TACK COAT PERFORMANCE AND MATERIALS STUDY

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16. Abstract

A good bond provided by a tack coat can improve performance of asphalt overlays. The objectives of this research were: (1) develop a method for testing the bond between pavement layers; (2) evaluate the bond performance and predict long-term performance of different tack coat strategies; (3) assess the minimum bond to achieve acceptable performance; and (4) evaluate the cost effectiveness of different tack coat strategies.

Field test sections were constructed considering surface type, tack type, tack rate, and application method. Core bond performance, initial and after 8-months, was tested in the lab with an interface shear strength tester. Tack type, application method, and bond age were statistically significant variables. Trackless tack had the highest bond performance. High performance was also achieved by SS-1H placed with a distributor, and by no-tack samples. The rubberized tack and SS-1H placed with a spray paver had the lowest bond performance; however, after eight months, bond performance for these sections doubled and was well acceptable.

Performance was predicted considering reflection cracking, rutting, and fatigue cracking. Generally, higher bond strength resulted in longer service life; however, on the milled HMA sections, the optimal performance was achieved at a partially bonded condition. The differences among pavement life-cycle costs for the different materials and methods were small, between 2 and 6 percent of the overall project cost.

The shear bond strength test is recommended to evaluate field bond performance. A tack coat construction specification, with a minimum initial bond strength of 70 psi, may be considered for exploratory work.

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EXECUTIVE SUMMARY

Introduction

The long-term performance of a hot-mix asphalt (HMA) overlay is largely dependent on the quality of its bond to the underlying layer. Tack coats are placed between pavement layers to improve bonding, but even after extensive research on the topic, the industry is divided about what are the most effective construction methods and materials. The debate includes applying higher tack rates, adopting newer tack products, and using spray paver equipment. Whether these tack coat strategies can yield cost-effective benefits in terms of bond quality and long-term pavement performance is unknown.

The goal of this research was to enable ODOT to (1) justify or reject higher-cost tack coat strategies, and (2) decide whether to use a performance-based or method-based specification for tack coat construction. To achieve this goal, the objectives of this research were: (1) develop a method for testing the bond between pavement layers; (2) evaluate the bond performance and predict long-term performance of different tack materials, application rates, and application methods; (3) assess the minimum bond necessary to achieve acceptable performance; and (4) evaluate the cost effectiveness of different tack materials, rates, and application methods.

Methods

The researchers constructed test sections in the field considering surface type (new HMA and milled HMA), tack type (SS-1H, trackless tack, and rubberized tack), tack rate (0.04 to 0.13 gal/sy application), and application method (distributor and spray paver). Cores were collected after construction and after eight months in service. The bond strength and bond energy were measured in the lab with an interface shear strength tester at a rate of 2 inches/min. The results were analyzed statistically to identify which variables affected bond performance.

A life-cycle cost analysis was performed for the statistically significant tack coat strategies. This involved (1) predicting the long-term performance, and (2) estimating initial, maintenance, and rehabilitation costs. Pavement performance indicators were reflection cracking, rutting, and fatigue cracking. Prediction was done with finite element, multi-layer elastic, and mechanistic-empirical models. The life-cycle costs of the test sections were estimated by summing the initial material costs, maintenance costs, and rehabilitation costs at failure over a 15-year period.

Findings

Bond strengths ranged from 80 to 420 psi with a median of 210 psi. Bond energy ranged from 0.4 to 6.0 ft-lb/in^2, with a median of 2.2 ft-lb/in^2. Tack type and application method, and bond age were statistically significant variables. Trackless tack had the highest bond performance High performance was achieved by SS-1H placed with a distributor, and no-tack samples. The rubberized tack and SS-1H placed with a spray paver had the lowest bond performance. After 8-months in service, the performance of spray paver sections doubled to an acceptable level. The effect of tack rate on bond performance was inconclusive. There was no statistical difference between bonding to new and milled HMA surfaces (though significant differences have been noted in other studies).

Performance predictions for reflection cracking varied significantly between the new HMA sections and the milled HMA sections. On new HMA, cracks start surfacing around year 3 and are fully developed after 5 to 7 years. Cracking is delayed for stronger bonds. For the milled HMA sections, cracking is fully developed in less than 2 years for low bond conditions, and around 10 years for full bonded conditions, and the best performance actually occurs with a partially bonded interface. For rutting performance, higher bond performance consistently reduces rutting. For fatigue cracking, higher bond performance increases pavement life. The no bond condition is very detrimental to service life (around 6 years) while the fully bonded condition predicts life well beyond practical serviceability. For milled sections, the trend is the same but the no bond condition is even more severe (less than 4-years to failure).

Based on the 8-month tests, all sections are expected to have similar long-term performance. The difference in life-cycle costs for the most and least expensive sections were from $3,000 to $10,000/lane-mile, or 2 to 6 percent of the overall cost.

Recommendations

The shear bond strength test is recommended to evaluate bond performance. (Appendix G) Two types of tack coat construction specifications were developed: (1) a method-based specification and (2) a performance-based specification. (Appendix G) The method-based specification had few modifications from the existing specification, allowing slightly higher application rates. The performance-based specification moves responsibility for selecting the tack rate to the contractor and requires a minimum bond strength of 70 psi. At this time, the researchers do not recommend enforcing the performance-based specification. Rather, the Department should collect bond and pavement performance data on a variety of projects, and should monitor the long-term performance of the test sections. A long-term data collection plan is in Appendix H.

The most cost-effective treatment was SS-1H placed with a spray paver, but the savings compared to other materials and methods were small. The Department should consider allowing the contractor to choose the tack material, application methods, and rates most convenient for their operations, considering they meet minimum application rate and uniformity requirements.

The Department should note that the initial bond from a spray paver is lower than from a distributor. The bond will increase significantly with time, likely within the month.

PROJECT BACKGROUND

Problem Statement

The long-term performance of a hot-mix asphalt (HMA) overlay is largely dependent on the quality of its bond to the underlying layer. Tack coats are placed between pavement layers to improve bonding, but even after extensive research on the topic, the industry is still divided on what are the most effective construction methods and materials. Some research suggests that higher tack rates will improve bonding (*1*). Others highlight certain products with superior bond performance, and therefore imply longer pavement performance (*1, 2, 3*). And the emergence of spray pavers (a paver with an integrated tack spray bar), are thought to produce good bond performance by avoiding issue with tack coat contamination, and by permitting higher tack application rates. (*4*)

Adopting higher tack rates, more expensive tack products, and spray paver equipment would incur higher construction costs to the Ohio Department of Transportation (ODOT). Unknown, however, is whether these tack coat strategies will yield cost-effective benefits in terms of bond quality and long-term pavement performance.

Research Objectives

The goal of this research was to enable ODOT to:

1. Justify or reject higher-cost tack coat strategies, and
2. Decide whether to use a performance-based or method-based specification for tack coat construction.

To achieve this goal, the objectives of this research were:

1. Develop a method for testing the bond between pavement layers.
2. Evaluate the bond performance and predict long-term performance of different tack materials, application rates, and application methods.
3. Assess the minimum bond necessary to achieve acceptable performance.
4. Evaluate the cost effectiveness of different tack materials, rates, and application methods.

Project Scope

The scope of this project was to:

1. Review the literature and recommend an interlayer bond strength test.
2. Construct test sections in the field considering surface type, tack type, tack rate, and application method.

3. Test the bond strength of field cores and perform statistical analysis on the results.
4. Predict the long-term pavement performance with finite-element and mechanistic-empirical modeling.
5. Perform a life-cycle cost analysis of the different tack coat strategies.
6. Develop tack coat construction specifications.

INTERLAYER BOND STRENGTH TEST

A literature review on different bond strength tests, equipment, and criteria is contained in Appendix A. The researchers recommend using a shear test method. The key benefits to this method are:

- Reasonably represents loading scenario in the field.
- Intuitive test method.
- Ease of sample preparation.
- Ease of testing.
- Inexpensive equipment.

At the beginning of the project, the researchers knew of only two device manufacturers. They recommended the device which was less bulky and easier to handle (Figure 1). The device costs about $5,000. Another manufacturer has since developed a comparable shear test device at a similar price point.

Figure 1. Bond Shear Strength Apparatus.

The tension tests is not recommended because sample preparation requires more time and training. Poor sample preparation can yield invalid test results. There is also a higher likelihood of having an inconclusive result if failure were to occur in either the substrate or overlay away from the bond interface. Other methods in the literature include torque tests, direct tack tests, and composite stiffness. These are not recommended for poor repeatability and impracticality.

The literature was inconclusive about the ideal loading rate. Most agencies use a loading rate of 2 in./min (50 mm/min) because it is the same rate in the commonly available Marshall loading frame. By comparison, the rate is very fast compared to most HMA performance-tests. Other loading rates in the literature are 0.2 in./min (5 mm/min), 0.1 in./min (2.5 mm/min), and 0.02 in./min (0.1 mm/min). The most critical aspect of the recommended loading rate is that the test can distinguish among high, moderate, and low interface bonds. The researchers performed their own preliminary tests on loading rate and concluded that all rates could be successfully used, and that results from one rate could be converted to another rate through time-temperature superposition theory. The results and conversion equations are in Appendix C. All things being equal, the researchers recommended a loading rate of 2 inches/min (50.8 mm/min) because of convenience with existing Marshal loading frames.

TEST SECTION CONSTRUCTION

The testing plan considered the following variables (Table 1). The complete test matrix is shown in Appendix B. A total of 20 test sections were constructed, including 13 section on the new HMA and seven sections on the milled surface. The three tacks were SS-1H (a commodity tack), a hard-pen trackless tack, and a rubberized tack (an SS-1H modified with 3 percent styrene-butadiene rubber (SBR)). Trackless tack was applied with a distributor, the rubberized tack could only be applied with the spray paver, and the SS-1H was applied with both a distributor and a spray paver. The different tacks were applied at low, moderate, high, and very high rates, as appropriate for the tack type, application method, and surface type. Some sections were selected for tracking conditioning.

Table 1. Test Section Variables.

Property	Values
Surface Type	• New HMA, • Milled
Tack Type	• SS-1H • Trackless • Rubberized
Application Method	• Distributor • Spray paver
Tack Application Rate, (gal/sy)	• 0.04 – 0.13
Tracking	• Yes and No
Bond age	• Initial and 8-months

The tack test sections were constructed on FRA 270 in west Columbus, Ohio, near the US 40 and IH-70 interchanges. The test sections were all placed on the two southbound mainline lanes. The total roadway traffic volume was 113,000 ADT with 21 percent trucks. The existing pavement structure was determined based on historic records, ground-penetrating radar, and falling-weight deflectometer data. It consisted of 5.5 inches of asphalt concrete, 10 inches of jointed concrete, 6 inches of subbase, and a clayey subgrade. The pavement surface distress was characterized by reflection cracking every 25 to 60 ft, and several localized full-depth HMA repairs. Each repair area was carefully documented for consideration in long-term performance monitoring.

The test section layout is illustrated in Figure 2. Each section was about 500 ft long, All tack types and application methods were used on the new HMA surface, while only rubberized tack and SS-1H with a distributor were used on the milled surface. Tracking tests were done on both the new and milled HMA surfaces.

Construction occurred on July 23 and 24, 2016. First, 3.25 inches of the existing surface were milled and the surface swept clean. The spray paver sections were built first. The spray system was initially calibrated offsite using ASTM D2995 (Standard Practice for Estimating Application Rate and Residual Application Rate of Bituminous Distributors). The intermediate lift for the milled surface test sections used a 19 mm nominal maximum aggregate size (NMAS) mix, and was placed at a target 1.75 inches thick. The surface lift for the new HMA test sections used a 12.5 mm NMAS mix, and was placed at a target 1.5 inches thick. Actual average thicknesses were 1.6 and 1.2 inches, respectively. When constructing test sections with the distributor, all traffic was kept off the tack coat by loading the paver with a material transfer vehicle from the adjacent lane. The tack rate in each distributor section was measured using ASTM D2995. For sections with tracking, the asphalt distributor was directed to drive back and forth through the tack coat four times. Pictures of this process are in Appendix B.

The only issue encountered during construction was some discontinuity in the paving train for the spray paver sections. To achieve the target tack rates with the spray paver, the equipment had to travel faster than normal, but the material transfer vehicle had such tight tolerances with the paver hopper that it could not move and load the paver during laydown. This resulted in frequent stops to refill the paver.

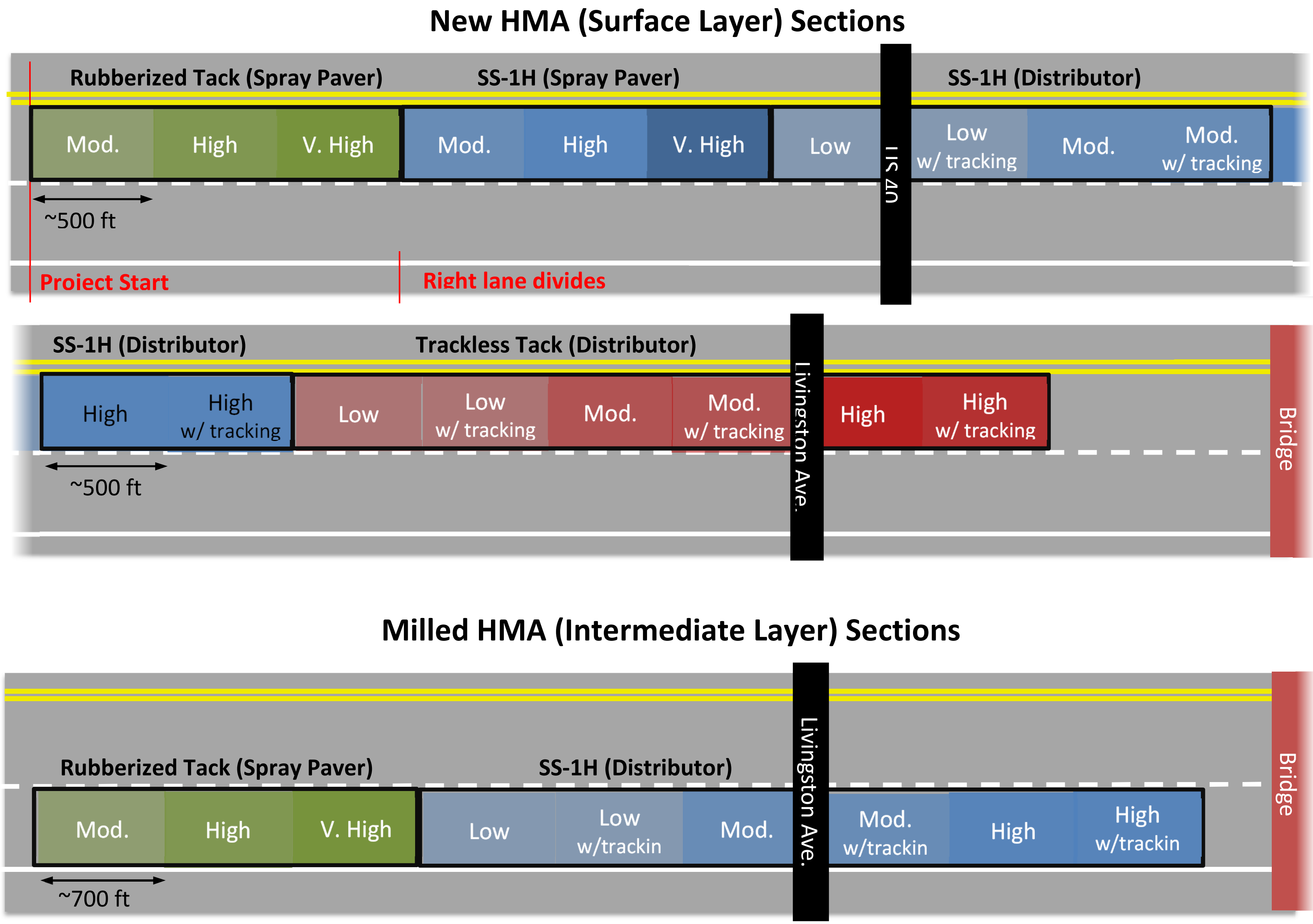


Figure 2. Test Layout on FRA 270.

Generally, three 6-inch cores were obtained at equally spaced intervals for each test section, allowing for 100 ft transition areas. The direction of traffic was marked on the cores. In the milled areas, cores were specifically obtained from the locations over the deep repairs since the substrate in other locations was weak and prone to failure. All cores were taken between the wheel paths except for the cores for "tracked" sections, which were taken in the wheel path. On select sections, replicate cores were taken to compare results from OU and TTI laboratories.

Eight months after construction, certain new HMA test sections were cored again to evaluate bond strength gain over time.

LABORATORY TESTING AND ANALYSIS

Testing

The field cores were air dried and tested approximately two weeks after construction. Cores were conditioned to 77 F (25C), placed in an interlayer shear test apparatus, and tested with a loading rate of 50-mm/min (2-inch/min). The cores were loaded in the direction of traffic in consideration of the milled surface texture. The samples were loaded through failure and terminated once the load had decreased substantially. The stress-displacement data was used to calculate maximum bond strength and total bond energy (Figure 3). Bond energy was defined as the area under the curve including after the peak but before the tail. A discussion of bond strength and bond energy is included in Appendix A.

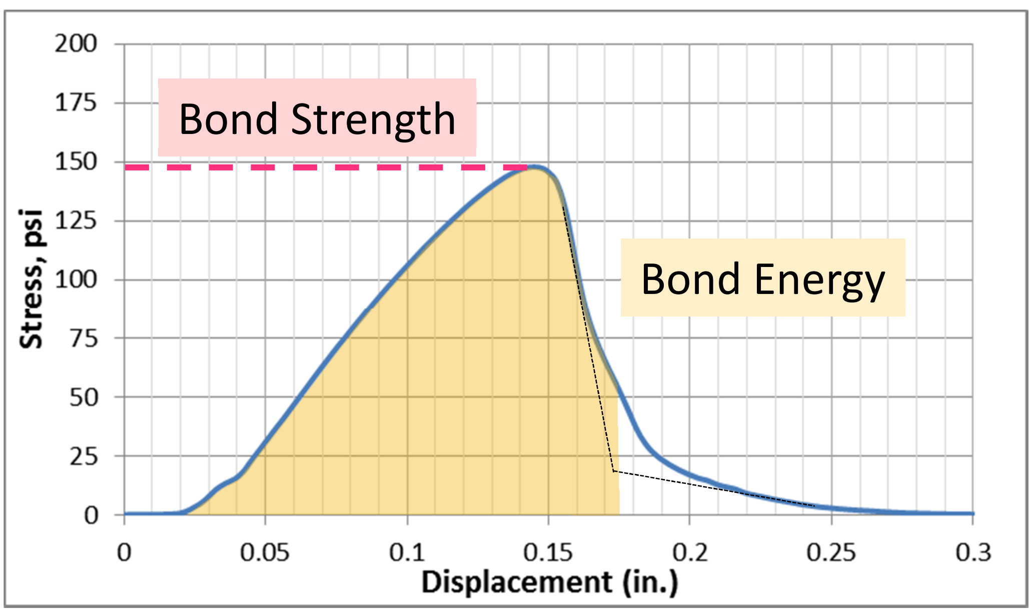


Figure 3. Bond Strength and Bond Energy Measurements.

The tack material properties were tested in the laboratory. The researchers confirmed that the tack met the material specifications. Supplementary bond tests on laboratory molded samples were performed, considering the following variables: tack type, tack rate, test loading rate, and test temperature. These results are all contained in Appendix C.

Analysis

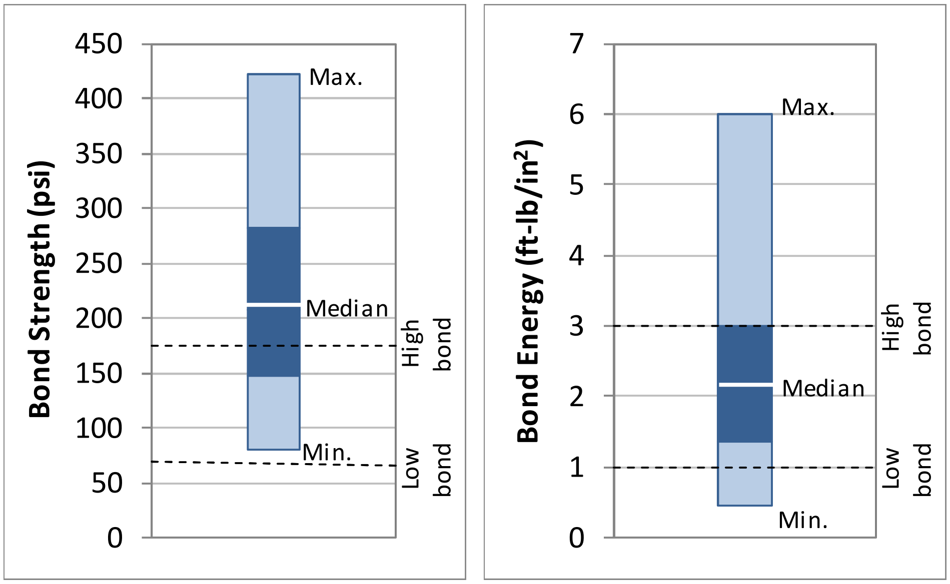
The bond strength and bond energy results were analyzed through a series of statistical analyses of variance (ANOVA's). These analyses considered the significance of the variables in Table 2. Each analysis used a subset of the data to ensure the ANOVA was performed with a balanced dataset. Each sample size was between 40 and 69 samples. Details of the data sets and the ANOVA models is contained in Appendix D.

Table 2. Analyses of Variance.

Variable	Comparison	Sample Size
Testing Agency	TTI laboratory. OU laboratory.	40
Tack Type and Application	SS-1H-Spray paver. SS-1H-Distributor. Trackless-Distributor. Rubberized-Spray paver. No tack.	49
Tack Rate	Residual rates (0.03 – 0.11 gal/sy).	69
Surface Type	New HMA surface. Milled HMA surface.	60
Tracking	Undisturbed tack coat. Tracked tack coat.	59
Bond Age	Immediately after construction 8 months after construction	53

Results

The range of initial bond strength and bond energy results is summarized in the box plots in Figure 4. The column represents the full range of results. The darker columns contain half the data (inner quartile) and the light bars comprise the remaining half of the data (outer quartiles). There were no outliers in the data set. For reference, approximate low and high bond criteria are given based on the researcher's experience and trends in the literature. (*3*) Bond strengths ranged from 80 to 420 psi with a median of 210 psi. Bond energy ranged from 0.4 to 6.0 ft-lb/in^2, with a median of 2.2 ft-lb/in^2. Most of the samples from this project had high bond strengths and approximately a third had moderate bond strength. For bond energy, a quarter were in the high range, half in the moderate range, and a quarter in the low range.



(a) **(b)**

Figure 4. Distribution of Results: (a) Bond Strength and (b) Bond Energy.

Table 3 summarizes the results of the statistical analyses. The results indicate which variables significantly affected bond performance. Only tack type, application method, and bond age were statistically significant. The other prediction models had high *p*-values (greater than 0.05), poor R^2 values (less than 0.6), or both.

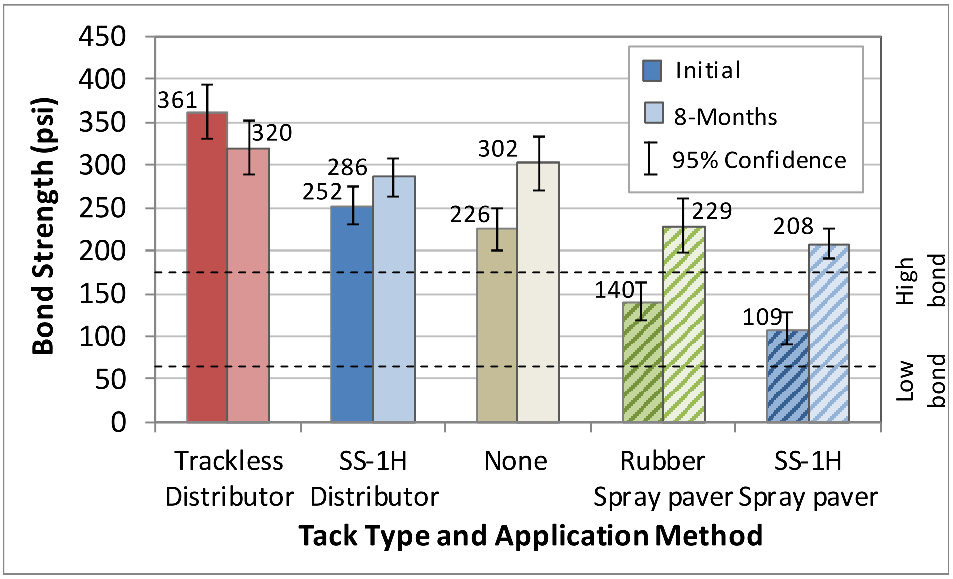
Table 3. Results of Statistical Analyses.

Variable	Bond Strength (psi)		Bond Energy (ft-lb/in^2)		Statistical Significance
	p-value[1]	Model R^2 Value	*p*-value[1]	Model R^2 Value	
Testing Agency	0.345	0.02	0.877	0.00	No
Tack Type and Application	<0.001	0.75	<0.001	0.85	**Yes**
Tack Rate	0.429	0.75	0.124	0.80	No
Surface Type	0.042	0.53	0.821	0.72	No
Tracking	0.103	0.48	0.888	0.25	No
Bond Age	<0.001	0.90	<0.001	0.87	**Yes**

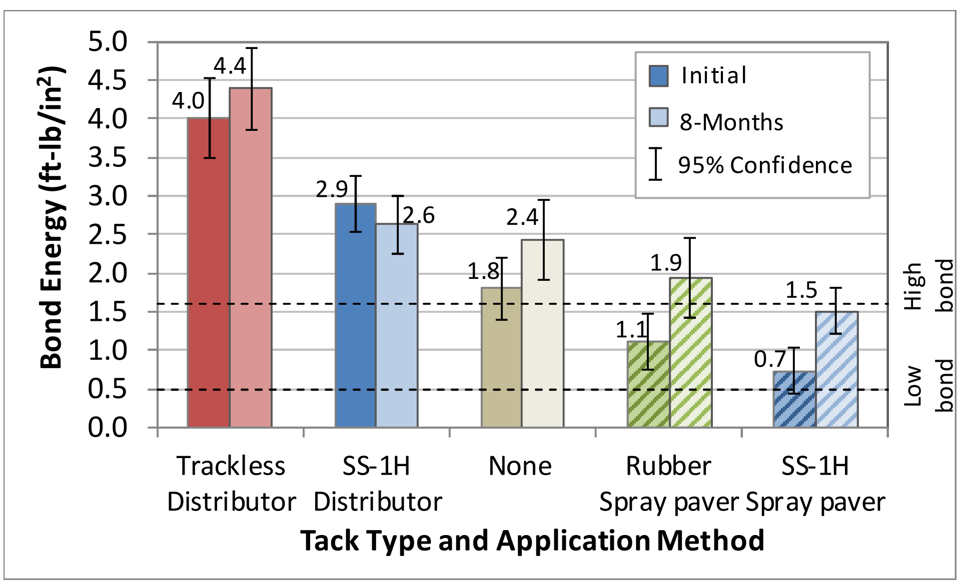
1 – The reported *p*-value is for the variable in question and not the overall model.

