Tack Coat Type and Application Rate Optimization to Enhance HMA Overlay-PCC Interface Bonding: Laboratory and APT Testing

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ABSTRACT

Interface bonding between hot-mix asphalt (HMA) overlays and Portland Cement Concrete (PCC) pavements is one of the most significant factors affecting overlay service life. The quality of tack coat and its application rate have long been postulated as primary factors in overlay performance. However, a laboratory test or field validated study did not exist to quantify the effects of these factors. Therefore, the objectives of this study were to conduct laboratory testing to optimize the tack coat application rate and to validate the laboratory results using accelerated pavement testing (APT). Laboratory direct shear tests were performed on specimens prepared with field extracted PCC cores and laboratory compacted HMA. The laboratory investigation was validated by conducting accelerated full-scale testing at the University of Illinois Advanced Transportation Research and Engineering Lab (ATREL). Two types of tack coats were applied to the test sections: SS-1hP and RC-70; each at three residual rates (0.09, 0.18, and 0.41 L/m^2). The HMA overlay thickness was 57 mm. In total, 24 various sections were included in the full-scale testing. Test sections were loaded by the Accelerated Transportation Loading ASsembly (ATLAS) at the centerline. The tensile strains at the bottom of HMA, to quantify potential interface slippage, were measured for selective sections. In addition, primary HMA rutting was analyzed. The study concluded that SS-1hP provided better interface shear strength than RC-70. Additionally, the optimum residual tack coat application rate was determined to be 0.18 L/m^2 based on the field validated laboratory testing results.

KEYWORDS: HMA Overlay, PCC Pavement, Tack Coat, Interface Bonding, Accelerated Pavement Testing

INTRODUCTION

Interface bonding between hot-mix asphalt (HMA) overlays and Portland Cement Concrete (PCC) pavements is one of the most significant factors affecting overlay service life. Characteristics that may affect the HMA-PCC bonding include the HMA material, tack coat material, tack coat application rate, PCC surface texture, temperature, and moisture. Considerable research has been conducted on the interface bonding between pavement layers (*1-8*). The research concludes that tack coat quality and its application rate are the main contributors to the interface bonding. However, most of these research studies have focused on the interface between HMA layers, and no field investigations have been conducted to validate these findings. Therefore, the objective of this study was to conduct laboratory testing to optimize the tack coat application rate for the HMA-PCC interface and validate the laboratory findings using accelerated loading of full scale test sections.

This paper first presents the laboratory direct shear testing results for tack coat type and application rate optimization. Two types of tack coat material, asphalt emulsion SS-1hP and cutback asphalt RC-70, were evaluated at various residual application rates from 0 to 0.41 L/m^2. An optimum tack coat rate was found for both SS-1hP and RC-70 at 20 ^{o}C. Effects of other variables such as PCC surface texture and temperature and moisture condition were also investigated (*9, 10*), but they are not the focus of this paper. In order to validate the laboratory finding, the two tack coat types were applied at three application rates on full-scale pavement test sections. Results from accelerated pavement loading on these sections proved that the optimum tack coat type and application rate obtained from the laboratory tests are valid.

BACKGROUND

Tack coat, also termed as an interface bonding agent, is defined by ASTM D8-02 as “an application of bituminous material to an existing relatively non-absorptive surface to provide a thorough bond between old and new surfacing” (*11*). Asphalt emulsions, asphalt cements, and cutbacks are three types of tack coat between pavement layers. The drawbacks of asphalt cements are following: 1) they must be sufficiently heated to allow spray application (*13*); and 2) due to the lower volume, they result in poor coverage. Better coverage occurs when tack coat material is applied in a diluted, higher volume state. Environmental pollution is also a major issue limiting the widespread use of cutback asphalts (*14*). Asphalt emulsions, on the other hand, are the most widely used materials for tack coat. They provide the additional volume, i.e. a lower residual rate, which allows the distributor to function at a normal speed when lower application rates are used. In addition, emulsions flow readily at ambient temperatures providing for a uniform application rate (*12*).

Both monotonic and cyclic shear tests have been used to identify the optimum tack coat application rate. Maximum shear strength is the criterion in monotonic shear tests; whereas total number of cycles to failure is the criterion in cyclic tests. These two parameters provide two distinct performance mechanisms. Both methods are sensitive to interface parameters such as tack coat type, mixture type, PCC surface texture, tack coat application rate, and temperature. The advantage of monotonic testing is that it is relatively easy to operate if the results can be validated by field performance. Although cyclic testing can better simulate field loading, its test repeatability is relatively difficult to control in the laboratory.

Literature on tack coat application indicates that the major factors affecting interface shear strength are rate of shear, tack coat type, tack coat application rate, temperature, mixture type, and magnitude of normal pressure at the interface. West et al. reported the superiority of a PG64-22 binder as a tack coat compared to a CRS-2 and a CSS-1 (*2*). Similarly, Woods concluded from his research that asphalt binders provide better interface bonding strength than asphalt emulsions (*6*). It has been pointed out that most tack coats are sensitive to normal pressure at high temperatures, e.g. 60 ^{o}C (*2*). At lower temperatures, most laboratory studies reported tack coat's insensitivity to normal pressures. When other interface parameters are held constant, higher temperatures result in reduced shear strength; while shear strength increases at high shear rate. However, almost all of these findings were obtained from laboratory tests only.

LABORATORY TESTING

Direct Shear Test Apparatus

In this study, a modified version of a direct shear apparatus developed by Al-Qadi et al. was used (*15*). 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 1. The testing apparatus houses, in specially designed steel chambers, 98.4-mm-diameter PCC and 100-mm-diameter HMA specimens. The apparatus is attached to a Universal Testing Machine 5P by IPC Ltd.

