NCHRP

REPORT 712

Optimization of Tack Coat for HMA Placement

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

COOPERATIVE RESEARCH PROGRAMS

FOREWORD

By Edward Harrigan
Staff Officer
Transportation Research Board

This report presents proposed test methods for measuring the quality and performance characteristics of tack coat in the laboratory and the field, as well as a training manual presenting proposed construction and testing procedures for tack coat materials. Thus, the report will be of immediate interest to staff of state highway agencies, materials suppliers, and paving contractors with responsibility for selection, testing, and use of tack coat materials.

NCHRP Project 9-40, "Optimization of Tack Coat for HMA Placement," was conducted by the Louisiana Transportation Research Center, Baton Rouge, Louisiana, with major participation by the Texas Transportation Institute, College Station, Texas, and consultant James A. Scherocman, Cincinnati, Ohio.

The objectives of this research were to determine optimum application methods, equipment type and calibration procedures, application rates, and asphalt binder materials for the various uses of tack coats and to propose new or revised AASHTO methods and practices related to tack coats. In accomplishing these objectives, both present and emerging technology in the United States and worldwide was evaluated.

In the research, the contractor developed two new test methods and associated criteria for characterizing the quality and performance of tack coat materials: the Louisiana Tack Coat Quality Tester (LTCQT) and the Louisiana Interlayer Shear Strength Test (LISST). The LTCQT is a small test unit that can measure the bond strength of a tack coat in the field. The LISST is a test fixture fitted into a universal testing machine to measure the interface shear strength (ISS) of a tack coat in a field or laboratory specimen. With the LISST, the effects of pavement surface types and conditions, tack coat material types, and tack coat application rates and methods on tack coat performance can be assessed.

The research demonstrated a strong direct relationship between the ISS and the residual application rate of a wide range of tack coat materials, including a PG 64-22 asphalt binder, and trackless, CRS-1, SS-1, and SS-1h emulsions. Similarly, the LISST results show that for a given tack coat material the ISS is directly related to the pavement surface roughness. Finally, the research established a proposed minimum laboratory-measured ISS to provide acceptable tack coat performance in the field as well as optimal tack coat residual application rates for different pavement surface types.

The report fully documents the research leading to the proposed LTCQT and LISST test methods and associated quality and performance criteria, and includes four appendixes:

- Appendix A: Worldwide Survey Questionnaire
- Appendix C: Standard Test Method for Assessing Tack Coat Installation Quality using the LTCQT

- Appendix E: Standard Test Procedure for Measuring Interface Bond Strength in the Laboratory using the LISST
- Appendix F: Training Manual

In addition, two appendixes are available for download from the NCHRP Project 9-40 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=974:

- Appendix B: ATacker™ Displacement Rate Verification Experiment
- Appendix D: Comparison of the LISST Device and the Simple Shear Tester (SST)

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

S U M M A R Y

Optimization of Tack Coat for HMA Placement

Selection of an optimum tack coat material and application rate are crucial in the development of proper bond strength between pavement layers. In general, selection of tack coats has been mainly based on experience, convenience, and empirical judgment. In addition, quality-control and quality-assurance testing of the tack coat construction process is rarely conducted, resulting in the possibility of unacceptable performance at the interface and even premature pavement failure. The main objectives of this project are to determine optimum application methods, equipment type and calibration procedures, application rates, and asphalt binder materials for the various uses of tack coats and to recommend revisions to relevant AASHTO methods and practices related to tack coats. During the course of this project, the research team developed the Louisiana Tack Coat Quality Tester (LTCQT) to evaluate the quality of the bond strength of tack coat in the field. Repeatability of measurements using the LTCQT was acceptable, with an average coefficient of variation of less than 11%. Research in this project also resulted in the development of a training manual, which is presented in Appendix F. The training manual provides a comprehensive presentation of the recommended construction and testing procedures for tack coat materials.

The Louisiana Interlayer Shear Strength Tester (LISST) was developed for the characterization of interface shear strength of cylindrical specimens in the laboratory. The LISST device was designed such that it will fit into any universal testing machine. The average coefficient of variation in the LISST test results was less than 10%. As part of the experimental program, the research team constructed full-scale test overlays at the Louisiana Transportation Research Center's (LTRC's) Pavement Research Facility (PRF). The overlays included different tack coat application rates between a new hot-mix asphalt (HMA) overlay installed over several types of pavement surfaces including old HMA, new HMA, milled HMA, and grooved portland cement concrete (PCC). Five types of tack coat materials were each applied at three application rates. The quality of tack coat application was evaluated using the LTCQT, specimens were cored from the test pavements, and interface shear strength was measured in the laboratory using the LISST device. Based on the findings of this project, the following conclusions were drawn:

- **With respect to the interface shear strength in the field:**
  - For the effect of emulsified tack coat type, trackless tack coat exhibited the highest interface shear strength (ISS), and CRS-1 resulted in the lowest interface shear strength. These results relate directly to the viscosity of the residual binders at the test temperature (25°C).
  - For the effect of application rate, all tack coat materials showed the highest interface shear strength at an application rate of 0.155 gsy. Within the tested application rate range, it was difficult to determine the optimum residual application rate. This may be attributed to the highly oxidized HMA surface at the LTRC PRF site, which required greater optimum tack coat rates than expected. It may also indicate that, under actual field conditions,

optimum application rates are greater than what is commonly predicted from laboratory-based experiments. It is noted, however, that while higher application rates may increase interface shear strength, excessive tack coat may migrate into the new asphalt mat during compaction, causing a decrease in the air void content of the mix.

– For the effect of confinement, the ratio of interface shear strength between confined and no-confinement test conditions was always greater than 1. This ratio increased as the residual application rate decreased. Therefore, a specification developed based on no-confinement testing conditions would yield a conservative estimate of the ISS values.

– For the effect of dust, the majority of the cases showed a statistically significant difference between clean and dusty conditions. It appears from these results that dusty conditions exhibited greater ISS than clean conditions, especially when tested with a confining pressure. This likely resulted when the dust combined with the asphalt and formed mastic with a resultant viscosity higher than that of the neat residual asphalt, plus the sand particles may have provided grit at the interface to further increase the ISS. However, one should note that these results are based on using a uniform and clean sand to simulate dusty conditions. *Therefore, cleaning and sweeping of the existing pavement surface is recommended to avoid negative effects of dusty conditions.*

– For the effect of water on the tacked surface, the majority of the cases showed no statistically significant difference between dry and wet conditions. This data indicates that a small amount of water can be flashed away by the hot HMA mat and, thus, have inconsequential effects on the quality of the tack coat. This study used only hot mix as the overlay material; the use of warm mix may change this finding. In addition, these results are based on using a small quantity of water to simulate rainy conditions. *Therefore, a dry and clean surface is recommended to avoid the negative effects of water on the bonding at the interface.*

– For the effect of surface type, a direct relationship was observed between the roughness of the existing surface and the shear strength at the interface. Therefore, the milled HMA surface provided the greatest interface shear strength followed by PCC, old HMA, and new HMA surface. Table S-1 presents the recommended tack coat residual application rates for different surface types.

– For the effect of tack coat coverage, the use of 50% coverage significantly reduced the interface shear strength by a factor ranging from 50% to 70%. In addition, the use of 50% tack coat coverage resulted in inconsistent and non-uniform interface bonding behavior for tacked surfaces.

– For the effect of preparation method, laboratory-prepared specimens grossly overestimated the interface shear strength when compared with pavement cores. In addition, when increasing tack application rates, a decreasing trend in ISS was observed in laboratory-prepared specimens, while an increasing trend was observed in the field.

– For the effect of temperature (from −10 to 60°C), ISS increased with the decrease in temperature. In addition, the bonding performance, as measured by the interface shear strength of the trackless emulsion, was superior to that of the CRS-1 emulsion, especially at temperatures greater than 40°C.

Table S-1. Recommended tack coat residual application rate.

Surface Type	Residual Application Rate (gsy)
New asphalt mixture	0.035
Old asphalt mixture	0.055
Milled asphalt mixture	0.055
Portland cement concrete	0.045

- Based on the results of the finite element (FE) analysis, the minimum laboratory-measured interface shear strength in the LISST device that provides acceptable performance is 40 psi.
- **With respect to the tack coat spray application quality in the field:**
  - Tensile strength of each tack coat material increased, reached a peak, and then decreased as the temperature increased. The tack coat materials tested using LTCQT exhibited a maximum tensile strength, S_{MAX}, at a distinct temperature, T_{OPT}. Thus, the response of tack coat material in tension was characterized using S_{MAX} at T_{OPT}.
  - For the tack coat materials evaluated, a good correlation was observed between the tensile strength and absolute viscosity. Within the range studied, an increase in viscosity (resistance to flow) was associated with an increase in tensile strength.
  - For the tack coat materials evaluated, a good relationship was observed between the maximum tensile strength and the corresponding softening point. An increase in the material softening point was correlated to an increase in the maximum tensile strength.
  - Based on the results of this study, it is recommended to conduct the LTCQT test at the tack coat base asphalt softening point, which is a quantity that can be easily measured and specified.

Introduction and Research Approach

This report presents the results of NCHRP Project 9-40, "Optimization of Tack Coat for HMA Placement." This section describes the problem statement, objective, scope, and research approach.

1.1 Problem Statement

Tack coat is a light application of asphalt, usually asphalt emulsion diluted with water, onto an existing relatively non-absorptive pavement surface (*1*). It is used to ensure adequate bond between the pavement being placed and the existing surface. A tack coat provides necessary bonding between pavement layers to ensure that they behave as a single system to withstand traffic and environmental stresses. Tack coat is normally applied to an existing pavement surface before a new layer of asphalt concrete is placed. It may also be applied to the surface of a new hot-mix asphalt (HMA) pavement layer before the next layer is placed, such as between an HMA leveling course and an HMA surface course.

Selection of an optimum tack coat material and application rate is crucial in the development of proper bond strength between pavement layers. Pavement surfaces with different conditions (e.g., new, old, milled, grooved, or cracked) require different tack coat application rates to achieve proper interface bond strength. In most paving operations, tack coat covers less than 90% of the existing surface. On the other hand, excessive tack coat may promote shear slippage at the interface. Most importantly, it is the residual amount of asphalt—not the quantity of diluted asphalt emulsion—that should be specified in tack coat applications.

Few guidelines are available for the selection of tack coat material type, application rate, placement, and evaluation. In general, selection of tack coats has been mainly based on experience, convenience, and/or empirical judgment. In addition, quality-control and quality-assurance testing of the tack coat construction process is rarely conducted, resulting in the possibility of unacceptable performance and even premature pavement failure.

1.2 Research Objective

The research objective, as stated in the project description, is "to determine optimum application methods, equipment type and calibration procedures, application rates, and asphalt binder materials for the various uses of tack coats and to recommend revisions to relevant AASHTO methods and practices related to tack coats."

1.3 Research Scope

Research tasks in this project were organized into two phases. In Phase I, a literature review was conducted to assess the current state of practice on the type of tack coat materials, application rates, application methods, and equipment calibration along with methods of measurement of tack coat quality, interface bond strength, and pavement performance related to tack coats. In Phase II, the research team conducted the necessary laboratory and field experiments to achieve the objective of this study. Variables and their ranges were carefully selected in the experimental program through a worldwide survey on the state of the practice on the use of tack coats conducted in Phase I. The experimental program considered emulsified tack coats and asphalt binder. In addition, the interface shear strength was evaluated for different types of pavement surfaces including old HMA, new HMA, milled HMA, and grooved portland cement concrete (PCC).

The findings of this report, presented in Section 4, are expected to be applicable to different climatic and traffic conditions across the United States; however, use of the recommended test methods and construction guidelines should be demonstrated and validated in different projects with different traffic and climatic conditions. While the demonstration phase was part of the original project description (in Task 6),

the Panel elected to extend the experimental program conducted in Task 4 in order to consider additional variables and to conduct the validation process in a future stand-alone study.

1.4 Research Approach

The research approach followed the one described in the project description (see Table 1). In Phase I, the research team conducted a review of the worldwide state of practice for the use of tack coats for both new HMA layers and HMA overlays on new, old, and milled HMA and for PCC pavements (Task 1). This review involved an extensive literature search of all published materials and ongoing research projects to obtain the latest information on the research of the bonding mechanisms of tack coat in pavement structure. Databases of TRB, the Transportation Research Information Service (TRIS), and COMPENDIX were searched. In addition, researchers conducted a worldwide survey on the state of practice of tack coats. Based on the results of the literature review and the worldwide survey, a statistically based test factorial was developed in Task 2 to (1) evaluate the bonding characteristics of tack coats; (2) select the tack coat material type and residual asphalt binder application rate required for optimum performance in new HMA pavement and HMA overlay construction, rehabilitation, and

reconstruction; (3) calibrate application equipment; and (4) maintain field quality control and quality assurance. In Task 3, the research team reported the findings of Phase I to the Project Panel. An interim report that provided a summary of the survey results and key findings of Task 1 (i.e., the literature review) and Task 2 (i.e., the design of comprehensive laboratory and field experiments) was submitted for review and approval by the Project Panel.

In Phase II, the research team conducted the laboratory and field experiments approved in Task 3. In Task 4, the research team developed the Louisiana Tack Coat Quality Tester (LTCQT) to evaluate the quality of the bond strength of tack coat in the field and the Louisiana Interlayer Shear Strength Tester (LISST) for the characterization of interface shear strength of cylindrical specimens in the laboratory. During the course of the experimental program, the research team constructed full-scale asphalt overlays at the Louisiana Transportation Research Center's (LTRC's) Pavement Research Facility (PRF). The overlays included different tack coat application rates between a new HMA overlay installed over several types of pavement surfaces including old HMA, new HMA, milled HMA, and PCC. Five types of tack coat materials were each applied at three application rates. Quality of tack coat application was evaluated using the LTCQT, specimens were

Table 1. Research approach in NCHRP Project 9-40.

Task ID	Task Description
Task 1	Literature Review
Task 2	Design a Comprehensive Experiment to Study Tack Coat Variables
Task 3	Develop Field and Laboratory Devices for Evaluation of Tack Coat Bond Performance
	Subtask 3-1: Develop Laboratory Experiment to Evaluate Tack Coats
	Subtask 3-2: Develop Field Experiment to Evaluate Tack Coat
Task 4	Field Tack Coat Application and Overlay Construction
	Subtask 4-1: Preparation of Test Lane for Tack Coat Field Application
	Subtask 4-2: Calibration of Tack Coat Application Rate
	Subtask 4-3: Field Tack Coat Application
	Subtask 4-4: Field Evaluation of Tack Coat Bond Performance
	Subtask 4-5: Overlay Construction
	Laboratory Evaluation of Tack Coat Bond Performance
	Subtask 5-1: ISS Test for Field-Cored Sample
	Subtask 5-2: ISS Test at Various Temperatures for Field-Cored Sample
	Subtask 5-3: ISS Test for Lab-Fabricated Sample
	Subtask 5-4: ISS Test at Various Permeability and Surface Textures for Lab-Fabricated Sample
Task 5	Recommend Test Methods, Criteria, and Construction Guidelines
Task 6*	Demonstrate the Use of Recommended Test Methods and Construction Guidelines
Task 7	Prepare Instructional Materials for a Training Course

*Project Panel recommended that Task 6 be conducted as a separate, stand-alone project.

cored from the test overlays, and interface shear strength (ISS) was measured in the laboratory using the LISST device. Laboratory testing of extracted cores and the effects of installation and design variables on the ISS were evaluated.

Based on the results of the experimental program, the research team adopted a finite element (FE) approach to relate laboratory-measured interface bond characteristics to field stresses in the pavement structure when subjected to vehicular loading (Task 5). Results of the FE approach ascertained how each tack coat material type and application rate will perform in pavements and examined the main failure mechanisms at the interface. Recommendations were provided on the following: (1) the candidate test methods to measure the performance of tack coats and (2) minimum laboratory-measured interface shear strength to provide acceptable field performance.

In Task 7, the research team developed instructional materials for a training course for agency and contractor personnel on the function of tack coats and how their proper selection and application affects pavement performance.

SECTION 2

State of Practice

A review of the existing state of practice was conducted to identify factors related to the use of tack coats for both new HMA pavements and overlays on new, old, milled HMA and for PCC pavements. This review involved an extensive search of all published materials and ongoing research projects to obtain the latest information on the research of the bonding mechanisms of tack coat in pavement structure. A worldwide survey on current tack coat practices was conducted to better understand the current state of tack coat practices and assist in designing an ensuing research experiment. Results of the survey provided the basis for the experimental factorial design that was used in Phase II of the NCHRP Project 9-40 research project.

2.1 Tack Coat Materials

According to *ASTM D8, Standard Terminology Relating to Materials for Roads and Pavements,* "Tack coat (bond coat) is an application of bituminous material to an existing relatively non absorptive surface to provide a thorough bond between old and new surfacing" (*1*). Generally, hot paving asphalt cement, cutback asphalt, and emulsified asphalt have all been used as tack coat materials, but cutback asphalts (asphalts dissolved in solvents such as kerosene or diesel) are not typically used for tack coat applications today due to environmental concerns. The most widely used tack coat material in the world is emulsified asphalt. Emulsified asphalt, or asphalt emulsion, is a nonflammable liquid substance that is produced by combining asphalt and water with an emulsifying agent such as soap, dust, or certain colloidal clays (*2*). The most common types of emulsions used for tack coats include slow-setting grades of emulsion such as SS-1, SS-1h, CSS-1, and CSS-1h and the rapid-setting grades of emulsion such as RS-1, RS-2, CRS-1, CRS-2, CRS-2P (polymer-modified), and CRS-2L (latex-modified). According to the *Construction Procedure Bulletin* (*CPB*) of the California DOT, several basic terms used in an asphalt emulsion tack coat application are as follows (*3*):

- *Original emulsion*—an emulsion of paving-grade asphalt and water that contains a small amount of emulsifying agent. Original slow-setting grade emulsions contain up to 43% water, and original rapid-setting grade emulsions contain up to 35% water.
- *Diluted emulsion*—an original emulsion that has been diluted by adding an amount of water equal to or less than the total volume of original emulsion.
- *Residual asphalt content*—the amount of paving asphalt remaining on a tacked pavement surface after the emulsion has broken and set (i.e., after all water has evaporated).
- *Tack coat break*—water separates from the emulsion and the color of the tack coat changes from brown to black.

A worldwide survey on tack coat application was conducted by the International Bitumen Emulsion Federation (IBEF) (*4, 5*). Seven countries—Spain, France, Italy, Japan, the Netherlands, the United Kingdom, and the United States—responded through their professional associations. The survey results indicated that the most frequently used tack coat material is cationic emulsion. Paul and Scherocman (*6*) conducted a survey of tack coat practices in the United States. This survey received responses from 42 state DOTs and the District of Columbia. They found that almost all the state DOTs use slow-setting emulsions for tack coats. The emulsions mostly used are SS-1, SS-1h, CSS-1, and CSS-1h. Only one responding state (Georgia) routinely used hot asphalts (AC-20 and AC-30) as tack coats. A recent phone survey conducted by Cross and Shrestha (*7*) in 13 mid-western and western U.S. states indicated that slow-setting emulsions are the primary materials for tack coat, except for California, where the AR-4000 was the most common tack coat material followed by either SS-1 or CSS-1. The Kansas DOT was the only agency that reported occasionally using cutback asphalts as tack coat. New Mexico DOT and Texas DOT reported that performance-grade (PG) binders (asphalt cement) were occasionally used as tack coat materials.

According to the *Unified Facilities Guide Specification (UFGS) 02744N* (*8*), the advantage of the slow-setting grades over the rapid-setting grades is that they can be diluted. Diluted emulsions are reported to give better results because (1) diluted emulsion provides the additional volume needed for the distributor to function at normal speed when lower application rates are used and (2) diluted emulsion flows easily from the distributor at ambient temperatures allowing for a more uniform application (*9, 10*). On the other hand, diluted slow-setting emulsions may take several hours to break or even several days to completely set. In addition, an overlay tacked with slow-setting emulsion may be vulnerable to slippage during its early life (*8*). Such an overlay exposed to heavy traffic immediately after construction could experience excessive slippage in a short period of time.

2.2 Tack Coat Application Rate

A proper bond between pavement layers is essential in order to provide a monolithic pavement structure. Selection of an optimum tack coat material and application rate is crucial in the development of this bond. Pavement surfaces with different conditions (e.g., new, old, or milled) require different tack application rates to achieve a proper interface bond. Excessive tack coats may promote shear slippage at the interface. Most importantly, it is the residual amount of asphalt cement, not the application rate of diluted asphalt emulsion, that should be specified.

From their survey, Paul and Scherocman (*6*) found that the residual application rates of the emulsions varied between 0.01 and 0.06 gal/yd^2, depending on the type of surface for application. The IBEF survey (*4*) indicated that the residual asphalt content ranged from 0.02 to 0.09 gal/yd^2 for tack coats applied on conventional asphalt surfaces. The Asphalt Institute (AI) specifications on tack coats reported that the application rates ranged from 0.05 to 0.15 gal/yd^2 for an emulsion diluted with one part water to one part emulsion (*11*), which is equivalent to residual application rates between 0.02 to 0.05 gal/yd^2. The lower application rates are recommended for new or subsequent layers, while the intermediate range is for normal surface conditions on an existing relatively smooth pavement. The upper limit is for old, oxidized, cracked, pocked, or milled asphalt pavement and PCC pavements. The residual asphalt contents, as specified in the Hot-Mix Asphalt Paving Handbook 2000 (*12*), should range from 0.04 to 0.06 gal/yd^2. Open-textured surfaces require more tack coat than surfaces that are tight or dense. Dry, aged surfaces require more tack coat than surfaces that are "fat" or flushed. A milled surface would require even more residual asphalt because of the increased specific surface area, as much as 0.08 gal/yd^2. Only half as much residual asphalt is typically required for new HMA layers, 0.02 gal/yd^2 (*7, 12*). Recently, Ohio published typical tack coat application rates for various pavement types using slow-setting asphalt emulsions (SS1, SS1-h) (*13*). As shown in Table 2, the overall residual rates vary from 0.03 to 0.08 gal/yd^2 for different pavement types.

2.3 Tack Coat Breaking and Setting Time

Before asphalt emulsion breaks, it is brown in color because it contains both asphalt cement and water. After broken, the water separates from the emulsion and the color of the emulsion changes from brown to black. Once all water is evaporated, the emulsion is said to have "set." Under most circumstances, an emulsion will set in 1 to 2 hours (*12*), but the literature generally lacks complete agreement concerning how long a tack coat should remain uncovered before placing the subsequent asphalt layer. The IBEF survey indicated that the lapse of time required between the application of the tack coat and the application of the next asphalt layer ranges from 20 minutes for a broken or cold binder to several hours for a "dry" binder (after all water has evaporated or set) (*4*). Paul and Scherocman (*6*) found that many state DOTs specified a minimum time between tack coat application and placement of HMA to provide adequate curing time for the emulsion to break and set. Three state DOTs had a maximum time that a tack coat could be left before placement of the asphalt concrete: Alaska DOT specified a maximum setting period of 2 hours for CSS-1; Arkansas DOT specified a maximum setting period of 72 hours for SS-1; and Texas DOT specified

Table 2. Typical tack coat application rates (*13*).

Pavement Condition	Application Rate (gal/yd^2)		
	Residual	Undiluted	Diluted (1:1)
New HMA	0.03 ~ 0.04	0.05 ~ 0.07	0.10 ~ 0.13
Oxidized HMA	0.04 ~ 0.06	0.07 ~ 0.10	0.13 ~ 0.20
Milled Surface (HMA)	0.06 ~ 0.08	0.10 ~ 0.13	0.20 ~ 0.27
Milled Surface (PCC)	0.06 ~ 0.08	0.10 ~ 0.13	0.20 ~ 0.27
Portland Cement Concrete	0.04 ~0.06	0.07 ~ 0.10	0.13 ~ 0.20

(a) Tack coat distributor truck

(b) Paver with tack coat tank and spray bar

Figure 1. Application equipment of tack coat.

a maximum setting period of 45 minutes for SS-1 or MS-2. Four states indicated that paving was required the same day the tack coat was applied.

It is generally recognized that an emulsion should be completely set before new mix is placed on top of the tack coat material. Laboratory studies (*14, 15*) agreed with this assumption showing that greater interface shear strengths are achieved with longer curing times for the tack coat prior to testing. This was true for both laboratory-fabricated samples (*14*) and field cores (*15*). However, experience has also shown that new HMA can usually be placed on top of unset tack coat and even over an unbroken tack coat emulsion with no detrimental effect on pavement performance (*12*). Indeed, in Europe, emulsified tack coat is often applied to the pavement surface underneath the paver just before the HMA in front of the paver screed. Some European firms have used this tacking process with conventional dense-graded HMA mixtures and normal emulsified asphalt tack rates without negative consequences, but there may be concerns with water vapor passing through a dense-graded mat. In the United States, this emulsion spray method is used in the Novachip™ construction process, as reported by Estakhri and Button (*16, 17*).

2.4 Tack Coat Application Methods

2.4.1 Equipment

Two types of tack coat application methods are shown in Figure 1: (a) a conventional tack coat distribution truck and (b) a special paver with tack coat tank and spray bar.

Generally, the best tack coat application results from a "double lap" or "triple lap" coverage. As shown in Figure 2, good "double/triple lap" means that the nozzle spray patterns overlap one another such that every portion of the pavement surface receives spray from two or three nozzles.

Several vehicle-related adjustments and settings are crucial to achieving uniform tack coat placement. Essentially, the nozzle patterns, spray bar height, and distribution pressure must work together to produce uniform tack coat application (*14, 19*). Specific guidance is summarized as follows:

- **Nozzle spray patterns should be identical to one another along a distributor spray bar.** To prevent the spray of liquid asphalt from interfering with adjacent spray nozzles, all nozzles should be set at the same angle (about 30°) to the axis of the spray bar (see Figure 3). Lack of a uniform angle
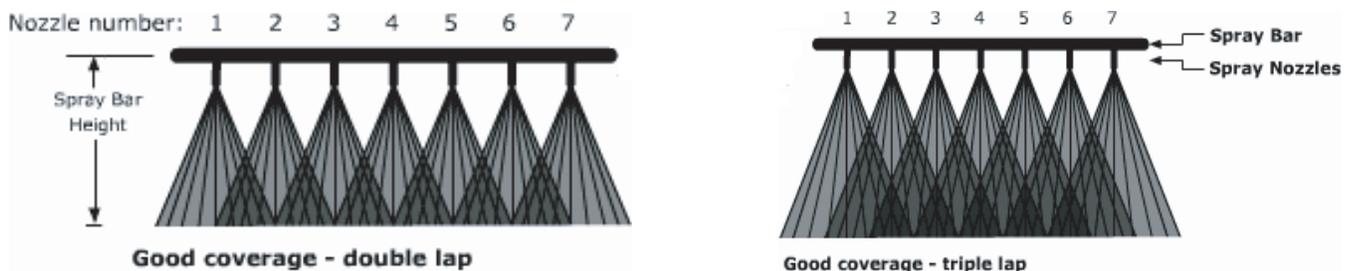
Figure 2. Uniform tack coat application with double and triple overlapping (18).
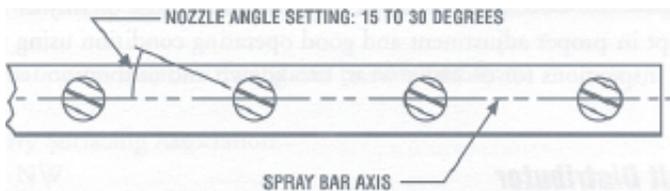
Figure 3. Proper nozzle angle setting (*14*).

will result in some areas of the pavement having thicker or thinner coverage and possible interference between nozzles. Differing coverage will result in streaks and gaps in the tack coat (see Figure 4).

- **The size of the nozzles needed to apply an asphalt emulsion material for a surface treatment, chip seal, or seal coat is significantly larger** than the size of the nozzles needed to apply a tack coat. Using a nozzle that is too small with too much pressure results in a surface that has a spider web coating of tack coat material (see Figure 5).
- **Spray bar height should remain constant.** As tack coat is applied, the vehicle will become lighter, causing the spray bar to rise. The tack coat application vehicle should be able to compensate for this. Excessively low spray bars result in streaks (see Figure 4), while excessively high spray bars cause non-uniform transverse coverage.
- **Pressure within the distributor must be capable of forcing the tack coat material out of the spray nozzles at a constant rate.** Inconsistent pressure will result in non-uniform application rates.
- **Tack distributors must be capable of maintaining temperature of the asphalt cement material to ensure the material will adequately flow.** For slow-setting asphalt emulsions such as SS-1, the spraying temperature within the distributor should be maintained between about 24°C

Figure 4. Non-uniform tack coat: streaks.

Figure 5. Small nozzle opening (*19*).

and 54°C. Excessive heating may cause the emulsion to break while still in the distributor.

2.4.2 Proper Tack Coat Application

Proper application of tack coat is a key component in high-quality asphalt pavement rehabilitation. Proper tack coat application begins with properly calibrated application equipment. If the distributor has not been used for some period of time, the operator should place a trial tack coat application over some convenient, unused area to ensure that all of the nozzles are open and operating properly. In addition, the distributor application rate needs to be calibrated, both in the transverse direction and in the longitudinal direction, using the procedure described in *ASTM Method D 2995* (*19*). Spray bar height depends on truck speed, nozzle configuration, and application pressure. Operators should adjust the spray bar height throughout the day depending on the amount of emulsion in the tank. As a summary, the literature suggests the fundamental aspects of achieving tack coat success are

- Having a thoroughly clean roadway surface,
- Ensuring all the equipment functions properly and is set up correctly,
- Choosing the proper application rate for the tack material used and the existing surface conditions,
- Applying the materials uniformly, and
- Allowing the tack to set prior to paving to ensure the best possible bond between layers.

One perpetual problem often associated with tack coat application using distributor trucks is that haul trucks normally drive on the applied tack coat, thus tracking the tack coat material and removing it from the pavement, as

Figure 6. Pick-up by haul truck tires.

shown in Figure 6. Currently, there are many methods for addressing the haul truck pickup problem. One method is to apply the tack coat to the pavement surface underneath the paver just ahead of the screed. This can be done by using a special paver fitted with a tack coat spray bar, as shown in Figure 1(b). A material transfer vehicle (MTV) may also be used to address the haul truck pickup problem. A third solution is to use modified tack coat materials without the stickiness or pick-up problem. An example of such a tack coat material is a patented procedure called COLNET, developed by Colas in France (*20*). The COLNET procedure was reported to allow immediate trafficking after the spraying by employing a clean-bond cationic asphalt emulsion—called Colacid R 70 C—with very fast, controlled breaking agents (see Figure 7).

Figure 7. COLNET application in Paris.

2.5 Characterization of Tack Coat Application

2.5.1 Laboratory Characterization of Tack Coats

As illustrated in Figure 8 and under traffic loading, pavement interface failure can be attributed to both shear and tension distress modes. In general, two test modes—shear and tension—are often used in laboratory testing to characterize the interface bond strengths of tack coats. Many studies have reported using different performance-related test tools to assess the bonding characteristics of tack coats (*14, 15,* and *21–29*).

Sangiorgi et al. (*21*) conducted a laboratory assessment of bond conditions using the Leutner shear test with specimens cored from laboratory-compacted slabs. Two surfacing materials [0.4-in stone mastic asphalt (SMA) and 1.2-in hot rolled asphalt (HRA)], one binder course (0.8-in dense bitumen macadams), and one asphalt-stabilized base material (0.8-in dense bitumen macadams) were used to simulate surfacing over binder and binder over base interfaces. Three different interface treatments were considered to simulate actual conditions: (1) with tack coat emulsion, (2) contaminated by dirt and without tack coat emulsion, and (3) with tack coat emulsion and a thin film of dirt. Results indicated that the best bond strength was achieved with an interface treatment prepared using an emulsified tack coat, while the poorest bond conditions were observed from binder course/base interfaces. SMA and HRA surfacings showed similar results.

Uzan et al. (*22*) studied the interface adhesion properties of asphalt layers based on a laboratory shear test. Test specimens were prepared using a 0.512-in Marshall mixture. A 60-70 penetration binder was used both in the mixture design and for the tack coat application. Tests were conducted on two asphalt binders at two different test temperatures, five tack coat application rates, and five vertical pressures. They concluded that (1) shear resistance of the interface increased significantly with increasing vertical pressure and decreased with increasing temperature and (2) shear resistance peaked at an optimum tack coat application rate that is
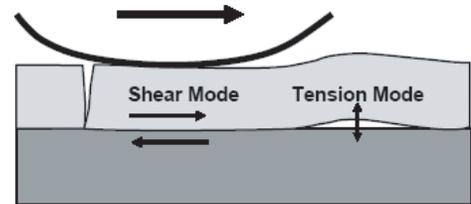
*Figure 8. Distress modes at pavement interface under service conditions (*30*).*

dependent on the test temperature. It was proposed that, for the 60-70 penetration binder used in this study, the optimum application rate at 25°C and 55°C were 0.11 gal/yd² and 0.22 gal/yd², respectively.

Hachiya and Sato (*14*) performed both simple shear tests and simple tension tests on samples cut from laboratory-compacted asphalt concrete blocks. Three cationic asphalt emulsions and three rubber-modified asphalt emulsions were used in the study. They concluded that, at low-temperature conditions (0°C), the rubber-modified asphalt emulsion (PK-HR2) provided the highest shear strength among the seven emulsions evaluated. At high temperatures (40°C), the rubber-modified asphalt emulsions (PK-R80, PK-HR1, and PK-HR2) were almost equally effective. The optimum application rate was 0.04 gal/yd².

In Italy, Canestrari and Santagata (*26*) utilized a direct shear test device named ASTRA (the Ancona Shear Testing Research and Analysis) to evaluate interface bond strength. Their objective was to determine the effects of different variables on the shear behavior of tack coat. They reported that (1) as the normal stress increased, dilatancy decreased (similar effects of reduced dilatancy were observed while decreasing the test temperature); (2) an increase of the applied normal stress caused an increase in the peak shear stress; (3) compared with the sample without tack coat, samples with emulsions as a bonding treatment at the interface exhibited higher peak shear stress at failure at all test temperatures and for each level of normal stress; and (4) an increase in shear resistance was observed as a function of decreasing test temperature.

In Switzerland, Raab and Partl (*30*) investigated the influence of tack coats on the interlayer adhesion of gyratory specimens in the laboratory using a Layer-Parallel Direct Shear (LPDS) test. Nearly 20 different types of tack coats were used to compare the behavior of specimens with and without tack coats. Two surface conditions (smooth and rough) and two compaction levels (240 and 50 gyrations) were considered to span actual conditions. The influence of moisture, water, and heat on tack coat mechanisms was investigated. Test results showed that all specimens with smooth surfaces sustained higher shear forces than those with rough surfaces because of the larger contact interface between the smooth surfaces. All types of tack coat yielded similar results. Using a certain tack coat, shear adhesion was improved up to 10% for a top-layer compaction at 240 gyrations, while such improvement was not observed for 50 gyrations. In addition, they showed that the use of tack coats led to better adhesion properties in case of a wet surface or oven heating of the specimens before the shear test.

Mohammad et al. (*23*) evaluated the effect of tack coat material types and application rates on bond strength using a direct shear device on the Superpave Shear Tester (SST).

Four emulsions—CRS-2P, SS-1, CSS-1, and SS-1h—and two asphalt binders—PG 64-22 and PG 76-22M—were evaluated as tack coat materials. Residual application rates were 0.00, 0.02, 0.05, 0.10, and 0.20 gal/yd². The study evaluated tack coats through the simple shear test at temperatures of 25°C and 54°C. Test results indicated that CRS-2P yielded the highest interface shear strength among the six tack coat materials evaluated and was identified as the best tack coat type in the study. The optimum application rate was 0.02 gal/yd². As expected, the mean interface shear strength increased with an increase in normal stress levels at both 25°C and 54°C. In addition, this study indicated that applying certain types of tack coat (e.g., CRS-2P) provided improved bond strength at the interface of the two asphalt concrete layers compared with that without tack coat application.

Sholar et al. (*15*) studied the effects of moisture, application rate, and aggregate interaction on bonding performance of tack coat between two pavement layers. A direct shear test apparatus and procedure were developed, and three field projects were constructed and examined over a period of time. Four diluted emulsion application rates were examined: no tack coat, 0.02 gal/yd², 0.06 gal/yd², and 0.08 gal/yd². Two diluted application rates were examined with water applied to the tacked surface to represent rainfall: 0.02 gal/yd² and 0.08 gal/yd². Roadway cores were obtained and tested to determine shear strength in the laboratory with the newly developed direct shear test. The test temperature was 25°C. Results indicated that (1) water applied to the surface of the tack coat significantly reduced the shear strength of the specimens, and, in long-term testing, specimens with water applied to them never developed a shear strength equivalent to the specimens that had remained dry; (2) varying tack coat application rates within the range of 0.02 to 0.08 gal/yd² had little effect on shear strengths; (3) the use of a tack coat to increase shear strength was less effective for coarse-graded mixtures than for fine-graded mixtures; (4) coarse-graded mixtures achieved significantly higher shear strength than did the fine-graded mixtures; and (5) a milled interface achieved the greatest shear strengths of surfaces tested.

Buchanan and Woods (*31*) conducted a comprehensive study of tack coat. Three emulsions (SS-1, CSS-1, and CRS-2) diluted and undiluted as well as one asphalt binder (PG 67-22) were used as tack coat materials. A prototype device (named ATacker™) was developed to evaluate the tensile and torque-shear strength of tack coat materials at various application temperatures, rates, dilutions, and set times. For non-diluted emulsions, tests were performed at application rates of 0.05, 0.09, and 0.13 gal/yd². The diluted emulsions contained one part water to each one part emulsion. SS-1 and CSS-1 emulsions were evaluated at temperatures of 24, 43, and 65°C, while CRS-1 emulsions were evaluated at

temperatures of 49, 63, and 77°C. PG 67-22 asphalt binder was evaluated at application rates of 0.04, 0.07 and 0.10 gal/yd² at an application temperature of 149°C. A laboratory bond interface strength device (LBISD), similar to the direct shear devices, was developed to assess interface shear strength and reaction index (the slope of load-displacement diagram) of laboratory-prepared specimens at 25°C. Tensile and torsional-shear test results showed that PG 67-22 yielded the highest overall strengths, while CRS-2 yielded the highest and CSS-1 the lowest strengths of the emulsions. Results indicated that application rate, tack coat type, and emulsion set time affect the tensile and torsional-shear strength.

West et al. (*32*) developed a new test method, the National Center for Asphalt Technology (NCAT) Bond Strength Test. The test results were used for the selection of the best type of tack coat material and optimum application rate. The project included both laboratory and field phases. For the laboratory work, the following were evaluated: two types of emulsion (CRS-2 and CSS-1) and a PG 64-22 asphalt binder; three residual application rates (0.02, 0.05, and 0.08 gal/yd²); and two mix types [0.75-in nominal minimal aggregate size (NMAS) coarse-graded and 0.19-in NMAS fine-graded]. Bond strengths were measured using normal Superpave mix-design specimens at three temperatures (10, 25, and 60°C) and three normal pressure levels (0, 10, and 20 psi). The main conclusions were as follows:

1. As the temperature increased, bond strength decreased significantly for all tack coat types, application rates, and mixture types at all normal pressure levels.
2. PG 64-22 exhibited higher bond strength than the two emulsions, especially for the fine-graded mixture tested at high temperature.
3. For the application rates studied, tack coats with low application rates generally provided high bond strength for the fine-graded mixture; however, for the coarse-graded mixture, bond strength did not change much when application rate varied.
4. At high temperature, when normal pressure increased, bond strength increased, while, at intermediate and low temperatures, bond strength was not sensitive to normal pressure.

In phase two of West et al. (*32*), seven field projects were performed to validate the bond strength test results of phase one using the same tack coat material. Tack coat was sprayed on milled or unmilled pavement surface before the HMA overlay was placed and compacted; three to five cores were obtained from each field section, and then bond strength was measured using NCAT Bond Strength Test. For projects using an emulsified asphalt tack coat material, the residual application rates were 0.03, 0.045, and 0.06 gal/yd². For projects using a pav-

ing grade binder as the tack coat material, the target application rates were 0.03, 0.05, and 0.07 gal/yd². Three distribution methods (hand wand sprayer, distributor truck spray bar, and Novachip™ spreader) were employed. A Novachip spreader featured a spray bar attached to the asphalt paver. The main observations of the field study were that

1. Milled HMA surfaces appear to significantly enhance bond strength with a subsequent asphalt pavement layer;
2. Despite the fact that paving-grade asphalt tack coats appeared superior to emulsified asphalt tack coats, the differences were not statistically significant; and
3. Bond strengths in sections that used the Novachip spreader for application of tack coat were significantly higher than similar sections that applied tack coat using a distributor truck.

Akhtarhusein et al. (*29*) evaluated the contribution of prime and tack coat to the interlayer properties in composite asphalt concrete pavement. The project had two main components: experimental and analytical. The experimental part involved determination and comparison of properties of different combinations of materials and test conditions. Some material characteristics were used in the stress-strain-displacement analysis of the analytical part. CMS-2 emulsion and PG 64-22 asphalt cement were used as tack coat, and three prime coats (EPR-1, CSS-1h, and EA-P) and three composite pavements (AC-AC, AC-PCC, and AC-CTB) were considered in this study. According to North Carolina DOT (NCDOT) specifications, the application rates for tack and prime coats are 0.06 gal/yd² and 0.24 gal/yd², respectively. Bond strength was determined on specimens from laboratory-fabricated composite slabs using simple shear test at constant height and axial ramp test. For composite pavements, AC-AC and AC-PCC, the shear tests were conducted at three temperatures—70, 104, and 140°C. For AC-CTB, the test temperatures were 40 and 60°C. Axial ramp tests were performed only for AC-AC composite, and test temperatures were 40 and 60°C. The main conclusions based on bond strength tests were as follows:

1. The absence of tack or prime coat severely hinders the development of bond between two layers, causing undue slippage.
2. For AC-AC composites, the strength of PG 64-22 tack coat was comparable with that of CMS-2.
3. For PCC-AC composites, the results confirmed the earlier observation that CMS-2 provided comparable adhesion to PG 64-22.
4. The bond between two similar surfaces (AC-AC) was stronger than the bond between two dissimilar surfaces (AC-PCC).

In the analytical portion, 3-D stress analysis software was developed to analyze the stress, strain, and displacement of composite pavement. The pavement was modeled primarily as a layered system of linear elastic materials with the possibility of treating the surface asphalt layer as a linear viscoelastic material. Anisotropy and temperature effects were incorporated. Besides vertical load, the development of a 3-D computer program takes into account the horizontal shear stresses induced on the pavement surface due to vehicle braking effects (acceleration and deceleration). Using the software, a detailed parametric study was conducted to investigate the effect of system parameters including layer thickness and stiffness on the stress-strain-displacement fields induced in the pavement. For the delaminating problem in layered pavements, it was found, through the analysis in this study, that higher loading leads to higher maximum interface shear stress and that increasing overlay thickness is an effective way to reduce maximum interface shear stress. Maximum interface shear stress can be found at the tire edges for a vehicle applying both normal and shear stresses to a pavement surface. After the maximum interface shear stress is available, it can be used to compare with the bond strength obtained through simple direct shearing testing so that an appropriate interface binder can be chosen.

The interface bond condition can seriously influence stress and strain distribution in a pavement structure. Hakim et al. (*27*) used falling weight deflectometer (FWD) deflection data to assess the bonding condition between bituminous layers. They reported that the FWD-backcalculated stiffness was lower than that obtained in the laboratory. This difference was attributed to the fact that the backcalculation procedure of modulus assumes full bonding between bituminous layers. To address this issue, the interface shear bond stiffness was considered in a modified FWD backcalculation method. Several studies derived interface constitutive models for characterizing the bonding condition of a pavement structure in a numerical simulation. Among them, the BISAR program considers the Goodman model for the surface and base interface (*33*). In this model, shear stress is proportional to the difference in the horizontal displacements of the bonding layers. Uzan et al. (*22*) reported that the interface reaction modulus used in the Goodman model is independent of the normal stresses at the interface. Crispino et al. (*34*) proposed the use of the Kelvin model to predict the viscous-elastic phenomenon of interlayer reaction under dynamic loading.

Romanoschi and Metcalf (*35*) reported that, in the direct shear test, the shear stress and displacement were proportional until the shear stress equaled the shear strength and the interface failed. Based on this observation, they proposed a constitutive model for the asphalt concrete layer

interface using three parameters: (1) the interface reaction modulus, which is the slope of the shear stress-displacement curves; (2) the maximum shear strength; and (3) the friction coefficient after failure. They concluded that the values of interface reaction modulus and shear strength were not affected by the normal stress for an interface with a tack coat. They were, however, affected for an interface without a tack coat. The study showed that the interface bond might also fail in fatigue and that the permanent shear displacement had a linear relationship with the number of load repetitions.

2.5.2 Interface Bond Strength and Tack Coat Film Test Devices

Table 3 describes interface bond strength and tack coat film test devices used in the laboratory and in the field to characterize tack coat application and performance (see Figure 9). In general, three test modes—shear, tension, and peel—have been used in both the laboratory and the field to characterize interface/bond strengths of tack coat materials.

2.6 Worldwide Survey

A worldwide survey on tack coat practices was conducted to better understand the current state of tack coat practices and to design a corresponding research experiment. The primary objective of the survey was to investigate the current tack coat state of practice related to types of materials used for tack coats, dilution rates of tack coat materials, residual application rates, determination of rate for different types of surfaces, methods used for tack coat distribution, and pavement failures related to tack coat application.

A questionnaire was developed to meet these objectives. The survey was organized into three main sections: tack coat materials, tack coat application methods, and characterization of tack coat application. In total, 27 questions were included in the questionnaire concerning all aspects of tack coat practices. All questions included in the survey are presented in Appendix A.
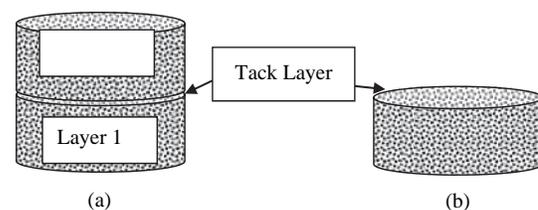
Figure 9. An interface bond strength test specimen (a) and a tack coat film test specimen (b).

Table 3. Available in situ and laboratory bonding tests.

Apparatus	Significance and Use	Procedure	Specimen	Test Results	Lab or in situ	Remark
1. Leutner Shear Test	The maximum shear load and corresponding displacement are measured to evaluate the bonding property of interface. The bonding property is used to determine the appropriateness of the material for use as tack coat.	A vertical shear load is applied to a double-layered specimen with a strain controlled mode at a constant rate of 2.0 in/min at 21.1°C until failure.	6.0-in-diameter specimen cored from laboratory-compacted composite (12 in × 12 in width by 2.8 in height)	(1) Maximum shear load (2) Corresponding maximum displacement	Lab	No normal load is applied
2. LTRC Direct Shear Test	Shear strength of the tack coat interlayer is measured to evaluate the bonding property of tack coat. The bonding property is used to determine the appropriateness of the material for use as tack coat.	A horizontal shear load is applied to a dual-layer specimen of asphalt concrete with a stress control mode at a constant rate of 50 lbs/min at a given temperature until the sample is separate. With a climate chamber, the temperature can be set in the range from −20 to 80°C.	(1) 5.9-in-diameter dual-layered specimen cored from the pavement or fabricated in laboratory (2) To be trimmed before testing to ensure the two ends are flat to fit the shear mold (3) Gap width between the shearing platens is around 1 in (25.4 mm)	Shear stress at failure	Lab	(1) Normal load is optional (2) Developed by Louisiana Transportation Research Center (LTRC)
3. TTI Torsional Shear Test	Plastic shear strength in torsion is measured to evaluate the shear resistance of the interface and the quality of the tack coat.	A twisting moment with constant rate of 2.9 E-04 radian/sec and a normal load is applied on the top of a double-layered cylinder specimen at a constant rate until failure.	(1) Dual-layered cylinder specimen with diameter of 6-in compacted in laboratory using two half-molds (2) Space between the two halves is 0.08 in (2 mm)	(1) Shear strength (2) Construct Mohr-Coulomb failure envelopes to get the cohesion and the tangent of internal friction angle	Lab	Developed by Texas Transportation Institute (TTI)
4. Florida Direct Shear Test	Bond strength of the tack coat interlayer is measured to evaluate the performance of tack coat.	A vertical shear load is applied to dual-layer asphalt concrete specimen with strain control mode at a constant rate of 2.0 in/min at 25°C until failure.	(1) Dual-layered cylinder specimen with diameter of 6-in (2) Samples can be roadway cores or laboratory-fabricated specimens and do not need to be trimmed to accommodate the device (3) Gap width between shear plates is 0.19 in	Shear strength at failure	Lab	(1) No normal loads can be applied during the test (2) Developed by Florida DOT
5. Virginia Shear Fatigue Test (36)	The number of shear loading cycles at failure is used to determine the optimum application rate of asphalt binder tack at interface between two layers.	Cyclic shear load [a 0.015-in deflection was applied to the specimen in the form of a 0.10-s half-sine wave, followed by a relaxation period of 0.9 s (the total cycle is 1s)] is applied at the geocomposite membrane interface of dual-layer sample composed of concrete and HMA specimens until failure at ambient temperature.	(1) Composite cylinder specimen with diameter of 3.7 is composed of concrete core, geocomposite membrane, HMA, and tack coat applied on the interface. (2) Concrete core is cored from laboratory-prepared concrete slab. (3) The upper HMA layer is gyratory-compacted on the top of concrete core after applied geocomposite membrane and tack coat.	(1) Maximum shear stress of each cycle (2) Maximum shear stress against the number of cycles of failure (3) Optimal tack coat application rate	Lab	Developed by Virginia Polytechnic Institute & State University and the Virginia Tech Transportation Institute
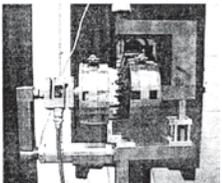
Table 3. (Continued).