For prediction models of tack type and application method, the *p*-values were less than 0.001, and the models had good R^2 values of 0.75 and 0.85 for bond strength and energy, respectively. Similarly, the *p*-value for bond age was also less than 0.001 and the models had R^2 values of

0.90 and 0.87. This means that there was a significant difference among certain tack type and application method combinations, and that performance changes with time. The modeled results are shown in Figure 5. Trackless tack had the highest bond performance with bond strength and bond energy above 300 psi and 4.0 ft-lb/in^2, respectively. After 8-months, the performance of trackless tack did not change significantly. High performance was also achieved by SS-1H placed with a distributor and no-tack samples. With time, both increased in bond strength, but increases in bond energy were not statistically significant. The rubberized tack and SS-1H placed



(a)



(b)

Figure 5. Performance vs. Tack Type, Application Method, and Bond Age: (a) Bond Strength and (b) Bond Energy.

with a spray paver had the lowest bond performance, and were not statistically unique. Initially, the average bond strengths were about 140 and 110 psi, and bond energies were 1.1 and 0.7 ft-lb/in^2, respectively. The performance of these samples range from moderate to low. However, after 8-months, the bond increased substantially (above 200 psi and 1.5 to 1.9 ft-lb/in^2). These values are still lower than the other applications, but the results are in an acceptable range.

The increase in strength with time was most dramatic for spray paver applications. When the pavement is constructed, the emulsion is not able to break before being overlaid with HMA. Moisture is trapped at the interface, thus reducing the initial bond performance. With time, the moisture migrates away from the interface, thus improving the bond condition. The researchers have not directly measured the time required for this to occur, but expect most of the strength gain to occur within the first month.

There was no statistical or practical difference in the bond strengths measured in the TTI and OU laboratories. While not a conclusive comparison of inter-laboratory variability, this suggests the test has good reproducibility.

Tack rate did not have a clear effect on bond strength. There was a downward trend (more tack resulted in lower bond) for applications with rubberized tack and SS-1H with a distributor, an upward trend for trackless tack (more tack resulted in higher bond), and no trend for SS-1H with a spray paver. The researchers have noted similarly mixed trends versus tack rate in past research projects. (*3*)

Surface type on this project was not clearly significant. For bond strength results, the model R^2 value was less than 0.6, and for bond energy the *p*-value was much higher than 0.05. The new HMA and milled HMA surface samples were not statistically different. In previous research projects, the researchers have seen more significance differences here, generally with higher bond performance for milled surfaces. (*1, 3, 5*) Performance on milled surfaces largely depends on the quality of the milled pavement. In this project, the milled HMA in some locations was moisture damaged, resulting in lower shear strengths.

Finally, the effect of tracking over the tack coat did not affect the bond performance. Often, the argument for trackless tack and spray pavers is that exposed tack coat is liable to being picked up or contaminated under construction traffic, which may affect the bond strength. On this particular project, this was not the case. Tracking issues were mitigated for the following reasons: the new and milled surfaces were clean; some sections had high tack rates which minimized tack loss; and tracking was performed only with the distributor, which did not transfer dust and debris from offsite to the tack coat. During a given construction project, the surface could have issues with cleanliness, lower tack rates, and offsite traffic tracking dust and debris.

LIFE-CYCLE COST ANALYSIS

The life-cycle cost analysis involved two parts: (1) predicting the long-term performance for each tack coat strategy, and (2) obtaining initial construction costs and estimated long-term maintenance and rehabilitation costs.

Performance Prediction

Pavement performance for the statistically significant tack coat test sections was predicted for 15-years. The primary performance indicators were reflection cracking and rutting. Fatigue cracking was also considered, but with less robust prediction models. The methods for predicting performance involved:

1. Collection and assumption of model input parameters.
2. Development of models.
3. Performance prediction outputs.

Input parameters include layer properties (thickness, moduli, Poisson's ratio), interface properties (shear modulus as estimated by bond strength/energy), climate condition (historic minimum and maximum daily temperatures), and traffic condition (AADT, percent trucks, lane distributions, and projected growth). The reflection cracking model was based on mechanistic-empirical (ME) theory. Stress intensity factors driving the growth of bottom-up cracks were obtained for climate and traffic events. The rutting model was based on the same ME model and considered the cumulative permanent strain in each layer. Fatigue cracking was predicted with BISAR, a finite-element multilayer elastic program. The horizontal strains at the bottom of each layer were calculated and the number of fatigue cycles calculated with the Asphalt Institute equation. (*6*) The complete analysis procedures are detailed in Appendix E.

The models from this research are helpful to illustrate general trends and useful for comparison purposes. The results are not expected to be perfect predictions of actual performance. The most significant unknown in these models is the conversion between laboratory bond performance to the infield interface shear modulus. The conversion is based on past experience and findings in the literature as described in Appendix E. The researchers were unable to identify a mechanistic relationship from bond strength and bond energy to the interface shear modulus. The prediction models are very sensitive to the shear index, and under certain scenarios, slight changes in the index can lead to drastically different performance predictions.

For this project, the trend between the interface bond condition and reflection cracking is shown in Figure 6. Other distress types are discussed subsequently. Under a no bond condition, reflection cracking will happen rapidly. As expected, a full bond condition will perform better. What may seem counter-intuitive, however, is that a partially bonded interface will have the best performance. Under the right circumstances (layer thicknesses and stiffnesses), there can be an optimal degree of bonding that allows the interface to relieve tensile stresses and inhibit crack growth. Under other circumstances, the full bond condition can yield the best performance.

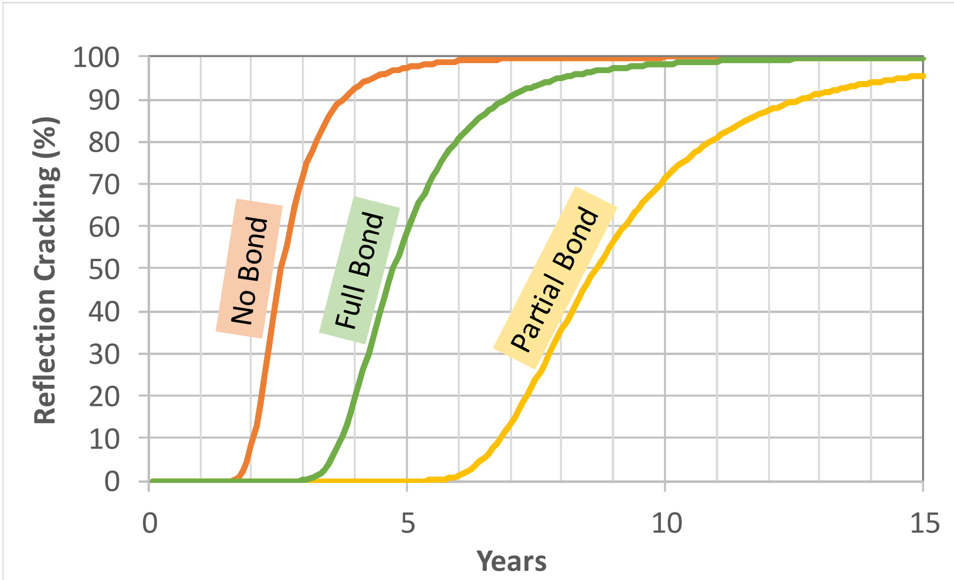


Figure 6. Predicted Reflection Cracking Performance.
(with both bond conditions equal)

Rutting performance is illustrated in Figure 7. For this distress, higher bond performance consistently reduces rutting. For this project, rutting is not expected to be an issue. Even for a no-bond condition, the rutting after 15 years is 0.25 inches.

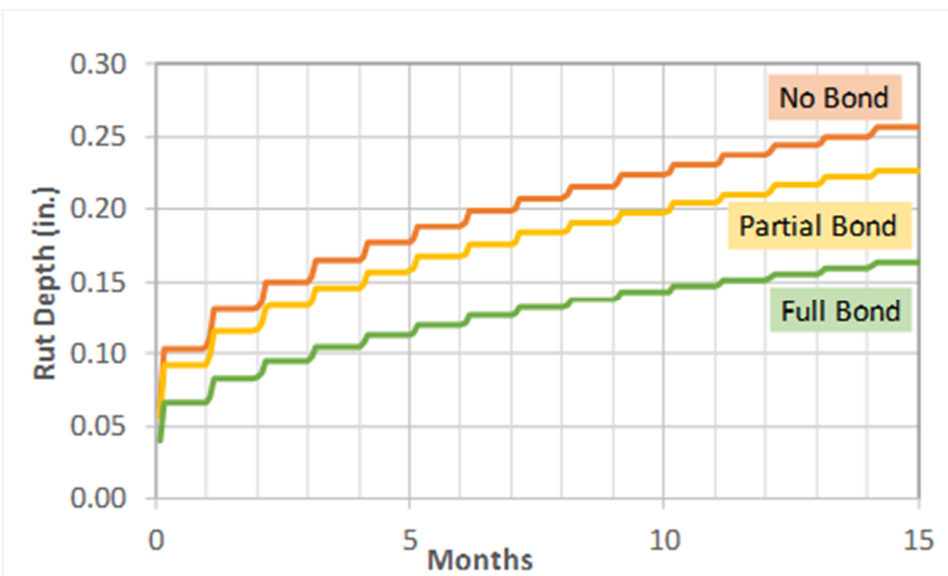


Figure 7. Predicted Rutting Performance.
(with both bond conditions equal)

Fatigue cracking life was predicted based on strain levels at the bottom of the HMA layers in the multi-layer elastic model. This simple model does not consider crack development over time or changing climate conditions. The predicted fatigue life for various bond conditions is shown in Figure 8. Fatigue life increases with high bond performance. The no bond condition has a service life around 6 years, and for stronger bonding, the fatigue life is considerably higher than the practical pavement life.

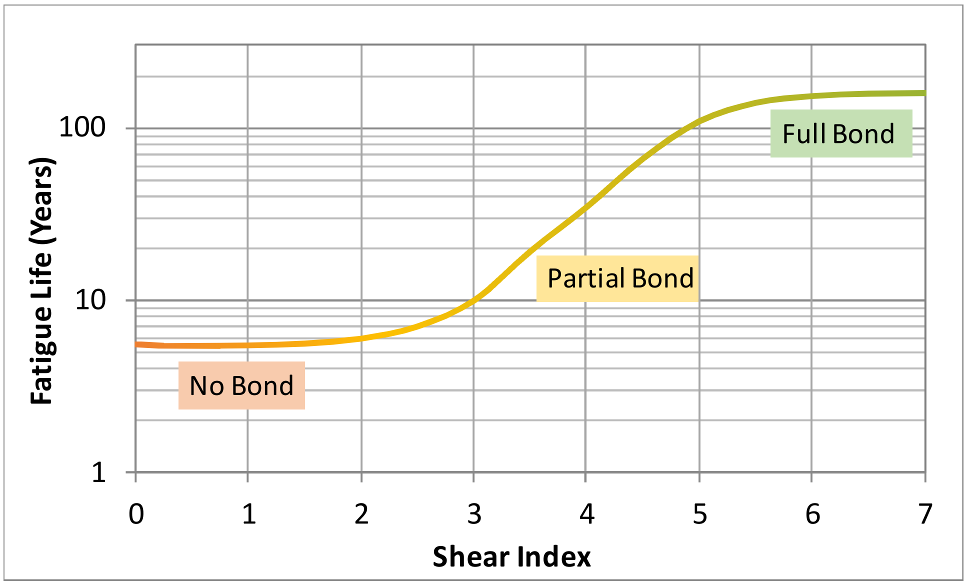
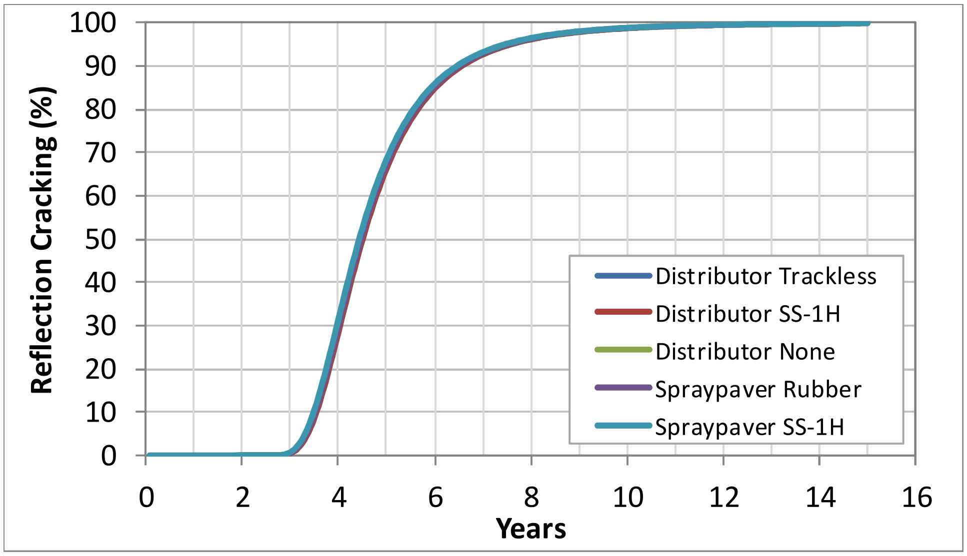


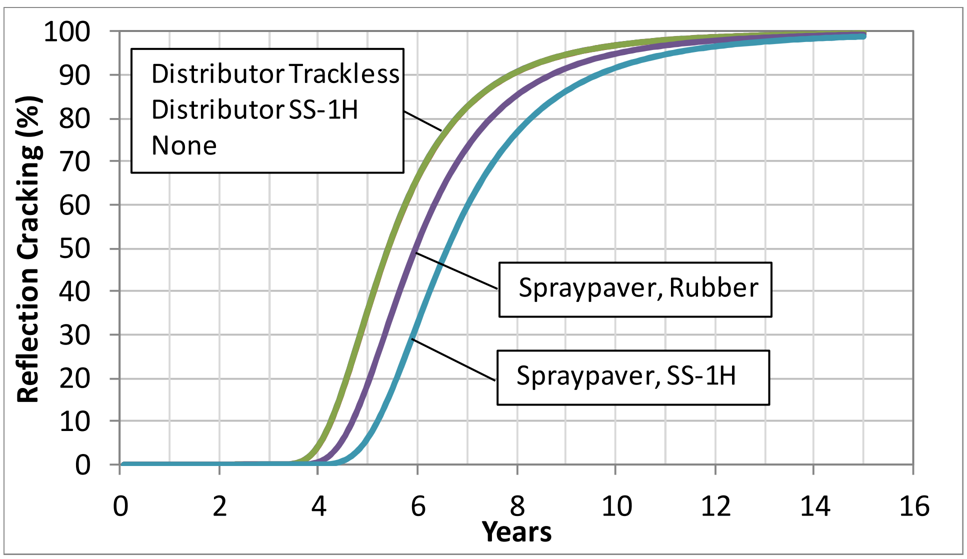
Figure 8. Predicted Fatigue Performance.
(with both bond conditions equal)

Based on 8-month laboratory bond strengths and the qualitative conversion from bond strength to the shear modulus in the models, all tack types and application methods had near "Full Bond" conditions. In contrast, only trackless tack and SS-1H were fully bonded just after construction. When considering the test sections over new HMA, and assuming the milled interface to be fully bonded, the performance for all sections is identical (Figure 9). Reflection cracks start surfacing around year 3 and are fully developed by year 7. When considering test sections over the milled HMA, and assuming the surface interface fully bonded, the predicted performance favors treatments with lower, but still acceptable, bond strengths. Cracking for all sections starts around year 4 and is fully developed by year 8 for the high strength sections. The spray paver sections are fully cracked after nine or ten years. The difference between the two graphs highlights that the deeper bond to the milled surface is important, perhaps more so, than the bond near the surface.

Given the unknowns inherent in the performance models, the researchers conclude that all of these bonding strategies are equally viable.



(a)



(b)

Figure 9. Performance Prediction of Test Sections:
(a) New HMA (Surface) Sections, Milled Interface Fully Bonded,
(b) Milled HMA (Intermediate) Sections, Surface Fully Bonded.

Life-Cycle Cost

The life-cycle cost of the test sections was estimated by summing the initial material costs, routine maintenance costs (based on cracking over time), and rehabilitation costs at failure over a 15-year period. (Appendix F) Since rutting was not significant, only the reflection cracking and the fatigue cracking performance were considered. Failure was defined as fatigue cracking over 20 percent of the area, and reflection cracking at 90 percent of joints. Not included in this analysis is the cost of a spray paver. New and retrofitted paver costs are summarized in Table 4.

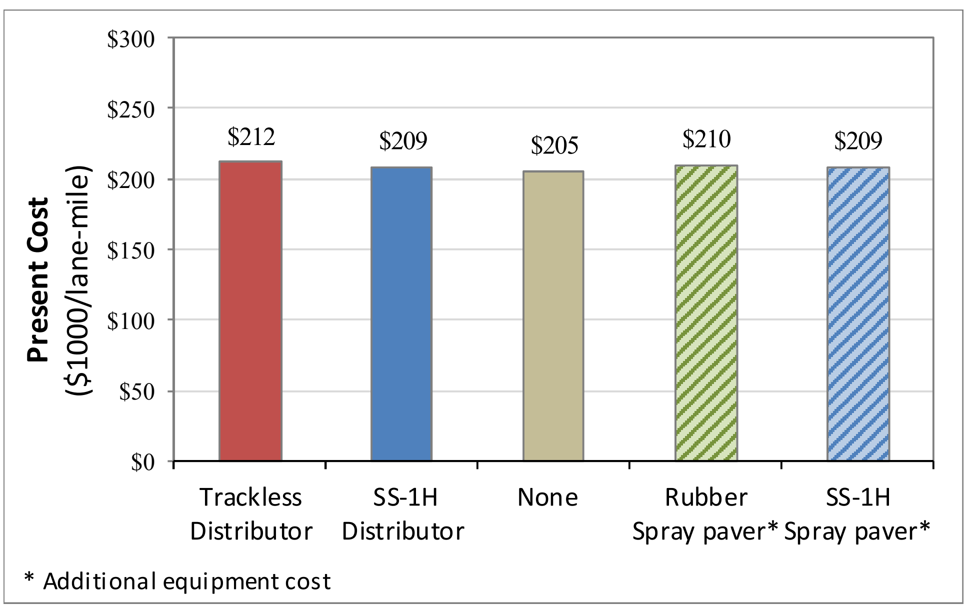
While the equipment represents a substantial upfront investment, the cost should be distributed across several years of paving.

Table 4. Paving Equipment Costs.

Equipment	Manufacturer	Cost ($1,000)
Standard Paver	NA	$400 - $450
Spray Paver	Roadtec	$875 - $950
	Vogel	$925
	Caterpillar (Integral dx)	$740 - $800
Spray Paver Retrofit*	Caterpillar (Integral dx)	$350

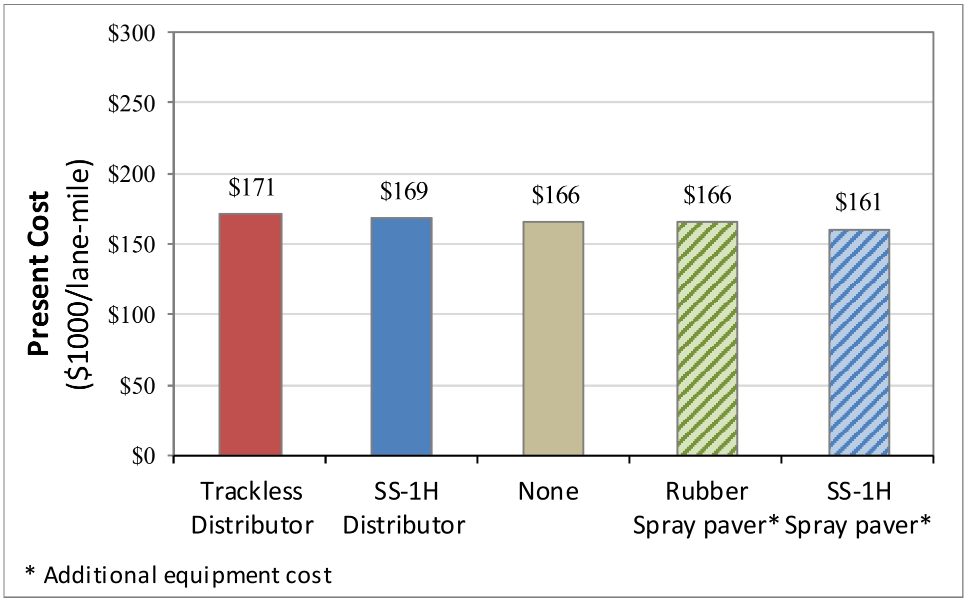
*Available for limited models

Figure presents the life cycle costs for the new HMA and milled surface test sections based on the 8-month bond strength data. Since the predicted life for the milled sections were all greater than the new HMA test sections, the life-cycle costs were lower. Performance differences among the tack-application methods were negligible, and the material costs of tack are small compared to the total material costs; therefore, the differences among life-cycle costs for each section were minimal. On new HMA sections, the cost difference between the least expensive section (no tack) and most expensive section (trackless tack) was $3,000/lane-mile, or less than 2 percent of the overall cost. On the milled sections, the least expensive section was SS-1H placed with a spray paver, which was $10,000/lane-mile cheaper than trackless tack, or about, or 6 percent of the overall cost.



(a)

Figure 10. Life-Cycle Costs: (a) New HMA Surface and (b) Milled Surface Test Sections.



(b)

Figure 10. Life-Cycle Costs: (a) New HMA Surface and (b) Milled Surface Test Sections. (cont.)

CONCLUSION

Findings

Bond strength

Bond strengths ranged from 80 to 420 psi with a median of 210 psi. Bond energy ranged from 0.4 to 6.0 ft-lb/in^2, with a median of 2.2 ft-lb/in^2. Most of the samples from this project had high bond strengths and approximately a third had moderate bond strength. For bond energy, a quarter were in the high range, half in the moderate range, and a quarter in the low range.

Tack type, application method, and bond age were statistically significant variables. This means that there was a significant difference between certain tack type and application method combinations, and that bond performance changed with time. Trackless tack had the highest bond performance with average bond strength and bond energy above 300 psi and 4.0 ft-lb/in^2, respectively. High performance was also achieved by SS-1H placed with a distributor and no-tack samples. The rubberized tack and SS-1H placed with a spray paver had the lowest bond performance and were not statistically unique. The average bond strengths were about 140 and 110 psi, and bond energies were 1.1 and 0.7 ft-lb/in^2, respectively. The performance of these samples ranged from moderate to low; however, after 8-months, the bond strengths and energies increased to about 200 psi and to 1.5 and 1.9 ft-lb/in^2.

The bond after eight months doubled for spray paver sections but for trackless tack and SS-1H placed with a distributor, the bond did not change significantly. This suggests moisture trapped under the mat in the spray paver migrates away with time.

There was no statistical or practical difference in the bond strengths measured in the TTI and OU laboratories. The effect of tack rate on bond performance is inconclusive. There was no statistical difference between bonding to new and milled HMA surfaces. In previous research projects, the researchers have seen greater differences here, generally with higher bond performance for milled surfaces. Performance on milled surfaces largely depends on the quality of the milled pavement and cleanliness after sweeping. Finally, the effect of tracking over the tack coat did not affect the bond performance.

Life-Cycle Cost Analysis

Performance predictions were done considering reflection cracking, rutting, and fatigue cracking. The results for reflection varied significantly between the new HMA sections and the milled HMA sections, not because of the bond condition, but because of change in stresses given the layer thicknesses and crack growth mechanics.

For reflection cracking on new HMA, cracks start surfacing around year 3 and are developed after 5 to 7 years. Cracking is delayed for stronger the bond. For the milled HMA sections, cracking is fully developed in less than 2 years for low bond conditions, and around 10 years for full bonded conditions. In this scenario, the best performance actually occurs with a partially bonded interface.

For rutting performance, higher bond performance consistently reduces rutting. Rutting was not an issue on this project. Even for a no-bond condition, the rutting after 15 years was 0.25 inches.

The predicted fatigue life increases with higher bond performance. The no bond condition is very detrimental to the service life (6 years) and the fully bonded condition predicts life well beyond practical serviceability. For milled sections, the trend is the same but the no bond condition is even more severe (less than 4-years to failure).

Based on the 8-month tests, all tack materials and both distributor and spray paver application methods have near "Full Bond" conditions and similar long-term performance. Under very specific circumstances, spray paver applications, which have lower strength but more flexibility, might increase the pavement life.

The differences among life-cycle costs for the new HMA sections were minimal. The costs were around $210,000/lane-mile over 15 years with a cost difference of $3,000 between the least expensive and most expensive section, less than 2 percent of the overall cost. For milled HMA sections, with longer service life, the sections cost around $165,000/lane-mile with a range of $10,000 among highest and lowest performers, about 6 percent of the overall cost.

Recommendations

The researchers recommend using the shear bond strength test to evaluate bond performance of field and laboratory samples (see Appendix G). Possible scenarios for implementation include:

- Forensic analysis
- Deployment on specialty projects (e.g. spray paver construction, new tack products, paving grid fabrics, etc.)
- Quality control: Demonstrate acceptable bond during demo projects
- Quality assurance: Potentially used to qualify materials and methods for routine paving.

Two types of tack coat construction specifications were developed during this project: (1) a method-based specification and (2) a performance-based specification. These are contained in Appendix G.

The method-based approach prescribes the technical steps to correctly apply tack coat. The existing specification was thorough, so only slight modifications were made to better incorporate spray pavers and to allow slightly higher application rates for HMA pavements. The researchers still recommend to always use tack even though the findings show that, in some circumstances, an overlay may bond with no tack better than with tack. In many scenarios, a tack coat is critical, and the risk of not applying tack when it should outweighs issues with slightly lower bond strengths when tack may not be necessary.

For the performance-based specification, responsibility to select the tack rate was moved to the contractor:

> *The application rate is chosen by the contractor and must conform to the minimum rates specified in Table 407.06-1.*

Also, bond strength testing was added to the Measurement section:

> *The Department will measure the bond strength of the new overlay to the existing surface on the first day of paving. Core locations will be selected randomly and cores will be tested in accordance to the shear bond strength test (ODOT XXX). The average shear bond strength of three cores should be 70 psi or greater, with no single test result below 60 psi. If the contractor fails to meet this criteria, they must make changes to the tack material type, surface preparation procedures, and/or application procedures. Paving may be suspended until the contractor constructs a 1,000-ft test section meeting the criteria.*

Other sections in the current specification remained. A pure performance-based specification, relying solely on the bond strength test, could cause more problems especially as it relates to tack uniformity.

At this time, the researchers do not recommend enforcing the performance-based specification. Rather, the Department should collect bond and pavement performance data on a variety of projects with different surface types and construction parameters. The Department should also monitor the long-term performance of the test sections built during this project. A suggested data collection plan is detailed in Appendix H. These data can be used to refine the performance prediction models and general recommendations.

The most cost-effective treatment was SS-1H placed with a spray paver, but the savings compared to other materials and methods were small. The Department should consider allowing the contractor to choose the tack material, application methods, and rates most convenient for their operations, considering they meet minimum application rate and uniformity requirements.

The Department should note that the initial bond from a spray paver operation is lower than from a distributor application. This is because the water in the tack does not have time to escape the emulsion. The bond will increase significantly with time, likely within the month. Still, this may be a concern when paving in severe stopping/accelerating traffic conditions, where high bond performance is needed immediately after construction.

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Appendix A
LITERATURE REVIEW DETAILS

This memorandum presents a literature review on the following topics:

- Effect of bonding on pavement performance
- Bond strength tests
- Bond strength performance factors
- Managing tack tracking (trackless tack and spray pavers)

A primary goal of this task was to recommend a bond strength test.

Effect of Bonding on Pavement Performance

The strength of a layered pavement is largely dependent on the bond quality at the layer interface. A perfect bond will cause the two layers to act as one, dispersing traffic loads from one layer into the next. (Figure 11) On the other hand, a poor bond will concentrate compressive, tension, and lateral shear stresses within the upper layer, expediting fatigue cracking, slippage cracking, and delamination. All of these problems are then exacerbated by moisture accumulating at the de-bonded interface.