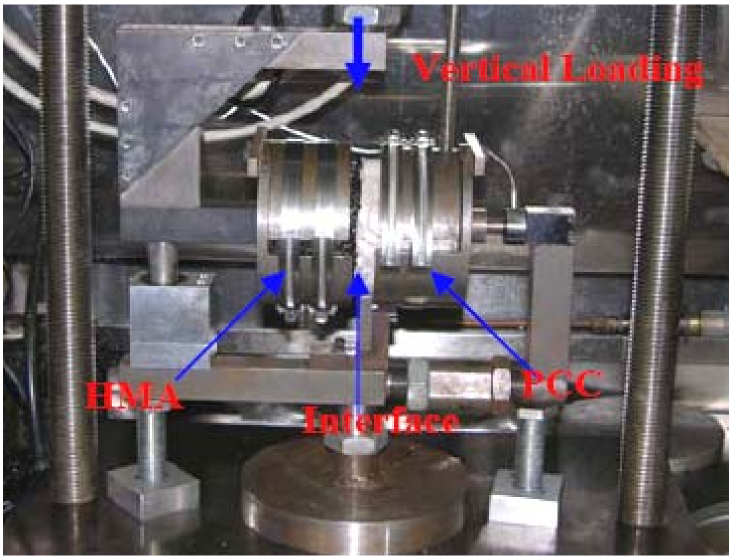


FIGURE 1 Direct shear test apparatus.

During testing, the vertical load is applied to the HMA while the PCC is held completely stationary. The relationship between loading and displacement is recorded by a data acquisition system of the loading machine until the interface fails. The shear strength at the interface is calculated using the maximum vertical load required to cause interface failure.

In this study, a monotonic testing mode was selected, since preliminary test results showed that monotonic testing could more precisely quantify the effect of interface characteristics than cyclic testing. The testing was conducted in a displacement control mode at a constant shear rate of 0.2 mm/s. This rate is consistent with other studies (*1*).

Specimen Preparation

Test specimens were prepared using field PCC cores, laboratory prepared HMA, and tack coats obtained from a tack coat supplier. Portland cement concrete cores, 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, where an HMA overlay was later placed for the accelerated pavement testing (APT). The HMA was compacted in a gyratory compactor at 100-mm-diameter on top of the PCC cores and after placing the tack coat if applicable. The total height of the specimen is 115 mm (60 mm PCC + 55 mm HMA); the target air void of the HMA was set at 7%, which is representative of initial field value. Prepared specimens were conditioned in an environmental chamber for at least four hrs before being tested. Figure 2 shows an HMA-PCC specimen in the steel chambers which is ready for testing. More detailed information about specimen preparation can be found in the referenced literature (*9*).

FIGURE 2 HMA-PCC specimen ready for testing.

Testing Materials and Program

Two types of tack coat material, asphalt emulsion SS-1hP and cutback asphalt RC-70, were evaluated in the laboratory. A 19.0 mm intermediate/binder-mix design (IM-19.0) typically used in Illinois was selected to prepare the HMA material. The properties of the tack coats and HMA are shown in Table 1.

In order to find the optimum tack coat application rate, each tack coat was tested at four residual rates, 0, 0.09, 0.23, and 0.41 L/m^2. These application rates were selected according to the recommended tack coat application rate range for field construction by the Illinois Department of Transportation. All the tests were performed at 20 ^{o}C, and all the PCC cores had smooth surfaces.

TABLE 1 HMA Job Mix Formula and Tack Coat Properties

HMA Property		**IM-19.0**	
Aggregate Gradation	Sieve Size (mm)	Passing Percentage (%)	
	25.4	100	
	19.0	98.4	
	12.5	75.0	
	9.5	64.2	
	4.75	38.8	
	2.36	22.2	
	1.18	13.3	
	0.6	6.5	
	0.3	5.9	
	0.15	4.4	
	0.075	3.8	
Asphalt Cement Grade		PG 70-22	
HMA Asphalt Content (%)		5.4	
HMA Maximum Specific Gravity		2.501	
Tack Coat Property		**SS-1hP**	**RC-70**
Tack Coat Specific Gravity @ 15.6 ^{o}C		1.006	0.943
Tack Coat Asphalt Residue Rate by Volume (%)		62	66

It should be noted that in addition to tack coat type and tack coat application rate, other variables such as HMA type, PCC surface texture, temperature, and moisture were also evaluated through laboratory testing. However, this paper is focused on the optimization of tack coat type and tack coat application rate.

Laboratory Testing Results

Interface shear strength is considered the critical parameter to optimize the tack coat application rate. Interface shear strength is calculated as the measured peak shear load divided by the interface area. A typical interface shear stress-shear displacement is shown in Figure 3.

