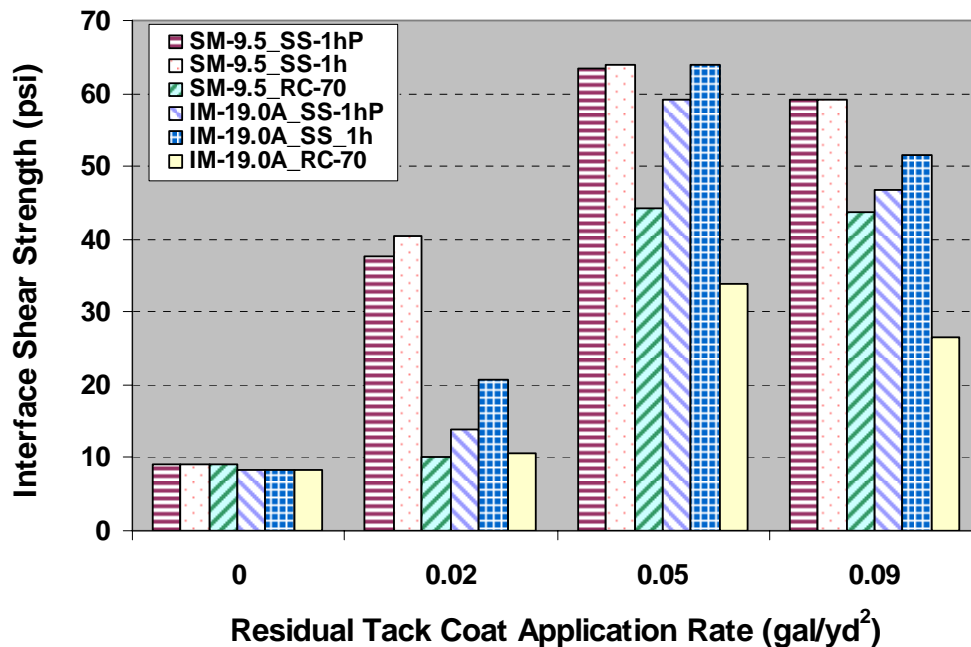


Figure 5-2. Effect of HMA, tack coat and tack coat application rate.

The effect of HMA type, tack coat type, and application rate on interface strength was evaluated statistically. Test data was first divided into two sets: surface mix SM-9.5 and standard binder mix IM-19.0A. This partitioning allows investigation of the effects of tack coat type and tack coat application rate for each HMA. Next the data was grouped according to the tack coat type: SS-1hP, SS-1h, and RC-70, to evaluate the effects of HMA type and tack coat application rate for each tack coat. Each data set was considered an independent completely randomized design (CRD).

The data was checked for a normal distribution. The Shapiro-Wilk test (Ott, 2000), which checks data normality, was performed for each data set. As can be seen in Figure 5-3, all the Shapiro-Wilk test p-values are greater than 0.05. This suggests the null hypothesis that the data is normally distributed cannot be rejected at a significance level of 0.05.

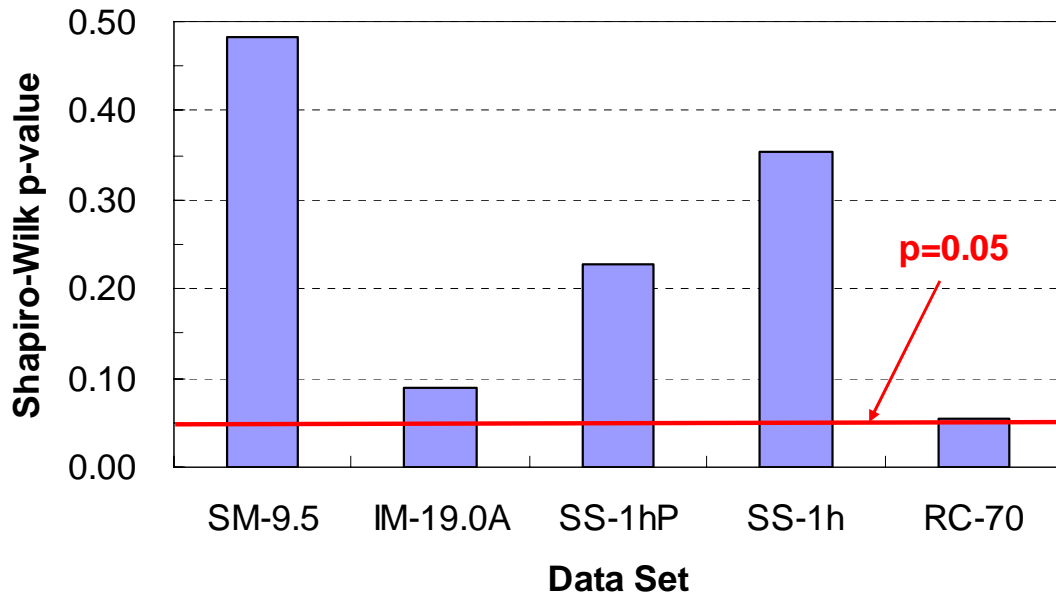


Figure 5-3. Shapiro-Wilk test p-values for each data set.