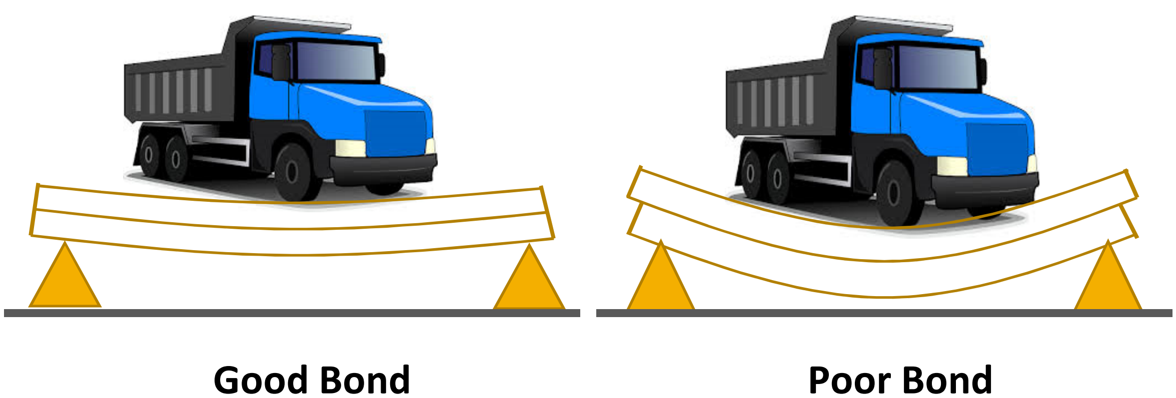


Figure 11. Simplified Physics of Bonding.

The following examples are distresses associated with poor bonding (Figure 12):

Fatigue cracking in poorly bonded layers occurs because of high tensile stresses that concentrate at the base of the overlay. Cracks may initially develop as longitudinal cracks in the wheel path. This distress is theorized to be the most common poor bonding distress, but correctly identifying the cause can be difficult because of the delayed occurrence of cracking.

Slippage failure can occur at locations with frequent braking and accelerating traffic. The vehicles induce a high lateral shear force on the pavement surface. When this force exceeds the capacity of the bond, the stress causes the upper layer to slip and tear. This type of cracking is characterized by crescent-shaped cracks, with the crack ends pointing in the direction of traffic.

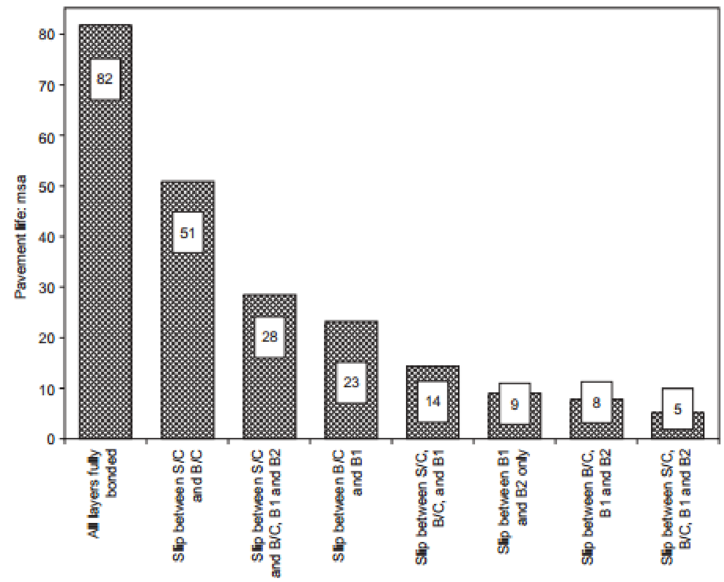
Delamination is the most severe result of poor bonding. The pavement layer has completely detached from the existing surface is removed under moving traffic. This may be a subsequent distress to either fatigue cracking or slippage failure.

(a) **(b)**

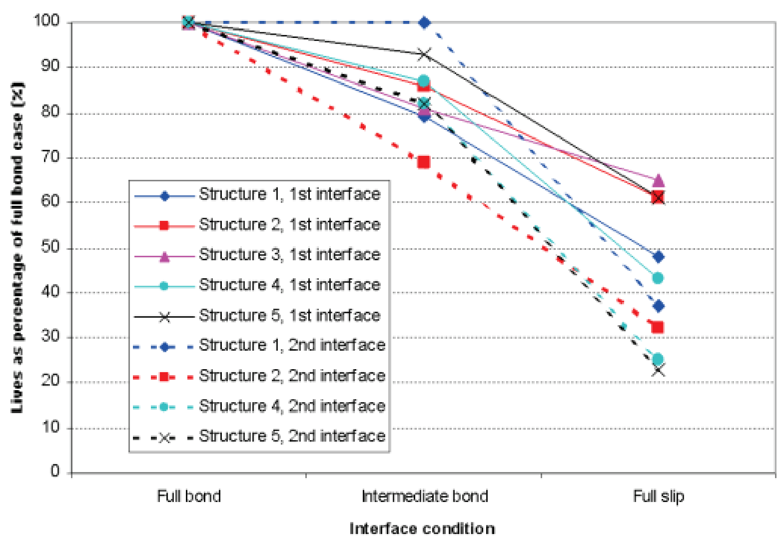
(c)

Figure 12. Distresses Associated with Poor Bonding: (a) Fatigue Cracking, (b) Slippage Failure, and (c) Delamination.

Figure 13 presents a few examples that highlight the importance of bonding to pavement life. Khweir and Fordyce modeled several bonding scenarios by varying slip conditions between base and subgrade layers and estimating millions of standard axles (*7*). They found that the most rapid failures occurred when slip occurred between multiple layers. Brown and Brunton concluded that a full-slip conditions at the second interface would reduce the pavement life as much as 75 percent and an intermediate slip as much as 30 percent (*8*). Al Hakim quantified slippage by a shear reaction modulus and found that full slip conditions can reduce pavement life by 50 percent (*9*).

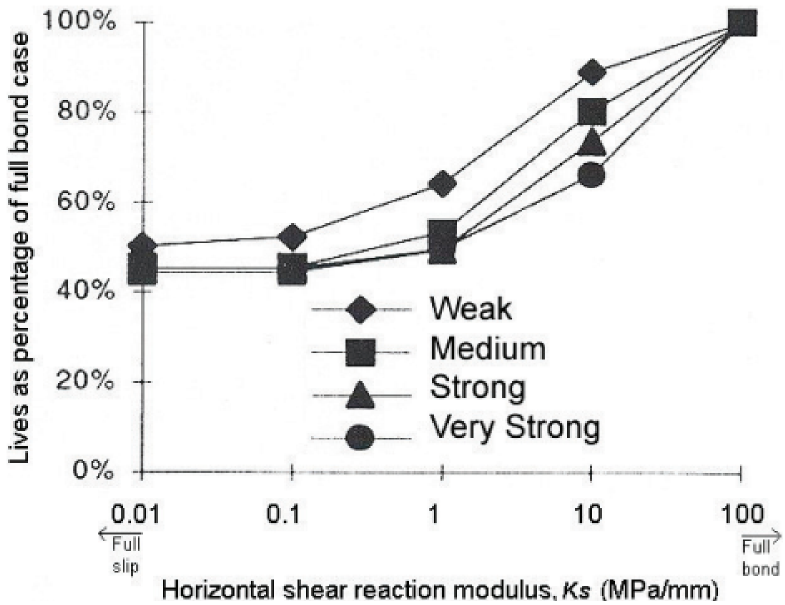


(a)



(b)

Figure 13. Influence of Layer Bonding on Pavement Life: (a) Khweir and Fordyce, (b) Brown and Brunton, and (c) Al Hakim.



(c)

Figure 14. Influence of Layer Bonding on Pavement Life: (a) Khweir and Fordyce, (b) Brown and Brunton, and (c) Al Hakim. (continued)

Bond Strength Tests

Several bond strength tests have been developed and studied, as documented in NCHRP 712 (*Optimization of Tack Coat for HMA Placements*) (*1*) and other reports (*5, 10, 11, 12*). These assess the bond strength by testing laboratory or field compacted samples in shear and tension. The literature also sites torque testing as an option; however, findings suggest the shear and tension tests are much more robust. Another approach for bond testing in the literature is measuring bond **potential** of the tack coat; however, this will not be considered, as it is not appropriate of testing trackless tacks or spray paver applications.

Effect of Load Rate during Testing

An aspect of any bond strength test is the specified loading rate. Because asphalt is a viscoelastic material, the measured strength largely depends on the testing rate. A faster loading rate increases the strength measurements.

The question is, therefore, is there an optimal loading rate? The answer depends on what the operator wants to learn. If the goal is to model the performance in the field, then the load mechanism should be similar to loading in the field. Many research grade tests employ cycling loading at either high- or low-frequency depending on the traffic conditions. To simulate free-flow traffic, a higher frequency is suitable, while congested traffic and breaking/accelerating cars may use a lower frequency. This type of testing requires more sophisticated equipment, technician training, and a longer testing time.

If the goal is to correctly rank the performance of different samples, and assign the result a performance rating (e.g. pass/fail or high/moderate/low), then replicating the exact field conditions is not as important. This is more along the lines of what we want to accomplish in this study. Still, different loading conditions may results in different performance rankings. Consider a the dynamic modulus curves of two HMA materials in Figure 14. The stiffness rankings favor HMA 1 as low frequencies but this switches to favoring HMA 2 at high frequencies. To an extent, the same can be true for testing the interface bond strength. During a bond strength test, the interface strength is a combination of tack cohesive and adhesive strength, aggregate fracture strength, and stiffness of the individual HMA layers. Two of these, tack strength and HMA layer stiffness, have viscoelastic behavior.

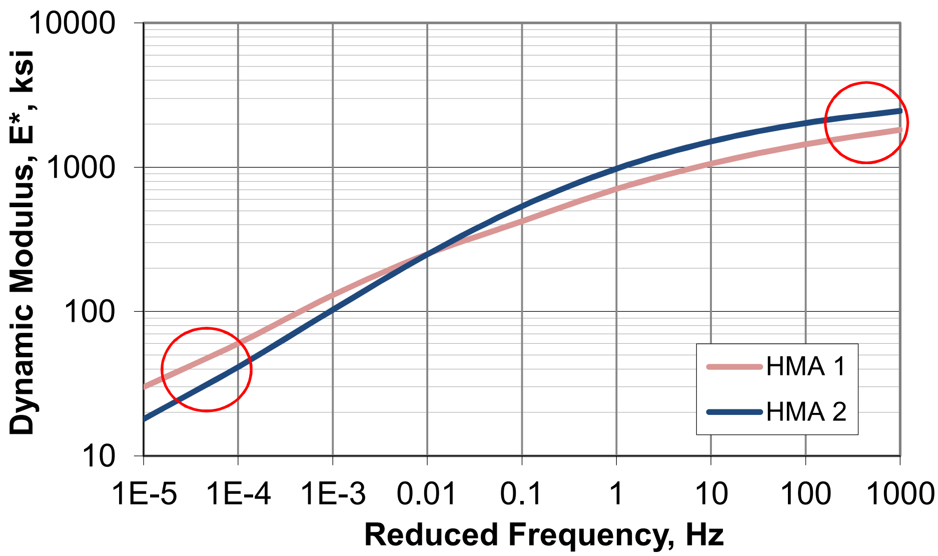


Figure 14. Dynamic Modulus Master Curves.

The bond strength tests described in this section employ a wide range of loading rates, ranging from 0.01 in./min up to 4 in./min. A chart of shearing and tensile loading rates from the literature are summarized in Table 5. While most of these are used just for research, a few have been incorporated into agency standards. A common loading rate used in the U.S. and Europe is 2.0 in./min. Within the U.S., this is convenient as it is the rate for the Marshall Flow Test, which has been repurposed here as a shear test loading frame.

From the slowest rate (0.02 in./min) to the fastest rate (2 in./min) is a factor of 100. Testing at each rate will result in different strength measurements (which is not a problem); however, there is a chance that the performance ranking of two samples could when tested at each rate (which is a problem). The literature does not go into detail about which rate is most appropriate, though researchers at Road Science noted more interface failures of lab-molded samples at lower loading rates.   Hachiya and Sato tested a low and high rate and only noted the difference in strength values, but not any difference in performance ranking (*13*). This is a topic that may be addressed with some preliminary laboratory testing.

Table 5. Compilation of Loading Rates in the Literature

Test Method	Test Method	Loading Rate	Location (citation)
Shear	Leutner-type (includes PINE device)	2.0 in./min	Switzerland (*14*) United Kingdom (*15*) FL, USA (*16*) VA, USA (*17*) AL, USA (*5*)
		0.2 in./min	TX, USA (*3*)
		0.1 in./min	LA, USA (*1*)
	SST, Astra	0.1 in./min	MN, USA (*18*) Italy (*19*)
		50 lb/min	LA, USA (*20*)
	Cyclic	570 lb. @ 1 Hz	FL, USA (*21*)
	Unknown type	0.33 in./min	Netherlands (22)
		4 and 0.04 in./min	Japan (*13*)
Tension	Pull-Off	5 psi/sec	TX, USA (*10*)
		0.02 in./min	Road Science, USA (*23*)
	Direct	20 lb/sec	VA, USA (*17*)
	IBT	0.02 in./min	IL, USA (*24*)
	Tack only	0.5 in./min	LA, USA (*1*)
Torque	Manual	Uncontrolled	United Kingdom (*14*)

Shear

Several direct shear tests have been developed in the past decade. In this test, a cylindrical bonded specimen is placed horizontally in a testing apparatus that has a fixed half and a sliding half. A load is applied to the free-sliding side in a loading frame until failure. Samples may have a normal confining load. Within the literature, there is little consensus on loading rates, confinement pressure, and gap between the sliding and fixed halves. The pros and cons of using a shear test are outlined below:

Pros

- Best represents field conditions
- Test focuses near the bond interface
- Easiest test preparation
- Equipment inexpensive

Cons

- More difficult to isolate tack performance
- More difficult to test thin lifts

- Requires loading frame (not a field test)
- Equipment can be bulky

One shear device was developed at the National Center for Asphalt Technology (NCAT) by the company PINE (*5, 25*). This device (Figure 15) has two cylindrical sleeves through which the sample is placed. Reducer sleeves are used to test smaller samples, however if either the reducer sleeves or the apparatus gets bent, the sleeves will no longer fit without machining. A confining load can be applied with either a fixed screw or a spring mechanisms. The testing gap can be modified which could be useful when testing samples with large nominal maximum aggregate sizes. In addition, the device has two large handles for convenience. In the research at NCAT, the test was run with a loading rate of 2 inches/minute (in a Marshall loading frame). TTI has been using this model the past two years and prefers to use a slower rate of 5 mm/minute and without confining pressure.

Figure 15. PINE Shear Strength Apparatus.

Another popular device is the LISST, developed as part of NCHRP 712 (Figure 16). This has been adopted by the state of Alabama and West Virginia. The difference with this device is that samples are placed into two half-cylinders, making it easier to insert samples that are very near the apparatus dimensions. The halves are then tightened around the sample, also making it easier to remove gaps between the sample and the device. The equipment is heavier and awkward to carry. The testing gap between the sliding plates is not adjustable. In the research, this device was run even slower at 2.54 mm (0.1 inch)/min, often using confinement pressure. Other test rates can be used. Because this device was used in the highly visible NCHRP report, it is slightly more common.

A few other devices are also available, like the West Virginia Division of Highways (WVDOH) shear device (Figure 17)(*2*) , layer-parallel direct shear test (*26*), an older FDOT model (since replaced by a simplified LISST), and an unnamed shear test from the Virginia Transportation Research Center (*27*).

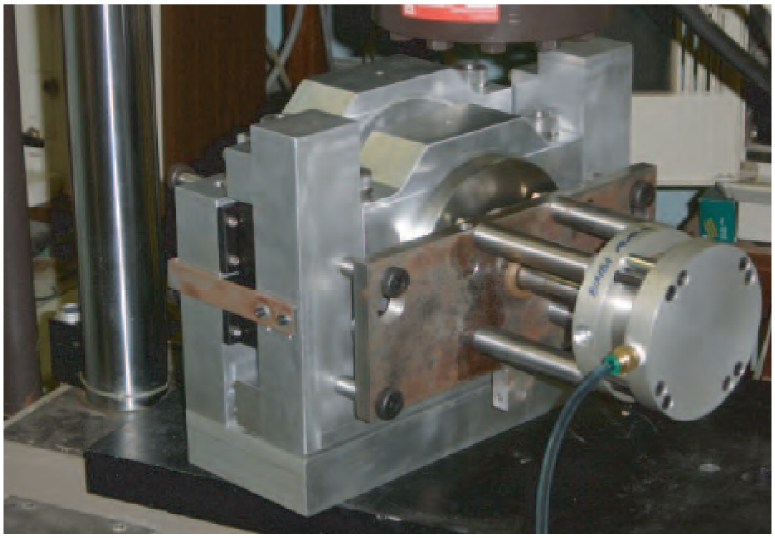


Figure 16. Louisiana Interlayer Shear Strength Tester (LISST).

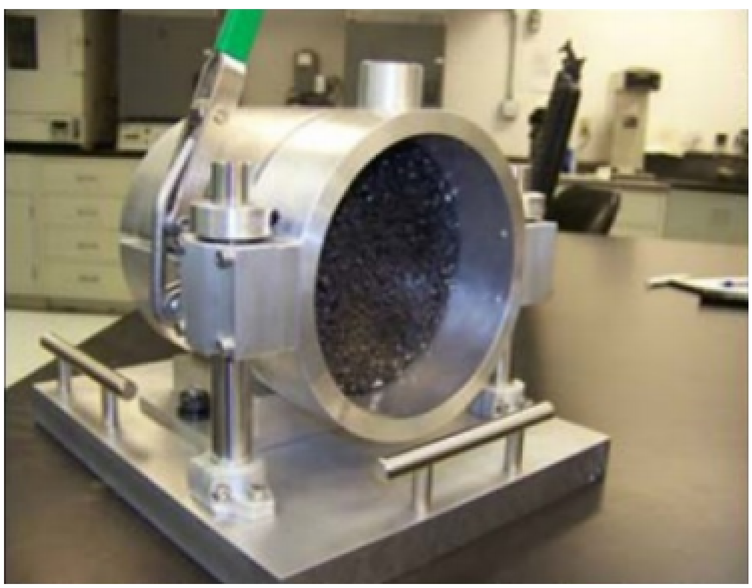


Figure 17. WVDOH Shear Device.

Tension

Like the shear test, there are a couple tensile strength test options. One approach is often called a pull-off test. A partial-depth core can be made in a core sample or even in the field. A metal disk is glued to the surface and then a device pulls the disk until failure. The sample cannot be forced to break at or near the interface in question but will only fail at the weakest point, which could be in the substrate or bonded layer.

Pros

- Measure tack coat performance, ignores surface texture
- No loading frame (some methods)
- Can test in the lab or field
- Equipment inexpensive

Cons

- Does not represent typical failure mode
- Cannot control failure location
- Requires loading frame (some methods)
- Test more likely to fail because of poor test preparation.

One direct tension test is the pull-off test. A bonded specimen is cored through the upper layer and partway through the bottom layer. A disk is glued to the top surface and is pulled in tension with a pull-off tester (Figure 18) until failure. The sample is then evaluated to see if failure occurred at the bond, in the upper or lower layers, or at the glue interface. A benefit of this test is that it can be done in the field. In addition, if performed on a 6-inch core, then three measurements can be made on one sample. While this gives some statistical power, it does not account variability from one location to another in the field. A drawback of the test is if failure occurs in either the substrate or the upper layer, no exact determination on the bond strength can be made, only that it is stronger than the materials around the bond. In addition, the ratio between HMA lift thickness and maximum aggregate size will often break the 3:1 ratio rule. The test is also vulnerable to failure by poor preparation of the steel disks or improper epoxy curing. One last drawback is that testing is done at a constant loading rate (e.g. psi/sec) instead of a constant displacement rate (e.g. inch/minute). Because of this, the user cannot calculate bond energy (area under the stress-strain curve). TTI has used this device in several studies and has assisted the TxDOT construction division with an in-house trackless study (*28*).

Figure 18. Pull-Off Tester and Tested Sample.

Another test approach is a direct tension test. Two ends of a cylindrical sample are fixed to steel disks, which are then mounted and tested in a loading frame. The limitation here is the specialized loading frame for testing.

Figure 19. Tension Test.

The interface bond test (IBT), which is primarily a tension test, was developed at the University of Illinois at Urbana-Champaign (*24*). It is inspired by the Disk-Shaped Comact Tension Test (DCT), and pulls apart a bonded sample is the help of a notch at the interface. In this loading mode, the researchers expect both a tension and a shear-loading characteristic. Using a crack-mouth opening displacement (CMOD) gauge the test measures the load vs CMOD opening, which then captures the total fracture energy. The authors use the fracture energy, rather than the peak load, to measure bond strength. Sample preparation, though non-typical, is not overly complicated. Cutting the notch requires a thin 1-mm masonry saw blade, which is not standard for a lab. The sample mounting equipment need to be fabricated, but are not expensive. The test does require testing with an advanced loading frame. An operator would require more training to run the test than for other methods discussed.

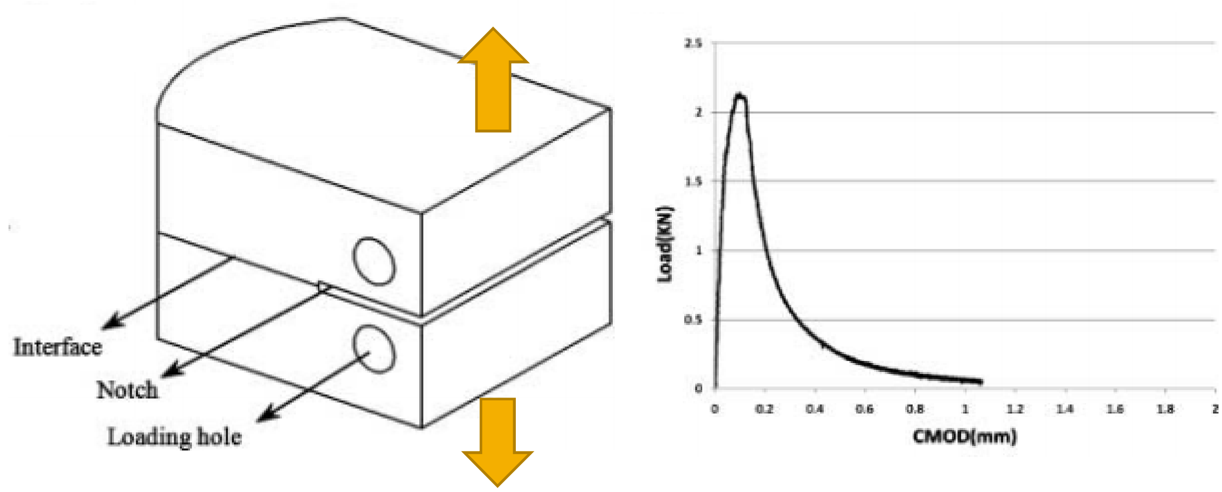


Figure 20. Interface Bond Test (IBT).

Bond Strength Performance

Bond strength performance can vary significantly. Several parameters can affect bond strength, including existing surface type, surface age/wear, surface cleanliness, compaction temperature, overlay mixture type, tack type, tack rate, etc. This section reviews the effect of these parameters and discuss the anticipated bond strengths observed in the field.

In one of the earliest bond strength studies from NCAT (*5*), test sampling was done on 7 unique overlay projects. The projects incorporated three surface types, three tack types, and residual asphalt rates from <0.02 to 0.06 gal/sy. The maximum bond strengths for each project ranges from 37 to 273 psi. The highest strength was on milled HMA and the lowest strength was on new HMA (dusty surface condition observed). Other new HMA projects had very good bond strength. Among the projects, there was no consensus that a certain tack rate was optimum. In some cases it was a low rate, in others it was a high rate, and in other projects there was no optimum identified. (All testing performed in shear at 2 in/min.)

Wilson et al. tested the bond strength on laboratory samples and on field cores from several overlay projects (*3*). The study focused on trackless tack materials. For bond strength of laboratory samples, all samples had acceptable bonding, but stiff-residue trackless tack had the highest bond energy, followed by soft-residue trackless tack, conventional tack, and then no tack. Higher ambient and HMA compaction temperatures improved bonding. Bonded trackless tack samples were resistant to fatigue cracking and cold temperature delamination. Bond strengths from field samples were considerably lower (15–95 psi) than for lab-molded samples (100–200 psi) and varied among different overlay projects. Example data from projects in the Laredo TxDOT District is shown in Figure 21. The variation in values underscores that bond strength is not simply a factor of the tack coat. Other variables like ambient and pavement temperature during construction, overlay

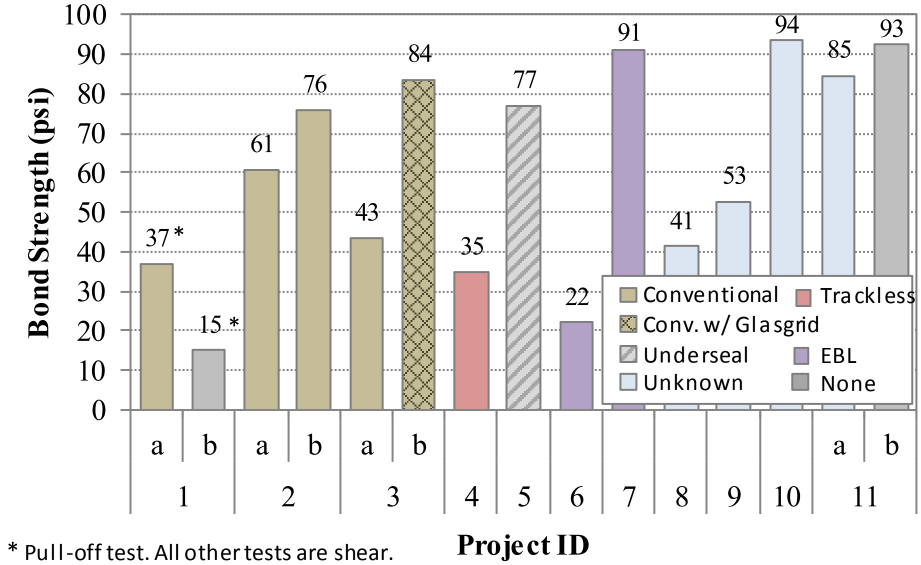


Figure 21. Bond Strengths from Laredo Projects. (*3*)

temperature, compaction effort, overlay density, etc. also influence bond strength. (All testing was performed in shear at 5 mm/min.)

Bae et al. (*29*) investigated the tack coat interface shear strength of two types of emulsified tack coat (CRS-1 and trackless) and three application rates from 0.031 to 0.155 gal/sy on full scale pavement test sections. The trackless tack coat had greater interface shear strength than conventional tack coats in temperatures above 40˚C. Also, the interface shear strength at all application rates increased when the binder rheology parameter, $|G^*|/\sin \delta$, increases.

Mohammad et al (*30*) compared the interface shear strength of different surface types, tack types, tack rates, the wet/dry condition, and field-molded to lab-molded. The values for each parameter are as follows: surface type - new HMA, existing, HMA, milled HMA, and concrete; tack type - SS1-h, SS-1, CRS-1, trackless, PG 64-22; and residual tack rate - no-tack, 0.14, 0.28, 0.7 L/m2. Most of the samples were field molded. The results of this study (Figure 22) indicated that surface type did have a significant effect on bond strength, but less significant at higher tack rates for some surface types. Trackless tack had the highest bond strength, followed by SS-1h, PG 64-22, then CRS-1. For emulsion tack coats the wetness of layer did not affect the interface shear strength. The wet condition was simulated by spraying water at a rate of 0.27 L/m2 on tack coat layer before placing the overlay. All testing was performed at 2.54 mm/min, with 138 kPa confinement and without confinement.