Apparatus	Significance and Use	Procedure	Specimen	Test Results	Lab or in situ	Remark
6. **ASTRA Interface Shear Test**	Maximum interface shear stress is measured to evaluate the shear resistance property of interface. The shear resistance property is used to evaluate the tack coat properties.	Horizontal load is applied along the interface of dual-layered sample at constant rate until failure; meanwhile, a constant normal load is applied on top of the specimen.	(1) Dual-layered cylindrical specimen with diameter of 3.94 in (2) Laboratory-fabricated or extracted from pavement	Shear stress at failure	Lab	If carried out at different normal load, a Mohr-Coulomb failure envelope can be obtained.
7. **Layer-Parallel Direct Shear (LPDS)**	Nominal average shear stress and maximum shear stiffness are measured to determine the in-layer and interlayer shear properties of asphalt concrete layers. The in-layer shear properties are used to evaluate the quality of the mixture and the interlayer shear properties are used to evaluate the tack coat properties.	Vertical shear load is applied to a composite specimen with strain control mode at constant rate.	(1) Cylindrical composite specimen of 3.94-in diameter (2) Laboratory-fabricated sample and pavement core (3) The specimen needs to be glued	Tensile strength	Lab	(1) Shear-plane can be along interface or within the layers (2) Modified by EMPA, Swiss Federal Laboratory for Materials Testing and Research
8. **Switzerland Pull-Off Test**	Tension strength values are measured to evaluate the interlayer shear performance between different asphalt concrete layers. Shear performance is used to evaluate the quality of the tack coat and in comparison of various tack coat materials.	A tensile load is applied to asphalt concrete specimen composed of two layers at constant rate.	(1) Cylindrical composite specimen of 3.94-in diameter (2) Laboratory-fabricated sample and pavement core (3) The specimen needs to be glued	Tensile strength	Lab	Test is carried out according to German testing specification ZTV-SIB 90
9. **Loboratorio de Caminos de Barcelona Shear Test (LCB)**	Shear strength of the tack coat interlayer is measured to evaluate the bonding property of tack coat. The bonding property is used to determine the appropriateness of the material for use as tack coat.	The dual-layer specimen with tack coat interlay is used as a beam located over two supports and a vertical load is applied to the specimen at a constant deformation speed of 0.05 in/min in the middle of the two supports until failure.	(1) Cylindrical composite specimen of 3.94-in diameter and 7.0-in high (2) Laboratory-fabricated sample and/or pavement core	(1) Shear strength (2) Shear modulus and the specific cracking energy	Lab	(1) No normal load can be applied during this test (2) Developed by DOT, Technical University of Catalonia, Spain
10. **Wedge-Splitting Test**	Maximum horizontal force (F_{max}) and specific fracture energy (G_F) are determined to characterize the fracture-mechanical behavior of layer bonding. The fracture-mechanical behavior is used to determine the appropriateness of the material for use as tack coat.	A vertical load is applied through a wedge to a dual-layered specimen with a groove and starter notch along the interface at a constant rate until complete separation of the specimen.	(1) Cubic or cylindrical composite specimen with interface in the middle and a start notch in the interface (2) Laboratory-fabricated or cored or cut from pavement	(1) Maximum horizontal force (2) Specific fracture energy	Lab	Developed by Technical University, Austria
11. **Dynamic Interaction Test**	Interlayer reaction complex modulus KI^* is determined for the pavement structure analysis. The pavement structure analysis evaluates the capacity of the pavement and can be used to predict the remaining life of the pavement.	A sinusoidal shear force is applied to dual-layered specimen at particular temperature and given load frequency.	Cylindrical composite specimen of 3.94-in diameter, cored from laboratory-compacted twin layer slab or from pavement.	The norm of Interlayer reaction complex modulus KI^* and phase angle	Lab	Developed by University of Naples, Italy

Table 3. (Continued).

Apparatus	Significance and Use	Procedure	Specimen	Test Results	Lab or in situ	Remark
12. NCAT Shear Test	The interface shear strength of core samples is measured to evaluate the bonding property of pavement layers. The bonding property is used to determine the appropriateness of the material for use as tack coat.	A vertical shear force is applied to dual-layered specimens along the interface with strain control mode at constant rate until failure.	(1) Cylindrical composite specimen with 5.9 in (2) Height of the core above the interface being tested is greater than 3 in. The height of each layer should be greater than 1.97 in, less than 5.9 in.	Bond shear strength	Lab	Developed by National Center for Asphalt Technology (NCAT)
13. HasDell EBSTTM Emulsion Shear Test	The bond strength between two layers is measured to determine the appropriateness of the material for use as tack coat.	A shear force is applied along the interface until failure.	(1) Cylindrical composite specimen with 5.9 in diameter (2) 2.95-in x 2.95-in-square composite specimen	Bond shear strength	Lab or in situ	Marketed by R/H Specialty and Machine, Terre Haute, Indiana
14. Traction Test	Tensile strength of the tack coat interlayer is measured to evaluate the bonding property of tack coat. The bonding property is used to determine the appropriateness of the material for use as tack coat.	A tensile force is applied at constant rate of 54 lb/s to a cylindrical sample until failure	Cylindrical lab or field sample of 4-in diameter	Bond tensile strength	Lab or in situ	Developed by Ministère des Transports du Québec, Canada
15. The ATacker™ Test	Shear and/or tensile strength of tack coat material are measured to evaluate its bonding property. The bonding property is used to determine the appropriateness of the material for use as tack coat.	A pull and/or torque force is applied to detach the tack-coated plates or detach the contact plate and tack-coated pavement.	Tack-coated plates or attach plate to tack-coated pavement	Tensile strength and/or shear strength	Lab or in situ	Developed by Introtek, Inc.
16. UTEP Pull-Off Test	Tensile strength of tack coat material is measured to determine its bonding property. The bonding property is used to determine the appropriateness of the material for use as tack coat.	A torque force is applied to detach the tack-coated plates or detach the contact plate and tack-coated pavement	Tack-coated plates or attach plate to tack-coated pavement	Tensile stress at the point of failure	Lab or in situ	Developed by University of Texas at El Paso
17. UTEP Simple Pull-Off Test	Tensile strength of tack coat material is measured to determine its bonding property. The bonding property is used to determine the appropriateness of the material for use as tack coat.	A tensile force is applied directly to pull off the contact plate from the tack-coated surface.	Tack-coated plates or attach plate to tack-coated pavement	Tensile stress at failure	Lab or in situ	Developed by University of Texas at El Paso
18. Impulsive Hammer Test	The vertical dynamic response of pavement and fractal dimension (FD) are determined to evaluate the bond condition between asphalt layers in field. The bonding condition is used to determine the appropriateness of the material for use as tack coat.	An impulsive loading is applied with a hammer to the pavement surface at particular locations and given loading frequency.	Pavement in field	FD number	In situ	Under development at Nottingham University
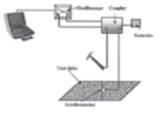
Table 3. (Continued).

Apparatus	Significance and Use	Procedure	Specimen	Test Results	Lab or in situ	Remark
19. Torque Bond Test	Torque force at failure is measured to evaluate the in-place bond effectiveness of wearing course system.	A torque force is applied to core sample from pavement with a torque wrench to failure.	Core sample of 3.94-in or 5.9-in diameter	Bond strength	In situ	Developed by Highway Agency, United Kingdom
20. In situ Shear Stiffness Test	The shear strength is measured to evaluate the shear properties of asphalt concrete pavements in the field. Shear properties of pavement relate to the performance of the pavement.	A rotational force is applied to the pavement through a test plate, meanwhile a normal weight is provided by the test equipment.	Pavement in field	Shear strength and shear modulus	In situ	Developed by Carleton University, Canada

Figure 10. State DOTs that responded to the survey.

In order to facilitate participation in the survey, the questionnaire was converted into a web-based format. Other forms such as PDF, MSWord, and hard-copy were used, based on request of the respondents. Questionnaires were sent to state DOTs, FHWA, the Asphalt Institute, field engineers, contractors, and selected highway agencies in Canada, Europe, and South Africa during the period of August 2005 through January 2006. Follow-up emails and phone calls were made to ensure the respondents understood the questions and completed all the questions on the questionnaire.

Remarkably, responses were received from 46 state DOTs; from Washington, D.C.; and from Canada (7 responses). Other countries that participated in the survey were Denmark, Finland, South Africa, and the Netherlands. Figure 10 indicates the state DOTs that responded to the survey.

SECTION 3

Experimental Program

3.1 Introduction

Based on the results of Task 1, a comprehensive experimental plan was designed to identify consistent, reliable, and practical methods for (1) evalutracating the bonding characteristics of tack coats; (2) selecting the tack coat material type and residual asphalt binder application rate required for optimum performance in new HMA pavement and HMA overlay construction, rehabilitation, and reconstruction; (3) calibrating application equipment; and (4) maintaining field quality control and quality assurance. Findings reported in Chapter 2 also identified a number of factors that were reported to influence interface bond strength including tack coat type, tack coat application rate, tack coat curing time, surface condition, and pavement temperature. Responses from the worldwide survey indicated that the residual application rates of emulsions typically vary from 0.02 to 0.08 gal/yd^2, depending on the type of pavement surface. As pavement temperature increases, laboratory bond strength significantly decreases for all tack coat types and application rates. The most common types of emulsions used for tack coats include slow-setting and rapid-setting grades of emulsions. In the United States, most states use slow-setting grades of emulsions. To this end, the experimental plan investigated the influence of a number of factors on the interface shear strength: HMA and PCC surface type and properties (e.g., texture, air voids content, and permeability), surface cleanliness, tack coat material type, and application rate and method.

The majority of the research activities conducted in this project were based on tack coat experiments conducted in a field environment. Field experiments were complemented with a number of laboratory experiments to assess the influence of variables such as laboratory compaction, rheological properties of tack coat materials, and test temperature. The experimental program was divided into experimental test matrices, which answered specific objectives of the experimental program. Since all experiments made use of full-scale test lanes, a description of the construction process and the test variables in the field experiment is presented in the following section.

3.2 Tack Coat and Overlay Construction at the Test Site

Table 4 presents the test matrix simulated in the LTRC PRF field experiment, which used conventional paving equipment and a computerized tack coat distributor truck. Four types of pavement surfaces and five tack coat materials were evaluated, but only one emulsion (SS-1h) was used on the new HMA surface, and two emulsion grades (SS-1h and SS-1) were used on the milled surface. Four residual application rates were selected including zero (no-tack). Effects of wet and dusty conditions during construction operations were simulated for the different surface types as part of the experimental program. To evaluate variation in the results, triplicate samples were tested for each condition; 375 samples were tested as part of the test matrix. Laboratory specimens (cores) were obtained from the pavement test sections.

3.2.1 HMA Pavement Surface Preparation

Figure 11 presents a plan view of the five test lanes constructed at the LTRC PRF. Each lane was a total of 215 ft in length and 12 ft in width. It is noted that each lane contained test and distributor truck access areas. Each test section had a length of 15 ft and a width of 6.5 ft. The lengths of the adjacent (access) areas were selected to ensure that the distributor truck could attain the required speed in order to achieve the correct tack coat application rate. All test lanes selected for this experiment contained a similar old HMA surface type. Surface texture values for each lane were measured using a laser type device (DYNATEST 5051 Mark III road surface profiler), according to *ASTM E 1845, Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth.* The

Table 4. Test factorial for field-prepared samples.

Variables*	Content	Levels
Pavement surface type	Old HMA, New HMA, PCC, Milled HMA	4
Tack coat material	SS-1h, SS-1, CRS-1, Trackless, PG 64-22	5
Residual application rate	0- (No-Tack), 0.031, 0.062, 0.155-gal/yd^2	4
Wet (rain) condition	Wet, Dry	2
Dusty condition	Dusty, Clean	2
Test temperature˜	25°C	1
Confinement pressure (psi)	0, 20	2
Tack coat coverage	50%, 100%	2
Number of replicates	3	3
Total Number of Samples		**474**

*Some variables were partially evaluated according to the test factorial; ˜ test temperature was varied in the sub-matrix that evaluated the effect of temperature on ISS.

roughness value for Lane 1, Lane 2, and Lane 3 were 0.042, 0.043, and 0.043 in, respectively. Lane 4 was not utilized for the experiment because the surface texture was different from that of Lanes 1, 2, 3, and 5. Figure 12 presents the measurements and markings of the grid on the actual test lanes, which correspond to the layout presented in Figure 11. The markings were used to assist the tack coat distributor truck in determining the correct location for each type of material and the corresponding application rate.

3.2.2 Dusty and Wet Conditions Simulation

The effects of dusty or wet (rainfall) conditions of the existing pavement surface were investigated. In order to simulate dusty conditions, a silty-clay-type soil, classified as A4 based on the AASHTO soil classification, was reasonably uniformly applied at a rate of 0.070 lb/ft^2 onto the old HMA surface prior to tack coat application (see Figure 13a and b). Wet condition was simulated by uniformly spraying water at a rate of 0.06 gal/yd^2 on tacked surfaces and prior to placement of the HMA mixture (see Figure 13c and d). Wet condition was considered only for the SS-1h tack coat due to the limited number of test lanes that could be constructed at the PRF.

3.2.3 Tack Coat Application

Prior to the day of tack coat application, several calibration trials were performed over a 3-month period for the computerized distributor truck to ensure that the selected application rates might be installed successfully given the restrictions at the site. During these trials, the application rate was found to be in error as much as 40%. Both the owner of the truck and the manufacturer of the equipment worked to identify

the sources of the problems and correct them. Several repair and maintenance actions were completed on the distributor truck prior to tack coat application.

Application of tack coat materials was performed directly after testing and preparation of the existing surface was completed. Tack materials were SS-1, SS-1h, CRS-1, PG 64-22, and trackless (NTSS-1HM). The truck speed and spray tip used for each tack coat material along with the corresponding application rate are provided in Figure 14. As indicated in this figure, 10 passes by the distributor truck were made. A pass is completed when the distributor truck has traversed a given lane. An Etnyre computerized tack coat distributor truck Model 2000 was used to apply the tack coat materials. The truck had a heated tank for holding tack coat materials at the desired application temperature. While the trackless tack coat was applied at 82°C, the SS-1h and CRS-1 tack coat materials were applied at 68°C. Tack coats were applied in the undiluted state. Mounted on the back of the truck, a spray bar fitted with nozzles distributed tack coat material at the specified application rate. The total width of the spray bar was extended to 13 ft in order to provide full coverage of a single lane. Application rate was adjusted by altering the truck speed and nozzle type and size.

Distribution of tack coat materials was coordinated so that the wheels of the distributor truck never came in contact with the tack coat material (see Figure 15). The application of SS-1h for 100% and 50% coverage were conducted in the same manner. For application of the residual rate of 0.031 gal/yd^2, the distributor truck drove the entire span of Lanes 1 and 2 at the specified speed to deposit the tack coat at the end of each lane. The residual application rate of 0.062 gal/yd^2 was applied at the specified speed in the same manner as the previous application rate. The residual application rate of 0.155 gal/yd^2 was
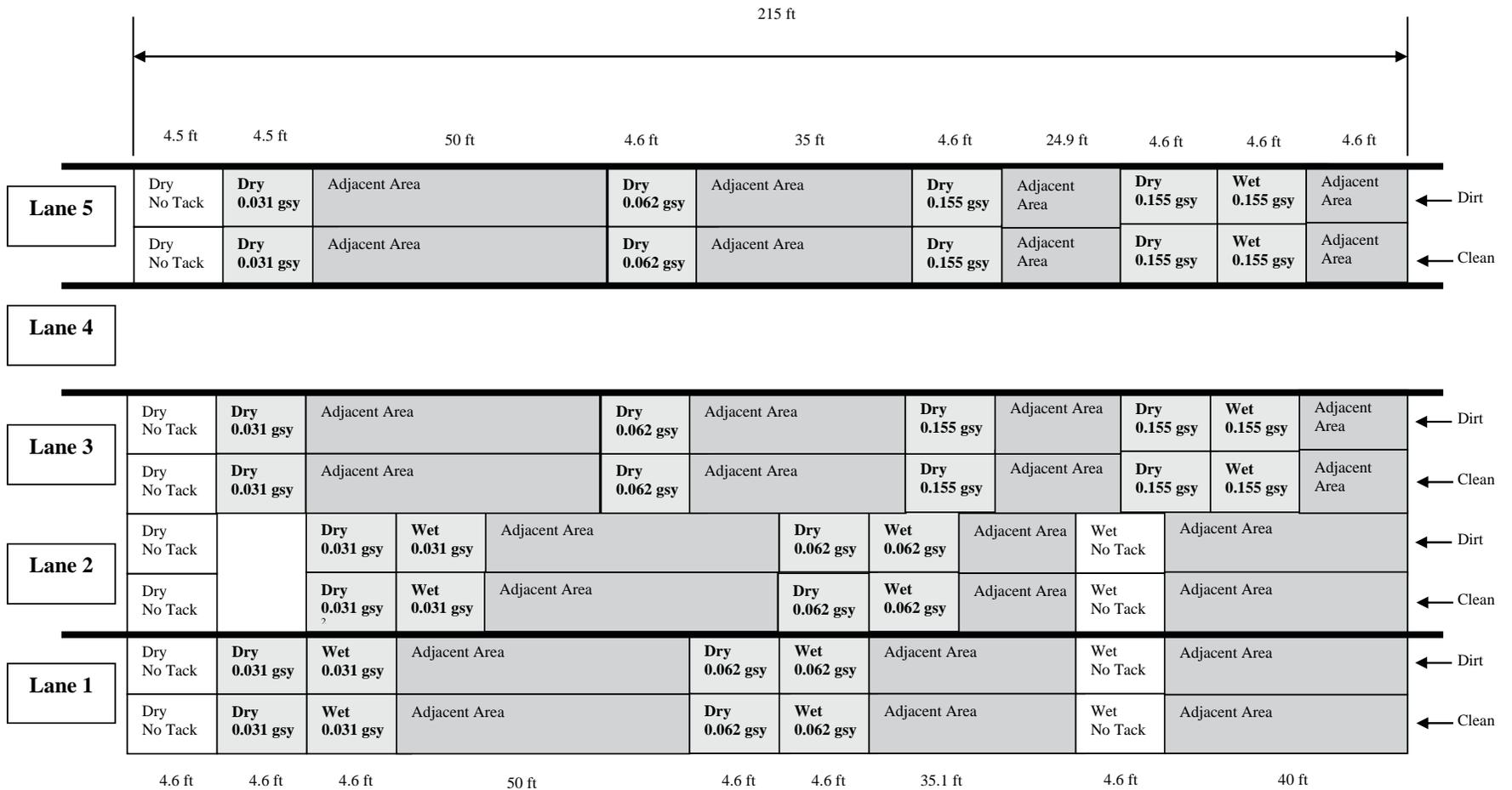
Figure 11. *Layout of test lanes in the field experiment.*

Figure 12. Preparation of test lanes for tack coat application.

applied at the end of Lanes 3 and 5 for 100% and 50% coverage, respectively. Figure 16 illustrates 50% coverage of SS-1h for each application rate compared with a typical section with 100% coverage. Both trackless and CRS-1 emulsions were applied to Lanes 3 and 5 in a similar manner at three application rates (0.031, 0.062, and 0.155 gal/yd^2).

3.2.4 Overlay Construction

A 12.5-mm NMAS HMA mixture was placed on top of the tacked surfaces at a thickness of approximately 3 in. A material transfer device was used to transfer the mixture from the haul trucks to the hopper of the paver (see Figure 17b) in
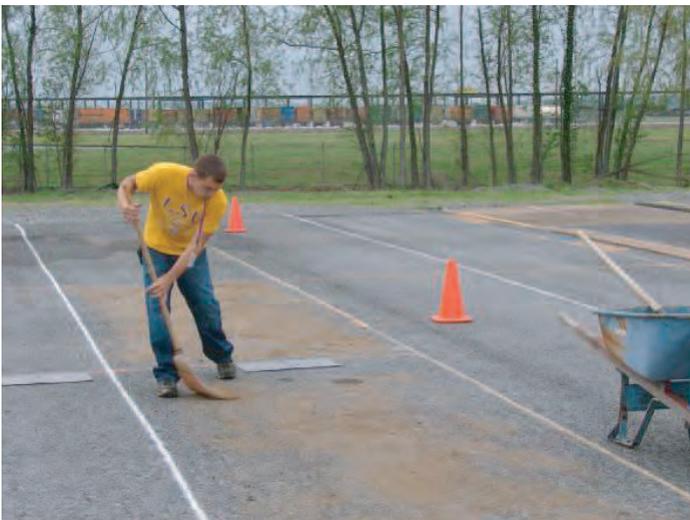
(a) Dust Application

(b) Tack Coat Application on Dusty Surface

(c) Water Spraying Using a Hose

(d) Overlaying on Wet Surface

Figure 13. Simulation of dusty and wet conditions.

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LTRC Tack Application Schedule for April 2, 2008

SS-1H	62% Residual	
Trackless	55% Residual	
CRS-1	63% Residual	

Spray Tips Used

Etnyre	3351008	S36-4 V Slot(small)
Etnyre	3352205	Multi-Material V Slot(big)

Spray Bar Width 13 ft

Pass	Lane	Product	Coverage	Residual Rate	Application Rate	Truck Speed(fpm)	Spray Tip
1	2	SS-1H	50%	0.031	0.050	350	3352205
2	2	SS-1H	50%	0.062	0.100	220	3352205
3	5	SS-1H	50%	0.155	0.250	150	3352205
4	1	SS-1H	100%	0.031	0.050	1150	3351008
5	1	SS-1H	100%	0.062	0.100	580	3351008
6	3	SS-1H	100%	0.155	0.250	260	3351008
7	3	Trackless	100%	0.031	0.055	1050	3351008
8a	3	Trackless	100%	0.155	0.280	210	3351008
8b	3	Trackless	100%	0.062	0.115	500	3351008
9	5	CRS-1	100%	0.031	0.050	1150	3351008
10a	5	CRS-1	100%	0.155	0.245	280	3351008
10b	5	CRS-1	100%	0.062	0.100	590	3351008

Figure 14. Spraying process plan for four lanes at the test site.

Figure 15. Distributor truck spray application at 50% coverage.

(a)   (b)

Figure 16. Tack coat application (a) 0.155 gal/yd² with 100% coverage and (b) 0.031 gal/yd² with 50% coverage (SS-1h).

order to eliminate construction traffic on tacked surfaces. Subsequent to completion of HMA overlay placement, each lane was marked based on previously documented reference points identifying the various test sections within each lane (see Figure 17f).

3.2.5 Quality Testing of Tack Coat Application

The calibration of the distributor truck was a lengthy process in this project and required multiple calibration runs to ensure the accuracy and uniformity of tack coat application. This difficulty highlights the importance of regularly checking the calibration of the distributor in practice. The procedure outlined in Test Method A of *ASTM D 2995, Standard Practice for Estimating Application Rate of Bituminous Distributors,* was followed. The surface of each pavement was initially cleaned. Square (1 ft by 1 ft) textile pads were attached to the surface of the pavement using a two-sided adhesive tape. The geometrical layout of the pads is illustrated in Figure 18. Two pads were aligned in the transverse direction relative to the lane. At least 2 ft were given to accommodate the space needed for the wheels of the truck during the spray process. Once the pads were positioned correctly, the tack coat distributor truck applied the material to the section.

For emulsion tack coats, the pads were allowed to remain in position for 3 hours to ensure that all water had evaporated. After this period, the weight of each pad was measured. The final weight, minus the initial weight of the pads with no tack, represented the residual asphalt cement and was used in the computation of the residual application rate. Table 5 presents the results of these measurements for the tack coat

distribution conducted at the test site. For SS-1h with 100% coverage, trackless, and CRS-1, target application rates of 0.062- and 0.155- gal/yd² were achieved with relatively low errors, although errors for trackless and SS-1h exceeded the 10% error limitation specified by ASTM 2995D. For the 0.031 gal/yd² target application rate, errors were relatively higher than those of other application rates, but it is noted that coefficient of variation (COV) values for 0.031 gal/yd² rate were relatively low and showed high consistency. In summary, it is noted that the measured application rates were slightly different than the target values; however, the measured rates met the objectives of the test matrix to simulate low, medium, and high levels. On the other hand, for SS-1h with 50% coverage, it was observed that high errors occurred at all application rates. Figure 19 shows a comparison of 50% to 100% coverage from two cores extracted from the test facility.

3.2.6 Specimen Coring and Conditioning

A minimum of six test specimens were obtained from each test section using a Simco® 255 Pavement Test Core Drill. The core barrel was positioned over the area in which a sample was to be extracted, and water was allowed to flow down the inside of the barrel in order to reduce friction (see Figure 20). The core barrel was then driven to the bottommost layer in order to remove the sample undisturbed. Samples were cored all the way through to avoid pre-stressing of the samples. The sample was then removed from the core barrel, labeled, and packaged for transportation. It is noted that a manual corer (i.e., Milwaukee Dynodrill B-1000) was used for weaker samples that required smaller amounts of torque.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 17. Overlay construction at the test site.
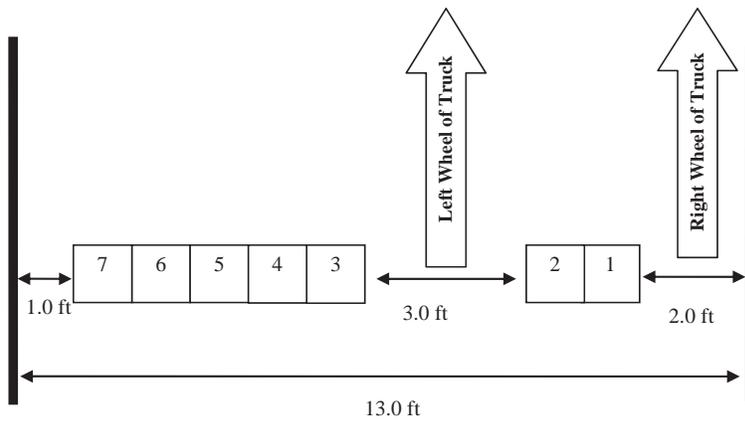
Figure 18. Tack coat rate measurement pad layout for each section.

Table 5. Tack coat distribution test results at the PRF site.

| Tack Coat | Target Residual Application Rate (gal/yd^2) | Measured Residual Application Rate | | | |
		Average (gal/yd^2)	Standard Deviation (gal/yd^2)	COV	Error (%)
SS-1h 50 %	0.031	0.062	0.007	11.8	102.3
	0.062	0.071	0.009	10.8	16.0
	0.155	0.166	0.099	59.6	45.8
SS-1h 100 %	0.031	0.044	0.004	8.8	42.0
	0.062	0.073	0.007	9.1	19.6
	0.155	0.139	0.022	16.6	10.8
Trackless*	0.031	0.040	0.002	6.1	28.7
	0.062	0.068	0.004	7.7	10.8
	0.155	0.177	0.011	5.9	14.9
CRS-1*	0.031	0.035	0.004	15.3	20.8
	0.062	0.062	0.004	5.7	3.9
	0.155	0.152	0.007	4.5	3.6

* Trackless and CRS-1 were distributed with 100% coverage.
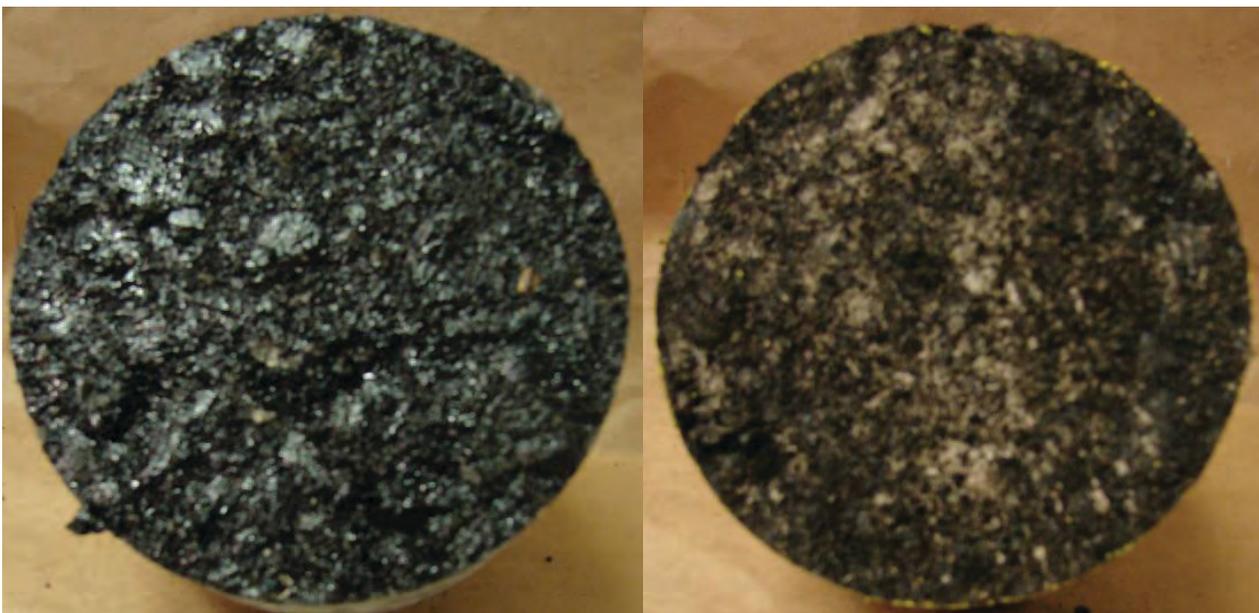
(a) 100% Coverage Surface   (b) 50% Coverage Surface

Figure 19. Typical tack coat surface coverage on old HMA surface (0.155 gal/yd² residual application rate).

<div align="center">(a)</div> <div align="center">(b)</div>

Figure 20. Description of the coring procedure.

Prior to testing, cored samples were cut to a height of 6.0 in, avoiding disturbances to the interface and the top layer. Because water was used as a coring lubricant, the samples were placed in an oven at 40°C to dry for a minimum of 24 hours. The dried samples were placed in a conditioning chamber at 25°C for a minimum of 4 hours. This conditioning period was adequate as determined through experimentation. A hole was drilled through a dummy core to its interface in which a temperature probe was inserted. The core was heated to 40°C and then placed inside the conditioning chamber at 25°C to determine how long it would take the core to reach 40°C at the center. After conditioning the sample for a minimum of 4 hours, the sample was ready for interface shear strength testing.

3.3 Experiment Plan I: Development of a Test Device to Evaluate the Quality of the Bond Strength of Tack Coat Spray Application in the Field

The objective of Experiment I was to develop a consistent and reliable test method to evaluate the bonding characteristics of tack coat spray application in the field. Developing a consistent and reliable test method to evaluate the bonding characteristics of tack coat in the field was achieved in three main phases. In the first phase, a comprehensive review of current interface bond strength test devices was conducted (see Task 1). After careful evaluation of these test methods, a test method known as the ATacker™, was selected for further evaluation and possible improvement (*37*). After several modifications were introduced to the original ATacker test setup,

a new pull-off test device—the Louisiana Tack Coat Quality Tester (LTCQT)—was developed. Details of the development of this test device are presented in Section 4 of this report. The efficiency of this device was evaluated in the field, and a consistent and reliable test procedure was developed. Subsequent to the application of the tack coat materials described in the previous section, tack coat material quality testing was conducted using the LTCQT device. The sections tested were those of high cleanliness with no water present. The materials tested for tack coat quality were SS-1h, CRS-1, and trackless. The sections for which tack coat quality was measured are presented in Table 6. A minimum of three locations were tested for each section.

Table 6. LTCQT test sections.

Material	Residual Application Rate (gal/yd^2)
SS-1h 50 % Coverage	0.031
	0.155
SS-1h 100 % Coverage	0.031
	0.062
	0.155
Trackless	0.031
	0.062
	0.155
CRS-1	0.031
	0.062
	0.155

3.4 Experiment Plan II: Rheological Properties and Superpave PG of Tack Coat Materials

Performance-graded and softening point tests were performed on the asphalt binder residues according to *ASTM D 6373, Standard Specification for Performance Graded Asphalt Binder,* and *ASTM D 36, Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus)* respectively (*38*). All asphalt binder residues were obtained according to *AASHTO D 244, Residue by Evaporation.* While this study assumed the applicability of the binder-aging protocol for tack coat emulsions, validation of this assumption was necessary in order to understand the aging mechanism for emulsified tack coats.

To establish sound correlations between the rheological properties of emulsified tack coat materials and the shear strength at the interface, two tack coat materials (trackless and CRS-1) were tested using the dynamic shear rheometer at temperatures ranging from −10 to 60°C with a 10°C interval. This was the same temperature range used in interface shear testing. Testing was conducted using an AR2000 rheometer that was set up to work in the dynamic shear mode. Two sample sizes were used, depending on the testing temperature: a sample with a 25-mm diameter and a thickness of 1 mm was used at high temperatures (from 40 to 60°C) and a sample with an 8-mm diameter and a thickness of 2 mm was used at low and intermediate temperatures (from −0 to 30°C).

3.5 Experiment Plan III: Development of a Laboratory Test Procedure to Measure the Interface Bond Strength

A direct shear device was developed in Experiment III for the characterization of interface shear strength of cylindrical specimens in the laboratory. The device is referred to as the Louisiana Interlayer Shear Strength Tester (LISST). Details of the development and evaluation of this device are presented in Section 5. The LISST device consists of two main parts: a shearing frame and a reaction frame (see Figure 21). Only the shearing frame is allowed to move while the reaction frame is stationary. A cylindrical specimen is placed inside the shearing and reaction frames and is locked in place with collars. The shearing frame is then loaded. As the vertical load is gradually increased, shear failure occurs at the interface.

The LISST device was evaluated in a wide range of test conditions (see Table 4). Test specimens were obtained from pavement test sections described in the previous section. As shown in Table 4, direct shear tests were performed at 25°C under two confinement conditions, 0- and 20-psi. To assess
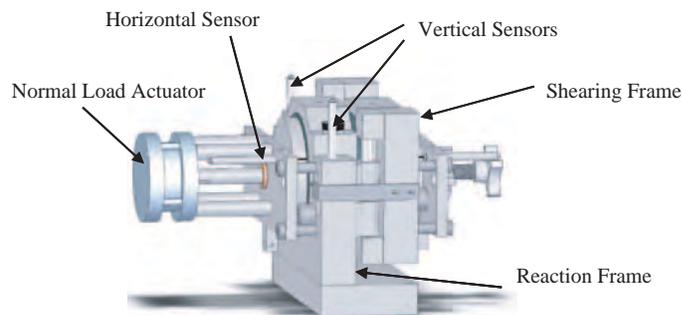
Figure 21. General description of the LISST device.

the variation in the results, triplicate samples were tested. A number of experiments were conducted in order to evaluate the ruggedness and reliability of the LISST. Experiments were also conducted comparing the results from this device with those of the Superpave Shear Tester.

3.6 Experiment Plan IV: Effects of Test Temperature and Its Relationship with Tack Coat Rheology

Experiment IV was designed to test the effects of temperature, emulsified tack coat type, and residual application rate on interface shear bond strength (see Table 7). The factorial matrix consisted of 8 temperatures, 2 emulsified tack coats, and 3 residual application rates resulting in a total of 48 test conditions. Each test condition had two replicates to minimize variation due to experimental errors, resulting in a total of 96 interface shear tests. Test temperatures ranged from −10 to 60°C with a 10°C interval. Three residual application rates were considered: 0.031, 0.062, and 0.155 gal/yd^2. The experimental program was designed to evaluate performance of tack coats between two HMA layers, a new overlay on an existing pavement. Tack coat was uniformly distributed with 100% coverage. The old HMA surface condition was dry and clean before distributing tack coat in the field. Two emulsified tack coats were tested in this part of the study, a cationic rapid setting (CRS-1) and a trackless tack coat, which consists of a polymer-modified emulsion with a hard base asphalt cement.

The test procedure was as follows. The LISST was used to measure ISS at different temperatures. The loading system was a universal testing machine (manufactured by Cox & Sons Company). This machine had a temperature chamber that can control the test temperature from −20°C to 80°C. The maximum load capacity of the actuator was 25,000 lb. Temperature conditioning and interface shear testing were conducted inside the test chamber. Figure 22 illustrates the followed test procedure. As shown in Figure 22a, two replicate samples were

Table 7. Test factorial to evaluate effects of test temperatures.

Variables	Contents	Levels
Emulsified Tack Coat	Trackless, CRS-1	2
Residual Application Rate	0.031, 0.062, and 0.155 gal/yd^2	3
Temperature	–10, 0, 10, 20, 30, 40, 50, 60°C	8
Replicates	Two replicates at each temperature	2
Total Number of Tested Specimens		**96**

(a) Sample conditioning (4 hours)

(b) Assemblage of sample and LISST device

(c) Stabilization of test temperature (30 min.)
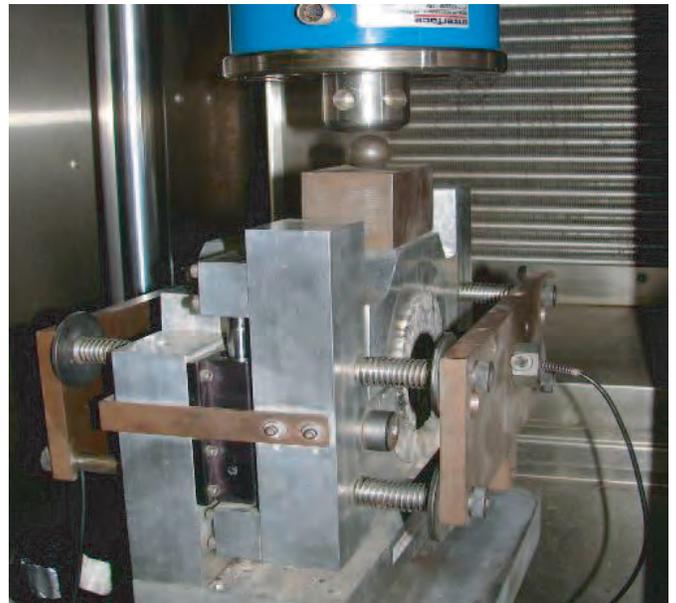
(d) Application of shear loading

Figure 22. Illustrations of the test procedure for interface shear testing.

conditioned for at least 4 hours at the test temperature. Samples were then placed in the testing chamber while attempting to minimize temperature loss (Figure 22b) and were then conditioned for 30 minutes at the target temperature to compensate for temperature loss during specimen placement in the LISST device (Figure 22c). Finally, shear load was applied by the shear loading frame at a loading rate of 2.54 mm/sec until failure, as shown in Figure 22d.

3.7 Experiment Plan V: Effects of Pavement Surface Type and Sample Preparation Method

Experiment V was designed to measure and compare the interface shear strength for different surface types and sample preparation methods. For this purpose, samples were prepared to simulate different field conditions and were tested using the LISST device. Table 8 presents the field test matrix. Four types of field pavement surfaces and five tack coat materials were evaluated. However, only one emulsion (SS-1h) was used on the new HMA surface and two emulsion grades (SS-1h and SS-1) were used on the milled surface. Four residual application rates were selected including, zero (no tack) application rate. The effects of rainy and dusty conditions during construction operations were simulated for the different surface types as part of this experiment. Test temperature and the tack coat coverage rate were kept constant at 25°C and 100% coverage, respectively. To assess variation in the results, triplicate samples were tested for each condition; 375 samples were tested as part of the test matrix.

To assess the influence of sample preparation methods, laboratory-fabricated specimens were prepared using five tack coat materials—SS-1h, trackless, locally-used trackless (AUT), PG 64-22, and CRS-1—as tack coat was applied at

four residual application rates—0 (No Tack), 0.031, 0.062, 0.155 gal/yd². Field-cored specimens for tack coat applied between new and new HMA surfaces were available for SS-1h tack coat. Sample sizes and other test conditions were the same as field-cored sample testing. Laboratory-fabricated specimens consisted of two layers, with a tack coat at the interface of these layers. The diameter of each specimen was 4.0 in. The bottom half of each specimen was prepared by compacting the mixture to a height of 2.0 in at 150°C using the Superpave Gyratory Compactor (SGC). The compacted specimen was then allowed to cool to room temperature, and its air void content was measured. Compacted bottom halves having an air voids content of 6 ±1 percent were prepared. The asphalt materials used as tack coat were then heated to the specified application temperature. The calculated amount of the preheated tack coat was then uniformly applied on the bottom half of the specimen using a brush. Once application of the tack coat was complete, it was allowed to cool to room temperature and the top half of the sample was compacted by placing the bottom half in the SGC mold and compacting loose mix on top of the tack-coated bottom half.

3.8 Experiment Plan VI: Effects of Surface Texture and Permeability on Interface Shear Strength

The objective of this experiment was to evaluate the effects of surface texture and permeability on tack coat interface shear strength using laboratory-prepared specimens. Three mixture types with different texture and permeability compositions (see Table 9) were considered to use as the layer on which the tack coat was applied. Table 10 presents the mix designs adopted in the preparation of the three mix types.

Table 8. Test factorial for field-prepared samples.

Variables*	Content	Levels
Pavement surface type	Old HMA, new HMA, grooved PCC, milled HMA	4
Tack coat material	SS-1h, SS-1, CRS-1, Trackless, PG 64-22	5
Residual application rate	0- (No-Tack), 0.031-, 0.062-, 0.155-gal/yd²	4
Wetness (Rain) condition	Wet, Dry	2
Cleanliness condition	Dusty, Clean	2
Test temperature	25°C	1
Confinement pressure (psi)	0, 20	2
Tack coat coverage	50%, 100%	2
Number of replicates	3	3
Total Number of Samples		474

* Some variables were partially evaluated according to the test factorial.

Table 9. Test matrix to evaluate effects of texture and permeability on SS-1 tack coat.

Mixture Type	Texture Roughness	Permeability	Tack Coat	Residual Application Rate (gsy)	No. of Tested Specimens
Sand	Low	Low	SS-1	0.000	3
				0.031	3
				0.062	3
				0.155	3
SMA	High	Low	SS-1	0.000	3
				0.031	3
				0.062	3
				0.155	3
Open-graded friction course (OGFC)	High	High	SS-1	0.000	3
				0.031	3
				0.062	3
				0.155	3

Table 10. Job mix formula.

Mixture Type	Sand	SMA	OGFC
Binder Type	PG 70-22	PG 76-22	PG 76-22
Binder Content (%)	6.0	6.2	6.5
Air Voids (%)	13.2	3.5	21.2
Aggregate Gradation			
Sieve Size	% Passing		
37.5 mm (1½ in)	100	100	100
25 mm (1 in)	100	100	100
19 mm (¾ in)	100	100	100
12.5 mm (½ in)	100	93	95
9.5 mm (⅜ in)	100	66	67
4.75 mm (No.4)	97	29	17
2.36 mm (No.8)	90	23	8
1.18 mm (No.16)	81	19	6
0.6 mm (No.30)	66	18	5
0.3 mm (No.50)	25	15	5
0.15 mm (No.100)	8	12	4
0.075 mm (No.200)	4	8.8	3

Table 11. Texture test results for selected mixtures.

Mixture Type	Sand Mix	SMA	OGFC
Texture Category	Low	High	High
Texture (in)	0.019	0.039	0.071
COV (%)	1.1	0.4	2.5

Table 12. Permeability test results for selected mixtures.

Mixture Type	Sand Mix	SMA	OGFC
Permeability Category	Low	Low	High
Permeability (ft/day)	2.2	1.4	408
	2.8	1.3	441
	2.8	1.9	401
Average (ft/day)	2.6	1.8	417
Standard Deviation (ft/day)	0.3	1.5	21.1
COV (%)	13.1	21.0	5.1

These mixtures were used to fabricate the bottom layer of the specimens in the laboratory for interface shear strength testing. The top layer of the test specimens used the mix design adopted for preparation of the HMA overlay at the PRF site. A complete specimen consisted of two layers, top and bottom, with a tack coat placed at the interface of the two layers. Each layer was compacted to achieve a 6 ±1 percent air void.

The diameter of each specimen was 6.0 in. The bottom half of each specimen was prepared by compacting the mixture to a height of 2.2 in at 165°C using the SGC. Each compacted bottom layer was allowed to cool to room temperature, then its air voids content was measured. The calculated amount of preheated SS-1 tack coat was then applied on the bottom half of the sample. The tack coat was allowed to cure. Once the application and curing of the tack coat was completed, the top half of the specimen was applied by placing the bottom half in the SGC mold and compacting the prescribed mixture on top of the tack coated bottom half. Four-inch-diameter specimens were then cored from the SGC-compacted samples, and the interface shear strength was measured at 25°C.

Texture and permeability of the selected three mixtures (see Table 9) were quantitatively measured. Mixture surface texture measurements were performed according to *ASTM E 965, Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique,* which is known as the sand patch test method. Permeability tests were conducted according to *ASTM PS-129-01, Measurement of Permeability of Bituminous Paving Mixtures using*

a Flexible Wall Permeameter. All texture and permeability test results are presented in Table 11 and Table 12.

3.9 Theoretical Investigation

The effects of tack coat interface shear bond characteristics, as measured by the LISST, on pavement responses at the interface were investigated using a 2-D FE approach. Six pavement structures typically used in Louisiana were simulated using the commercial FE software, ABAQUS Version 6.9-1 (see Figure 23). Structure A consisted of a 1.5-in HMA overlay on top of a 2.0-in old HMA layer and a 4.0-in crushed stone base layer. Structure B consisted of a 2.0-in HMA overlay on top of a 3.0-in old HMA layer and an 8.0-in crushed stone base course. Structure C consisted of a 2.0-in HMA overlay on top of a 6.0-in old HMA layer and a 12-in crushed stone base layer. Structure D consisted of a 2.0-in HMA overlay on top of a 4.0-in old HMA layer and a 12.0-in crushed stone base course. Structure E consisted of a 2.0-in HMA overlay on top of a 2.0-in old HMA layer and a 12.0-in crushed stone base course. Structure F consisted of a 2.0-in HMA overlay on top of an 8.0-in old HMA layer and a 12.0-in crushed stone base course. The six structures are constructed on the same subgrade material, A-7-6 clayey soil.

For the FE analyses, the tacked interface is located between the HMA overlay and the old HMA layer. Table 13 presents the assumed mechanical properties for the pavement materials. As shown in the table, the base and subgrade materials were assumed to respond elastically to the load. On the other hand, the HMA overlay and old HMA layer were simulated as a viscoelastic material using a Generalized Kelvin model. As part of the viscoelastic definition of asphaltic materials, the initial instantaneous moduli, presented in Table 13, were used to define the elastic component of HMA.

Elastic element foundations were used to simulate the support provided to the pavement structure by the subgrade. These elements, which act as nonlinear springs to the ground, provide a simple way of including the stiffness effects of the subgrade without fixation of nodes at the bottom of the model. A dual-tire assembly applying a load of 9,000 lbf on the pavement structure over an equivalent rectangular area was simulated with a uniform pressure of 105 psi and for a total loading time of 0.1 sec. The surface interactions between the old HMA and the base layer and between the base and subgrade layers were assumed to be a friction-type contact (Mohr–Coulomb theory). Limited sliding was also allowed between the aggregate layers. This formulation assumes that a slave node will interact with the same local area of the master surface throughout the analysis.

The interface conditions between the HMA overlay and the old HMA layer was simulated according to the constitutive model adopted by Romanoschi and Metcalf (*35*) for asphalt pavements. In this model, the stiffness penalty
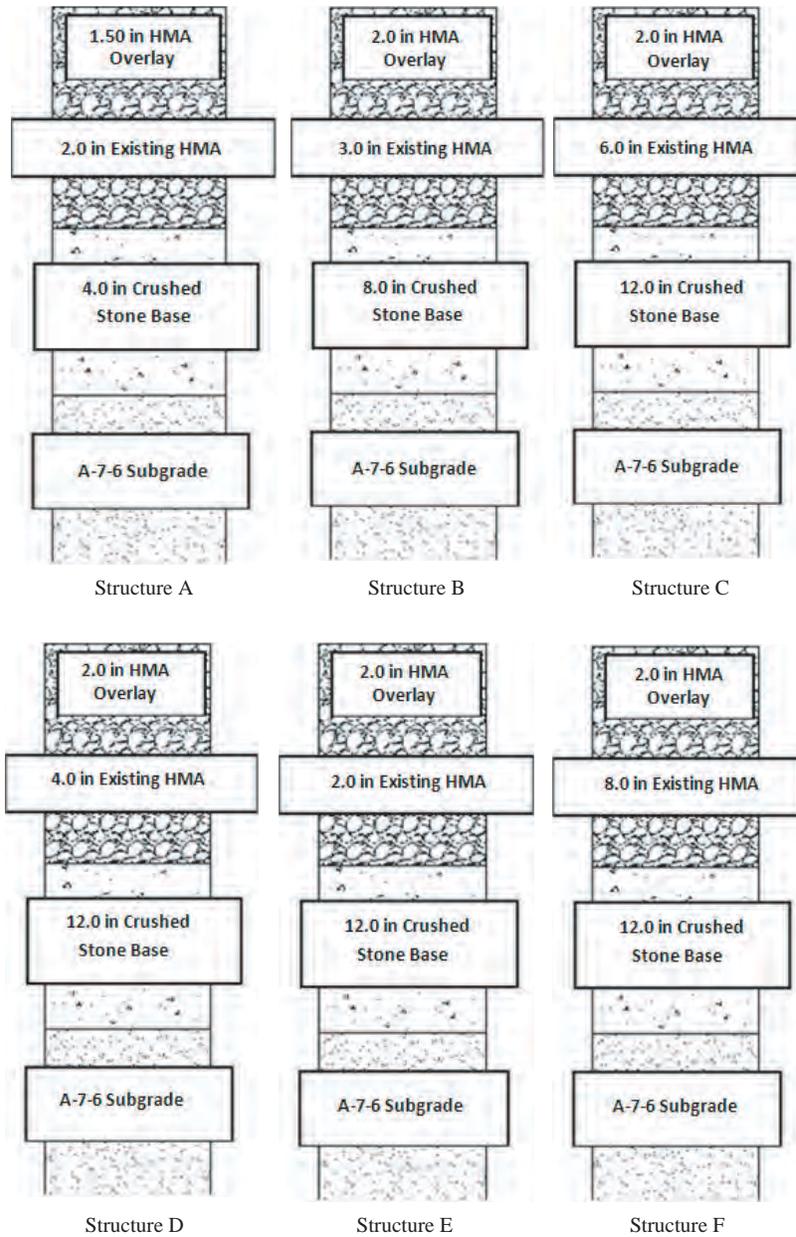
Figure 23. Pavement structures simulated in the FE analysis.

Table 13. Mechanical properties of pavement materials in the FE analysis.

Material Description	Constitutive Behavior	Elastic Modulus (psi)	Poisson's ratio
HMA Overlay	Viscoelastic	650,000	0.25
Old HMA	Viscoelastic	500,000	0.25
Base	Elastic	40,000	0.30
Subgrade	Elastic	6,000	0.35
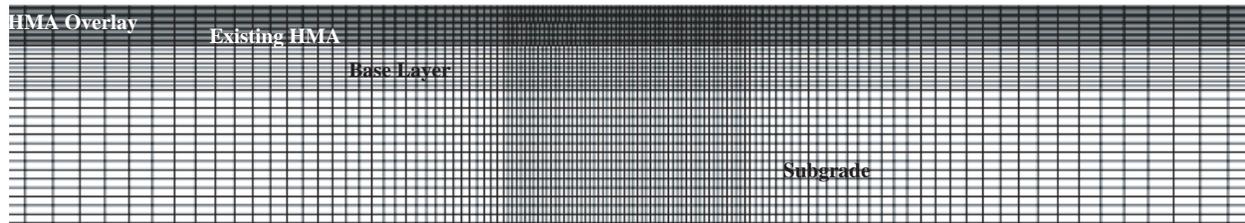
(a)
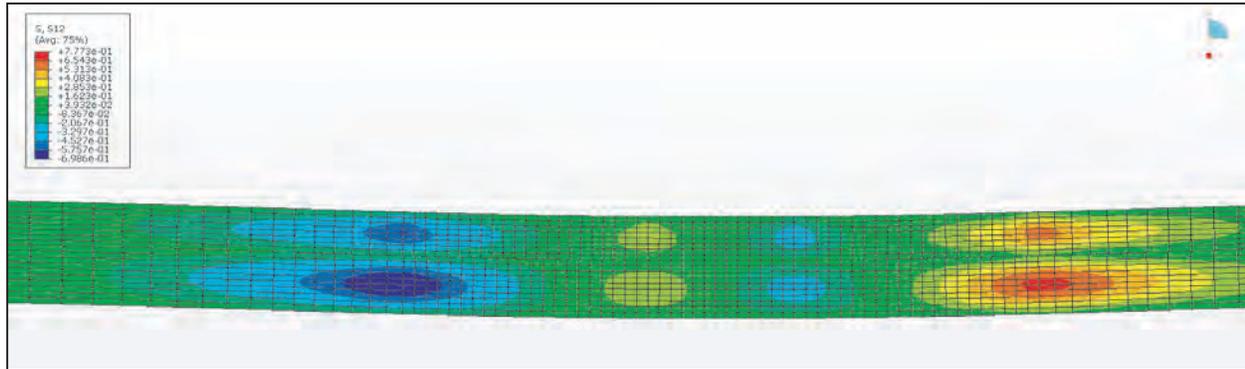
(b)

Figure 24. General layout of the FE model (a) and shear stress distribution in the HMA overlay and the old HMA layer (b).

method is used to describe the interface conditions. The penalty method allows relative motion between the surfaces as long as the behavior is in the elastic region, as defined by d_{max} (limiting displacement in the elastic region). While the surfaces are sticking (i.e., $\tau < \tau_{max}$), the motion between the surfaces is elastic and recoverable. However, if the applied shear stress exceeds the interface shear strength, the interface fails and the interface condition is converted to a simple friction model, defined by a friction coefficient ($\mu = 0.7$).