Using the SAS statistical software package, the Fisher LSD (Least Significant Difference) procedure was performed for pair-wise comparisons within each set of interface shear strength under the different test conditions. Results of the LSD tests are shown in Table 5-2. The test results are rank ordered and each mean is given a letter, in the first column. The letter is changed when the mean is statistically different from the previous value (Ott, 2000). The following observations are made:

- From Tables 5-2 (a) and 5-2 (b), for the same application rate, all average interface strengths, when RC-70 is used, are smaller than those when SS-1hp or SS-1h is used. For example, at the application rate of 0.05 gal/yd² (0.23 L/m²) in table 5-2(a), the t group for RC-70 is C, and for both SS-1hP and SS-1h is A. The average interface shear strengths of SS-1hP and SS-1h are not significantly different at various tack coat application rates. The exception is the tack coat application rate of 0.09 gal/yd² (0.41 L/m²) when IM-19.0A was used.
- From Tables 5-2 (c), 5-2 (d), and 5-2(e), for the same application rate, the average interface strength is greater when SM-9.5 surface mix is used compared to using IM-19.0A standard binder mix. There are two exceptions: when SS-1h and RC-70 are used at a low rate (0.02gal/yd² (0.09 L/m²)), the interface strengths provided by SM-9.5 and IM-19.0A are statistically same.
- 0.05 gal/yd² (0.23 L/m²) application rate provides the highest interface strengths under all conditions; hence, it is approximately the optimum residual application rate.

Table 5-2 (a). LSD Results for SM-9.5

| t group | Mean of Interface Shear Strength (psi) | N | Tack Coat Type | Residual Tack Coat Application Rate (gal/yd²) |
|----------------|---|----------|-----------------------|---|
| A | 71.8 | 3 | SS-1hP | 0.05 |
| A/B | 64.0 | 3 | SS-1h | 0.05 |
| A/B | 63.2 | 3 | SS-1hP | 0.09 |
| B | 59.0 | 3 | SS-1h | 0.09 |
| C | 49.6 | 3 | RC-70 | 0.05 |
| C/D | 40.4 | 3 | SS-1h | 0.05 |
| D | 38.6 | 3 | RC-70 | 0.09 |
| D | 37.7 | 3 | SS-1hP | 0.02 |
| E | 10.0 | 3 | RC-70 | 0.02 |
| E | 9.1 | 3 | No tack coat | 0.00 |

Table 5-2 (b). LSD Results for IM-19.0A

| t group | Mean of Interface Shear Strength (psi) | N | Tack Coat Type | Residual Tack Coat Application Rate (gal/yd²) |
|----------------|---|----------|-----------------------|---|
| A | 64.0 | 3 | SS-1h | 0.05 |
| A/B | 58.2 | 3 | SS-1hP | 0.05 |
| B | 48.6 | 3 | SS-1h | 0.09 |
| C | 42.5 | 3 | SS-1hP | 0.09 |
| D | 34.0 | 3 | RC-70 | 0.05 |
| D/E | 26.4 | 3 | RC-70 | 0.09 |
| E/F | 20.7 | 3 | SS-1h | 0.02 |
| F/G | 13.9 | 3 | SS-1hP | 0.02 |
| G | 10.6 | 3 | RC-70 | 0.02 |
| G | 9.0 | 3 | No tack coat | 0.00 |

Table 5-2 (c). LSD Results for SS-1hP

| t group | Mean of Interface Shear Strength (psi) | N | HMA Type | Residual Tack Coat Application Rate (gal/yd²) |
|----------------|---|----------|-----------------|---|
| A | 71.8 | 3 | SM-9.5 | 0.05 |
| B | 63.2 | 3 | SM-9.5 | 0.09 |
| B | 58.2 | 3 | IM-19.0A | 0.05 |
| C | 42.5 | 3 | IM-19.0A | 0.09 |
| C | 37.7 | 3 | SM-9.5 | 0.02 |
| D | 13.9 | 3 | IM-19.0A | 0.02 |
| D | 9.1 | 3 | SM-9.5 | 0.00 |
| D | 71.8 | 3 | IM-19.0A | 0.00 |