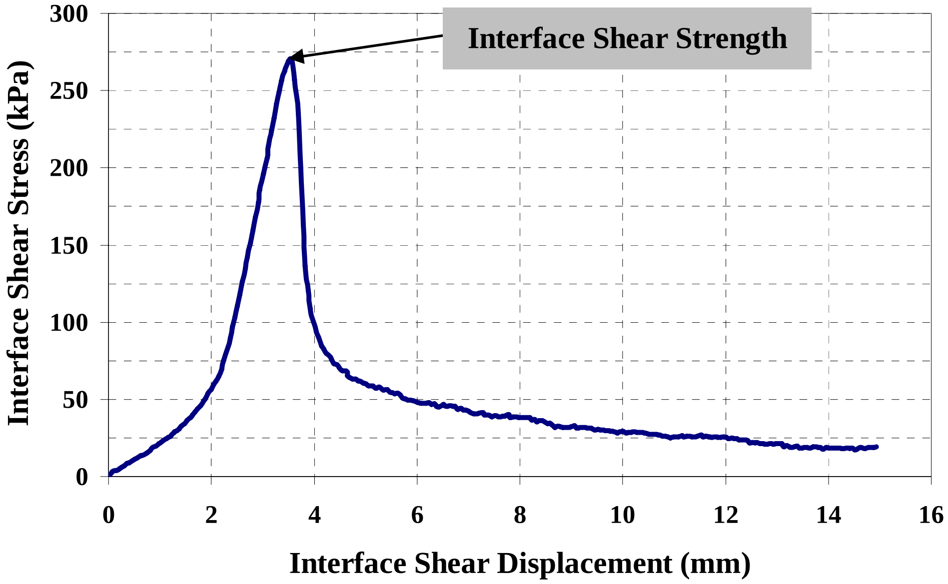


FIGURE 3 Interface shear stress–displacement curve.

The testing results for two tack coats at three application rates are presented in Table 3 and Figure 4. The test results shown in Figure 4 indicated that 0.23 L/m^2 always provided the maximum interface shear strength among the four investigated tack coat application rates for both tack coats, and the two tack coats showed similar trend between interface shear strength and tack coat application rate. Generally, SS-1hP provided higher interface shear strength than RC-70 for the same tack coat application rate.

TABLE 3 Interface Shear Strength (kPa)

Tack Coat	**Residual Tack Coat Application Rate (L/m^2)**			
	0.00	**0.09**	**0.23**	**0.41**
RC-70	62.8 (15.8)	69.3 (12.5)	305.7 (13.1)	302.3 (6.4)
SS-1hP	62.8 (15.8)	259.8 (2.1)	495.4 (10.0)	407.9 (7.5)

Notes: The values in the table are the average from three individual specimens;
The values in the parentheses represent the coefficient of variation (%).

It is evident that 0.23 L/m^2 is the preliminary optimum residual tack coat application rate. However, it is unclear how the interface shear strength varies with respect to tack coat application rate in the close proximity of the preliminary optimum value, 0.23 L/m^2. Therefore, tests at three additional residual tack coat application rates, 0.14, 0.18, and 0.32 L/m^2, were added to fine-tune the optimum tack coat application rate. Given that the two tack coats have the same trend of interface shear strength and tack coat application rate, only SS-1hP was tested. Figure 5 presents the complete test results for SS-1hP at seven application rates. The maximum interface shear strength was found at 0.18 L/m^2. Therefore, 0.18 L/m^2 was determined as the optimum residual tack coat application rate to maximize the interface shear strength, and it would then be validated by the accelerated field testing.

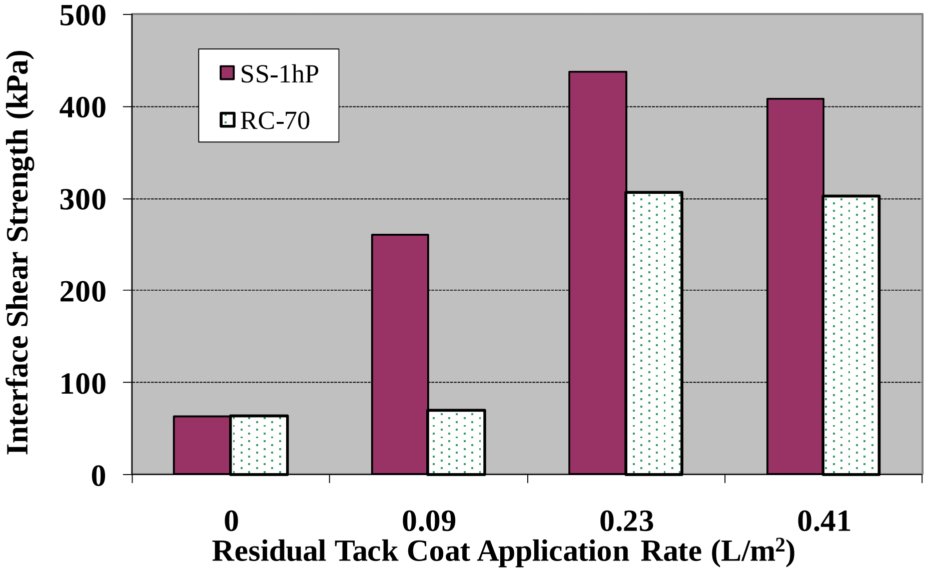


FIGURE 4 Effects of tack coat and tack coat application rate.

