Investigation of Tack Coat Materials Tracking Performance

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WisDOT ID 0092-17-06
July 2019

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1. Report No. 0092-17-06	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Investigation of Tack Coat Materials Tracking Performance		**5. Report Date:** July 2019
		6. Performing Organization Code
7. Author(s) Hussain Bahia[1], Abu Sufian[1], Daniel Swiertz[2], Louay Mohammad[3] and Moses Akentuna[3]		**8. Performing Organization Report No.** WHRP 0092-17-06
9. Performing Organization Name and Address [1] University of Wisconsin - Madison [2] Bitumix Solutions, LLC [3] Louisiana State University- Louisiana Transportation Research Center		**10. Work Unit No.**
		11. Contract or Grant No. WHRP 0092-17-06
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation - Research & Library Unit 4822 Madison Yards Way Madison, WI 53707		**13. Type of Report and Period Covered** Final Report; June 2017- July 2019
		14. Sponsoring Agency Code
15. Supplementary Notes: None		

16. Abstract

This research evaluated the performance of asphalt emulsion tack coat used in Wisconsin to provide recommendations that make tack coat usage more efficient and effective. The study focused on measuring curing as measured by moisture loss, tracking as measured by a bond strength test and a wheel tracking device in the lab, and Interlayer Shear Strength using aa AASHTO provisional standard. The study also included a Field sampling task in which several projects in Wisconsin were included to take cores before and after application of tack coats and construction of overlays. For materials currently in use in Wisconsin, the results indicate that there is no practically significant difference between material types in terms of curing rate, however dilution is shown to significantly increase curing time for all materials. Tracking of emulsion residue is found to be primarily a function of the residual asphalt properties, and stiffness of the residual asphalt can be used to predict tracking behavior. There is no clear relationship between the shear strength of laboratory and field specimens, and shear strength of laboratory prepared specimens is primarily a function of surface texture. Considering only tack coat materials currently specified by WisDOT, no significant effect of emulsion type on shear strength is found. However, if highly stiff base asphalts are used, the base binder could influence the interlayer shear strength. Findings from the study are used to provide recommendations to modify the exiting tack coat specification in Wisconsin.

17. Key Words	**18. Distribution Statement**
Tack Coat, emulsions, tracking, application rate, mass loss, curing, setting, surface texture, wheel tracking	No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	71	

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This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project 0092-17-06. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

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Executive Summary

This research evaluated the performance of asphalt emulsion tack coat used in Wisconsin to provide recommendations that make tack coat usage more efficient and effective. Based on a synthesis of research, a work plan was developed to: (1) evaluate curing characteristics of tack coat materials under various curing conditions using mass loss; (2) evaluate the propensity of tack materials to track using a modified Loaded Wheel Tester (LWT); and (3) evaluate the shear strength of laboratory and field materials to validate specifications currently in use by WisDOT. Six emulsions with widely varying residual asphalt properties were selected for the laboratory portion of the study, including a commercially available "trackless" material. Mixtures exhibiting extreme levels of surface texture were sampled from two Wisconsin asphalt plants for the laboratory shear testing portion of the study. Field materials and cores from five active paving projects representing nine combinations of existing surface condition, tack coat type, and residual application rate were tested to validate current specification and the use of the Interlayer Shear Strength Tester in the laboratory to predict field performance.

Based on the findings from the execution of the work plan, the following conclusions were made:

- **Curing Time**: The naming convention used by AASHTO to designate reactivity (SS, QS, RS, etc.) can be misleading for tack coats due to the thin films used during this process. The five standard emulsions tested were generally within 10% of each other in terms of mass loss at a given cure time for all curing conditions and were all dry between 30 and 60 minutes. Dilution of the asphalt emulsion was found to significantly delay curing, doubling the total curing time for some emulsions. The effect of dilution is found to be material dependent, and the level of dilution can also change the relative ranking of materials.
- **Resistance to Tracking**: Tracking of dried emulsion is found to be dependent on the residual asphalt properties of the emulsion and pavement temperature is the most important factor affecting tracking behavior after the emulsions have dried. The residual asphalt properties of the emulsion appear to be good indicators of tracking potential, with increased residue stiffness at a given temperature resulting in greater resistance to tracking at that temperature. Based on the LWT, the proposed lower limit for $G^*/\sin(\delta)$ of the emulsion residue to limit tracking is 10-18 kPa at the design pavement temperature at the time of construction. Based on this finding, all emulsions currently specified by WisDOT are expected to track during periods of high pavement temperature (Summer).
- **Laboratory Shear Performance**: The shear strength (ISS) of laboratory prepared specimens is primarily a function of surface texture and emulsion residue properties; considering only tack coat materials currently specified by WisDOT there is not a significant effect of emulsion type on shear strength. Within the range of residual asphalt rates used in this study, the change in ISS due to application rate is not practically significant and no clear trend between residual application rate and ISS is observed. Testing temperature is found to significantly affect ISS, with higher temperatures resulting in lower ISS; surface texture, however, is still found to dominate ISS at higher testing temperature.

- **Field Shear Performance**: There is not a clear relationship in ISS between field and laboratory prepared samples; if bond strength needs to be tested or verified in the field, cores must be taken. Within the range of application rates reported, ISS is not significantly affected by application rate for nearly all of the combinations tested. If the National Cooperative Highway Research Program (NCHRP) 09-40 recommended minimum ISS of 40 psi is considered, all combinations tested during this study except one met this requirement. Emulsion type is not found to significantly affect ISS for most combinations, although for this data set significant differences between the two emulsions were not expected for this study. There is evidence that poor construction practice can significantly reduce the ISS in the field.

Recommendations

The following general recommendations to make tack coat usage more efficient and effective in Wisconsin are offered based on the conclusions from this project:

- **Material Selection for Timeliness of Construction**: Emulsion type does not appear to be a determining factor in curing time for tack coats. However, the practice of dilution is shown to dramatically increase curing time due to the added water. Therefore, during conditions where lower evaporation rates are likely to be encountered (night paving, cool/damp weather, etc.) and for time-critical project applications, use of undiluted emulsions is recommended. Experience has shown that modern equipment is capable of achieving the currently specified residual application rates safely with undiluted emulsion.
- **Material Selection for Tracking Performance**: All emulsions currently specified by WisDOT are expected to track in the warm weather months of the season. Use of hard base asphalt emulsion will allow greater reliability against tracking, but will still track in the warmest periods. Trackless emulsions are a viable solution, and it is recommended that WisDOT consider trial/pilot projects using these materials to evaluate field performance.
- **Surface Preparation and Application**: There is evidence that poor construction practice can significantly reduce the ISS in the field. It is recommended to keep current cleaning/preparation guidelines in the specification.
- **Application Rate:** Based on the limited data presented in this study, there is no justification for changing the residual application rate listed in the current specification; however, there is evidence to suggest inadequate coverage can lead to low ISS values. Therefore, it is suggested to use an application no less than that required to achieve uniform coverage and using a higher rate will reliably ensure uniform coverage while not reducing ISS.
- **Laboratory Shear Testing:** Although the ISS is shown to be sensitive to tack coat type and surface condition, more research is required before ISS testing can be considered for implementation in Wisconsin.

Acknowledgements

This research project is financially supported by Wisconsin Highway Research Program (WHRP) and Wisconsin Department of Transportation (WisDOT).

Table of Contents

Disclaimer ..... **iii**

Executive Summary ..... **iv**

1. Introduction & Research Objectives **1**

2. Research Approach **3**
2.1 Laboratory Tack Coat Performance Study **3**
2.1.1 Background 3
2.1.2 Materials Selection for the Laboratory Study 4
2.1.3 Initial Rolling Ball Test Findings 8
2.1.4 Development of a Mass Loss Test to Measure Drying Time 9
2.1.5 Development of a Residue Test to Measure Tracking Potential 11
Binder Bond Strength (BBS) Test: AASHTO T361 11
Modified BBS Test 12
Loaded Wheel Tracking Test 15
2.1.6 Interlayer Shear Strength Test 17
Surface Texture Measurement 17
2.2 Field ISS Validation Study **18**

3. Results **19**
3.1 Asphalt Emulsion Curing Time using Mass Loss **19**
3.1.1 Effect of Residual Application Rate 19
3.1.2 Effect of Emulsion Type & Storage Conditions 19
3.1.3 Effect of Dilution 21
3.1.4 Effect of Curing Temperature and Humidity 23
3.1.5 Summary of Findings Related to Mass Loss Rate and Curing Time 24
3.2 Residue Resistance to Tracking **26**
3.2.1 Modified BBS Results 26
3.2.2 Effect of residue application rate on the tracking performance 28
3.2.3 Effect of humidity on the tracking performance 28
3.2.4 Effect of tack coat type, temperature and dilution rate on the tracking performance 29
3.2.5 Rheological Properties and Relationship to Tracking performance 31
3.2.6 Verification of Tracking Behavior using the Loaded Wheel Tracking Test 32
3.3 Laboratory Interlayer Shear Strength Performance **34**
3.3.1 Effect of Emulsion Type and Residual Application Rate on ISS 34
3.3.2 Effect of Surface Texture on ISS 36
3.3.3 Effect of Testing Temperature on ISS 41
3.3.4 Statistical Analysis of Laboratory ISS Testing 42
3.4 Field ISS Validation Study **45**

4. Conclusions & Recommendations **51**
4.1 Laboratory Evaluation of Tack Coat Materials **51**
4.1.1 Evaluation of Curing Time using Mass Loss 51
4.1.2 Evaluation of Tracking Propensity 52
4.1.3 Evaluation of Laboratory Shear Strength using ISS 53
4.2 Validation of Laboratory ISS using Field Cores **53**
4.3 Recommendations for WisDOT Standard Specifications, Construction Materials Manual, and Facilities Development Manual regarding tack coat usage in Wisconsin **54**