Table 5-2 (d). LSD Results for SS-1h

| t group | Mean of Interface Shear Strength (psi) | N | HMA Type | Residual Tack Coat Application Rate (gal/yd ²) |
|---------|--|---|----------|--|
| A | 49.6 | 3 | SM-9.5 | 0.05 |
| B | 38.6 | 3 | SM-9.5 | 0.09 |
| B | 35.3 | 3 | IM-19.0A | 0.05 |
| C | 26.4 | 3 | IM-19.0A | 0.09 |
| D | 10.6 | 3 | SM-9.5 | 0.02 |
| D | 10.0 | 3 | IM-19.0A | 0.02 |
| D | 9.1 | 3 | SM-9.5 | 0.00 |
| D | 49.6 | 3 | IM-19.0A | 0.00 |

Table 5-2 (e). LSD Results for RC-70

| t group | Mean of Interface Shear Strength (psi) | N | HMA Type | Residual Tack Coat Application Rate (gal/yd ²) |
|---------|--|---|----------|--|
| A | 49.6 | 3 | SM-9.5 | 0.05 |
| B | 38.6 | 3 | SM-9.5 | 0.09 |
| B | 35.3 | 3 | IM-19.0A | 0.05 |
| C | 26.4 | 3 | IM-19.0A | 0.09 |
| D | 10.6 | 3 | SM-9.5 | 0.02 |
| D | 10.0 | 3 | IM-19.0A | 0.02 |
| D | 9.1 | 3 | SM-9.5 | 0.00 |
| D | 49.6 | 3 | IM-19.0A | 0.00 |

Note: 1 kPa = 0.145 psi; 1 L/m² = 0.22 gal/yd²

5.2 OPTIMUM TACK COAT APPLICATION RATE DETERMINATION

Figure 5-2 indicates that 0.05 gal/yd² (0.23 L/m²) is approximately the optimum tack coat application rate. However, it is unclear how the interface shear strength behaves around 0.05 gal/yd² (0.23 L/m²). Therefore, tests at three additional residual tack coat application rates, 0.03, 0.04, and 0.07 gal/yd² (0.14, 0.18, 0.32 L/m²), were performed to fine-tune the optimum tack coat application rate. Given that the two mixes exhibit the same trend of interface shear strength with tack coat application rate for all three tack coat types, only the IM-19.0A standard binder mix and SS-1hP asphalt emulsion were investigated. Figure 5-4 presents the test results using the SM-9.5 with SS-1hP at seven application rates. The maximum interface shear strength was found at 0.04 gal/yd² (0.18 L/m²).

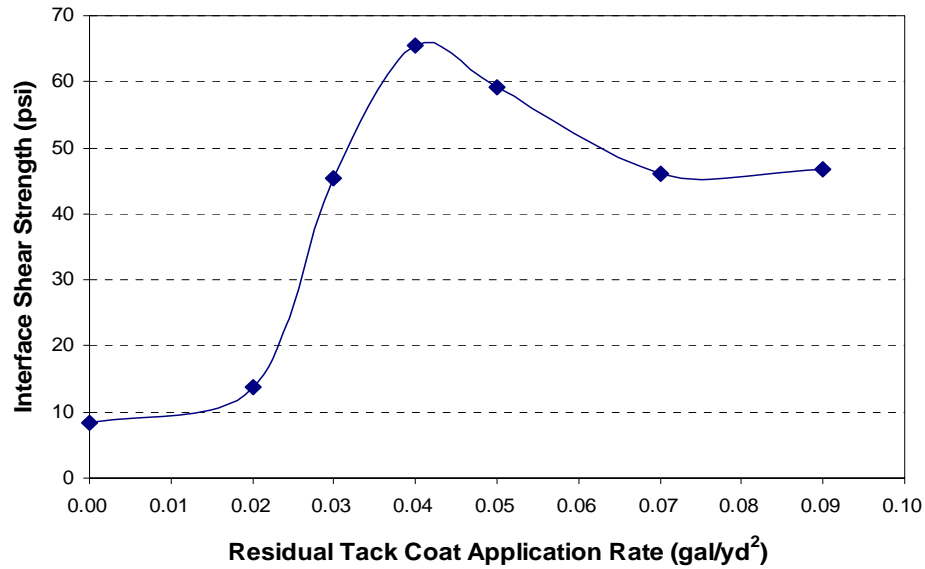


Figure 5-4. Optimum tack coat application rate determination.