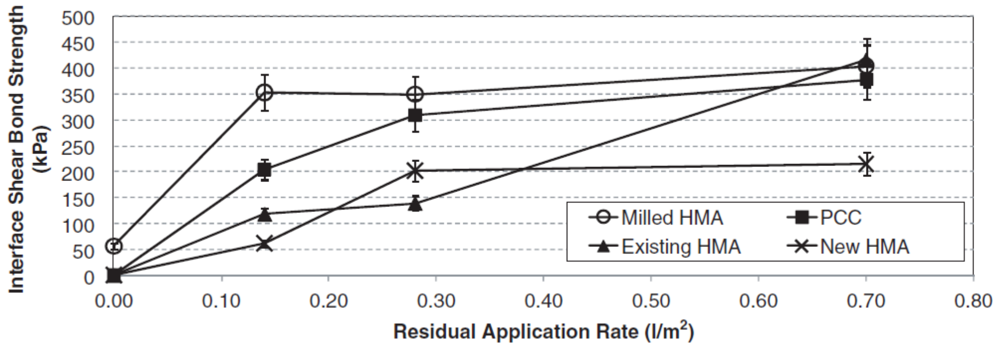


Figure 22. Effects of Surface types on interface shear strength for SS-1h tack coat. (*30*)

Bond Energy

While bond strength is most common for quantifying bond performance, bond energy may also be considered. Bond energy is often defined as the cumulative area under the stress-strain curve (Figure 23). One issue with bond strength is that a bond may have a very high strength that is reached after a short amount of strain, after which the strength dramatically decreases. This is indicative of a brittle material. In contrast, a high-energy bond may have a lower maximum strength, but it is able to maintain its strength over a greater amount of strain. This could indicate a more flexible bond. Previously the research noted that bond energy appeared to better distinguish among different materials. (*3, 4*)

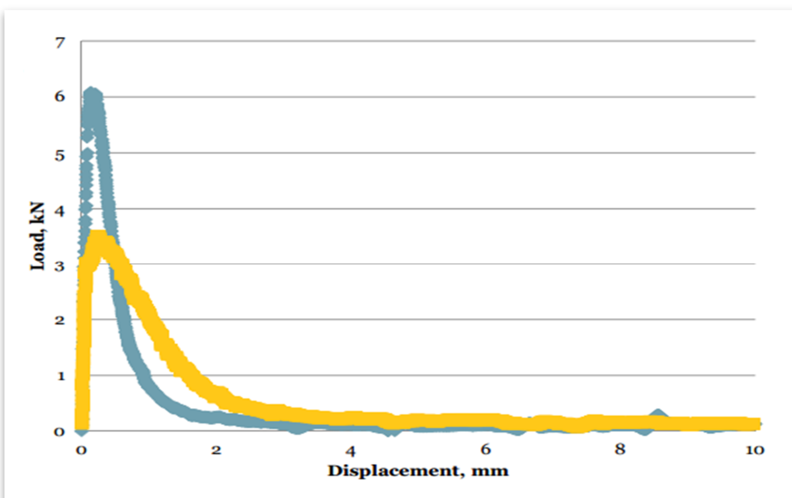


Figure 23. Peak bond strength vs. bond energy.

The following are arguments against bond energy. A higher bond strength strongly correlates with a high bond energy. In other words, the two parameters are not independent, and one could argue that bond strength is a good enough indicator, especially considering it is more simple. Another complaint is that this type of bond energy (area under the curve) is an over-simplification of true bond energy, which is a complex interaction of material surface energies and contact mechanics. An investigation of bond energy from this perspective is outside the scope of this project.

Managing Tack Tracking

Even if the tack is applied correctly, the material is often picked up and contaminated by construction traffic. Worse yet, the tack is usually lost in the wheel path where it is needed the most (Figure 24).

A clean, dry surface maximizes layer bonding. Milling of the existing surface has also been shown to typically increase bond strengths. However, milling does produce dust and it uses water. Both need to be eliminated from the milled surface prior to application of tack. Sweeping of the milled surface is typical. Judgement should be exercised in timing of the sweeping, as it will be most efficient after any moisture left from the milling has evaporated.

Figure 24. Tack Coat Tracking Problems.

Trackless Tack

Trackless tacks were recently introduced to the paving industry. They use a hard-pen base asphalt that hardens shortly after application and loses its tackiness (15-30 minutes for emulsion types, 30 seconds for some hot-applied types). Consequently, the coats should not stick to tires but remain intact and uncontaminated. When HMA is applied and compacted over trackless tack, the tack heats up, is reactivated, and bonds the new overlay with the existing surface. These products are new, so while performance appears acceptable to date, the short and long-term benefits of trackless tack are not well documented. Some in the industry suggest trackless tack are susceptible to fatigue cracking.

Trackless tack is not a fool-proof product, and not all of these products are equal. Tack has been shown to still pick up under very heavy construction equipment like a material transfer vehicle (MTV) (Figure 25), and actual curing times can be longer than anticipated. For these reasons, some still recommend keeping traffic off the tack coat, and require that HMA be fed into the paver from an MTV in the adjacent lane. While the approach is ideal, this is often not an option on two-lane and heavy-volume roads.

Figure 25. Trackless Tack Picking Up Under MTV

Studies have shown that trackless tacks yield higher bond strength compared to traditional tacks (Figure 26). Others note that this high strength is also associated with an immediate decrease in strength after the peak, indicative of a failure in a stiff material. It has also been shown to fail much sooner at lower temperatures than other polymer-modified emulsions.

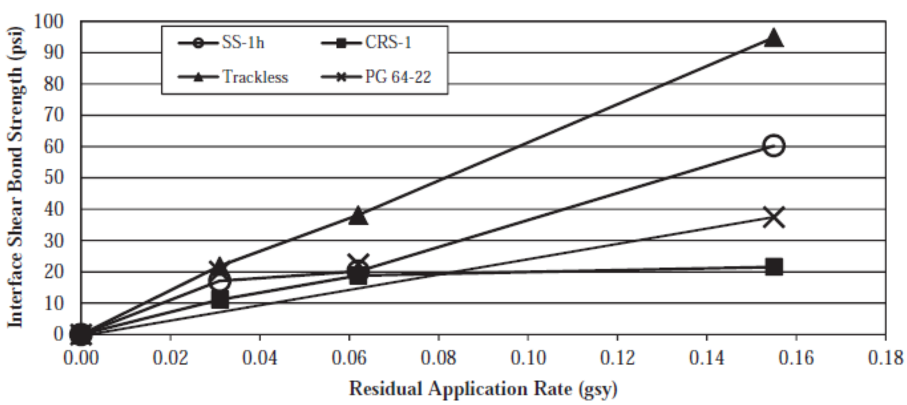


Figure 26. Bond Strength Comparison of Trackless Tack to Other Tack Materials. (*1*)

Spray pavers

Another approach to mitigating problems with tack tracking is using a spray paver. As mentioned earlier, spray pavers also use for application of underseal membrane. This equipment is a paver with an on-board tack spray bar and tack reservoir. In this manner, the machine can apply tack directly in front of the HMA and completely avoids problems with tack tracking. There are currently two models on the market, the Vogel SUPER 1800-2 with Spray-Jet Module, and the Roadtec SP-200 (Figure 27). The popularity of these pavers varies quite a bit from state to state. Some of the draw backs with this approach are:

1. Initial equipment costs,
2. Inconvenience with frequent refilling of tack reservoir,
   (~500 gal. capacity on spray paver compared to 1,000-4,000 gal. on a distributor truck)
3. More difficult to check quality of coat during application,
4. Concern with inadequate time for emulsion curing,
5. Not recommended for use with hard-pen base asphalt tacks, and
6. Limited equipment models available.

All in all, in order for a contactor to successfully move to using a spray paver system, there needs to be a change in mindset and habits of how tack coats should be constructed. Once this change is made, many of these problems may be resolved.

(a) (b)

Figure 27. Spray pavers: a) Vogel SUPER 1800-2 with Spray-Jet Module, and b) Roadtec SP-200.

In the case of trackless tacks and spray pavers, it can be difficult to quantify the benefits that reduced tracking provide. We assume the quality of the undamaged/uncontaminated coat is superior—and we could measure the resulting bond strength—but the convenience to contractors and the public by limiting/eliminating tack tracking, while significant, may not be calculable.

Recommendation

We recommend using a shear test method. The key benefits to this approach are:

1. Representative of field failure conditions.
2. Intuitive method.

3. Ease of sample preparation
4. Ease of testing
5. Inexpensive equipment.

Within the different types of shear devices, we recommendation the Shear Strength Apparatus by PINE. We have found the PINE device to be lighter, easier to handle, and more polished. Some of the initial drawbacks with the device (inconvenient sample loading, inadequately designed sample-diameter reducers), have been resolved through discussions with the manufacturer. The issue of a less robust sample confinement method is not a concern since ODOT does not intend to test in the confined mode. The LISST by Association Technologies & Mfg, on the other hand, is a much bulkier device and awkward to handle and store.

The tension tests is not recommended because sample preparation is more particular and can even cause a failed test is not properly done. The final test result is also more likely to be inconclusive if failure were to occur in either the substrate or overlay. Other methods mentioned, but not discussed (torque, direct tack tests, composite stiffness) are not recommended.

The literature review was inconclusive about the recommended loading rate. Most agencies use a loading rate of 2 in./min, which is fast compared to most HMA performance-tests. Other loading rates in the literature are 0.2 in./min, 0.1 in./min, and 0.02 in./min. The most important aspect of the loading rate is that it can correctly distinguish among good, fair, and poor interface bonds. The researchers recommend performing preliminary tests on samples with these types of bond strengths before selecting a loading rate. If all results are reasonable, the recommended loading rate will be the one most convenient for ODOT and local contractors.

Appendix B
TEST SECTION DETAILS

Preliminary Site Assessment

To minimize the effect of external confounding variables on the testing plan, the proposed site was assessed for traffic uniformity, accessibility, and pavement condition/uniformity.

Site Location and Configuration

Figure 28 shows an overview of the site. The IR-270 project starts 0.87 miles north of US-40 to 0.02 miles south of the Conrail RR (straight line mileage (SLM) point 40.45 to 43.13.) At the northern interchange, IR-270 travels under two overpasses, and at the southern interchange, IR-270 bridges over I-70. Ramps are also part of the project, but are not illustrated here.

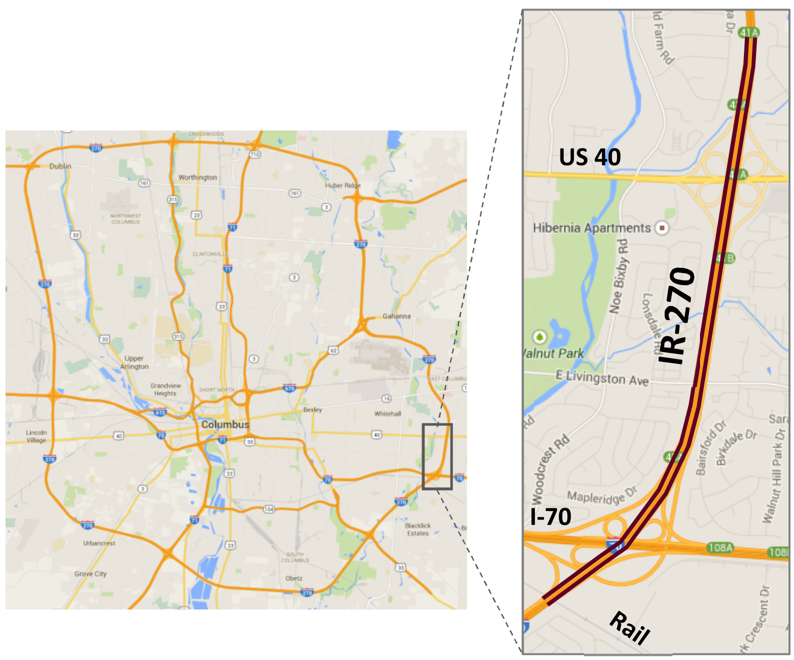


Figure 28. Proposed project location: FR-270 in Columbus.

The lane configuration of IR-270 is shown in Figure 29. There are two southbound and two northbound main line lanes, and as many as four southbound and four northbound collector-distributor (outer) lanes. The outer and mainline lanes are divided by a jersey barriers for most of this section, except at the upper and lower extents of the project. While the outer lanes have various exit and off-ramps, which allows weaving traffic and variable traffic volumes per lane, the protected mainline lanes have more consistent flowing traffic. The mainline lanes also have wide shoulders which allows for easy site access during and after construction. Lane closures are allowed at night.

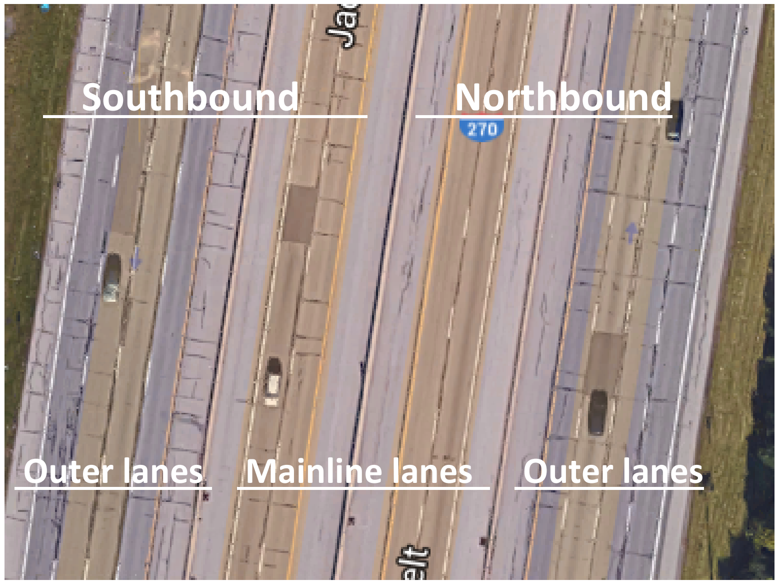


Figure 29. Lane configuration.

Pavement Condition and Uniformity

The pavement condition was assessed visually and with ground-penetrating radar (GPR). This non-destructive technology helps identify subsurface anomalies in layer thickness, distress, and moisture damage. Data was collected in the right wheel path in every lane of the project.

From the GPR data, locations were selected for falling-weight deflectometer (FWD) testing and coring. The tested locations represented a range of pavement conditions: aged existing HMA, repaired/patched pavement, and distressed areas. The goal of this testing was to identify how similar or dissimilar different pavement sections might be, in case a test section spans different pavement conditions. A total of 34 locations were tested with FWD and 10 locations were cored. The FWD data was analyzed using the back-calculation software MODULUS 6.1. The inputs for the back-calculations are shown in Table 6.

The dynamic moduli of the cores were tested in an asphalt mixture performance tester (Figure 30). Testing was done in general accordance with AASHTO TP 62 (Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt). Because of the limited core height, the tested samples were smaller than normal with a 3-inch diameter and approximately 4.5-inch height.

Table 6. FWD Back-Calculation Input Parameters.

Surface		Base		Subbase		Subgrade	
Thickness	5.4	**Thickness**	10	**Thickness**	6	**Thickness**	120
Temp	75/95**	**Type**	Concrete	**Type**	Flexible Base	**Type**	Clay LL<50
Min	100	**Min**	1500	**Min**	10	**Most probable**	10
Max	1500	**Max**	6000	**Max**	80		
v* **	0.35	**v**	0.20	**v**	0.35	**v**	0.40

* Average height of core samples.
** Depends on temperature during testing.
*** Poission’s ratio

Figure 30. Dynamic modulus test in the Asphalt Mixture Performance Tester (AMPT).

Results

The mainline lanes have very good traffic uniformity and good access for construction and later assessment. The pavement uniformity on the mainline lanes, however, has some significant shortcomings. There are numerous full-depth repair areas ranging from 25 to 500 ft in length. The southbound mainline left-hand lane has fewer concentrated repair areas than the other mainline lanes. The researchers have documented the location and extent of each patched area.

Figure 31 and Figure 32 are GPR images from the southbound mainline lanes. In the old HMA section, the average HMA thickness was 5.4 inches ranging between 5.2 and 6.2 inches. The GPR images indicate surface cracking and occasional areas of shallow subsurface damage (1-2 inches deep). The 3.25-inch mill and inlay during construction removed much of the damaged area, though the some locations of this layer were still structurally deficient. The repaired areas were clearly visible in the GPR data. The repair depth is between 4.75 and 5.25-inches deep. The proposed milling depth should not interfere with the repair interface.

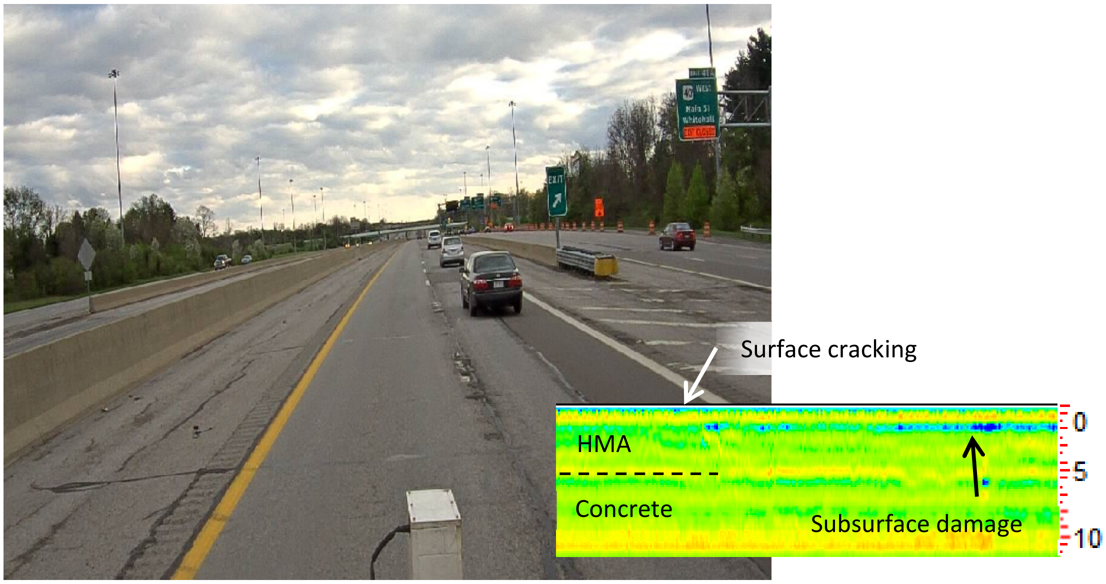


Figure 31. Typical old HMA section.

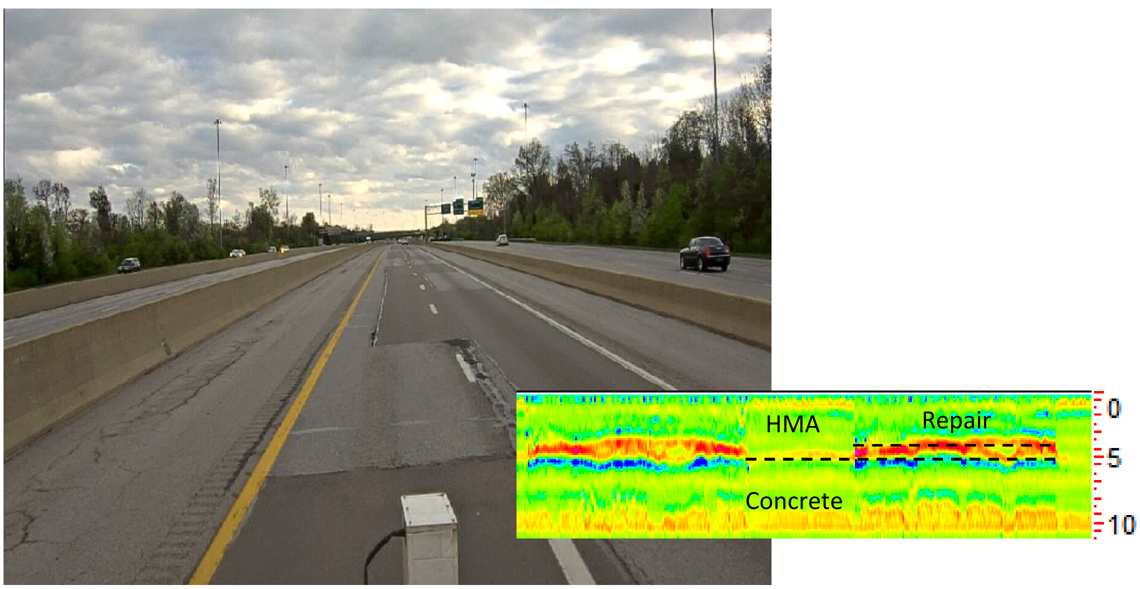


Figure 32. Typical repaired section.

The results of the FWD testing are shown in Table 7. The average modulus of the old HMA sections was 364 ksi, and was statistically lower than the 733 ksi repaired sections. Other pavement layer stiffness wase not statistically different between the old and repaired HMA sections. The dynamic modulus test results in Table 8 and Figure 33 show a statistical significant difference in the old HMA and repaired HMA at higher frequencies but not at lower frequencies. The main take-a-way from these tests is that overlay performance on our test sections could be affected by whether they are built over an old or repaired HMA section.

Table 7. Falling-Weight Deflectometer Results.

Section Type	Modulus, ksi							
	Asphalt		Concrete		Subbase		Subgrade	
	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.
Old HMA	364	105.3	4348	1127.3	42	19.7	16	3.0
Repaired HMA	733	275.7	3889	1034.1	27	17.5	20	5.7

Table 8. Dynamic Modulus Results.

Section Type	High-Frequency (10 Hz)		Low Frequency (0.001 Hz)	
	Average	St. Dev.	Average	St. Dev.
Old HMA	1062	220.0	101	52.0
Repaired HMA	1509	300.7	103	39.0

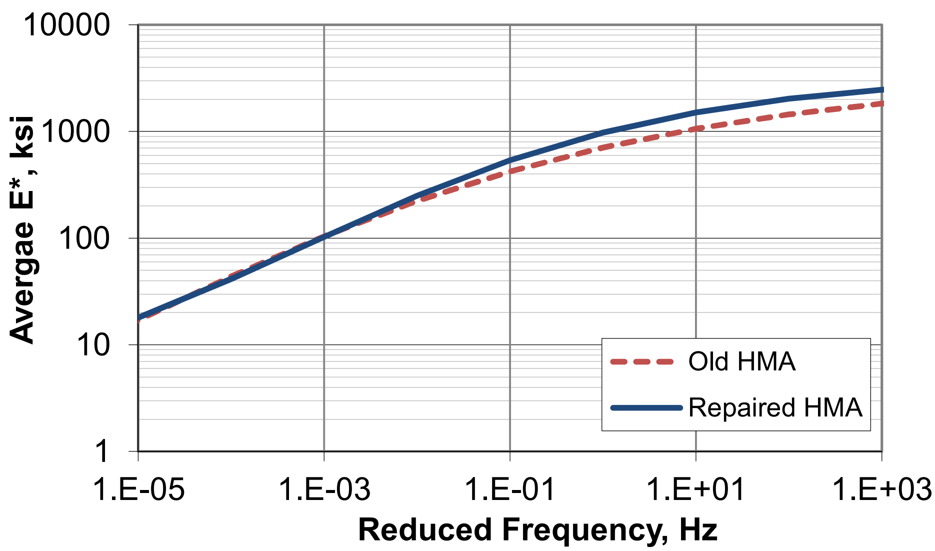


Figure 33. Dynamic Modulus Results.

Test Section Construction

The testing plan is detailed in Table 9. The plan is a fractional factorial design to improve research efficiency. In general, the plan considered two surface types, three tack materials and no tack, two tack application methods, four tack rate rankings, and selective tack tracking in the wheel path.

Table 9. Testing Plan

Surface Type	Tack Material	Application Equipment	Tack Application Rate		Tracking	Additional Samples
			Rank	(gal/sy)		
Milled Surface (Intermediate Course)	None	NA	None	0	NA	OU
	Rubberized tack	Spray Paver	Mod.	0.08	N	
			High	0.12		OU
			V. High	0.16		
	SS-1h	Distributor truck	Low	0.04	N	
					Y	
			Moderate	0.08	N	OU
					Y	
			High	0.12	N	
					Y	
New Surface (Surface Course)	None	NA	None	0	NA	OU 8-Month
	SS-1h	Distributor truck	Low	0.04	N	8-Month
					Y	
			Mod.	0.07	N	OU
					Y	
			High	0.10	N	8-Month
					Y	
	Rubberized tack	Spray paver	Mod.	0.07	N	OU
			High	0.10		8-Month
			V. High	0.13		
	Trackless tack	Distributor truck	Low	0.04	N	
					Y	
			Mod.	0.07	N	OU
					Y	
			High	0.10	N	8-Month
					Y	
	SS-1h	Spray paver	Low	0.04	N	8-Month
			Mod.	0.07		OU 8-Month
			High	0.10		8-Month

Table 10 gives the location of each test section.

Table 10. Test Section Locations

Surface Type	Tack Type	Application Method	Target Rate (gal/sy)	Tracking	Station (###+##)		Section Length, ft
					Begin	End	
New	Rubber	SprayPaver	0.07	None	1146+00	1140+00	600
New	Rubber	SprayPaver	0.1	None	1140+00	1134+00	600
New	Rubber	SprayPaver	0.13	None	1134+00	1128+00	600
New	SS-1H	SprayPaver	0.07	None	1128+00	1122+00	600
New	SS-1H	SprayPaver	0.1	None	1122+00	1117+00	500
New	SS-1H	SprayPaver	0.13	None	1117+00	1112+00	500
New	SS-1H	Distributor	0.04	None	1108+00	1103+00	500
New	SS-1H	Distributor	0.04	Tracking	1103+00	1099+00	400
New	SS-1H	Distributor	0.07	None	1099+00	1094+00	500
New	SS-1H	Distributor	0.07	Tracking	1094+00	1090+00	400
New	SS-1H	Distributor	0.1	None	1090+00	1085+00	500
New	SS-1H	Distributor	0.1	Tracking	1085+00	1081+00	400
New	Trackless	Distributor	0.04	None	1081+00	1076+00	500
New	Trackless	Distributor	0.04	Tracking	1076+00	1072+00	400
New	Trackless	Distributor	0.07	None	1072+00	1067+00	500
New	Trackless	Distributor	0.07	Tracking	1067+00	1063+00	400
New	Trackless	Distributor	0.1	None	1063+00	1058+00	500
New	Trackless	Distributor	0.1	Tracking	1058+00	1054+00	400
Milled	Rubber	SprayPaver	0.08	None	1089+00	1080+00	900
Milled	Rubber	SprayPaver	0.12	None	1080+00	1073+00	700
Milled	Rubber	SprayPaver	0.16	None	1073+00	1066+00	700
Milled	SS-1H	Distributor	0.04	None	1063+00	1056+00	700
Milled	SS-1H	Distributor	0.04	Tracking	1056+00	1049+00	700
Milled	SS-1H	Distributor	0.08	None	1049+00	1043+00	600
Milled	SS-1H	Distributor	0.08	Tracking	1043+00	1037+00	600
Milled	SS-1H	Distributor	0.12	None	1037+00	1031+00	600
Milled	SS-1H	Distributor	0.12	Tracking	1031+00	1024+00	700

Photos of the paving operation, tack measurement, and tack tracking are presented in Figure 34 to Figure 36.

(a)

(b)

Figure 34. Paving operations: (a) Spray paver sections and (b) distributor and conventional paver sections.