5. References **56**

6. Appendix A: Emulsion Certificates for Laboratory Study **57**

7. Appendix B: Example Field Report for Validation Study **62**

List of Tables

Table 1. List of Factors and Level Descriptions for Laboratory Tracking Study. 5
Table 2. List of Factors and Level Descriptions for Laboratory Shear Testing Study....... 5
Table 3. Residual Asphalt Properties for the Emulsions....... 6
Table 4. Extended Testing on Distillation Residue for the Four Base Asphalts....... 6
Table 5. Schematic of Potential Failure Modes in Modified BBS Test....... 15
Table 6. Summary of Curing Study Factors 25
Table 7. Initial Modified BBS Test Matrix....... 26
Table 8. Results of Initial Modified BBS Testing....... 27
Table 9. Effect of Residual Application Rate on Modified BBS....... 28
Table 10. Effect of Humidity on Modified BBS Results....... 29
Table 11. Modified BBS Test Results for Various Tack Coats at Different Temperatures and Dilution Rates....... 30
Table 12. Comparison between LWTT and Modified BBS Tracking Temperatures 32
Table 13. ANOVA for ISS Main Factors 43
Table 14. ANOVA for ISS Main Factors (Without trackless emulsion) 44
Table 15. Combinations Received and Tested for Field Validation Study. 45
Table 16. Air and Pavement Temperatures for the STH 45 Project 46
Table 17. P-values from T-tests on Groupings of ISS Data for Field Validation Study....... 47
Table 18. Commentary and Recommendations for WisDOT Standard Specifications, Construction Materials Manual, and Facilities Development Manual. 54

List of Figures

Figure 1. Hypothetical differentiation between breaking, tracking, and trackless characteristics of asphalt emulsion tack coat....... 4
Figure 2. Rolling ball test apparatus using felt paper substrate. 8
Figure 3. Example rolling ball test data using glass substrate at lab temperature....... 9
Figure 4. Methods for applying a uniform emulsion film using a wet film applicator for relatively high viscosity emulsions (left) and gravity leveling for relatively low viscosity emulsions (right). 10
Figure 5. Effect of substrate type on curing of CRS-1 emulsion at 0.02 gal/yd^2 residual. 11
Figure 6. AASHTO T361 BBS test setup. 12
Figure 7. Difference between T361 and modified BBS stub geometry. 13
Figure 8. ISSA TB139 cohesion test device used to apply uniform pressure to stub. 13
Figure 9. Loaded Wheel Tracking Test Setup. Note masking tape is shown for clarity in the picture but testing for this study used rubberized tape on the loaded wheel....... 16
Figure 10. Example of high texture (left) and low texture (right) mixtures used in this study. 18
Figure 11. Effect of residual application rate on curing rate of CRS-1 emulsion. 19
Figure 12. Effect of emulsion type on curing rate at 0.02 gal/yd^2 residual application rate. 20
Figure 13. Effect of storage (application) temperature on curing of CSS-1h at 0.05 gal/yd^2 residual....... 21
Figure 14. Effect of dilution on curing rate for CSS-1 emulsion. 22
Figure 15. Effect of 1:1 dilution on curing rate for all emulsions....... 23
Figure 16. Effect of curing temperature and relative humidity on curing of CSS-1 at 0.02 gal/yd^2 residual. 24
Figure 17. POTS and moisture loss versus curing time. 28

Figure 18. Relationship between tracking performance in the modified BBS test and G*/sin(δ) of the residue. 31
Figure 19. Relationship between tracking performance in the LWTT test and G*/sin(δ) of the residue. 33
Figure 20. Effect of emulsion type and residual application rate for low texture (top) and high texture (bottom) existing surfaces. 35
Figure 21. Effect of emulsion type and residual application rate on laboratory compacted specimens during NCRHP 09-40. 36
Figure 22. Effect of emulsion type and residual application rate on laboratory compacted specimens from the ODOT Study (Ghabchi et al., 2017). 36
Figure 23. Effect of existing surface texture on ISS for 0.02 gal/yd^2 residual application rate (top) and 0.05 gal/yd^2 residual application rate (bottom). 37
Figure 24. Effect of surface texture on ISS from NCHRP 09-40. Red circle shows the ISS for application rates similar to those used in this study (Mohammad et al., 2012). 38
Figure 25. Effect of surface conditions on ISS at the optimum residual application rates (mostly 0.031 gal/yd^2 for SS-1, CRS-1S, CBC-1H, and CRS-1) from ODOT (Ghabchi et al., 2017). 38
Figure 26. Effect of loss of texture on ISS for CSS-1hL. 39
Figure 27. Effect of residual application rate of SS-1h for laboratory and field prepared specimens during NCHRP 09-40 project (Mohammad et al., 2012). 40
Figure 28. Examples of the interlay bonding performance of field samples from the EMPA's research (Raab and Partl, 2015). 41
Figure 29. Effect of test temperature on ISS using two surface textures for the bottom layer 42
Figure 30. Regression fit for ISS using main factors. 44
Figure 31. Comparison of Lab and Field ISS for Field Validation Study. 47
Figure 32. Sample showing deformation/shear of lower layer in addition to tack layer; two shear planes are circled. 49
Figure 33. Interface of field cores showing uniform coverage on clean surface (top) and non-uniform coverage on dusty surface (bottom) for 25 mm New, QS-1h. 50

1. Introduction & Research Objectives

Tack coats are used to bond overlaid pavement layers or lifts together to ensure they react as a monolithic layer under loading. Insufficient bonding between layers has been found as a major cause of layer slippage failures as well as severe early fatigue bottom-up cracking in pavements. Conversely, applying too heavy of a tack coat has been reported to result in a low strength shear plane between adjacent layers. The application rate of the tack coat, specifically the residual asphalt application rate, is therefore critical to the success of the process (Mohammad et al., 2012).

The recent proliferation of new tack coat materials and renewed focus on pavement quality at the agency level has prompted several tack coat themed initiatives and projects. The FHWA, in conjunction with the Asphalt Institute, hosted tack coat best practices workshops throughout the country between 2014-2016; feedback from these workshops and industry committee meetings directly led to the NCHRP commissioned Synthesis 516: Tack Coat Specifications, Materials, and Construction Practices, which is an extensive agency and practitioner survey and literature review released in May, 2018. Although this research synthesis provides extensive guidance on best practices, several of the findings and recommendations need to be calibrated locally. Many of the most relevant findings of this study and other landmark studies were included in the literature review report submitted for this project and used to further develop or refine the project work plan.

Recent changes to tack coat specification by WisDOT have largely addressed the issue of application rate by including minimum residual asphalt content requirements for tack coat emulsion, as well as an increased range of application rates. However, according to the request for proposal for this project, the pickup and subsequent tracking of tack coat materials remains a concern to WisDOT. The purpose of this study is to verify the optimum residual asphalt application rate for tack coat in terms of bond strength between pavement layers and develop guidance on materials and methods to reduce the pickup and tracking of tack coat materials in Wisconsin.

The work plan approved for this study was developed based on extensive literature review by the research team which was summarized in a report submitted in September, 2017 (Bahia et al., 2017). The literature review findings can be summarized in the following points:

- Regarding the effect of surface type, a direct relationship is observed between the roughness of the existing surface and the shear strength at the interface. The milled surfaces show significantly higher shear strength relative to un-milled pavement surfaces. Based on these findings, the field-testing plan should include milled and non-milled surfaces. It is also necessary to clearly document the milling conditions using texture measurements since not all milling operations are equal.
- The curing rate is not expected to substantially affect the results of the interlayer shear testing, so the type of emulsions chosen should ideally vary by residue properties. Three emulsions are suggested for field evaluation. It is recommended that CSS-1 and CSS-1h be included to test the effects of base asphalt and one polymer modified emulsion to include the effects of polymer.
- For the purposes of the laboratory tracking study, a more diverse set of emulsions should be evaluated. For this testing, six emulsions can be evaluated including one slow set, one

rapid set, and one polymer modified emulsion. In addition, a trackless or reduced tracking product should be evaluated.

- Excessive tack coat is found to be detrimental, since it can act as a lubricant, creating a slippage plane between the pavement layers. On the other hand, the application of insufficient tack coat can also cause pavement slippage and de-bonding problems.
- Dilution rates are critical in determining the final application rates of tack coats. The most common dilution rate is 1:1 (one-part undiluted emulsion and one-part additional water). The dilution process can help to achieve a more uniform application, without applying excessive amounts of asphalt binder. However, problems can result from improper dilution, such as delayed emulsion break. In this study, a subset of the selected tack coat materials will also be tested in a diluted state to evaluate the effects of dilution on curing.
- There is no agreement regarding the requirement that tack coat be allowed to break and set before placing the new Hot Mix Asphalt (HMA) layer. Many publications reported that the tack coat should be either cured or cured until tacky before placing the new pavement layer. However, some researchers related that experience has also shown that a new HMA can be placed on top of unset tack coat, and even over an unbroken tack coat emulsion with no detrimental effect on pavement performance.
- Regarding relative humidity level, the cure time for asphalt emulsions is extended when the relative environmental humidity is high. In this study temperature and humidity will be included as factors to be evaluated for subset of the emulsions.
- The use of a spray paver guarantees that 100% of the tack sprayed on the ground is present during paving assuming the paver is functioning properly. Due to project scope and budget limitations, investigation of the use of a spray paver for tack coats in Wisconsin will not be studied in the field or laboratory. Several factors can affect the tack coat application in the field, such as: uniformity of nozzle spray patterns, size of nozzles, height of spray bar, pressure of the application, and temperature of tack coat.
- Many factors are shown to affect laboratory interface shear strength: including rate of shear, magnitude of normal force, test temperature, milling, traffic load or test confinement, and sample preparation method. The shear strength increased with decreased test temperature, increased traffic load or confinement pressure.
- Laboratory prepared specimens resulted in higher interlayer shear strength than field pavement cores. For the purpose of this research project, the shear test methods developed during the NCHRP 09-40 project and drafted as AASHTO provisional standards (TP114) will be used.

Based on these findings a detailed testing plan was designed to conduct a critical evaluation of the materials and application methods used in Wisconsin for asphalt emulsion tack coats and to provide recommendations that make tack coat usage more efficient and effective. The following specific objectives have been identified by the research team based on the literature review, and the project work plan developed in coordination with the Project Oversight Committee:

- Determine the proper timeliness of tack coat application with consideration given to project scope (paving times, lane closures, etc.).
- Evaluate different tack coat materials to determine which product should be used based on prevailing climate and other project considerations.
- Evaluate other techniques, innovations, and technologies that may allow for greater efficiency relative to standard WisDOT practice.
- Develop recommendations for WisDOT Standard Specifications, Construction Materials Manual, and Facilities Development Manual regarding tack coat usage and best-practices.

2. Research Approach

The research plan was divided into two phases. The first phase involved a laboratory evaluation of commonly used tack coat materials for rate of curing, tracking propensity, and interlayer shear performance. The second phase involved validation of the interlayer shear performance findings using field cores extracted from new paving projects during the 2017 and 2018 paving seasons. This chapter presents the research approach for each of the phases.