5.3 PORTLAND CEMENT CONCRETE SURFACE TEXTURE EFFECT

In this study, several PCC surfaces texture, as shown in Figure 5-5, were considered, including smooth, transverse tining, longitudinal tining, and milling. Test specimens were prepared using IM-19.0A standard binder mix and SS-1hP tack coat at three residual application rates, 0.02, 0.05, and 0.09 gal/yd² (0.09, 0.23, 0.41 L/m²). The tests were conducted at 68 °F (20 °C). Results presented in Table 5-3 and Figure 5-6 show that the orientation of the tining does not have an effect on interface shear strength. The effect of tack coat application rate on smooth surfaces is more pronounced than its effect on tined and milled surfaces. The surface tining appears to increase interface shear strength when the tack coat application rate is low compared to smooth surface. The milled surface provided significantly larger interface shear strength than tined and smooth surfaces at various tack coat application rates.

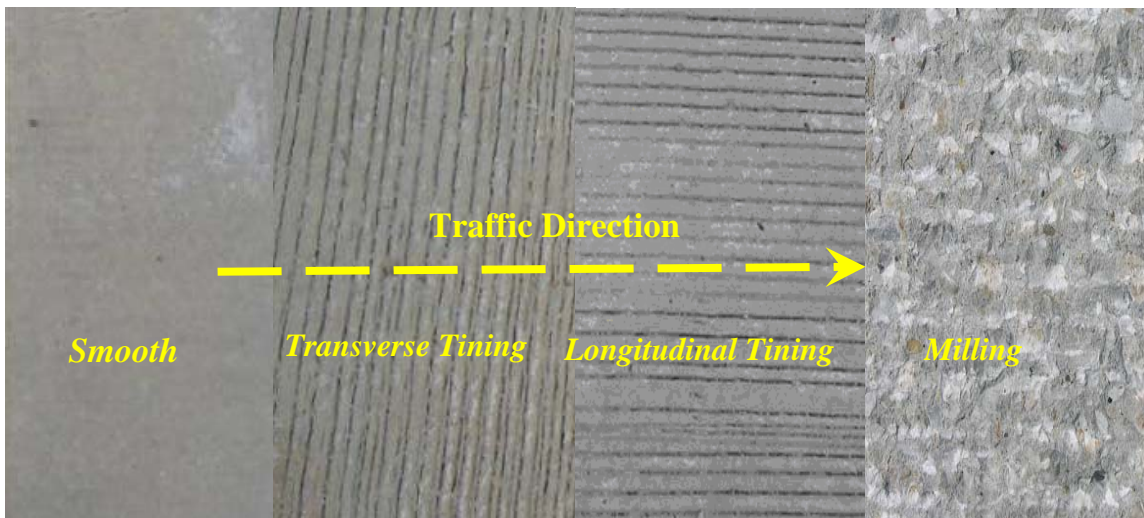


Figure 5-5. PCC surface textures.

Table 5-3. Interface Shear Strength (psi)

| Concrete Surface Texture | Residual Tack Coat Application Rate (gal/yd ²) | | |
|--------------------------|--|-------------|-------------|
| | 0.02 | 0.05 | 0.09 |
| Smooth | 13.9 (23.1) | 59.0 (6.5) | 46.8 (17.9) |
| Transverse Tining | 27.9 (13.8) | 48.9 (11.6) | 45.3 (8.3) |
| Longitudinal Tining | 45.3 (8.7) | 47.6 (13.9) | 45.3 (0.3) |
| Milled | 86.0 (16.9) | 79.1 (6.7) | 61.5 (16.8) |

Notes: 1 kPa = 0.145 psi

1 L/m² = 0.22 gal/yd²

The values in the table are the average from three individual specimens;

The values in the parentheses represent the coefficient of variation (%).