Figure 35. Location of tack rate measurement.

Figure 36. Construction of “tracked” sections.

Appendix C
LABORATORY TESTING AND ANALYSIS DETAILS

Bond Results from Field Sections

The complete bond test results are given in Table 11.

Table 11. Bond Strength and Bond Energy Results.

Sample Period	Surface Type	Tack Type	Application Method	Tack Rate (gal/sy)		Tracking	Location	Agency	Bond Strength (psi)	Bond Energy (ft-lb/in^2)	Interface Failure (%)
				Target	Residual						
Initial	Milled	None	NA	0.00	0.00	NA	BWP	TTI	162.2	1.51	80
Initial	Milled	None	NA	0.00	0.00	NA	BWP	TTI	178.1	1.36	80
Initial	Milled	None	NA	0.00	0.00	NA	BWP	TTI	123.2	0.62	100
Initial	Milled	Rubber	Spray Paver	0.08	0.06	None	BWP	TTI	165.8	1.07	40
Initial	Milled	Rubber	Spray Paver	0.08	0.06	None	BWP	TTI	200.6	2.04	80
Initial	Milled	Rubber	Spray Paver	0.08	0.06	None	BWP	TTI	160.1	2.99	100
Initial	Milled	Rubber	Spray Paver	0.12	0.08	None	BWP	TTI	133.5	0.87	100
Initial	Milled	Rubber	Spray Paver	0.12	0.08	None	BWP	TTI	194.6	1.81	100
Initial	Milled	Rubber	Spray Paver	0.12	0.08	None	BWP	TTI	109.9	0.55	100
Initial	Milled	Rubber	Spray Paver	0.16	0.11	None	BWP	TTI	152.3	1.17	100
Initial	Milled	Rubber	Spray Paver	0.16	0.11	None	BWP	TTI	88.3	1.00	20
Initial	Milled	Rubber	Spray Paver	0.16	0.11	None	BWP	TTI	116.4	1.23	40
Initial	Milled	Rubber	Spray Paver	0.16	0.11	None	BWP	TTI	124.5	0.98	90
Initial	Milled	Rubber	Spray Paver	0.16	0.11	None	BWP	TTI	132.6	0.97	100
Initial	Milled	SS-1H	Distributor	0.04	0.03	None	BWP	TTI	256.1	3.64	25
Initial	Milled	SS-1H	Distributor	0.04	0.03	None	BWP	TTI	252.5	3.01	60
Initial	Milled	SS-1H	Distributor	0.04	0.03	Tracking	WP	TTI	131.4	1.47	50
Initial	Milled	SS-1H	Distributor	0.04	0.03	Tracking	WP	TTI	139.8	1.82	50
Initial	Milled	SS-1H	Distributor	0.04	0.03	Tracking	WP	TTI	158.2	2.40	60
Initial	Milled	SS-1H	Distributor	0.08	0.05	None	BWP	TTI	199.1	3.77	40
Initial	Milled	SS-1H	Distributor	0.08	0.05	None	BWP	TTI	189.3	2.63	80
Initial	Milled	SS-1H	Distributor	0.08	0.05	None	BWP	TTI	172.2	2.69	80
Initial	Milled	SS-1H	Distributor	0.08	0.05	Tracking	WP	TTI	313.1	4.99	20
Initial	Milled	SS-1H	Distributor	0.08	0.05	Tracking	WP	TTI	323.0	4.83	30
Initial	Milled	SS-1H	Distributor	0.08	0.05	Tracking	WP	TTI	282.6	3.24	100
Initial	Milled	SS-1H	Distributor	0.12	0.07	None	BWP	TTI	314.9	2.41	50
Initial	Milled	SS-1H	Distributor	0.12	0.07	None	BWP	TTI	164.9	2.15	70

Sample Period	Surface Type	Tack Type	Application Method	Tack Rate (gal/sy)		Tracking	Location	Agency	Bond Strength (psi)	Bond Energy (ft-lb/in^2)	Interface Failure (%)
				Target	Residual						
Initial	Milled	SS-1H	Distributor	0.12	0.07	None	BWP	TTI	184.2	2.09	80
Initial	Milled	SS-1H	Distributor	0.12	0.07	Tracking	WP	TTI	124.3	1.85	100
Initial	Milled	SS-1H	Distributor	0.12	0.07	Tracking	WP	TTI	148.8	1.59	80
Initial	Milled	SS-1H	Distributor	0.12	0.07	Tracking	WP	TTI	148.6	2.32	75
Initial	New	None	NA	0.00	0.00	None	BWP	TTI	202.3	1.82	100
Initial	New	None	NA	0.00	0.00	None	BWP	TTI	254.2	2.20	100
Initial	New	None	NA	0.00	0.00	None	BWP	TTI	239.8	1.93	100
Initial	New	Rubber	Spray Paver	0.07	0.05	None	BWP	TTI	143.2	0.97	95
Initial	New	Rubber	Spray Paver	0.07	0.05	None	BWP	TTI	141.0	0.93	100
Initial	New	Rubber	Spray Paver	0.07	0.05	None	BWP	TTI	148.0	1.10	100
Initial	New	Rubber	Spray Paver	0.10	0.07	None	BWP	TTI	136.2	1.09	100
Initial	New	Rubber	Spray Paver	0.10	0.07	None	BWP	TTI	130.7	0.91	100
Initial	New	Rubber	Spray Paver	0.10	0.07	None	BWP	TTI	135.1	1.03	100
Initial	New	Rubber	Spray Paver	0.13	0.09	None	BWP	TTI	82.3	0.58	100
Initial	New	Rubber	Spray Paver	0.13	0.09	None	BWP	TTI	144.0	1.10	100
Initial	New	Rubber	Spray Paver	0.13	0.09	None	BWP	TTI	111.3	0.67	95
Initial	New	SS-1H	Spray Paver	0.07	0.05	None	BWP	TTI	129.5	1.60	100
Initial	New	SS-1H	Spray Paver	0.07	0.05	None	BWP	TTI	136.5	0.95	100
Initial	New	SS-1H	Spray Paver	0.07	0.05	None	BWP	TTI	88.7	0.45	100
Initial	New	SS-1H	Spray Paver	0.10	0.07	None	BWP	TTI	103.3	0.48	100
Initial	New	SS-1H	Spray Paver	0.10	0.07	None	BWP	TTI	142.3	0.95	100
Initial	New	SS-1H	Spray Paver	0.10	0.07	None	BWP	TTI	89.9	0.49	100
Initial	New	SS-1H	Spray Paver	0.13	0.09	None	BWP	TTI	103.0	0.57	100
Initial	New	SS-1H	Spray Paver	0.13	0.09	None	BWP	TTI	80.6	0.45	100
Initial	New	SS-1H	Spray Paver	0.13	0.09	None	BWP	TTI	105.7	0.64	100
Initial	New	SS-1H	Distributor	0.04	0.03	None	BWP	TTI	231.9	3.21	100
Initial	New	SS-1H	Distributor	0.04	0.03	None	BWP	TTI	222.4	2.74	100
Initial	New	SS-1H	Distributor	0.04	0.03	None	BWP	TTI	195.5	2.81	90

Sample Period	Surface Type	Tack Type	Application Method	Tack Rate (gal/sy)		Tracking	Location	Agency	Bond Strength (psi)	Bond Energy (ft-lb/in^2)	Interface Failure (%)
				Target	Residual						
Initial	New	SS-1H	Distributor	0.04	0.03	Tracking	WP	TTI	304.6	3.24	100
Initial	New	SS-1H	Distributor	0.04	0.03	Tracking	WP	TTI	257.2	2.15	100
Initial	New	SS-1H	Distributor	0.04	0.03	Tracking	WP	TTI	320.9	3.15	95
Initial	New	SS-1H	Distributor	0.07	0.05	None	BWP	TTI	188.4	2.81	100
Initial	New	SS-1H	Distributor	0.07	0.05	None	BWP	TTI	200.2	2.52	100
Initial	New	SS-1H	Distributor	0.07	0.05	None	BWP	TTI	321.9	3.63	90
Initial	New	SS-1H	Distributor	0.07	0.05	None	WP	TTI	275.4	3.09	100
Initial	New	SS-1H	Distributor	0.07	0.05	None	WP	TTI	280.8	3.05	90
Initial	New	SS-1H	Distributor	0.07	0.05	None	WP	TTI	235.8	2.18	100
Initial	New	SS-1H	Distributor	0.07	0.05	Tracking	WP	TTI	240.2	2.00	95
Initial	New	SS-1H	Distributor	0.07	0.05	Tracking	WP	TTI	238.1	2.09	100
Initial	New	SS-1H	Distributor	0.07	0.05	Tracking	WP	TTI	309.3	2.89	100
Initial	New	SS-1H	Distributor	0.10	0.06	None	BWP	TTI	276.2	2.38	100
Initial	New	SS-1H	Distributor	0.10	0.06	None	BWP	TTI	273.4	2.78	100
Initial	New	SS-1H	Distributor	0.10	0.06	None	BWP	TTI	311.9	3.46	100
Initial	New	SS-1H	Distributor	0.10	0.06	Tracking	WP	TTI	278.4	2.64	100
Initial	New	SS-1H	Distributor	0.10	0.06	Tracking	WP	TTI	304.6	3.10	100
Initial	New	SS-1H	Distributor	0.10	0.06	Tracking	WP	TTI	295.5	2.48	100
Initial	New	Trackless	Distributor	0.04	0.02	None	BWP	TTI	351.7	3.79	95
Initial	New	Trackless	Distributor	0.04	0.02	None	BWP	TTI	312.9	2.60	100
Initial	New	Trackless	Distributor	0.04	0.02	None	BWP	TTI	341.7	3.57	90
Initial	New	Trackless	Distributor	0.04	0.02	Tracking	WP	TTI	293.0	2.99	90
Initial	New	Trackless	Distributor	0.04	0.02	Tracking	WP	TTI	254.9	2.46	90
Initial	New	Trackless	Distributor	0.07	0.05	None	BWP	TTI	348.4	5.03	100
Initial	New	Trackless	Distributor	0.07	0.05	None	BWP	TTI	232.0	2.66	80
Initial	New	Trackless	Distributor	0.07	0.05	None	BWP	TTI	300.1	3.90	95
Initial	New	Trackless	Distributor	0.07	0.05	None	WP	TTI	390.4	3.28	100
Initial	New	Trackless	Distributor	0.07	0.05	None	WP	TTI	422.8	3.94	100

Sample Period	Surface Type	Tack Type	Application Method	Tack Rate (gal/sy)		Tracking	Location	Agency	Bond Strength (psi)	Bond Energy (ft-lb/in^2)	Interface Failure (%)
				Target	Residual						
Initial	New	Trackless	Distributor	0.07	0.05	Tracking	WP	TTI	410.5	5.61	30
Initial	New	Trackless	Distributor	0.07	0.05	Tracking	WP	TTI	422.7	4.23	80
Initial	New	Trackless	Distributor	0.07	0.05	Tracking	WP	TTI	413.5	4.24	90
Initial	New	Trackless	Distributor	0.10	0.06	None	BWP	TTI	383.6	4.64	90
Initial	New	Trackless	Distributor	0.10	0.06	None	BWP	TTI	320.1	2.85	90
Initial	New	Trackless	Distributor	0.10	0.06	None	BWP	TTI	380.6	4.54	90
Initial	New	Trackless	Distributor	0.10	0.06	Tracking	WP	TTI	370.5	5.99	30
Initial	New	Trackless	Distributor	0.10	0.06	Tracking	WP	TTI	327.5	2.61	100
Initial	Milled	Rubber	Spray Paver	0.12	0.08	None	BWP	OU	141.4	1.66	80
Initial	Milled	Rubber	Spray Paver	0.12	0.08	None	BWP	OU	165.6	1.71	95
Initial	Milled	Rubber	Spray Paver	0.12	0.08	None	BWP	OU	124.7	1.21	95
Initial	Milled	None	Distributor	0	0.00	None	BWP	OU	171.2	1.33	100
Initial	Milled	None	Distributor	0	0.00	None	BWP	OU	129.3	1.72	90
Initial	Milled	None	Distributor	0	0.00	None	BWP	OU	167.6	1.37	95
Initial	Milled	SS-1H	Distributor	0.08	0.05	None	BWP	OU	181.1	2.67	97
Initial	Milled	SS-1H	Distributor	0.08	0.05	None	BWP	OU	184.8	2.55	98
Initial	Milled	SS-1H	Distributor	0.08	0.05	None	BWP	OU	187.6	3.53	90
Initial	New	None	Distributor	0	0.00	None	BWP	OU	250.9	1.69	100
Initial	New	None	Distributor	0	0.00	None	BWP	OU	180.9	1.37	97
Initial	New	Rubber	Spray Paver	0.1	0.07	None	BWP	OU	144.2	1.28	100
Initial	New	Rubber	Spray Paver	0.1	0.07	None	BWP	OU	153.9	1.12	100
Initial	New	Rubber	Spray Paver	0.1	0.07	None	BWP	OU	140.1	1.24	100
Initial	New	SS-1H	Distributor	0.07	0.05	None	BWP	OU	195.5	2.84	98
Initial	New	SS-1H	Distributor	0.07	0.05	None	BWP	OU	204.2	2.07	100
Initial	New	SS-1H	Distributor	0.07	0.05	None	BWP	OU	246.5	3.11	96
Initial	New	Trackless	Distributor	0.07	0.05	None	BWP	OU	251.0	4.68	95
Initial	New	Trackless	Distributor	0.07	0.05	None	BWP	OU	218.6	2.84	93
8-Month	New	None	NA	0.00	0.00	None	BWP	TTI	275.2	2.20	100

Sample Period	Surface Type	Tack Type	Application Method	Tack Rate (gal/sy)		Tracking	Location	Agency	Bond Strength (psi)	Bond Energy (ft-lb/in^2)	Interface Failure (%)
				Target	Residual						
8-Month	New	None	NA	0.00	0.00	None	BWP	TTI	314.0	2.57	100
8-Month	New	None	NA	0.00	0.00	None	BWP	TTI	315.8	2.52	100
8-Month	New	Trackless	Distributor	0.10	0.06	None	BWP	TTI	351.5	5.11	50
8-Month	New	Trackless	Distributor	0.10	0.06	None	BWP	TTI	282.0	3.21	90
8-Month	New	Trackless	Distributor	0.10	0.06	None	BWP	TTI	326.8	4.85	50
8-Month	New	SS-1H	Distributor	0.04	0.03	None	BWP	TTI	325.0	3.32	100
8-Month	New	SS-1H	Distributor	0.04	0.03	None	BWP	TTI	319.4	2.98	100
8-Month	New	SS-1H	Distributor	0.04	0.03	None	BWP	TTI	271.7	2.58	100
8-Month	New	SS-1H	Distributor	0.10	0.06	None	BWP	TTI	265.3	2.12	100
8-Month	New	SS-1H	Distributor	0.10	0.06	None	BWP	TTI	268.0	2.17	100
8-Month	New	SS-1H	Distributor	0.10	0.06	None	BWP	TTI	266.6	2.59	100
8-Month	New	SS-1H	Spray Paver	0.07	0.05	None	BWP	TTI	195.9	1.81	100
8-Month	New	SS-1H	Spray Paver	0.07	0.05	None	BWP	TTI	202.5	1.42	100
8-Month	New	SS-1H	Spray Paver	0.07	0.05	None	BWP	TTI	171.3	0.85	100
8-Month	New	SS-1H	Spray Paver	0.10	0.07	None	BWP	TTI	197.0	1.27	100
8-Month	New	SS-1H	Spray Paver	0.10	0.07	None	BWP	TTI	209.4	1.49	100
8-Month	New	SS-1H	Spray Paver	0.10	0.07	None	BWP	TTI	206.1	1.45	100
8-Month	New	SS-1H	Spray Paver	0.13	0.09	None	BWP	TTI	237.1	1.59	100
8-Month	New	SS-1H	Spray Paver	0.13	0.09	None	BWP	TTI	216.0	1.83	100
8-Month	New	SS-1H	Spray Paver	0.13	0.09	None	BWP	TTI	239.9	1.97	100
8-Month	New	Rubber	Spray Paver	0.10	0.07	None	BWP	TTI	232.8	1.93	100
8-Month	New	Rubber	Spray Paver	0.10	0.07	None	BWP	TTI	222.9	1.77	100
8-Month	New	Rubber	Spray Paver	0.10	0.07	None	BWP	TTI	230.6	2.12	100

Tack Results

SS-1h

Emulsion Supplier	Shelly Liquid Toledo			
Tested By	Shelly Liquid Toledo			

Tests on emulsions:	Result	Min	Max	
Viscosity, Saybolt Furol at 25C	29.0	20	100	SFS
Storage stability, 24-h	---		1.0	%
Sieve test	---		0.10	%
Residue by distillation	62.6	57		%
Residue by evaporation	---			%

Tests on residue from distillation test:	Result	Min	Max	
Penetration, 25C, 100 g, 5 s	55	40	90	dmm
Softening Point	---			C

Comments: Sample Date: 7/18/2016

Non-Tracking Tack

Emulsion Supplier	Apple-Smith			
Tested By	Shelly and Sands Lab			

Tests on emulsions:	Result	Min	Max	
Viscosity, Saybolt Furol at 25C	40.5	20	100	SFS
Storage stability, 24-h	0.4		1.0	%
Sieve test	0.0		0.30	%
Residue by distillation	54.6	50		%
Oil distillate by volume of emulsion	0.0		1.0	%
Residue by evaporation	---			%

Tests on residue from distillation test:	Result	Min	Max	
Penetration, 25C, 100 g, 5 s	7.3		20	dmm
Softening Point	73	60		C
Original DSR at 82C, 25 mm, 1 mm gap, 6% strain	4.6	1.0		kPa

Comments: Sample Date: 7/20/2016

Rubberized Tack

Base Emulsion Supplier	Phillips Oil
Base Emulsion	SS-1h
SBR Application Rate	3 %

Base Emulsion Properties

Test By	Phillips Oil Company

Tests on emulsions:	Result	Min	Max	
Viscosity, Saybolt Furol at 25C	26.0	20	100	SFS
Storage stability, 24-h	---		1.0	%
Sieve test	---		0.10	%
Residue by distillation	63.2	57		%
Residue by evaporation	---			%

Tests on residue from distillation test:	Result	Min	Max	
Penetration, 25C, 100 g, 5 s	66.0	40	90	dmm
Softening Point	---			C

Comments:	Sample Date: 7/21/2016

Analysis of Bonding in Laboratory Prepared Samples

Experimental Design

The asphalt mixtures used for the intermediate course and the surface course of I-270 field project were used to prepare bonded mixture for the shear test following the shear bond test presented in Appendix G. The intermediate course mixture was used to produce 2in. thick compacted substrates with 7% air void. The selected tack coat materials were applied on the compacted substrates with brush and then compacted with the surface course mixtures to produce 4in. long bonded test samples. Variables used in this laboratory study were

Tack Materials: 4 levels

- Control
- SS-1h
- Rubberized Tack
- Trackless Tack

Tack Rate: 2 levels

- 0.04 gal/yd^2
- 0.10 gal/yd^2

Loading Rate: 2 levels

- 0.1 in./min.
- 2.0 in./min.

Test Temperature: 2 levels

- 20°C
- 25°C

Specimen Diameter: 2 levels

- 4 in. (100 mm)
- 6 in. (150 mm)

Full factorial of the variables were tested with 3 replicate samples. Each sample was conditioned at the test temperature for minimum of 4 hours prior to the test.

Bond Shear Test Results

Figures 1 and 2 show the bond shear strength and bond energy results of the 6-inch diameter samples. The statistical analysis results are presented in Tables 1. All test variables, including the tack type, are statistically significant factors except the tack application rate. The relative magnitude of contribution of each variable on the variation of test results can be estimated by the percent sum of square (%SS) in the ANOVA (Tables 1 and 2). For both shear bond strength and bond energy, the loading rate and test temperature influenced the test results the most. As test temperature decreased or as loading rate increased, the shear bond strength and the bond energy significantly increased. Among tack materials, the trackless tack showed the highest shear bond strength and bond energy. The shear bond strength and the bond energy for SS-1h emulsion tack and rubberized tack showed similar values to those of the control mixture (no tack).

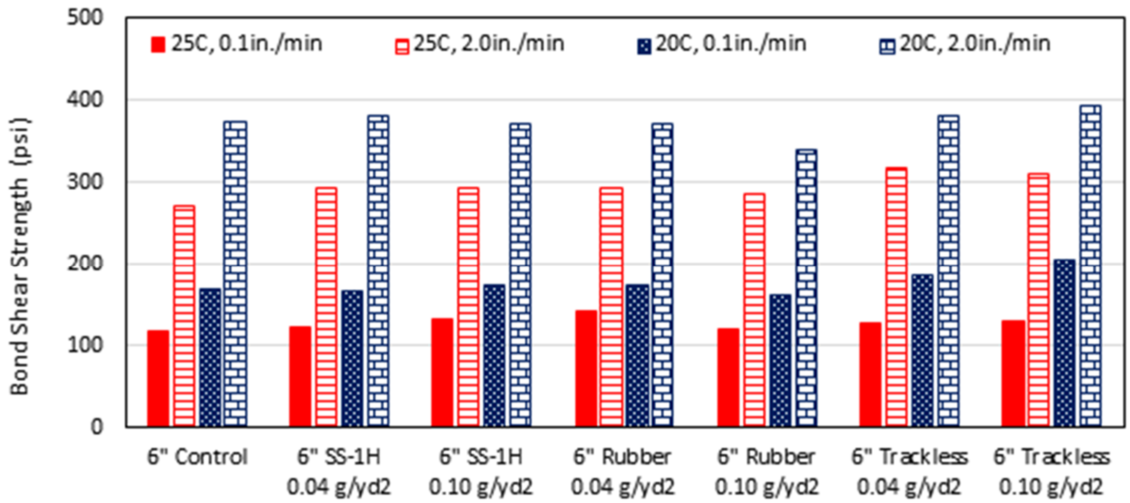


Figure 37. Bond Shear Strength of Laboratory Prepared 6 in. Diameter Specimens.

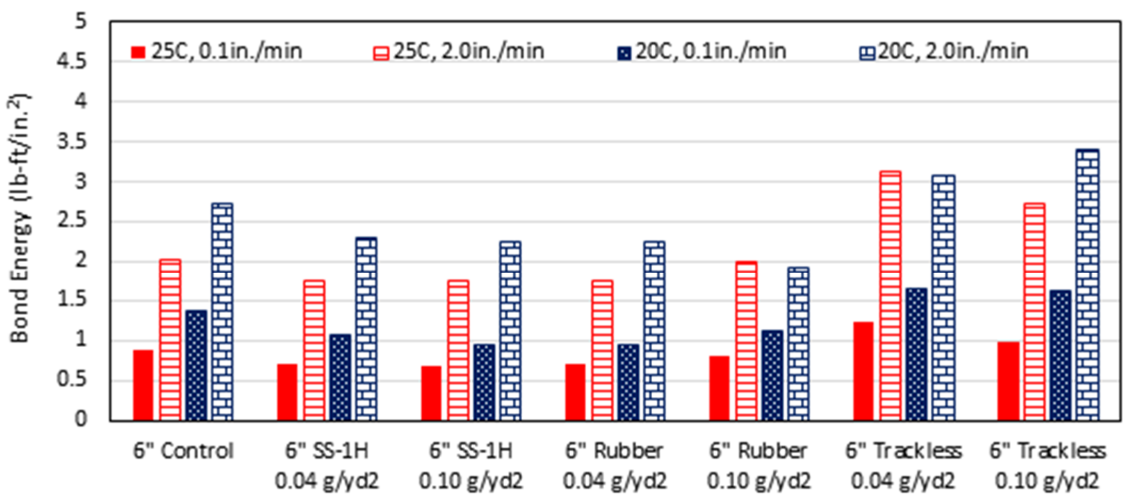


Figure 38. Bond Energy of Laboratory Prepared 6 in. Diameter Specimens.

Table 12. Analysis of Variance of Laboratory Molded Shear Bond Study.

Property	Bond Strength				Bond Energy			
	Type III SS	%SS	df	p-value	Type III SS	%SS	df	p-value
Corrected Model	165.3		7	0.000	1636483		7	0.000
Intercept	578.9		1	0.000	7916441		1	0.000
Tack_Type	34.5	19%	2	0.000	30312	1.8%	2	0.000
Tack_Rate	0.0	0%	1	0.795	65	0.0%	1	0.712
Load_Rate	99.9	55%	1	0.000	1396196	81.5%	1	0.000
Test_Temp	9.7	5%	1	0.000	190704	11.1%	1	0.000
Diameter	22.9	13%	1	0.000	7694	0.4%	1	0.000
Error	16.8	9%	162		76760	4.5%	162	
Total	871.7		170		11058303		170	

Corrected Total	182.1	100%	169		1713243	100%	169	
Adj R Squared	0.953				0.904			

Regression Analysis

Using the test results of the laboratory prepared bonded samples, two regression equations, one for the shear bond strength (Eq. 1) and bond energy (Eq. 2), were derived. The bond energy equation underestimates for the large and small bond energy values and overestimates for the intermediate bond energy values, suggesting non-linear effects of some variables. Further study with more levels of each variable is needed to fully understand the non-linear behavior of the bond energy.

$$\text{Bond Shear Strength} = 475.7 + C_{Tack\_Type} + C_{Load\_Rate} + C_D - 22.2 * (Tack\_Rate) - 13.4 * (Test\_Temp) \quad \text{(Eq. 1)}$$

C_{Tack_Type}: Constant for tack type (-22.4 for no tack; -31.0 for SS-1h tack; -30.4 for rubberized tack; 0.0 for trackless tack)
C_{Load_Rate}: Constant for loading rate (0.0 for 0.1 in./min; -181.4 for 2.0/min.)
C_D: Constant for specimen diameter (0.0 for 6 in.; -13.5 for 4 in.)

$$\text{Bond Energy} = 4.481 + K_{Tack\_Type} + K_{Load\_Rate} + K_D - 0.232 * (Tack\_Rate) - 0.735 * (Test\_Temp) \quad \text{(Eq. 2)}$$

K_{Tack_Type}: Constant for tack type (-0.738 for no tack; -1.039 for SS-1h tack; -1.033 for rubberized tack; 0.0 for trackless tack)
K_{Load_Rate}: Constant for loading rate (0.0 for 0.1 in./min; 1.534 for 2.0/min.)
K_D: Constant for specimen diameter (0.0 for 6 in.; -0.095 for 4 in.)

One of utility of the regression equations are to estimate the test results from the tests performed at non-standard conditions. The recommended test condition for shear bond strength test is to use 6 in. diameter sample and test at 25°C. The test results obtained from 4 in. diameter sample at a different temperature, T, can be converted to test results with 6 in. diameter at 25°C using following two equations.

$$\text{Shear Bond Strength } (6, 25°C) = \text{Shear Bond Strength } (4, T) + 13.5 + 13.4 * (25 - T) \quad \text{(Eq. 3)}$$

$$\text{Bond Energy } (6, 25°C) = \text{Bond Energy } (4, T) + 0.095 + 0.735 * (25 - T) \quad \text{(Eq. 4)}$$

Appendix D
STATISTICAL ANALYSIS DETAILS

Table 13. Statistical Analysis Details.