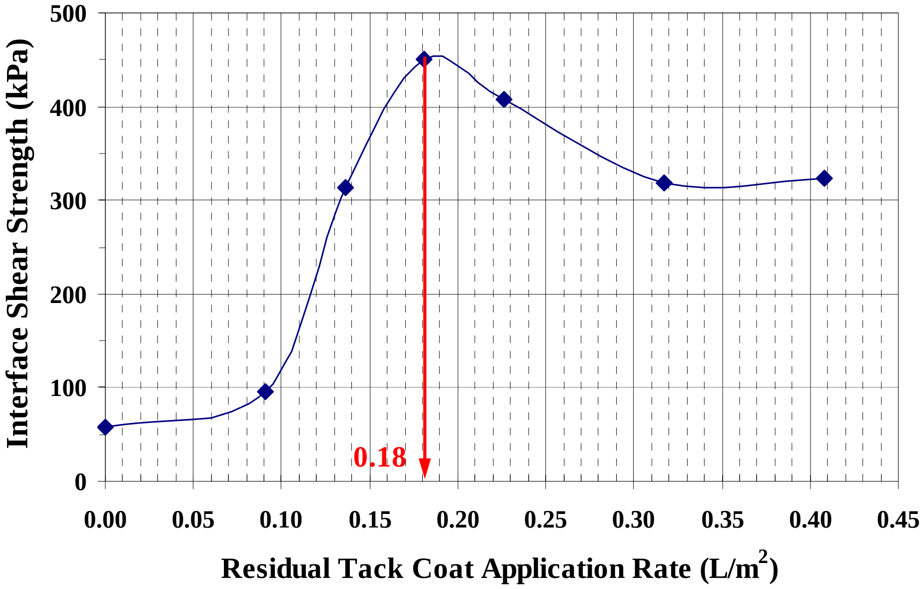
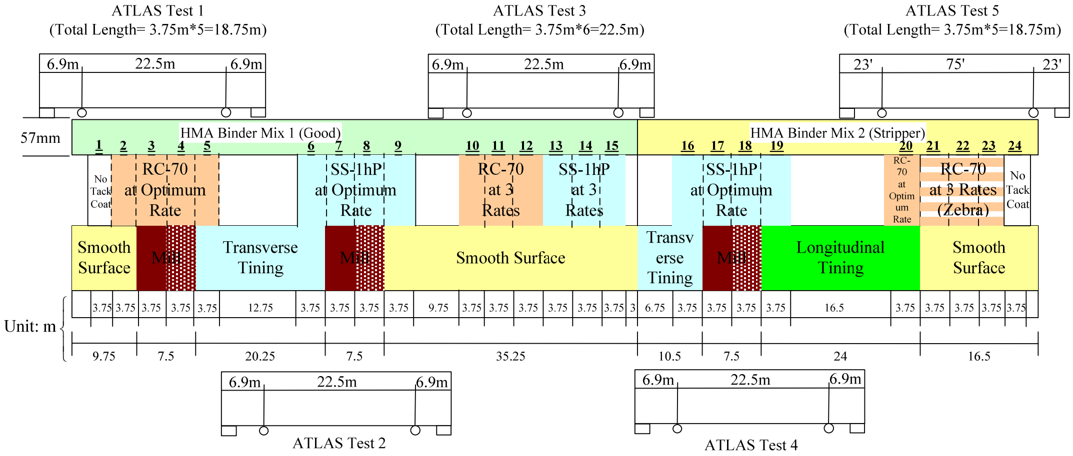


FIGURE 5 Optimum tack coat application rate determination.

ACCELERATTED PAVEMENT TESTING

Overlay Construction Layout and Testing Plan

In order to validate the laboratory test findings, an HMA overlay was placed over the existing concrete pavement which contains various pavement surface textures at the testing yard of ATREL at UIUC. As shown in Figure 6, in total, 24 sections were designed and built to evaluate the effects of various factors such as HMA type, PCC surface texture, tack coat type, and tack coat application rate on the interface bonding strength in the field. The pavement width is 3.6 m, and each pavement section is 3.75 m long. Five accelerated pavement tests will be performed utilizing the Advanced Transportation Loading ASsembly (ATLAS) with each test covering five or six test sections. At a loading speed of 8 km/h, ATLAS can cover a testing distance of 22.5 m. A side view of the ATLAS machine is shown in Figure 7.



* ATLAS Test 3 above shall be used to compare the tack coat application rates.

* ATLAS Tests 1, 2, & 4 above shall be used to compare different surface texture types under one tack coat application rate.

* ATLAS Test 5 above shall be used to compare the zebra stripping effect at different application rates.

🟥 Indicates a milled surface that is broom cleaned only.

▨ Indicates a milled surface that is thoroughly cleaned with an air blast.

FIGURE 6 HMA overlay construction layout.

FIGURE 7 Advanced Transportation Loading ASsembly (ATLAS).

As shown in Figure 6, the effects of various parameters on the overlay performance are evaluated in five ATLAS tests. However, this paper focuses on ATLAS test 3 for optimizing the tack coat type and tack coat application rate. ATLAS test 3 covers six sections, which are sections 10, 11, 12, 13, 14, and 15. All of these six sections have the IM-19.0 HMA overlay (Table 1) on smooth PCC surfaces. RC-70 at optimum rate, high rate, and low rate were applied to sections 10, 11, and 12, respectively; SS-1hP at low rate, optimum rate, and high rate were applied on sections 13, 14, and 15, respectively. The magnitudes of low rate, optimum rate, and high rate were determined according to the laboratory test findings, as shown in Table 4. Tire configurations for the APT tests on these sections are shown in Table 5.

TABLE 4 Field Tack Coat Application Rates

SS-1hP (Diluted with the same amount of water)			
Asphalt Residue Rate (%)	64		
Application Rate Level	Low	Optimum	High
Asphalt Residue (L/m^2)	0.09	0.18	0.41
Rate for Truck (L/m^2)	0.28	0.56	1.28
RC-70 (No dilution)			
Asphalt Residue Rate (%)	66		
Application Rate Level	Low	Optimum	High
Asphalt Residue (L/m^2)	0.09	0.18	0.41
Rate for Truck (L/m^2)	0.14	0.27	0.62