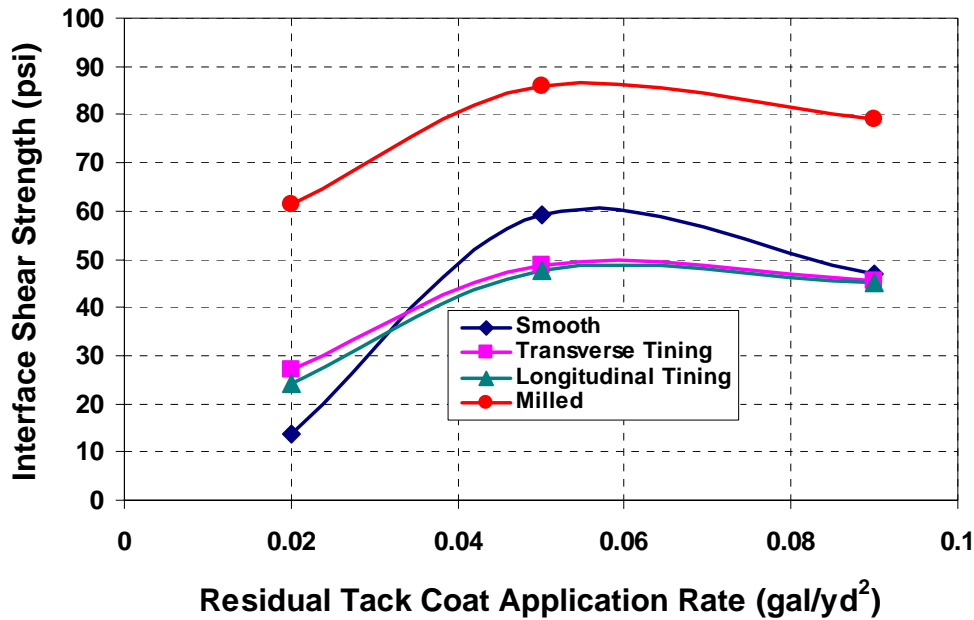


Figure 5-6. Effect of PCC surface texture.

The Shapiro-Wilk test gave a p-value of 0.452, indicating that this test data is normally distributed. Results from the LSD tests are shown in Table 5-4. At the same residual application rate, the interface strength of the milled PCC surface is always statistically larger than those of the other types of surface textures. This means the interlocking between the rough milled PCC and HMA always has a dominant effect at various tack coat application rates. At a lower residual application rate, 0.02 gal/yd² (0.09 L/m²), the interface strength of the smooth PCC surface is statistically lower than that of transverse or longitudinal tined surfaces. As the residual tack coat application rate increases to 0.05 gal/yd² (0.23 L/m²), the effect of tack coat becomes more pronounced than the effect of surface tining. At a low tack coat application rate, the interlock between tined PCC and HMA is higher in spite of any reduced contact area between the two surfaces resulting from the tining. This interlock effect becomes less as the tack coat application rate increases. Therefore, at a medium residual application rate, 0.05 gal/yd² (0.23 L/m²), any reduced contact area surpasses the effect of interlock. As the tack coat increases beyond the medium tack coat application rate, the effect of surface condition diminishes and becomes irrelevant. However, it is also clear that the smooth PCC surface is more sensitive to tack coat application rate than interfaces with tined and milled PCC surfaces at 68 °F (20 °C).

Actually, for milled and tined surfaces, the shear strength at 0.05 and 0.09 gal/yd² (0.23 and 0.41 L/m²) are statistically the same. It has to be emphasized that all tests were conducted at zero normal loading on the interface. It is expected that interlocking between HMA surface and milled and tined concrete surfaces would increase when normal pressure is applied, increasing the interface strength.

Table 5-4 LSD Results for Various Surface Textures

| t group | Mean of Interface Shear Strength (psi) | N | Concrete Surface Texture | Residual Tack Coat Application Rate (gal/yd²) |
|----------------|---|----------|---------------------------------|---|
| A | 86.0 | 3 | Milling | 0.05 |
| A | 79.1 | 3 | Milling | 0.09 |
| B | 61.5 | 3 | Milling | 0.02 |
| B | 59.1 | 3 | Smooth | 0.05 |
| C | 47.7 | 3 | Transverse Tining | 0.05 |
| C | 47.7 | 3 | Longitudinal Tining | 0.05 |
| C | 46.8 | 3 | Smooth | 0.09 |
| C | 45.4 | 3 | Longitudinal Tining | 0.09 |
| C | 45.3 | 3 | Transverse Tining | 0.09 |
| D | 27.0 | 3 | Transverse Tining | 0.02 |
| D | 24.2 | 3 | Longitudinal Tining | 0.02 |
| E | 13.9 | 3 | Smooth | 0.02 |

Notes: 1 kPa = 0.145 psi; 1 L/m² = 0.22 gal/yd²

5.4 TEMPERATURE EFFECT

Tests were conducted at three temperatures: 50, 68, and 86 °F (10, 20, and 30 °C) using the SM-9.5 surface mix, smooth surfaced PCC, and the SS-1hP tack coat at an application rate of 0.05 gal/yd² (0.23 L/m²). Figure 5-7 clearly shows that within the temperature range evaluated, the interface shear strength decreases significantly with increased temperature. This observation is consistent with previous studies (Hachiya, 1997; Woods, 2004).

The Shapiro-Wilk statistical analysis gives a p-value of 0.82, suggesting test data has good normality. The LSD test results given in Table 5-5 shows that the interface strengths at the three temperatures are statistically different. It has to be noted that the temperature significance decreases as the tack coat application rate decreases, since at low application rates the effect of interlocking between two bulk materials will be more significant. In addition, at very low temperature, close to the binder and/or tack coat glassy temperature, the interface strength is expected to reduce because of material brittleness and possible debonding from thermal characteristic differences.