Figure 24a presents the general layout of the FE model for Structure A; in total, 7,168 elements were used to simulate the pavement structure. The shear response of the top two layers is presented in Figure 24b. As shown in this figure, the axisymmetric shear response of the pavement structure to the applied tire load is demonstrated. In addition, while the maximum shear stress is located in the middle of the layer, the critical shear stress for the interface is the one calculated at the bottom of the HMA overlay.

SECTION 4

Findings

This section presents the main findings of NCHRP Project 9-40. It includes the main findings of the worldwide survey, the results of the experimental program described in the previous chapter, and the theoretical investigation that was used to relate laboratory-measured interface bond characteristics to the field stresses in the pavement structure when subjected to vehicular loading.

4.1 Findings of the Worldwide Survey

A total of 72 responses were identified as having met the criteria for inclusion in this study. Where more than one response was received from the same state, the data were combined, and only one respondent was counted in the analysis. Most of the survey results were presented in terms of percentage of respondents. Two questions on the questionnaire considered the weight of each option (i.e., percentage of use for each option/the importance index of each option). Accordingly, two methods were employed to analyze the data:

1. Data were presented by means of summing the products of the percentage of use and the number of responses,

$$\sum \text{Percentage of use} \times \text{number of responses}$$

2. Weighted average was used to show the overall importance of each option,

$$\frac{\sum \text{Importance index} \times \text{number of responses}}{\sum \text{Number of responses}}$$

4.1.1 Types and Grades of Commonly Used Tack Coat Materials

Figure 25 shows that 100% of the responding agencies indicated that asphalt emulsions are permitted by their agency. The percentage of respondents that use asphalt cement and cutback asphalts are 27% and 20%, respectively. Figure 26

lists the asphalt cements or cutbacks used by the different agencies. Sixty percent of the 15 agencies indicated their use of PG 64-22 asphalt cement. Eleven agencies reported the use of eight cutback asphalts for tack coat. MC-70 had the highest rate of use with 55% of those respondents using cutback asphalts as tack coat.

The most commonly used emulsions were slow-setting SS-1 (41%), SS-1h (39%), CSS-1 (37%), and CSS-1h (41%) (see Figure 27). The asphalt content of the emulsions generally ranged between 50% and 65%. A few extremely diluted emulsions were used by some respondents. The residual rate reported for the cutback asphalt materials ranged from 50% to 87%.

The survey questions focused on tack coat materials used in recent construction projects and the percentage of their use. Figure 28 was developed by multiplying the percentage of use of tack coat materials by the number of responses in order to evaluate the recent usage. Emulsified asphalts were, by far, the most commonly used tack coat material followed by asphalt cement and then cutback asphalts. SS-1, CSS-1h, SS-1h, and CSS-1 ranked as the most used emulsified asphalts (see Figure 29). PG 64-22 was the most commonly used asphalt cement. RC-70 ranked as the most commonly used cutback asphalt (Figure 29).

4.1.2 Types of Tack Coat Applied to Different Pavement Surfaces

Most of the respondents indicated that their agencies monitor the application of tack coats and specify ranges for dilution rates as well as application rates. Of the respondents, 4% indicated that the dilution rate is determined by the contractor, 2% stated that they do not monitor the application rates, and 2% stated that the application rates are monitored visually. Figure 30 shows the most common materials used as tack between new HMA layers. Tack coat materials used on old HMA surfaces and milled HMA surfaces are listed in
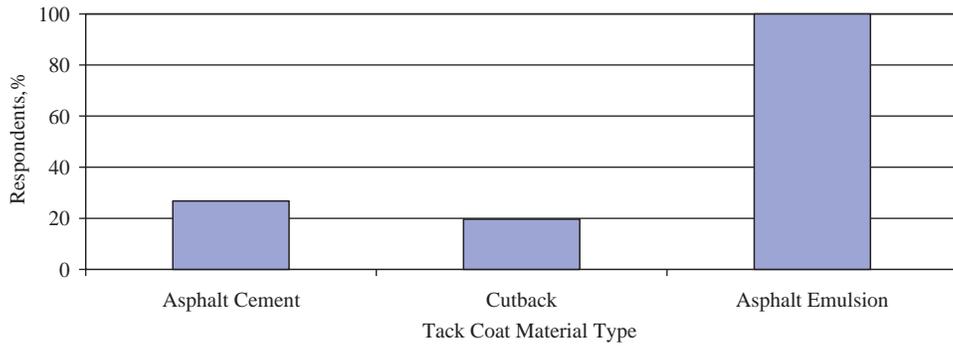
Figure 25. Tack coat material types.
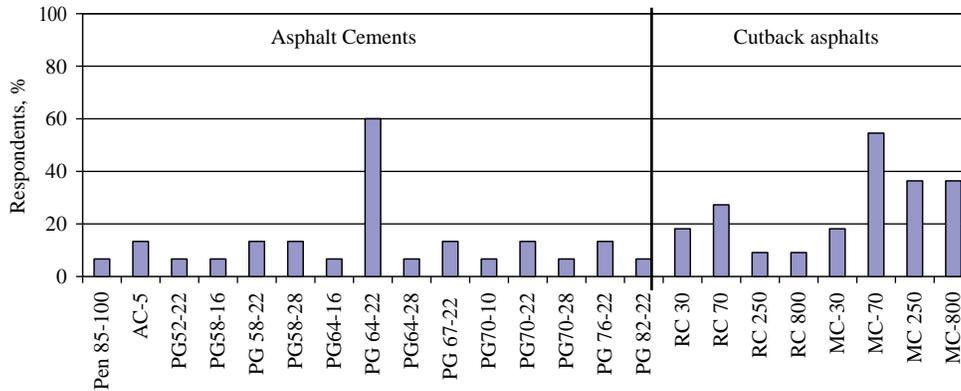
Figure 26. Asphalt cements and cutbacks used as tack coats.
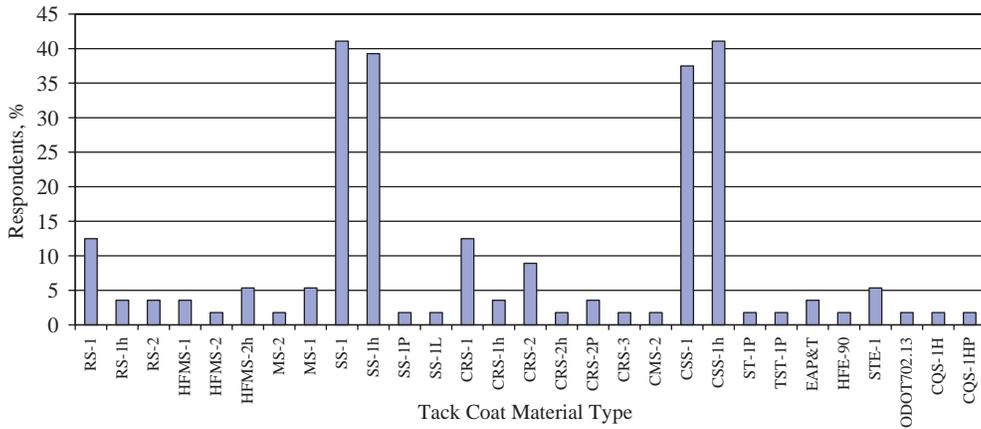
Figure 27. Emulsions used as tack coats.
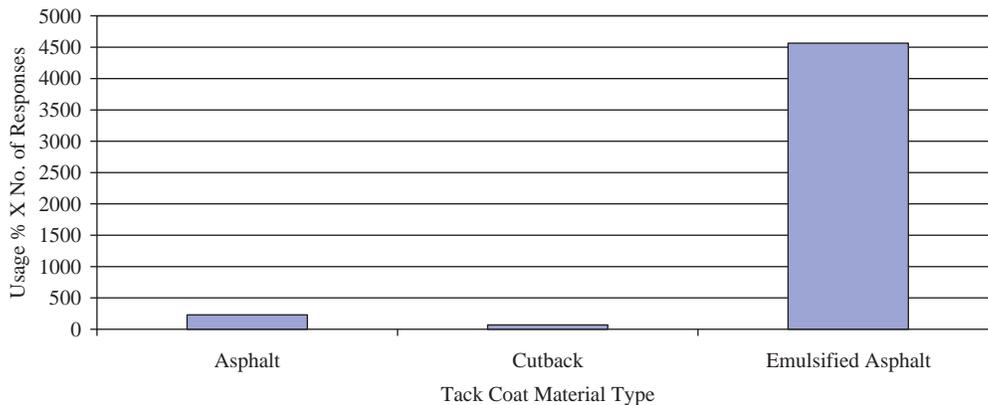
Figure 28. Weighted use for the material used as tack coat.
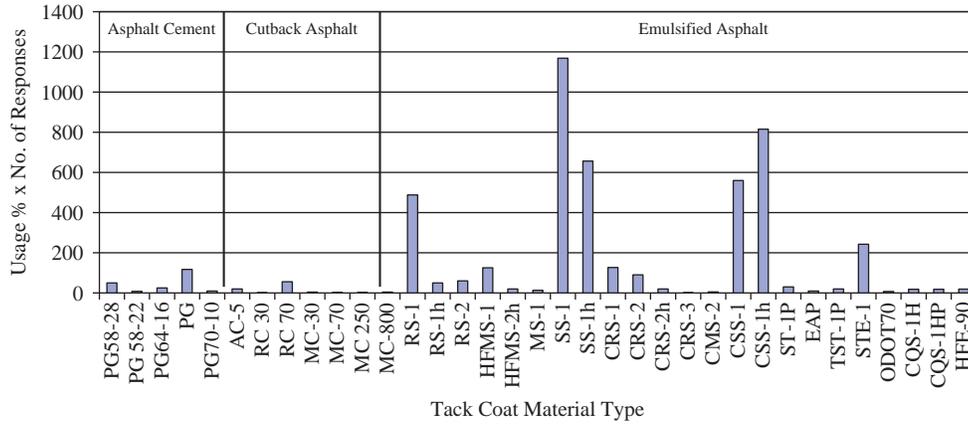
Figure 29. Commonly used tack coat materials.

Figures 31 and 32, respectively. Of the agencies, 4% indicated that they do not require tack coats between new HMA layers, while 2% indicated that no tack is required on old HMA surfaces.

For tack coats applied between new, old, and milled HMA layers, the commonly used tack coat materials were CSS-1H (32%–34%), SS-1 (30%–32%), SS-1h (29%–32%), and CSS-1 (21%–27%). PG 64-22 was the most used asphalt cement with an average of 11%, and RC-70 was the most commonly used cutback asphalt with a usage range of 5% to 7%. The residual application rates for most of the emulsions were within the range of 0.03 to 0.05 gal/yd^2. Asphalt cement application rates ranged from 0.04 to 0.10 gal/yd^2. The range of residual rates for cutback asphalts was 0.03 to 0.05 gal/yd^2. Only 27% of the respondents gave feedback for tack coat materials used on top of surface treatments or seal coats, as well as asphalt-treated base courses (see Figures 33 and 34, respectively). These two

surface conditions yielded similar results as the first three surfaces, with CSS-1h, CSS-1, SS-1h, and SS-1 being the most used tack coat materials.

Figures 35 and 36 list the materials used on PCC pavements or diamond-ground PCC pavements, respectively. Again, SS-1, SS-1h, CSS-1, and CSS-1h were the most used materials with the high-float emulsions ranking highest among the emulsions.

4.1.3 Findings Related to Tack Coat Application Methods

The Dilution Process Location

Several agencies allow dilution at multiple locations: 49% reported that the dilution process occurs while the material is in the supplier's tank (see Figure 37). Another 45% allow
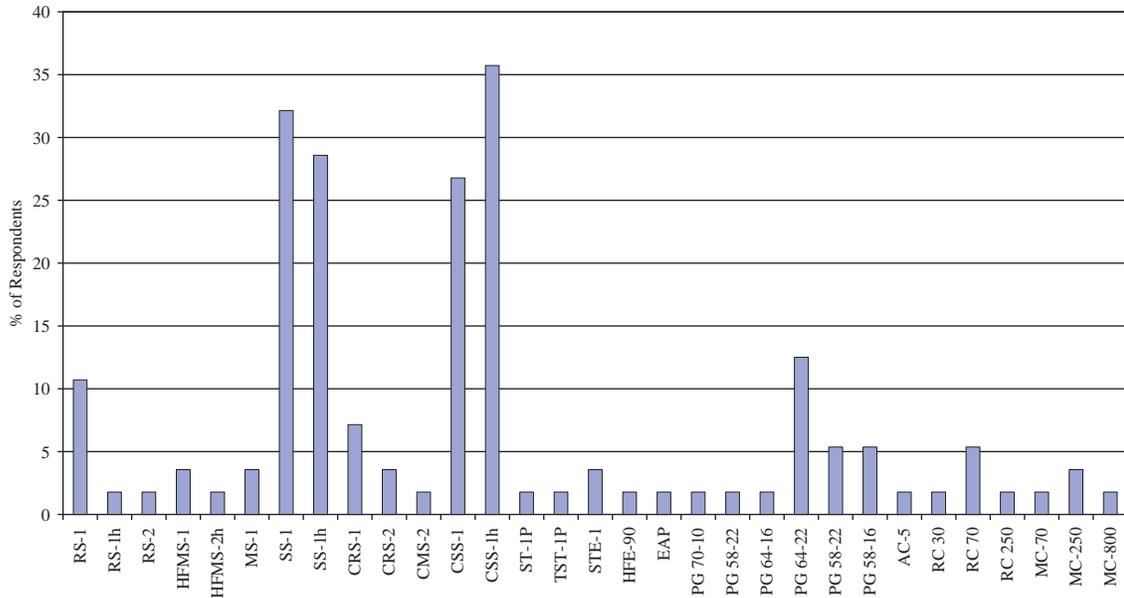
Figure 30. Tack coat materials placed between new HMA layers.
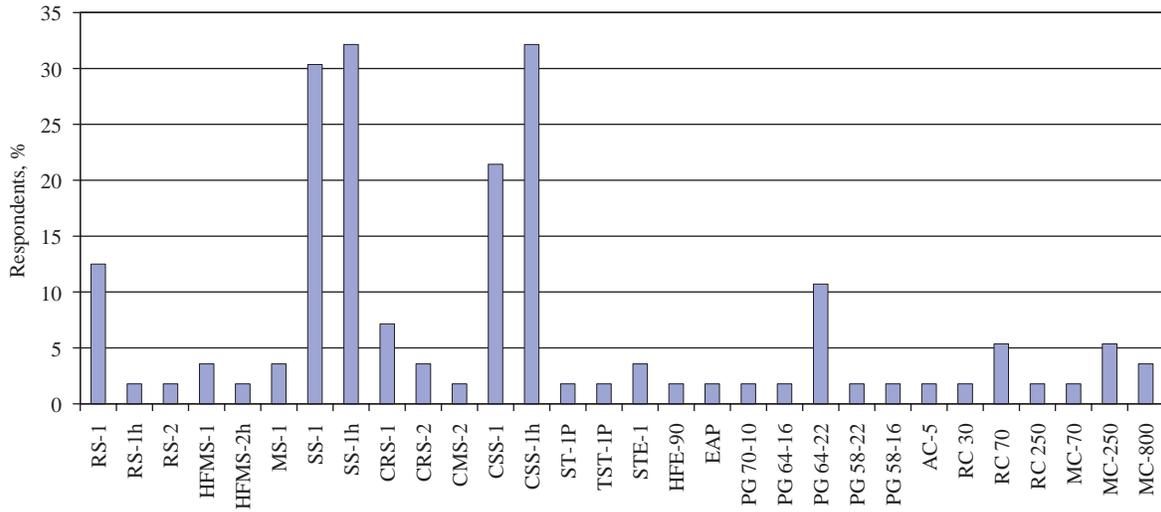
Figure 31. Tack coat materials placed on old HMA.
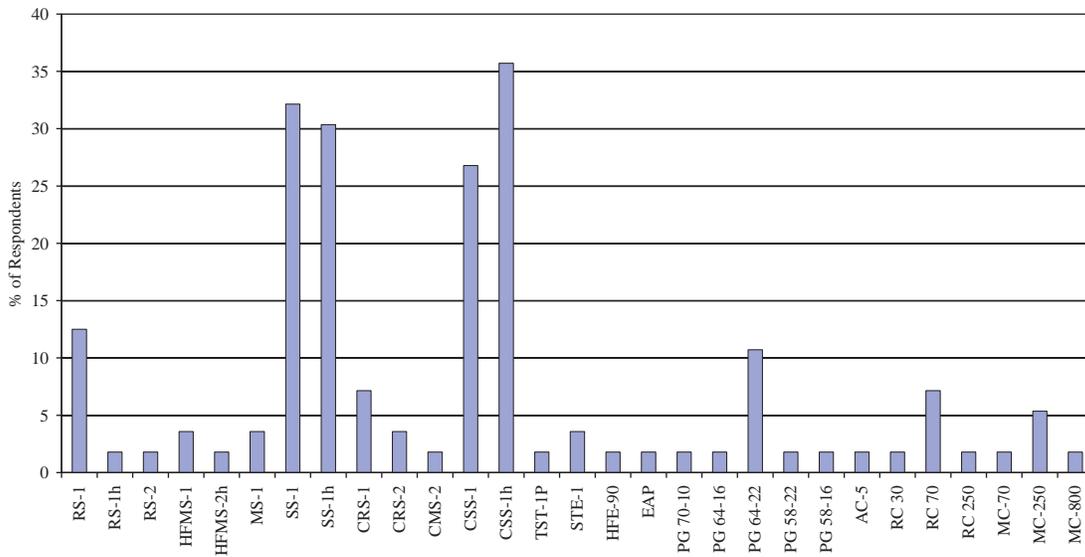
Figure 32. Tack coat materials placed on milled HMA surfaces.
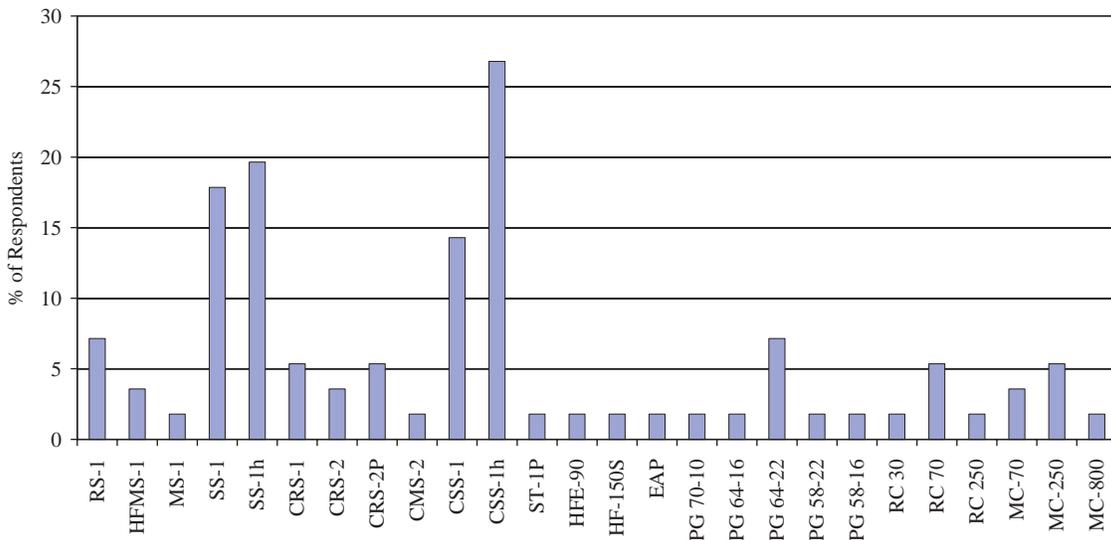
Figure 33. Tack coat materials used on surface treatments, seal coats, or chip seals.
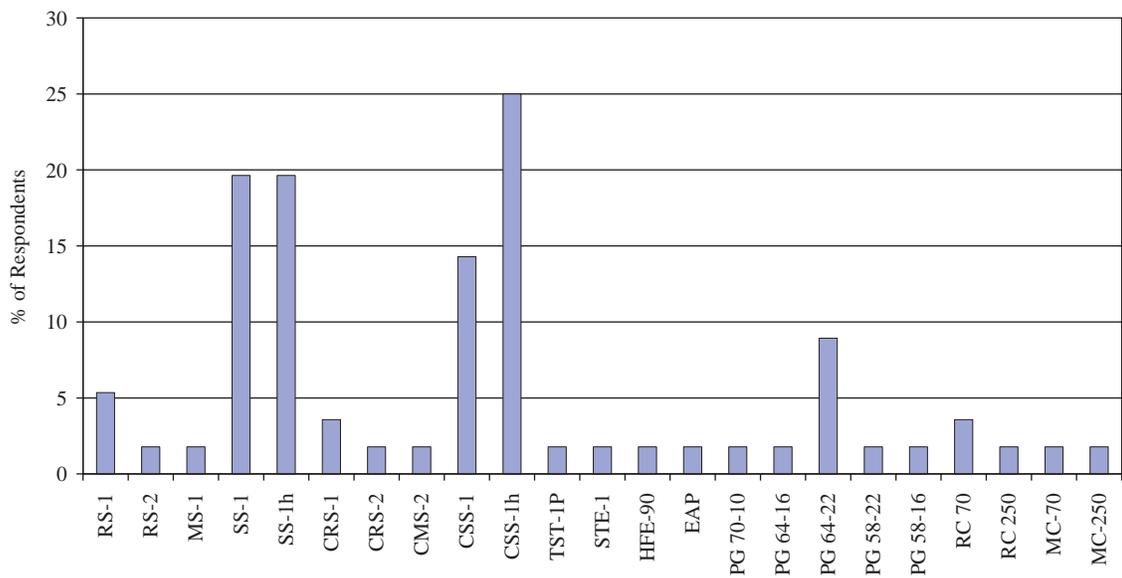
Figure 34. Tack coat materials used on asphalt-treated base.
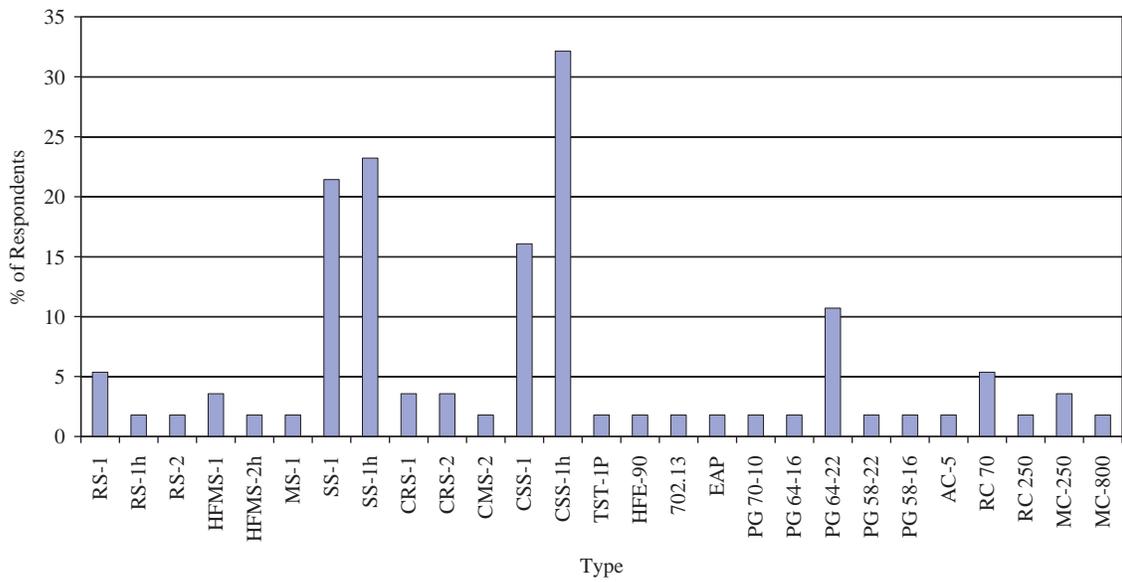
Figure 35. Tack coat materials used on PCC surfaces.
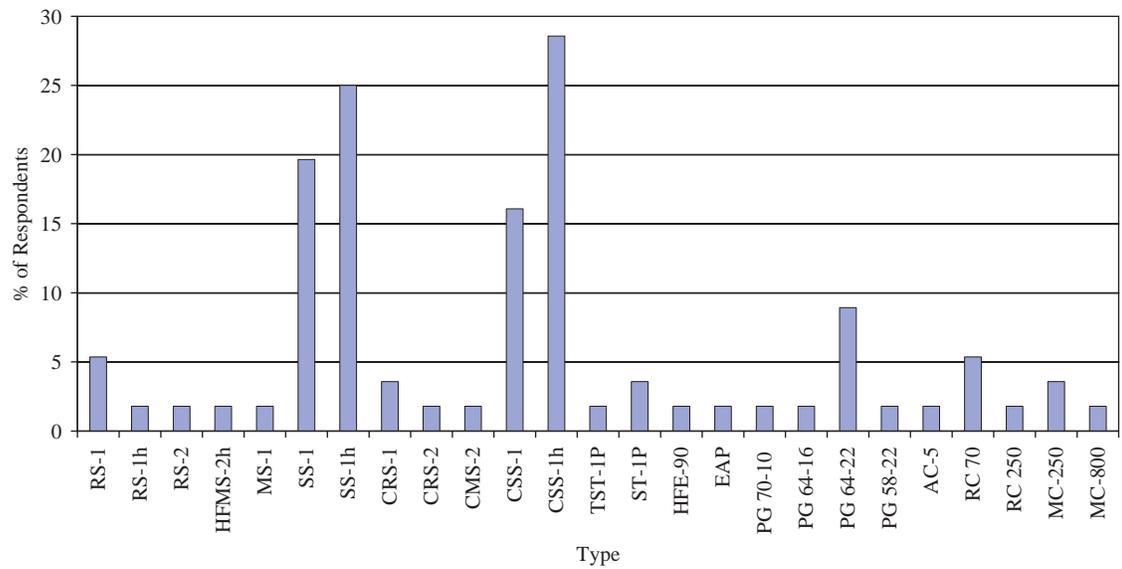
Figure 36. Tack coats used on milled or diamond-ground PCC.
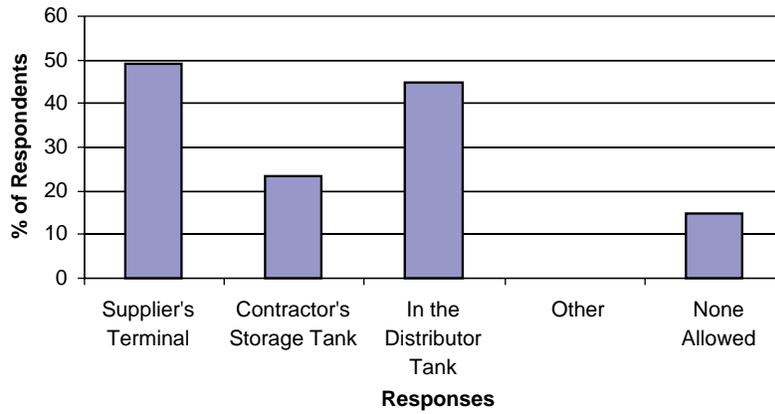
Figure 37. Potential sites for dilution of emulsified asphalt.

dilution to occur in the distributor tank. Only 15% of the respondents do not allow dilution of emulsified asphalt for tack.

Verification of Asphalt Emulsion Dilution Rate

Half of the respondents stated that emulsion was sampled from the distributor and tested for verification. Another 39% of the respondents required certification from the supplier. Only 29% allowed the certification to be performed by the contractor (see Figure 38).

Frequency of Verification of Dilution Rate

Of the respondents, 36% verify the dilution rate of an asphalt emulsion (see Figure 39); 26% indicated that the dilution rate is not checked; another 26% indicated criteria different from those queried in the questionnaire. Some of these different criteria included the following: verify the dilution rate for every delivery unit, leave it up to the contractor, verify every 2 weeks, verify every 43,000 ft^2, and periodically test. Only 10% verify the dilution rate daily.

Traffic on Tacked Surfaces

The majority of respondents—78%—stated that highway traffic is not allowed on tack coat materials prior to HMA placement. Of the respondents who do allow traffic on the tack materials, most stated that the tack coats should be cured first. Some reported a time of 1 to 2 hours before traffic is allowed onto the tacked pavement. All of the respondents who allowed traffic prior to placement of HMA indicated that surface type did not affect the time required before traffic was allowed.

Of the respondents, 47% allow highway traffic for a maximum of 24 hours before placing the covering HMA layer; 18% do not allow highway traffic prior to the placement of the subsequent HMA layer; and 6% allow 5 days of trafficking before the tack coat must be covered (see Figure 40).

Tack Coat Application Equipment

By far, most agencies (98%) indicated that an asphalt distributor with spray bar was the most common specified application method (see Figure 41); 42% allow an asphalt
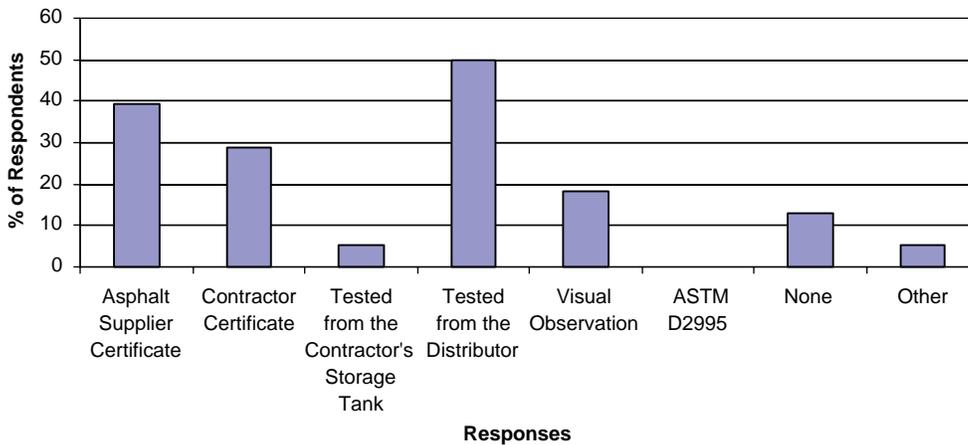
Figure 38. Verification of the dilution process.
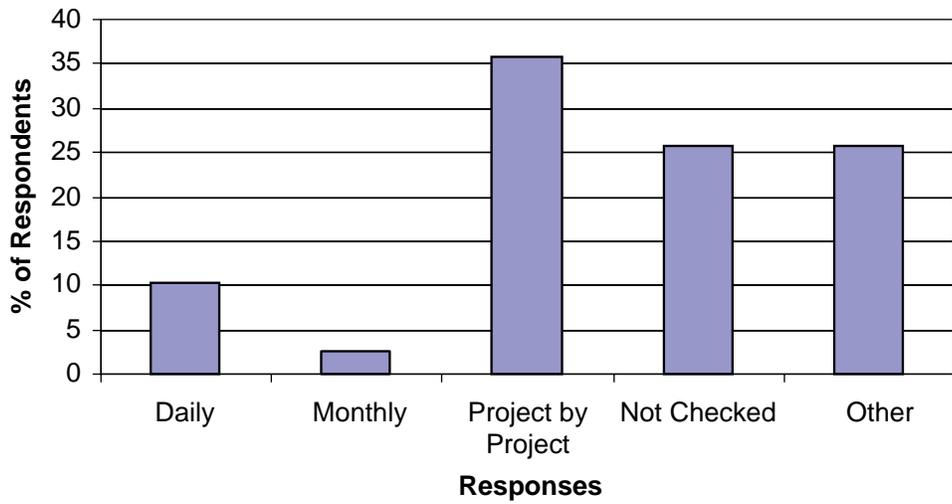
Figure 39. Frequency of verification of dilution.
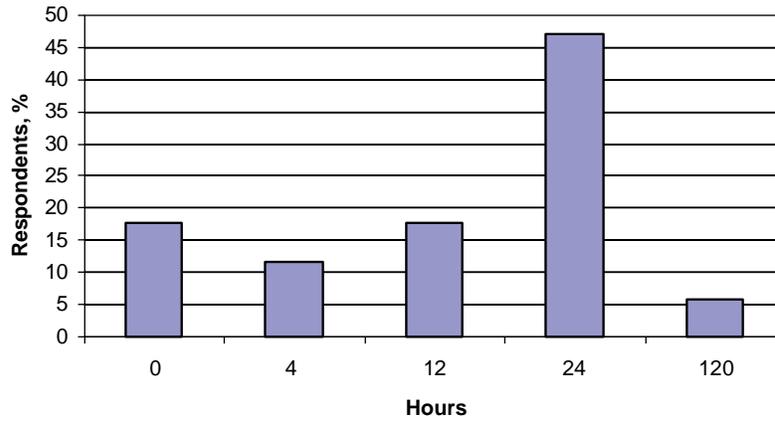
Figure 40. Time that tack coat can be exposed to traffic before covering with HMA.
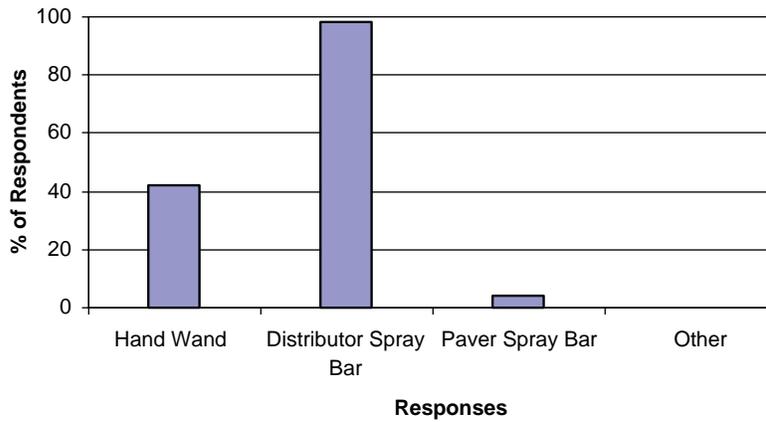
Figure 41. Method for applying tack coat materials.

distributor with hand wand, and 4% require a spray bar attached to the paving machine. However, the average percentage of use for the asphalt distributor with spray bar was 97% compared with 6% asphalt distributor with hand wand. Half of the agencies that use a spray bar attached to a paver use it 100% of the time, while the remaining half used it for 1% of their mainline paving areas. Not all agencies provided a percentage of use with their survey response.

Breaking/Setting of Emulsified Asphalts

Of the respondents, 26% permit haul trucks to drive on unbroken emulsion. The majority of respondents, 70%, allow haul trucks on an unset emulsion after it breaks. Out of 53 responses, 74% of the responding agencies allow paving to begin immediately after the tack coat material breaks, whereas 26% do not allow paving until the emulsion sets.

In ranking the factors that affect the break and set times for an emulsified asphalt, respondents indicated that ambient temperature and pavement temperature were the most important factors. Other factors that were reported were road surface condition, solar effect, and emulsion temperature. Application rate, dilution rate, wind velocity, and humidity were considered essentially equivalent in level of importance. The break/set factors are listed below in order of importance, from highest to lowest:

1. Ambient temperature,
2. Pavement surface temperature,
3. Dilution rate,
4. Application rate,
5. Humidity,
6. Wind velocity, and
7. Others.

Pickup of Tack Material by Truck Tires

Of the respondents, 67% indicated that pickup of tack coat material is a continuing problem; 38% indicated that the tack material is required to be completely set before haul trucks are allowed on it. Few respondents, 13%, allow haul trucks to drive on the tack coat material before breaking (see Figure 42). Other methods specified to reduce pickup include the following: tack coat is required to break before haul trucks are allowed, reduce the application rate, clean the surface before applying tack coat, and minimize the distance that haul trucks are allowed to drive on the tack coat.

Percentage of Tack Coat Coverage

Tack coat coverage is defined herein as the percentage of the pavement surface area coated by asphalt tack. Most agencies, 64%, responded that the coverage area is typically above 90%. The percentages of responses are as follows:

1. 100% coverage (37%),
2. 90%–100% coverage (27%),
3. 70%–90% coverage (18%),
4. 50%–70% coverage (9%), and
5. Less than 50% coverage (9%).

A majority of the agencies, 73%, indicated that no specific requirement was used to regulate the application of tack coat material; 25% reported that the amount of spray overlap between adjacent nozzles on the distributor spray bar is a specified requirement. Out of the 13 agencies that reported a requirement for overlap, 46% use a double-overlap configuration, while 23% use single- and triple-lap. The remaining 8% did not mention which degree of overlap was used. That the angle of the nozzles to the axis of the spray bar is a speci-
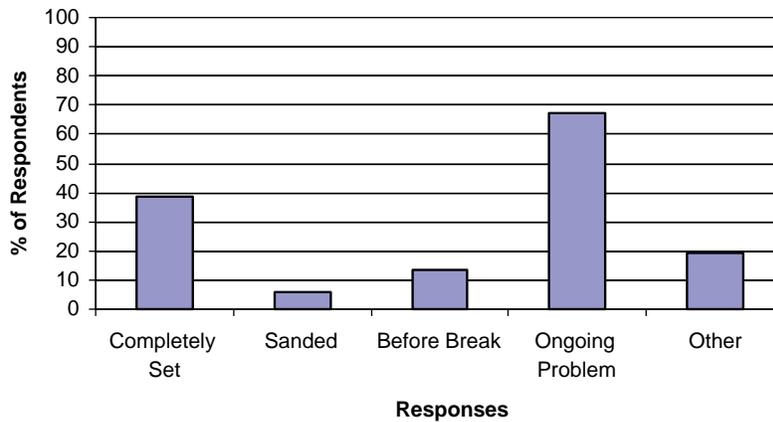
Figure 42. Methods used to prevent pickup of tack coat by haul trucks.
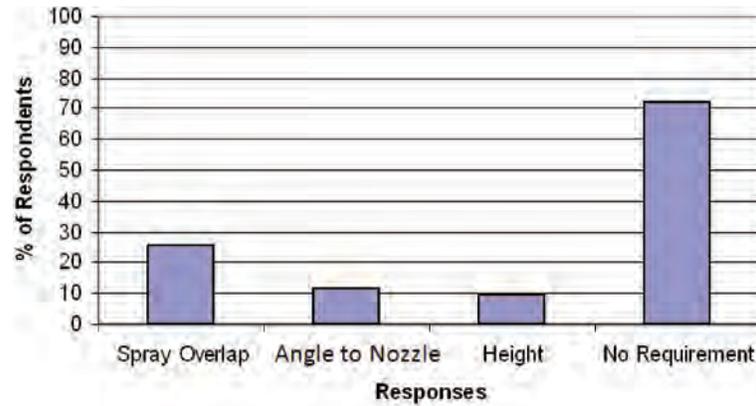
Figure 43. Specified requirements for tack coat application.

fied requirement was reported by 12% of respondents. Of those who indicated the angle of the nozzles as a requirement, the average minimum angle was 23° and the average maximum angle was 32°. That the height of the spray bar above the pavement surface is a requirement was reported by 10% of respondents. Figure 43 presents the percent of responses for each requirement.

Environmental Restrictions

In discussing the environmental restrictions placed on the application of the tack coat material, almost half of the respondents, 43%, reported a minimum ambient temperature. The average minimum ambient temperature was 6°C. Less than 2% reported a maximum allowable ambient temperature of 65°C; 38% reported that a minimum pavement surface temperature was a restriction. The average minimum pavement surface temperature was 3°C. No agency reported a maximum pavement for surface temperature as a restriction. Impending rainfall was an environmental restriction for 55% of respondents. More than 75% of the respondents reported that a wet pavement surface was a restriction, whereas 38% indicated that a damp pavement surface was a restriction. Approximately the same number reported that time of year

(i.e., paving season) was a restriction. The percentages of responses are given in Figure 44.

Some additional common restrictions for application of tack coat were as follows:

1. Surfaces must be free of standing water or contamination,
2. Manufacturer's recommendations,
3. Do not apply tack coat unless HMA will be immediately placed, and
4. Cannot apply tack coat materials in foggy conditions

Application Rates and Residual Tack Coat Rate Verification

Of the responses, 51% indicated that measuring the change in the amount of material in the distributor tank after applying a given section was the best way to check the application rates (see Figure 45). Less than 2% of the agencies reported that *ASTM D 2995* (*19*) is used. The differences in the weight of the asphalt distributor over a given area were about 27%. Some of the common methods specified by the respondents, but not queried in the questionnaire, are as follows: meter on the distributor, visually, and dipstick reading before and after an application on a pavement segment.
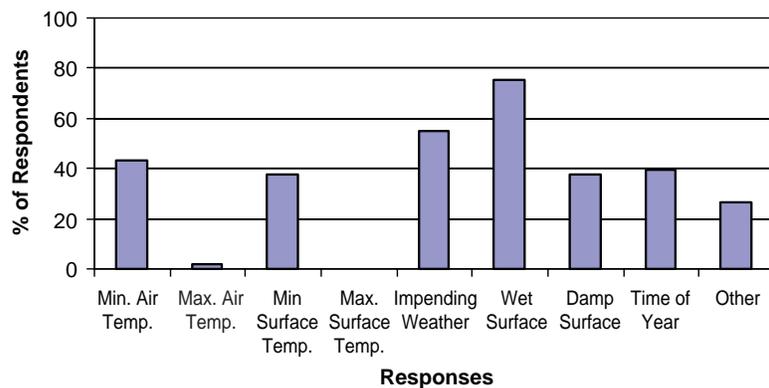
Figure 44. Environmental restrictions on tack application.
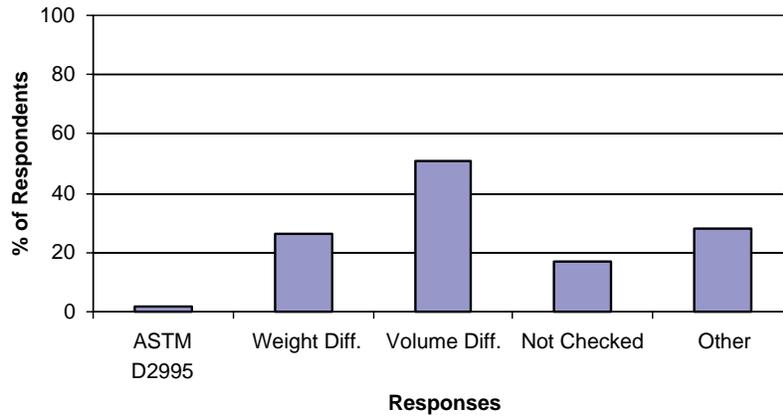
Figure 45. Methods to verify tack application rate.

Uniformity of the Applied Tack Coat

Most of the respondents, 66%, indicated that the requirement to have the entire surface covered with tack coat material was the main specification to check for uniformity (see Figure 46). The second most-used requirement was to ensure that no nozzles are completely or partially blocked, 34%. The remaining options ranged from 13% to 26%.

More than half of the respondents (56%) reported that they do not change their application rate due to any factor. Almost all of the remaining 44% of respondents who change their application rate changed them based on the condition of the pavement surface. The remaining of the conditions ranged between 0% and 10% (see Figure 47).

Remedy for Non-uniform Tack Coat Application

Out of the responses compiled, 70% require the contractor to reapply the tack coat material. Of those responses, 70% require a lower application rate for the reapplication. The remaining respondents who require reapplication of the tack coat material either applied the same rate, or they did not specify which approach was taken. Two percent asked the contractor not to do it on the next pass (and no other action

to fix non-uniformity is taken); 17% do nothing. The results are illustrated in Figure 48.

4.1.4 Findings Related to Tack Coat Application

Pavement Failures Related to Improper Tack Rate/Material

The respondents reported slippage and delamination of the pavement surface layer as approximately equal to results from poor tack coat type or application, 89% and 87%, respectively. Fatigue cracking was the only other type of failure that received over 25% of the responses. Other types of failures included shoving, bottom up stripping due to water intrusion, and flushing/bleeding due to excessive tacking (see Figure 49).

Lab/Field Test Methods to Determine the Interface Bond Strength

The vast majority of the respondents, 92%, indicated that no testing is performed to measure the bond strength between pavement layers. Eight percent of the agencies indicated that testing is performed on the pavement interface. The traction
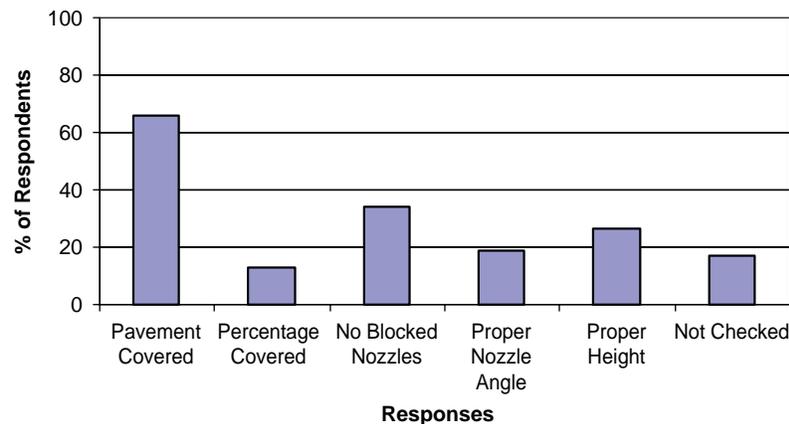
Figure 46. Methods for assurance of tack coverage.
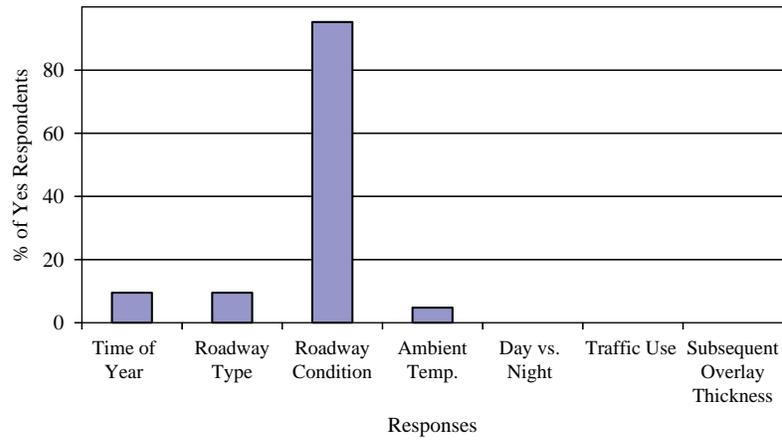
Figure 47. Reason for tack coat rate change.
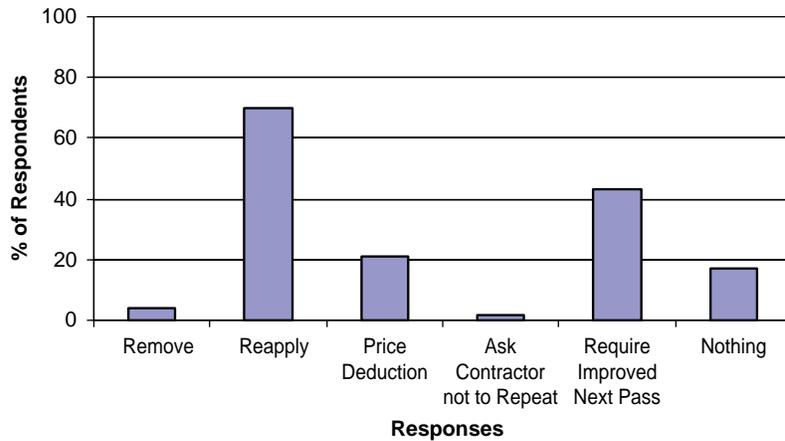
Figure 48. Steps to correct poor application of tack coat.

test, Texas pull-off test, and Florida shear test are some of the laboratory and field test methods being used to quantify interface bond strength between pavement layers.

Quality of Tack Coat Materials

Only 18% of the responses indicated they use a field or laboratory test to evaluate tack coat material quality. Some

Figure 49. Failures attributed to improper tack application or type.

of the procedures listed for testing the quality of tack coat materials are residual percentage test; traction test; penetration test on the residual asphalt; *AASHTO M 208, Cationic Emulsified Asphalt* (*39*); and oil distillate test.

Current Research Related to Performance of Tack Materials

Of the respondents, 37% reported that their state or country is conducting or has recently conducted research on tack coat performance.

4.2 Experiment I: Development of a Test Device to Evaluate the Quality of the Bond Strength of Tack Coat Spray Application in the Field

The Louisiana Transportation Research Center (LTRC) and InstroTek, Inc., manufacturer of the ATacker™, partnered to develop the Louisiana Tack Coat Quality Tester (LTCQT), which was developed in this project to evaluate the

quality of the bond strength of tack coat in the field. LTCQT is a modification of the ATacker. The following sections describe details of the development process and evaluation of the LTCQT.

4.2.1 First Generation of LTCQT

Figure 50 presents the first generation of the LTCQT that was used to measure the quality of tack coat applications in the field. The modifications included automated operation of the device and installation of electronic sensors for the measurement of load and deformation. Subsequent to the initial evaluation of this version of the ATacker, it was determined that additional fine-tuning items needed to be incorporated, such as fixing the flap plates to hold the device firmly in place during testing, increasing the travel distance of the actuator, and additional modifications to the software to make it more user-friendly. Distinctive features of the first generation of LTCQT included:

- Automated operation by installation of electronic sensors for load and displacement measurements. This led to improved reliability and repeatability of the measurements and minimized operator error.
- Incorporation of user-friendly software.

4.2.2 Second Generation of LTCQT

Figure 51 shows the second generation of the LTCQT. Several modifications were introduced to the first generation of LTCQT to improve the reliability of the results. The modifications introduced in this version addressed several issues observed in the first generation (details of these modifications are discussed in the following sections):

- Improved sensitivity/reliability of the load cell sensor,
- Improved sensitivity/reliability of the actuator rate of loading, and
- Improved adhesion of the LTCQT test plate to tacked surface.