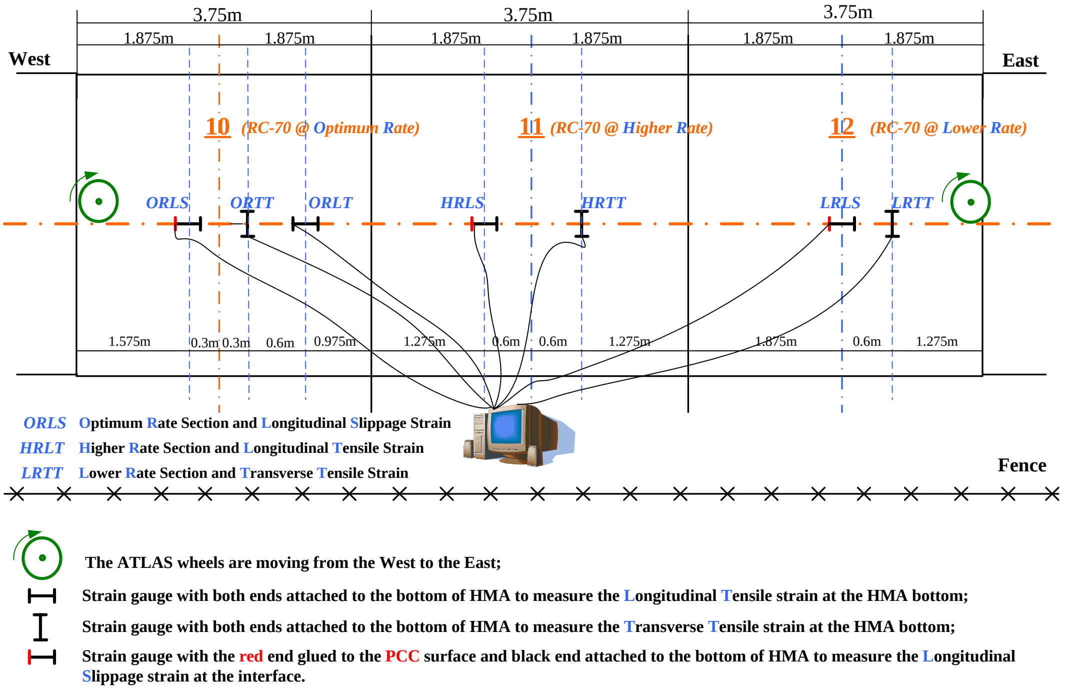
TABLE 5 APT Loading Tire Configurations

Loading Cycle Configuration	Before 20,000 Cycles	After 20,000 Cycles
Tire Type	425 Single Wide Base	425 Single Wide Base
Tire Pressure (kPa)	827	827
Loading Amplitude (kN)	53	62

Instrumentations and Strain Responses

Seven H-type strain gauges were installed in sections 10, 11 and 12 to obtain the strain responses at the interfaces of the sections with various tack coat application rates. Strain gauges were placed to collect transverse and longitudinal strains at the bottom of HMA, as well as longitudinal slippage strain between HMA overlay and PCC pavement. The strain gauges for measuring slippage strain were placed as follows: one end (red end in Figure 8) was glued to the PCC pavement surface, while the other end (black end) was controlled by the bottom of HMA movement. It should be pointed out that this was an attempt to collect information which might be helpful to understand the relative movement at the HMA-PCC interface.

In addition to strain gauge installation, thermocouples were also installed at four depths to obtain the temperature profile inside the HMA overlay, as shown in Figure 9. For the completed ATLAS test 3, the HMA overlay temperature range measured by the thermocouples is from 13 to 40 ^{o}C. Thermocouple readings also indicated that the temperature difference within the HMA layer is less than 2 ^{o}C.



ORLS Optimum Rate Section and Longitudinal Slippage Strain
HRLT Higher Rate Section and Longitudinal Tensile Strain
LRTT Lower Rate Section and Transverse Tensile Strain

The ATLAS wheels are moving from the West to the East;
Strain gauge with both ends attached to the bottom of HMA to measure the Longitudinal Tensile strain at the HMA bottom;
Strain gauge with both ends attached to the bottom of HMA to measure the Transverse Tensile strain at the HMA bottom;
Strain gauge with the red end glued to the PCC surface and black end attached to the bottom of HMA to measure the Longitudinal Slippage strain at the interface.

FIGURE 8 Strain gauge layout.

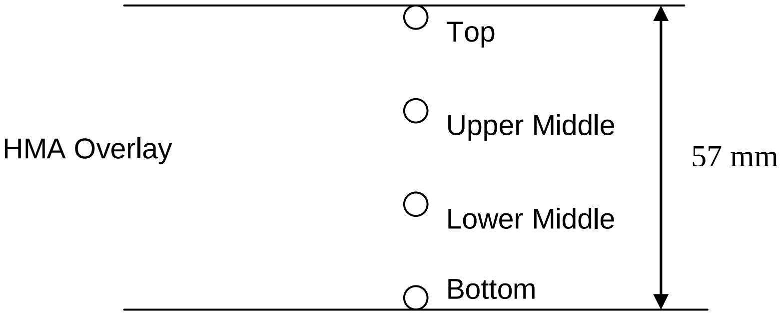


FIGURE 9 Thermocouple locations.

Figure 10 presents typical HMA strain responses at an early stage for each test section. By comparing the peak reading of each strain gauge, it is clear that the section having a high tack coat application rate experienced the highest transverse tensile strain and slippage strain, while the section having an optimum rate showed the lowest strain. Another finding from this plot is that although the strain gauge readings are auto-zeroed at the beginning of each loading cycle, they do not actually go back to zero at the end of the wheel pass. This means that when the pavement is unloaded, there are residual strains accumulated at the interface, and these residual strains will cause permanent shear deformation in the overlay ultimately.