Variable	Data Used for Analysis	Sample Size
Testing Agency	Surface: Milled, New Tack: SS-1H, Rubber, None Application: Distributor, Spray Paver Tracking: No Tack Rate: None, Mod, High Testing Agency: TTI, OU Bond Age: Initial	40
Tack Type and Application	Surface: New Tack: SS-1H, Trackless, Rubber, None Application: Distributor, Spray Paver Tracking: No Tack Rate: None, Low, Mod, High, V. High Testing Agency: TTI, OU Bond Age: Initial	49
Tack Rate	Surface: Milled, New Tack: SS-1H, Trackless, Rubber Application: Distributor, Spray Paver Tracking: No Tack Rate: Low, Mod., High, V. High Testing Agency: TTI, OU Bond Age: Initial	69
Surface Type	Surface: Milled, New Tack: SS-1H, Rubber, None Application: Distributor, Spray Paver Tracking: No Tack Rate: Low, Mod, High, V. High Testing Agency: TTI, OU Bond Age: Initial	60
Tracking	Surface: Milled, New Tack: SS-1H, Trackless Application: Distributor Tracking: Yes, No Tack Rate: Low, Mod., High Agency: TTI, OU Bond Age: Initial	59
Bond Age	Surface: New Tack: SS-1H, Trackless, Rubber, None Application: Distributor, Spray Paver Tracking: No Tack Rate: None, Low, Mod, High, V. High Testing Agency: TTI Bond Age: Initial, 8-month	53

Testing Agency

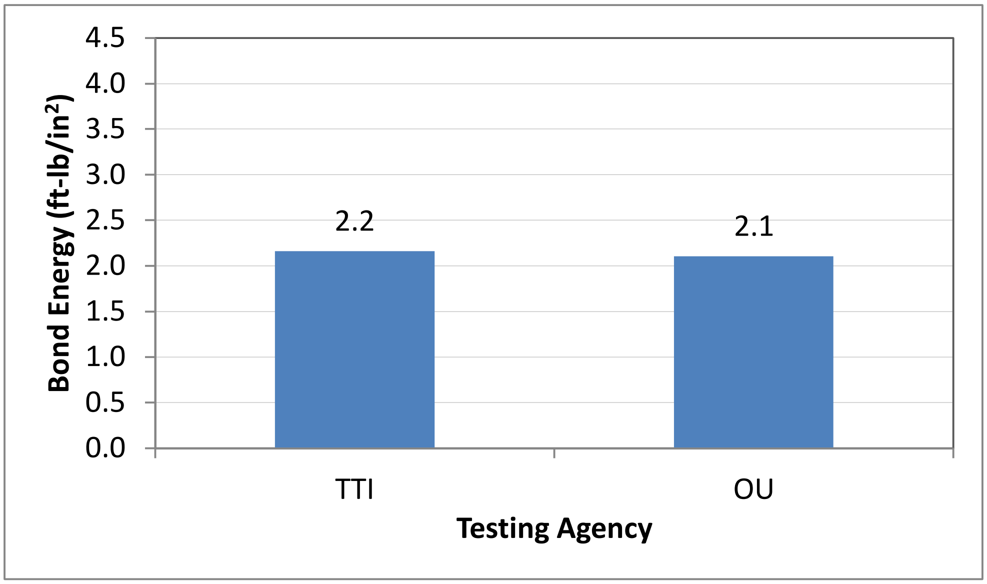


Figure 39. Bond Energy Results by Testing Agency.

Table 14. Statistical Analysis of Testing Agency on Bond Results.

Explanatory Variable	Bond Energy		Bond Strength	
	p-value	Model R^2	*p*-value	Model R^2
Testing Agency	0.877	0.00	0.345	0.02

Table 15. Comparison of Average Results and Statistical Grouping by Testing Agency: (a) Bond Energy and (b) Bond Strength

(a)

Tack Type	Surface	TTI				OU			
		Average ($ft\text{-}lb/in^2$)	Statistical Grouping*			Average ($ft\text{-}lb/in^2$)	Statistical Grouping*		
Trackless	New	3.86	A			3.76	A		
SS1h	Milled	3.03	A	B		2.92	A	B	
SS1h	New	2.99	A	B		2.67		B	
None	New	1.98		B	C	1.53			C
None	Milled	1.16			C	1.47			C
Rubber	Milled	1.08			C	1.53			C
Rubber	New	1.01			C	1.21			C

*Tukey's HSD

Table 15. Comparison of Average Results and Statistical Grouping by Testing Agency: (a) Bond Energy and (b) Bond Strength (cont.)

(b)

Tack Type	Surface	TTI Average (psi)	TTI Statistical Grouping*			OU Average (psi)	OU Statistical Grouping*		
Trackless	New	293	A			235	A		
SS1h	New	237	A	B		215	A	B	
None	New	232	A	B		216	A	B	
SS1h	Milled	187		B	C	185		B	C
None	Milled	154			C	156			C
Rubber	Milled	146			C	144			C
Rubber	New	134			C	146			C

*Tukey's HSD

Tack Rate

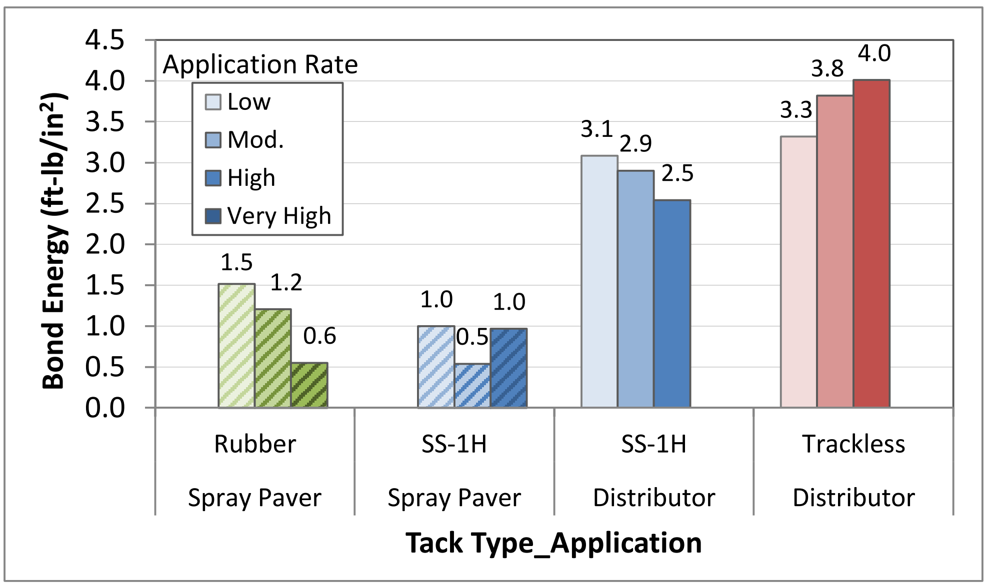


Figure 40. Bond Energy Results by Application Rate.

Table 16. Statistical Analysis of Tack Rate on Bond Results.

Explanatory Variable	Bond Energy Variable *p*-value	Bond Energy Model *p*-value	Bond Energy Model R^2	Bond Strength Variable *p*-value	Bond Strength Model *p*-value	Bond Strength Model R^2
Tack Type_Application	0.0164	< 0.001	0.81	0.099	< 0.001	0.77
Tack Rate	0.559			0.788		
Tack Rate* Tack Type_Application	0.154			0.383		

Tack Type_Application

Table 17. Statistical Analysis of Tack Type and Application Method on Bond Results.

Explanatory Variable	Bond Energy		Bond Strength	
	p-value	Model R^2	*p*-value	Model R^2
Tack Type_Application	< 0.001	0.85	< 0.001	0.81

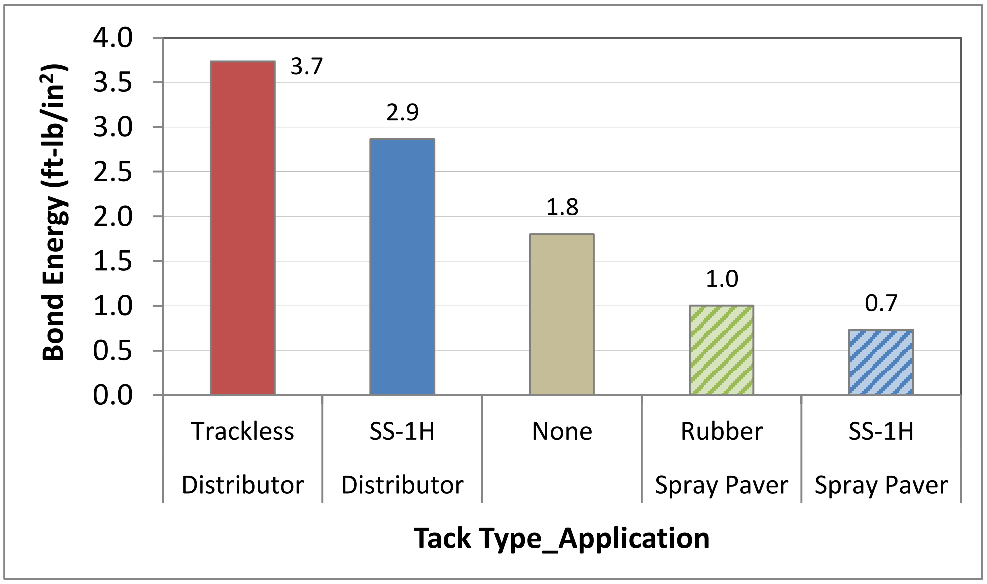


Figure 41. Bond Energy Results by Application Rate.

Table 18. Performance vs. Tack Type and Application Method with Grouping.

Tack Type and Application Method	Bond Energy (ft-lb/in²)					Bond Strength (psi)			
	Average	Statistical Grouping*				Average	Statistical Grouping*		
Trackless-Distributor	3.74	A				313	A		
SS-1H-Distributor	2.86		B			239		B	
None	1.80			C		226		B	
Rubber-Spray paver	1.00				D	134			C
SS-1H-Spray paver	0.73				D	109			C

*Tukey's HSD

Surface Type

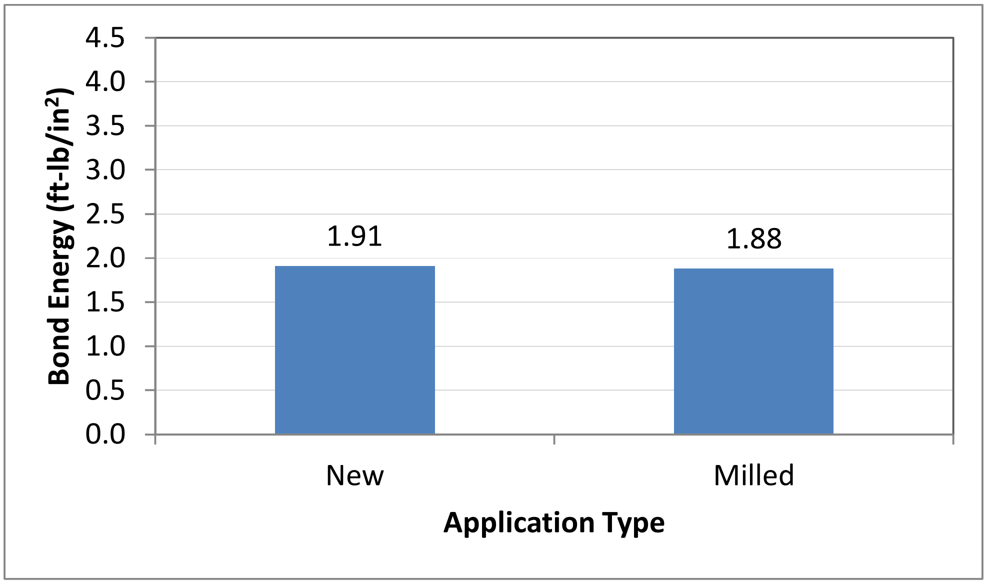


Figure 42. Bond Energy Results by Surface Type.

Table 19. Statistical Analysis of Surface Type on Bond Results.

Explanatory Variable	Bond Energy		Bond Strength	
	p-value	Model R^2	*p*-value	Model R^2
Surface Type	0.903	0.00	0.082	0.05

Tracking

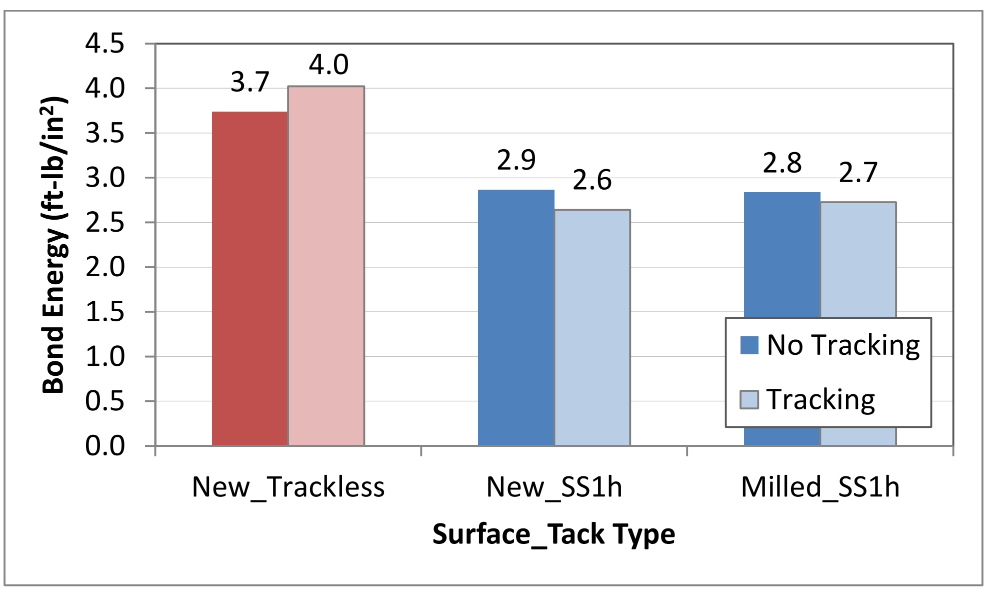


Figure 43. Bond Energy Results With and Without Tracking.

Table 20. Statistical Analysis of Tracking on Bond Results.

Explanatory Variable	Bond Energy			Bond Strength		
	Variable *p*-value	Model *p*-value	Model R^2	Variable *p*-value	Model *p*-value	Model R^2
Tracking	0.889	0.001	0.25	0.103	< 0.001	0.48
Surface_Tack Type	< 0.001			< 0.001		

Bond Age

Table 21. Statistical Analysis of Tracking on Bond Results.

Explanatory Variable	Bond Energy			Bond Strength		
	Variable *p*-value	Model *p*-value	Model R^2	Variable *p*-value	Model *p*-value	Model R^2
Tack_Application	< 0.001			< 0.001		
Period	< 0.001	0.001	0.87	< 0.001	< 0.001	0.90
Tack_Appl * Period	0.029			< 0.001		

Table 22. Performance vs. Age, Tack Type, and Application Method and Statistical Grouping.

Tack Type	Application Method	Bond Age	Bond Energy Average	Bond Energy Statistical Grouping*						Bond Strength Average	Bond Strength Statistical Grouping*					
Trackless	Distributor	8-Month	4.39	A						361	A					
Trackless	Distributor	Initial	4.01	A						320	A	B				
SS-1H	Distributor	Initial	2.90		B					252			C			
SS-1H	Distributor	8-Month	2.63		B					286		B				
None	NA	8-Month	2.43		B	C				302		B				
Rubber	Spray Paver	8-Month	1.94			C	D			229			C	D		
None	NA	Initial	1.80			C	D			226			C	D		
SS-1H	Spray Paver	8-Month	1.52				D	E		208				D		
Rubber	Spray Paver	Initial	1.11					E	F	140					E	
SS-1H	Spray Paver	Initial	0.73						F	109						F

*Tukey's HSD

Appendix E
LONG-TERM PERFORMANCE ANALYSIS

Introduction

A pavement structure has several different material layers each with a certain degree of bonding at the interface. Extensive research has been carried out in the field of pavement material performance. In contrast, very little research has been carried out on the adhesion properties of the various layers of flexible pavements or on the overall influence of bonding on the pavement life. In practical terms, very few procedures or standards exist related to the necessary quality of layer interfaces.

At present, for design purpose it is typically assumed that full bonding exists between the pavement layers (*31*). However, under real conditions, the state of adhesion is unknown, ranging from full adhesion to zero adhesion, depending on material properties and construction quality.

The bond condition at the interface between layers is known to have significant impact on the overall road performance. Uzan et al. (*18*) used the Bitumen Stress Analysis in Roads, Shell Global Solutions (BISAR) program to demonstrate that most of the change in tensile radial stress/tensile radial strain occurs when the shear reaction modulus (Ks) varied between 100 and 10,000 MN/m^3. The study clearly demonstrated that, in the case of upper interface varying from perfectly smooth (full slip) to perfectly rough (full bond), the tensile radial strain at the bottom of the first layer becomes higher and the tensile radial strain at the top of the second layer reverses to become compressive. It can be concluded that the stress or strain distribution is significantly affected by the properties of the interface.

Brown and Brunton (*8*) investigated the effect of poor bonding between layers on the pavement life. BISAR was used to analyze the pavement structure. As a reference case, the structure was analyzed assuming rough interfaces, which is equivalent to full bond. Then the structures were reanalyzed for smooth first and second interfaces. Finally partly rough interfaces were considered. The study concluded that an intermediate bond at either of the interfaces reduces pavement life significantly.

In this study, the pavement structure of Interstate Route (IR) 270 in Franklin County was simulated for analysis. First the BISAR program was used to determine the AC bottom strains and vertical strains on the surface of subgrade under different bond conditions. Then the allowable axle load repetitions were determined according to asphalt institute equations and corresponding fatigue cracking and rutting criteria. Following that the stress intensity factors (SIF) were determined using a specifically developed pavement finite element (FE) program. By incorporating the FE program, a mechanistic-empirical (ME) analysis program was developed to predict the pavement performance such as rutting and reflective cracking under different bond conditions. Finally, sensitivity analysis was performed and conclusions were provided.

Pavement Structure and Interface Shear Reaction Modulus

Table 23 lists the pavement layer properties such as layer thickness, elastic modulus, and Poisson Ratio of IR-270 based on the lab and field data.

Table 23. Pavement Structure and Layer Properties

Layers	Thickness (mm)	Modulus (MPa)	Poisson's Ratio
AC Overlay 1	30	5000	0.35
Tack Coat 1	NA	NA	NA
AC Overlay 2	40	7000	0.35
Tack Coat 2	NA	NA	NA
Existing AC	50	4000	0.35
Existing PCC	250	30000	0.15
Subbase	150	240	0.35
Subgrade		120	0.35

The tack coat layers in the pavement are treated as interface layers rather than structure layers. The state of bond at the tack coat interfaces is quantified by the horizontal shear reaction modulus (Ks), which is defined following Goodman's constitutive law (*32*):

$$\tau = K_s(\Delta U)$$

where τ = shear stress at the interface

Δu = relative horizontal displacement of the two faces at the interface, and

Ks = horizontal shear (interface) reaction modulus.

Larger Ks values indicate better interface bond condition. Previous research (*33*) shows that for *Ks* values less than 100 MN/m^3 (or MPa/m), the interface is considered fully debonded in a state of full slip. For values above 10^6 MN/m^3 (or MPa/m), the interface can be considered as fully bonded which ensures the same displacements above and below the tack coat layer. Beyond this range, the pavement response (stress, strain or displacement) changes very little when *Ks* value changes.

Strain Analysis Based On Multilayer Elastic Theory

Two types of strains have frequently been considered the most critical for the design of asphalt pavements. One is the horizontal tensile strain at the bottom of the asphalt layer, which causes fatigue cracking; the other is the vertical compressive strain on the surface of the subgrade, which causes permanent deformation or rutting. These two strains are used as failure criteria in the Asphalt Institute method.

BISAR Calculation

The Shell program BISAR was used to perform the strain calculation. To carry out the BISAR analysis, simplifications of both the structure and loading conditions are required. The pavement is considered as an elastic multilayered system. Figure 44 illustrates a schematic of pavement structure with a standard vertical dual-tire load. The red star icons in the figure show the locations of the points where calculations for strains are performed.

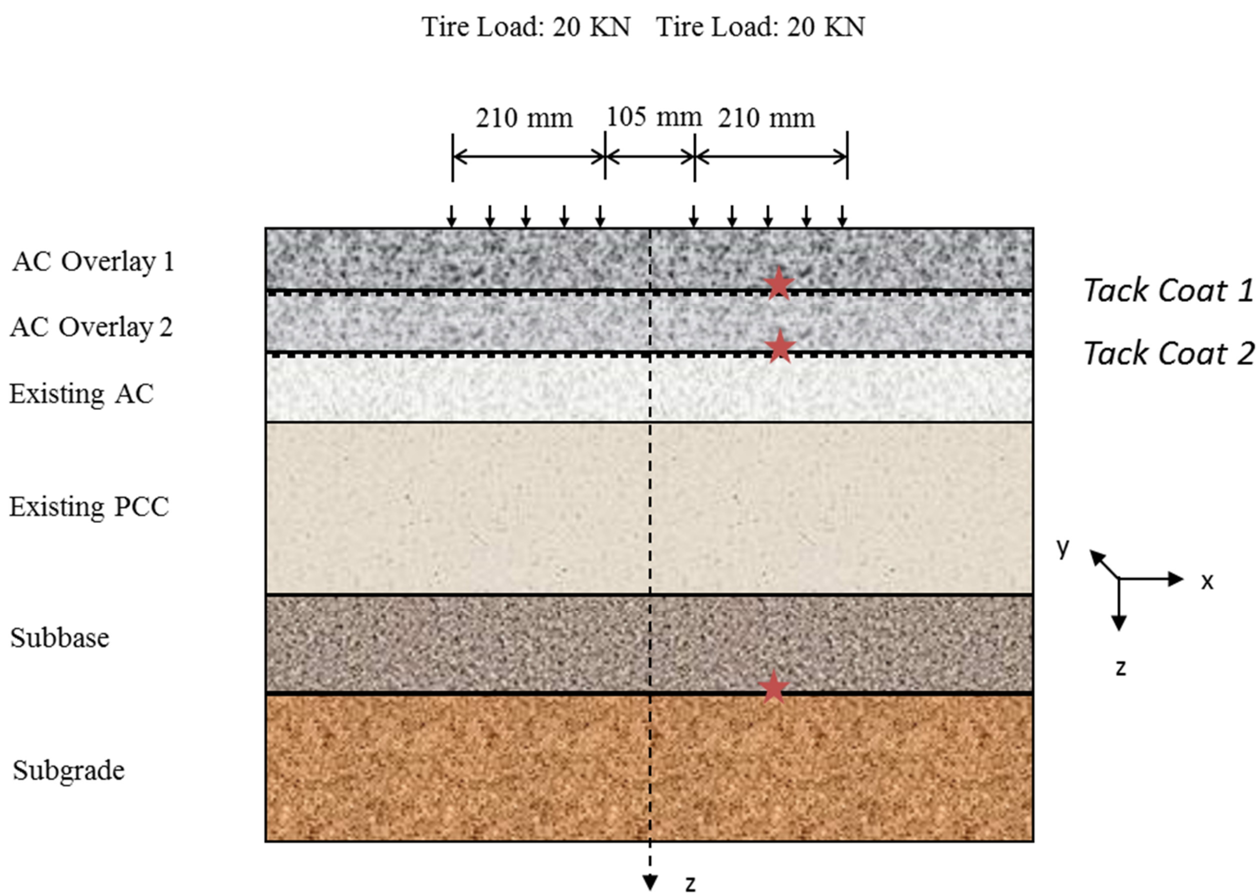


Figure 44. Schematic of multi-layer elastic analysis under dual-tire loading using BISAR program

Horizontal Strain

Figure 45 shows the tensile strains at the bottom of the first AC layer and the second AC layer respectively, when the bond condition of both interfaces (tack coat layers 1 and 2) changes from full slip to full bond simultaneously. Notice that the curve of strain value vs. log Ks exhibits sigmoidal shape and changes very little when log Ks is larger than 6 (Ks=10^6 MPa/m, fully bonded) or smaller than 2 (Ks=10^2 MPa/m, fully sliding).

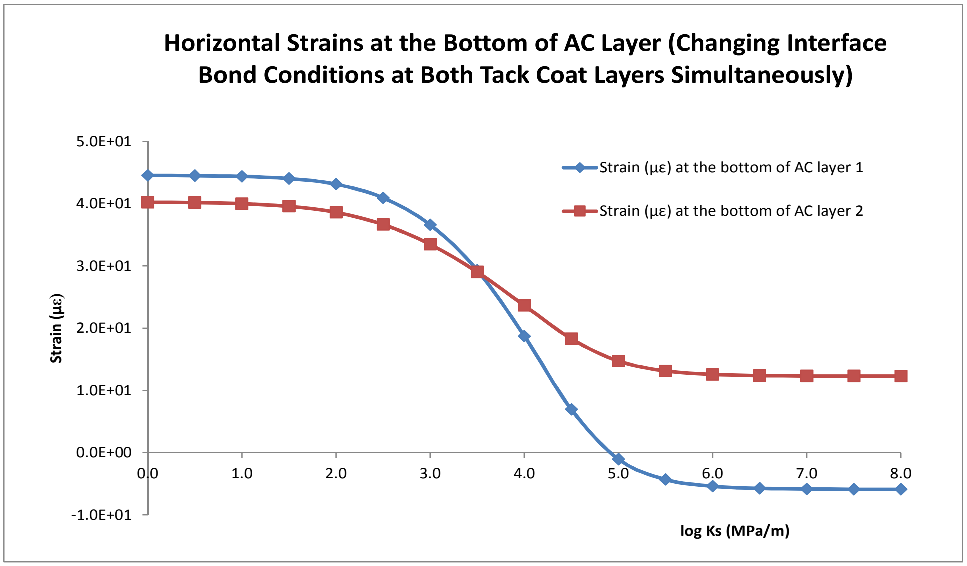


Figure 45. AC layer tensile strains for different bond conditions

Vertical Strain

Figure 46 shows the compressive vertical strains on the surface of the subgrade. Again the sigmoidal curve and similar log Ks range was observed – log Ks value 6 corresponds to fully bonded and 2 corresponds to fully sliding.

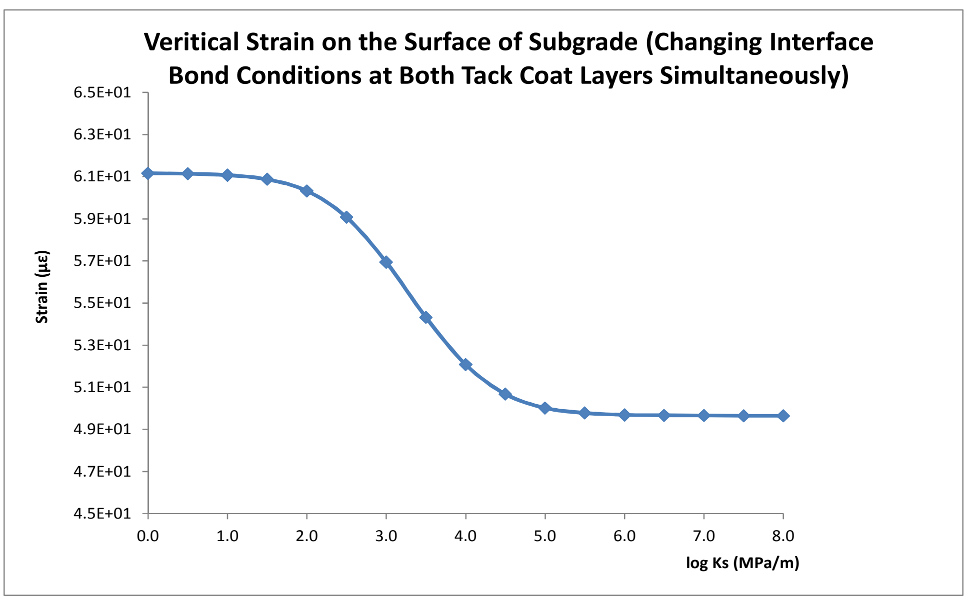


Figure 46. Vertical compressive strains for different bond conditions

Asphalt Institute Method for Predicting Fatigue Cracking Life and Rutting Life

Fatigue Cracking Life

Asphalt Institute equation for fatigue cracking life is as follows:

$$N_f = 0.0796(\varepsilon_t)^{-3.291}|E^*|^{-0.854} \quad (1)$$

where

N_f = allowable number of load repetitions to control fatigue cracking,
ε_t = tensile strain at the bottom of AC layer, and
$|E^*|$ = dynamic modulus of the asphalt mixture

It was reported that the use of the above equation would result in fatigue cracking of 20% of the total area (45% of the wheel path area), as observed on selected sections of the American Association of State Highway Officials (AASHO) Road Test (*34*).