Improved Sensitivity/Reliability of the Load Cell Sensor

Several experiments using the first generation of LTCQT were conducted to examine the sensitivity and reliability of the load cell sensor. During this evaluation, it was observed that the load cell had a high noise level (approximately 10% of the load cell capacity), which exceeded the specification value set by *ASTM E 74, Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines* (*40*). Therefore, a new load cell with a maximum capacity of ±100 lbs and a signal conditioner were installed. The aforementioned changes yielded a stable load cell signal that met *ASTM E 74* standards. In addition, the LTCQT acquisition software was updated to match the new device.

Improved Sensitivity/Reliability of the Actuator Rate of Loading

Loading rate of the actuator was examined. Several experiments were conducted to verify the rate of loading using two tack coat materials with contrasting bond strengths: CRS-1 and PG 64-22. Results from these experiments showed that the device could not maintain the specified displacement rate during testing. Results of this evaluation are presented in Appendix B. The displacement rate changed depending on the strength of the material; therefore, a new actuator and driving motor (closed loop, servo-controlled) with improved control of the displacement rate were installed. It is noted
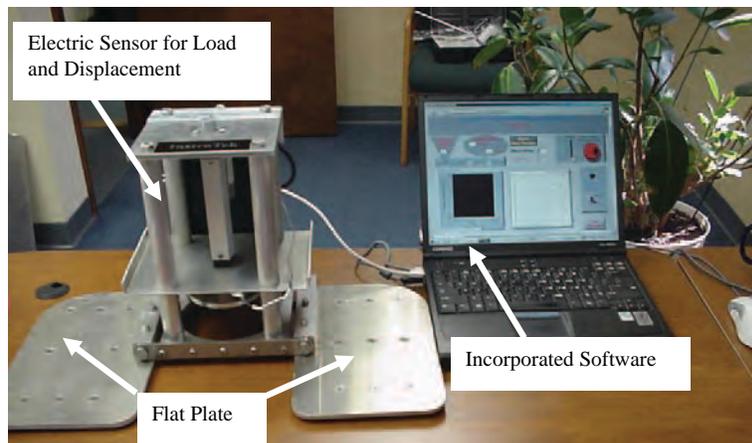
Figure 50. First version of the LTCQT.

Weights

Load Cell and
Signal Conditioner

Contact Plate: 5.71 in
Diameter

(a) LTCQT Tester

(b) Software Incorporated in LTCQT
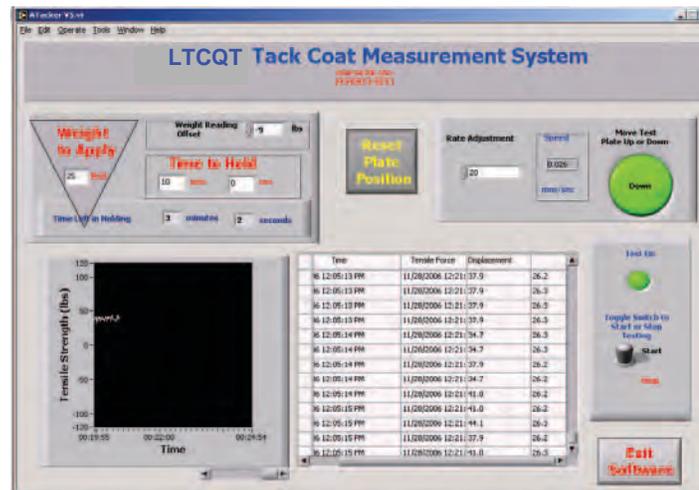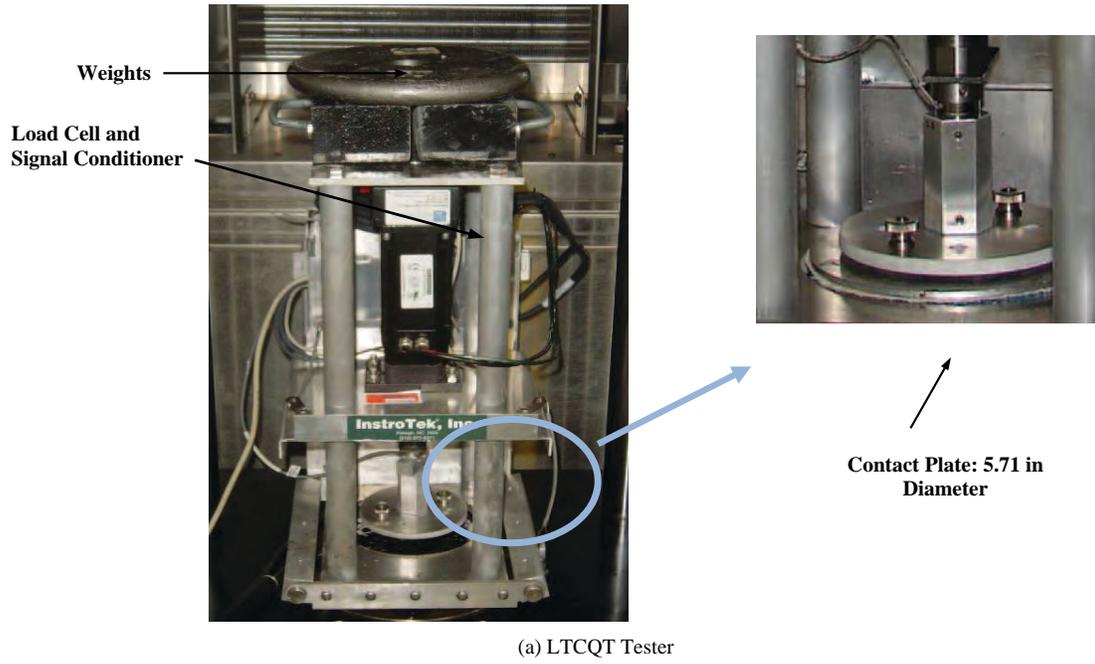
Figure 51. Second generation of LTCQT.

that the displacement of the actuator was measured using a position transducer that has a total travel of 3.94 in. The maximum loading rate was 0.30 in/sec. Experiments were then conducted with the improved device to verify the loading rate. It was observed that the "set" and "measured" displacement rates of loading were in good agreement in these experiments, indicating that the second generation of LTCQT can provide a consistent and reliable displacement rate of loading.

Improved Adhesion of Test Plate to Tacked Surface

Most of the laboratory research that was performed to evaluate tack coat quality using the ATacker test device was performed with the tack coat applied between two metal plates. During the LTCQT tack coat field evaluation tests, poor adhesion (i.e., not measurable) was observed between the metal plate and the tacked pavement surface. Several types of flexible materials (to better conform to a textured surface) that attach to the metal plate were evaluated. Rubber, insulation foam, sill foam, and polyethylene foam are among the materials evaluated. Rubber and the insulation foam showed poor adhesion to the pavement surface; however, polyethylene foam yielded good adhesion. Therefore, polyethylene foam was used to ensure adequate adhesion. The foam can be easily attached onto the metal plate with double-sided tape.

4.2.3 Development of Tack Coat Test Procedure Using LTCQT

A procedure for evaluation of tack coat quality in the field was developed based on the second generation of the LTCQT test device. Loading rate, time required for breaking of emulsified tack coat, contact pressure, and contact time between contact plate and tacked surface were examined. Based on the results of this evaluation, a test procedure was written in AASHTO format.

Loading Rate

Since the loading rate significantly affects the test results, it is essential to select an appropriate rate that can distinguish between the tensile strength of different tack coat materials. Experiments for determining appropriate loading rate were conducted in the laboratory. The tack coat materials used were SS-1h, CRS-1, trackless, and PG 64-22. Tack coat tensile strength was measured in the laboratory using LTCQT at 50°C and at two loading rates (i.e., 004 and 0.008 in/sec). Based on the applied loading rates, it was found that LTCQT is able to differentiate between different tack coat materials in terms of the measured tensile strengths. Since this trend was consistent at both displacement rates, and to ensure prompt evaluation of tack coats in the field, a 0.008-in/sec loading rate was selected for the test procedure.

Evaluation of Cure Time and Accelerating Devices

The LTCQT was developed to evaluate the quality of the bond strength of tack coat in tension in the field. For emulsions or cutbacks, tack coat quality must be evaluated based on the residual material (i.e., material remaining after the emulsion/cutback has cured) and not the total emulsion. Thus, the set or cure time (i.e., the time required for water to evaporate) for tack coat materials needs to be determined prior to the LTCQT testing. This was achieved by continuously measuring the weight of a tacked specimen until a constant weight was obtained. Three emulsion types were evaluated, namely, CRS-1, SS-1h, and trackless. Each one of these emulsions was applied to the surface of a HMA specimen with dimensions of 5.9 in in diameter and 2.2 in in height. The weight of the tacked specimen was measured to 1/100th of a gram at several time intervals subsequent to the application of the emulsion on the specimen. It was observed that complete curing of the emulsions was achieved after approximately 12 hours. This time period needed to be shortened in order to permit same-day measurements in field tack coat construction. Three devices were evaluated in order to accelerate emulsion curing time: a portable fan/heater, a heat gun, and an infrared reflective heating (IRH) lamp.

The IRH source device used in the first, second, and fourth test setup was positioned 2.95 in above the surface of the sample (see Figure 52). SS-1h emulsion was applied to the surface of the sample specimen at 43.3°C with a residual application rate of 0.05 gal/yd^2. To avoid evaporation of light oil components during the heating process, the surface temperature of the specimen was not allowed to exceed 135°C for any device. Results of these experiments are presented in Figure 52b. It was noted that the target residual asphalt weight (i.e., the weight after approximately 12 hours of evaporation at room temperature) was achieved after approximately 1 hour for each of the four test setups considered. Based on these results, the IRH lamp was selected for use in accelerating water evaporation time and was subsequently adopted in the field experiments. The IRH device provided the most uniform heat distribution on the sample among the four devices evaluated. Furthermore, this device was comparatively simple to setup and use.

Contact Time and Pressure

A contact pressure, compressive preload, is applied to the contact plate for a preset period of time as a part of the LTCQT. A contact pressure of 1.57 psi for 3 minutes was found to be adequate to provide uniform adhesion between the tacked surface and the loading plate of the LTCQT.

(a) Infrared reflective heating (IRH) lamp.
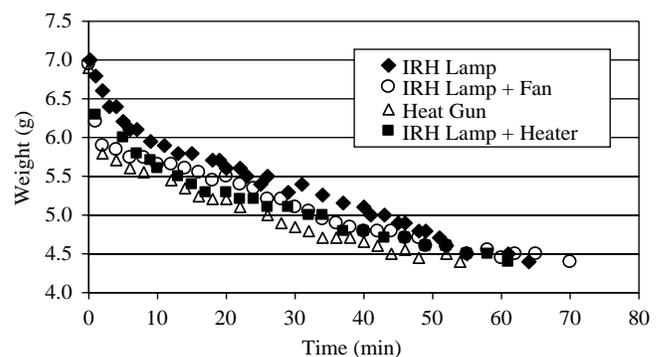
(b) Breaking time of tack coat SS-1h with different heating conditions.

Figure 52. Determination of heat source for accelerating water evaporation in emulsions.

Table 14. Test parameters in the test method.

Category	Level
Loading Rate	0.5 in/min
Contact Time	3 minutes
Contact Pressure	1.5 psi
Tack Coat Evaporation Time	1 hour
Tack Coat Evaporation Device	Infrared reflected heating (IRH) source

Summary of Test Parameters

A summary of the test parameters is shown in Table 14. Field test results presented in the following sections were evaluated based on these test parameters.

4.2.4 LTCQT Test Procedure

The existing pavement surface at the LTRC PRF facility was thoroughly cleaned (see Figure 53a). An area of 6 in × 6 in was used for each test (see Figure 53b). The tack coat material was then applied with a paint brush at the prescribed residual application rate and application temperature (see Figure 53c). Subsequent to the application of the tack coat material, the IRH device was positioned above the test area (for emulsion only) for one hour to accelerate the curing time (see Figure 53d). Surface temperature was allowed to cool to the testing temperature, and then the cured surface was ready to test for tack coat quality using the LTCQT. The LTCQT was positioned on the surface (see Figure 53g). A compressive preload of 1.57 psi was applied to the surface via the LTCQT foot, loading plate, which has the polyethylene foam for 3 minutes. Then, a tensile force was applied at a displacement rate of 0.008 in/sec until failure. The tensile force was continuously recorded. The ultimate load (P_{ULT}) was measured, and the tensile strength (S_{ULT}) was computed and used in the analysis. Four tack coat materials—trackless, CRS-1, SS-1h, and PG 64-22—were tested in the field. A minimum of three replicate tests were performed for each condition. A test procedure for assessing tack coat installation quality in the field using the LTCQT device is presented in Appendix C.

4.2.5 Effect of Tack Coat Temperature on the Ultimate Tensile Strength

Testing temperature plays a vital role in the response of the tack coat material as measured by the LTCQT. A series of LTCQT tests were conducted in the field at intervals of

(a) Surface cleaning
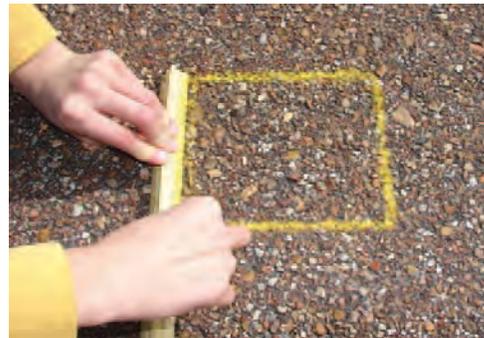
(b) Drawing test area

(c) Tack coat application

(d) Water evaporation (curing) for 1 hour

Figure 53. Main steps in the LTCQT test procedure.

(e) Foam material attachment on loading plate
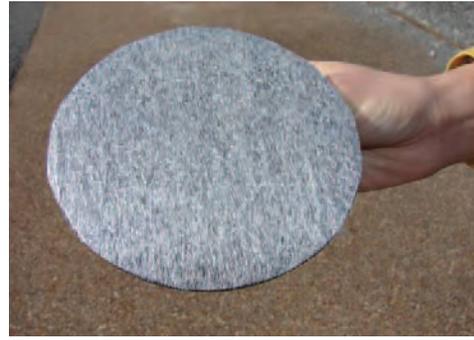
(f) Foam material attachment on loading plate II

(g) Placement of LTCQT

(h) Pull-off testing and data recording

Figure 53. (Continued).

approximately 10°C ranging from 30° to 90°C on the afore-mentioned four tack coat materials at a residual application rate of 0.05 gal/yd². Three replicates were tested for each tack coat material. Figure 54 presents the variation of the ultimate mean tensile strength (i.e., S_{ULT}, average of three replicates) of the tack coat materials considered in this experiment along with the test temperatures. The temperatures presented in these graphs are the ones measured at the end of the test. It is believed that these temperatures are

the closest ones at the point where the tensile strengths were measured. In general, the variation in temperature between the start and end of each test was controlled to within 5°C.

Tensile strength of each tack coat material increased, reached a peak, and then decreased as the temperature increased (see Figure 54); however, the tensile behavior of each tack coat material was different between the asphalt cement and emulsions in the post-peak region. PG 64-22 exhibited a rapid softening with increasing temperature, whereas the emulsions had
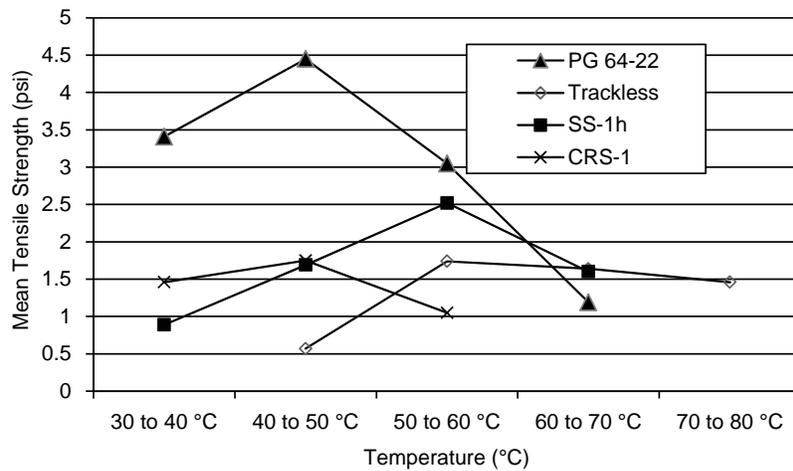
Figure 54. Variation of the mean tensile strength with temperature.

Table 15. Maximum tensile strength and optimum temperature.

	Trackless	SS-1h	PG 64-22	CRS-1
Maximum Tensile Strength (psi)	1.84	2.51	4.34	1.84
Optimum Temperature (°C)	60	52	43	42

a lower drop in the tensile strength from the peak value as the temperature increased. Furthermore, trackless emulsion maintained its tensile strength in the post peak region with the increase in temperature. Results shown in Figure 54 indicate that each tack coat material exhibits its maximum tensile strength at a distinct temperature. This temperature was referred to as the optimum temperature, T_{OPT}. At a temperature higher or lower than T_{OPT}, the tensile strength normally decreased. To determine the peak tensile strength (S_{MAX}) and the optimum temperature (T_{OPT}), polynomial regression lines were fitted for each tack coat. The peak strength from the trend lines was then set to S_{MAX}, and the temperature corresponding to S_{MAX} was set to T_{OPT}. Trackless material had the highest optimum temperature of 60°C. SS-1h, CRS-1, and PG 64-22 had a T_{OPT} of 54, 43, 42°C, respectively. PG 64-22 material showed the highest maximum tensile strength of 4.3 psi. Table 15 summarizes the measured T_{OPT} and S_{MAX} for the four tack coat materials evaluated.

4.3 Experiment II: Rheological Properties of Tack Coat Materials and Its Relationship to Bond Strength

Four consistency tests were conducted on PG 64-22 binder and the residuals of SS-1h, CRS-1, and trackless emulsions (see Figure 55). The residual asphalts were obtained according to *ASTM D 244, Residue by Evaporation.* Trackless, SS-1h, and CRS-1 are emulsified asphalts with residual percentages of 55.3%, 63.0%, and 58.2%, respectively. On the other hand, PG 64-22 has 100% residual. The tests performed were penetration, absolute viscosity, rotational viscosity, and softening point. Two replicates of each test were conducted. As shown in Figure 55a, trackless material was the hardest followed by SS-1h, PG 64-22, and CRS-1. Ranking of viscosity of the materials from this test was consistent with the results of the penetration test (see Figure 55b). In addition, trackless
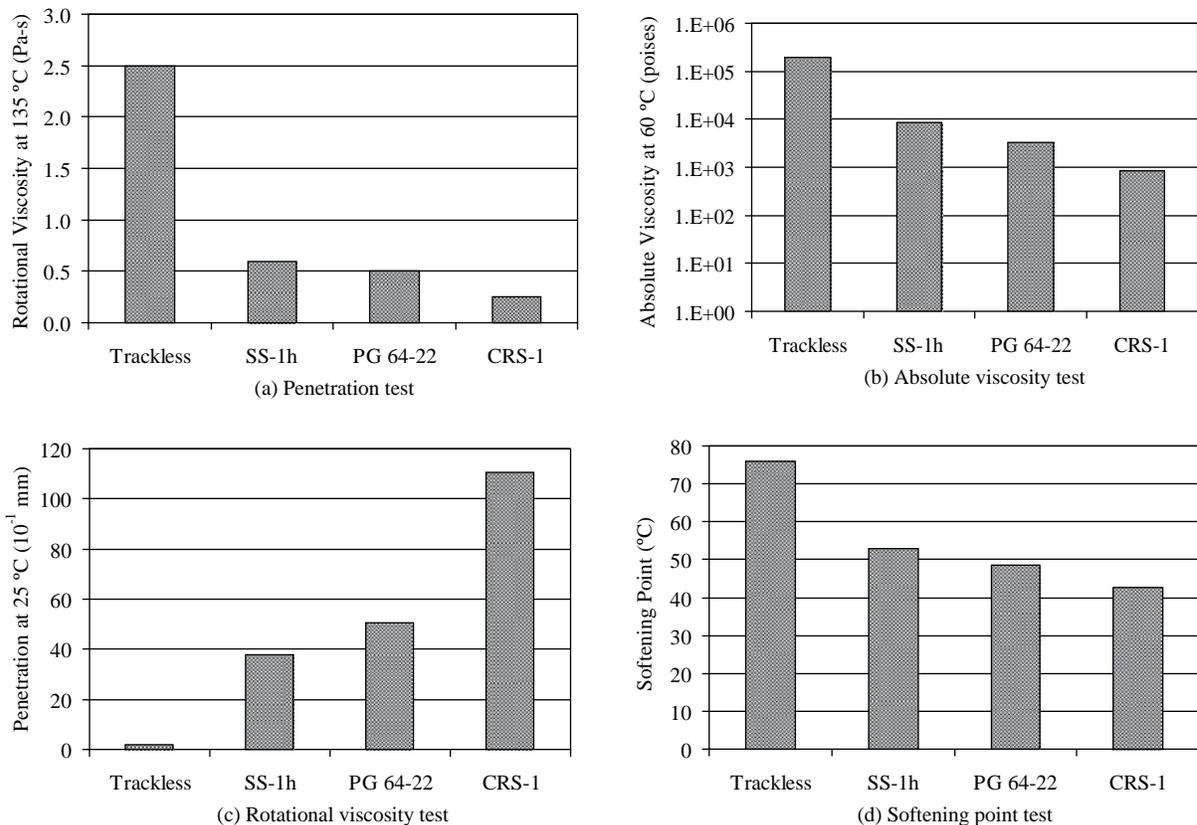
Figure 55. Rheological test results of tack coat materials.

residues exhibited the highest rotational viscosity, whereas CRS-1 residues had the lowest rotational viscosity (see Figure 55c). Furthermore, the ranking of the softening point test results was similar to the ranking of the results of the penetration test, absolute viscosity test, and rotational viscosity test (see Figure 55d). The ranking of the materials from hardest to softest was trackless residual, the SS-1h residual, PG 64-22 binder, and the CRS-1 residual.

4.3.1 Superpave Grading of Emulsified Tack Coats

Emulsified tack coats are composed of three basic ingredients: asphalt, water, and emulsifying agent. The asphalt binder residues were obtained according to *AASHTO D 244, Residue by Evaporation.* Table 16 presents the results of tests performed on these residues. It is noted that the residues of CRS-1 and SS-1h emulsions were graded as PG 58-22 and 70-22, respectively. The trackless material, however, failed the intermediate- and low-temperature performance criteria. This response was expected since trackless is a polymer-modified emulsion with a hard base asphalt cement.

To establish sound correlations between the rheological properties of emulsified tack coat materials and ISS, trackless and CRS-1 were tested using the dynamic shear rheometer at temperatures ranging from −10° to 60°C with a 10°C interval. Testing was conducted using an AR2000 rheometer in the dynamic shear mode. Two sample sizes were used, depending on the testing temperature: a sample with a 25-mm diameter and 1-mm thickness was used at high temperatures (from 40° to 60°C), and 8-mm diameter and 2-mm thickness was used at low and intermediate temperatures (from −10° to 30°C). Figure 56 presents the dynamic shear rheometer (DSR) test results for both tack coat materials. As shown in this figure, the complex shear modulus (G^*) increased linearly for both tack coat materials on a semi-logarithmic scale. As expected, the trackless materials produced higher G^* values than did CRS-1.

4.3.2 Relationship Between LTCQT Test Results and Tack Coat Rheological Properties

The LTCQT test was performed on four tack coat materials: trackless, CRS-1, SS-1h, and PG 64-22. Based on these

Table 16. Rheological test results of emulsified tack coat residues.

Aging Status	Test Property	AASHTO Method	Spec.	PG 64-22	SS-1h residual	SS-1 residual	CRS-1 residual	Trackless residual
Original Binder	Rotational viscosity, Pa.s 135°C	T 316	3.0–	0.5	0.6	0.3	0.3	2.5
	Dynamic shear 10 rad/s G*/sinδ, kPa	T 315	1.0+	1.86 (64°C)	15.4 (52°C)	2.5 (52°C)	3.0 (52°C)	19.0 (64°C)
					6.5 (58°C)	1.3 (58°C)	1.3 (58°C)	7.6 (70°C)
					2.9 (64°C)	0.8 (64°C)	0.6 (64°C)	3.4 (76°C)
					1.4 (70°C)			1.5 (82°C)
					0.7 (76°C)			0.7 (88°C)
	Softening Point				53°C		42.5°C	76°C
Rolling Thin-Film Oven Residue	Mass change, %	T 240	1.0–	0.009	0.1	0.1	0.1	NA
	Dynamic shear 10 rad/s, G*/sinδ, kPa	T 315	2.20+	4.4 (64°C)	2.8 (70°C)	2.2 (58°C)	2.9 (58°C)	16.9 (70°C)
								7.4 (76°C)
								3.4 (82°C)
								1.5 (88°C)
Pressure Aging Vessel Residue 100°C	Dynamic shear, 10 rad/s , G*sinδ, kPa	T 315	5000–	3,177 (25°C)	3,239 (25°C)	2,411 (19°C)	3,306 (19°C)	10,907 (25°C)
	Bending Beam Creep stiffness, S, MPa 60s	T 313	300–	210 (−12°C)	165.0 (−12°C)	84.5 (−12°C)	86.8 (−12°C)	*
						174 (−18°C)	187.0 (−18°C)	
	Bending Beam Creep stiffness, m-value 60s	T 313	0.300+	0.285 (−12°C)	0.320 (−12°C)	0.42 (−12°C)	0.340 (−12°C)	*
						0.34 (−18°C)	0.310 (−18°C)	
	Direct tension 1.0 mm/min, %	T 314	1.0+	1.2 (−12°C)	1.6 (−12°C)	1.1 (−18°C)	1.1 (−18°C)	*
PG Grading				PG 64-22	PG 70-22	PG 58-28	PG 58-28	—

*Sample was brittle and failed.
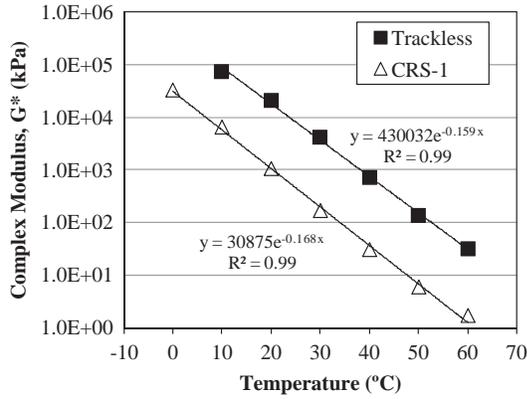
Figure 56. Relationship between complex modulus (G*) for unaged residues of trackless and CRS-1 and temperature.

measurements, the relationship between tack coat bonding characteristics and the rheology of the material was established. Figure 57b shows the relationship between the tensile strength and the corresponding absolute viscosity, both at 60°C, for each tack coat material (i.e., residual from emulsion). As expected, the increase in viscosity (i.e., resistance to flow) is associated with an increase in tensile strength. Figure 57a presents the relationship between the optimum temperature (T_{OPT}), at which S_{MAX} occurs, and the corresponding softening point for each tack coat material. At the softening point, an applied tack coat is in a rheological state that provides sufficient adhesion to the LTCQT loading plate for tensile testing. As the temperature is increased, tack coat consistency is not sufficient to provide full adhesion in the LTCQT loading plate. Based on these results, it is recommended to conduct the LTCQT test at the tack coat material softening point, which is a property that is readily available and can be easily specified.

4.3.3 Measurements of Tack Coat Bond Strength at the Softening Point

Additional LTCQT tests were conducted in the field to evaluate the repeatability of the ultimate tensile load, P_{ULT}, of the four tack coat materials (CRS-1, SS-1h, trackless, PG 64-22) at the softening point. For each tack coat material, at least three LTCQT tests were performed. Table 17 presents the measured tensile strength at the softening point for the four tack coat materials. Test temperature was controlled within ±5°C from the material softening point. Test results show that PG 64-22 and CRS-1 had the highest and lowest tensile strengths (or ultimate tensile loads), respectively. Tensile strengths for both SS-1h and trackless were similar, and they were ranked between those of PG 64-22 and CRS-1. Figure 58 presents the ultimate tensile loads for the four tack coat materials. The ranking of tensile strength is in good agreement with those presented in Table 17; therefore, it may be concluded that conducting the tack coat pull-off test at the softening point can successfully and consistently evaluate the quality of tack coat application in the field. Following the recommended testing procedure, the LTCQT has shown acceptable repeatability for all of the tested tack coat materials. For all four materials tested, the repeatability of the results was reasonable with an average coefficient of variation less than 11%.

4.4 Experiment III: Development of a Laboratory Test Procedure to Measure the Interface Bond Strength

A direct shear device was developed for the characterization of ISS of cylindrical specimens (see Figure 59). The device, which was developed through an iterative process, is

(a)　　　　　　　　　　　(b)
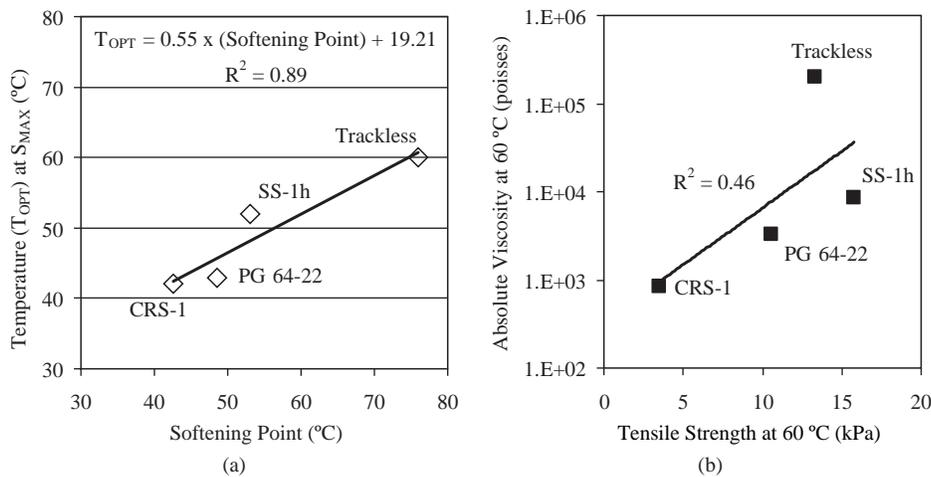
Figure 57. Relationship between absolute viscosity and softening point and the optimum test temperature.

Table 17. Tensile strength at softening point for four tack coat materials.

Material Type	Softening Point (°C)	Ultimate Tensile Load P_{ULT}, (lb)	Tensile Strength S_{ULT}, (psi)	Mean (P_{ULT}/S_{ULT})	Standard Deviation (P_{ULT}/S_{ULT})	COV (%)
CRS-1	42.5	30.9	1.6	37.7 / 1.9	4.9 / 0.2	13.0/12.4
		43.8	2.2			
		35.5	1.8			
		40.4	2.1			
		38.1	1.9			
PG 64-22	48.5	66.9	3.4	62.8 / 3.2	6.0 / 0.3	9.6/10.2
		65.6	3.3			
		55.9	2.8			
SS-1h	53.0	40.3	2.0	44.7 / 2.3	3.9 / 0.2	8.7/9.1
		49.8	2.5			
		44.4	2.3			
		44.3	2.3			
Trackless	76.0	44.7	2.3	44.5 / 2.3	5.4 / 0.3	12.0/11.1
		49.8	2.5			
		39.1	2.0			

referred to as the Louisiana Interlayer Shear Strength Tester (LISST). It consists of two main parts—a shearing frame and a reaction frame. Only the shearing frame is allowed to move while the reaction frame is stationary. A cylindrical specimen is placed inside the shearing and reaction frames and is locked in place with collars. Loading is then applied to the shearing frame. As the vertical load is gradually increased, shear failure occurs at the interface.

The LISST device was designed such that it will fit into any universal testing machine. It has a nearly frictionless linear bearing to maintain vertical travel and can accommodate sensors that measure vertical and horizontal displacements. The device provides a specimen-locking adjustment, applies a constant normal load up to 100 psi, and accommodates a specimen with 4-in or 6-in diameters. The gap between the shearing and the reaction frame is 0.5 in. A wide range of experiments was conducted in order to evaluate the ruggedness and reliability of the LISST. Experiments were conducted comparing the results from this device with those of the Superpave Shear Tester (SST). ISSs of the LISST and SST were similar when dilation was allowed; however, those results were significantly different when dilation was not allowed or was limited in the SST device. Details of these experiments are described in Appendix D. Three shear displacement rates of loading were evaluated (i.e., 2 in/min, 0.1 in/min, and 0.02 in/min). Based on these evaluations, a rate of loading of 0.1 in/min was recommended in the testing procedure to simulate the slow rate of loading encountered at the interface in the field. A test procedure for measuring interface bond strength in the laboratory using the LISST device, written in AASHTO format, is presented in Appendix E.

Figure 60 presents a typical test result of shear stress versus displacement curve. The ISS is computed as follows:

$$ISS = P_{ULT}/A \qquad (1)$$

where,

ISS = interface shear strength (ksi);
P_{ULT} = ultimate load applied to specimen (lb); and
A = cross-sectional area of test specimen (in^2).

Figure 58. Ultimate tensile load (P_{ULT}) for tack coat materials at the softening point.
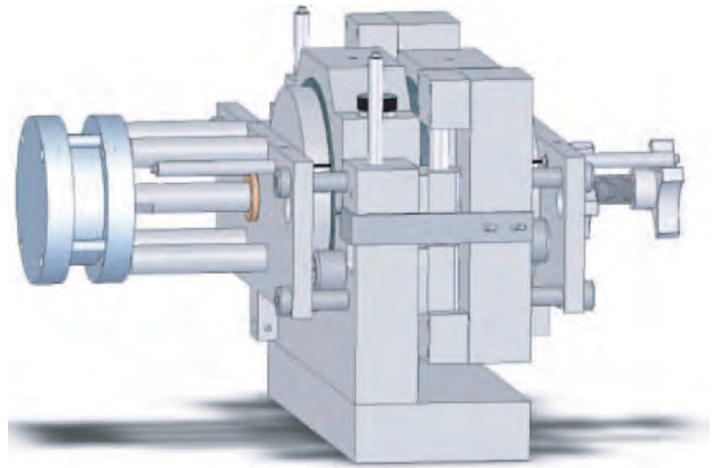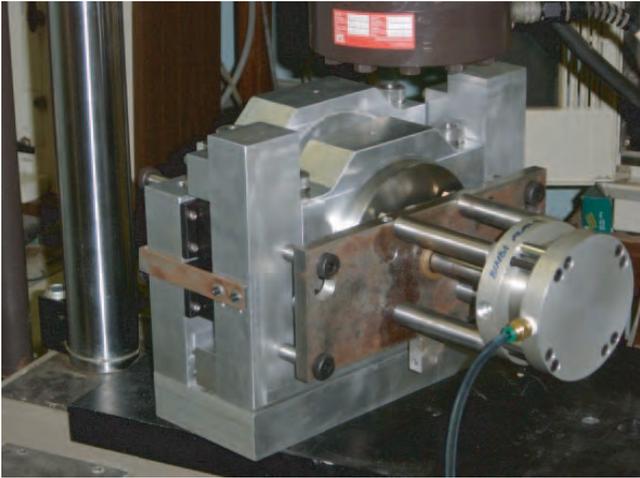
Figure 59. General description of the Louisiana Interlayer Shear Strength Tester.

$$\tau = k\xi \qquad (2)$$

where,

τ = interlayer shear stress (ksi);
ξ = interlayer displacement within the interface (in); and
k = interlayer tangential modulus (lb/ft^3).

The k-modulus is computed by dividing the peak stress by the displacement at failure from the stress versus displacement curve (see Figure 60).

4.4.1 Effects of Tack Coat Characteristics on Interface Shear Strength

Tables 18 and 19 present the mean ISS test results along with their standard deviations and coefficient of variations

for SS-1h, CRS-1, and trackless tack coats, respectively. Triplicate specimens were tested for each test condition defined by tack coat type, residual application rate, confining pressure, and dusty and wet conditions. All tests were performed at a temperature of 25°C. In general, the COVs in the test results were less than 10%. As shown in the following sections, results were analyzed to investigate the effects of variables considered in the test factorial on the ISS.

Effect of Emulsified Tack Coat Types and Residual Application Rates

Tables 20 and 21 present the statistical analyses of the effects of application rates and tack coat types on ISS based on a two-tailed *t*-test at a 95% confidence level. As shown in these
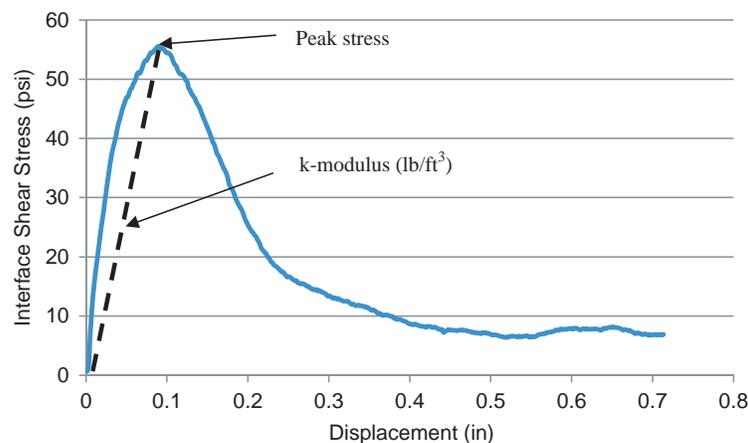
Figure 60. Typical interface shear stress versus displacement for trackless at 0.06 gal/yd².

Table 18. ISS of SS-1h emulsified tack coat.

Confinement Pressure (psi)	Tack Coat	SS-1h											
	Residual Appl. Rate (gal/yd²)	0.031				0.062				0.155			
	Surface Condition	D[1] H[3]	D L[4]	W[2] H	W L	D H	D L	W H	W L	D H	D L	W H	W L
0	ISS (psi)	11.1	13.5	13.6	12.7	14.6	7.5	16.3	12.7	36.8	32.9	44.0	34.0
		9.7	12.9	13.1	13.2	12.0	8.0	18.1	11.7	41.7	40.1	37.7	34.5
		12.9	14.5	15.5	15.0	13.2	7.8	16.8	13.6	40.3	34.9	37.8	34.8
	Mean	11.2	13.6	14.0	13.6	13.3	7.8	17.1	12.7	39.6	36.0	39.8	34.4
	S.D.	1.6	0.8	1.3	1.2	1.3	0.3	0.9	0.9	2.5	3.7	3.7	0.4
	COV	14.2	5.9	9.0	8.8	9.8	3.7	5.4	7.3	6.4	10.3	9.2	1.2
20	ISS (psi)	16.5	20.9	13.7	24.5	18.6	10.4	15.2	15.5	40.4	51.9	38.5	47.7
		15.7	20.2	16.1	22.4	14.9	11.6	17.8	16.6	43.6	44.0	38.5	45.4
		18.8	26.1	15.9	19.3	17.6	12.9	19.1	16.3	40.7	43.9	41.2	43.4
	Mean	17.0	22.4	15.2	22.1	17.0	11.6	17.4	16.2	41.6	46.6	39.4	45.5
	S.D.	1.6	3.2	1.4	2.6	1.9	1.2	1.9	0.6	1.8	4.6	1.6	2.1
	COV	9.5	14.3	9.0	11.7	11.3	10.6	11.2	3.4	4.2	9.8	4.0	4.7

[1] Dry Condition, [2] Wet Condition, [3] Clean Condition, [4] Dusty Condition.

Table 19. ISS of CRS-1 and trackless emulsified tack coat.

Confinement Pressure (psi)	Tack Coat	CRS-1						Trackless					
	Residual Appl. Rate (gal/yd²)	0.031		0.062		0.155		0.031		0.062		0.155	
	Surface Condition	D[1] H[2]	D L[3]	D H	D L	D H	D L	D H	D L	D H	D L	D H	D L
0	ISS (psi)	6.9	10.3	12.3	10.3	12.6	24.6	13.3	20.1	28.4	51.3	58.0	60.2
		6.6	10.0	11.4	13.1	15.6	23.9	16.0	22.4	24.6	49.7	61.0	60.5
		8.5	7.8	13.3	12.2	14.3	24.1	13.9	23.6	22.2	61.2	68.1	65.1
	Mean	7.3	9.4	12.4	11.8	14.2	24.2	14.4	22.0	25.1	54.1	62.4	62.0
	S.D.	1.0	1.3	0.9	1.4	1.5	0.4	1.5	1.8	3.1	6.3	5.2	2.7
	COV	14.1	14.2	7.6	11.9	10.9	1.5	10.2	8.1	12.3	11.6	8.3	4.4
20	ISS (psi)	10.2	16.9	14.0	18.8	12.9	34.2	18.0	34.3	35.2	75.2	65.2	79.6
		13.3	13.6	11.5	20.3	15.6	33.4	22.6	26.4	34.0	76.9	55.8	74.9
		11.0	15.4	11.7	17.5	16.8	34.2	22.2	31.9	38.6	69.7	70.2	75.3
	Mean	11.5	15.3	12.4	18.9	15.1	33.9	20.9	30.8	35.9	73.9	63.7	76.6
	S.D.	1.6	1.6	1.4	1.4	2.0	0.5	2.5	4.0	2.4	3.8	7.3	2.6
	COV	14.3	10.5	11.2	7.3	13.1	1.4	12.0	13.1	6.7	5.1	11.5	3.4

[1] Dry Condition, [2] Clean Condition, [3] Dusty Condition.

Table 20. Statistical analysis of the effects of application rates on ISS.

Tack Coat	Statistical Test	Condition	Confinement	*P*-value	Results
SS-1h	Application Rates	Clean-Dry	Unconfined	< 0.0001	Significant
	Application Rates	Clean-Dry	Confined	< 0.0001	Significant
	Application Rates	Dusty-Dry	Unconfined	< 0.0001	Significant
	Application Rates	Dusty-Dry	Confined	< 0.0001	Significant
	Application Rates	Clean-Wet	Unconfined	< 0.0001	Significant
	Application Rates	Clean-Wet	Confined	< 0.0001	Significant
	Application Rates	Dusty-Wet	Unconfined	< 0.0001	Significant
	Application Rates	Dusty-Wet	Confined	< 0.0001	Significant
CRS-1	Application Rates	Clean-Dry	Unconfined	0.0010	Significant
	Application Rates	Clean-Dry	Confined	0.0893	Not Significant
	Application Rates	Dusty-Dry	Unconfined	< 0.0001	Significant
	Application Rates	Dusty-Dry	Confined	< 0.0001	Significant
Trackless	Application Rates	Clean-Dry	Unconfined	< 0.0001	Significant
	Application Rates	Clean-Dry	Confined	< 0.0001	Significant
	Application Rates	Dusty-Dry	Unconfined	< 0.0001	Significant
	Application Rates	Dusty-Dry	Confined	< 0.0001	Significant

tables, all cases except one indicated that tack coat types and application rates had significant effects on the measured ISS.

Figure 61a presents the variation of ISS with emulsified tack coat types and residual application rates. The results were obtained from clean and dry specimens with no confinement at 25°C. For each residual application rate, the trackless tack coat exhibited the highest shear strength and CRS-1 exhibited the lowest. Trackless and SS-1h yielded similar and higher ISSs than CRS-1 at the low residual application rate—that is, 0.031 gal/yd^2.

All tack coat materials showed the highest strength at a residual application rate of 0.155 gal/yd^2. Shear strength of SS-1h and trackless consistently increased as residual application rate increased. In contrast, measured shear strength for CRS-1 appeared to stabilize at a residual application rate

around 0.062 gal/yd^2. Similar trends were noted at a confinement pressure of 20 psi. For the residual application rates tested, it was not possible to determine the optimum residual application rate. This may be attributed to the highly oxidized HMA surface at the PRF site, which required greater tack coat rates than expected. It may also indicate that, under actual field conditions, optimum residual application rates may be greater than that commonly predicted from laboratory-based experiments. While higher residual application rates may increase ISS, excessive tack coat may migrate into the HMA mat during compaction, causing a decrease in the air void content of the mix. Figure 61b presents the variation of the measured air voids of the overlaid mixture for each residual application rate. As shown in this figure, the increase in residual tack coat application rate was associated with a decrease in air

Table 21. Statistical analysis of the effects of tack coat types on ISS.

Rate	Statistical Test	Condition	Confinement	*P*-value	Results
0.031	Tack Coat Type	Clean-Dry	Unconfined	0.0022	Significant
	Tack Coat Type	Clean-Dry	Confined	0.0032	Significant
	Tack Coat Type	Dusty-Dry	Unconfined	< 0.0001	Significant
	Tack Coat Type	Dusty-Dry	Confined	0.0027	Significant
0.062	Tack Coat Type	Clean-Dry	Unconfined	0.0004	Significant
	Tack Coat Type	Clean-Dry	Confined	< 0.0001	Significant
	Tack Coat Type	Dusty-Dry	Unconfined	< 0.0001	Significant
	Tack Coat Type	Dusty-Dry	Confined	< 0.0001	Significant
0.155	Tack Coat Type	Clean-Dry	Unconfined	< 0.0001	Significant
	Tack Coat Type	Clean-Dry	Confined	< 0.0001	Significant
	Tack Coat Type	Dusty-Dry	Unconfined	< 0.0001	Significant
	Tack Coat Type	Dusty-Dry	Confined	< 0.0001	Significant
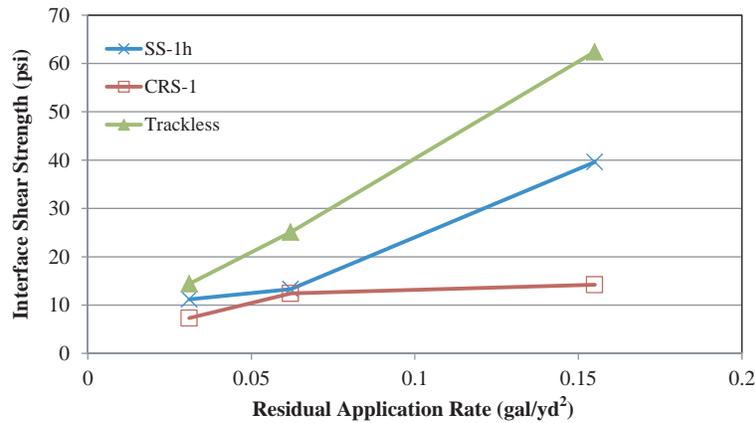
(a)
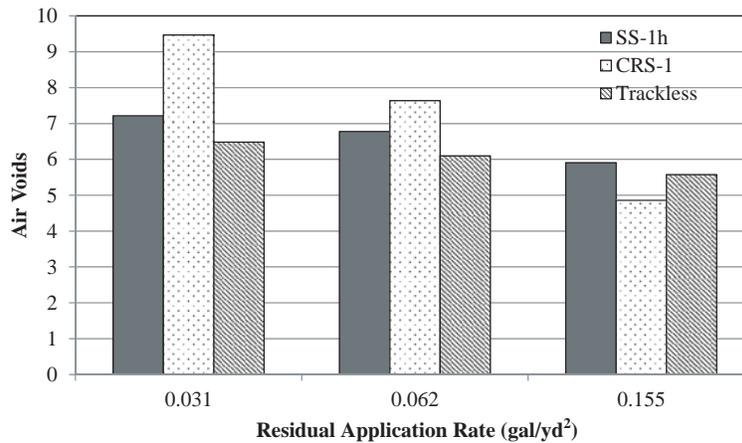
(b)

Figure 61. Variation of ISS with residual application rates (a) and variation of air voids with residual application rates: clean and dry condition, no confinement, 25°C (b).

voids. This may result in negative effects on the overlay performance, such as the appearance of "fat spots" on the pavement surface, which may affect the friction properties of the mat.

Several attempts were made to core the no-tack coat test area; however, these specimens failed at the interface during the coring process. It is noted that the best tack coat performer—trackless at the highest residual application rate—provided 60% of the monolithic (no interface) mixture shear strength at 25°C, which was estimated at 105 psi. The worst tack coat performer—CRS-1—provided only 15% of the mixture shear strength at the highest residual application rate. This suggests that the construction of flexible pavements in multiple layers introduces weak zones at these interfaces.

Figure 62 presents the relationships between rotational viscosity, $G^*/\sin \delta$, and the softening point of the tack base asphalt with ISS at a residual application rate of 0.155 gal/yd^2. In general, good correlations were observed between these rheological properties and the ISS values. The measured interface strength increased as the tack coat viscosity

and its resistance to deformation at high temperatures ($G^*/\sin \delta$) increased. Similar trends were observed at the low and intermediate residual application rates.

4.4.2 Effect of Confining Pressure

Table 22 presents the statistical analysis of the effects of confinement on ISS based on t-tests. As shown in this table, the majority of the cases (17 out of the 24 cases) indicated that confinement has a significant effect on the measured ISS. Figure 63 shows the ratio of ISS between the 0 and 20 psi confinement test conditions. The ratio of ISS between these two test conditions increased as the residual application rate decreased. As the residual application rate decreased, increasing the confining pressure resulted in a more pronounced contribution of the effect of roughness and aggregate resistance to sliding at the interface; however, at higher residual application rates (i.e., greater lubrication), the effect of aggregate roughness and resistance to sliding was less crucial since most of the ISS was

(a) Rotational Viscosity

(b) Dynamic Shear Rheometer

(c) Softening Point
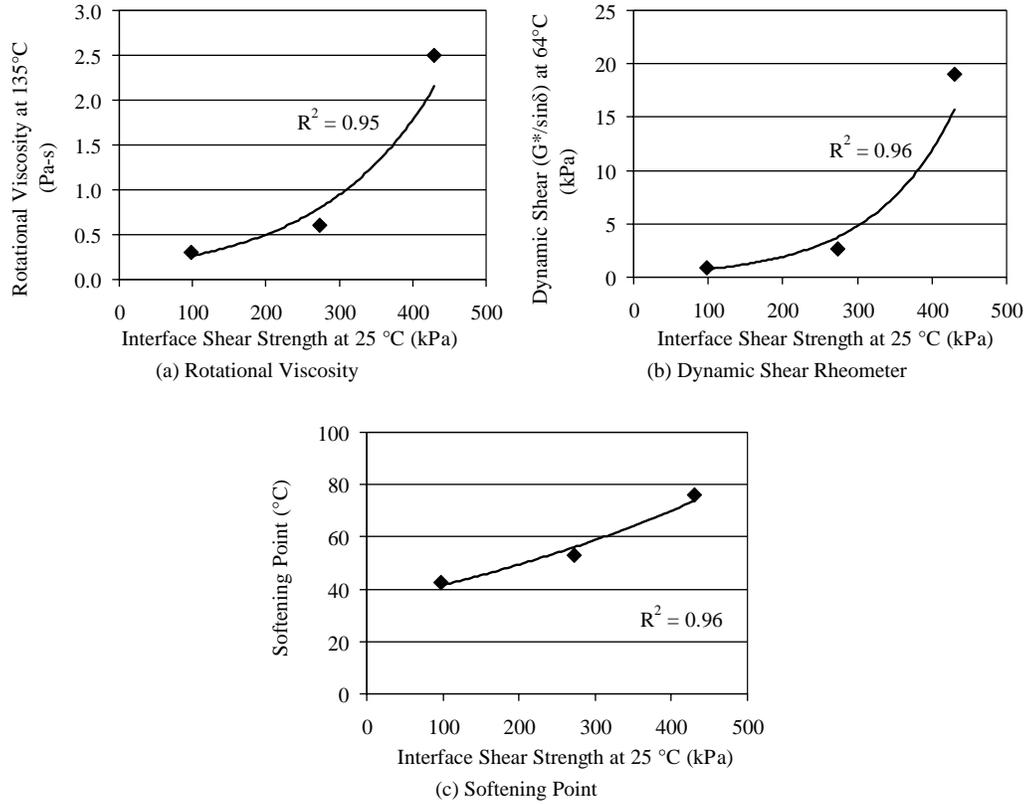
Figure 62. Relationship between ISS with 0.155 gal/yd² and rheology test results.