2.1 Laboratory Tack Coat Performance Study

2.1.1 Background

Asphalt emulsion tack coats break and cure as a result of a combination of chemical and physical interactions with the substrate onto which they are sprayed as influenced by the local climate conditions. Many specifications use the terms "break" and "cure" interchangeably, although they have different meanings. The emulsion "break" is the separation and subsequent evaporation of water from the residual asphalt film; in practice this process is observed as the emulsion transitioning from a coffee-like brown or mottled-brown appearance to black. Emulsion "curing" is the subsequent restoration of the residual asphalt mechanical properties. In other words, an emulsion that has broken may not be fully cured at a given time (James, 2006). For the purposes of this project, however, the terms "drying", "breaking", and "curing" are assumed to be practically equivalent and are defined as the point when the mass loss of a given emulsion at a given set of laboratory or field conditions stabilizes. It is assumed by many practitioners that tracking and pick up is related to the breaking and curing of the emulsions and that all unbroken emulsions (that is emulsions that still contain appreciable water) will readily pick up from the roadway and track, analogous to driving on wet paint.

However, it is well known that even after emulsions have broken, there is a possibility of pickup and subsequent tracking. This phenomenon of pickup or tracking is hypothesized to be primarily controlled by the residual asphalt properties of the emulsion. Furthermore, since the mechanical properties of asphalt binder are temperature sensitive, it is hypothesized that tracking behavior is also dependent on pavement temperature. Therefore, a single emulsion at a given set of application and climate conditions may be classified as both tracking and non-tracking at various curing times depending on the pavement temperature and water content of the emulsion.

This concept is the foundation for the laboratory curing study conducted during this project and is illustrated in Figure 1.

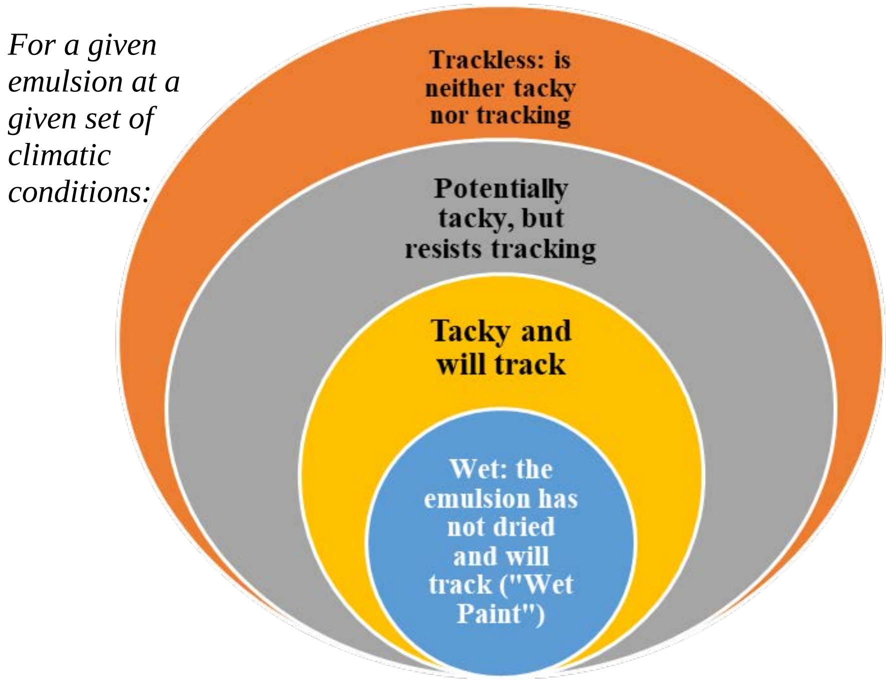


Figure 1. Hypothetical differentiation between breaking, tracking, and trackless characteristics of asphalt emulsion tack coat.

The general concept in Figure 1 is that all water-based emulsions will track immediately after spraying since the emulsion is very soft, has limited cohesive strength and thus will adhere to tires and track. After drying, an emulsion residue may occupy any (or a combination) of the other conditions (tacky/tracking, tacky/non-tracking, and non-tracking) depending on residue properties and climate conditions. As the emulsion breaks, the residual asphalt properties begin to dominate tracking performance. As climatic conditions or time changes, the residue may remain prone to tracking, become non-tracking, or transition from tracking to non-tracking. As such, it is critical to separate breaking (drying) from tracking for materials intentionally made with different residue characteristics. The selection of materials and testing methods for this project follows this concept.

2.1.2 Materials Selection for the Laboratory Study

In addition to emulsion type, factors related to the breaking time of asphalt emulsions were identified in the literature for this study. The factors identified for this study are tack coat residual application rate, storage and curing temperature, curing humidity, surface type, and level of dilution. In addition, three substrate types were included in the initial development of the breaking time test. Not all combinations were included in this study (i.e., a full factorial) for all tests methods, however a complete listing of factors and level descriptions for the tracking portion of this study is shown in Table 1. A subset of these factors was included for the Interlayer Shear

Strength test, which was selected based on the literature review as the most promising to measure the bonding of pavement layers. Table 2 shows the listing of factors and level descriptions for the laboratory interlayer shear testing portion of the study.

Table 1. List of Factors and Level Descriptions for Laboratory Tracking Study.

Factor	Level	Description of Levels
Emulsion Type*	6	CSS-1, CSS-1h, CRS-1, CSS-1hL, CQS-1h, Trackless (NTQS-1hh)
Residual Application Rate (gal/yd^2)	2	0.02 gal/yd^2 0.05 gal/yd^2
Dilution Level	3	Undiluted Diluted to 50% Residual Asphalt in Emulsion Diluted 1:1
Emulsion Storage (Application) Temperature (°C)	2	Lab Temperature 60°C (140 °F)
Curing Temperature (°C)	2	10°C (50 °F) 60°C (140 °F)
Curing Relative Humidity (RH) (%)	2	45% 75%
Substrate Type	3	Ground (Frosted) Glass Stone Tile Asphalt Mixture Disks (cut from gyratory pill)

*4 emulsions chosen for laboratory ISS study: CSS-1, CQS-1h, CSS-1hL, and Trackless
** C–Cationic, S-Slow, S-Setting, h-Hard, R-Rapid, L-Polymer, Q-Quick, NT-Non-Tracking

Table 2. List of Factors and Level Descriptions for Laboratory Shear Testing Study.

Factor	Level	Description of Levels
Emulsion Type	4	CSS-1, CSS-1hL, CQS-1h, Trackless (NTQS-1hh)
Residual Application Rate (gal/yd^2)	2	0.02 gal/yd^2 0.05 gal/yd^2
Existing Surface Texture*	2	Low – Dense graded, fine mix (Mean Texture Depth, (MTD** = 0.17 mm) High – Stone Mastic Asphalt (SMA) type mix (MTD = 0.96 mm)
Test Temperature	2	25°C 46°C
Confining Pressure	1	7 psi
Replicate Samples	3	Three specimens tested per factor combination.

*As quantified using modified Sand Patch Method
** Average Pavement Macrotexture Depth

Emulsion types were selected to be representative of materials in use in Wisconsin and that could provide direct comparison of the effects of residue properties and modification. For example, the difference between CSS-1 and CSS-1h is principally the base asphalt grade used in production, with CSS-1 typically produced with PG 58-28 or similar grade as the base asphalt, while the CSS-1h produced with PG 64-22 or similar grade as the base asphalt. The difference between CSS-1h and CQS-1h or CSS-1 and CRS-1 is the chemistry of the emulsifier, which controls the reactivity of the emulsion and may impact the timing of curing. Finally, a polymer modified emulsion is included to determine whether polymer modification can reduce tracking behavior or improve the interlayer shear bonding strength. A commercial "Trackless Tack" product is added as a control to compare tracking behavior as such materials are known to show no tracking in the field. A summary of the base asphalt properties and design proportions for the six emulsions is given in Table 3, and extended residue testing results are shown in Table 4.

The six standard asphalt emulsions were produced by a local Wisconsin material supplier instructed to produce materials that are or would be commercially viable and that meet AASHTO specification (AASHTO M208/M316); emulsion certificates of compliance from the manufacturer are attached as Appendix A. The trackless emulsion was donated to the study from a contractor local to Louisiana.

Table 3. Residual Asphalt Properties for the Emulsions

Tack coat type	Base Asphalt High PG	Residue Softening Point, °C	Residue Penetration, 25°C, 100 g, 5 s, dmm	Residue Content, % wt.
Trackless	PG 88	71.1	8	61.8
CSS-1h	PG 64	45.1	79	62.6
CQS-1h	PG 64	45.1	77	65.5
CSS-1hL	PG 64+ Latex	61.0	57	66.7
CRS-1	PG 58	43.2	105	65.7
CSS-1	PG 58	40.9	110	61.6

Table 4. Extended Testing on Distillation Residue for the Four Base Asphalts

Residue	Multiple Stress Creep and Recovery, MSCR @ 58 °C		G*/sin(δ), kPa		TP123 Recovery	Modulus at Delta Critical for Design Low Temp., kPa	
	$J_{nr,\ 3.2}$ kPa, 1/kPa	%R	58°C	64°C	25°C	-31°C	-37°C
Soft Base, Includes: CSS-1, CRS-1	5.10	0.0%	2.24	1.06	4.4%	39,786	62,745
Hard Base, Includes: CSS-1h, CQS-1h	3.39	0.5%	2.90	1.32	5.0%	43,666	66,798
Polymer Modified Base, Includes: CSS-1hL	0.55	49.4%	7.33	3.65	39.8%	32,676	56,682
Trackless Base	0.05	22.5%	108.89	44.21	14.6%	22,469	33,135

The data shown in Tables 3 and 4 clearly demonstrate the wide range of residual asphalt properties used to manufacture these emulsions and illustrate the relative effects of the distillation procedure used to generate emulsion residue for testing. The data shows the effect of the latex polymer modification used in the CSS-1hL emulsion in terms of both high and intermediate temperature strain recovery. In terms of stiffness, the Trackless residue exhibits a J_{nr} value at 58°C, an order of magnitude lower than the next lowest emulsion residue and a G*/sin(δ) over ten times higher than that of the CSS-1hL emulsion.