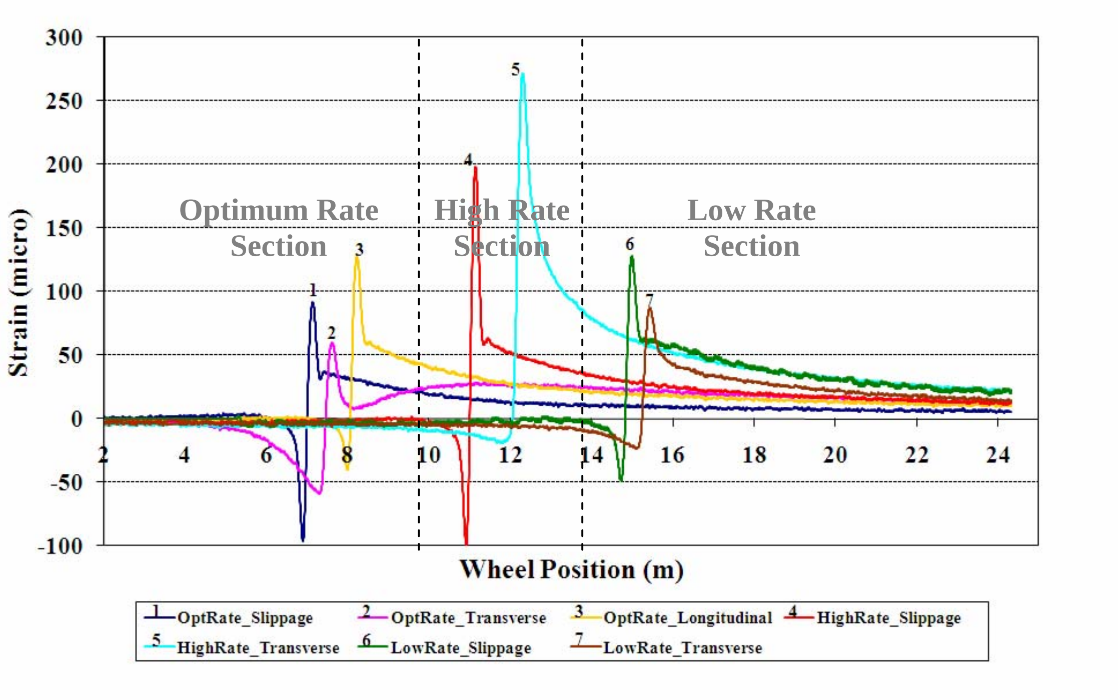


FIGURE 10 Typical strain responses at early age.

It should be noted that the residual strains at the end of the loading cycle are not the same as the true residual strain occurring at the interface, since there is not enough time for the strains to recover. Therefore, the following normalization method was utilized to allow comparison. As shown in Figure 11, the transverse tensile strain responses at each section are plotted against time. The residual strain is measured at 4 s after the maximum strain response. For example, strains at points A, B, and C in Figure 11 correspond to the residual transverse tensile strains at low-rate section, high- rate section, and optimum-rate section respectively. Hence, the reported residual strain is not cumulative.

Using the aforementioned normalization method, the residual transverse strains and the residual slippage strains for each section were calculated at various loading cycle levels. As shown in Figure 12, the high application rate section always exhibits the highest residual transverse strain; especially at an early stage. With the loading cycle increasing, the residual transverse strain in the high-rate section decreases. The optimum-rate section always exhibits the lowest residual transverse strain; there is no obvious trend found for its relationship with the number of loading cycle.

Figure 13 shows the residual slippage strains for each section at different loading cycles. It can be seen that at an early stage (10,000 cycles), the residual slippage strain in the high-rate section is the largest. With the loading cycle increasing, residual slippage strains in all three sections decrease. At the middle stage (40,000 cycles) and late stage (70,000 cycles), the low-rate section exhibits the largest residual slippage strain. The optimum-rate section always has the minimum residual slippage strain.

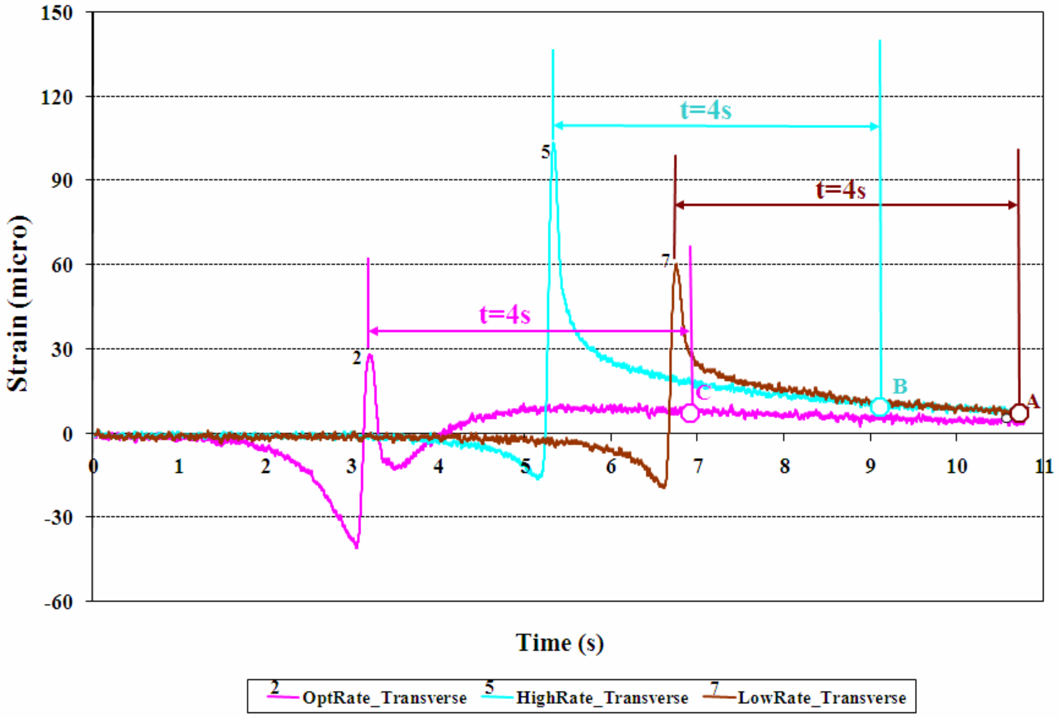


FIGURE 11 Residual strain calculation.