Table 22. Statistical analysis of the effects of confinement on ISS.

Tack	Rate	Statistical Test	Condition	*P*-value	Results
SS-1h	0.031	Unconfined vs. Confined	Clean-Dry	0.0110	Significant
		Unconfined vs. Confined	Dusty-Dry	0.0440	Significant
		Unconfined vs. Confined	Clean-Wet	0.3330	Not Significant
		Unconfined vs. Confined	Dusty-Wet	0.0150	Significant
	0.062	Unconfined vs. Confined	Clean-Dry	0.0480	Significant
		Unconfined vs. Confined	Dusty-Dry	0.0344	Significant
		Unconfined vs. Confined	Clean-Wet	0.8279	Not Significant
		Unconfined vs. Confined	Dusty-Wet	0.0123	Significant
	0.155	Unconfined vs. Confined	Clean-Dry	0.3309	Not Significant
		Unconfined vs. Confined	Dusty-Dry	0.0356	Significant
		Unconfined vs. Confined	Clean-Wet	0.8608	Not Significant
		Unconfined vs. Confined	Dusty-Wet	0.0128	Significant
CRS-1	0.031	Unconfined vs. Confined	Clean-Dry	0.0323	Significant
		Unconfined vs. Confined	Dusty-Dry	0.0087	Significant
	0.062	Unconfined vs. Confined	Clean-Dry	0.9486	Not Significant
		Unconfined vs. Confined	Dusty-Dry	0.0037	Significant
	0.155	Unconfined vs. Confined	Clean-Dry	0.5532	Not Significant
		Unconfined vs. Confined	Dusty-Dry	< 0.0001	Significant
Trackless	0.031	Unconfined vs. Confined	Clean-Dry	0.0303	Significant
		Unconfined vs. Confined	Dusty-Dry	0.0407	Significant
	0.062	Unconfined vs. Confined	Clean-Dry	0.0087	Significant
		Unconfined vs. Confined	Dusty-Dry	0.0179	Significant
	0.155	Unconfined vs. Confined	Clean-Dry	0.8048	Not Significant
		Unconfined vs. Confined	Dusty-Dry	0.0026	Significant

(a) Clean and Dry Conditions (b) Dusty and Dry Conditions
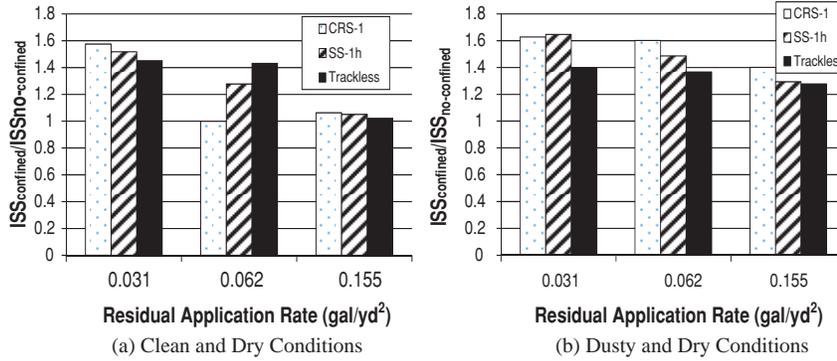
Figure 63. Ratio of ISS with confinement to no confinement.

derived from the tack coat material. The effect of confinement was more pronounced under dusty and dry conditions.

4.4.3 Effect of Dusty Conditions of HMA Surface

Table 23 presents the statistical analysis of the effects of dusty conditions on ISS based on a two-tailed *t*-test at a 95% confidence level. As shown in this table, results were mixed, with 13 out of the 24 cases indicating that dusty conditions

had a significant effect on the measured ISS. Figure 64 presents the effects of dust on the ISS values at no confinement and confinement (20 psi) test conditions. As shown in Figure 64, the majority of the cases showed differences between clean and dusty conditions. In general, dusty conditions exhibited higher interface strength than clean conditions, especially when tested with a confinement condition. One possible explanation for these results is that a high-viscosity, gritty mastic was formed when tack coat combined with dust and, thus, provided a greater resistance to shear movement.

Table 23. Statistical analysis of the effects of dusty conditions on ISS.

Tack	Statistical Test	Rate	Condition	Confinement	*P*-value	Results
SS-1h	Clean vs. Dusty	0.031	Dry	Unconfined	0.1036	Not Significant
	Clean vs. Dusty	0.031	Dry	Confined	0.0806	Not Significant
	Clean vs. Dusty	0.031	Wet	Unconfined	0.6903	Not Significant
	Clean vs. Dusty	0.031	Wet	Confined	0.0274	Significant
	Clean vs. Dusty	0.062	Dry	Unconfined	0.0188	Significant
	Clean vs. Dusty	0.062	Dry	Confined	0.0264	Significant
	Clean vs. Dusty	0.062	Wet	Unconfined	0.0046	Significant
	Clean vs. Dusty	0.062	Wet	Confined	0.4097	Not Significant
	Clean vs. Dusty	0.155	Dry	Unconfined	0.2339	Not Significant
	Clean vs. Dusty	0.155	Dry	Confined	0.1744	Not Significant
	Clean vs. Dusty	0.155	Wet	Unconfined	0.1234	Not Significant
	Clean vs. Dusty	0.155	Wet	Confined	0.0165	Significant
CRS-1	Clean vs. Dusty	0.031	Dry	Unconfined	0.1078	Not Significant
	Clean vs. Dusty	0.031	Dry	Confined	0.0462	Significant
	Clean vs. Dusty	0.062	Dry	Unconfined	0.6699	Not Significant
	Clean vs. Dusty	0.062	Dry	Confined	0.0048	Significant
	Clean vs. Dusty	0.155	Dry	Unconfined	0.0078	Significant
	Clean vs. Dusty	0.155	Dry	Confined	0.0039	Significant
Trackless	Clean vs. Dusty	0.031	Dry	Unconfined	0.0044	Significant
	Clean vs. Dusty	0.031	Dry	Confined	0.0369	Significant
	Clean vs. Dusty	0.062	Dry	Unconfined	0.0055	Significant
	Clean vs. Dusty	0.062	Dry	Confined	0.0007	Significant
	Clean vs. Dusty	0.155	Dry	Unconfined	0.9063	Not Significant
	Clean vs. Dusty	0.155	Dry	Confined	0.0640	Not Significant
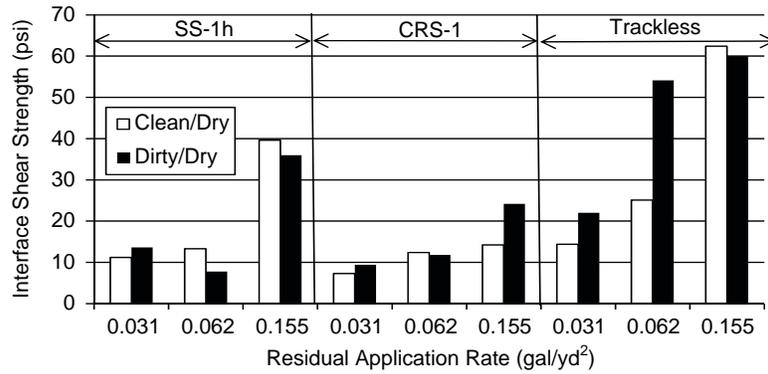
(a) No-Confinement Condition
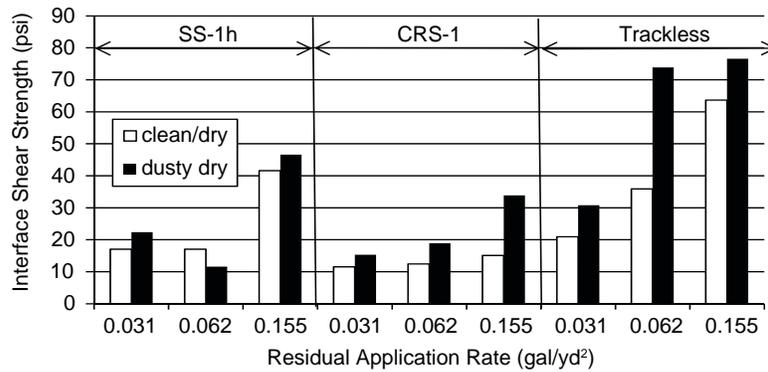
(b) Confinement Condition

Figure 64. Dust effect on ISS with (a) no-confinement and (b) confinement.

4.4.4 Effect of Wet (Rainfall) Conditions of Tacked Surface

Table 24 presents the statistical analysis of the effects of wet conditions on ISS based on a two-tailed *t*-test at a 95% confidence level. As shown in this table, the majority of the cases indicated that wet conditions had no significant effect on the measured ISS. Figure 65 presents the effects of water (i.e., light rainfall) of a tacked surface at no confinement and with confinement (20 psi) on ISS. It is noted that the majority of the cases showed no significant differences between dry and wet conditions.

4.4.5 Effects of Tack Coat Coverage

As previously discussed, 50% tack coat coverage was only investigated for SS1-h. For the application of SS-1h, the residual application rate of 0.031 gal/yd^2 was achieved with a high level of error (see Table 5); therefore, this residual application rate was not considered in the analysis. On the other hand, the residual application rates of 0.062 and 0.155 gal/yd^2 at 50% coverage were comparable with the ones at 100% coverage. Figure 66 compares the measured ISS for 50 and

100% coverage. As shown in this figure, using 50% coverage significantly reduced the ISS by a factor ranging from 50% to 70%.

Table 25 presents the LTCQT test results for 50% coverage. The tensile strength test results were highly variable. This may be due to the partial coverage of the tacked surfaces. For actual pavements, this suggests inconsistent interface bonding behavior for tacked surfaces with incomplete or non-uniform coverage.

4.5 Experiment IV: Effects of Test Temperature and Its Relationship with Tack Coat Rheology

4.5.1 Interface Bond Strength at Various Temperatures

Table 26 presents the ISS test results for trackless and CRS-1 specimens. Each value represents the average of two test specimens. At temperatures over 50°C, some specimens collapsed before shearing due to their own weights. This mostly occurred at the low residual application rate and for the CRS-1 emulsion. As shown in Table 26, the trackless material

Table 24. Statistical analysis of the effects of wet conditions on ISS.

Tack	Statistical Test	Rate	Condition	Confinement	*P*-value	Results
	Dry vs. Wet	0.031	Clean	Unconfined	0.0743	Not Significant
	Dry vs. Wet	0.031	Clean	Confined	0.2168	Not Significant
	Dry vs. Wet	0.031	Dusty	Unconfined	1.0000	Not Significant
	Dry vs. Wet	0.031	Dusty	Confined	0.8961	Not Significant
	Dry vs. Wet	0.062	Clean	Unconfined	0.0147	Significant
	Dry vs. Wet	0.062	Dusty	Confined	0.8444	Not Significant
SS-1h	Dry vs. Wet	0.062	Clean	Unconfined	0.0132	Significant
	Dry vs. Wet	0.062	Dusty	Confined	0.0108	Significant
	Dry vs. Wet	0.155	Clean	Unconfined	0.9313	Not Significant
	Dry vs. Wet	0.155	Dusty	Confined	0.1865	Not Significant
	Dry vs. Wet	0.155	Clean	Unconfined	0.5511	Not Significant
	Dry vs. Wet	0.155	Dusty	Confined	0.7320	Not Significant
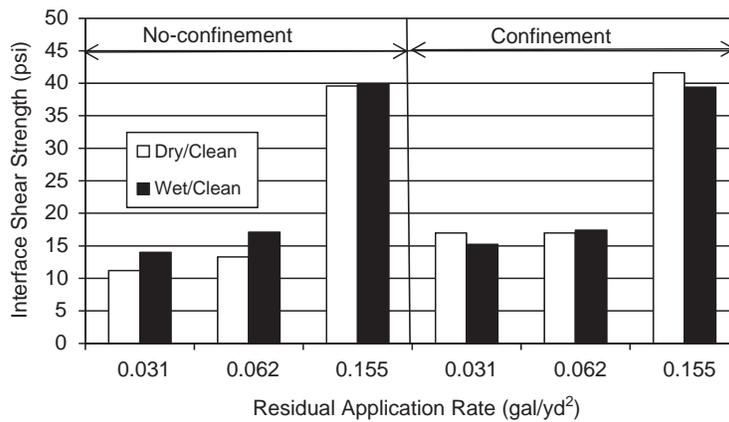
(a) Clean Condition
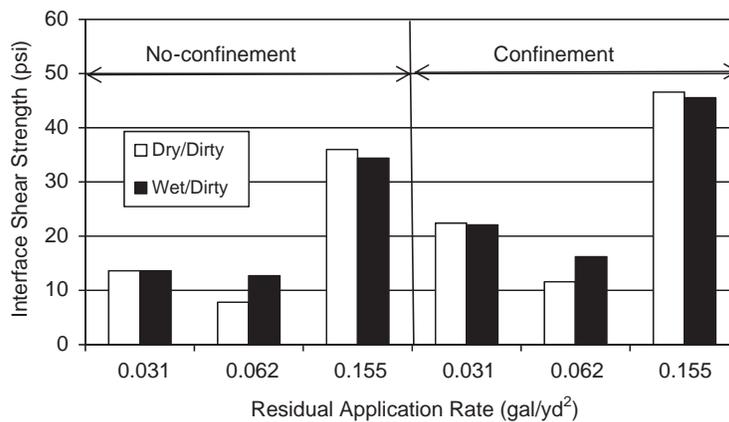
(b) Dusty Condition

Figure 65. Effect of wetness on ISS for SS-1h tack coat with (a) clean and (b) dusty conditions.
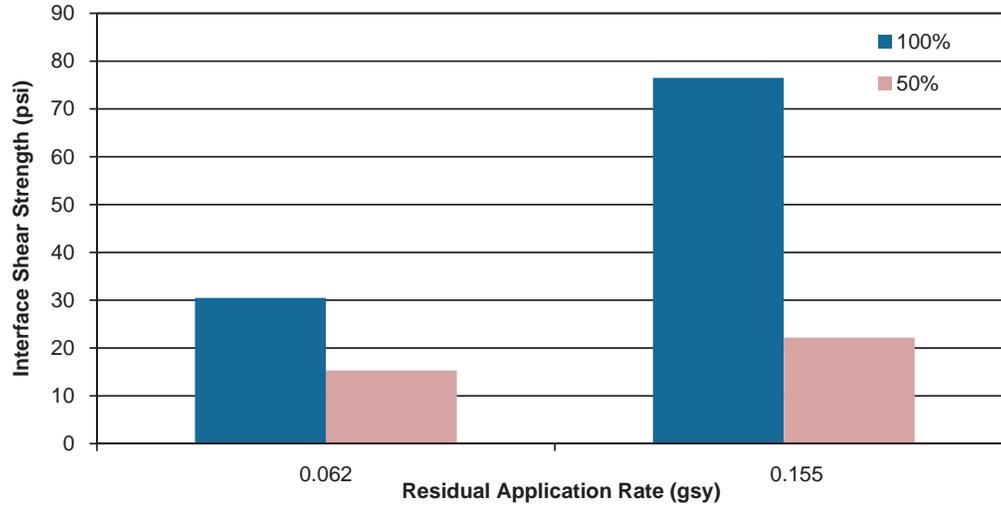
Figure 66. Effect of tack coat coverage on ISS.

Table 25. LTCQT test results with 50% coverage surface.

Tack Coat Material[1]	Residual Application Rate	Test Temperature (°C)	Maximum Tensile Load (lb)	Maximum Tensile Strength (psi)	Average (P_{ULT}/S_{ULT})	Standard Deviation (P_{ULT}/S_{ULT})	COV (%)
SS-1h 50%	0.031	51.0	12.3	0.63	8.6/0.44	3.48/0.18	40.4
		55.0	5.4	0.28			
		57.0	8.1	0.41			
	0.155	52.0	14.3	0.73	12.3/0.62	2.78/0.14	23.0
		51.0	9.1	0.46			
		53.0	13.4	0.68			

[1] All tack coats were tested at 53°C.

Table 26. ISS at various test temperatures.

Temperature (ºC)	Mean ISS (psi)					
	Trackless			CRS-1		
	0.031 gal/yd^2	0.062 gal/yd^2	0.155 gal/yd^2	0.031 gal/yd^2	0.062 gal/yd^2	0.155 gal/yd^2
−10	132.0	255.7	370.4	147.6	196.8	331.7
0	127.1	263.1	401.9	111.7	171.3	216.3
10	88.5	194.1	322.7	85.4	91.1	120.4
20	39.7	101.8	167.5	46.0	46.3	45.5
30	21.9	45.8	75.3	11.0	16.8	21.5
40	3.8	17.8	34.1	2.9	1.9	3.2
50	*	4.4	14.2	*	*	2.8
60	*	5.4	18.0	*	*	*

*Specimens collapsed under their own weights before shear loading.
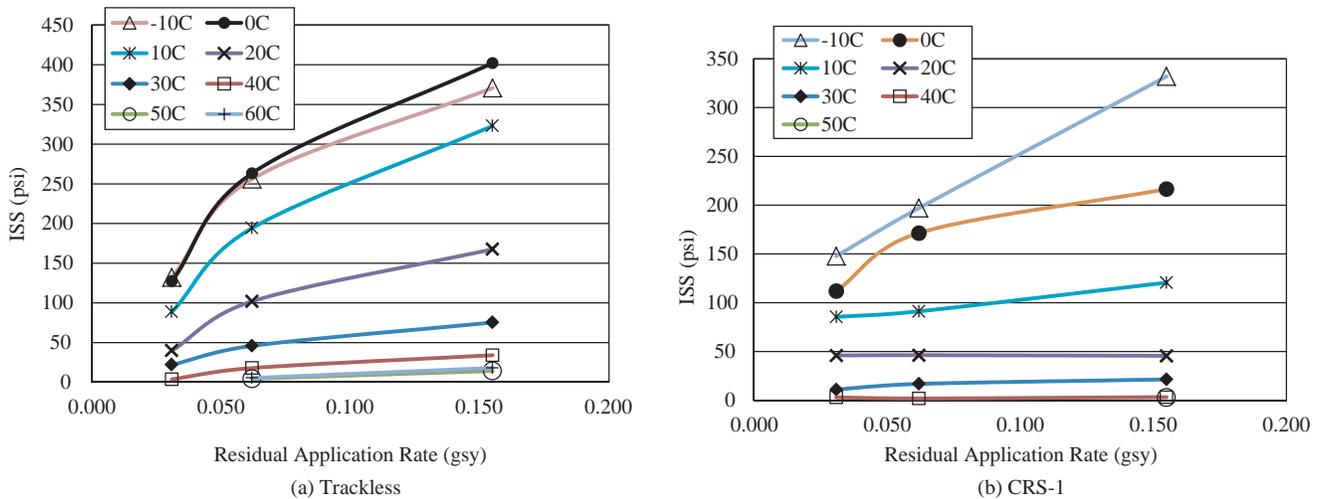
Figure 67. Variation of the ISS with residual application rate and test temperature.

had a greater shear resistance than CRS-1 at high temperatures. It is noted that the PG binder used in the asphalt mixture was PG 64-22; therefore, test temperatures ranging from 0° to 60°C did not exceed the associated PG-grading range.

Figure 67 (a and b) presents the variation of the ISS with residual application rates and test temperatures. For both tack coat materials, as the residual application rate increased, the ISS increased at all temperatures, and the highest ISS values were measured at the rate of 0.155 gal/yd^2; therefore, for the range of residual application rates from 0.031 to 0.155 gal/yd^2, there was no optimum tack coat residual application rate as might have been expected. This may be attributed to the highly oxidized and coarse HMA surface at the selected site, which required greater tack coat rates than expected.

It is also noted that, for CRS-1, the ISS did not consistently increase with the increase in residual application rates at a temperature of 20°C or higher. On the other hand, ISS consistently increased with residual application rate for the trackless material, even at high test temperatures.

Variation of the ISS with test temperatures at each residual application rate is presented in Figure 68. As shown in this figure, ISS of the trackless increases from 60°C to 0°C and then decreases toward −10°C. This is due to the low elongation properties of the trackless at low temperatures (see Table 16). In contrast, the ISS for CRS-1 continuously increased as temperature decreased. However, the trackless material still produced higher shear strengths than CRS-1 at low temperatures and at residual application rates of 0.062 and 0.155 gal/yd^2.
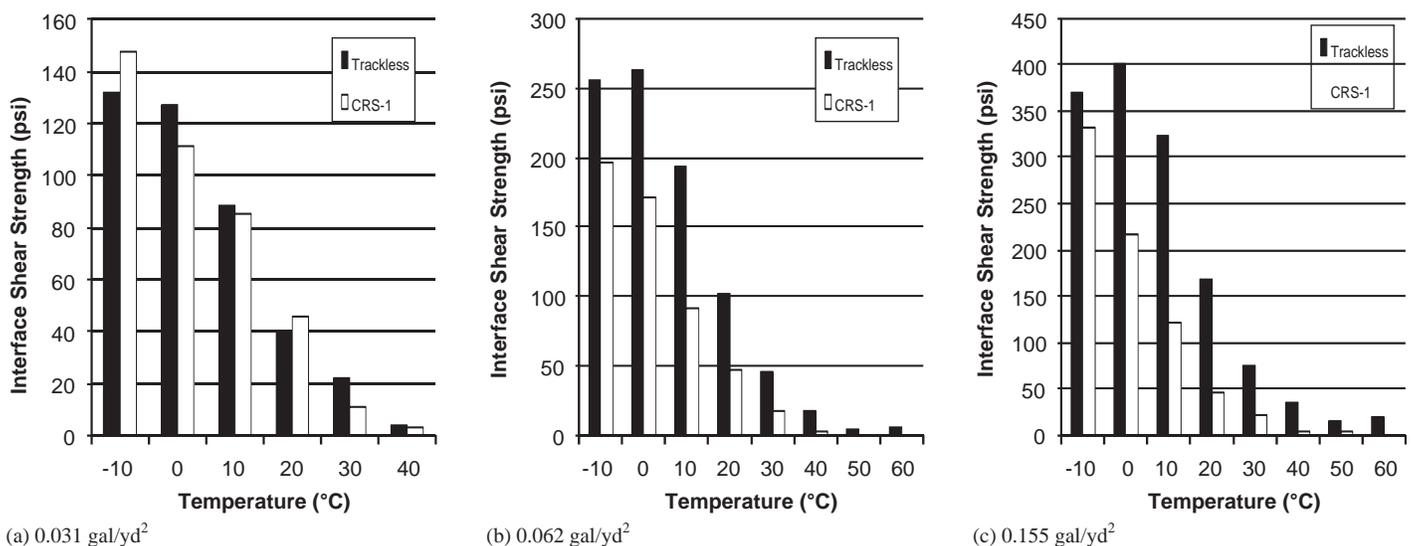
Figure 68. Variation of the ISS with test temperature.
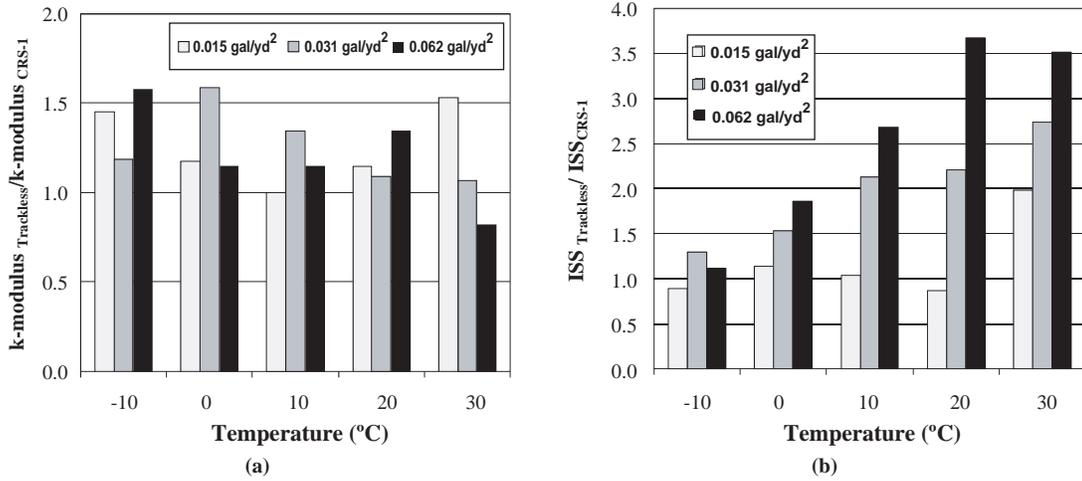
Figure 69. Ratio of trackless to CRS-1 in terms of (a) k-modulus and (b) ISS.

4.5.2 Interface Stiffness Characteristics at Various Temperatures

Variation of the *k*-modulus ratio and the ISS ratio between trackless and CRS-1 are shown in Figure 69 (a and b). In Figure 69a, it is observed that the *k*-modulus of the trackless material was greater or equal to that for the CRS-1 tack coat, except for the residual application rate of 0.062 gal/yd[2] at 30°C. In addition, the difference between the two tack coats was marginal at a residual application rate of 0.031 gal/yd[2], except at a test temperature of 30°C (see Figure 69b); however, at an application rate of 0.062 and 0.155 gal/yd[2], the bonding performance of the trackless was superior to that of the CRS-1 as the temperature increased. The ratio of the *k*-modulus and ISS was not plotted at a temperature greater than 40°C since the bonding resistance of CRS-1 was significantly lower than the trackless material. It is worth noting that the ISS values for the trackless emulsion tested at temperatures greater than 40°C were much higher than those of similar specimens with CRS-1 emulsion (see Table 26). Since the temperature at a pavement interface can reach 40°C or higher during the summer months, the use of a trackless-type of emulsion would provide greater shear resistance than that of the CRS-1 emulsion.

4.5.3 Relationship Between Interface Shear Strength and Tack Coat Rheology

Interface Shear Strength versus G*/sin δ

The parameter $G^*/\sin\delta$ is used as an indicator of the binder susceptibility to permanent deformation in the Superpave binder specification system. It was, however, adopted in this study because it simulates oscillation in a shear mode, which closely resembles the interface shear mode between two layers. The relationships between ISS and $G^*/\sin\delta$ and *k*-modulus and $G^*/\sin\delta$ are presented in Figures 70 and 71, respectively. Results presented in Figure 70 indicate that as $G^*/\sin\delta$ increased, the ISS for both tack coat materials at each residual application rate also increased. On the other hand, interface stiffness did not vary noticeably with the residual application
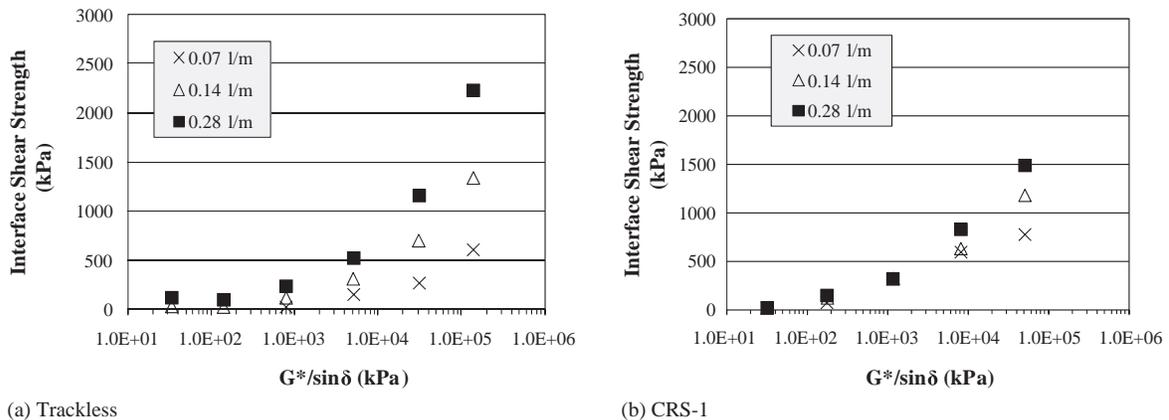
Figure 70. Relationship between ISS and G*/sin δ.
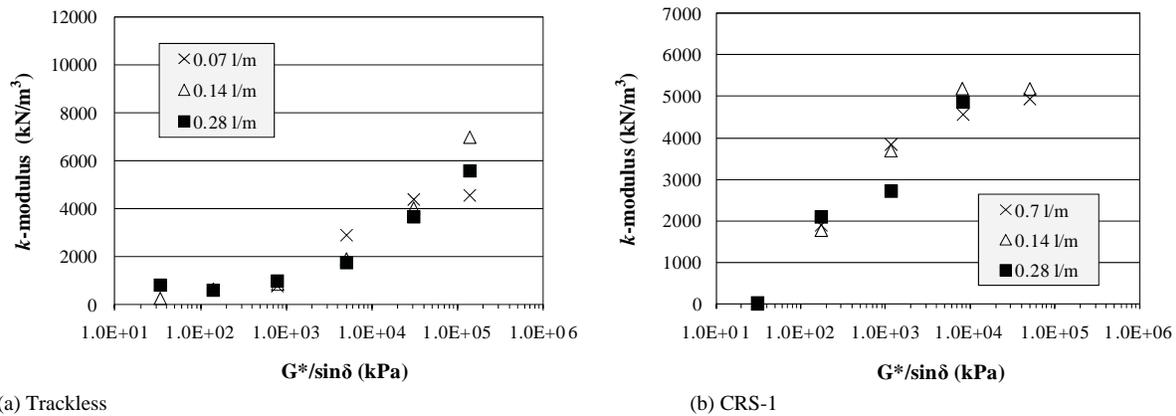
Figure 71. Relationship between k-modulus and G*/sin δ.

(a) Trackless

(b) CRS-1

rate (see Figure 71). Therefore, it may be concluded that the amount of tack coat material influences the ISS but not the interface stiffness. The authors postulate that the interface stiffness modulus may be mainly influenced by surface texture.

As shown in Figure 70, the ISS values did not exhibit much difference for a G^*/sin δ value below about 100 kPa (14.5 psi) and 1000 kPa (145.03 psi) for trackless and CRS-1, respectively. At higher G^*/sin δ values, the difference in ISS between the three residual application rates became more pronounced. Further, the trackless material produced greater ISS differences than did CRS-1 at the same G^*/sin δ values. The relationship shown in Figure 70 between the ISS and G^*/sin δ may be used to establish a laboratory design threshold for this parameter in order to ensure that the selected residual application rate and tack coat material would perform acceptably in the field. However, setting this limit on G^*/sin δ would require field validation of tack coat performance and that the required ISS be greater than the predicted shear stress at the interface due to traffic and/or thermal loading. The variation of the limit on G^*/sin δ with surface texture and surface type should also be investigated. The influence of surface texture on tack coat ISS has been investigated as part of NCHRP Project 9-40 and is presented in the next section. Results implied a direct relationship between the roughness of the existing surface and the shear strength at the interface; therefore, a milled HMA surface would provide the greatest ISS, followed by PCC, old HMA, and new HMA.

4.6 Experiment V: Effects of Pavement Surface Type and Sample Preparation Method

The mean ISSs along with their standard deviations and COVs were obtained for each condition considered in the test factorial. Triplicate samples were tested for each test condition defined by tack coat type, residual application rate, confining pressure, dusty surface, and wet conditions. The COVs

in the test results were less than 15% for all conditions. As presented in this section, test results were analyzed to investigate the effects of the variables considered in the test factorial on ISS. Since the focus of this experiment was on the effects of surface types and preparation methods, the effects of surface cleanliness were presented in Experiment III.

4.6.1 Effects of Tack Coat Type and Residual Application Rate

Figure 72 (a through d) presents the variation of the ISS with emulsified tack coat types and residual application rates for the different surface types (i.e., old HMA surface, PCC surface, milled HMA surface, and new HMA). As previously mentioned, only one emulsion (SS-1h) was used on the new HMA surface and two emulsions (SS-1h and SS-1) were applied on the milled HMA surface. These results were obtained for clean and dry samples with no confinement pressure at 25°C.

As shown in Figure 72, all tack coat materials showed that the ISS increased as the residual application rate increased within the evaluated application-rate range (0.031 to 0.155 gal/yd²); hence, it was not possible to identify an optimum residual application rate. This may indicate that, under actual field conditions, optimum residual application rates may be greater than that commonly predicted from laboratory-based experiments. However, while higher application rates may increase ISS, excessive tack coat may migrate into the HMA mat during compaction and service, causing a decrease in the air void content of the mix, and may even cause the appearance of fat spots on the HMA surface. One study reported that excess tack might be picked up by hauling trucks and paving equipment—causing safety concerns when tracked onto pavement markings in traffic intersections close to the construction area (42).

For old HMA and PCC surface types, the trackless tack coat exhibited the highest shear strength at the residual application rates of 0.031 and 0.062 gal/yd² for both old HMA and PCC surfaces, and CRS-1 and SS-1 exhibited the lowest.
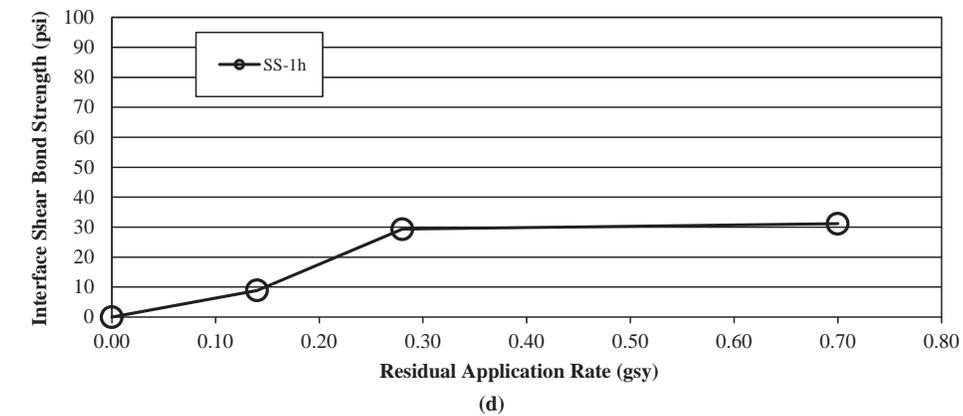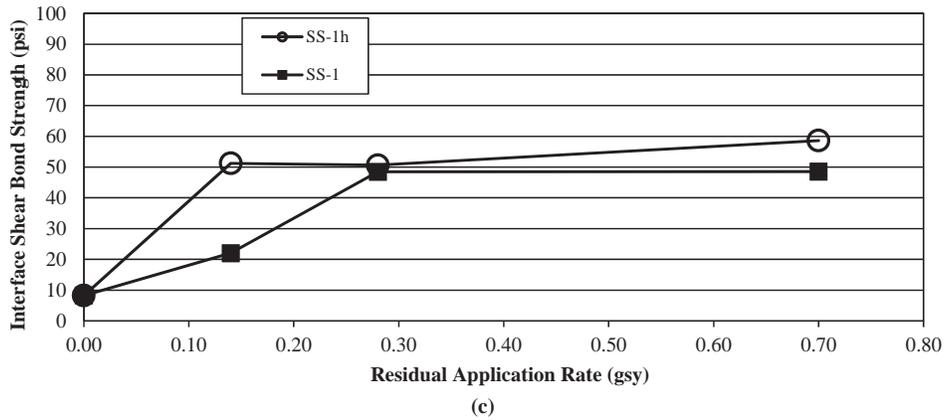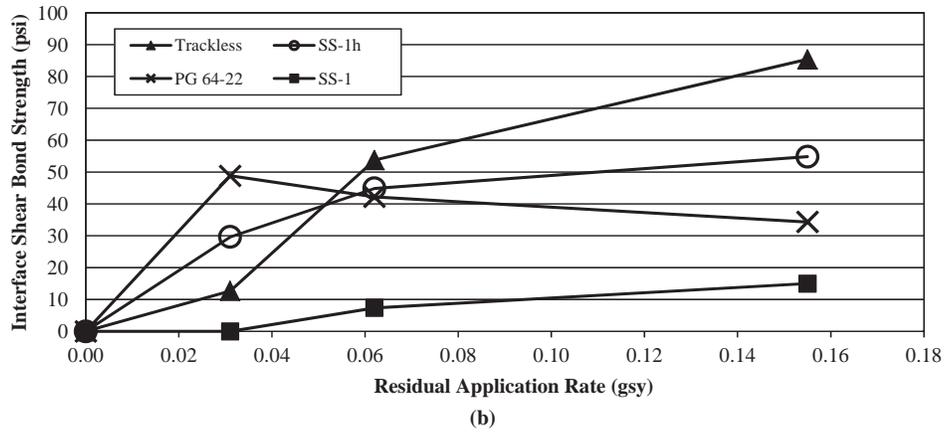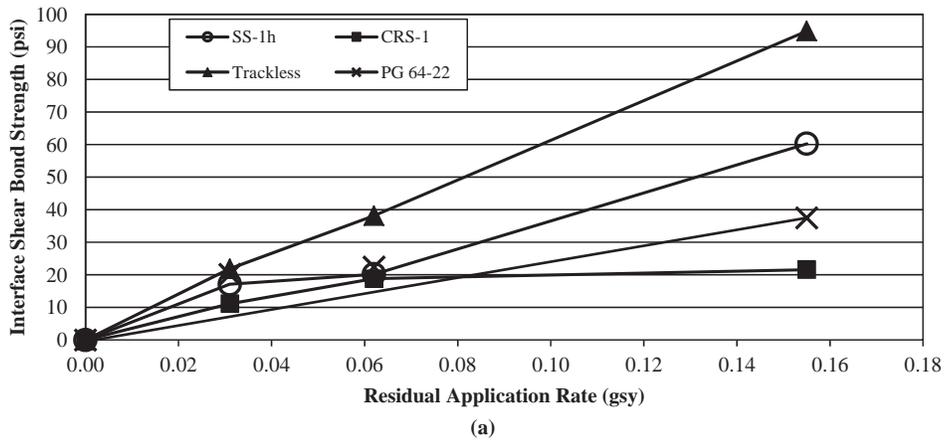
Figure 72. Effects of residual application rates and tack coat types on ISS for (a) old HMA surface, (b) PCC surface, (c) milled HMA surface, and (d) new HMA surface.

Trackless tack coat consists of a polymer-modified emulsion with hard base asphalt cement. These results relate directly to the viscosity of the residual binders at the test temperature. The influence of tack coat type appears to increase with the increase in the residual application rate. Except for the milled HMA surface, the no-tacked cores failed during extraction due to the poor bonding at the interface. This emphasizes the importance of using a tack coat material at the interface to avoid poor bonding between the layers. To balance the aforementioned factors, one should select a tack coat residual application rate that would ensure that the ISS is greater than the calculated shear stress at the interface due to traffic and thermal loading.

4.6.2 Effects of Surface Type

SS-1h emulsified tack coat was evaluated on all four surface types. On the other hand, the trackless tack coat and PG 64-22 asphalt binder were evaluated for two surface types: old HMA and grooved PCC surfaces. PCC samples were tested parallel to the direction of the grooves. This test arrangement should generate the lowest ISS, which is in the direction of traffic and, therefore, is more conservative. Figure 73 (a through c) presents the variation of ISS with surface types and residual application rates. As shown in these figures and due to its high roughness, the milled HMA surface provided the highest ISSs, followed by the PCC surface. In most cases, the old HMA surface provided greater interface strength than did the new HMA surface. It is noted that differences are more pronounced at low and intermediate residual application rates and less pronounced at high residual application rates. It is likely that the effects of microstructure features that contribute to the surface roughness or texture are less pronounced when they are filled with tack coat materials.

4.6.3 Effects of Surface Wetness

The effects of surface wetness on the ISS were evaluated for old HMA, PCC, and milled surfaces. Figure 74 (a through c) presents the effects of surface wetness. Sta-

(a)

(b)
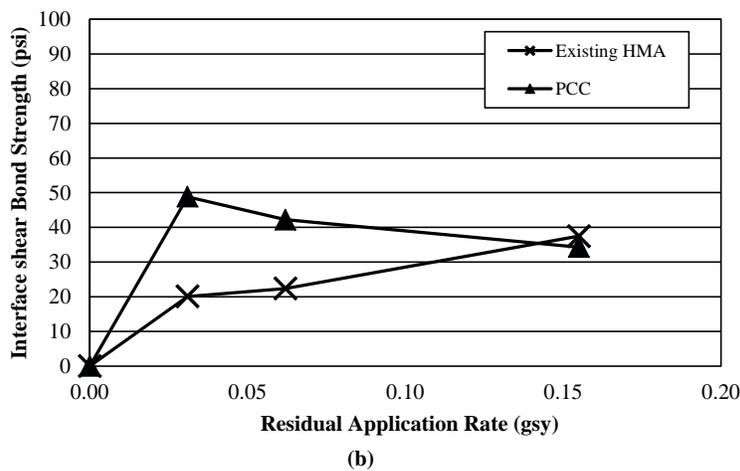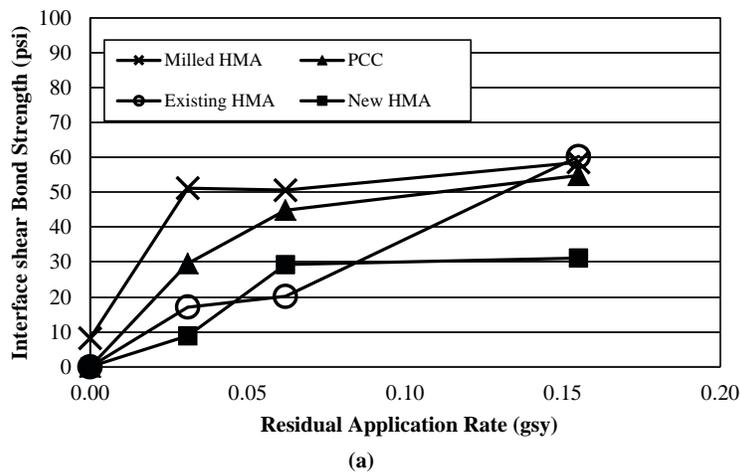
Figure 73. Effects of surface types on ISS for (a) SS-1h tack coat (b) PG 64-22 and (c) trackless tack coat.
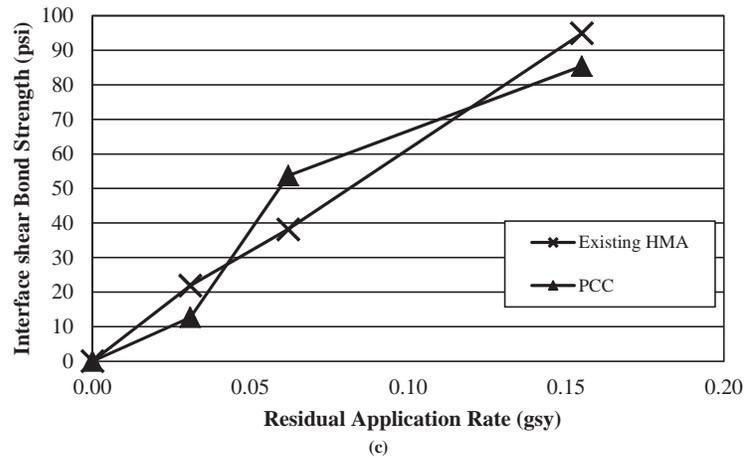
Figure 73. (Continued).

tistically different sets are identified in these figures with an asterisk above the bar. As shown in Figure 74a, statistically significant sets, shown with an asterisk, are often cases where wet conditions provided greater ISS than dry conditions. This is probably due to unaccounted-for factors such as the presence of coarse aggregates at the surface (higher/coarser texture), which increased the friction resistance of the interface at the selected coring locations. This indicates that, even in the presence of light rain, the placement temperature of an HMA overlay will cause the water to evaporate or infiltrate into the underlying layer with no practical consequence on the interface bond strength. For the PCC surface, SS-1h, SS-1, trackless, and PG 64-22 were evaluated (see Figure 74b). The use of PG 64-22 did not generate sufficient bond strength at 0.031 and 0.062 gal/yd^2 under wet conditions, indicating possible negative effect of surface wetness at low tack rates. On the other hand, for SS-1 and trackless tack coats, surface wetness did not affect the ISS. Only SS-1h was evaluated for the milled surface in dry and wet conditions. The influence of surface wetness did not follow a consistent trend (see Figure 74c).

4.6.4 Effects of Preparation Methods

Figure 75 and Table 27 present the measured ISS for laboratory-fabricated specimens. For SS-1h, AUT, and PG 64-22, it was found that the optimum rate—at which the greatest ISS was achieved—is 0.062 gsy. For CRS-1, as the residual application rate increased, the ISS value decreased. On the other hand, the trackless material showed continuous increase of ISS from 0.031 to 0.155 gsy.

To assess the influence of sample preparation methods, Figure 76 compares the ISS of laboratory-fabricated samples with that of field-extracted cores for tack coat SS-1h in the case of the new HMA surface. As shown in this fig-

ure, laboratory-prepared samples grossly overestimated the ISS by a factor ranging from 2 to 10 when compared with field-extracted cores. In the laboratory, ISS decreased with tack rate, whereas, in the field, ISS increased with tack rate. A number of factors may cause this discrepancy, including the difference in mixing and compaction methods and application method for the tack coat materials. Difference in compaction methods may result in differences in air void contents and distributions in the specimen, mix resistance to shear loading, and mix density. The most probable factor appears to be the greater asphalt film thickness at the interface of the new HMA and the smoother/flatter surface of the freshly made specimens.

4.7 Experimental VI: Effects of Texture and Permeability on Tack Coat Bond Strength

The objective of this laboratory experiment was to evaluate the effects of surface texture and permeability of the existing pavement on tack coat ISS. The details of the mixtures' design, surface texture and permeability measurements, and specimen fabrication were previously reported. The tack coat material used in this experiment was SS-1 emulsion. ISS tests were conducted for open-graded friction course (OGFC), SMA, and sand mixtures. Table 28 presents the mean ISSs along with their standard deviations and COVs for the three mixtures evaluated. Figure 77 shows the variation of the ISS with the residual application rate.

For the SMA mixture, the peak ISS was observed at a residual application rate of 0.031 gsy. The ISS was lower at residual application rate 0.155 gsy than that for the no-tack condition. For the sand mixture, the peak ISS occurred at the no-tacked condition. For smooth interface conditions and a new surface (i.e., still coated with asphalt) such as the one simulated
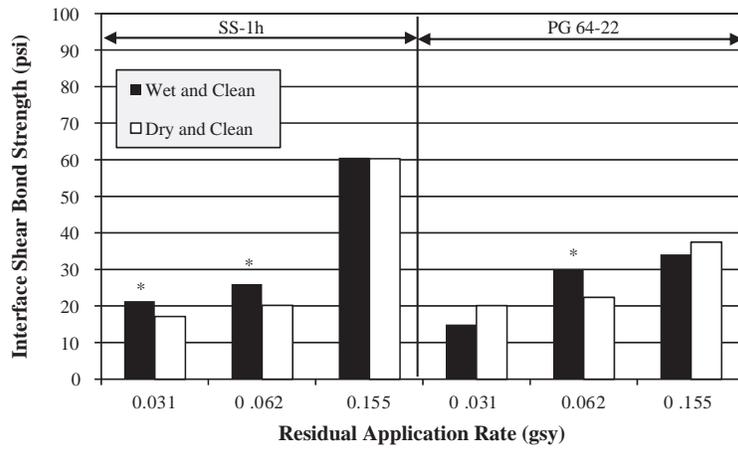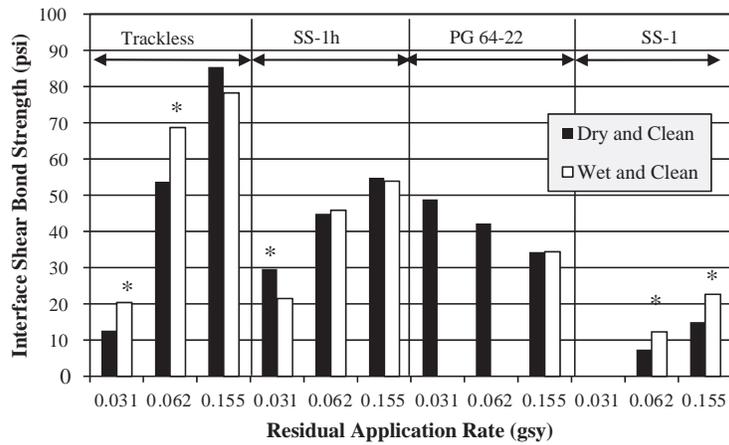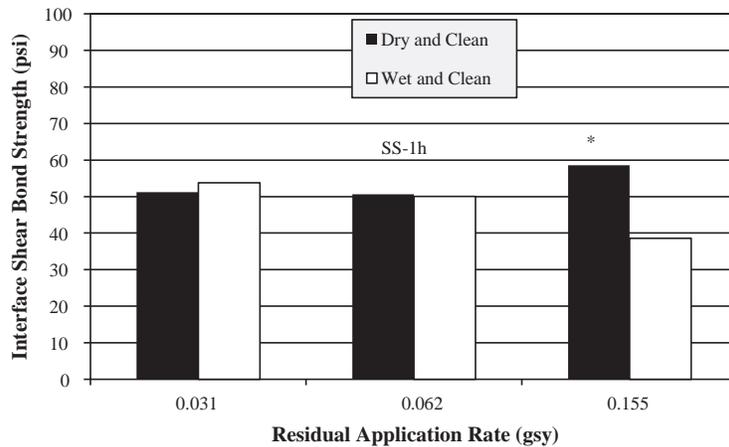
Figure 74. Effects of surface wetness on ISS for (a) old HMA, (b) PCC, and (c) milled surfaces.
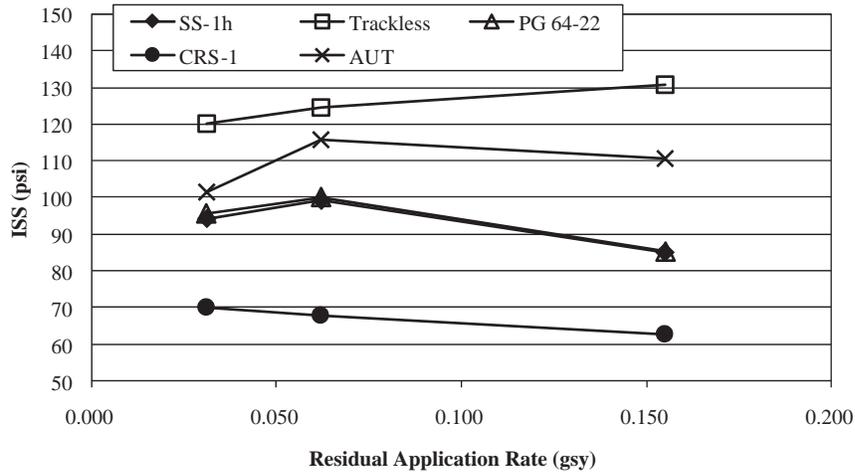
Figure 75. Effects of residual application rate on ISS for lab-compacted samples.