The Modulus at Delta Critical is a parameter developed during the NCHRP 09-50 study to measure the low temperature raveling (chip loss) potential of chip seals. Although tack coats do not exhibit raveling, some correlation may be drawn between raveling potential and propensity to delaminate between layers. A lower modulus at a given design low temperature is considered desirable (Kim et al., 2017). Interestingly, the Trackless emulsion residue shows the lowest modulus determined by this parameter, which is the opposite of what is observed at high temperature. It should be noted, however, that the temperature at which the critical phase angle occurs for the Trackless residue was found to be approximately 25-30°C higher than the other three emulsion base asphalts. It is therefore suggested that interpretation of these results be used with caution. This is analogous to the concept of testing the Bending Beam Rheometer (BBR), where ≥0.300 is the limit for m-value acceptance. A binder that exhibits this m-value at a lower temperature is better for low temperature performance (magnitude, not the rate of relaxation), than a binder that exhibits this m-value at a higher temperature.

Residual application rates were selected to include rates used in Wisconsin as well as to cover a range listed in the findings of NCHRP 09-40 project. Residual application rate is the volume of residual asphalt on the surface after the emulsion completely breaks per unit area (does not include water). Unless otherwise specified, all application rates listed in this report are assumed to be residual application rates. Residual application rates are used because each emulsion has a different residue content; specifying the residual application rate normalizes all emulsion application rates during testing. Dilution of tack coat materials is also common practice in Wisconsin. The rate of dilution allowed by specification in Wisconsin is a dilution rate that results in 50% minimum residual asphalt in the emulsion. Many States, however, allow dilution at a level of 1:1 (water: emulsion) regardless of emulsion type. For this project all dilution was conducted the day of testing using warm tap water slowly incorporated into the emulsion by hand mixing.

Curing temperature and humidity were selected to span typical pavement temperatures and average relative humidity levels encountered in Wisconsin during typical paving seasons and for practicality in the laboratory (a wider range exists in practice); these conditions were controlled using an environmental chamber and verified with a portable thermometer/hygrometer. Initially one storage and application temperature of 140 °F was selected in order to maintain uniformity in testing and because 140°F is a reasonable storage temperature for all emulsions used in this study. Since some emulsions are allowed to cool to ambient temperature during storage, a second storage/application temperature was investigated for a limited number of combinations. For all testing, emulsion is removed from the storage oven and immediately applied to the substrate.

2.1.3 Initial Rolling Ball Test Findings

During the initial work plan development for this project, it was envisioned that a modified ASTM D 3121 rolling ball test as developed during the recently completed NCHRP 09-50 project could be used to capture a combined effect of breaking and tracking behavior of asphalt emulsion. This test was eventually abandoned by the research team after several test setup iterations continued to produce inconsistent results. For example, ASTM D 226, Type II (30 lb.) asphalt roofing felt was used as the initial substrate following guidance from other asphalt emulsion tests such as ASTM D 7000 (sweep test). It was found that applying a uniform film of asphalt emulsion on the felt paper was difficult due to the surface texture of the paper, and that the paper readily warped during the curing process even after manipulating to be flat prior to testing. A picture of the rolling ball test setup using asphalt felt paper substrate is shown in Figure 2.

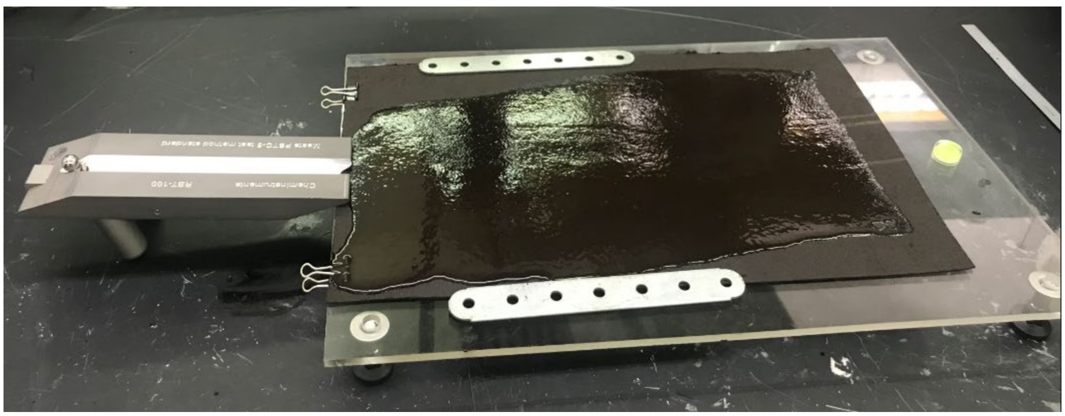


Figure 2. Rolling ball test apparatus using felt paper substrate.

Trials using ground glass plates as the substrate seemingly solved the issue of non-uniformity in the film thickness and warping, but results for two emulsion types show inconsistent and potentially misleading results with regards to tracking behavior. It was expected that the tracking is reflected by the distance the ball will travel, however the results did not show this trend consistently. As shown in Figure 3, the distance that the steel ball travels on the surface of CSS-1h increased consistently and stabilized after one hour. By comparison, the distance on the surface of CRS-2 increased first, then decreased and finally increased again. The inconsistent distance vs. curing time curve may indicate that there is a confounding effect in the rolling ball test. According to ASTM D 3121, there are two major retarding forces applied by the binder or tack coat to the ball: (1) the adhesion between the ball and the binder/tack coat, often called “grab,” and (2) the “plowing effect” or energy required to push the binder out of the ball’s path. For the asphalt binder, the “plowing effect” is highly related to the compliance or stiffness of the binder. The research team of this study believes that the weight of the steel ball is too small (especially when compared to tire pressure) such that the “plowing effect” may influence the result to a great extent. In fact, the penetration of CSS-1h is 80 dmm compared to that of CRS-2 which is 155 dmm. This may explain why the CSS-1h performed much better than CRS-2 did in the rolling ball test. To solve these issues with the test set-up, various types of balls were tried including glass balls and rubber balls as well as changing the angle of rolling, but the inconsistencies persisted. It was therefore decided that the effects of breaking and subsequent tracking potential should be evaluated using separate test procedures for moisture loss and for tracking in this project.

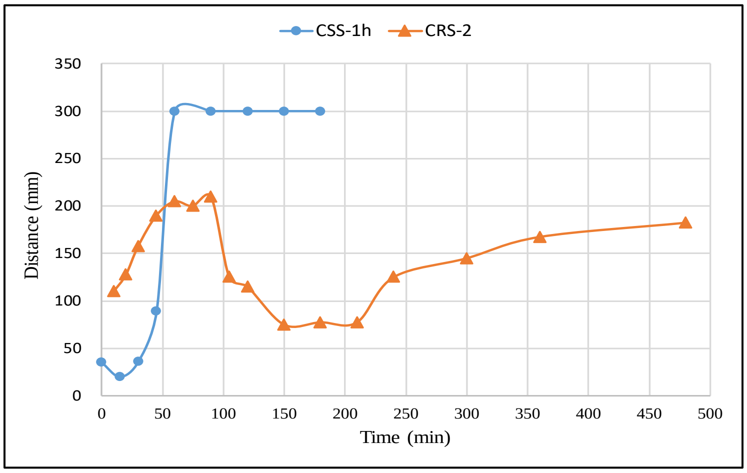


Figure 3. Example rolling ball test data using glass substrate at lab temperature.

2.1.4 Development of a Mass Loss Test to Measure Drying Time

The literature review for this study clearly indicated that breaking and curing time could have a significant role in tracking due to the water evaporation from the emulsions. Therefore, mass loss was selected as the means to compare breaking time of the emulsions during this study due to the ease and practicality of measurement and the intuitive nature of the test. Observation of test samples in the laboratory confirm that when the mass loss for a given time interval is near zero, the appearance of the emulsion residue is black, signifying that the emulsion has broken. Mass loss has been used successfully in other research studies and has been demonstrated to be sensitive to material and curing condition factors (Yaacob, et al. 2014).

The general concept of the mass loss test is to apply a film of asphalt emulsion on a given substrate, record the initial mass, and cure the emulsion at a given set of conditions while measuring mass at predetermined intervals. Two methods were employed in this study to achieve a uniform film of emulsion. An adjustable wet film applicator (such as a Bird Film Applicator ®) was used for emulsions with relatively high viscosity; the specific gravity and residue content of the emulsion is used to convert from a volume per unit area to mass per unit area. For lower viscosity emulsions (such as diluted specimens) gravity leveling was used. For this method, a template (fixed area) is placed over the substrate and the predetermined mass of emulsion is applied and spread with a gentle tipping of the substrate until uniformly dispersed. Both application methods are shown in Figure 4.

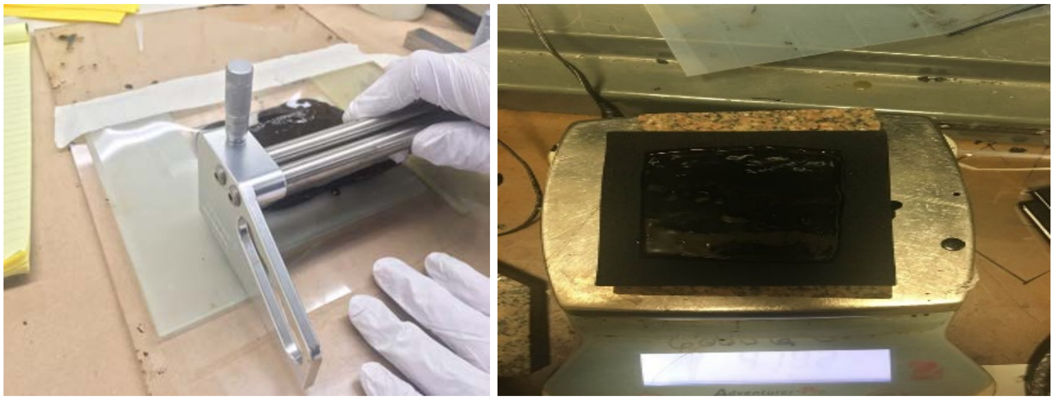


Figure 4. Methods for applying a uniform emulsion film using a wet film applicator for relatively high viscosity emulsions (left) and gravity leveling for relatively low viscosity emulsions (right).