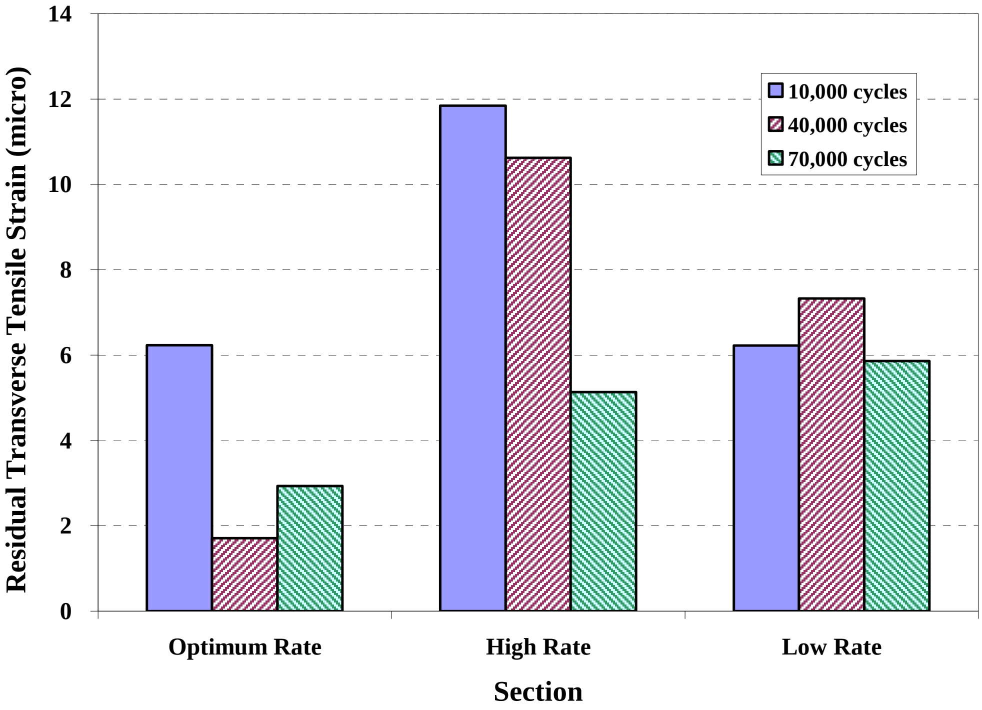


FIGURE 12 Residual transverse tensile strain.

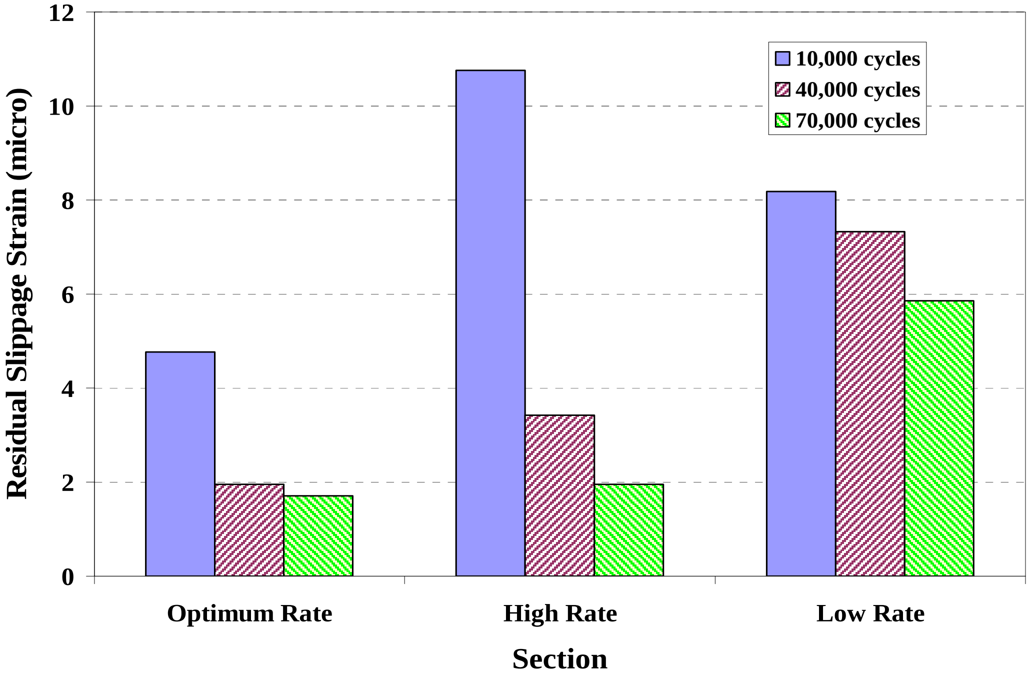


FIGURE 13 Residual slippage strain.

The following summarizes the findings from the stain gauge data:

- At optimum application rate section, minimum peak strain and residual strain were measured.
- The high application rate section had the maximum residual strain at an early stage, and this residual strain decreases with the increased loading cycle.