Table 27. ISS test results for lab-compacted samples.

	SS-1h			Trackless			PG 64-22			CRS-1			AUT		
	0.031	0.062	0.155	0.031	0.062	0.155	0.031	0.062	0.155	0.031	0.062	0.155	0.031	0.062	0.155
	90.6	93.2	83.0	117.9	125.4	129.1	76.4	98.8	82.7	67.0	65.1	60.1	93.5	112.3	106.8
ISS (psi)	92.5	97.3	84.6	119.3	123.0	131.2	105.2	99.8	85.2	70.4	69.3	62.4	99.2	115.4	109.4
	100.1	107.6	87.9	122.6	124.5	131.7	105.6	101.9	88.2	73.1	69.8	66.0	111.6	119.5	115.4
Mean	**94.4**	**99.4**	**85.1**	**119.9**	**124.3**	**130.7**	**95.7**	**100.2**	**85.4**	**70.2**	**68.1**	**62.8**	**101.4**	**115.7**	**110.5**
S.D.	**5.0**	**7.4**	**2.5**	**2.4**	**1.2**	**1.4**	**16.8**	**1.6**	**2.7**	**3.1**	**2.6**	**3.0**	**9.3**	**3.6**	**4.4**
COV (%)	**5.3**	**7.5**	**2.9**	**2.0**	**1.0**	**1.1**	**17.5**	**1.6**	**3.2**	**4.4**	**3.8**	**4.7**	**9.1**	**3.1**	**4.0**
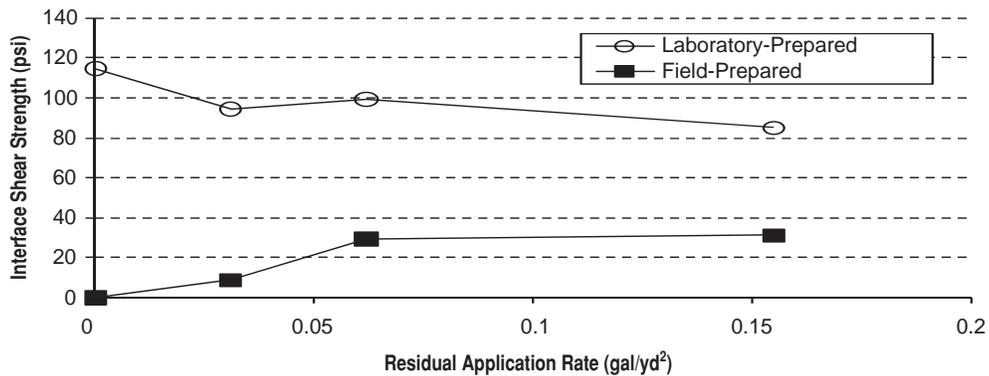
Figure 76. Effects of sample preparation methods on the ISS.

Table 28. ISS test results for the OGFC, sand, and SMA mixtures.

Residual application rate (gsy)	OGFC				Sand				SMA			
	0.000	**0.031**	**0.062**	**0.155**	**0.000**	**0.031**	**0.062**	**0.155**	**0.000**	**0.031**	**0.062**	**0.155**
ISS (psi)	64.6	60.1	57.6	70.6	83.5	71.6	74.0	63.5	62.4	77.7	66.8	39.5
	65.7	64.1	55.3	70.7	87.6	79.5	73.7	68.4	59.4	91.3	73.0	40.4
	73.2	66.4	52.3	75.2	89.3	86.4	70.8	70.3	69.4	91.8	73.2	43.7
Mean	67.8	63.6	55.1	72.2	86.8	79.2	72.8	67.4	63.7	86.9	71.0	41.2
SD	4.7	3.2	2.7	2.6	5.0	7.4	1.8	3.5	5.1	8.0	3.6	2.2
COV (%)	6.9	5.0	4.8	3.6	5.8	9.3	2.4	5.2	8.1	9.2	5.1	5.4

with the sand mixture, tack coat application reduces interface shear bond strength. It appears that—for a new, smooth surface—tack coat acts as a lubricant and, thus, decreases the shear strength at the interface.

For the OGFC mixture, the ISS decreased slightly from the no-tack condition with an increase in the residual application rate, reached a minimum at residual application rate of 0.062 gsy, and then increased with an increase in the residual application rate at 0.155 gsy. It appears that the higher voids in the surface of the OGFC initially yielded lower shear strength than did that for the sand mix. However, when the voids in the surface of the OGFC are filled with asphalt at the highest residual application rate (0.155 gsy), the shear strength becomes equivalent to that of the sand.

One would expect that higher surface texture would yield higher ISS, such as a milled surface or an OGFC; however, it was observed that the surfaces of the laboratory-compacted specimens (which are compressed against a smooth, flat steel plate) were flat but with significant voids in the case of the OGFC. These highly permeable voids likely absorbed the asphalt from the tacked interface and, thus, reduced the ISS of the OGFC to a lower level than that of the relatively smooth, voidless, impermeable surface of the sand mix. Once the voids in the surface of the OGFC were filled with tack coat material, the OGFC showed an increase in ISS to a value that is slightly higher than that of the sand mix.

4.8 Theoretical Investigation

Peak values of ISS, k-modulus, and displacement at failure (d_{max}) were calculated for each tack coat material and are presented in Table 29. As previously noted, all tack coat materials showed the highest strength at a residual application rate of 0.155 gsy. Within the residual application rate range considered, no optimum residual application rate was determined. This was attributed to the highly oxidized HMA surface at the PRF site, which required greater tack coat rates than expected. The mean profile depth (MPD) for the old HMA surface, which was measured using a road surface profiler according to *ASTM E 1845*, was 0.04 in (1.05 mm). While higher residual application rates may increase ISS, excessive tack coat may migrate into the HMA mat during compaction, causing a decrease in the air void content of the mix. It is also observed from the results presented in Table 29 that
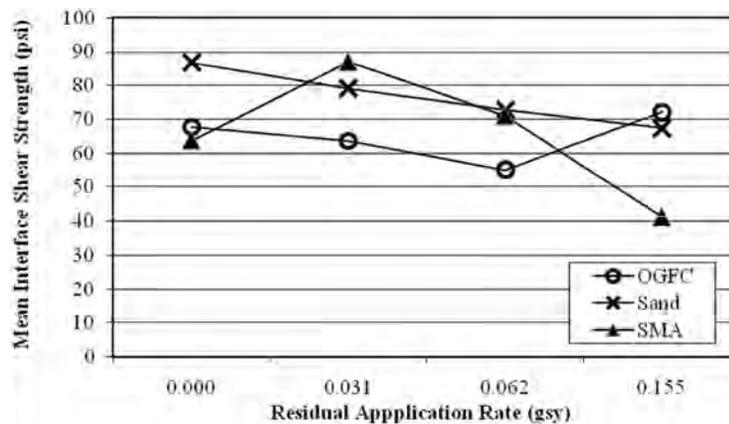
Figure 77. Mean interface shear bond strengths for the OGFC, sand, and SMA mixtures.

Table 29. Interface shear behaviors for different tack coat types and at three residual application rates.

FE Case ID	Tack Coat Material	Residual Application Rate (gal/yd²)	ISS (MPa x 10³)	ISS (psi)	COV (%)	k (N/mm³)	d_{max} (mm)
1	CRS-1	0.031	76.5	11.1	14.1	0.1916	0.39
2		0.062	129.6	18.8	7.6	0.1845	0.70
3		0.155	148.9	21.6	10.9	0.1304	1.14
4	SS-1h	0.031	117.9	17.1	14.2	0.2297	0.51
5		0.062	139.3	20.2	9.8	0.2826	0.49
6		0.155	415.7	60.3	6.4	0.2769	1.51
7	Trackless	0.031	150.9	21.9	10.2	0.2688	0.56
8		0.062	263.4	38.2	12.3	0.2642	0.99
9		0.155	655.0	95.0	8.3	0.2456	2.67
10	PG 64-22	0.031	138.6	20.1	13.0	0.1757	0.79
11		0.062	154.4	22.4	12.7	0.1898	0.81
12		0.155	258.5	37.5	7.2	0.1411	1.83

the interlayer tangential modulus decreased with the increase in residual application rate, which is indicative of greater deformability and flexibility at the interface. In addition, the trackless tack coat exhibited the highest shear strength, and CRS-1 exhibited the lowest.

The effects of tack coat interface shear bond characteristics, as measured by the LISST test on pavement responses at the interface, were investigated using the results of the FE model. Figure 78 (a to f) compares the calculated shear stress at the interface between the old and HMA overlay with the ISS for the different tack coat material types and residual application rates. As shown in Figure 78, only two cases (Structure A and Structure E with CRS-1 at 0.031 gal/yd² residual application rate) failed due to a single load application. For the other structures, none of the evaluated cases failed at the interface due to a single load application. It is also noted that the calculated shear stress did not substantially change from one tack coat application case to another. However, the calculated shear stress changed from one pavement design to another.

While the results presented in Figure 78 relate to the shear response of the interface against a single tire load application, pavement structures are typically subjected to repeated fluctuating vehicular loads. Such load patterns may cause fatigue failure at the tacked interface through a process of cyclic cumulative damage. To assess the potential for fatigue failure at the interface, the stress ratio (which is the ratio of the predicted shear stress at the interface to the ISS) was calculated. If the stress ratio was less than 0.50, the interface response against fatigue failure was assumed to be acceptable. On the other hand, if the stress ratio was greater than 0.50, the inter-

face was expected to experience fatigue failure before the end of its service life. A stress ratio of 0.50 is usually assumed in laboratory fatigue testing of HMA and tacked interface as an indication of failure (35, 43). It is also hypothesized that, at a stress ratio of 0.50 or less, the fatigue life at the tacked interface would be infinite (i.e., no fatigue-related distress at the interface).

Based on this theoretical approach, Figure 79 (a to f) presents the calculated stress ratio for each tack coat type and residual application rate. For Structure A, it is noted that trackless—at intermediate and high residual application rates—and SS-1h and PG 64-22—at a high residual application rate—passed this criterion. CRS-1 did not meet this criterion at any of the rates evaluated. For Structure B, the majority of the tack coat types and residual application rates would be expected to perform satisfactorily against fatigue damage at the interface. In this case, only CRS-1 and SSh-1h at the low residual application rate (0.031 gal/yd²) would be expected to experience fatigue damage at the interface. It is evident from these results that the performance of tack coat materials at the interface is primarily dictated by the pavement design. In other words, the influence of tack coat type and residual application rate becomes more relevant in thin pavements and less dominant in thick pavements.

Based on the results presented in Figures 78 and 79, Figure 80 presents the variation of the predicted shear stress ratio with the ISS for the different tack coat materials and residual application rates. As shown in this figure, a power law model is adequate in describing the relationship between the shear stress ratio and the ISS. Utilizing the presented models, it was determined that the minimum laboratory-measured ISS at the
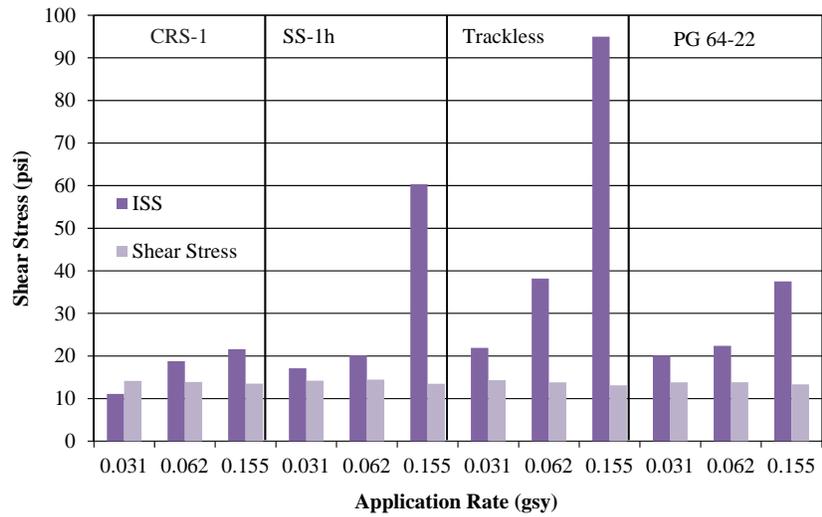
(a) Structure A
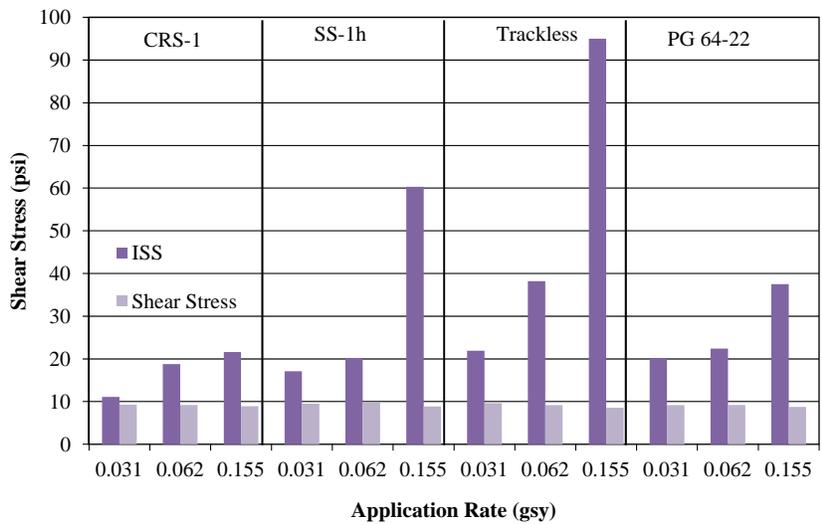
(b) Structure B
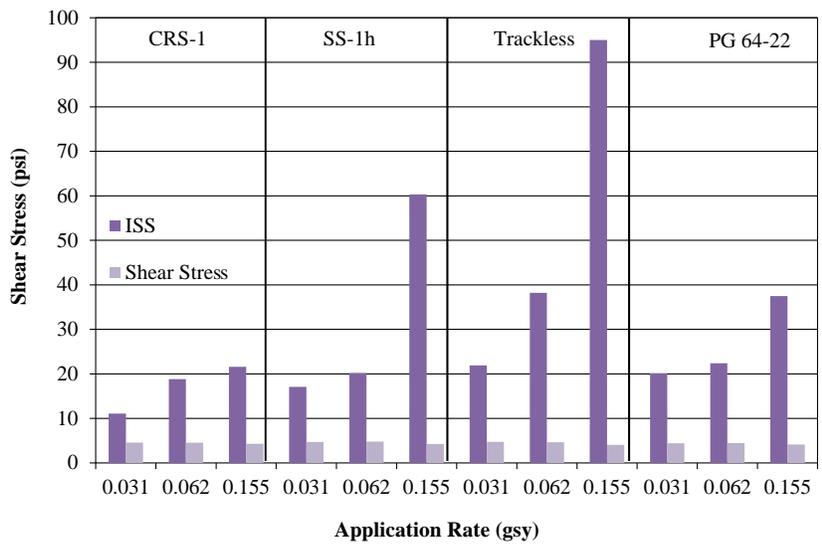
(c) Structure C

Figure 78. Comparison of the calculated shear stress to the ISS.

(d) Structure D

(e) Structure E

(f) Structure F
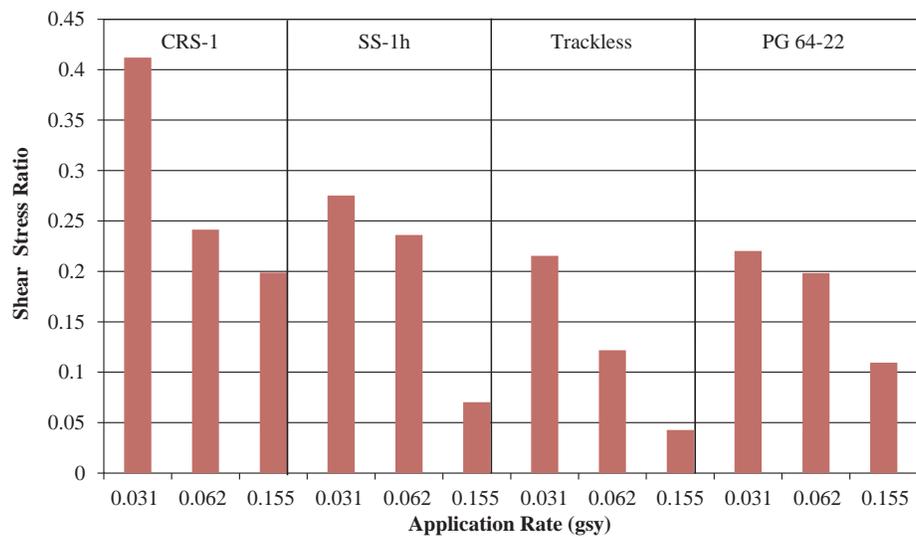
Figure 78. (Continued).

Figure 79. Calculated shear stress ratios for different tack coat types and residual application rates.
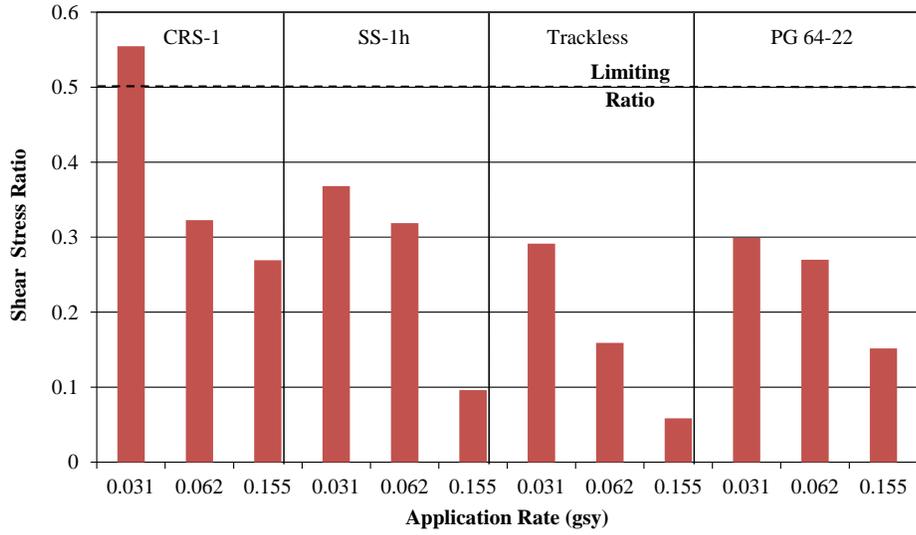
(d) Structure D
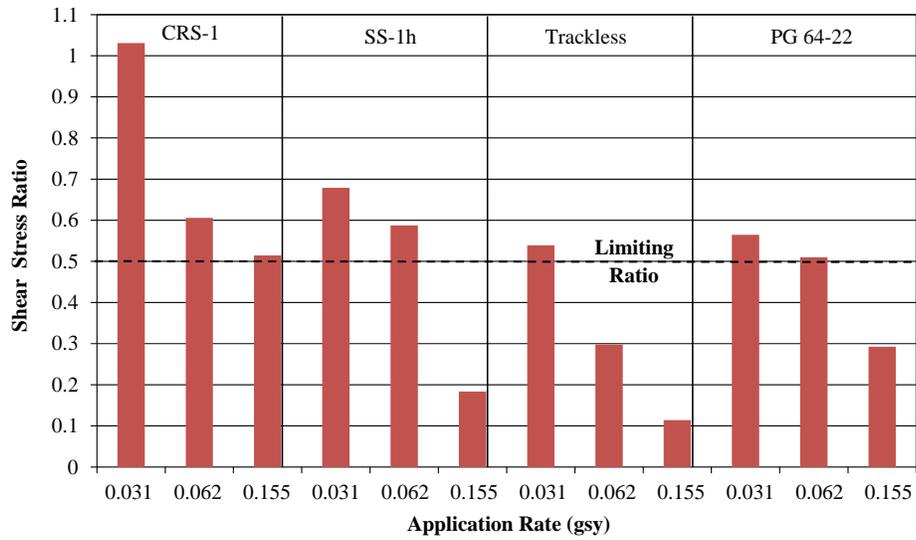
(e) Structure E
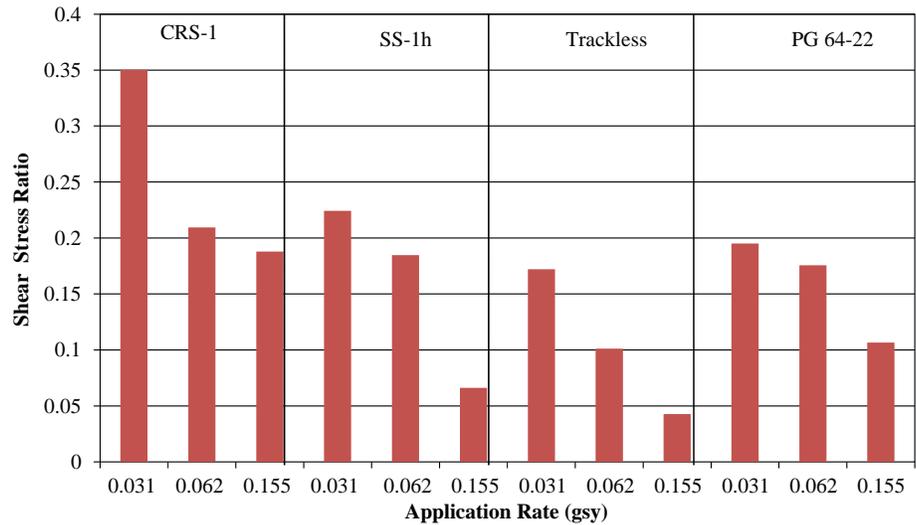
(f) Structure F

Figure 79. (Continued).
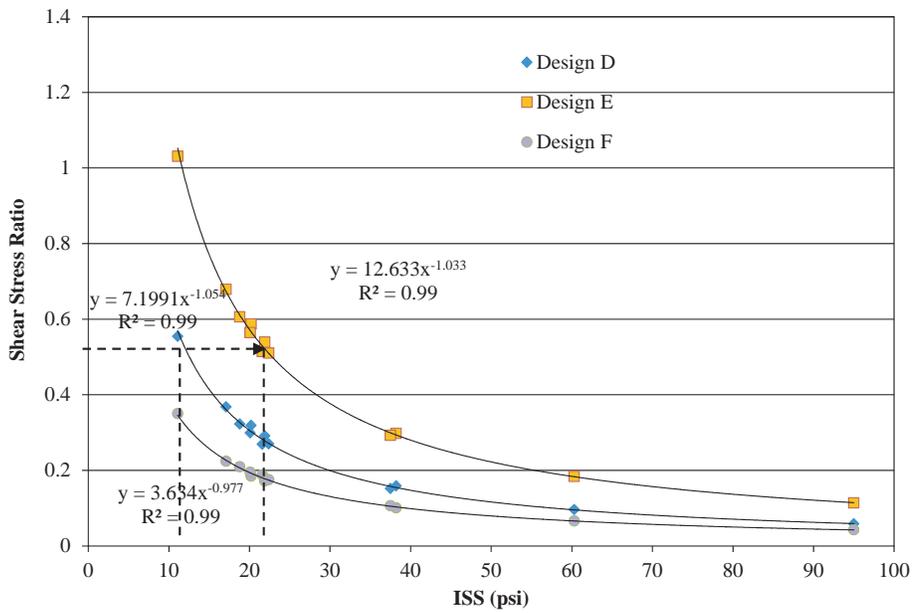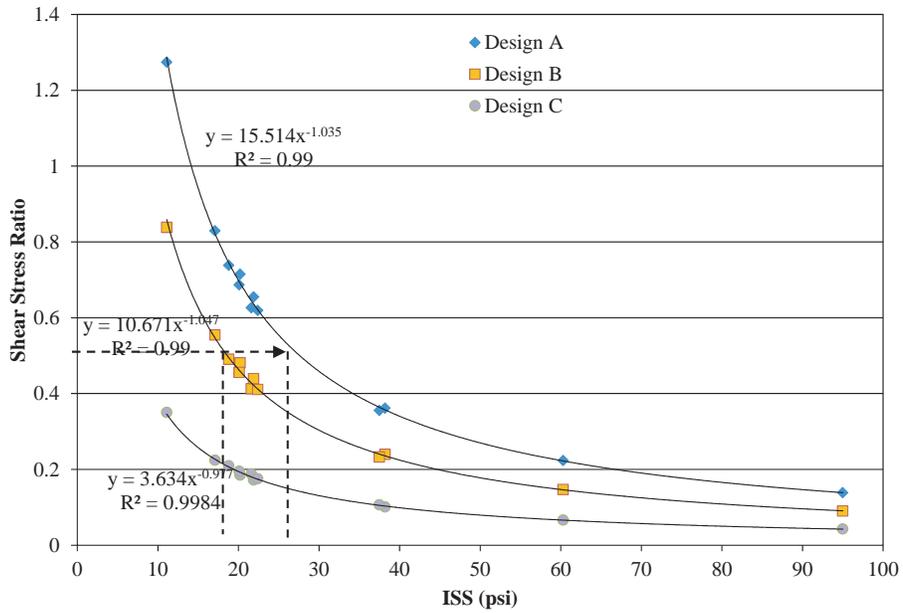
Figure 80. Relationship between shear stress ratio and laboratory-measured ISS.

interface to achieve a shear stress ratio of 0.50 or lower was 28 psi for Structure A, 19 psi for Structure B, and 8 psi for Structure C. Similarly, the minimum laboratory-measured ISS at the interface to achieve a shear stress ratio of 0.50 or lower was 23 psi for Structure D, 13 psi for Structure E, and 8 psi for Structure F. These limits can be used in the selection of tack coat materials and residual application rates based on laboratory DST results to predict performance at the interface in the field. If a single ISS value needs to be specified to prevent failure at the interface, and considering a safety factor of 1.4 against variability in measurements and in construction, an ISS value of 40 psi is recommended.

Based on the results of the FE analysis, findings of the experimental program for different surface types, and dis-

Table 30. Recommended tack coat residual application rates.

Surface Type	Residual Application Rate (gsy)
New Asphalt Mixture	0.035
Old Asphalt Mixture	0.055
Milled Asphalt Mixture	0.055
Portland Cement Concrete	0.045

cussions with state dots and industry personnel, Table 30 lists the recommended tack coat residual application rates for the various pavement surfaces.

SECTION 5

Conclusions

The main objectives of this project were to determine optimum application methods, equipment type and calibration procedures, residual application rates, and asphalt binder materials for the various uses of tack coats and to recommend revisions to relevant AASHTO test methods and practices related to tack coats. During the course of this project, the research team developed the Louisiana Tack Coat Quality Tester (LTCQT) to evaluate the quality of tack coat spray application in the field. The LTCQT and associated test procedure were demonstrated to be viable methods for evaluating tack coat quality in the field. The LTCQT could serve as a valuable tool for highway agencies to perform comparative evaluations of various tack coat materials and application methods and rates in the field. Repeatability of measurements using the LTCQT was acceptable, with an average coefficient of variation of less than 11%. Research in this project also resulted in the development of a training manual (which is presented in Appendix F). The training manual provides a comprehensive presentation of the recommended construction and testing procedures for tack coat materials.

The Louisiana Interlayer Shear Strength Tester (LISST) was developed for characterization of interface shear strength (ISS) of cylindrical specimens in the laboratory. The LISST device was designed such that it will fit into any universal testing machine. The average coefficient of variation in the LISST test results was less than 10%. As part of the experimental program, the research team constructed full-scale test overlays at the Louisiana Transportation Research Center Pavement Research Facility. The overlays included different tack coat residual application rates beneath a new HMA overlay installed over several types of pavement surfaces including old hot-mix asphalt, new HMA, milled HMA, and grooved portland cement concrete. Five types of tack coat materials were applied at three residual application rates. The calibration of the distributor truck was a lengthy process in this project and required multiple calibration runs to ensure the accuracy and uniformity of tack coat application. This difficulty high-

lights the importance of regularly checking the accuracy of the distributor in practice. Quality of tack coat application was evaluated using the LTCQT, samples were cored from the test pavements, and ISS was measured in the laboratory using the LISST device. Based on the findings of this project, the following conclusions were drawn with respect to both the ISS and the tack coat spray application quality in the field.

With respect to ISS in the field:

1. **For the effect of emulsified tack coat type,** trackless tack coat exhibited the highest shear strength and CRS-1 resulted in the lowest strength. These results relate directly to the viscosity of the residual binders at the test temperature (25°C).
2. **For the effect of application rate,** all tack coat materials showed the highest shear strength at a residual application rate of 0.155 gsy. Within the tested residual application rate range, it was difficult to determine the optimum residual application rate. This may be attributed to the highly oxidized HMA surface at the LTRC site, which required greater optimum tack coat rates than expected. It may also indicate that, under actual field conditions, optimum residual application rates are greater than what is commonly predicted from laboratory-based experiments. It is noted, however, that while higher residual application rates may increase ISS, excessive tack coat may migrate into the new asphalt mat during compaction causing a decrease in the air void content of the mix.
3. **For the effect of confinement,** the ratio of ISS between confined and no-confinement test conditions was always greater than 1. This ratio increased as the residual application rate decreased; therefore, a specification developed based on no-confinement testing conditions would yield a conservative estimate of the ISS values.
4. **For the effect of dust,** the majority of the cases showed a statistically significant difference between clean and dusty conditions. It appears from these results that dusty con-

ditions exhibited greater ISS than did clean conditions, especially when tested with a confining pressure. This likely resulted when the dust combined with the asphalt and formed mastic with a resultant viscosity higher than that of the neat residual asphalt, plus the sand particles may have provided grit at the interface to further increase the ISS. However, one should note that these results are based on using a uniform and clean sand to simulate dusty conditions—*therefore, cleaning and sweeping of the existing pavement surface is recommended to avoid negative effects of dusty conditions.*

5. **For the effect of water on the tacked interface,** the majority of the cases showed no statistically significant difference between dry and wet conditions. This data indicates that a small amount of water can be flashed away by the hot HMA mat and, thus, have inconsequential effects on the quality of the tack coat. This study used only hot mix as the overlay material; the use of warm mix may change this finding. In addition, these results are based on using a small quantity of water to simulate rainy conditions—*therefore, a dry and clean surface is recommended to avoid the negative effects of water on the bonding at the interface.*

6. **For the effect of surface type,** a direct relationship was observed between the roughness of the existing surface and the shear strength at the interface; therefore, the milled HMA surface provided the greatest ISS followed by PCC, old HMA, and new HMA surfaces. Table 31 presents the recommended tack coat residual application rates for different surface types.

Table 31. Recommended tack coat residual application rates.

Surface Type	Residual Application Rate (gsy)
New Asphalt Mixture	0.035
Old Asphalt Mixture	0.055
Milled Asphalt Mixture	0.055
Portland Cement Concrete	0.045

7. **For the effect of preparation method,** laboratory-prepared specimens grossly overestimated the ISS when compared with pavement cores. In addition, when increasing tack residual application rate, a decreasing trend in ISS was observed for laboratory-prepared specimens, while an increasing trend was observed in the field.

8. **For the effect of temperature** (from $-10°$ to $60°C$), ISS increased with the decrease in temperature. In addition, the bonding performance—as measured by the ISS of the trackless emulsion—was superior to that of the CRS-1 emulsion, especially at temperatures greater than $40°C$.

9. **Based on the results of the FE analysis,** the minimum laboratory-measured ISS obtained from the LISST device, tested at $25°C$, that provides acceptable performance is 40 psi.

With respect to the tack coat spray application quality in the field:

10. **For pavement cores,** tensile strength of each tack coat material increased, reached a peak, and then decreased as the temperature increased. The tack coat materials tested using LTCQT exhibited a maximum tensile strength, S_{MAX}, at a distinct temperature, T_{OPT}. Thus, the response of tack coat material in tension was characterized using S_{MAX} at T_{OPT}.

11. **For the tack coat materials evaluated,** a good correlation was observed between the tensile strength and absolute viscosity. Within the range studied, an increase in viscosity (i.e., resistance to flow) was associated with an increase in tensile strength.

12. **For the tack coat materials evaluated,** a good relationship was observed between the maximum tensile strength and the corresponding softening point. An increase in the material softening point was correlated to an increase in the maximum tensile strength.

13. **Based on the results of this study, it is recommended** to conduct the LTCQT test at the tack coat base asphalt softening point, which is a quantity that can be easily measured and specified.

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APPENDIX A

Worldwide Survey Questionnaire

Worldwide Survey Questionnaire

National Cooperative Highway Research Program
Project 9-40

"Optimization of Tack Coat for HMA Placement"

Questionnaire

Tack Coat Materials

1. Which types and grades of asphalt binder materials are commonly used for tack coat on your agency's asphalt paving projects?

Asphalt cements	Emulsified asphalt		Cutback asphalt	
	Type	% Residual Asphalt	Type	% Residual Asphalt

2. How much (approximate percentage) of each of the various materials listed in Question 1 was used in the past few years?

Asphalt cements		Emulsified asphalt		Cutback asphalt	
Type/Grade	%	Type/Grade	%	Type/Grade	%

3. What type(s) of tack coat material is (are) typically applied to each of the following existing pavement surfaces?

Pavement Type	Tack Coat Material		Dilution Rate	Application Rate	Residual Application Rate
	Type/ Grade	% Residual Asphalt	(ratio)	(gal/yd^2)	(gal/yd^2)
Between new HMA layers					
On top of an existing HMA surface					
On top of a milled HMA surface					
On top of a surface treatment, seal coat, or chip seal					
On top of an asphalt treated base course					
On top of an existing PCC surface					
On top of a milled or diamond-ground PCC surface					

Tack Coat Application Method

4. If the emulsion material is allowed to be diluted, where does the dilution process take place?
    a. At the asphalt supplier's terminal. _____ Yes _____ No
    b. At the contractor's storage tank. ___ Yes _____ No
    c. After the undiluted tack coat material is in the distributor tank. _____ Yes _____ No
    d. Other location. Please specify. _____
    e. None of the above
    If dilution is not allowed, go to Question 7

5. How is the dilution rate of an asphalt emulsion verified? (Check all that apply.)
    _____ a. Certification by the asphalt supplier.
    _____ b. Certification by the contractor.
    _____ c. Sample taken and tested from the contractor's storage tank.
    _____ d. Sample taken and tested from the distributor.
    _____ e. Visual observation of the actual dilution of the asphalt emulsion.
    _____ f. Use of ASTM D2995: Estimating Application Rate of Bituminous Distributors.
    _____ g. None of above.
    _____ h. Others. Please specify. _____

6. How often is the diluted rate verified?
    _____ a. Daily.
    _____ b. Monthly.
    _____ c. Project by project.
    _____ d. Not checked.
    _____ e. Others. Please specify. _____

7. Is traffic allowed on the tack coat materials prior to placing the HMA mix?
    _____ a. No.
    _____ b. Yes. Please specify the minimum time required prior to trafficking (Min, Hrs, Days).
          _____ Min   _____ Hrs   _____ Days

8. If the answer to Question 7 is "yes," is the minimum time required prior to trafficking affected by the type of the existing pavement surfaces (i.e., "Between new HMA layers," "On top of a milled HMA surface," "On top of an existing PCC surface," etc.)?
    _____ a. No.
    _____ b. Yes. Please specify. _____

9. What is the maximum time that the tack coat can be exposed to traffic before it is covered by HMA mix?
       Min _____   Hrs _____   Days _____

10. How is the asphalt tack coat material commonly applied on a mainline paving area? (Check all that apply.)
    _____ a. Asphalt distributor/Hand wand. Please specify % of use
    _____ b. Asphalt distributor/Spray bar. Please specify % of use
    _____ c. Spray bar attached to the paver. Please specify % of use
    _____ d. Others. Please specify. _____

11. Are the haul trucks permitted to drive over the asphalt emulsion tack coat material before it
    a. Breaks? (Emulsion color changes from brown to black). _____ Yes _____ No
    b. Sets? (All water has evaporated from the pavement surface). _____ Yes _____ No

12. When is the paver permitted to place HMA over the applied tack coat?
    _____ a. Immediately after it breaks (emulsion color changes from brown to black).
    _____ b. Immediately after it sets (all water has evaporated from the pavement surface).

13. Rank the following factors that affect the break and set time for an asphalt emulsion tack coat material. (1–most important, 7–least important)
    _____ a. Application rate.
    _____ b. Dilution rate.
    _____ c. Ambient temperature.
    _____ d. Pavement surface temperature.
    _____ e. Wind velocity.
    _____ f. Humidity.
    _____ g. Others. Please specify. _____

14. What methods are used to prevent/minimize pickup of the tack coat materials by the tires of the haul trucks? (Mark all that apply.)
    _____ a. The tack coat is required to be completely set before the haul trucks travel over the material.
    _____ b. The pavement surface is sanded after the tack coat material is applied.
    _____ c. The haul trucks travel over the emulsion tack coat material before it breaks.
    _____ d. Pick up is a continuing problem.
    _____ e. Others. Please specify. _____

15. What percentage of the existing pavement surface area is typically covered with residual tack coat material?
_____ a. 100 percent.
_____ b. 90 to 100 percent.
_____ c. 70 to 90 percent.
_____ d. 50 to 70 percent.
_____ e. Less than 50 percent.

16. Indicate which, if any, of the following are specified requirements for application of tack coat material?
_____ a. Amount of spray overlap between nozzles on the distributor spray bar
_____ single lap   _____ double lap   _____ triple lap
_____ b. Angle of the nozzles to the axis of the spray bar
_____ (Min, degree)   _____ (Max, degree)
_____ c. Height of the spray bar above the pavement surface
_____ (Min, inches)   _____ (Max, inches)
_____ d. None

17. What environmental restrictions are placed on the application of the tack coat material? (Mark all that apply.)
_____ a. Minimum ambient temperature __ °C.
_____ b. Maximum ambient temperature __ °C.
_____ c. Minimum pavement surface temperature __ °C.
_____ d. Maximum pavement surface temperature __ °C.
_____ e. Impending rainfall.
_____ f. Wet pavement surface.
_____ g. Damp pavement surface.
_____ h. Time of year (paving season).
_____ i. Other. Please specify. _____

18. How are the application rate and the residual tack coat rate checked?
_____ a. Use of ASTM D2995: Estimating Application Rate of Bituminous Distributors.
_____ b. Difference in weight of the asphalt distributor over a set width and length.
_____ c. Difference in the amount of material in the asphalt distributor tank ("sticking the tank") over a set width and length.
_____ d. Not checked.
_____ e. Other. Please specify. _____

19. What are the specified requirements for the uniformity of the applied tack coat material? (Check all that apply.)
_____ a. Total pavement surface must be covered with tack coat material.
_____ b. Percentage of pavement surface covered with tack coat material.
_____ c. No blocked or partially blocked nozzles on the asphalt distributor.

_____ d. Proper angle of nozzles.
_____ e. Proper height of the spray bar and lap between spray from adjacent nozzles.
_____ f. Not checked.

20. Does the tack coat residual application rate change due to any of the issues listed below?
Yes _____ No _____
If "yes," it is due to
_____ a. Time of year.
Indicate how much the rate change is
_____
_____ b. Type of roadway—interstate, primary, secondary roadway.
Indicate how much the rate change is
_____
_____ c. Condition of roadway, i.e., aging, raveling, cracking, etc.
Indicate how much the rate change is
_____
_____ d. Ambient temperature.
Indicate how much the rate change is
_____
_____ e. Daytime versus nighttime paving.
Indicate how much the rate change is
_____
_____ f. Traffic use before overlay.
Indicate how much the rate change is
_____
_____ g. Thickness of subsequent overlay.
_____

21. If the tack coat application is not uniform, what steps are taken to correct the problem?
_____ a. Remove the tack coat? If so, please specify how. _____
_____ b. Reapply the tack coat
i. At the same application rate.
ii. At a lesser application rate.
_____ c. Take a price deduction from the contractor.
_____ d. Ask the contractor not to do it again.
_____ e. Required improved application on next pass.
_____ f. Do nothing.

Characterization of Tack Coat Application

22. In your experience, what type of pavement failure is related to improper application or type of the tack coat material? (Check all that apply.)
_____ a. Slippage of the surface course layer on top of the underlying layer.
_____ b. Delamination of the surface course layer from the underlying layer.

_____ c. Fatigue cracking of the pavement structure.
_____ d. Top-down cracking.
_____ e. Rutting of the pavement surface.
_____ f. Other distress: _____

23. What laboratory or field test methods do you used to determine the interface bond strength between layers?
_____ a. Laboratory, please specify.
_____

_____ b. Field, please specify. _____
_____

_____ c. None.

24. Beyond specification and bond strength requirements, are there any other field or laboratory tests used to evaluate the quality of tack coat materials?
_____ a. Yes. Please specify.
_____

_____ b. No.

25. Are you aware of any recently completed or on-going research projects in your agency that related to the performance of tack coat materials?
_____ a. Yes. Please specify.
_____

_____ b. No.

26. Please provide any additional comments.
_____
_____
_____
_____
_____
_____

27. I would like to be contacted by a member of the research team.
_____ a. Yes.
_____ b. No.

APPENDIX B

ATacker™ Displacement Rate Verification Experiment

Appendix B is not published herein but can be found at the following address: http://apps.trb. org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=974.

Standard Test Method for Assessing Tack Coat Installation Quality Using the LTCQT

Proposed Standard Method of Test for

DETERMINING THE TACK COAT QUALITY OF ASPHALT PAVEMENT IN THE FIELD OR LABORATORY

AASHTO Designation: TP XX-XX

Proposed test method under review before submitting to AASHTO Subcommittee on Materials

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001

Proposed test method under review before submitting to AASHTO Subcommittee on Materials – Month Day, 20XX

Proposed Standard Method of Test for

DETERMINING THE TACK COAT QUALITY OF ASPHALT PAVEMENT IN THE FIELD OR LABORATORY

AASHTO Designation: TP XX-XX

1. SCOPE

1.1. This test method covers the determination of the tack coat spray application quality as measured by the tensile strength of tack coat materials on free surface of asphalt concrete in the field or laboratory.

1.2. This test can be performed in the field on surface of asphalt concrete or 150 mm (5.9 in.) diameter gyratory compacted samples.

1.3. This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1. AASHTO Standard:
T 53 Softening Point Of Bitumen (Ring-And-Ball Apparatus)

3. TERMINOLOGY

3.1. *Tack Coat Spray Application Quality* – A measure of the uniformity of coverage of tack coat application on a pavement surface, also referred to as tack coat quality. The quality of tack coat is described by the tensile strength of the tack coat material.

4. SUMMARY OF METHOD

4.1. The standard test materials and test apparatus consist of the Louisiana Tack Coat Quality Tester (LTCQT), LTCQT software, computer, weights to hold the LTCQT in place during testing, and an Infrared Reflective Heating (IRH) device used to desiccate emulsion. A heat gun and fan are recommended to heat the surface to testing temperature. A thermometer should be used to determine the surface temperature.

4.2. The test procedure involves desiccating a tacked surface using the IRH device, adjusting the temperature of the surface with the fan or heat gun to reach testing temperature, and applying a compressive load to the tacked pavement surface for a given amount of time using the LTCQT device and software. At a prescribed displacement rate, the movement of the loading plate away from the tacked surface

results in tensile loading until failure. The maximum tensile strength reflects the tack coat quality of the material.

5. SIGNIFICANCE AND USE

5.1. This test method is suitable for field or laboratory tests to determine the tack coat quality of a tacked surface as measured by the tensile strength. The knowledge of tack coat quality serves as a tool in characterizing the tack coat material.

6. APPARATUS

6.1. Louisiana Tack Coat Quality Tester – The device shall be equipped with a closed-loop servo motor actuator for precision control of the rate of displacement during testing. It shall be capable of measuring loads of up to 446 N (100 lbf) with an accuracy of ±1%. The displacement of the actuator shall be measured using a position transducer that has a total travel of 100 mm.

6.2. Computer and Software – The software shall be designed such that it displays the time, normal load, and displacement of the actuator continuously during testing while graphically illustrating the relationship of the normal load and time. It shall allow the user to input the required compressive load, the time to hold the compressive load, and the displacement rate required. The actual holding time of the compressive load shall be displayed during testing as well as the actual displacement rate. In addition, the software shall allow the user to move the actuator manually.

6.3. Infrared Reflective Heating Source – It shall be equipped with a 250 watt, 120 volt bulb. It shall be designed such that it can be positioned six inches from the surface to be tested without contact made with the tacked surface.

6.4. Thermometer – The thermometer shall be suitable to measure the temperature of a tacked surface without directly contacting the test area. It is recommended that an infrared thermometer be utilized.

6.5. Weights – The weights used shall be equal or greater than the expected maximum normal load. Note that the normal load applied by the machine cannot exceed 446 N (100 lbf).

6.6. Temperature control devices – The mechanism of the temperature control device shall be to adjust the surface temperature to the required test temperature. It is recommended that a fan be used to cool the tacked surface and a heat gun be used to heat the tacked surface.
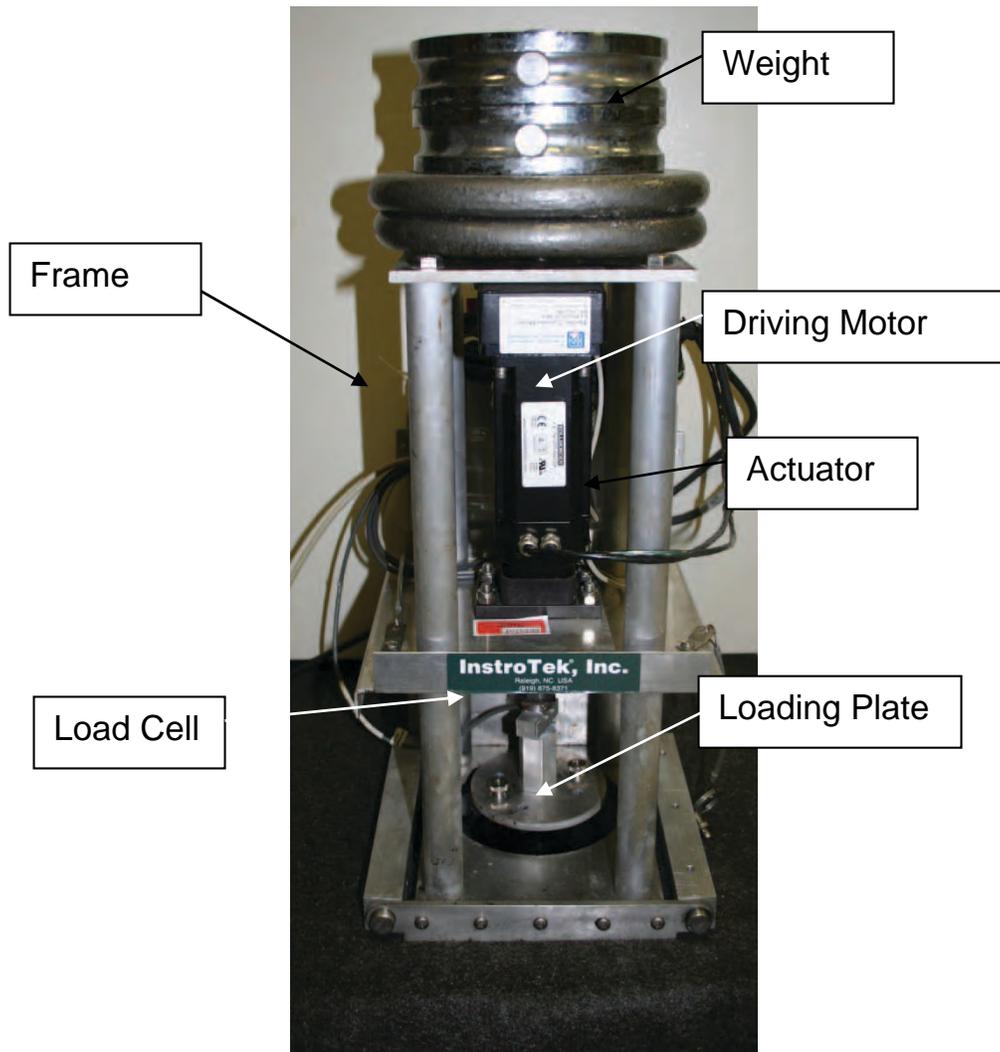
Figure 1. Illustration of the LTCQT device.

7. HAZARDS

7.1. Standard laboratory safety precautions must be observed when preparing and testing asphalt concrete specimens.

8. TEST SPECIMENS

8.1. Testing area shall be cleaned prior to tack coat application.

8.2. Tack coat material shall be applied using the appropriate method.

8.3. Emulsified tacked surfaces shall be desiccated prior to testing. It is recommended that this shall be accomplished by placing the Infrared Reflective Heating source six inches above the tacked surface for a minimum of one hour. Note that this time may be extended for bulk application rates greater than 0.05 gal/yd².

8.4. Number of test areas – a single test shall consist of at least three test areas.

8.5. Test area shall be numbered and the location shall be documented.

9. PROCEDURE

9.1. Testing areas shall be conditioned to the correct testing temperature using a heat blower or fan. It is recommended that the testing temperature shall be the softening point of the tack coat material.

9.2. Device positioning – Place the LTCQT directly above the tacked surface to be tested. Lift up the front end of the device to verify that the loading plate is positioned directly above the tacked surface that will be tested.

9.3. The correct weight shall be placed on top of the LTCQT device.

9.4. The compressive load, time to hold the compressive load, and the displacement rate shall be entered into the computer by the user. The compressive load shall not exceed the weight placed on top of the LTCQT device.

9.5. Immediately following the initiation of the test, the load shall be offset such that the software displays a load of 0 N (lbf) prior to the contact between the loading plate and the tacked surface. It is also recommended that the plate be positioned as close as possible to the tacked surface prior to testing so as to minimize the change in temperature. The initial position of the loading plate shall be determined to allow sufficient time for the observation of the initial load and application of the offset.

9.6. The compressive load shall be mechanically applied to the tacked surface for the specified amount of time. Once the allotted time has ended, the loading plate shall automatically move away from the tacked surface at the prescribed displacement rate. The software shall by design record the normal load, vertical displacement, and time throughout the test. Record the ultimate tensile load, Pult, of the tack coat material, Figure 2..

10. CALCULATIONS

10.1. Calculate the tack coat tensile strength, TS, as follows:

$$TS = \frac{P_{ult}}{\frac{\pi D^2}{4}}$$

where:

TS = Tensile Strength, Pa

P_{ult} = ultimate tensile load, N

D = diameter of the loading plate, m

11. REPORT

11.1. Test location.

11.2. Note the appearance of the tacked surface before and after testing including any contaminants, milling striations, stripping, tack coat streaks, etc.