To compare emulsions with different residual asphalt contents and at different curing conditions, a parameter called “Percent Terminal Loss” is derived. First, the mass of the substrate is recorded (W_p) and the mass of the substrate plus the emulsion film immediately after applying the emulsion film is recorded to establish a baseline (W_0). The sample is transferred into the environmental chamber previously brought to the desired humidity and temperature levels. For this study masses were taken at 30-minute intervals for practicality and to avoid opening the chamber and altering the temperature/humidity levels. The percentage of mass loss at each time interval is calculated following Equation 1 and the percentage of mass loss at time, t, ($W_{loss,t}$) relative to the terminal mass loss ($W_{terminal}$) is calculated following Equation 2. Terminal loss is defined as the highest mass loss achieved for a given set of testing conditions.

$$Percent\ Mass\ Loss\ (\%) = \left[\frac{W_0 - W_t}{W_0 - W_p}\right] \times\ 100 \qquad \text{Equation 1}$$

$$Percent\ Terminal\ Loss\ (\%) = \frac{W_{loss,t}}{W_{terminal}} \qquad \text{Equation 2}$$

In addition to the asphalt felt paper, three testing substrates were evaluated to determine if the testing substrate significantly affected the results. The first substrate type is ground (sometimes referred to as “frosted”) glass as used in the standard Plastic Limit test for soil plasticity; the slight surface texture prevents the emulsion film from separating due to surface tension and glass can be assumed non-absorbent. For a partially absorbent surface, disks cut from gyratory pills were selected to represent a pavement surface and because they eliminated the warping issue of using asphalt felt paper. Finally, unglazed marble tiles were included to simulate stone surfaces.

To evaluate the effect of the type of substrate, curing and application conditions were fixed at 10°C/45% RH using 0.02 gal/yd^2 residual application rate. The most reactive emulsion by AASHTO designation (CRS-1) is chosen for this portion of the study as it is hypothesized that this emulsion would be most sensitive to substrate type. The results of this sub-study are shown in Figure 5.

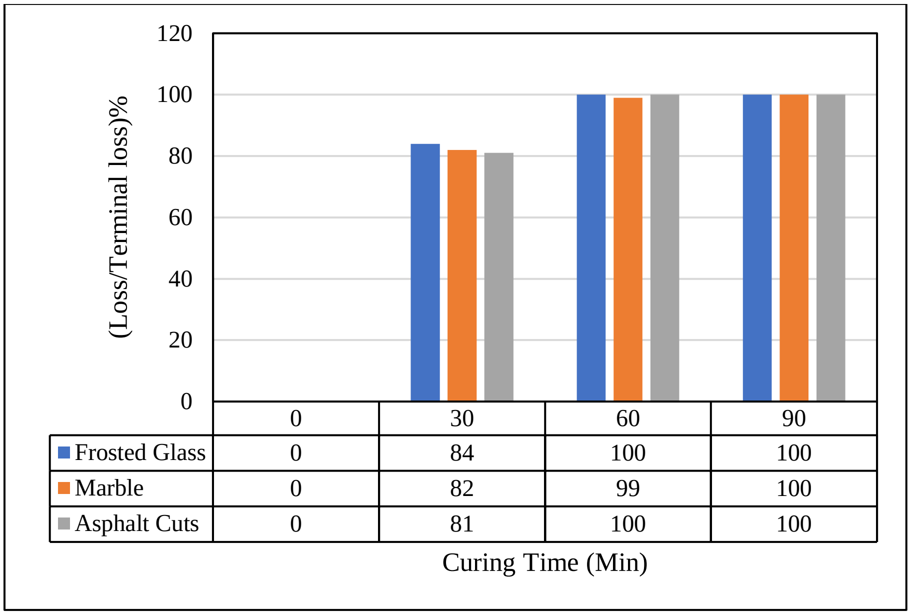


Figure 5. Effect of substrate type on curing of CRS-1 emulsion at 0.02 gal/yd^2 residual.

Results in Figure 5 indicate that the type of substrate has a negligible effect on the curing rate or ultimate curing time for this emulsion and for the conditions listed. Since the goal of this portion of the study is to compare emulsion types and curing conditions, the frosted glass substrate was chosen for subsequent testing because of its availability, ease of cleaning for reuse, and uniform physical and chemical properties. It should be noted that in practice substrate conditions (surface area, absorption, etc.) are observed to affect curing rate; this study represents a comparative analysis.

2.1.5 Development of a Residue Test to Measure Tracking Potential

Two laboratory test methods were developed in this study to quantify the effects of residue properties on tracking potential. Test methods were selected based on current use in industry (availability), standardization, and ability to differentiate between emulsion residue. This section outlines the development of the tracking tests.

Binder Bond Strength (BBS) Test: AASHTO T361

The motivation for selecting the BBS device is related to the hypothesis that the tack coat residue would be considered “tracking” if the adhesion between tire and tack coat is stronger than the cohesion of the tack coat material itself, or stronger than the adhesion between the tack coat and the substrate. In other words, an emulsion will not track as long as it has the internal strength (cohesion) that is stronger (higher) than the adhesion to tires, and that the adhesion between the substrate and emulsion is also stronger than the adhesion to the tires.

The regular BBS test was performed according to AASHTO T361. A typical test sample is shown as in Figure 6. In the regular BBS test, curing can be divided into two types: curing without stub and curing with stub applied. In this study, after the tack coat cured for different curing times (without stub), the stub was applied on the tack coat and cured for another one hour before measuring the Pull Off Tensile Strength (POTS).

Initial testing results revealed that because the stubs used for the BBS test have lips to control film thickness to 0.8 mm, the representation of this test to tack coat residue (films <0.25 mm) is questionable. Therefore, a modified BBS test was designed to better simulate the tire-tack coat residue-substrate interaction by allowing the application of same film thickness as tack coats in the field.

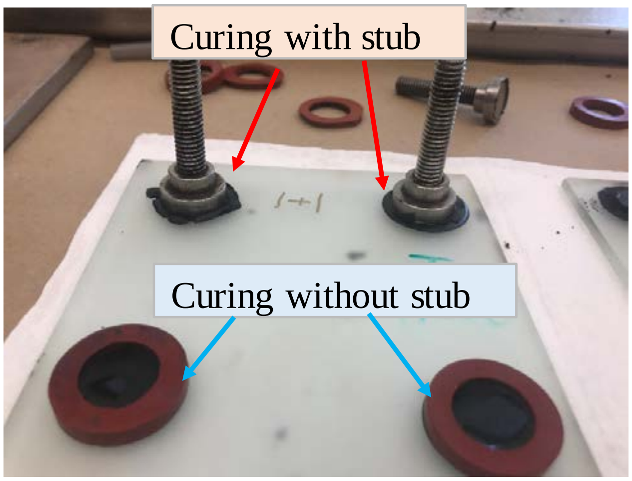


Figure 6. AASHTO T361 BBS test setup.

Modified BBS Test

The modified BBS test follows the same testing concept as the T361 test, with the added advantage of better simulating film thickness and tire pressure in the field. Figure 7 shows the differences in stub geometry between the T361 BBS test and the modified BBS test. To apply pressure to the stub, an ISSA TB139 cohesion test device was used; this device uses a pneumatic piston to apply uniform pressure to the sub. The piston was calibrated during this study to apply 100 psi of pressure. A picture of this test device and pressure application is shown in Figure 8.

Figure 7. Difference between T361 and modified BBS stub geometry.

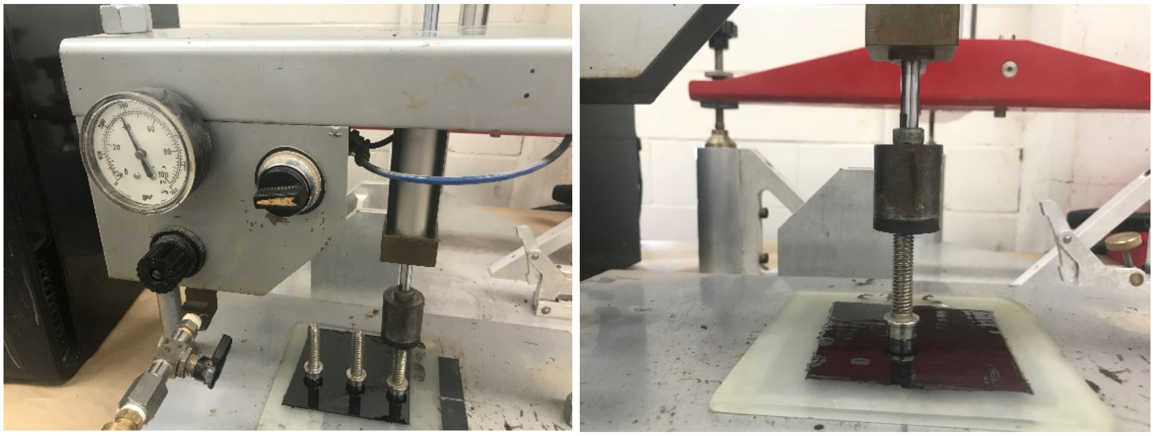


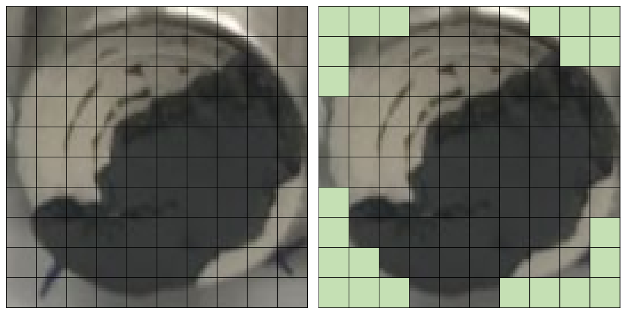
Figure 8. ISSA TB139 cohesion test device used to apply uniform pressure to stub.

Sample preparation for this test is the same as for the mass loss test described earlier (the same samples can be used after the conclusion of the mass loss test). During testing, samples are removed from the environmental chamber at predetermined times, the stub is applied, and a pressure of 100 psi is applied, and the BBS test is run to determine the POTS. Testing can be repeated at predetermined intervals to determine whether the residue is transitioning from tracking to trackless or if the residue is remains tracking.

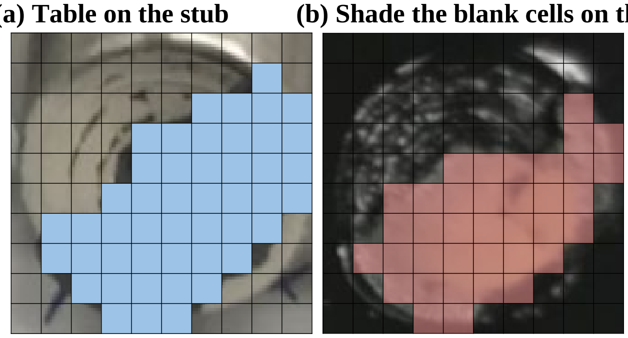
Determination of tracking potential involves analysis of the POTS and visual inspection of the failure mode. A schematic of possible failure modes in the modified BBS test and their corresponding interpretation regarding the tracking performance is shown in Table 5. Note that the failure type "c" is different from the failure type "e" and "f" in Table 5. In the case of type "c" if there is any tack coat attached to the testing stub, there should be no tack coat on the corresponding surface of the tested substrate (frosted glass). In this study, the frosted glass was selected as the substrate for easy handling and repeated use. As a result, there was some substrate or stub/substrate failure due to the poor bonding between some tack coats and the glass substrate.