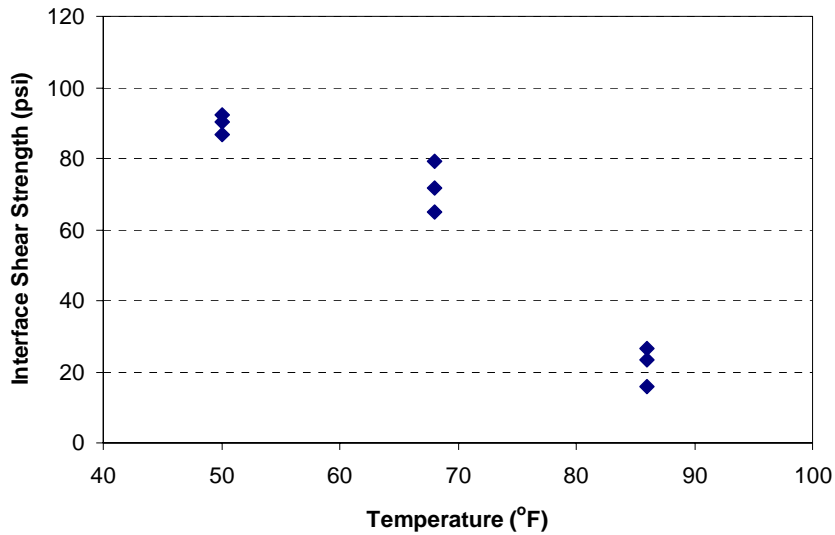


Figure 5-7. Temperature effect on interface shear strength.

Table 5-5. LSD Results for Various Temperatures

| t group | Mean of Interface Shear Strength (psi) | N | Temperature (°F) |
|---------|--|---|------------------|
| A | 89.8 | 3 | 50 |
| B | 71.8 | 3 | 68 |
| C | 21.9 | 3 | 86 |

Note: 1 kPa = 0.145 psi; °C = (°F-32)*5/9

5.5 MOISTURE EFFECT

Test results for specimens with two types of binder mixes before and after moisture conditioning are shown in Tables 5-6 and 5-7. Figure 5-8 shows the effect of moisture conditioning on the interface shear strength. The interface shear strengths for both mixes were greatly reduced after moisture conditioning. For the standard binder mix, the interface shear strength decreased from 59.1 psi to 33.7 psi (407.6 kPa to 232.4 kPa) (43% reduction); while for the stripping-vulnerable mix, the decrease was from 65.3 psi to 21.9 psi (450.3 kPa to 151.0 kPa) (67% reduction). All testing was conducted with three replicates. The coefficients of variation (COV) for the standard binder mix were 6.5% and 15.2% before and after moisture condition, respectively. For the moisture sensitive mix, the COV's were 10.9% and 9.8%, respectively. It was evident that moisture conditioning can significantly reduce the interface shear strength between HMA overlays and PCC pavements. This effect is more pronounced when a stripping-vulnerable HMA is used. Hence, durable HMA can improve HMA-PCC interface shear strength.

Table 5-6. Test Results for Specimens with Standard Binder Mix

| Testing Condition | Replicate | Interface Shear Strength (psi) | Average Strength (psi) | Standard Deviation (psi) | COV (%) |
|----------------------|-----------|--------------------------------|------------------------|--------------------------|---------|
| Dry | 1 | 56.3 | 59.1 | 2.7 | 4.6 |
| | 2 | 61.8 | | | |
| | 3 | 59.1 | | | |
| Moisture Conditioned | 1 | 33.2 | 33.7 | 5.1 | 15.2 |
| | 2 | 39.0 | | | |
| | 3 | 28.8 | | | |

Table 5-7. Test Results for Specimens with Stripping-vulnerable Binder Mix

| Testing Condition | Replicate | Interface Shear Strength (psi) | Average Strength (psi) | Standard Deviation (psi) | COV (%) |
|----------------------|-----------|--------------------------------|------------------------|--------------------------|---------|
| Dry | 1 | 60.3 | 65.3 | 7.1 | 10.9 |
| | 2 | 62.2 | | | |
| | 3 | 73.5 | | | |
| Moisture Conditioned | 1 | 20.3 | 21.9 | 1.5 | 9.8 |
| | 2 | 23.4 | | | |
| | 3 | 22.1 | | | |