11.3. Test results:

11.3.1. Loading plate dimensions – including the diameter, and the cross-section area.

11.3.2. Ultimate tensile load applied.

11.3.3. Tensile strength, Pa.

11.3.4.   Corresponding vertical deformation.

11.3.5.   Average and standard deviation of tensile strength for the set of tested areas.

---

12. PRECISION AND BIAS

12.1. The precision and bias statements for this method have not been determined.

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13. KEYWORDS

13.1. Tack Coat Quality, Tensile Strength, Asphalt Overlay, Tack Coat, Slippage Failure.
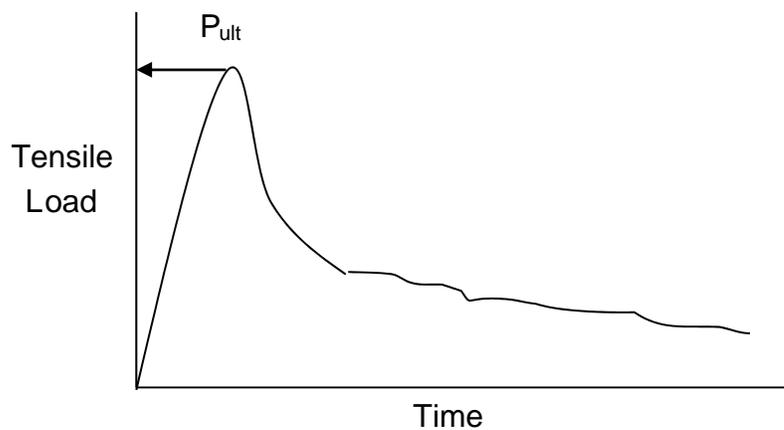
Figure 2. Typical LTCQT test result.

APPENDIX D

Comparison of the LISST Device and the Simple Shear Tester

Appendix D is not published herein but can be found at the following address: http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=974.

Standard Test Procedure for Measuring Interface Bond Strength in the Laboratory Using the LISST

Proposed Standard Method of Test for

DETERMINING THE INTERLAYER SHEAR STRENGTH OF ASPHALT PAVEMENT LAYERS

AASHTO Designation: TP XX-XX

Proposed test method under review before submitting to AASHTO Subcommittee on Materials

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Proposed Standard Method of Test for

DETERMINING THE INTERLAYER SHEAR STRENGTH OF ASPHALT PAVEMENT LAYERS

AASHTO Designation: TP XX-XX

1. SCOPE

1.1. This test method covers the determination of the interlayer shear strength of asphalt concrete layers using laboratory prepared or core samples.

1.2. This test can be performed on 150-mm (5.9-in.) or 100-mm (3.9-in.) diameter specimens of asphalt concrete.

1.3. This test is applicable if both the asphalt overlay layer and the base layer thickness are 50 ± 5 mm (1.97 ± 0.2 in.), each. The total specimen thickness must not exceed 150 mm (5.9 in). Layers may be saw cut to the recommended layer thickness.

1.4. This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1. AASHTO Standards:

- T 166, Bulk Specific Gravity Of Compacted Hot Mix Asphalt Using Saturated Surface-Dry Specimens
- T 168, Sampling Bituminous Paving Mixtures
- T 209, Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt
- T 269, Percent Air Voids in Compacted Dense and Open Asphalt Mixtures
- T 312, Preparing and Determining the Density of Hot Mix Asphalt (Hma) Specimens By Means Of the Superpave Gyratory Compactor

2.2. ASTM Standards:

- D 3549, Standard Test Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens

3. TERMINOLOGY

3.1. Interlayer Shear Strength (ISS) –The maximum capacity of the interface to resist failure due to shearing stresses.

4. SUMMARY OF METHOD

4.1. The Louisiana Interlayer Shear Strength Tester (LISST) was developed for the characterization of interface shear strength of cylindrical specimens. The device (Figure 1) consists of two main parts, a shearing frame, and a reaction frame. Only the shearing frame is allowed to move while the reaction frame is stationary. A cylindrical specimen is placed inside the shearing and reaction frames and is locked in place with collars. Loading is then applied to the shearing frame. As the vertical load is gradually increased, shear failure occurs at the interface.

5. SIGNIFICANCE AND USE

5.1. Tack coats are applied on a pavement surface before overlay construction to ensure adequate interface bond strength between two layers. If the interface cannot provide enough strength to resist stresses due to traffic and environmental loading, shear failure may occur at the interface. Poor interface bond strength may also accelerate the appearance of other distresses such as slippage and surface cracks.

6. APPARATUS

6.1. *Interlayer Shear Strength Tester* - The device used for the interlayer shear strength test shall be designed such that it adapts to any universal testing machine, has a nearly frictionless linear bearing to maintain vertical travel, accommodates sensors that measure the vertical and horizontal displacements, provides specimen locking mechanism, applies consistent normal loads, and accommodates 100- and 150-mm sample diameters. The gap between the loading frame and the reaction frame shall be 12.7 mm (1/2 in.). The device is illustrated in Figures 1 and 2.

6.2. *Loading Machine* - The loading machine shall produce a uniform vertical movement of 2.54 mm (0.1 in.) per minute. Universal mechanical or hydraulic testing machine may be used such that it can provide a displacement rate of 2.54 mm (0.1 in.) per minute. The loading device shall be capable of meeting the minimum requirements specified in Table 1.

Table 1- Minimum Test System Requirements

	RANGE	ACCURACY (PERCENT)
LOAD (N)	0 – 25000	± 1.0
LOADING RAM LVDT (MM)	0 – 150	± 0.5
VERTICAL, HORIZONTAL LVDTS (MM)	0 – 2	± 0.5

6.3. Air compressor - capable of supplying 7.5 SCFM at 40 psi to operate the pneumatic normal load actuator.

6.4. *Wet masonry saw.*
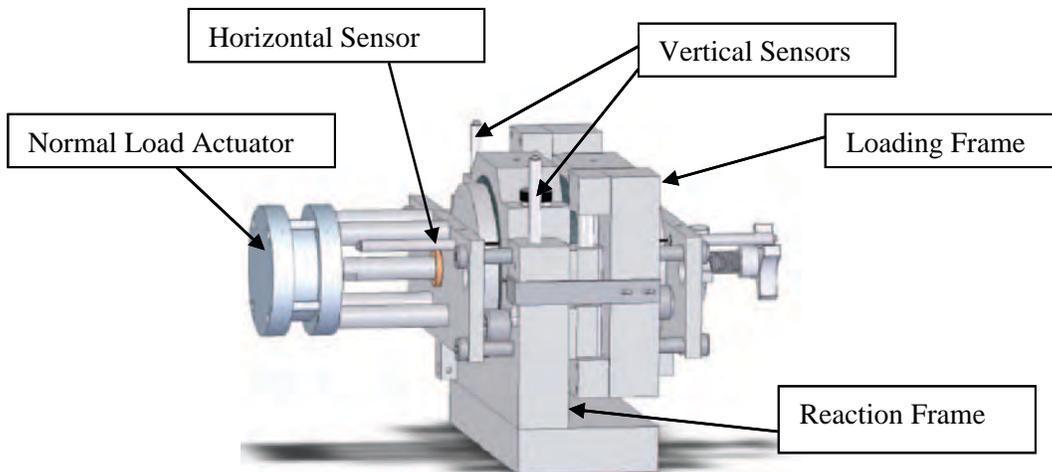
Figure 1. 3-D Illustration Of The Louisiana Interface Shear Strength Tester (LISST) Device.
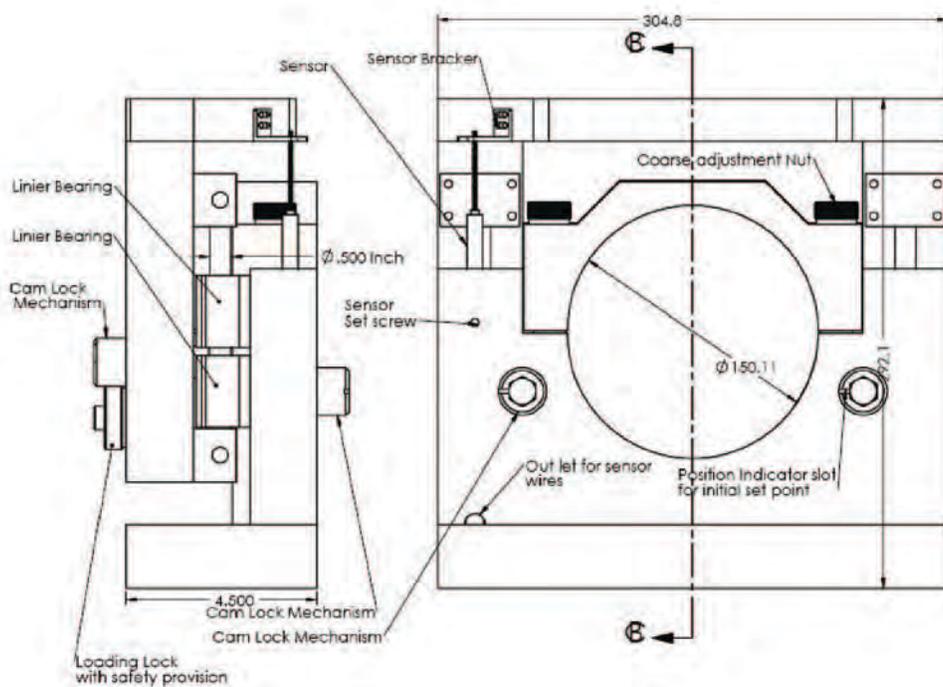
Figure 2. Front and side view of the LISST device.

7. HAZARDS

7.1. Standard laboratory safety precautions must be observed when preparing and testing asphalt concrete specimens.

8. TEST SPECIMENS

8.1. Test specimens may be either laboratory-compacted HMA or sampled from HMA pavements.

8.2. Samples cored from HMA pavement:

8.2.1. Mark the direction of traffic on the roadway surface before coring so that it can be identified once the core is removed.

8.2.2. Cores shall be taken full depth so that no prying action is needed to extract the cores from the pavement. Care shall be taken to avoid stress or damage to the interface during coring, handling, and transportation. If a core debonds at the interface of interest during the coring operation, make note of it on the coring report.

8.2.3. Label core specimens with a paint pen.

8.2.4. Roadway core specimens shall be approximately 150 mm (5.906 in.) diameter with all surface of the perimeter perpendicular to the surface of the core within 6 mm (¼ in.). If the height of the core above or below the interface being tested is greater than 50 mm (1.969 in.), it shall be trimmed with a wet masonry saw to a height of approximately 50 mm (1.969 in.).

8.2.5 Mark the location of the interface layer with white or silver paint.

8.3. Laboratory-compacted HMA samples:

8.3.1. To prepare laboratory samples, compact a cylindrical specimen 150 mm in diameter with a thickness of 50 mm using the Superpave Gyratory Compactor by AASHTO T312. Brush the tack coat material on the top of the prepared specimen. The amount of tack coat will be determined by the application rate. Pour appropriate amount of HMA mixture on top of this tacked lower half. The amount of HMA mixture should be enough to obtain a 50 mm thick "top half".

8.3.2. Measure the diameter of the specimen and the thickness of both layers to the nearest 1 mm.

8.4. Number of Test Specimens – a single test shall consist of at least three specimens.

9. PROCEDURE

9.1. Specimen conditioning – The specimens shall be allowed to stabilize at each test temperature of 4.4, 25.0, and 60.0±1°C (40, 77, and 140 ±2 °F) for a minimum of 2 hours.

9.2. Specimen positioning – Orient the core in the interlayer shear strength tester device so that the direction of traffic marked on the core is vertical.

9.3. The specimen should be loaded in such a manner that the interlayer is located directly in the middle of the gap between the loading and the reaction frames. The loading frame is the frame that can move up and down and the reaction frame is the stationary portion of the apparatus, Figures 1 and 2.

9.4. Normal load, if required, can be applied by means of normal load actuator. The normal load actuator should be able to apply normal pressure up to 206.84 kPa (30 psi) on a 150-mm diameter sample.

9.5. Rate of displacement – Apply the displacement continuously and without shock, at a constant displacement rate of 2.54 mm (0.1 in.) per minute until failure. Record the resulting ultimate load, Pult, vertical, and horizontal deformations, Figure 3.

10. CALCULATIONS

10.1. Calculate the interlayer shear strength, ISS, as follows:

$$ISS = \frac{P_{ult}}{\frac{\pi D^2}{4}}$$

where:

ISS   = interlayer shear strength, Pa

P_{ult} = ultimate load applied to specimen, N

D   = diameter of test specimen, m

11. REPORT

11.1. Report the following for each specimen tested:

11.2. Core identification.

11.3. Report the failure surface location. Failure should occur at the interface of the two material layers.

11.4. Note the appearance of the interface including any contaminants, milling striations, stripping, tack coat streaks, etc.

11.5. Test results.

11.6. Specimen dimensions – including thickness of the overlay asphalt, thickness of existing layer, and diameter of specimen.

11.7. Ultimate load applied.

11.8. Interlayer shear strength, nearest Pa.

11.9. Corresponding vertical and horizontal deformations.

11.10. Average and standard deviation of interlayer shear strength for the set of cores.

12. PRECISION AND BIAS

12.1. The precision and bias statements for this method have not been determined.

13. KEYWORDS

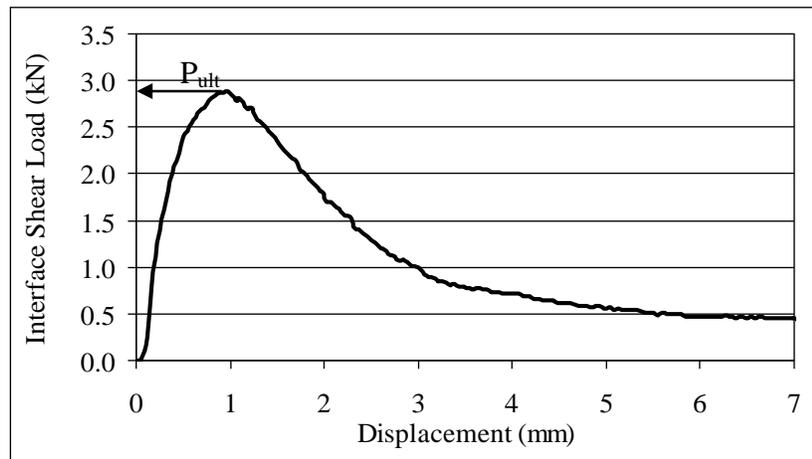13.1. Interlayer Shear Strength, Asphalt Overlay, Tack Coat, Shear Strength, Slippage Failure.

Figure 3. Typical LISST test result.

A P P E N D I X   F

Tack Coat Training Manual

CONTENTS

The Purpose of a Tack Coat

The primary purpose of a tack coat is to enhance the bond between two asphalt concrete pavement layers. As used in this manual, the term asphalt concrete is applied to both hot mix asphalt (HMA) mixtures and warm mix asphalt (WMA) mixtures. A tack coat also serves to ensure acceptable bond when a new asphalt pavement layer is placed over a Portland Cement Concrete (PCC) surface.

A good bond between pavement layers is necessary in order for traffic loads applied to the pavement surface to be transmitted down through the whole pavement structure. If the surface layer is not properly bonded to the underlying pavement layer, horizontal shear forces at the interface between the layers will increase the tendency for cracking, debonding, and fatigue failure to occur in the upper portion of the pavement structure. The tack coat and the bond created between the layers allow the various courses within the pavement structure to act as a whole.

If a proper bond is not established between the existing pavement surface and the new asphalt pavement layer, delamination may occur between the layers. This will result in a slippage or sliding failure of the new mix on top of the existing pavement surface. Thus, in order to construct a durable, long-lasting asphalt concrete pavement, it is very important to apply the proper type and amount of tack coat between the new and old pavement layers.

Types of Tack Coat Materials

Three basic types of asphalt materials can be used for a tack coat. Those three materials include asphalt emulsion, performance graded (PG) type asphalt cement binder, and cutback asphalt. By far, the most common type of material used for tack coats is asphalt emulsion. Cutback asphalts, which are combinations of asphalt cement and a petroleum-based diluent (cutter stock) material, such as naphtha or kerosene, are rarely used today in the US due to environmental considerations related to the evaporation of the cutter stock material. PG asphalt binder is used in some jurisdictions for tack coat.

Performance Graded Asphalt Tack Coat Materials

PG type asphalt binders consist of one hundred percent asphalt cement without any added water or diluent material. Thus, if a PG asphalt is employed as the tack coat material, all of the material that is applied to the existing pavement surface is useful in achieving the bond between the old and new layers. For PG type asphalt, therefore, the residual asphalt binder rate and the application rate are the same.

When the tack coat consists of a PG asphalt, the grade of the PG material used is usually the same as the grade of the

PG binder incorporated into the asphalt mixture. For example, if PG 64-22 is used in the mix, the same grade of material is typically used for the tack coat material.

If a polymer-modified asphalt, such as a PG 76-22, is required in the asphalt mixture, in most cases, the tack coat will be a different PG material, which is not polymer-modified. This is done primarily to reduce cost. In this example, the tack coat material would most likely be PG 64-22 in lieu of the PG 76-22.

A polymer-modified PG asphalt is sometimes used as a tack coat material. In most cases, this use is related to pavement locations where there is substantial stopping or turning traffic applied to the new asphalt concrete pavement surface. Polymer-modified binders are often used as a tack coat for thin lift asphalt concrete pavement surface layer construction.

Asphalt Emulsion Tack Coat Materials

Types of Emulsions: Asphalt emulsions are divided into three categories. Those three categories are anionic, cationic, and nonionic. An anionic emulsion has a negative electrical charge and a cationic emulsion has a positive electrical charge in a zeta potential test. If the letter "C" is placed in front of the emulsion grade, the emulsion type is cationic. If the letter "C" is not shown in front of the emulsion grade, the emulsion type is anionic. Nonionic emulsions are not generally used for pavement construction. For use as tack coat, the selection of anionic or cationic emulsion is generally not significant due to the relatively very small amount of emulsion applied to the existing pavement surface.

Emulsions are divided into three additional categories depending on how quickly the asphalt will coalesce or revert back to the form of an asphalt cement. Those three additional categories are rapid set (RS), medium set (MS), and slow set (SS) emulsions. MS emulsions can additionally be classified as "HF" or high-float. In HF emulsions, the emulsifier forms a gel structure in the asphalt residue. The thicker asphalt film allows HF emulsions to perform in a wider temperature range. Further, some emulsions are graded with the letter "h" following the emulsion classification. The "h" means that harder base asphalt has been used in the emulsion.

Asphalt emulsion consists of a blend of three different materials. The majority of the emulsion is asphalt cement, typically between 55 and 70 percent of the total weight of the emulsion. Water is the second largest ingredient, typically, from 44 to 29 percent of the total weight of the emulsion. The remaining material is the emulsifying agent.

SS emulsion is most often used as tack coat. SS-1, SS-1h, CSS-1, and CSS-1h are four types of slow set emulsions. For anionic asphalt emulsions, the minimum required amount of residual asphalt binder in the emulsion is given in ASTM Standard Specification D 977. The minimum residual asphalt

amount is 57 percent for both SS-1 and SS-1h emulsions. For cationic asphalt emulsions, the minimum amount of residual asphalt binder is found in ASTM Standard Specification D 2397. That residual asphalt amount is also 57 percent for both CSS-1 and CSS-1h emulsions.

Other types of asphalt emulsions are sometimes used as a tack coat. Those emulsions include rapid setting (RS) emulsions: RS-1, RS-2, as well as CRS-1 and CRS-2. It is noted that the minimum binder content required by the ASTM standards are shown to be 55 percent for RS-1, 63 percent for RS-2, 60 percent for CRS-1, and 65 percent for CRS-2.

Calculation of the Application Rate for Emulsion

It is the residual asphalt binder that creates the bond between the pavement layers. To calculate the application rate for an asphalt emulsion tack coat material, the starting point is the required residual tack coat amount. The calculations must work backward from the residual amount of tack coat to arrive at the application rate for the same tack coat material. Based on a constituent ratio of ⅔ asphalt binder and ⅓ water, the required application amount of asphalt in an asphalt emulsion will be 1.5 times greater than the residual amount.

For example, if the residual amount of asphalt binder on an existing pavement surface is 0.06 gallons per square yard (g/sy), the application rate of the asphalt emulsion will need to be 0.09 gallons per square yard. For an undiluted asphalt emulsion, the application rate is 1.5 times greater than the residual rate of the emulsion, or 0.06 g/sy times 1.5 = 0.09 g/sy. For an undiluted asphalt emulsion, if the required residual amount of asphalt in the tack coat is required to be 0.04 g/sy, the application rate for that emulsion would be 0.06 g/sy (or $0.04 \times 1.5 = 0.06$).

Diluted Asphalt Emulsions

Many SS asphalt emulsions are diluted with additional water before they are sprayed onto the existing pavement surface as a tack coat. The primary reason for diluting emulsion is to provide for a more uniform application of the tack coat material. The greater volume of the diluted emulsion provides a more consistent and uniform spray pattern from the nozzles on the distributor. The most common dilution rate is a 1:1 (50% : 50%) ratio of SS asphalt emulsion and additional water. This results in a material that is one part asphalt emulsion and one part additional water.

Based on the assumption that an undiluted emulsion consists of ⅔ asphalt binder and ⅓ water, an asphalt emulsion that is diluted 1:1 with additional water will have residual asphalt binder that is only ⅓ of the weight of the diluted emulsion. Thus, if the residual amount of asphalt binder on a particular pavement surface is required to be 0.06 gallons per square yard, the application rate of the diluted asphalt emulsion would need to be 0.18 g/sy. For a 1:1 diluted emulsion, the application rate is 3.0 times greater than the residual rate of the emulsion, or 0.06 g/sy times 3.0 = 0.18 g/sy. For a 1:1 diluted asphalt emulsion, if the required residual amount of asphalt binder in the tack coat is intended to be 0.04 g/sy, the application rate for that emulsion would be 0.12 g/sy (or $0.04 \times 3.0 = 0.12$).

Most often, dilution of the asphalt emulsion occurs at the terminal of the emulsion supplier. This is the preferred location since the dilution rate can be carefully controlled. On occasion, a contractor will purchase an undiluted emulsion and add the water to the undiluted emulsion when that material is in the tank of the asphalt distributor. Although this can be done, it is important that the proper amount of water be added to the undiluted emulsion so that the application rate and the residual rate of the diluted emulsion are correct. Therefore, it is important that a sample of the emulsion, whether undiluted or diluted, be taken from the asphalt distributor prior to first use to assure that the proper residual amount of asphalt binder material is actually present on the pavement surface once the water in the emulsion evaporates.

Polymer-Modified Asphalt Emulsion

If a polymer-modified asphalt emulsion is to be used as tack coat, the residual tack coat rate will be the same as for a non-polymer-modified asphalt emulsion. The use of a polymer-modified emulsion may be justified for pavement locations where there is a substantial amount of stopping and/or turning traffic applied to the new asphalt pavement surface.

Trackless Tack Coat Emulsion

A polymer-modified asphalt emulsion has been developed which incorporates a hard base asphalt binder (low penetration asphalt cement) as part of the emulsion. Hard base asphalt, combined with the polymer additive, reduces the amount of tracking that might occur on the tires of the haul trucks as well as the tire or tracks of the asphalt paver. The residual asphalt binder in the trackless tack coat material is similar to that of a standard asphalt emulsion. Thus, the application rate for this material would be similar to that of a normal, undiluted asphalt emulsion.

It is noted that the trackless tack coat material typically breaks and sets faster than a standard asphalt emulsion. This change in both the break time and the set time of the trackless tack coat can significantly reduce the amount of tracking that occurs on the tires of the construction traffic. (Note: Break and set times are defined in the section titled, "TACK COAT BREAK TIME AND SET TIME.")

During the research that led to this manual, trackless tack products performed exceptionally well in that they provided excellent adhesion and strong shear resistance between the tacked layers.

Cutback Asphalt Tack Coat Materials

Types of Cutback Asphalt Materials

Cutback asphalt is a combination of asphalt binder and a diluent material, sometimes called petroleum distillate or cutter stock. The three primary types of cutback asphalt are differentiated by the relative speed of evaporation of the diluent used: rapid curing (RC), medium curing (MC), and slow curing (SC). RC materials typically contain gasoline or naphtha as the diluent material. MCs use kerosene. SCs contain diesel or fuel oil.

Cutback materials have occasionally been used for tack coat applications. Typically, RC-70, MC-30, MC-70, or SC-70 is employed. For tack coat use, cutback asphalts are not diluted and are thus used full strength. Due to the low flash point (thus fire danger) and environmental concerns (volatile organic compound emissions), cutbacks are not recommended. For these reasons, many state DOTs have prohibited the use of cutback asphalts.

Residual Amount of Binder in a Cutback Asphalt

The minimum amount of asphalt binder required by ASTM Specification D 2028, Standard Specification for Cutback Asphalt (Rapid Curing Type) for a RC-70 cutback is 55 percent. Typically, RC-70 will consist of approximately 60 percent asphalt and 40 percent cutter stock.

Calculation of the Application Rate for Cutback Asphalt

Similar to the calculations for asphalt emulsion, to determine the application rate for cutback asphalt, the starting point is the required residual tack coat amount. Calculations must work backward from the residual amount of tack coat to arrive at the application rate for the same tack coat material.

If the residual amount of asphalt tack coat on a particular pavement surface should be 0.06 gallons per square yard, the application rate of the cutback asphalt will need to be approximately 0.10 gallons per square yard. For RC-70, the application rate is about 1.7 times greater than the residual rate of the emulsion, or 0.06 g/sy times 1.7 = 0.102 g/sy, rounded to 0.10 g/sy. If the residual amount of asphalt tack coat is required to be 0.04 g/sy, and cutback asphalt is employed for the tack coat material, the application rate for the RC-70 would be approximately 0.07 g/sy (or $0.04 \times 1.7 = 0.068$ g/sy, rounded to 0.07 g/sy).

Conditions of the Existing Pavement Surface

The application rate of a tack coat should vary depending on the conditions of the pavement surface being overlaid. What is really important is not the application rate of the tack coat material, but the residual rate of the tack coat or the amount of asphalt binder that remains after the water has evaporated out of the asphalt emulsion or the diluent has evaporated out of the cutback asphalt material. The actual application rate must be back-calculated starting from the residual rate.

The objective is to apply a sufficient quantity of tack coat, which results in a thin, uniform coating of asphalt binder material over the existing pavement surface. Coordinating the residual tack coat rate, and thus the actual application rate, of the tack coat to the conditions of the pavement surface is extremely important.

The residual rate of tack coat needed, and thus, the actual application rate, depends on the conditions of the existing pavement surface including:

1. Dusty or dirty pavement surface.
2. New pavement surface.
3. Old, aged pavement surface.
4. Texture of the pavement surface.
5. Milled asphalt pavement surface.
6. Bleeding surface.
7. Portland cement concrete surface.

Dust and Dirt

If the pavement surface is dusty or dirty, it must be cleaned in order to prevent the new asphalt pavement surface from sliding or delaminating at the dusty/dirty interface. Tack coat must be applied to a clean surface. Further, when using either a PG asphalt tack coat or a cutback asphalt tack coat, the pavement surface must be dry. Cleaning operations can be accomplished either by mechanical brooming or by flushing the existing surface with water or blowing off debris using high-pressure air. If the asphalt pavement or PCC pavement surface is dusty or dirty, there will be a tendency for the new asphalt concrete surface to slide or slip (delaminate) at the dusty interface. This type of bond failure is shown in Figure 1. Sliding failures occur most often at locations where traffic decelerates, such as stop signs or traffic signals. Sliding failures also occur where traffic accelerates or where traffic makes tight turning maneuvers.

The residual tack coat application rate should not be changed in order to compensate for a dusty or dirty pavement surface. A heavier residual tack coat application rate may increase a

Figure 1. Delamination type of sliding failure.

potential sliding failure problem. The dust coating will create a slip plane and any added, excess residual tack coat will further weaken the bond between the layers and thus make the problem worse. The only remedy for a dusty or dirty pavement surface is to clean that surface and remove all loose dust or dirt.

A small amount of moisture on the pavement surface from a passing shower probably will not be detrimental to the long-term function of a tack coat. If the amount of the moisture is minimal, this moisture should be flashed off by the subsequent hot asphalt mixture overlay. However, if the pavement surface layer is saturated with water and the existing pavement surface is damp, the ability of the tack coat material to provide adequate bond between the existing and the new pavement layers may be significantly compromised.

New Pavement Surface

A common perception is that a tack coat may not be needed between two new asphalt concrete pavement layers. If one layer of asphalt mixture was placed yesterday and the next layer is placed over that surface today, a tack coat is sometimes thought to be unnecessary between the two new layers of mix. This recommendation, however, assumes that the underlying surface is clean when the overlay is placed. If traffic, including construction traffic, travels over the bottom layer and the bottom layer becomes dusty or dirty for some reason, it will be necessary to clean the surface of the bottom layer and apply a tack coat to the cleaned surface. Results from NCHRP Project 9-40 indicated that tack coat is needed between two new asphaltic concrete pavement layers.

If a tack coat is applied, the residual rate should be reduced to compensate for the lack of absorption of the tack coat material into the new asphalt concrete pavement layer. In most cases, the residual rate should be approximately one-half the amount applied to an old, oxidized pavement surface.

Old, Aged Asphalt Concrete Pavement Surface

If the asphalt concrete pavement surface contains an extensive number of cracks, a portion of the tack coat material may flow into the cracks and not be available to create the bond between the pavement layers. Significant flow of tack coat into cracks is usually a problem only when diluted emulsion is used. In this situation, the residual tack coat rate may need to be increased slightly in order to account for the loss of tack material into the pavement cracks. To avoid the potential for tack coat flow, consider the use of undiluted emulsion or PG asphalt, being sure to utilize the appropriate nozzle size to ensure proper coverage. Care must be taken that the amount of the residual tack coat in the non-cracked areas is not so heavy as to create a slip plane or bleeding at those locations. If the existing asphalt concrete pavement surface is highly oxidized and brittle, a slightly higher residual tack coat rate may be needed.

Texture of the Pavement Surface

As demonstrated by the results of NCHRP Project 9-40, the surface texture of the existing pavement has a significant effect on the residual amount of tack coat needed. If that surface has a relatively fine texture, less residual tack coat will be required. If that surface has a relatively coarse texture, more residual tack coat will be needed.

A pavement surface that has raveled will normally have a rougher surface texture. An old, aged pavement surface will also normally have a rougher surface texture. In both cases, it will be necessary to increase the residual tack coat application rate in order to account for the rougher surface texture.

Milled Asphalt Concrete Surface

A common perception is that a tack coat may not be needed when a new asphalt concrete pavement layer is placed on top of a milled asphalt pavement surface. It has been suggested that the surface texture of the clean milled surface will provide the amount of roughness and bond necessary between the old pavement and the new asphalt concrete overlay (Figure 2). This roughness may prevent the new asphalt mixture from sliding on the milled pavement surface and thus permit the applied traffic loads to be transmitted from the new overlay to the original, milled, pavement layers. However, results from NCHRP Project 9-40 indicated that the amount of bond generated between the milled surface and the new asphalt concrete overlay used in that study with no tack coat material was not sufficient to provide an adequate level of shear strength at the interface between the milled surface and the new asphalt concrete overlay.

It is necessary, however, for the dust that is created during the milling operation to be removed to ensure that the milled surface is free of dust before the new overlay is placed, particularly the dust in the bottom of the grooves. Aggressive brooming followed by flushing of the milled surface with water or use of compressed air is needed to assure that all of the dust has been removed prior to tack coat application. If the dust is not removed from the grooves in a milled surface and a tack coat is applied, the tack coat material can cause the dust to become sticky and adhere to the tires of the construction equipment. The sticky material may build up on the tires to the extent that it may be carried off on the tires and become unavailable to provide the bond between existing and new pavement layers (Figure 3).

If a tack coat is applied to a milled asphalt concrete surface, the residual tack coat rate should be reduced in order to prevent the tack coat material from draining into the milled

Figure 3. Tack coat and debris picked up by construction traffic from a dirty milled/tacked surface.

grooves and collecting in the bottom of the grooves. If this situation occurs, the degree of bond achieved will obviously vary from the top of the grooves to the bottom of the grooves and, therefore, decrease the strength of the bond instead of increasing the strength of the bond with the new asphalt concrete layer. Use of diluted emulsion as tack coat will exacerbate this problem.

Bleeding Surface

Care must be taken when a tack coat is applied to an existing pavement surface that is flushed or bleeding. In this situation, the tack coat application rate must be reduced in order to take into account the amount of asphalt material already

Figure 2. Clean milled surface.

on the pavement surface. In addition, the tack coat application rate may have to be adjusted for different pavement surface conditions transversely across a traffic lane. Less tack coat may be needed, for example, in the wheel paths of an existing pavement surface that is bleeding compared to the amount of tack coat needed between the wheel paths and along the outside edges of the lane.

A change in the residual tack coat rate across the width of the pavement lane being tacked will necessitate a change in the size of the nozzles on the distributor spray bar at different locations along the length of the spray bar. In order to apply different amounts of tack coat (and thus different amounts of residual tack coat) at different transverse locations, the amount of bleeding across the width of the pavement lane being tack coated must be consistent. If the bleeding areas vary longitudinally in width or severity, it will be impossible to apply the correct amount of residual tack coat in the bleeding areas compared to the non-bleeding areas. In this case, it would be advisable to mill the surface to remove the bleeding areas and to provide a uniform pavement texture.

Portland Cement Concrete Surface

The amount of residual tack coat applied to an existing PCC pavement surface will depend on two primary factors. For most PCC surfaces, the amount of residual tack coat will be the same as for an asphalt concrete pavement surface that is in relatively good condition. In general, no increase in the residual tack coat rate is required to account for the joints or cracks in the PCC surface.

If the PCC surface has been diamond ground, a slight increase in the tack coat residual rate may be necessary due to the increased texture of the diamond ground surface. If the PCC surface has been milled, the milled surface should be cleaned, as described above, for the milled asphalt concrete surface, and a tack coat should be applied.

Pavement Conditions and Residual Tack Coat Rate

Table 1 presents a summary of the range of the residual asphalt binder application rates for the various pavement surface types. A detailed discussion for each pavement surface type is given below.

Table 1. Typical residual asphalt binder for tack coats.

Condition of the Existing Pavement Surface	Residual Asphalt Binder
Dusty or Dirty	Clean the Surface
New Asphalt	0.03 to 0.04 g/sy
Old, Aged Asphalt	0.04 to 0.06 g/sy
Milled Asphalt	0.03 to 0.05 g/sy
Portland Cement Concrete	0.04 to 0.06 g/sy

Dusty or Dirty Pavement Surface

There is no recommended residual tack coat rate for a dusty or dirty existing pavement surface. A dusty or dirty surface must be cleaned and all of the dust or dirt removed before any type of tack coat material is applied to that surface. Cleaning can be accomplished using a mechanical broom or by flushing the surface with water or using compressed air.

New Asphalt Pavement Surface

A new asphalt concrete pavement surface will typically not absorb a significant amount of tack coat material. A simple test can be used to determine the amount of tack coat that might be absorbed into the new surface. The test consists of pouring a small amount of water onto the new asphalt pavement surface. If the water simply "beads up" or just runs off, the new surface will not absorb any significant amount of tack coat material. In such a case, placement of a tack coat between the new underlying asphalt concrete layer and the new asphalt concrete overlay is probably not necessary.

If the water penetrates into the new surface (due to improper compaction of the new mix, for example), then it can be assumed that a portion of the tack coat material would penetrate into the new asphalt mixture surface. Because of the tightness of the new surface and the amount of asphalt binder in that surface, the amount of residual asphalt binder in the applied tack coat normally needs to be significantly less than the amount needed for an old, aged pavement surface. For a new, clean asphalt concrete pavement layer placed one day, and a second layer to be placed within a day or two, the residual tack coat rate on the pavement surface should be in the range of 0.03 to 0.04 g/sy.

Old, Aged Pavement Surface

An old, aged, oxidized asphalt pavement surface will normally absorb a significant amount of the applied tack coat material. This is particularly true when using a diluted asphalt emulsion but not normally an issue when using PG asphalt as tack coat. In order to have enough tack coat remaining on the pavement surface to create an adequate bond between the old and new pavement layers, the residual tack coat rate will have to be increased. In general, the residual amount of tack coat material should be in the range of 0.04 to 0.06 g/sy, Table 1.

Surface Texture

An asphalt concrete pavement surface that has a fine surface texture will normally require a lower residual tack coat rate than an asphalt concrete pavement surface that has a coarser surface texture. Further, if the existing pavement surface is raveled, a

greater residual tack coat rate will be needed to compensate for the increase in the surface area due to the rough texture. In addition, if the existing pavement surface is extensively cracked, a greater amount of residual tack coat will be needed.

Because the variation of surface texture of an existing asphalt pavement surface can be significant due to a wide range of surface issues, the range of residual tack coat rates is also greater. In general, the residual tack coat range would be from 0.04 to 0.08 g/sy.

Open-Graded Asphalt Pavement Surfaces

A new open-graded asphalt pavement (OGAP) surface is generally much more open than the surface of an OGAP surface that has been used by traffic for a number of years. In addition, some OGAP surfaces have been clogged with dust and dirt with time and traffic, and the air void content of the mix has been reduced significantly due to the amount of dust and dirt that may have accumulated in the pores of the mix. It is, therefore, very difficult to predict the amount of residual tack coat material that is needed to create the bond between the existing OGAP surface and the new asphalt concrete overlay. Thus, no residual tack coat material rate is suggested in this manual.

More importantly, it has been found that overlaying an OGAP surface with a dense-graded asphalt pavement layer has led to early failure of the new overlay due to the amount of water that may accumulate in the now underlying open-graded layer. Water can enter the open-graded layer both from above and below. Many overlaid OGAP layers have experienced significant stripping when overlaid with a dense-graded asphalt concrete mixture. It is generally recommended, therefore, that the OGAP surface be removed prior to the placement of another asphalt concrete layer.

Milled Asphalt Pavement Surface

A common perception is that a tack coat may not be needed in order to create a bond between a milled surface of an asphalt concrete pavement and the new asphalt concrete overlay and that the roughness and exposed new asphalt surface created by the milling operation provides the necessary bond between the old and new layers. However, results from NCHRP Project 9-40 indicated that the roughness of the milled surface was not sufficient to provide the required shear strength at the interface. Thus, a tack coat material will normally be needed.

If a tack coat is applied to a milled surface, the residual amount of the tack coat should be reduced compared to that amount used for an old, aged pavement surface. A typical residual tack coat rate for a clean, milled asphalt pavement surface should be in the range of 0.03 to 0.05 g/sy. Excessive residual tack coat might actually reduce the bond achieved between the milled surface and the new asphalt concrete overlay.

Bleeding Surface

Rarely is the amount of bleeding or flushing that occurs on the surface of an asphalt concrete pavement uniform either in the transverse direction or the longitudinal direction. In most cases, the amount of bleeding is much greater in the wheel paths of the roadway as compared to the pavement areas between the wheel paths or outside the wheel paths. This significant difference in the condition of the pavement surface at different locations makes it extremely difficult to determine the amount of residual tack coat material that is needed to provide the proper bond between the new overlay and the existing bleeding pavement surface across the width and down the length of the roadway.

If the existing pavement surface is bleeding, the best approach is to mill that surface and remove the excess binder material. If milling is not needed to correct the grade or cross slope of the existing pavement structure, the depth of milling can be minimal—the depth of the milling can be limited to ½ inch or even less. If the asphalt concrete mix is unstable, however, and is the cause of the bleeding, the deficient layer should be entirely removed.

It is possible to use different size nozzles on the asphalt distributor spray bar to apply different amounts of tack coat material at different transverse locations across the width of the pavement lane being overlaid. This is feasible, however, only if the bleeding areas are consistent in width and length. In the vast majority of the cases related to the overlay of an existing asphalt pavement that is bleeding, the proper solution to the problem is to mill off the bleeding surface rather than attempt to apply the "correct" amount of residual asphalt tack material to all of the surface locations. Due to significant variation in the amount of bleeding that can occur on a pavement surface, it is basically impossible to provide a typical range for the residual asphalt binder in this guide.

Portland Cement Concrete Pavement Surface

In most cases, the residual amount of asphalt binder needed for a tack coat applied to a PCC surface is essentially the same as that for an old, aged asphalt concrete pavement surface. In general, the residual tack coat rate will be at the lower end of the range, usually between 0.04 and 0.05 g/sy. If the PCC surface has been diamond ground and has relatively high texture, the residual asphalt tack coat rate should be in the range of 0.05 to 0.06 g/sy.

Application Rate Versus Residual Asphalt Binder

As discussed above, the residual asphalt binder is the amount of material that actually provides the bond between two different pavement layers. Thus, the application rate of the asphalt

Table 2. Typical application rates using PG asphalt.

Condition of the Existing Pavement Surface	Applied PG Asphalt Binder Rates
New Asphalt	0.03 to 0.04 g/sy
Old, Aged Asphalt	0.04 to 0.06 g/sy
Milled Asphalt Mixture	0.03 to 0.05 g/sy
Portland Cement Concrete	0.04 to 0.06 g/sy

APPLICATION RATES USING UNDILUTED ASPHALT EMULSIONS

Condition of the Existing Pavement Surface	Applied Undiluted Asphalt Emulsion Rates
New Asphalt	0.04 to 0.06 g/sy
Old, Aged Asphalt	0.06 to 0.09 g/sy
Milled Asphalt	0.04 to 0.07 g/sy
Portland Cement Concrete	0.06 to 0.09 g/sy

APPLICATION RATES USING 1:1 DILUTED ASPHALT EMULSIONS

Condition of the Existing Pavement Surface	Applied Diluted Asphalt Emulsion Rates
New Asphalt	0.09 to 0.12 g/sy
Old, Aged Asphalt	0.12 to 0.18 g/sy
Milled Asphalt	0.09 to 0.50 g/sy
Portland Cement Concrete	0.12 to 0.18 g/sy

APPLICATION RATES USING RC-70 CUTBACK ASPHALT

Condition of the Existing Pavement Surface	Applied Cutback Asphalt Rates
New Asphalt	0.05 to 0.07 g/sy
Old, Aged Asphalt	0.07 to 0.10 g/sy
Milled Asphalt	0.05 to 0.09 g/sy
Portland Cement Concrete	0.07 to 0.10 g/sy

material must be back-calculated from the desired residual rate of the asphalt binder.

In Table 2, the application rates for the four types of materials listed are determined based on the following relationships: For the PG asphalt, the application rate is the same as the residual rate. Based on the residual rate for a new asphalt concrete pavement surface of 0.03 to 0.04 gallons per square yard (Table 1), the application rate is the same, as shown in Table 2.

For the undiluted asphalt emulsion material, the application rate is approximately 1-½ times more than the residual rate (based on a ratio of the emulsion being ⅔ asphalt binder and ⅓ water, which is a useful approximation). Thus, for an undiluted asphalt emulsion applied to a new asphalt pavement surface, for a residual application rate of 0.03 to 0.04 g/sy, the required application rate for the undiluted asphalt emulsion is in the range of 0.04 to 0.06 g/sy, or approximately 1-½ times more than the residual binder.

For an emulsion that is diluted 1:1 with water, the application rate is approximately three times more than the required residual rate (based on the diluted asphalt emulsion being approximately ⅓ asphalt binder and ⅔ water). Thus, for a 1:1 diluted asphalt emulsion applied to a new asphalt pavement surface, for a residual application rate of 0.03 to 0.04 g/sy, the required application rate for the diluted asphalt emulsion is in the range of 0.09 to 0.12 gallons per square yard.

For RC-70 cutback, using an estimated asphalt content of 60 percent, the application rate would need to be approximately 1.6 times greater than the residual binder rate. Thus, for a RC-70 cutback asphalt that is applied to a new asphalt pavement surface, for a residual application rate of 0.03 to 0.04 g/sy, the required application rate for the cutback asphalt is in the range of 0.05 to 0.07 gallons per square yard.

It is very important to realize that the tack coat application rate MUST be determined by starting at the desired residual application rate for the type of asphalt material being used for tack coat and working backward to calculate the actual application rate. Table 3 provides a summary of the multiplication factors that need to be used to determine the application rate for the four common types of tack coat materials—PG type asphalt binder, undiluted asphalt emulsion, 1:1 diluted asphalt emulsion, and RC-70 cutback asphalt.

Table 3. Typical residual rate—application rate multiplication factors.

Type of Tack Coat Material	Multiplication Factor
PG Type Asphalt Binder	1.0
Undiluted Asphalt Emulsion	1.5
1:1 Diluted Asphalt Emulsion	3.0
RC-70 Cutback Asphalt	1.6

Asphalt Distributors

Parts of an Asphalt Distributor

An asphalt distributor is normally employed to apply a tack coat to an existing pavement surface. The distributor (Figure 4) consists of a number of primary parts. Those parts include the truck frame, asphalt tank, liquid heating system, variable or constant speed pump, spray bar with spray nozzles, and computer system to control the rate of the tack coat application. Tack coat material, however, can also be applied manually, using a hand wand or single spray nozzle system.

Asphalt Tank

An asphalt tank holds tack coat material until it is ready to be applied to the pavement surface. The tank is insulated and typically has a capacity of 500 to 5,500 gallons of tack coat material. Tanks normally contain a series of baffle plates to keep the tack coat material from sloshing around when the truck is moving.

Tack Coat Material Temperatures

Distributors are equipped with burners, which are used to maintain the temperature of tack coat material to assure the correct viscosity in order to be sprayed properly. Proper temperature for the tack coat material depends on the type of product.

The temperature at which an asphalt emulsion is maintained in the distributor tank depends on the grade of the emulsion. Most rapid set (RS) emulsions are applied at a temperature in the range of 70°F to 140°F. The spraying temperature for a high float rapid set (HFRS) material, however, is typically in the range of 125°F to 185°F. Most medium set (MS) and slow set (SS) emulsions are maintained at a temperature in the range of 70°F to 160°F, including high float medium set (HFMS) materials. When polymer-modified asphalt emulsions

Figure 4. A typical asphalt distributor (courtesy of Etnyre).

are used, the spray temperature is typically in the range of 180°F to 200°F. Table 4 presents a summary of guidelines of storage and application temperatures for tack coat materials. Details of storage, handling, and sampling are presented elsewhere (*1*).

Application temperature for cutback asphalt, such as RC-70, is normally in the range of 120°F to 150°F. For PG asphalt, the temperature in the distributor tank is much higher, in the range of 280°F to 325°F. For a polymer-modified PG asphalt binder, the temperature in the distributor tank is typically in the range of 320°F to 340°F. Table 4 presents a summary of guidelines of storage and application temperatures for cutback tack coat materials. However, recommendations for the appropriate spraying temperatures for polymer-modified asphalt should be obtained from the supplier.

Cleaning the Distributor Tank

It is very important that the interior of the tank on the asphalt distributor be cleaned when changing from one asphalt materials to another. For example, PG asphalt added on top of an asphalt emulsion remaining in the distributor tank may cause severe foaming depending on the amount emulsion in the tank. In addition, mixing materials will significantly change both the properties of the desired tack coat material and the appropriate application rate.

It is extremely important that the tack coat material be maintained in the distributor tank at the appropriate temperature for the material being used in order to assure uniform flow of the material through the nozzles on the spray bar. If the tack coat material is too cold when it is sprayed onto the existing pavement surface, the material will come out in strings instead of a uniform spray. The distributor is equipped with a thermometer that displays the temperature of the tack coat materials in the tank. If the tack coat material is not within the proper temperature range for the type of product being used, application of the tack coat should be delayed until the material is brought to the correct application temperature.

Distributor Pump

Asphalt distributors typically are equipped with one of two types of pumps, a variable speed pump or a constant speed pump. Different distributors use different methods to maintain the necessary pressure to pump asphalt materials at different temperatures and different application rates. It is also important for the pump on the distributor to operate at the proper speed or pressure in order to assure the desired spray pattern for the tack coat material.

On older model asphalt distributors, a tachometer is usually employed to maintain a constant travel speed during the spraying process. A chart is used by the distributor operator to determine the correct combination of pump speed or pump pressure and distributor travel speed. In order to achieve a consistent tack coat application rate, it is very important on

Table 4. Guideline temperatures for tack coat materials.
(courtesy of Asphalt Products Unlimited)

Type and Grade	Spraying Temperature		Storage Temperature	
	°C	°F	°C	°F
Asphalt Cements				
AC -2.5	149+	300+	160	320
AC-5	149+	300+	166	330
AC-10	163+	325+	174	345
AC-20	163+	325+	177	350
AC-40	177+	350+	177	350
AR-1000	149+	300+	163	325
AR-2000	149+	300+	168	325
AR-4000	177+	350+	177	350
AR-8000	177+	350+	177	350
PEN 40-50	177+	350+	177	350
PEN 60-70	177+	350+	177	350
PEN 85-100	163+	325+	177	350
PEN 120-150	163+	325+	177	350
PEN 200-300	149+	300+	168	335
Emulsified Asphalts				
Trackless	71-85	160-180	71-85	160-180
RS-1	21-71	70-160	20-60	70-140
RS-2	60-85	140-185	50-85	125-185
HFRS-2	60-85	140-185	50-85	125-185
MS-1	21-71	70-160	10-60	50-140
MS-2	60-85	140-180	50-85	125-185
MS-2h	60-85	140-180	50-85	125-185
HFMS-1	21-71	70-160	10-60	50-140
HFMS-2	60-85	140-180	50-85	125-185
HFMS-2h	60-85	140-180	50-85	125-185
HFMS-2s	60-85	140-180	50-85	125-185
SS-1	21-71	70-160	10-60	50-140
SS-1h	21-71	70-160	10-60	50-140
CRS-1	21-71	70-160	50-85	125-185
CRS-2	60-85	140-180	50-85	125-185
CMS-2	60-85	140-180	50-85	125-185
CMS-2h	60-85	140-180	50-85	125-185
CSS-1	21-71	70-160	10-60	50-140
CSS-1h	21-71	70-160	10-60	50-140
Cutback Asphalts (NOTE: Use Caution on upper limits due to flash point)				
MC-30	30+	80+	54	130
MC-70	50+	120+	71	160
MC-250	75+	165+	91	195
MC-800	95+	200+	99	210
MC-3000	110+	230+	99	210
RC-70	50+	120+	71	160
RC-250	75+	165+	91	195
RC-800	95+	200+	99	210
RC-3000	110+	230+	99	210
SC-70	50+	120+	71	160
SC-250	75+	165+	91	195
SC-800	95+	200+	99	210
SC-3000	110+	230+	99	210

the older distributors for the operator to maintain a constant speed when spraying the tack coat material.

Newer model distributors are equipped with an onboard computer system that determines the relationship between the distributor travel speed and the pump speed or pressure. When the speed of the distributor changes, a consistent application rate is maintained by the computer, which automatically changes the pump pressure to compensate for the change in travel speed. Tack coat material is circulated from the tank on the distributor to the spray bar. In addition, when the tack coat application is complete, the pump is used to pull the material from the spray bar back into the tank.

It is impossible to describe all types of distributor functions here. Therefore, the operator should refer to the owner's manual or manufacturer instructions for the specific distributor.