If there is no cohesive failure (no residue of tack coat on stub and on substrate in the same areas), the tack coat is reported as trackless. By contrast, once the cohesive failure occurred, no matter if it occurred completely (type "d") or partially (type "e" or "f"), the tack coat is considered to be tracking. In the latter case, the percentage of cohesive failure mode is calculated to give a quantitative representation. The percentage of cohesive failure is quantified by taking a picture of the stub surface and overlaying a 10 × 10 table and counting the number of cells in the table that are covered by residue against the number that are not covered. The Cohesive Failure Percentage (CFP) is then calcualted as follows:

1. Create a 10 × 10 table in any software and put this table on the top of the tested stub image as shown in Figure a;



(a) Table on the stub **(b) Shade the blank cells on the stub**

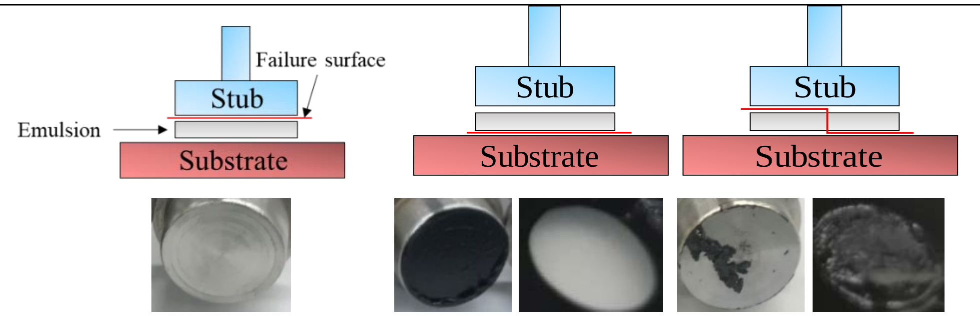
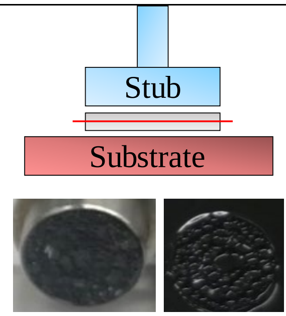
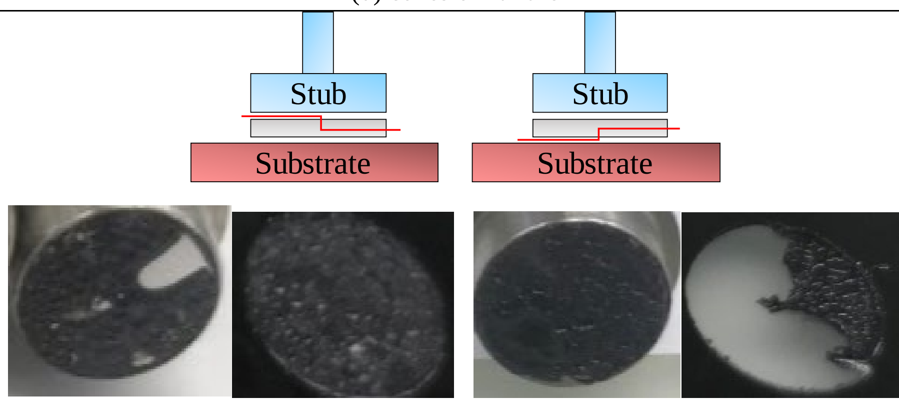


(c) Shade the binder covered cells on the stub **(d) Shade the blank cells on the substrate**

2. Shade the cells that were not covered by the stub and record the number as $number_{blank}$ (Figure b);
3. Shade the cells covered by the binder on the tested stub and record the number as $number_{stub}$ (Figure c);
4. Repeat step 1 on the tested substrate and shade the cells that were not covered by the binder and record the number as $number_{substrate}$ (Figure d);
5. Calculate the cohesive failure percentage (CFP) according to equation [2] and round the result to 10:

$$\text{Cohesive Failure Percentage (CFP\%)} = \frac{number_{stub} - number_{substrate}}{100 - number_{blank}} \times 100$$

Table 5. Schematic of Potential Failure Modes in Modified BBS Test

Failure mode	Schematic failure pictures	Meaning
Adhesive	 (a) stub failure (b) substrate failure (c) stub/substrate failure	Trackless: No residue on stub or substrate
Cohesive	 (d) cohesion failure	Tracking: Significant residue observed on stub and substrate
Combined	 (e) stub/cohesion failure (f) substrate/cohesion failure	

Loaded Wheel Tracking Test

After collecting initial data with the modified BBS, there was a concern that the BBS is not simulating the rolling action of the tracking in the field and a need to simulate a moving wheel could be a better representation of the phenomena in the field. Therefore, a wheel tracking test was also developed to validate findings of the BBS and because of the intuitive nature of using a rolling wheel to measure tracking potential. The Loaded Wheel Tester used in this study is the device specified in ASTM D6372/ISSA TB 147. A picture of the testing device is shown in Figure 9. The detailed procedure for the Loaded Wheel Tracking Test (LWTT) is as follows:

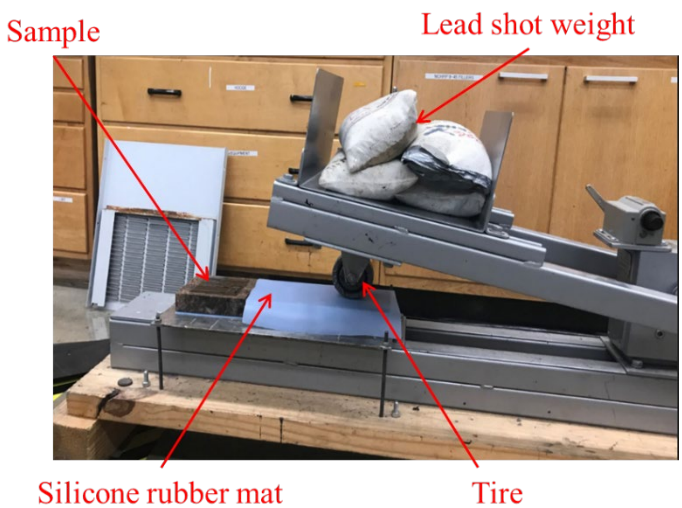
(1) Sample preparation is the same as that in the moisture loss test. The substrate for the LWTT is changed from glass to stone tiles as the glass substrate was found to easily crack under testing conditions.

(2) The sample is preconditioned in the environment chamber at the predetermined curing condition for one hour.

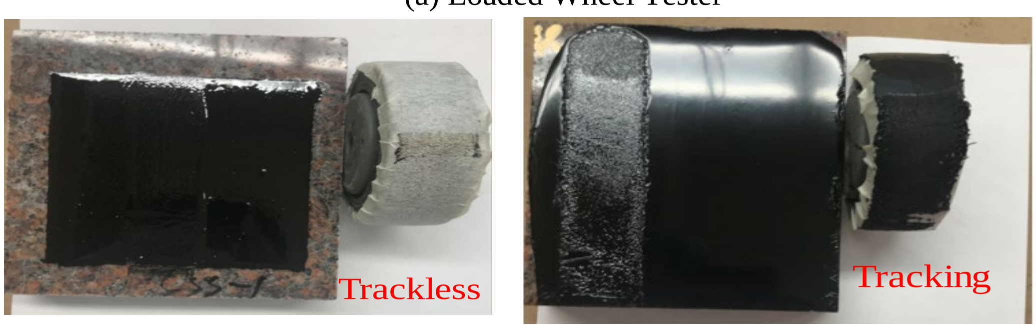
(3) The rubber wheel is wrapped with the rubberized tape* to facilitate easier cleaning and a uniform surface between tests (tape is discarded and reapplied between tests).

*It should be mentioned that during initial testing there was a concern that results are sensitive to the type of tape used to wrap the tire. In all six tape variations were tested: duct tape, masking tape, medical tape, masking tape sprayed with a rubber coating, rubber electrical insulation tape, and rubberized tape (marketed as Flex Tape®). After initial trials with all tape types, it was determined that the rubber tapes provided the most reasonable and representative results and the rubberized tape was ultimately selected based on availability and ease of use.

(4) Take the sample out from the chamber and run the Loaded Wheel Tester for 10 loading cycles. Visually inspect and record the surface of the sample and the tire. Conduct three replicates for each tack coat at each curing condition.



(a) Loaded Wheel Tester



(b) Sample considered as trackless (c) Sample considered as tracking

Figure 9. Loaded Wheel Tracking Test Setup. Note masking tape is shown for clarity in the picture but testing for this study used rubberized tape on the loaded wheel.

Initial testing with the Modified BBS at two tire pressures (15 psi and 100 psi) confirmed that that the test method is sensitive to tire pressure, with samples at 100 psi resulting in more tracking and lower trackless temperatures (more conservative). This will be expanded upon in the results section, but the results suggested that the LWTT should be ran at 100 psi for future work, which was followed in this study.

2.1.6 Interlayer Shear Strength Test

Shear strength testing conducted during this study followed the AASHTO TP 114 using the Louisiana Interlayer Shear Strength Tester (LISST) which was developed as a product of the NCHRP 09-40 study. The LISST device can be used in either mechanical or hydraulic testing machines and is available from at least two different vendors; specific details of the device are found in AASHTO TP 114. AASHTO TP 114 specifies a testing temperature of 25°C for all samples, although a limited subset of laboratory prepared specimens was tested at 46°C in this study to evaluate effect of temperature. For this study a constant displacement rate of 2.54 mm/min was applied to the specimen until failure with a confining pressure of 7 psi. Although the standard does specify a specific confining pressure, in this study confining pressure was needed to hold the sample together during placement in the device. The use of low confining pressure was used in at least one other recent study (Ozer and Rivera-Perez, 2017). The need for the confining pressure is also justified by the self-weight of the paved layer in pavements.