HMA Surface Profile Measurement

In addition to the strain response, HMA overlay surface profile data was also collected before APT testing and after 10,000, 30,000, 60,000, and 75,000 APT loading cycles. The profile data was collected using a straight steel beam and digital caliper as shown in Figure 14.

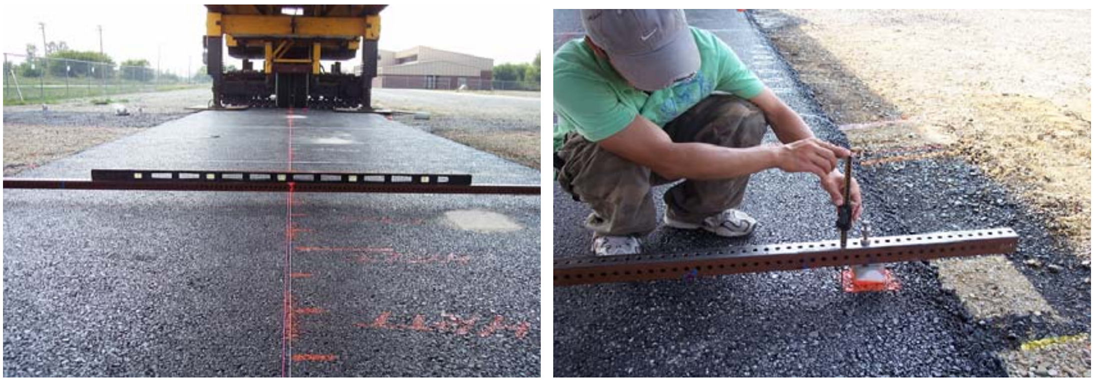


FIGURE 14 HMA overlay surface profile measurement.

Seven surface profiles were measured for each section. Figure 15 shows the rutting depth development at the center of each section. The rutting depth was calculated according to the vertical deflection at the center of each section compared to its initial location before ATLAS testing. The following conclusions can be drawn based on the rutting data in Figure 15:

- Rutting depth ranking after 75,000 loading cycles from high to low is RC-70 at high rate, RC-70 at low rate, SS-1hP at low rate, RC-70 at optimum rate, SS-1hP at high rate, and SS-1hP at optimum rate;
- Optimum application rate sections experienced minimum rutting;
- Generally, SS-1hP sections had smaller rutting than RC-70 sections for the same application rate level.

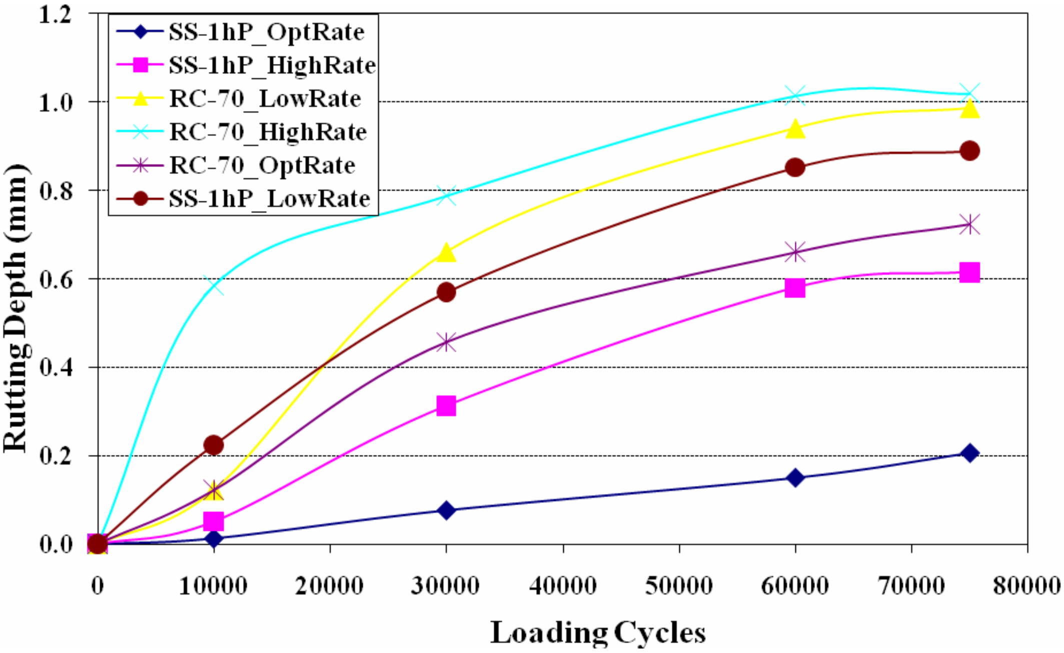


FIGURE 15 Rutting depth development.

CONCLUSIONS

This paper investigated the effects of tack coat type and tack coat application rate on the HMA-PCC interface bonding through a comprehensive study combining both laboratory testing and field validation. A good agreement was observed between the laboratory testing results and accelerated pavement testing to date. The following summarizes the findings of this study:

- Laboratory testing indicated that SS-1hP provides better interface shear strength than RC-70; but both tack coats exhibit the similar pattern of relationship between the interface shear strength and tack coat application rate. An optimum residual tack coat application rate was found at 0.18 L/m^2 for SS-1hP.

- Strain response data from the accelerated pavement testing validated the laboratory findings by showing that the optimum tack coat application rate section had the smallest strain responses compared to the sections with high and low tack coat application rates.
- HMA overlay surface profiling data before and after accelerated pavement testing also showed good agreement with laboratory test findings. Among the six test sections investigated, the section with SS-1hP tack coat at optimum application rate exhibited the lowest primary rutting; while the test section with RC-70 at high tack coat application rate showed the highest primary rutting.

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