Rutting Life

Asphalt Institute equation for rutting life is as follows:

$$N_d = 1.365 \times 10^{-9}(\varepsilon_c)^{-4.477} \quad (2)$$

where

N_d = allowable number of load repetitions to control permanent deformation (rutting) and
ε_c = vertical compressive strain on the surface of subgrade

It was thought that as long as good compaction of the pavement components is obtained and the asphalt mix is well designed, Equation 2 should not result in rut depth greater than 0.5 in. (12.7 mm) for the design traffic (*35*).

Finite Element Analysis

Pavement and Loading Simulation

In order to apply fracture mechanics and Paris' law to predict the crack propagation in the pavement, finite element analysis needs to be performed to determine the stress intensity factors (SIF). Figure 47 shows the three different crack modes and their associated stress intensity factors. For pavement cracking analysis, usually only K_I (K1) and K_{II} (K2) exist and need to be analyzed.

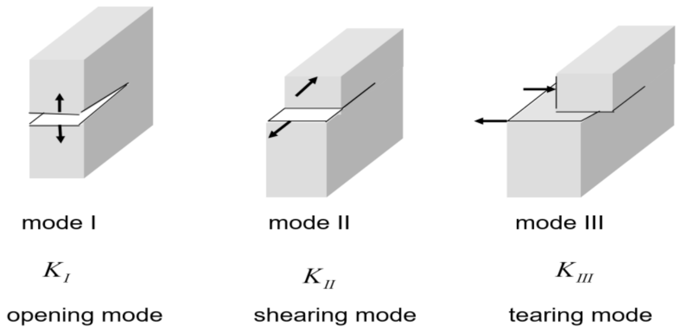
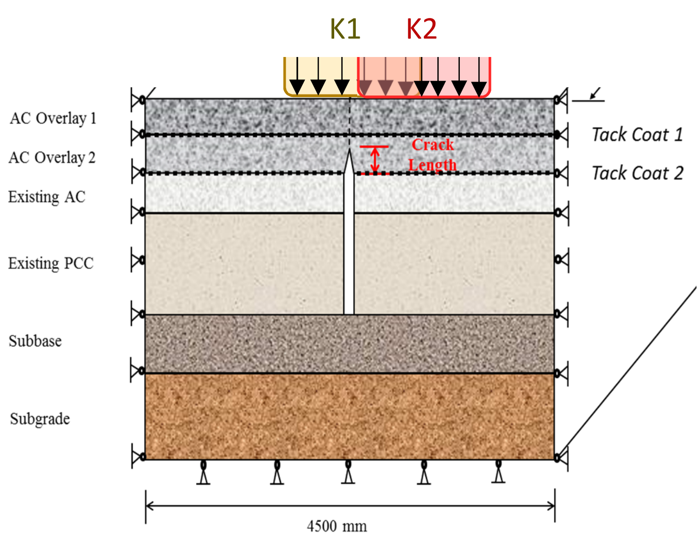


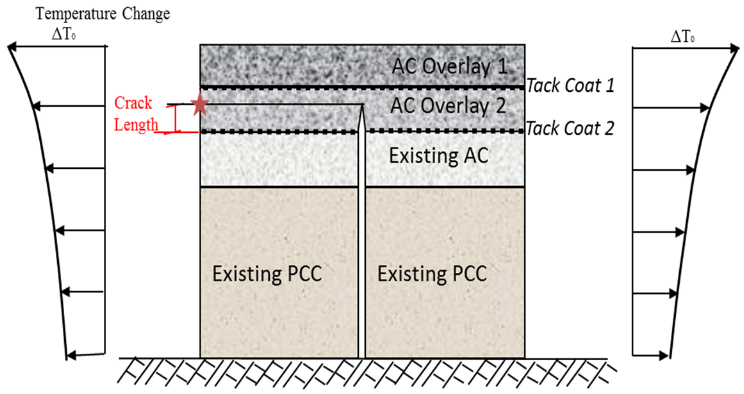
Figure 47. Crack modes and corresponding SIFs

Figure 48 shows the schematic and parameters of pavement structure and loading for finite element analysis of bending SIF (K1), shearing SIF (K2), and thermal SIF (K1) respectively. The existing AC layer and the existing PCC layer are modeled as cracked layers. The crack length in the AC overlay is considered from the bottom of AC overlayer 2 to the crack tip. The load is a standard 18-kip (80 KN) axle load (single axle, dual-tire) and the tire pressure is 100 psi (0.689 MPa). The tire-pavement contact area is assumed to be rectangular and sizes are illustrated in the figures. Note that bending SIF and shearing SIF require 3D analysis and thermal SIF only requires 2D analysis.

A specifically developed finite element program SA-CrackPro (*36, 37*) was used to perform this analysis.



(a)

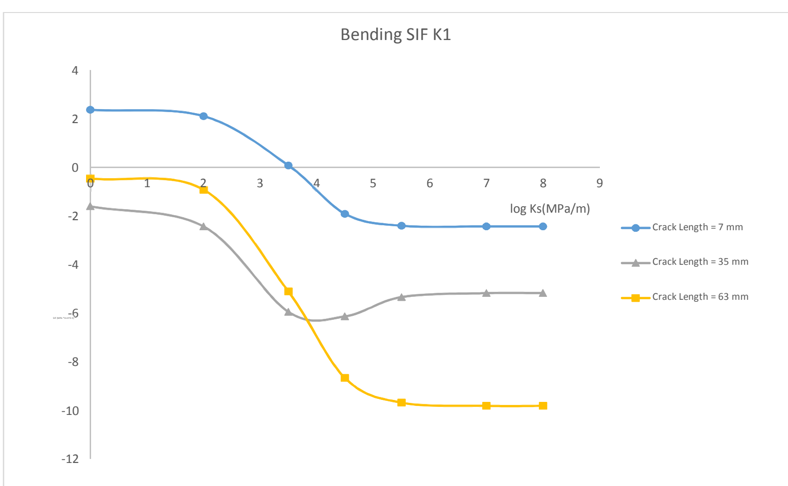


(b)

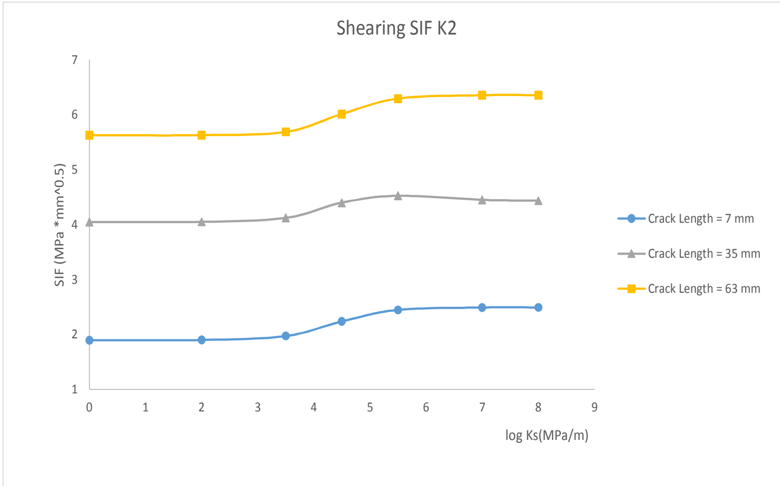
Figure 48. Pavement structure and loading schematics of SIF analysis for (a) bending (K1) and shearing (K2), and (b) thermal (K1)

Stress Intensity Factor (SIF) Comparison

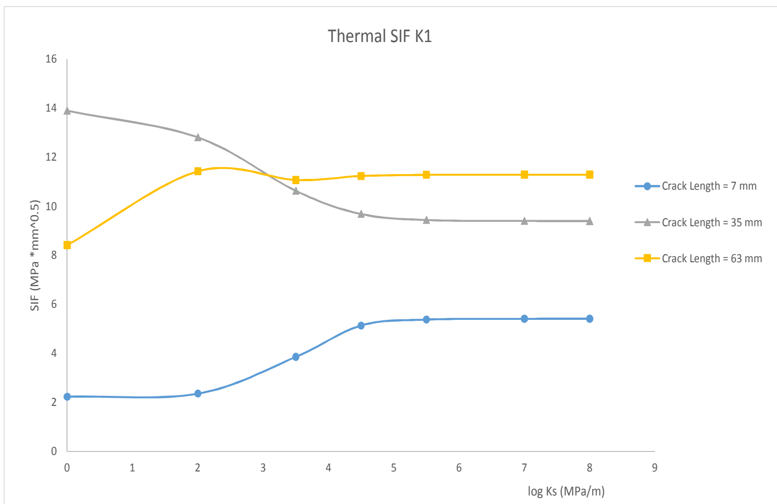
Figure 49 shows the SIF values when bond condition of tack coat 1 and tack coat 2 change from full slip to full bond simultaneously. Figures 8a, 8b, and 8c show the bending SIF (K1), shearing SIF (K2), and thermal SIF (K1) respectively. Since the SIF value depends on the crack length, different crack lengths such as short (7 mm), medium (35 mm), and long (63 mm) were chosen for the SIF calculation and comparison. Notice that most curves of SIF value vs. log(Ks) still exhibit sigmoidal shape and change with slight variation when log(Ks) is larger than 6 ($Ks=10^6$ MPa/m, fully bonded) or smaller than 2 ($Ks=10^2$ MPa/m, fully sliding). Better bonding in tack coat layers sometimes leads to larger SIF values, and sometimes leads to smaller SIF values, depending on SIF types (Bending K1, Shearing K2, or Thermal K1) and crack lengths.



(a)



(b)



(c)

Figure 49. Figure 8 SIF analysis for (a) bending (K1), (b) shearing (K2), and (c) thermal (K1)

Performance Prediction

Reflective Cracking Propagation Model

To predict the long term cracking performance, the Paris' law model (*38*) was followed, which combines the effect from bending, shearing, and thermal loading (*39, 40*).

$$\Delta C = k_1 A\left(K_{bending}\right)^n \Delta N_i + k_2 A\left(K_{shearing}\right)^n \Delta N_i + k_3 A\left(K_{thermal}\right)^n \qquad (3)$$

where

ΔC = daily crack length increment

ΔN = daily load repetitions

A, n = HMA fracture properties
$K_{bending}$ = SIF caused by bending load, same as Bending SIF K1
$K_{shearing}$ = SIF caused by bending load, same as Shearing SIF K2
$K_{thermal}$ = SIF caused by thermal load, same as Thermal SIF K1
k_1, k_2, and k_3 = calibration factors.

Rutting Model

To predict the long term rutting performance, the following model (VESYS model) was recommended (*39, 41*):

$$R_D = \sum_{i=1}^{N} k_{RD} \int \left(U_i^+ - U_i^-\right) \mu_i N^{-\alpha_i} \qquad (4)$$

Where
U_i^+ and U_i^- = deflection at top and bottom of finite layer i due to axle group
N = number of load repetitions
μ_i and α_i = permanent deformation parameters of overlay layer i
k_{RD} = calibration factor

Both models were successfully validated and calibrated in previous projects, such as NCHRP 1-41 (cracking model), FHWA/TxDOT project 0-5123, and FHWA/TxDOT project 0-5798 (both rutting model and cracking model).

Input Parameters

To implement these two performance models while considering the pavement layer bond conditions, a specific mechanistic-empirical (ME) based pavement performance analysis software was developed. The software incorporated the finite element program to determine the SIF values at different crack lengths during the cracking propagation. The input screens of traffic, climate, pavement structure, and material properties are illustrated and described in the following.

Traffic Input

According to the traffic info in the Ohio DOT official website, the Equivalent Standard Axle Loads (ESALs) was determined to be 24.8 million in 20 years. The lastest AADT was 11,300 vehicles/day, directional distribution was 50 percent, lane distribution was 25 percent, growth was 1.7 percent annually, percent trucks was 12, and the truck factor was 1.7 ESALs/truck.

Climate Input

Based on the location of the test section, the weather station Columbus, OH was selected. The corresponding hourly climatic data file will be used to determine the temperature at different pavement depth which is a major factor for calculating asphalt layer modulus and other properties.

Structure Input

Figure 50 shows the structure input screen. Notice that in the bond condition input column, 1 means fully bonded (corresponding to log Ks =7), 0 means fully sliding (corresponding to log Ks=0), and 0.5 means half bonded which corresponds to log Ks=3.5. For each layer, users can input the layer thickness and material type and click the button in the last column to edit the material properties.

Status	Pavement Structure				Material Properties
	Layer	Thickness	Material Type	Bond Condition	
AC OverLay1		1.6	Type D	1	OK
AC OverLay2		1.75	Type C	1	OK
Existing AC or PCC		2.1	Existing AC	1	OK
Existing AC or PCC		10	Existing JPCP	1	OK
Existing Base1		6	Granular Base	1	OK
Subgrade Layer			Subgrade		OK

Figure 50. Structure input screen

Material Properties Input

For asphalt overlays, users can input the dynamic modulus, fracture property and rutting property; and for existing AC layer, users need to input the falling weight deflectometer (FWD) back calculated modulus and the load transfer efficiency (LTE) value. These data were collected through field testing, mixture design spreadsheets, and laboratory testing.

Sensitivity Analysis

To further explore the influence of bond condition on the long term performance, the following sensitivity analysis was designed and performed. While many scenarios were considered, the three most pertinent are discussed as follows:

- Scenario 1, varying the interface bond condition of tack coat 2 while keeping tack coat 1 fully bonded.
- Scenario 2, varying the interface bond condition of tack coat 1 while keeping tack coat 2 fully bonded.
- Scenario 3, varying the interface bond condition of both tack coat layers simultaneously.

The reflection cracking failure criteria is often defined as 50% of cracks reflecting to the surface. Figure 51 illustrates the influence of the different tack coat scenarios on the AC reflective cracking life. Bond condition has a significant influence to reflective cracking. Better bond condition does not always result in longer reflective cracking life, as is seen in scenarios 1 and 3.

These scenarios have a significant optimal bond condition just lower than fully bonded. This occurs because the interface is able to relieve strain rather than translate all that energy into the new HMA layer.

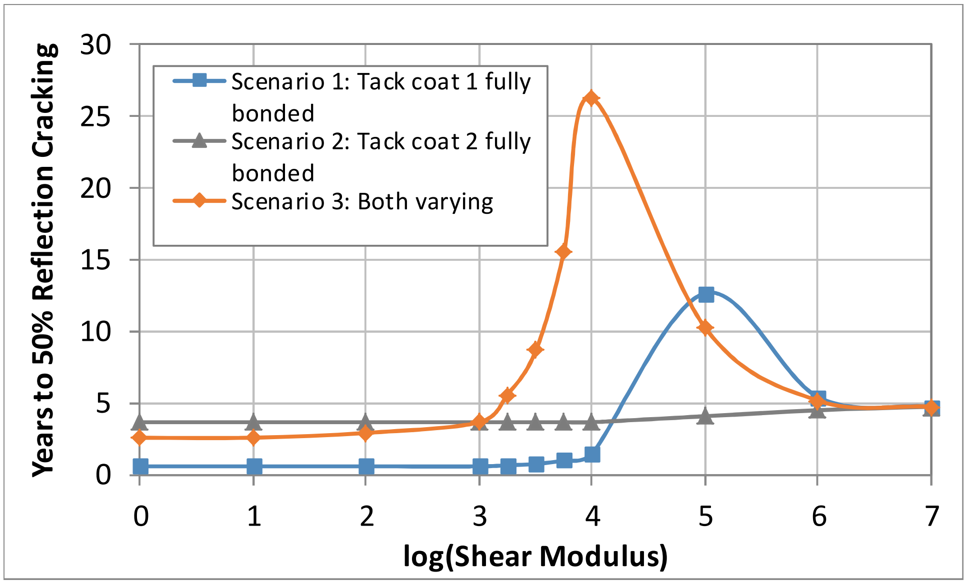


Figure 51. Influence of tack coat 1 bond condition on AC reflective cracking life

Figure 52 illustrates the influence of the bond condition on the rutting performance. Rut depth vs. log(Ks) curves are all sigmoidal shape, and better bond condition always result in less rut depth. The rut depth reduces about 15-25% if one tack coat bond condition change from fully sliding to fully bonded and reduces about 40% if both layers are fully bonded.

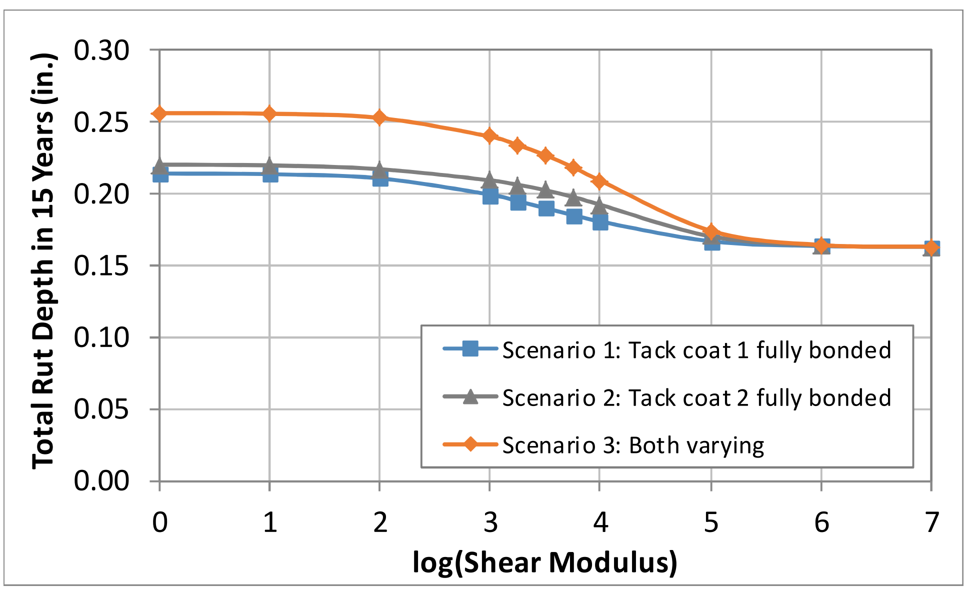


Figure 52. Influence of bond condition on rutting performance

The fatigue cracking results were calculated based on asphalt institute equation (Equation 1) and may not necessarily be comparable to the real field performance. According to Figure 53, higher bond strengths result in longer service life, but again there may be an optimum bonding condition that promotes slightly longer life. For this analysis, the expected service life for well-bonded interfaces is well above the practical service life.

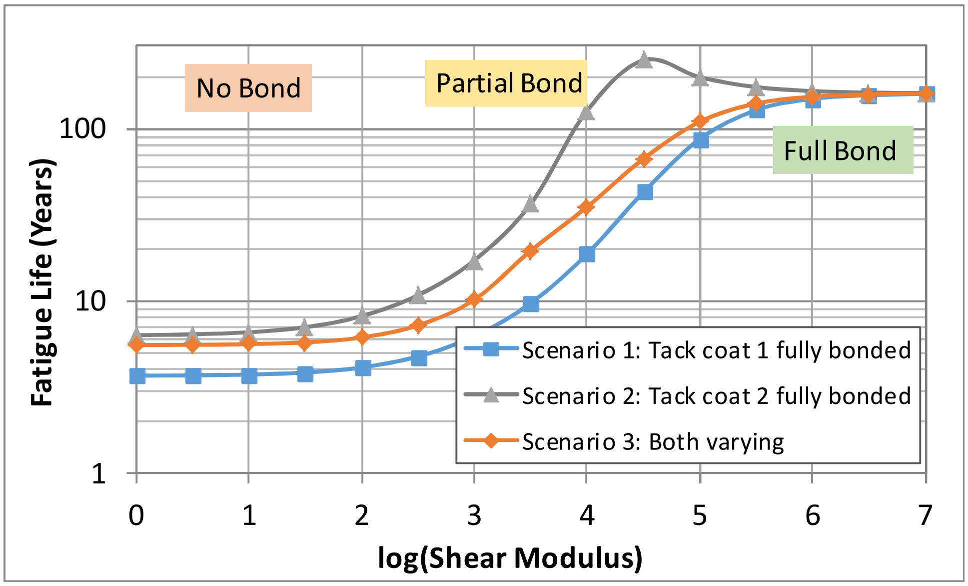


Figure 53. Influence of bond condition on fatigue cracking performance

Developing Bond-to-Log(K_s) Transformation

The shear reaction modulus (K_s) was not be directly measured from the shear bond strength test. Instead, the researchers qualitatively mapped lower and upper bounds for bond strength onto the log(K_s) scale, correlating with similar no-bond and full-bond conditions. A sinusoidal mapping line was generated and was the basis for transforming shear bond results to the performance models in this research. The assumptions are described in Table 24 and the transformation graphs are given in Figure 54.

Table 24. Justifications for Mapping Shear Results to log(K_s): (a) Strength and (b) Energy.

(a)

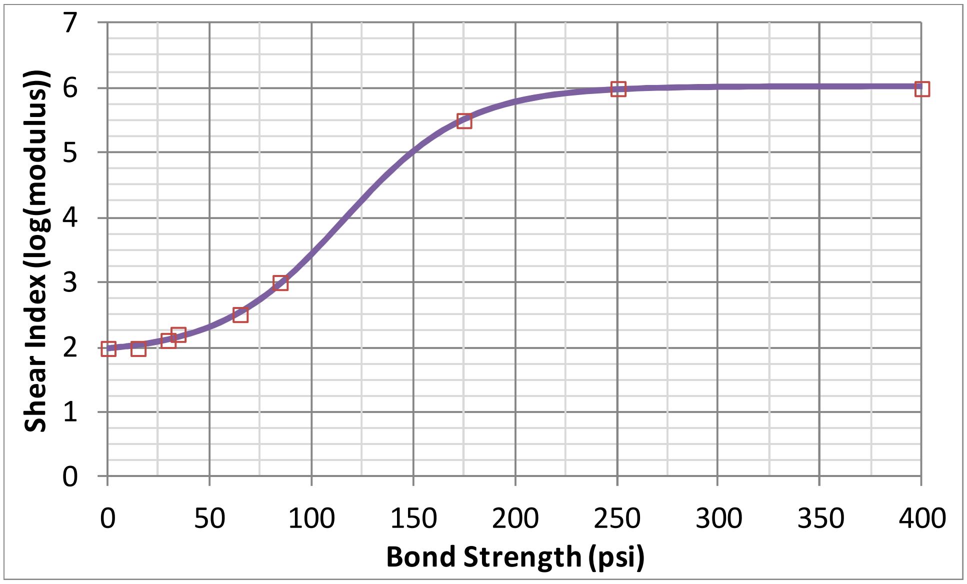
Bond Strength* (psi)	log(Ks)	Description/Justification
0	2	No Bond
15	2	Lowest bond strength observed. Samples below this could not be cored.
30	2.1	From NCAT, lowest bond strength observed near delaminated areas.
35	2.2	Upper range of samples from similar low-bond locations.
65	2.5	From NCAT, highest bond strength observed near delaminated areas.
85	3	From NCAT, lowest bond strength observed on projects away from delaminated areas. Consideration given as a minimum bond-strength criteria.
175	5.5	Generally, the maximum observed shear strength from Texas field samples.
250	6	Lowest internal HMA shear strength among ODOT's samples
400	6	Highest observed bond strength and also highest internal HMA shear strength from ODOT.

*Loading rate = 2-inch/min

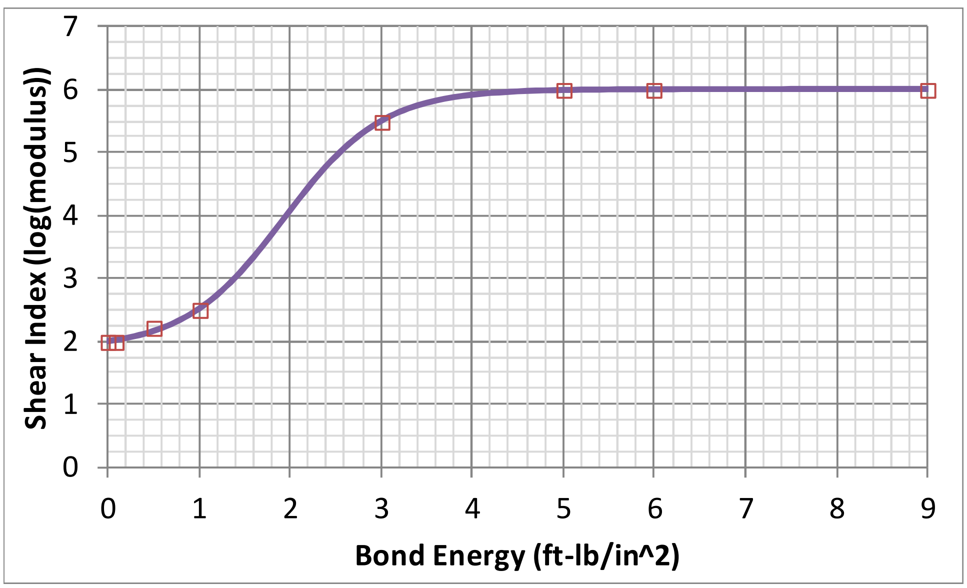
(b)

Bond Energy* (ft-lb/in^2)	log(Ks)	Description/Justification
0.0	2	No Bond
0.1	2	Lowest bond energy recorded. HMA on concrete, no tack. (actually <0.1)
0.5	2.2	
1.0	2.5	From limited experience, the lower bound of bond energy value.
3.0	5.5	Upper range of associated energies at PSI = 175. Corresponds to an average strength of 250 psi. Close to highest observed energy from Texas field.
5.0	6	Upper range of associated energies at PSI = 250.
6.0	6	Highest bond energy from ODOT
9.0	6	Highest bond energy from Tx Lab

*Loading rate = 2-inch/min



(a)



(b)

Figure 54. Mapping Shear Results to log(K_s): (a) Strength and (b) Energy.

Appendix F
LIFE-CYCLE COST ANALYSIS DETAILS

Life cycle cost analysis of new HMA (surface) sections and the milled HMA (intermediate) test sections on IR 270 were performed. The analysis was conducted according to Ohio DOT Pavement Design Manual guidelines and using RealCost Version 2.5, a life cycle cost analysis software developed by the Federal Highway Administration (FHWA). The considered test sections included sections without tack coat as well as sections with different tack coat material and application methods: trackless (Distributor), SS-1H (Distributor), Rubber (Spray paver), SS-1H (Spray paver). An analysis period of 15 years was used in this study. The initial costs of asphalt mixes and tack coat material used in the life cycle cost analysis were obtained from the asphalt contractor and are provided in Table 25. The service life of the overlay was determined based on the performance prediction. In addition, the maintenance and repair frequency were determined based on the predicted performance curve and priority system decision tree used by ODOT. The cost of the repairs were based on information provided by ODOT office of pavement engineering.

Table 25. Material Costs Used in Life-Cycle Cost Analysis.