The test is applicable to road cores or laboratory prepared specimens. Road cores are cut, trimmed (if applicable), and tested. Laboratory specimens are produced in two separate layers. The bottom layers are compacted to a height of 50 mm at 135˚C using the Superpave Gyratory Compaction (SCG) with a target air void of 7% ± 1% and allowed to cool to lab temperature. Emulsion is then applied to the surface of the bottom layer using a laboratory balance to ensure the correct amount of tack coat was applied. The tack coat material is allowed to cure for 30 minutes at lab temperature. Finally, the top half of the sample was compacted by placing the bottom half in a preheated SGC mold and compacting loose mix on top of the tack-coated bottom half, again targeting a 50 mm thick compacted sample at 7%±1% air voids. After cooling, the samples are ready for the ISS testing. Both the road cores and laboratory prepared specimens used in this study have a diameter of 150 mm, and this value was used for calculating the interlayer shear strength using the measured ultimate load applied to the tested specimen.

Surface Texture Measurement

In order to study the effects of surface texture on the ISS the research team sampled three different mixtures from area contractors and measured the surface texture using a modified Sand Patch test (ASTM D965). Two of the mixtures (dense graded 12.5 mm Nominal Maximum Aggregate Size, NMAS and dense graded 19 mm NMAS) initially produced substantially similar texture depths so a third mixture was sampled (a 12.5 mm SMA). The Sand Patch method is designed to be run on an existing pavement surface using a known volume of sand; to modify the test to be run on cores, the researchers allowed the volume of sand to vary based on the texture of the sample, but following the same testing procedure of spreading the sand to fill surface voids. The volume of sand retained in the surface voids is calculated and divided by the area of the sample to calculate the Mean Texture Depth (MTD), which is a quantification of the macrotexture of a pavement surface expressed in mm. For this study, the average MTD of the "low texture" mix was found to be 0.17 mm (Standard Deviation = 0.04 mm) while the "high texture" mix was found to be 0.96 mm (Standard Deviation = 0.10 mm). Figure 10 shows an example of the low and high surface texture mixtures used in this study. Note that the upper mixture used in the laboratory portion of the study (the hot mixture placed on the existing surface and compacted) was the low texture mixture for all testing.

Figure 10. Example of high texture (left) and low texture (right) mixtures used in this study.

2.2 Field ISS Validation Study

The literature review indicated that laboratory prepared specimens cannot be used to predict the field performance and that a well-defined relationship does not exist. Therefore, the ISS test was also used to test road cores taken during this study from active paving projects during the 2017 and 2018 paving seasons. Materials from the active paving projects were collected to produce the laboratory prepared specimens for comparison, which include the field cores of the existing layer, emulsions for the interlayer bonding, and loose mixes of the new asphalt layers. After collection of these materials, the laboratory specimens were prepared by using the Superpave Gyratory Compactor (SGC). These samples were all tested at 25°C following AASHTO TP 114. Detailed descriptions of the materials used and project information are given in the results section of this report. This testing was conducted to (1) validate that the application rates and materials used in Wisconsin are providing adequate shear strength, and (2) provide comparison to laboratory ISS values to validate the concept of using laboratory specimens to predict field performance of tack coat materials in Wisconsin.

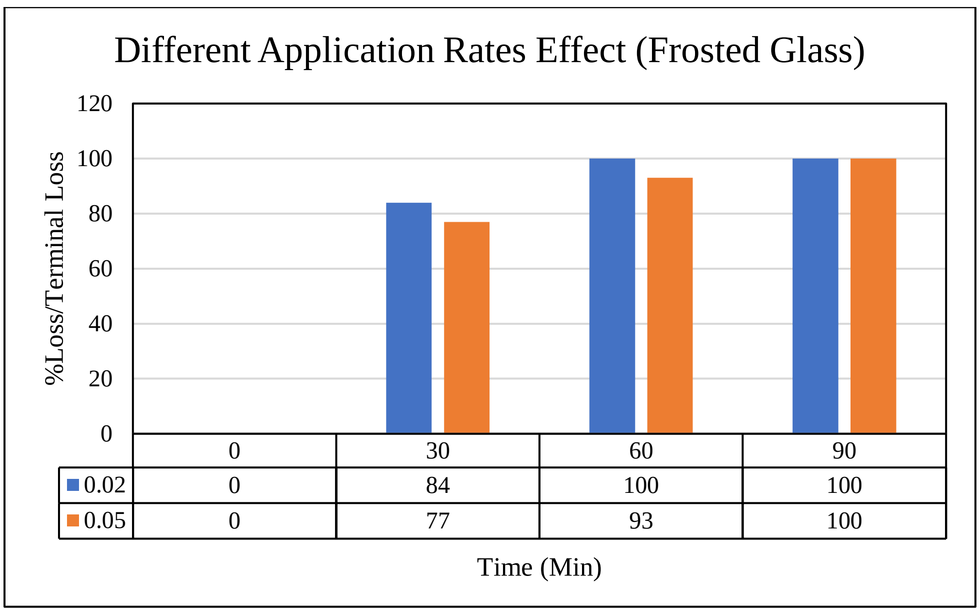
3. Results

3.1 Asphalt Emulsion Curing Time using Mass Loss

3.1.1 Effect of Residual Application Rate

The residual application rate controls the initial and cured film thickness of the emulsion. It is therefore expected that higher residual application rates would result in lower rates of curing. To evaluate the effect of residual application rate in this study, emulsion type and curing conditions were fixed at 10°C/45% RH. CRS-1 was used as the emulsion applied at two residual application rates (0.02 gal/yd^2 and 0.05 gal/yd^2). These rates required spreading a film of 0.090 mm and 0.226 mm respectively. All testing was completed on frosted glass substrate. Results are shown in Figure 11.

Although the curing rate is found to decrease with increasing application rate as expected, the results show the differences to be minimal from a practical perspective. It does not appear that application rate of emulsion is a limiting factor in construction timing as more than doubling the application rate (from 0.02 to 0.05 gal/yd^2) extended curing time by only minutes.



	0	30	60	90
0.02	0	84	100	100
0.05	0	77	93	100

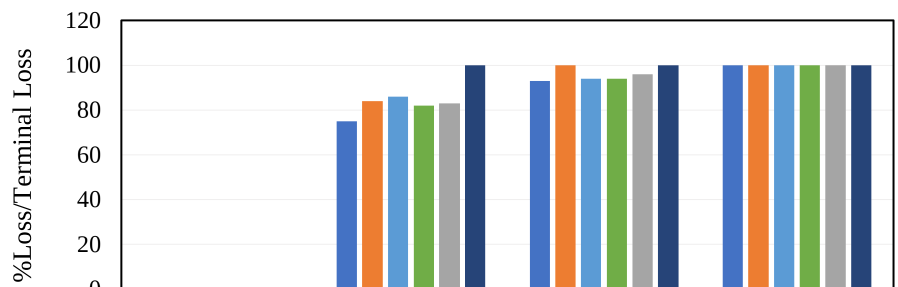
Figure 11. Effect of residual application rate on curing rate of CRS-1 emulsion.

3.1.2 Effect of Emulsion Type & Storage Conditions

With application rate fixed (0.02 gal/yd^2), all six emulsions were compared at a curing condition of 10°C/45% RH. The results are shown in Figure 12. All testing was completed on frosted glass substrate. Based on the results shown in Figure 12, it is concluded that the emulsion type can significantly affect the rate of curing as a spread in curing at the 30-minute condition of 25% exists (75% at the lowest to 100% highest), but for most of the commodity emulsions the differences are minimal.

The three CSS emulsions show the lowest three mass loss percentages at the 30-minute interval, although the difference between the CSS-1h/CSS-1hL and the CRS-1/CQS-1h is only about two percent. The difference in curing between the CSS-1 and the CRS-1/CQS-1h emulsions is about 10% at 30 minutes cure time. At 60 minutes cure time all emulsions are within 7% of the terminally cured condition. Note that the commercial Trackless product was fully cured at the 30-minute cure time, the significance of which will be discussed further with regard to dilution.

The AASHTO naming convention used in the asphalt emulsion industry to designate reactivity Slow Setting (SS), Quick Setting (QS), Medium Setting (MS), Rapid Setting (RS) may be misleading for applications such as tack coat in which a very thin film is sprayed on a relatively clean surface. From a construction timing point of view, there does not appear to be a significant advantage of choosing one emulsion product over another in terms of cure time, and choice of emulsion should instead focus on other considerations such as sprayability (viscosity), tracking (pickup of emulsion residue), and bond performance.

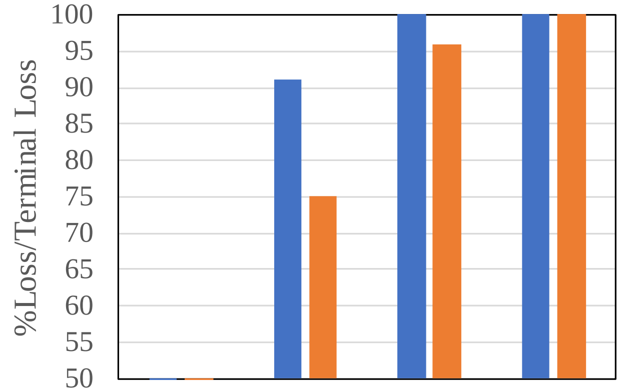


	0	30	60	90
CSS-1	0	75	93	100
CRS-1	0	84	100	100
CQS-1h	0	86	94	100
CSS-1hL	0	82	94	100
CSS-1h	0	83	96	100
Trackless	0	100	100	100

Time (Min)

Figure 12. Effect of emulsion type on curing rate at 0.02 gal/yd^2 residual application rate.

Since many SS type emulsions are allowed to cool to ambient temperature after production, a sample of the CSS-1h emulsion was split and half was stored at 140°F and the other half was left to cool to lab temperature (approximately 70°F) overnight. The mass loss test was then conducted on both samples using the 10°C/75% RH condition at 0.05 gal/yd^2 residual. The results are shown in Figure 13 and confirm that application temperature can have an effect on the curing rate of the emulsion with higher storage/application temperatures leading to higher rates of curing. This is expected as the chemical breaking reaction of emulsions is temperature sensitive.