Note: 1 kPa = 0.145 psi

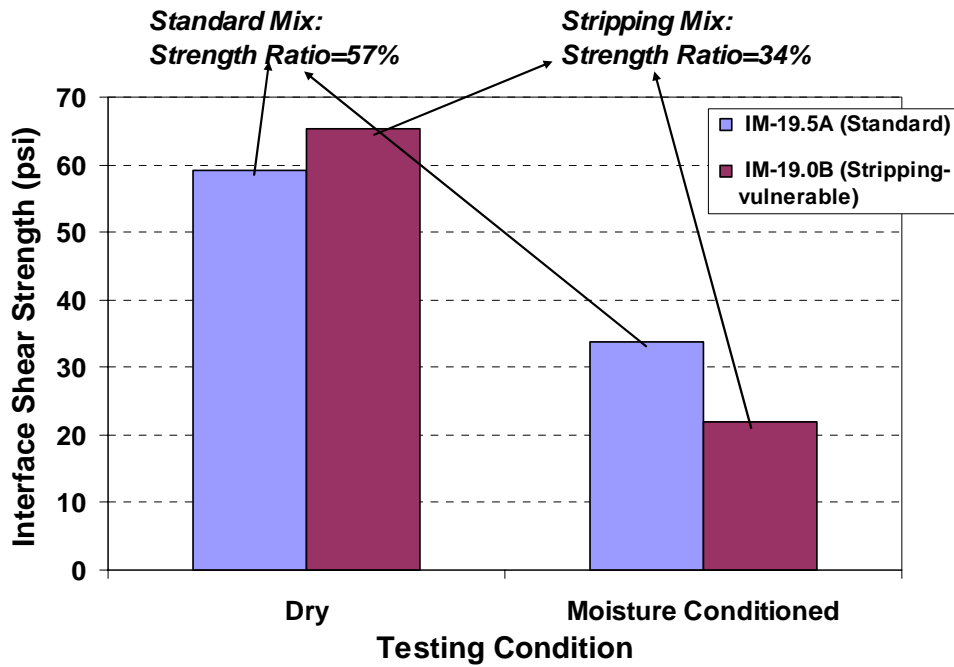


Figure 5-8. Interface shear strength under various moisture conditions.

CHAPTER 6 SUMMARY

A monotonic direct shear test with no normal force was used to determine optimum tack coat application rate at the HMA overlay-PCC pavement interface. This test measures the interface shear strength, and several interface parameters were examined including the following: HMA type, tack coat type, tack coat application rate, PCC surface texture, temperature, and moisture. The significance of the test results was statistically validated. This laboratory study concludes the following:

- Surface mix provides better interface shear strength than binder mixes.
- Asphalt emulsions, SS-1hP and SS-1h, provides better interface shear strength than cutback asphalt, RC-70. No significant difference in the interface shear strength is found between SS-1hP and SS-1h.
- The mixes tested have the same trend of interface shear strength and tack coat application rate for various tack coat types. The optimum residual tack coat application rate for SS-1hP asphalt emulsion using IM-19.0A binder mix was found to be 0.04 gal/yd² (0.18 L/m²) in the lab.
- Four concrete surface textures were evaluated in this study including smooth, transverse tining, longitudinal tining, and milling. The milled PCC surface provides the highest interface shear strength
- The direction of tining in the PCC surface has no effect on the interface shear strength at 68 °F (20 °C).
- While tined PCC surfaces provide higher interface shear strength than a smooth surface at low tack coat application rates, at the optimum tack coat application rate the smooth surface can provide better bonding at intermediate temperatures given that no normal forces are applied.
- At intermediate to high temperatures, the lower temperature produces better bonding. However, this may not hold true as the temperature approaches the extremely low glassy temperature of the HMA and/or tack coat.
- Moisture conditioning significantly decreases the interface shear strength. This reduction is more pronounced when a stripping-vulnerable binder mix is used.

Full-scale testing is being performed during the preparation of this report that includes 25 test sections. For those test sections which undergo accelerated loading it is hoped they will provide field validation of the laboratory results reported herein.