Item	Cost
Surface Asphalt mix	$73/ton
Intermediate Asphalt mix	$62 /ton
SS1h	$1.83/gallon
Trackless	$3.66/gallon
Rubberized tack	$2.72/gallon

Appendix G
DRAFT TEST METHOD AND SPECIFICATIONS

This appendix contains the following:

- Draft interface bond strength test method
- Draft method-based specification for Item 407 – Tack Coat.
- Draft performance-based specification for Item 407 – Tack Coat.
- Draft entry for Item 407 – Tack Coat for the Manual of Procedures.

OHD X-##
DRAFT TEST PROCEDURE FOR SHEAR BOND STRENGTH TEST

1. SCOPE

1.1 Use this test to determine the shear strength between two bonded pavement layers. Speciemns are most often cores from the field, but bonded laboratory specimens may also be tested.

1.2 This test may also determine the shear strength of a uniform layer.

1.3 The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. APPARATUS

2.1 *Interlayer shear strength aparatus* - Holds a cyclidrical core horizontally beneath a loading frame, and consists of two parts:1) a ridged sleeve to hold one side of the specimen and provide a reaction force; and 2) a sliding sleeve holding the other side of the specimen and moves perpendicular to the core's vertical axis, producing the shear load.

2.1.1 The device should accommodate 6-inch and 4-inch-diameter cores with the use of a reducer sleeve.

2.1.2 The gap between the sliding and reaction halves should be 1/4-in., and optionally adjust to accommodate larger gaps.

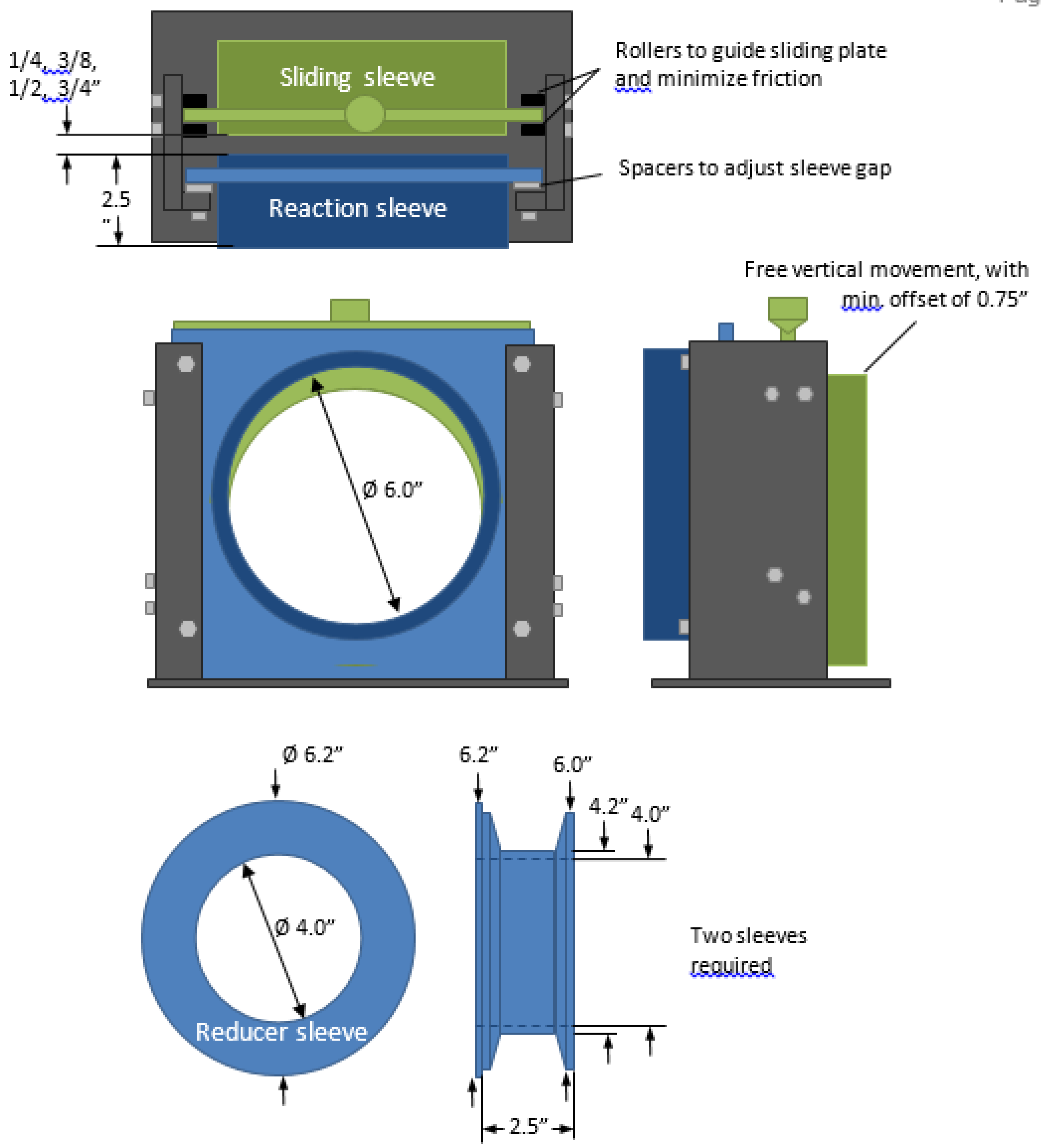


Figure 1 – Interlayer shear strength apparatus and reducer sleeve.

2.2 *Loading Frame* – Must apply a uniform vertical displacement rate of ____ in. (___mm) / minute. The displacement should be accurate within ____ in. (____mm). The load cell must have an accuracy or ____ lbs within the range of _________ lbs (____kN).

2.3 *Core Drill and 4-inch Core Barrel* – Used to reduce the diameter of core specimens when testing layer thicknesses less than 1.5 in. (38 mm).

3. SPECIMENS

3.1 Measurements on three specimens constitute a single test.

3.2 *Core Specimens* — Specimen diameter must be 6 ± 0.1 in. (150 ± 2 mm) or 4 ± 0.1 in (100 ± 2mm). The smaller core size must be used for specimens with layer thickensses less than 1.25 in. (32 mm). There is no specific density requirement.

3.2.1 Mark the direction of traffic on the surface prior to coring.

3.2.2 Carefully remove the core as to minimize stress bond and surrounding layers. Make a note if the core debonds at the interface in question.

3.2.3 Trim cores so the thickness between the bond and specimen end is between no more than 3 in.

3.2.4 Allow specimens to fully dry after coring and trimming.

3.3 *Laboratory-Molded Specimen*–4-inch diameter bonded specimen, consisting of a substrate, tack, and overlay.

3.3.1 Prepare or obtain a 4 or 6-inch substrate specimen with a height of 2 in. (50 mm). Prepared specimens should generally conform to Tex-241-F. The density may be adjusted as necessary to meet the purpose of the test. A core specimen from the field may also be used as a substrate.

NOTE: To ensure a laboratory prepared substrate sample will fit back into the mold in 3.3.4, consider heating the mold in this step to a temperature 25 F below the compaction temperature.

3.3.2 Preheat substrate to 140 F (60C) to simulate summer daytime construction conditions.

3.3.3 Apply tack to the surface at the specified rate using one of the following methods and cure.

3.3.3.1 Place sample on a scale and zero the reading. Brush pre-heated tack to the sample surface until scale reading matches calculated tack rate by weight. Cure the sample and tack for 45 minutes at 140 F (60C).

3.3.3.2 Pour calculated tack weight into a 6- or 4-inch diameter silicon mold and cure at 140 F (60 C) for at least 30 minutes. To transfer the tack from the mold to the sample, invert the sample onto the tack and remove the sample. Allow to cure for 15 more minutes at 140 F (60 C).

3.3.4 Place substrate sample with tack into a heated mold and immediately compact another layer in general accordance with Tex-241-F. Lift thickness and density should be adjusted to meet the purpose of the test.

NOTE: To ensure a laboratory substrate sample fits back into the mold, consider heating the mold to a temperature 50 F above the mold temperature in 3.3.1.

3.4 For specimens with emulsion tack, allow addequate time for tack to cure.

3.5 Measure the specimen diameter three times to the nearest 0.03 in. (1 mm) and average.

4. PROCEDURE

4.1 *Testing:*

4.1.1 Slide the specimen into the shearing apparatus and position the interface in question in the center of the gap. Orient the specimen so the direction of traffic from field cores is vertical. Use the 4-in. diameter sleeve when necessary.

NOTE: If the sample is excessively loose, wrap layers of masking tape around the sample near the interface. To aid in locating the bond, clearly mark the bond before placing it in the apparatus.

4.1.2 Position the apparatus in the loading frame and carefully bring the loading frame head in contact with the top of the shear apparatus. Apply a 10 lb seating load.

4.1.3 Apply the shearing load at a constant rate of displacement of 0.2 in. (5 mm) /minute and record the maximum load before failure.

4.1.4 Calculate the maximum shear strength using the following equation:

$$Shear_{max} = 4 * F_{Max}/(\pi D^2)$$

$Shear_{max}$ = Maximum shear strength, psi
F_{Max} = Maximum load, lbs.
D = Average specimen diameter, in.

4.1.5 Note the location of the failure (at the bond interface, or in the adjacent layers).

5. REPORT

5.1 Report the following for each specimen

- Maximum shear strength for individual specimens
- Note samples that fail at a location other than the bond
- Average shear strength and standard deviation of the three speciemens.

ITEM 407 TACK COAT
METHOD BASED SPECIFICATION

407.01 Description. This work consists of preparing and treating a paved surface with asphalt material, and cover aggregate if required.

407.02 Materials. Conform to the applicable requirements of 702 for the asphalt material and use one of the following types: 702.04 RS-1, SS-1, SS-1h, CRS-1, CSS-1, or CSS-1h; 702.12 Non-Tracking Asphalt Emulsion or 702.13 SBR Asphalt Emulsion. Supply 702.12 Non-Tracking Asphalt Emulsion any time Item 407 Non-Tracking Tack Coat is specified. Conform to 703.06 for cover aggregate.

407.03 Equipment. Provide adequate cleaning equipment, spreader boxes, distributors, and spray bar-integrated pavers (spray pavers).

Use distributors or a spray paver designed, equipped, maintained, and operated to apply asphalt material at the specified rate per square yard (square meter) with uniform pressure over the required width of application. Ensure that the distributor or spray paver includes a tachometer, pressure gauges, and an accurate volume measuring device or a calibrated tank. Mount an accurate thermometer with a range covering the specified application temperature for asphalt material at approximately center height of the tank with the stem extending into the asphalt material. Ensure that the distributor or spray paver has a full-circulating system with a spray bar that is adjustable laterally and, for distributors, vertically. Ensure that the spray bar will maintain a constant height above the pavement under variable load conditions. Supply each distributor or spray paver with suitable charts showing truck and pump speeds and other pertinent application data necessary to obtain the required results.

Do not use equipment that cannot obtain the correct tack application.

407.04 Weather Limitations. Do not apply the asphalt material if the surface temperature is below the minimum placement temperature for the pavement course to be placed, as specified in 401.06.

407.05 Preparation of Surface. Ensure that the surface is thoroughly clean and dry when the asphalt material is applied. Remove material cleaned from the surface and dispose of it as the Engineer directs.

407.06 Application of Asphalt Material. Uniformly apply the asphalt material with a distributor or spray paver having clean nozzles functioning properly.

For irregular areas such as driveways and intersections, apply the asphalt material using a method the Engineer approves.

If paving asphalt concrete directly onto Portland cement concrete or brick pavement, tack the pavement with SBR asphalt emulsion conforming to 702.13.

Apply the asphalt material in a manner that offers the least inconvenience to traffic. Only apply the asphalt material to areas that will be covered by a pavement course during the same day. Ensure the tack breaks before releasing to construction traffic unless the paver is equipped with a spray bar system to apply tack just prior to mat placement.

Apply asphalt material to obtain uniform coverage within the range specified in Table 407.06-1, as directed by the Engineer. Obtain the Engineer's approval for the quantity, rate of application, temperature, and areas to be treated before application of the asphalt material. The Engineer will determine the actual application in gallons per square yard (liters per square meter) by a check on the project.

TABLE 407.06-1

TYPICAL TACK COAT APPLICATION RATES

Existing Pavement	**Application Rate** gal/yd2 (L/m2)
New Asphalt	0.05 to 0.08 (0.23 to 0.36)
Oxidized Asphalt	0.08 to 0.10 (0.36 to 0.45)
Milled Asphalt Surface	0.08 to 0.10 (0.36 to 0.45)
Milled PCC Surface	0.06 to 0.08 (0.27 to 0.36)
PCC Surface	0.06 to 0.08 (0.27 to 0.36)

The application is considered satisfactory when the actual rate is within ±10 percent of the required rate and the material is applied uniformly with no visible evidence of streaking, ridging or pickup by construction traffic. The Engineer will require proper correction when ridging, streaking, pickup or other non-uniform coverage is observed. Correct non-uniform tack only in areas of non-uniform coverage. Do not reapply tack in areas where the tack meets uniformity and application requirements.

If the coverage is not uniform and not corrected the total square yardage of non-uniform application will be considered non-specification material. The Engineer will determine the number of gallons (liters) for non-payment by using the approved rate of application times the total square yards (square meters) of non-uniform application.

407.07 Method of Measurement. The Department will measure Tack Coat and Non-Tracking Tack Coat by the number of gallons (liters) of undiluted asphalt material applied for each according to Item 109.

407.08 Basis of Payment. The cost of cover aggregate is incidental to Tack Coat.

The Department will not pay for non-uniformly applied materials as defined in 407.06.

The Department will pay for accepted quantities at the contract prices as follows:

Item	**Unit**	**Description**
407	Gallon (Liter)	Tack Coat
407	Gallon (Liter)	Non-Tracking Tack Coat

ITEM 407 TACK COAT
PERFORMANCE BASED SPECIFICATION

407.01 Description. This work consists of preparing and treating a paved surface with asphalt material, and cover aggregate if required.

407.02 Materials. Conform to the applicable requirements of 702 for the asphalt material and use one of the following types: 702.04 RS-1, SS-1, SS-1h, CRS-1, CSS-1, or CSS-1h; 702.12 Non-Tracking Asphalt Emulsion or 702.13 SBR Asphalt Emulsion. Supply 702.12 Non-Tracking Asphalt Emulsion any time Item 407 Non-Tracking Tack Coat is specified. Conform to 703.06 for cover aggregate.

407.03 Equipment. Provide adequate cleaning equipment, spreader boxes, distributors, and spray bar-integrated pavers (spray pavers).

Use distributors or a spray paver designed, equipped, maintained, and operated to apply asphalt material at the specified rate per square yard (square meter) with uniform pressure over the required width of application. Ensure that the distributor or spray paver includes a tachometer, pressure gauges, and an accurate volume measuring device or a calibrated tank. Mount an accurate thermometer with a range covering the specified application temperature for asphalt material at approximately center height of the tank with the stem extending into the asphalt material. Ensure that the distributor or spray paver has a full-circulating system with a spray bar that is adjustable laterally and, for distributors, vertically. Ensure that the spray bar will maintain a constant height above the pavement under variable load conditions. Supply each distributor or spray paver with suitable charts showing truck and pump speeds and other pertinent application data necessary to obtain the required results.

Do not use equipment that cannot obtain the correct tack application.

407.04 Weather Limitations. Do not apply the asphalt material if the surface temperature is below the minimum placement temperature for the pavement course to be placed, as specified in 401.06.

407.05 Preparation of Surface. Ensure that the surface is thoroughly clean and dry when the asphalt material is applied. Remove material cleaned from the surface and dispose of it as the Engineer directs.

407.06 Application of Asphalt Material. Uniformly apply the asphalt material with a distributor or spray paver having clean nozzles functioning properly.

For irregular areas such as driveways and intersections, apply the asphalt material using a method the Engineer approves.

If paving asphalt concrete directly onto Portland cement concrete or brick pavement, tack the pavement with SBR asphalt emulsion conforming to 702.13.

Apply the asphalt material in a manner that offers the least inconvenience to traffic. Only apply the asphalt material to areas that will be covered by a pavement course during the same day. Ensure the tack breaks before releasing to construction traffic unless the paver is equipped with a spray bar system to apply tack just prior to mat placement.

The application rate is chosen by the contractor and must conform to the minimum rates specified in Table 407.06-1. Obtain the Engineer's approval for the areas to be treated before application of the asphalt material. The Engineer will determine the actual application in gallons per square yard (liters per square meter) by a check on the project.

TABLE 407.06-1

MINIMUM TACK COAT APPLICATION RATES

Existing Pavement	**Application Rate** gal/yd2 (L/m2)
New Asphalt	0.05 (0.23)
Oxidized Asphalt	0.08 (0.36)
Milled Asphalt Surface	0.08 (0.36)
Milled PCC Surface	0.06 (0.27)
PCC Surface	0.06 (0.27)

The application is considered satisfactory when the actual rate is within ±10 percent of the rate selected by the contractor and the material is applied uniformly with no visible evidence of streaking, ridging or pickup by construction traffic. The Engineer will require proper correction when ridging, streaking, pickup or other non-uniform coverage is observed. Correct non-uniform tack only in areas of non-uniform coverage. Do not reapply tack in areas where the tack meets uniformity and application requirements.

If the coverage is not uniform and not corrected the total square yardage of non-uniform application will be considered non-specification material. The Engineer will determine the number of gallons (liters) for non-payment by using the approved rate of application times the total square yards (square meters) of non-uniform application.

407.07 Method of Measurement. The Department will measure Tack Coat and Non-Tracking Tack Coat by the number of gallons (liters) of undiluted asphalt material applied for each according to Item 109.

The Department will measure the bond strength of the new overlay to the existing surface on the first day of paving. Core locations will be selected randomly and cores will be tested in accordance to the shear bond strength test (ODOT XXX). The average shear bond strength of three cores should be 70 psi or greater, with no single test result below 60 psi. If the contractor fails to meet this criteria, they must make changes to the tack material type, surface preparation procedures, and/or application procedures. Paving will be suspended until the contractor constructs a test section meeting the criteria.

407.08 Basis of Payment. The cost of cover aggregate is incidental to Tack Coat.

The Department will not pay for non-uniformly applied materials as defined in 407.06.

The Department will pay for accepted quantities at the contract prices as follows:

Item	**Unit**	**Description**
407	Gallon (Liter)	Tack Coat
407	Gallon (Liter)	Non-Tracking Tack Coat

407 TACK COAT MANUAL OF PROCEDURES

Description (407.01)

Tack coat is an application of liquid asphalt material on an existing pavement surface that provides a bond with a new asphalt pavement. The bonding of pavement courses together creates a monolithic structure. The entire pavement structure is needed to resist shear and tensile stresses caused by traffic. The tack coat keeps the new pavement layers from sliding over the old layer (delamination). Proper application of tack coat is a key factor in producing a quality asphalt paving project.

Materials (407.02)

The specification requires tack coat to be an asphalt emulsion conforming to 702.04 which includes types RS-1, SS-1, SS-1h, CRS-1, CSS-1 and CSS-1h; or 702.13 which includes SBR Asphalt Emulsions. The most commonly used tack in Ohio is SS-1h.

Emulsions are classified as rapid setting (RS or CRS), medium setting (MS or CMS), or slow setting (SS or CSS). The letter "C" in front of an emulsion type (CRS, CMS, or CSS), denotes a cationic (positively charged) emulsion. If the emulsion type is followed by an "h" (SS-1h) it means the emulsion was made from harder base asphalt cement.

SBR asphalt emulsions are required for use on concrete pavements. This replaces the older specification that required rubberized asphalt emulsion.

Tack is not to be diluted with water. However the Contractor may request dilution and if the Department grants this request the diluted material must have a minimum viscosity of 20 Saybolt Furol seconds. The color of diluted tack will appear browner on application than does undiluted tack. The color of undiluted tack will appear black at the time of application.

Non-Tracking Tack may also be specified by the project plans. Non-Tracking Tacks are products that are applied like ordinary tack coats, but cure and set up very quickly, generally within 10 to 15 minutes, thus helping to eliminate tracking onto adjacent pavements. Note, that pick up and tracking due to the application of tack on dirty pavements is not solved merely by using Non-Tracking Tack; pavement cleaning is still required as well as proper application. The non-tracking characteristic makes them very suitable where construction zones are short, for example urban paving conditions. If the Non-Tracking Tack provided does not perform in the field, the Contractor shall discontinue its use. Examples of non-performance would include long cure times and tracking of the material.

Equipment (407.03)

Distributor trucks are used to apply tack coat using a tank and spray bar system. The distributor is required to have a tachometer, thermometer, pressure gauges, and an accurate volume measuring device or a calibrated tank. A calibrated tank means there is a dedicated measuring stick for the tank and a chart that correlates the stick reading to the volume in the tank. The spray bar system must be fully circulating and the spray bar must be adjustable both laterally (to apply coverage to the correct width) and vertically (to adjust the spray fans). The spray bar must also maintain a constant height above the pavement surface as the load in the tank changes.

Many distributor trucks are now computerized and automatically adjust the pump pressure/discharge (gpm) to obtain the required application rate. However, there are many older distributor trucks still in use that require synchronization of the truck speed/RPM, the asphalt pump pressure/discharge (gpm), and the bar height to obtain the required application rate. Where these trucks are used, the Contractor must provide charts or other information that shows truck and pump speeds that are required to obtain the application rate.

In general, the faster the distributor truck goes, the faster the asphalt pump has to turn in order to get the same application rate that one would get at a slower speed.

Appendix H
TEST SECTION PERFORMANCE MONITORING PLAN

In order to verify and refine the performance predictions results, the field test sections should be monitored over time. This primarily involves evaluating surface distress and also includes some falling-weight deflectometer (FWD) testing and bond strength testing of cores. The recommended monitoring plan is summarized in Table 26 and Table 27.

Table 26. Performance Monitoring Schedule.

Overlay Age (yr)	Month/Year	Action	Test Sections
0	July 2016	Construction Bond testing	All
0.6	Mar. 2017	Bond testing	Group A*
1.25	Oct. 2017	FWD measurements	Group B
1.5	Jan. 2018	Distress survey	Group B
2.5	Jan. 2019	Distress survey	Group B
2.75	April 2019	FWD measurements	Group B
3.25	Oct 2019	FWD measurements	Group B
3.5	Jan. 2020	Distress survey	Group B
4.5	Jan. 2021	Distress survey	Group B
5.5	Jan. 2022	Distress survey	Group C
5.75	Apr. 2022	FWD measurements	Group B
6.25	Oct 2022	Bond testing FWD measurements	Group A* Group B
7.5	Jan. 2024	Distress survey	Group B
8.75	April 2026	FWD measurements	Group B
9.25	Oct 2026	FWD measurements	Group B
9.5	Jan. 2026	Distress survey	Group B
11.5	Jan. 2028	Distress survey	Group C

*Also include no-tack locations

The distress surveys should cover at least 300 ft of each test section starting 100 ft away from the starting station. By performing the surveys in winter, any cracking distress should be open and easier to observe. The distress survey can safely be performed from the shoulder. Mapping the distresses manually would be overly time consuming, so instead the technician can count reflection cracks and note the linear extend of wheel path cracking. Of course, automated distress data collection at highway speeds would be ideal if available to the Department. The subsurface pavement has a mixture of aged HMA and repaired patch areas which may interfere with the analysis. The milled interface bond is strongest over the repair areas. Cores during initial testing were targeted over these repairs. The majority of the project, however, is located over the aged HMA. The detailed notes of the locations of each subsurface section are given in Table 28.

Table 27. Location and Group Assignment of Test Sites.

Surface Type	Tack Type	Application Method	Target Rate (gal/sy)	Tracking	Station (###+##)		Group		
					Begin	End	A	B	C
New	Rubber	Spray Paver	0.07	None	1146+00	1140+00		X	X
			0.1	None	1140+00	1134+00	X		X
			0.13	None	1134+00	1128+00		X	X
	SS-1H	Spray Paver	0.07	None	1128+00	1122+00	X	X	X
			0.1	None	1122+00	1117+00	X		X
			0.13	None	1117+00	1112+00	X	X	X
		Distributor	0.04	None	1108+00	1103+00	X	X	X
				Tracking	1103+00	1099+00			
			0.07	None	1099+00	1094+00			X
				Tracking	1094+00	1090+00			
			0.1	None	1090+00	1085+00	X	X	X
				Tracking	1085+00	1081+00			
	Trackless	Distributor	0.04	None	1081+00	1076+00		X	X
				Tracking	1076+00	1072+00			
			0.07	None	1072+00	1067+00			X
				Tracking	1067+00	1063+00			
			0.1	None	1063+00	1058+00	X	X	X
				Tracking	1058+00	1054+00			
Milled	Rubber	Spray Paver	0.08	None	1089+00	1080+00		X	X
			0.12	None	1080+00	1073+00			X
			0.16	None	1073+00	1066+00		X	X
	SS-1H	Distributor	0.04	None	1063+00	1056+00		X	X
				Tracking	1056+00	1049+00			
			0.08	None	1049+00	1043+00			X
				Tracking	1043+00	1037+00			
			0.12	None	1037+00	1031+00		X	X
				Tracking	1031+00	1024+00			

FWD testing can be performed every 50 ft for the length of the test sections. It will be performed roughly every 3 years, and should be done during the spring and later in the fall.

The first round of follow-up bond strength testing has already been done. One more set of bond strength tests is recommended after 6 years, corresponding with FWD testing. The Department may also consider coring after 3 years.

Table 28. Subsurface Layer Details: (a) New HMA Surface Test Sections and (b) Milled Surface Test Sections.

(a)

Repaired HMA			Aged Existing HMA Substrate		
Approx. Station		Approx. Length, ft	Approx. Station		Approx. Length, ft
Begin	End		Begin	End	
1116+49	1115+72	77	1146+00	1136+87	913
1106+19	1105+74	45	1136+87	1116+49	2038
1088+04	1087+24	80	1115+72	1106+19	953
1086+88	1085+24	164	1105+74	1088+04	1770
1084+33	1082+75	158	1087+24	1086+88	36
1082+18	1078+14	404	1085+24	1084+33	91
1074+25	1074+02	23	1082+75	1082+18	57
1072+28	1070+96	132	1078+14	1074+25	389
1065+56	1065+22	34	1074+02	1072+28	174
1059+94	1059+69	25	1070+96	1065+56	540
1046+28	1046+04	24	1065+22	1059+94	528
			1059+69	1046+28	1341

(b)

Repaired HMA			Aged Existing HMA Substrate		
Station		Length, ft	Station		Length, ft
Begin	End		Begin	End	
<1089+00	1088+00	100	1088+00	1087+10	90
1087+10	1085+15	195	1085+15	1085+59	44
1085+59	1085+05	54	1085+05	1084+70	35
1084+70	1084+12	58	1084+12	1082+42	170
1082+42	1081+02	140	1081+02	1080+29	73
1080+29	1080+02	27	1080+02	1079+40	62
1079+40	1078+94	46	1078+94	1078+32	62
1078+32	1078+18	14	1078+18	1074+85	333
1074+85	1074+27	58	1074+27	1072+71	156
1072+71	1072+18	53	1072+18	1071+97	21
1071+97	1071+39	58	1071+39	1070+00	139
1070+00	1068+57	143	1068+57	1067+76	81
1067+76	1067+53	23	1067+53	1060+15	738
1060+15	1059+50	65	1059+50	1042+50	1700
1042+50	1042+00	50	1042+00	1041+30	70
1041+30	1041+20	10	1041+20	1041+00	20
1041+00	1040+90	10	1040+90	1035+15	575
1035+15	1034+80	35	1034+80	1033+60	120
1033+60	1033+30	30	1033+30	1030+30	300
1030+30	1030+20	10	1030+20	1027+60	260
1027+60	1027+50	10	1027+50	1027+15	35
1027+15	1027+00	15	1027+00	1026+70	30
1026+70	1026+55	15	1026+55	1025+50	105
1025+50	1025+00	50	1025+00	1023+44	156