Spray Bar Nozzle Angle

The spray bar is located at the rear of the distributor, behind the rear wheels of the truck. Tack coat material is applied to the
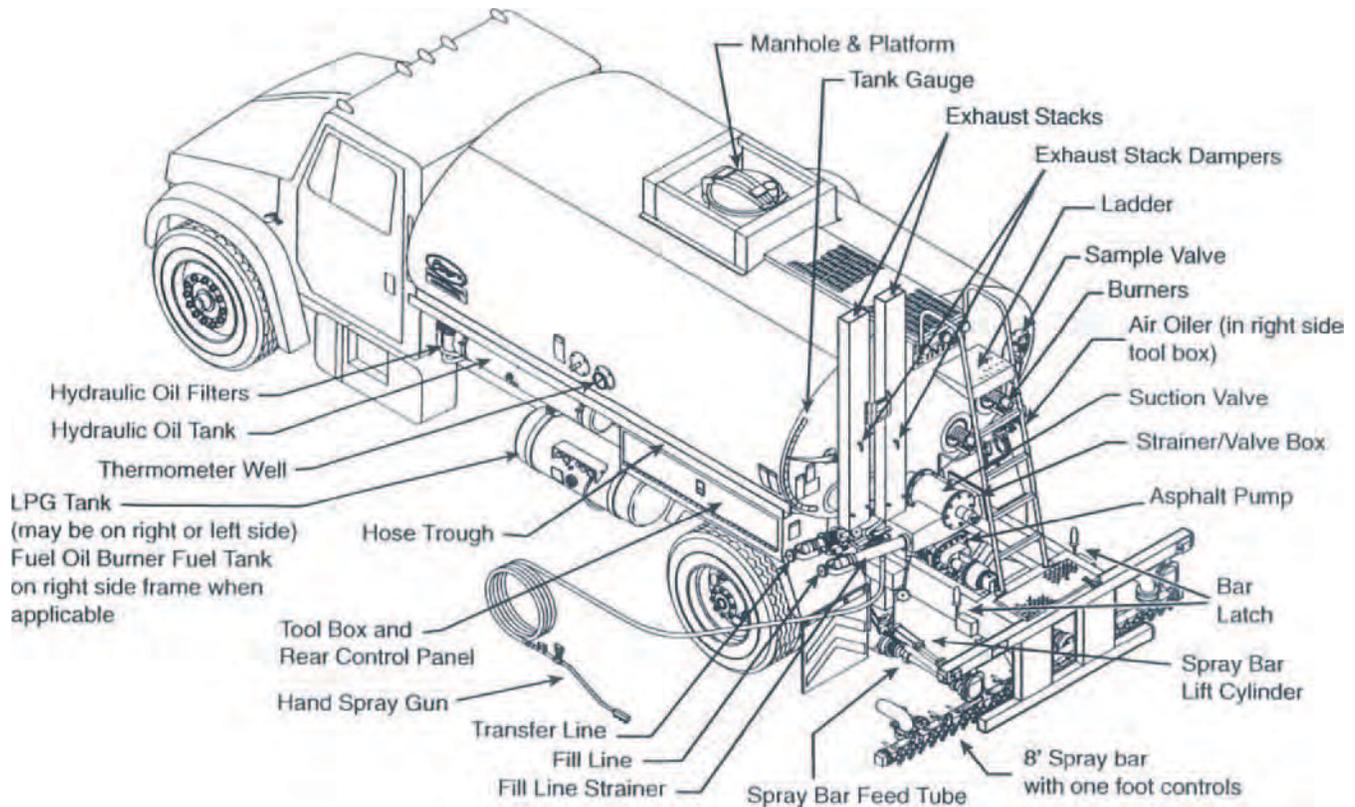
Figure 5. Rear and side component identification for distributor.

pavement surface using the nozzles on the spray bar. Optional extensions on the spray bar can be used to increase the width of tack application. The extensions simply fold upward when the distributor is being relocated or when they are not needed. Figure 5 illustrates the location of the spray bar. Figure 6 shows a folded spray bar extension.

Alignment of the nozzles on the spray bar is of extreme importance in achieving a uniform application of tack coat. Further, use of the proper size nozzles and the correct spray bar height is very important.

All nozzles used on the spray bar are 4 inches apart. Thus, there are three nozzles per foot of width of the spray bar. The angle of the opening of each nozzle must be set precisely the same in order to achieve the proper amount of overlap of the spray from each nozzle with the adjacent nozzle(s). As shown in Figure 7, the proper nozzle angle setting is between 15 and 30 degrees to the axis of the spray bar. In normal practice, the angle is set at 30 degrees to the axis of the spray bar.

If the nozzles are not all set at the same angle, the spray pattern from one nozzle will interfere with the spray pattern from the adjacent nozzles. This will result in a very non-uniform application of the tack coat material onto the pavement surface. Interference of the spray pattern from nozzle to nozzle will mean that some portions of the existing pavement surface will receive excessive tack coat material while adjacent portions will receive insufficient material. For example, if all of the nozzles are set in
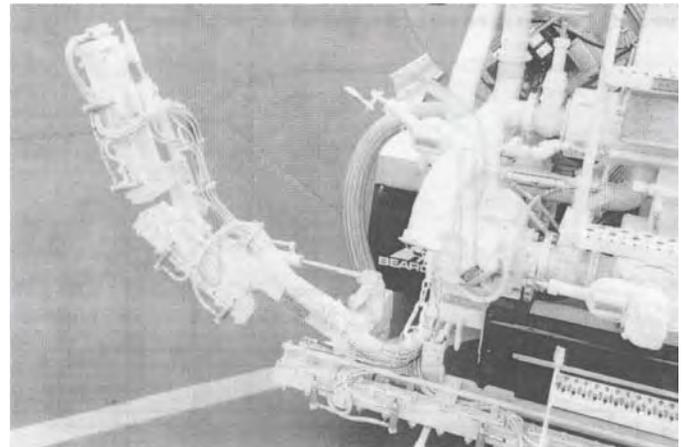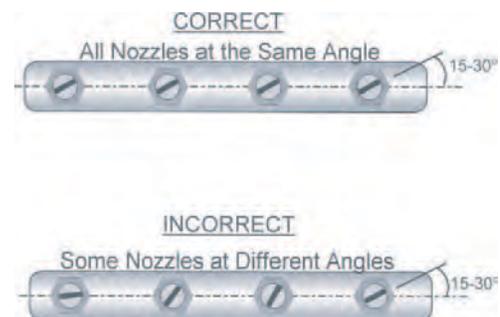

Figure 6. Double-fold wing configuration.

Figure 7. Spray bar nozzle alignment.

Figure 8. Poor spray pattern of tack coat due to improper nozzle alignment, nozzle size, and/or pump pressure.

a direction parallel to the axis of the spray bar, there will be an extremely heavy amount of tack coat applied where the spray from the adjacent nozzles strike each other and very little tack coat applied directly under the center of the nozzles.

In the other extreme, if the nozzles on the spray bar are set at an angle of 90 degrees to the axis of the spray bar, the resulting spray pattern will be strings of tack coat material on the pavement surface (Figure 8). Those strings will be 4 inches apart. In this case, less than 15 percent of the existing pavement surface will be covered with the tack coat material. Obviously, sufficient and uniform bond with the new overlay will not be achieved.

Many distributor operators use a nozzle alignment wrench to set the correct angle of the spray bar nozzles. Use of the wrench simplifies setting all of the nozzles to the same angle.

Spray Bar Height

Normally, the height of the spray bar is set to achieve a triple overlap between the adjacent nozzles (Figure 9). This
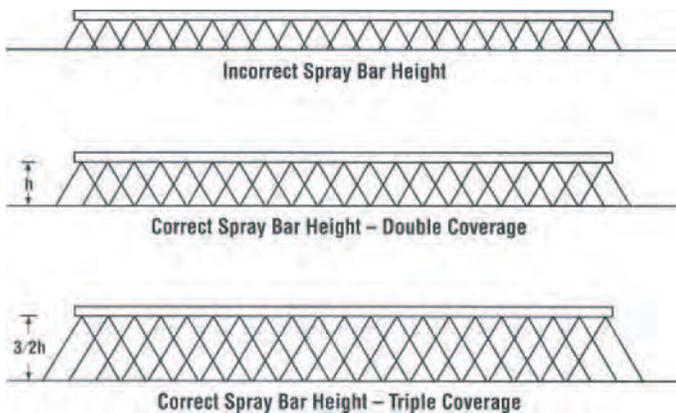

Figure 9. Spray bar height and tack coat coverage.

height, which depends, in part, on the make and model of the distributor, is typically in the range of 9 to 12 inches above the pavement surface. Single lap coverage is rarely employed because of the difficulty in achieving the exact meeting of the spray pattern from the adjacent nozzles. Some contractors choose to employ a double lap coverage, which is acceptable, if the resulting spray pattern uniformly covers the entire pavement surface.

As the amount of tack coat material in the distributor tank decreases during application, the height of the spray may increase. On some older distributors, it may be necessary to adjust (lower) the height of the spray bar as the amount of tack coat material in the tank is reduced. On most new distributors, the height of the spray bar is automatically adjusted as the weight of the tack coat material in the distributor tank is reduced. In either case, it is very important to maintain the correct height of the spray bar during application of the tack coat in order to achieve a consistent double or triple coverage overlap.

Spray Bar Nozzle Size

Proper spray bar nozzle size depends on three primary factors: tack coat application rate, speed of the distributor, and type of material being sprayed. In addition, different asphalt distributor manufacturers may use different nozzle sizes for different application rates. *It is very important to remember that the amount of asphalt material needed for tack coat application is significantly less than the amount of material needed for a chip seal or surface treatment application. Thus, the size of the nozzles on the spray bar must be checked to ensure that they are the correct size for uniform application of tack coat materials.*

Application rate of the asphalt material is directly dependent on the size of the nozzles. Table 5 provides information on the application rate (not residual rate) for various nozzle sizes for a Rosco distributor. This particular distributor manufacturer provides six different nozzle sizes. Those six sizes allow application rates from 0.03 to 1.00 gallons/square yard. As shown in the table, for tack coat usage, two nozzle sizes are available, 00 and 0.

Table 5. Rosco nozzle sizes and flow rate ranges.

Nozzle Size	Recommended Flow Rate - GPM	Application Rate Gal/Sq. Yd.
00	1.2	0.03 - 0.08
0	3.0	0.05 - 0.20
1	4.0	0.10 - 0.30
1.5	6.0	0.15 - 0.40
2	8.5	0.25 - 0.55
3	13.5	0.35 – 1.00

Table 6. Etnyre spray bar nozzles and associated application rate ranges.

Ref.	Part No.	Description	Application (per square yard)	Application (Metric) Liters per square meter	Flow Gallons per minute per foot
1	3353788	V Slot Tack Nozzle	0.05 - 0.20	0.19 - 0.75	3.0 to 4.5
2	3351008	S36-4 V Slot	0.10 - 0.35	0.38 - 1.30	4.0 to 7.5
3	3351009	S36-5 V Slot	0.18 - 0.45		7.0 to 10.0
4	3352368	Multi-Material V Slot	0.15 - 0.40	0.57 - 1.50	6.0 to 9.0
5	3351015	3/32-inch Coin Slot	0.15 - 0.40	0.57 - 1.50	6.0 to 9.0
6	3352204*	Multi-Material V Slot	0.35 - 0.95	1.30 - 3.60	12.0 to 21.0
7	3352205*	Multi-Material V Slot	0.20 - 0.55	0.75 - 2.08	7.5 to 12.0
8	3352210	End Nozzle	0.20 - 0.55	0.75 - 2.08	7.5 to 12.0
9	3351014	3/16-inch Coin Slot	0.35 - 0.95	1.30 - 3.60	12.0 to 21.0
10	3351010	¼-inch" Coin Slot	0.40 - 1.10	1.50 - 4.16	15.0 to 24.0

* Recommended nozzles for chip seal when using emulsified asphalt

It is important to note that, for this particular model of distributor, a nozzle size change may be required if an emulsion is undiluted versus an emulsion that is diluted 1 to 1 with water. For example, if an undiluted emulsion is to have a residual rate of 0.04 gallons per square yard, the application rate would be 0.06 gallons per square yard. Thus, for the Rosco distributor, either a nozzle size of 00 or 0 could be used. If a diluted emulsion were to be used, however, for the same residual application rate of 0.04 gallons per square yard, the application rate for the 1:1 diluted emulsion would calculate to be 0.12 gallons per square yard. In this latter case, nozzle size 00 could not be used. Nozzle size 0 would be required to achieve the proper application rate and spray pattern.

Another distributor manufacturer, Etnyre[1], uses an entirely different system for the selection of the nozzle size to achieve the desired application rate. As shown in Table 6, for the vast majority of tack coat application rates, either undiluted or diluted 1 to 1 with water, two different types of nozzles are recommended, a coin slot nozzle and a V slot nozzle. For the V slot tack nozzle, the applicable application rate is shown to be 0.05 to 0.20 gallons per square yard. For the S36-4 V slot nozzle, the applicable application rate is significantly higher, 0.10 to 0.35 gallons per square yard.

Using the example above, for a residual rate of 0.04 gallons per square yard, for an undiluted emulsion, the application rate would be 0.06 gallons per square yard. Only the V slot tack nozzle could be used to achieve the proper application rate. If a 1 to 1 diluted emulsion tack coat material is used, however, for the same residual rate, either the V slot tack nozzle or the S36-4 V slot nozzle could be used for the resulting application rate of 0.12 gallons per square yard.

If PG asphalt were to be used as tack coat material, for a residual tack coat rate of 0.04 gallons per square yard, the application rate would be exactly the same as the residual rate (0.04 gallons per square yard). According to the Etnyre information, no nozzle size is available for this particular situation.

For a BearCat[2] model distributor, again, different nozzle sizes are needed for different application rates (for the same residual tack coat rate). The choice of the proper nozzle size, however, is based on two factors: the rate of travel of the distributor in feet per minute and the required application rate of the tack coat in gallons per square yard. Four different nozzle sizes are available. A BearCat Road Oil Spreading Calculator (Figure 10) is used to determine the correct nozzle size for a distributor pump pressure range of 5 to 25 psi. BearCat recommends, however, that the nozzle size selected should yield a required application rate at a pump pressure of 6 to 12 psi.

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[1]E. D. Etnyre & Co., Oregon, Illinois
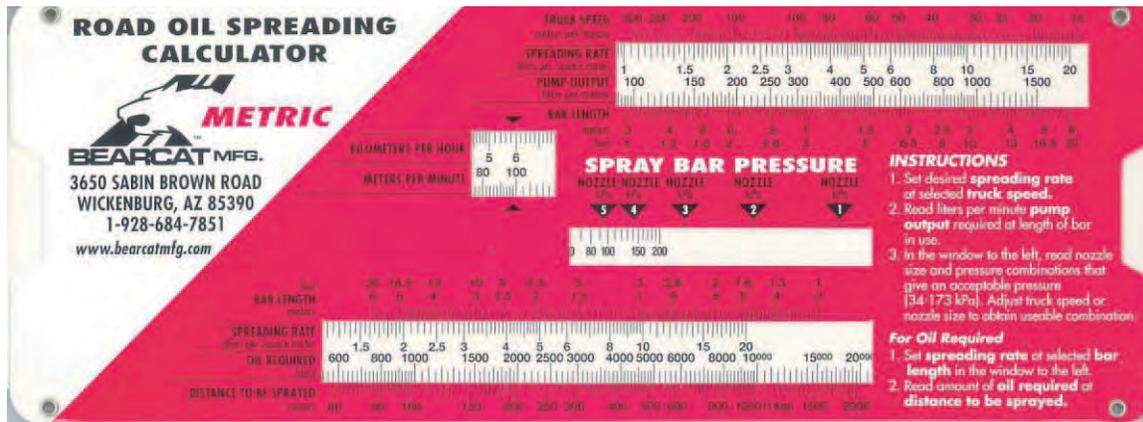
[2]BearCat Mfg., Wickenburg, Arizona

Figure 10. BearCat road oil spreading calculator.

For a BearCat distributor, the combination of the application rate of the tack coat and travel speed is used to determine the spray bar pressure. In general, the greater the application rate, the larger is the nozzle size. But, any of the four nozzle sizes can be used to apply the same amount of tack coat, depending on the travel speed of the distributor and the spray bar pressure. BearCat recommends that a lower bar pressure be used, when possible, to produce a more uniform application of the tack coat material.

Some contractors use the same distributor to apply asphalt material for chip seals, surface treatments, and tack coats. Although the same distributor can be used for both applications, the same nozzle size can NOT be used. If, for example, the application rate for an undiluted asphalt emulsion for a chip seal is 0.36 gallons per square yard, the residual rate would be approximately ⅔ of the application rate or 0.24 gallons per square yard. No make of distributor can apply less than 0.08 g/sy and greater than 0.30 g/sy when using the same size nozzle. Regardless of the manufacturer of the distributor, a different nozzle size would be required for the two different application rates used in this example.

This same comment is applicable if the asphalt distributor was previously used to apply a prime coat material, either cutback asphalt or asphalt emulsion. The normal residual rate for prime coat is significantly greater than that for tack coat. Thus, the nozzles on the distributor may have to be changed in order to reduce the application rate, and maintain a proper spray pattern to achieve uniform coverage.

Distributor Truck Inspection, Calibration, and Certification

Correct tack coat application begins with proper inspection and calibration of application equipment. Periodically, the operator should place a trial tack coat application over some convenient, unused area to assure that all of the nozzles are open and operating properly. Further, the distributor application rate needs to be calibrated, both in the transverse direction and in the longitudinal direction, using the procedure described in ASTM Method D 2995, "Standard Practice for Estimating Application Rate of Bituminous Distributors." Furthermore, many owner agencies require a valid certification to ensure the proper functioning of the distributor and its components. This is recommended practice. Calibration should address, as a minimum, spray bar height, nozzle angle, spray bar pressure, thermometers, and strapping stick.
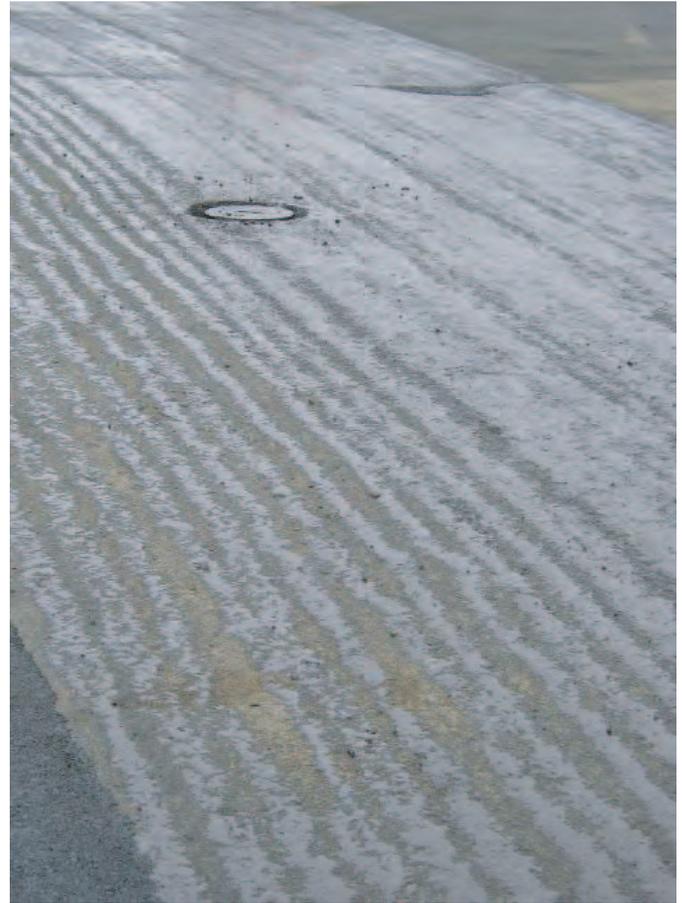
Blocked Nozzles

If an asphalt distributor is not properly maintained, it is very possible for some of the nozzles to become plugged. Figures 11a and 11b illustrate tack coat material that was applied using a distributor spray bar with blocked nozzles (and thus a very poor spray pattern). The operator of the distributor should be able to use his rear view mirrors to observe the uniformity or non-uniformity of the tack coat application. In addition, the foreman of the paving crew should observe tack coat application regularly to ensure uniformity of the application and to stop the process if any nozzles are blocked.

Hand Wand Application

There are often areas on an asphalt paving project where it is not feasible to use the distributor to apply the tack coat material. Such locations are intersections, driveways, and around drainage structures. In these cases, the tack coat material is typically applied using a hand wand with the tack coat material fed from the asphalt distributor. Occasionally, a crack sealing bucket or "pot" is used to apply the tack coat material. Whichever method is employed, it is extremely important that the tack coat material be applied uniformly and completely cover the pavement surface.

(a)

(b)

Figure 11. Tack coat spray applied with partially blocked nozzles.

Figures 12 and 13 are examples of improper application of the tack coat material using hand methods. Figures 12 (a) and (b) are examples of tack coat applied using a crack sealing bucket. Figure 13 is an example of tack coat applied using a hand wand.

There is no measurable way to assure the correct application rate of the tack coat material when using a hand wand. The application rate is solely dependent on the experience and talent of the person using the wand. It is important, however, for the application rate to be, as much as possible, the same as that for the tack coat material applied using the asphalt distributor. That is, hand wand application should cover essentially 100 percent of the existing pavement surface and should be as uniform as possible. A crack sealing bucket should NEVER be used to apply the tack coat materials, since it is practically impossible to achieve complete or uniform coverage of the tack coat material.

Summary

In order for a tack coat to provide the necessary bond between the existing pavement surface and the new asphalt concrete overlay, it is extremely important that the following factors be considered:

1. Tack coat material must be maintained at the proper temperature in the distributor tank for the type of material being applied.
2. Required residual amount of the tack coat material must be known before starting application.
3. Application rate of the tack coat material must be calculated based on the residual amount of tack coat needed.
4. For an undiluted emulsion, the application rate should typically be about 1.5 times more than the residual rate (based on an assumption that the emulsion consists of ⅔ asphalt binder and ⅓ water, which is not always correct).
5. For an emulsion diluted 1:1 with water, the application rate should be approximately 3.0 times more than the residual rate. Spraying a diluted asphalt emulsion increases the total volume of material and thus can help achieve more uniform application.
6. For MC-30 or MC-70 cutback asphalt tack coat, the application rate should be about 1.7 times more than the required residual rate. The factor for RC-70 will also

(a)   (b)

Figure 12. Improper application of tack coat using a crack sealing bucket.

be about 1.7 and, for SC-70, about 2.0. Due to the low flash point (thus fire danger) and environmental concerns (emissions of volatile organic compounds), cutbacks are not recommended. For these reasons, many state DOTs have prohibited the use of cutback asphalts.

7. For a PG asphalt tack coat material, the application rate should be the same as the residual rate.
8. Height of the spray bar must be adjusted to obtain a double or triple lap of the spray. This is recommended to achieve uniform application and 100 percent coverage of the residual tack coat material.

Figure 13. Improper application of the tack coat using a hand wand.

9. All nozzles on the spray bar must be set to the same angle, typically 30 degrees to the axis of the bar.
10. All nozzles on the spray bar must be the same size, unless bleeding exists in the wheel paths and a different application rate is needed at those locations.
11. All nozzles must be clean, not blocked, and functioning properly.
12. Size of the nozzles must be selected based on recommendations of the distributor manufacturer for the desired application rate of the particular tack coat material.
13. Speed of the distributor and pump pressure need to be based on recommendations of the distributor manufacturer and the application rate of the tack coat material.
14. If a hand wand is used, care should be taken to assure that the application rate is as accurate and uniform as possible. A crack sealing bucket is never appropriate for applying tack.
15. Tack coat material should uniformly cover 100 percent of the existing pavement surface.

Tack Coat Break Time and Set Time

Type of Tack Coat Material

Asphalt Emulsion Tack Coat Material

As discussed above, asphalt emulsion contains approximately ⅔ asphalt binder and ⅓ water, in an undiluted form. In a 1:1 diluted form, the emulsion will contain approximately ⅓ asphalt binder and ⅔ water. In addition, the emulsion will

contain a small amount of emulsifying agent, typically, less than one percent by weight of the emulsion.

Immediately after application by a distributor to a pavement, the emulsion is brown in color. This color indicates that the material is still in emulsified form, that is, the micron-sized asphalt particles are still suspended in the water. When the color of the emulsion changes from brown to black, it is typically stated that the emulsion has "broken." This means that the asphalt particles have separated from the water and two distinct phases now exist. When all of the water has evaporated, it is stated that the emulsion has "set." When the emulsion has set, all that remains on the pavement surface is the asphalt binder—the water essentially is gone.

The comments in this section related to emulsions apply to trackless tack, as it is a polymer-modified asphalt emulsion.

Cutback Asphalt Tack Coat Material

For RC-70, the cutter stock used is typically naphtha (similar to gasoline). When cutback asphalt is applied to the existing pavement surface, approximately 60 percent asphalt and 40 percent naphtha is in that tack coat material. Different than an emulsion based tack coat material, no break time is involved with a cutback material. There is, however, a set time.

The set time for the cutback material is the time required for the diluent to evaporate. Once the naphtha is gone, the remaining asphalt binder material is said to be "set."

PG Asphalt Tack Coat Materials

As discussed above, if PG asphalt is used as the tack coat material, the residual rate and application rate of the material are exactly the same. The PG material is typically applied at a temperature in the range of 280°F to 325°F. Because the PG material does not contain any water (as in an emulsion) or any cutter stock (as in a cutback material), no break or set times are involved.

Typically, the safe time for allowing traffic on a PG tack coat is the time required for the asphalt to cool to the same temperature as the pavement surface on which it has been sprayed.

Factors Affecting the Break and Set Times

Many factors affect the break and set times, particularly for an asphalt emulsion. Among the factors are:

- ambient air temperature,
- relative humidity,
- wind speed,
- temperature of the pavement surface on which the tack coat material is placed,
- temperature of the tack coat material when sprayed,
- application rate of the tack coat material,
- dilution rate of an asphalt emulsion, and
- type of emulsifying agent used in an emulsion.

Asphalt Emulsion Tack Coat Material

One primary factor that affects the break and set times of emulsions is the application rate. The higher the application rate, everything else being equal, the longer it will take for the emulsion to both break and set. In addition, use of a diluted asphalt emulsion will require more time to both break and set compared to an undiluted emulsion, simply because of the increased amount of water in the diluted emulsion. If a rapid set (RS) emulsion is used, the break and set times will be shorter than if a slow set (SS) emulsion is used.

In general, the higher the application temperature of the asphalt emulsion, the more quickly the material will break and set. Further, if the ambient air temperature and/or the temperature of the existing pavement surface is relatively high, both the break and set times will be shorter. Further, emulsified asphalt will set more quickly on a windy day when compared to a calm day.

In most cases, an asphalt emulsion applied as a tack coat, depending on its application rate and dilution rate, will break in 10 to 20 minutes. This means, as discussed above, that the color of the tack coat will change from brown to black. Complete setting of the emulsion typically requires from 30 minutes to more than 2 hours. Unless the tack coat is set, there will be a strong tendency for the tack coat to be picked up on the tires of the trucks delivering the asphalt concrete mix to the material transfer vehicle or to the paver hopper.

Cutback Asphalt Tack Coat Material

One primary factor that affects the break time and set time of a cutback material is the application rate. Higher application rates require more time for the cutter stock to evaporate and thus for the material to set.

The higher the application temperature of the cutback asphalt material, the more quickly the material will set. Further, if the ambient air temperature and/or the temperature of the pavement surface are high, the cutback asphalt set time will be relatively shorter. Further, a cutback asphalt tack coat will set more quickly on a windy day as compared to a calm day.

In most cases, a cutback asphalt tack coat, depending on its application rate and amount of diluent, will set in 10 to 20 minutes. Unless the cutback is set, there will be a tendency for the tack coat material to be picked up on the tires of the trucks delivering the asphalt concrete mix to the paving site.

PG Asphalt Binder

For a PG asphalt tack coat, the residual rate and the application rate are exactly the same. Because the PG material does not

contain any water or any cutter stock, no break time is involved. Safe trafficking time is the time required for the PG asphalt to reach the temperature of the pavement surface on which it has been sprayed. Typical safe trafficking times are in the range of 2 to 5 minutes, depending on environmental conditions.

If the application (or residual) rate of the PG asphalt is relatively low (e.g., in the range of 0.04 gallons per square yard), and the material is uniformly applied to the existing pavement surface, there should be very little pick up of the tack coat on the haul truck tires.

Construction Problems

There are a number of potential problems with placement of a tack coat on an existing pavement surface. The three most common problems are (1) lack of uniformity of the tack coat application, (2) pick up of the tack coat on the haul truck tires and the paving equipment before the tack coat material is set, and (3) the need to pave over an emulsion tack coat before it is broken and/or set.

Uniformity of Tack Coat Application

It is extremely important that the tack coat material be uniformly applied to the pavement surface, both in a longitudinal direction and in a transverse direction. This is to assure that a consistent bond is achieved between the existing pavement surface and the new asphalt concrete pavement layer. Obviously, if the tack coat is applied in one area but not in another area, or in a greater quantity in one area as compared to an adjacent area, there will be a difference in the degree of bond attained (Figure 14).

Poor uniformity can be due to one or a combination of several factors. One or more of the nozzles may be blocked.

Figure 14. Non uniform tack coat spray application.

One or more of the nozzles may be set at an improper angle to the axis of the spray bar. One or more of the nozzles may be of a different size compared to the other nozzles. Truck speed and/or pump pressure may be inadequate.

Figures 15 (a) and (b) depict proper application of a tack coat. All of the nozzles on the spray bar are open and func-

(a)

(b)

Figure 15. Uniform tack coat spray application.

Figure 16. Non uniform tack coat spray application—blocked and oversize nozzles.

tioning correctly. All of the nozzles are set at the same angle to the axis of the bar. Height of the spray bar is adjusted to provide a triple lap of spray from the adjacent nozzles. This figure illustrates a uniform application of tack coat material.

Figure 16 illustrates blocked nozzles on the spray bar. This figure shows that several of the nozzles on the spray bar are not functioning. No tack coat is being applied to the pavement surface at those locations. In this case, the distributor needs to be stopped, the blocked nozzles removed and cleaned, the nozzles replaced onto the spray bar, and, only then, the application of the tack coat continued. In most cases, it is easier and faster to simply remove and replace the blocked nozzles with spare nozzles that should be kept on the distributor in the event of such a problem. The blocked nozzles can be cleaned at a later time. In addition to the blocked nozzles, the overlap of the tack coat spray from one nozzle to the adjacent nozzle is not correct. The proper amount of overlap should be achieved by either adjusting the angle of the nozzles, the distributor pump pressure, and/or the speed of the distributor.

Figures 17 (a) and (b) illustrate a series of nozzles that are not all set at the same angle to the axis of the spray bar. In this case, the spray fan from one nozzle comes in contact with the spray fan from the adjacent nozzle, resulting in an increase in the amount of tack coat applied where the two spray fans interfere with each other. Figure 18 shows the opposite problem; the angles of the adjacent spray bars are so different that no overlap is achieved between the nozzles. This type of application yields excessive tack coat in some areas and little or no tack coat in adjacent areas.

(a)

(b)

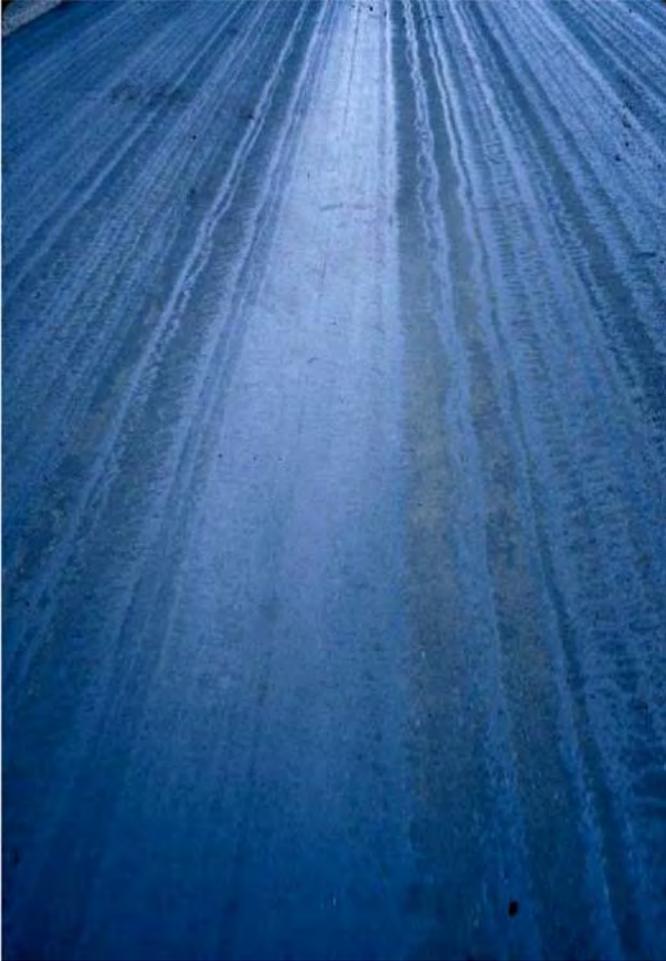**Figure 17 a, b. Non uniform tack coat spray application—improper nozzle setting.**

Figure 18. Non uniform tack coat spray application—improper nozzle setting.

Figure 19 shows excessive tack coat applied to a pavement surface. Although the tack coat application is uniform, this amount of tack coat is extreme.

Figure 20 shows a spray pattern where some of the nozzles are not functioning, some are set at improper angles, and/or some are just dribbling tack coat material onto the pavement
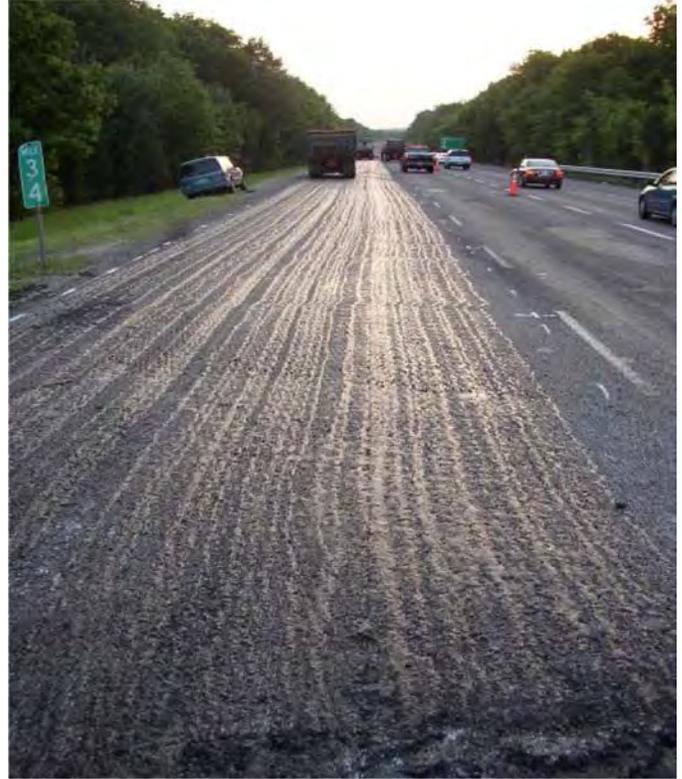

Figure 19. Excessive tack coat spray application.

Figure 20. Non uniform tack coat spray application—nozzles are not functioning and not at the correct angle.

surface. The correct solution is to remove the distributor from the project until the spray bar nozzle problems are corrected.

Pick Up of Tack Coat Material on Truck Tires

Until an emulsion tack coat is fully cured and all of the water has evaporated, the material is sticky. It will adhere to the tires of the haul trucks and be carried off of the pavement surface (Figure 21). If the tack coat is carried off of the roadway on the haul truck tires, it obviously is not available to provide any bond between the new and the old pavement layers. The important issue in this instance is that the typical location where the tack coat is picked up on the truck tires is exactly where the bond between the layers is most needed—in the wheel paths of traffic to later travel over the completed pavement structure.

In addition to the loss of the tack coat material, much of the tack coat that is picked up on the haul truck tires will be deposited on the adjacent pavement surface (Figure 22). Such an occurrence is unsightly. In addition, depending on how much tack coat material is deposited on the adjacent pavement, a reduction in friction, particularly during wet weather, can occur and create a hazard.

Pick up of PG tack coat material can be minimized if the tack coat is permitted to reach ambient temperature before construction vehicles are allowed to drive on the material. The safe time to allow traffic on PG asphalt is dependent on

Figure 21. Pickup of tack coat material in wheel paths by construction traffic.

Figure 22. Pick up of tack coat material by construction traffic.

the application rate and environmental conditions. In general, the suitable time for trafficking PG asphalt is 2 to 5 minutes after application.

An asphalt emulsion will first break and then set. When the emulsion breaks, the microscopic asphalt particles suspended in the water separate from the water and two distinct phases are present. When all of the water has evaporated, the emulsion is set. An emulsion that has broken but not set will typically be extremely susceptible to removal by the tires of the haul truck as well as by the tires or tracks of the paver.

Set time for an asphalt emulsion tack coat will be longer for a diluted emulsion compared to an undiluted emulsion. Further, the break and set times will depend on the application rate as well as environmental conditions. Therefore, the set time for an asphalt emulsion tack coat is usually in the range of 30 minutes to two hours.

Set time for trackless tack coat material, a type of asphalt emulsion containing much harder base asphalt, is significantly less than that for a normal asphalt emulsion. In most cases, the set time for trackless tack is in the range of 5 to 15 minutes, depending on application rate and environmental conditions.

A typical RC cutback asphalt tack coat will set more quickly than a typical asphalt emulsion. As discussed previously, a number of factors affect the time required for the cutter stock material in the cutback asphalt to evaporate. In most cases, depending on the dilution rate and the application rate of the material, a cutback asphalt tack coat will set in approximately 10 to 20 minutes. If trafficked before it is set, pick up of the cutback asphalt tack coat by the haul truck tires will occur.

Thus, to avoid pick up of the tack coat material, it is necessary for a tack coat to completely set so that it is not sticky and will not adhere to the tires of the construction vehicles. Depending on the type of the tack coat material and many other factors discussed previously, up to two hours may be required before the tack coat material is set and will not be picked up.

One additional method that can be used to avoid pick up of the tack coat material on the tires of haul trucks is to employ some type of material transfer device to convey the asphalt concrete mixture from the haul truck to the paver hopper. This can be accomplished by offsetting the material transfer device so that it is located in an adjacent lane to the one being paved. Using this method of delivery, neither the haul trucks nor the transfer vehicle will travel over the tacked surface.

Paving Over an Unbroken Emulsion

Many believe that it is not proper to place an asphalt mixture over an asphalt emulsion that is not yet broken. One of the reasons most often cited is that the water in the emulsion will affect the temperature of the asphalt mixture material placed on top of it and that a good bond will not be created.

Two things are important to consider. First, an emulsion, which is not yet broken, is typically not sticky. That is because the microscopic asphalt particles are still suspended in the water. If the asphalt mixture can be placed on the asphalt emulsion before it breaks, the tack coat material will usually not be significantly picked up on the tires of the haul trucks. As discussed above, the time delay for the emulsion to break depends on a number of factors. Paving over the emulsion before it breaks usually results in much less pick up of the tack coat on the haul truck tires. One way to delay the break of the emulsion is to dilute it with water. A 1:1 dilution rate is often used.

The second factor to consider is the amount of water that is actually in the emulsion and whether the amount of water is a problem with the ability of the emulsion to create a bond between the old and the new pavement layers. The amount of water in an undiluted emulsion tack coat is actually very small. For example, for an undiluted tack coat application rate of 0.06 gallons per square yard, the amount of water is approximately 0.02 gallons per square yard.

Although it is not good practice to place an asphalt mixture in even a light the rain, it is sometimes done. In general, the amount of water that is present on the pavement surface when it is raining, or has recently stopped raining, is significantly greater than the amount of water in undiluted emulsion. In the vast majority of the cases, the asphalt mix that has been placed in a light rain remains in place and performs properly over time and traffic. The bond between the old and the new pavement layers is formed even though some of the water remains in the emulsion. The heat of the asphalt mixture causes the emulsion to break. The water in the emulsion thus escapes in the form of steam, and stripping of the new asphalt mixture does not occur. Placing asphalt mixture over the tack coat when the emulsion is still brown (unbroken), instead of black, greatly reduces the tendency of the tires on the haul trucks to pick up and carry off the tack coat material.

Spray Pavers

European contractors have used spray pavers for a number of years. These pavers, which have been recently introduced into the United States, carry a tank of asphalt emulsion on the frame of the paver (Figure 23). A spray bar is installed on the paver immediately in front of the asphalt mixture on the augers. Asphalt emulsion tack coat is applied to the existing pavement surface typically less than two feet in front of the placement of

Figure 23. Asphalt paver with asphalt emulsion tank for tack coat.

Figure 23a. Roadtec Spray Paver-Spray bar is located at white square between track and screed.

the mix (Figure 24). Asphalt emulsions usually used in Europe are essentially the same as those specified in the U.S.

Using a spray paver eliminates the possibility of any construction traffic driving through the tack coat. The fact that the spray paver has been successfully used for more than twenty years and continues to be used today in Europe is an indication that it is possible to apply emulsion to the pavement surface, place the new asphalt mixture on top of the unbroken emulsion, and still create a suitable bond between the pavement layers.

Types of Tack Coat Failures

Three primary types of pavement failures are related to the application of the tack coat material:

- Inadequate bond between the old and the new layers.
- Delamination, with time and traffic, of the new asphalt concrete overlay from the underlying pavement course.

Figure 24. Tack coat application using spray paver.

- Slippage failure, where the new overlay slides horizontally, usually producing crescent shaped cracks.

Inadequate Bond

Many times, when a core is cut from a new asphalt concrete pavement structure, there appears to be a lack of bond between the new and the old pavement layers or between two new pavement courses. Pavement layers often separate at the interface as the cores are extracted from the core hole. Indeed, even if the coring operation takes place a week or two after the pavement has been constructed, it is not unusual for the creation of the bond to not yet be completed.

The presence or absence of a bond between the layers depends on a number of factors. Among those are residual rate of the tack coat, uniformity of the tack coat application, cleanliness of the underlying pavement surface, and exposure of the pavement surface to traffic at the core location. Usually, with time and traffic, a sufficient bond will develop between the old and the new layers.

Periodically, when a pavement overlay fails and is removed for some reason, such as with a sliding failure or delamination, no tack coat is visible on the underlying pavement surface. The location of the sliding failure or the delamination might have occurred in an area where the tack coat was removed due to pick up by haul truck tires during construction. Or, it may be due to excessive dilution of emulsion with water.

In the vast majority of the cases, the lack of bond is due to non-uniformity of the original tack coat application. This lack of uniformity can be due to blocked spray bar nozzles, nozzles set at the wrong angle to the axis of the spray bar, dribbling of the tack coat from the spray bar, and/or use of the wrong size nozzles.

Delamination of the Pavement Layers

Delamination (Figure 25) is generally caused by insufficient bond between the layers. In most cases, the surface course layer separates from the lower pavement course. Little, if any, tack coat can typically be observed on top of the underlying layer.

In some cases, delamination is due to excessive deflection of the pavement structure under load. Deflection of the pavement structure is so great that it causes the lower layer of the pavement structure to bend excessively under load and crack. With time and traffic, this deflection results in fatigue cracking of the pavement layers, from the bottom to the top. In most cases, the cracking appears on the asphalt concrete pavement surface in the form of fatigue or "alligator" cracking.

In some instances, however, the bending of the pavement structure is great enough to cause the lower courses of the pavement structure to fatigue crack and the surface course mixture to delaminate. This can occur even though the original bond between the layers was adequate. Thus, delamination of the surface course of the asphalt mixture may, or may not, be related to the uniformity of the application of the tack coat material.

Figure 25. Delamination failure in asphaltic concrete pavement.

Figure 26. Sliding failure in asphaltic concrete pavement.

Sliding Failures

Sliding or slippage type failures (Figure 26) are usually caused by tack coat related problems. In some instances, the sliding failure might be related to excessive deflection in the pavement structure, but this cause is relatively rare.

If the existing pavement surface is dusty or dirty, as discussed in details in this report, a lack of bond will occur regardless of how uniformly and adequately the tack coat material is applied. If the tack coat is applied non-uniformly, however, or if the tack coat in the wheel paths is picked up and carried off by the tires on the haul trucks, then the sliding failure will be directly related to the application of the tack coat. In most cases, sliding failures are directly related to the lack of uniformity of the tack coat.

Measuring Tack Coat Material

Tack coat material is normally paid for by the gallon (or liter). The quantity of tack coat material applied to the pavement surface is determined by making measurements prior to and after spray applications. The quantity of tack coat material in a distributor truck is measured using either a volume gauge or a measuring stick provided by the manufacturer of the truck. For trucks with a flow gauge, the gauge should be set to zero prior to spraying and recorded immediately after the spray application is completed. Whereas, when a measuring stick is used, the amount sprayed is the difference between the stick readings prior to and after spray application.

It is important to measure the asphalt temperature in the distributor truck. This temperature will be used in temperature-volume corrections for spray application and payment.

The linear distance of pavement that can be covered by a tack coat material in a distributor truck can be determined as followed:

$$L = \frac{9T}{WR}$$

Where:

L = Linear distance of spray, feet
T = Quantity of tack coat in distributor, gallons
W = Sprayed width of pavement, feet
R = Application rate, gallons per square yard

$$L = \frac{T}{WR}$$

Where:

L = Linear distance of spray, meters
T = Quantity of tack coat in distributor, liters
W = Sprayed width of pavement, meters
R = Application rate, liters per square meter

Characterization of the Interface Shear Strength

Tack coat materials are applied onto a pavement surface before overlay construction to ensure adequate interface bond strength between the two layers. If the interface cannot provide enough strength to resist stresses due to traffic and environmental loading, shear failure may occur at the interface. Poor interface bond strength may also accelerate the appearance of other distresses, such as slippage and surface cracks. A direct shear device was developed as a part of NCHRP Project 9-40, "Optimization of Tack Coat for HMA Placement," for the characterization of interface shear strength of cylindrical specimens (Figure 27). This device is referred to as the Louisiana Interlayer Shear Strength Tester (LISST) and can be used for the determination of the interface shear strength of two bonded asphalt mixture layers (*2*). A draft standard test method was developed as a part of NCHRP Project 9-40 and is presented in Appendix E.

Figure 27. The LISST device.
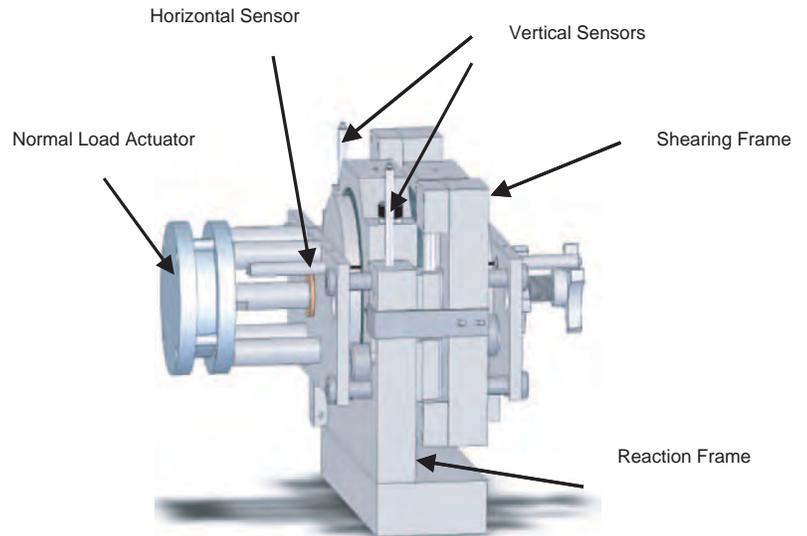
Summary

Long-term performance of an asphalt concrete pavement structure or an asphalt concrete overlay of an existing Portland cement concrete pavement is, in significant part, related to the bond that is developed between successive layers of pavement in the roadway structure. The bond between the layers is related to the uniformity of the application of the tack coat.

Three basic types of asphalt materials are used as a tack coat material: asphalt emulsions (the most used), cutback asphalt (rarely used), and asphalt cement. Each of these three materials is capable of creating the necessary bond between the pavement layers. Results of NCHRP Project 9-40, "Optimization of Tack Coat for HMA Placement," showed that the type or grade of the tack coat material has a significant influence on the resulting bond between the old and the new pavement courses.

Condition of the existing pavement surface is a primary factor that affects the performance of the tack coat material. Many different surface conditions can be present, including dusty or dirty, old or aged, rough or smooth texture, bleeding/flushing, wet, or a milled. Each of these situations requires different considerations and surface preparation processes.

It is very important to realize that there can be a significant difference in the amount of tack coat applied to a pavement surface and the residual amount of asphalt binder that remains after the tack coat material has set. For asphalt emulsion tack coats, in particular, whether the emulsion is diluted with additional water or not makes a major difference in the quantity of residual binder remaining on the existing pavement surface after the water has evaporated. It is the residual binder that is important in creating the bond between the old and the new pavement layers. For each existing pavement condition, and for each type of applied tack coat material, the amount of tack coat applied must be back-calculated from the residual binder content needed to create an adequate bond.

Tack coat is typically applied using an asphalt distributor. Factors that are important in the proper operation of the distributor are temperature of the tack coat material, operation of the nozzles on the spray bar, angle of the nozzles compared to the axis of the spray bar, height of the nozzles above the pavement surface, and size of the nozzles used on the spray bar. Blocked nozzles and/or nozzles set at incorrect angles are the main causes of non-uniform application of the tack coat.

Different types of tack coat materials have different break and/or set times. It is important to fully understand the significance of those times in order to prevent the tack coat from being picked up on the tires of the construction vehicles.

Construction problems related to the use of tack coats include non-uniformity of the tack coat application, pick up of the tack coat on the haul truck tires, and the time frame needed for the tack coat to break and/or set. This is particularly important when using an asphalt emulsion. Paving over an unbroken emulsion tack coat (while it is still brown) may be a means to reduce the pickup problem. In addition, the use of a spray paver, which applies the emulsion tack coat immediately in front of the asphalt mixture on the augers of the paver, can eliminate the potential pick up problem. It is noted, however, that the uniformity of the application of the tack coat material cannot be observed when using a spray paver, since the majority of the length of the spray bar is located underneath the paver.

Three types of failures are usually related to improper application of the tack coat material: lack of bond between layers, delamination of the layers, and sliding type failures. In each case, the uniformity of the application of the tack coat material can be a significant contributing factor to the occurrence of the failure.

Closure

It basically costs nothing extra to properly apply a tack coat to a pavement surface in a uniform manner. Attention by the contractor to a few basic issues, such as cleanliness of the existing pavement surface, proper temperature of the tack coat material before application, condition and position of the nozzles on the spray bar, correct application rate related to the specified residual rate for the tack coat, and pick up of the tack coat by the construction vehicles, will result in an asphalt concrete pavement structure that performs as expected under traffic. However, failure of a pavement due to insufficient interfacial bond is extremely costly.

It costs nothing to do it right, and to do it right the first time.

References

1. "A Basic Asphalt Emulsion Manual," Asphalt Institute, Manual Series No. 19, Second Edition, Lexington, Kentucky.
2. Mohammad, L. N, Elseifi, M., Button, J., and Scherocman, J. "Optimization of Tack Coat for HMA Placement," Final Report, National Cooperative Highway Research Program Project 9-40, Washington, DC, 2011.