REFERENCES

- Al-Qadi, I.L., H. Wang, and P.J. Yoo (2008). "Dynamic Analysis and In-Situ Validation of Perpetual Pavement Response to Vehicular Loading," 87 Annual Meeting of Transportation Research Board, Washington D.C.
- Asphalt Institute (2000). A Basic Asphalt Emulsion Manual. Manual Series No. 19 (MS-19), Third Edition, The Asphalt Institute, Lexington, KY.
- Asphalt Institute (2003). Construction of Hot Mix Asphalt Pavements, Manual Series No. 22 (MS-22), Second Edition. The Asphalt Institute, Lexington, KY.
- ASTM (2003). "ASTM D 8-02 Standard Terminology Relating to Materials for Roads and Pavements", Annual Book of ASTM Standards 2003, Section 4: Construction, Vol. 04.03, American Society for Testing and Materials, West Conshohocken, PA.
- Carpenter, S. H. and T. J. Freeman (1986), "Characterizing Premature Deformation in Asphalt Concrete Placed Over PCC Pavements," Transportation Research Board, Research Record No. 1070, TRB, National Research Council, Washington, D.C., pp. 30-42.
- DeJong, D.L. (1973). Computer Program, BISAR, Royal/Shell Laboratory, External Report AMSR 0006.73, Amsterdam, The Netherlands.
- Donovan, E. P., Al-Qadi, I. L., and Loulizi A. (2000). "Optimization of Tack Coat Application Rate for Geocomposite Membrane on Bridge Decks." Transportation Research Record: Journal of the Transportation Research Board, No. 1740, TRB, National Research Council, Washington, D.C., pp 143-150.
- Hachiya, Y., and Sato, K. (1997). "Effect of Tack Coat on Bonding Characteristics at Interface between Asphalt Concrete Layers." Proceedings of 8th International Conference on Asphalt Pavements, Vol. 1, pp. 349-362.
- Huang, Y.H. (2003). Pavement Analysis and Design, Second Edition. Prentice Hall, NJ.
- Khweir, K. and Fordyce, D. (2003). "Influence of Layer Bonding on the Prediction of Pavement Life." Proceedings of the Institution of Civil Engineering Transport 156, pp 73-83.
- Mohammad, L. N., Raqib, M. A., and Huang, B. (2002). "Influence of Asphalt Tack Coat Materials on Interface Shear Strength." In Transportation Research Record: Journal of the Transportation Research Board, No. 1789, TRB, National Research Council, Washington, D.C., pp. 56-65.
- Mohammad, L. N., Wu, Z., and Raqib, M. A. (2005). Interim Report: Investigation of the Behavior of Asphalt Tack Interface Layer. Louisiana Transportation Research Center, Baton Rouge, LA.
- Mrawira, D., and Damude, D. J. (1999). "Revisiting the Effectiveness of Tack Coats in HMA Overlays: The Shear Strength of Tack Coats in Young Overlays." Proceeding of 14th Annual Conference, Canadian Technical Asphalt Association Proceedings, pp 116-129.

Ott, R. L., and Longnecker, M. (2000). An Introduction to Statistical Methods and Data Analysis, 5th Edition. Duxbury Press, Pacific Grove, CA.

Romanoschi, S. A. (1999). Ph.D. Dissertation: Characterization of Pavement Layer Interfaces. Louisiana State University, Baton Rouge, LA.

Santagata, E., and Canestari, F. (1994) "Tensile and Shear Tests of Interfaces in Asphalt Mixtures: a New Perspective on Their Failure Criteria," Proceeding of the 2nd International Symposium on Highway Surfacing, Newtownabbey, UK.

Shahin, M., Van Dam, T., Kirchner, K., and Blackmon, E. W. (1987). Consequence of Layer Separation on Pavement Performance. Report DOT/FAA/PM-86/48, Federal Aviation Administration, Washington, D.C.

Tashman, L., Nam, K., and Papagiannakis, T. (2006). Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength between Pavement Layers. Washington Center for Asphalt Technology, Pullman, WA.

Tschegg, E. K., Kroyer, G., Tan, D., Stanzi-Tschegg, S. E., and Litzka, J. (1995). "Investigation of Bonding between Asphalt Layers on Road Construction." Journal of Transportation Engineering, pp 309-316.

TxDOT (2001). Proper Use of Tack Coat, Technical Advisory 2001-1. Texas Department of Transportation, Austin, TX.

USACE (1991). Guide Specifications for Military Construction. CEGS-02556, U.S. Army Corps of Engineers, Washington, DC.

USACE (2000). Hot-Mix Asphalt Paving Handbook 2000. AC 150/5370-14A, U.S. Army Corps of Engineers, Washington, DC.

USACE (2001). Unified Facilities Criteria Standard Practice Manual for Flexible Pavements, U.S. Army Corps of Engineers, Naval Facilities Engineering Command, Air Force Civil Engineer Support Agency.

Uzan, J., Livneh, M., and Eshed, Y. (1978). "Investigation of Adhesion Properties between Asphaltic Concrete Layers." Asphalt Paving Technology, Proceedings of the Association of Asphalt Paving Technologists, Technical Sessions, Vol. 47, Lake Buena Vista, FL. pp 495-521.

West, R., Zhang, J. and Moore, J. (2005). Evaluation of Bond Strength between Pavement Layers. NCAT Report 05-08, Auburn, AL.

Woods, M. E. (2004). Master Thesis: Laboratory Evaluation of Tensile and Shear Strengths of Asphalt Tack Coats. Mississippi State University, Starkville, MS.

Yildirim, Y., Smit, A. F., and Korkmaz, A. (2005). "Development of a Laboratory Test Procedure to Evaluate Tack Coat Performance." Turkish Journal of Engineering and Environmental Sciences, No. 29, pp. 195-205.