Cure Time (Min) >	0	30	60	90
Storage at 60 C	0	91	100	100
Storage at room temperature	0	75	96	100

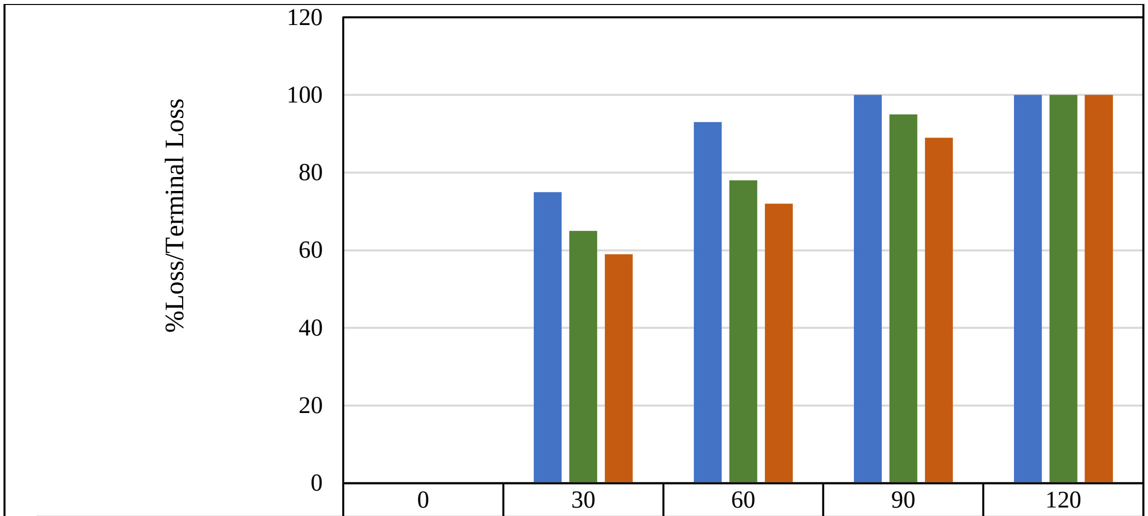
Figure 13. Effect of storage (application) temperature on curing of CSS-1h at 0.05 gal/yd^2 residual.

The difference in curing at the 30-minute interval is approximately 15%, but both conditions are fully or near fully cured at 60 minutes. The initial warmer temperature allows for greater initial mass loss, but once both sample temperatures stabilize, the ultimate curing times are approximately the same. In practice, the emulsion temperature very quickly assumes the temperature of the substrate given the thin films used for tack coat, so the effect of application temperature on curing may be less pronounced. Storage temperature, however, does affect emulsion storage stability and viscosity.

3.1.3 Effect of Dilution

Many asphalt emulsions can be diluted to facilitate uniform spraying by reducing viscosity and/or changing the residue content of the emulsion. Since tack coat application rates are comparatively low compared to chip seals for example, dilution allows the tack coat distributor truck to apply a uniform coverage of tack at a relatively low rate while maintaining a safe rate of speed within work zones. However, dilution is expected to substantially increase curing time of the emulsion due to the added water. For this study two dilution levels were investigated to compare to the undiluted emulsion for the CSS-1 emulsion. An application rate of 0.02 gal/yd^2 was used to test the hypothesis.

The results shown in Figure 14 confirm that dilution retards the curing rate of emulsion, and that the higher the dilution rate, the lower the curing rate and the longer the total cure time. For the CSS-1 emulsion shown in Figure 14, total curing is retarded by approximately 30 minutes for 1:1 dilution relative to the undiluted emulsion for this curing condition.

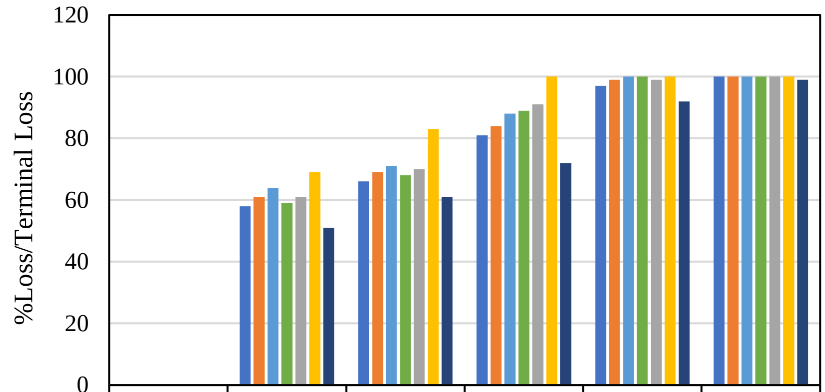


	0	30	60	90	120
CSS-1 Undiluted 68.2% Res	0	75	93	100	100
1:0.364 Dilution 50 % Res.	0	65	78	95	100
1:1 Dilution 34.1% Res	0	59	72	89	100

Figure 14. Effect of dilution on curing rate for CSS-1 emulsion.

Based on the initial results with diluted emulsion, an expanded experiment including all of the emulsion types was conducted. For this study, the most conservative curing condition of 10°C/75% RH was used at a dilution level of 1:1. The residual application rate for all emulsions is 0.02 gal/yd^2. Results are shown in Figure 15.

Based on the results shown in Figure 15, it is apparent that dilution affects the curing rate differently among emulsions. For example, the Trackless product, which exhibited the highest rate of curing in Figure 12, has the lowest rate of curing after dilution. Interestingly, the relative ranking of the other six emulsions is consistent between the undiluted and diluted samples at 30 minutes, with the CSS-1/CSS-1h/CSS-1hL emulsions showing lower rates of curing relative to the CRS-1/CQS-1h emulsions, although the differences are relatively small. However, by 90 minutes, the relative ranking changes with CSS-1h showing higher relative curing compared to the CRS-1/CQS-1h. These findings suggest that the relative effects of dilution are strongly influenced by emulsion chemistry (formulation).



	0	30	60	90	120	150
CSS-1	0	58	66	81	97	100
CRS-1	0	61	69	84	99	100
CQS-1h	0	64	71	88	100	100
CSS-1hL	0	59	68	89	100	100
CSS-1h	0	61	70	91	99	100
MS-2	0	69	83	100	100	100
Trackless	0	51	61	72	92	99

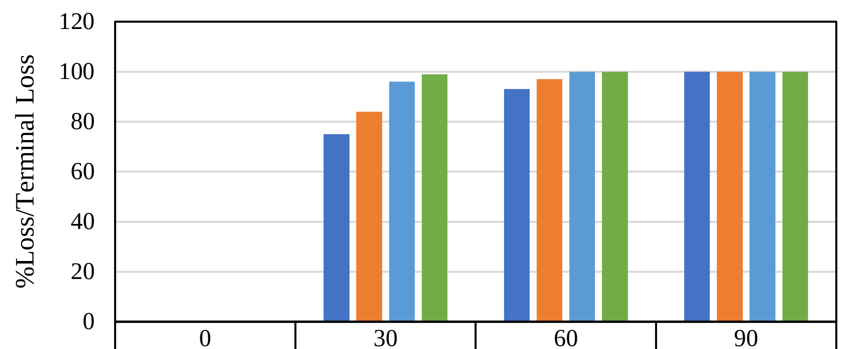
Time (Min)

Figure 15. Effect of 1:1 dilution on curing rate for all emulsions.

The results shown in Figure 15 present two practical concerns: First, from a specification point of view, allowing dilution uniformly across all acceptable products does not allow for the reliable prediction of cure time for the tack coat during construction. Second, one of the major concerns with dilution is the accuracy of dilution, particularly for agencies allowing contractor dilution in the field. Errors in dilution may unpredictably affect construction timing and add to the uncertainty in the scheduling process.

3.1.4 Effect of Curing Temperature and Humidity

To evaluate the effects of temperature and humidity, the CSS-1 emulsion was used at 0.02 gal/yd^2 residual. Curing temperatures were selected to span a significant range of pavement temperatures encountered in Wisconsin and to be practical to maintain in the laboratory. The 75% relative humidity level was selected as the average annual daily relative humidity in southern Wisconsin. The lower level of 45% was selected to be lower than the 75% but within reason for relative humidity in dry evenings in Wisconsin. Results are shown in Figure 16.



	0	30	60	90
10C and 75%	0	75	93	100
10C and 45%	0	84	97	100
60C and 45%	0	96	100	100
60C and 75%	0	99	100	100

Time (Min)

Figure 16. Effect of curing temperature and relative humidity on curing of CSS-1 at 0.02 gal/yd^2 residual.

Results confirm that higher curing temperature results in faster rate of curing, while higher level of humidity results in slower rate of curing. It appears that the humidity affects the rate of curing more at lower temperature, as a difference in curing percentage of approximately 10% was observed at 10°C, whereas the difference is only 3% at 60°C.

As pavement temperature and relative humidity change throughout the day, the rate at which the emulsion cures will also change. This is not unexpected and is a common observation in other asphalt emulsion applications such as chip seals, fog seals, etc. However, the results imply that the curing rate is relatively fast for all emulsions and that even at 10°C and high humidity the mass loss is complete within 2 hours period. Projects operating under tight scheduling restrictions (such as night paving, interstate work, etc.) must account for local weather in terms of emulsion curing. Night paving, in particular, compounds the effects of temperature and humidity as the pavement temperature slowly drops after sunset and the relative humidity may begin to increase.

It is noted that other environmental factors such as wind speed and moisture content of the in-situ surface also affect emulsion curing. Wind speed, in particular, can have a pronounced effect on curing as the authors' experience in the fog sealing industry suggests even a slight breeze can improve curing rate substantially due to convective evaporation.

3.1.5 Summary of Findings Related to Mass Loss Rate and Curing Time

Table 6 shows a summary of the factors evaluated during this portion of the study. Although the rate and terminal curing time is material dependent, it is observed that all of the standard type emulsions evaluated in this study cured between 30 minutes and one hour, with only minor differences observed due to the emulsion type. Therefore, there does not appear to be an advantage to specifying one product over another in terms of cure time. There may, however, be an advantage to non-standard products such as the Trackless product in terms of expediting cure time.

Dilution is shown to drastically affect the curing rate and terminal curing time for all emulsion types, although the relative effect of dilution is material dependent. Intuitively, increasing the rate of dilution further retards the curing process. Since dilution is essentially increasing the amount of water that must evaporate from the surface, the practice of dilution would be expected to significantly delay projects being constructed in cool, high humidity climate scenarios (or any scenario where water evaporation is slowed) if tracking of wet emulsion is to be avoided.

The effect of application rate is not considered significant for the range of rates used in this study, and although practically the substrate does have an effect of curing rate, for this comparative study there was minimal effect observed.

Table 6. Summary of Curing Study Factors

Factor	Description of Levels	Effect on Mass Loss Rate
Emulsion Type	CSS-1, CSS-1h, CRS-1, CSS-1hL, CQS-1h, Trackless (NTQS-1hh)	Rate is dependent on material type; "standard" emulsions exhibit similar rates.
Substrate Type	Marble Plate, HMA Surface Frosted Glass	Negligible
Rate of Application	0.02 gal/square yard 0.05 gal/square yard Residual	Minimal; Rate decreases with increasing rate of application.
Curing Relative Humidity	High: 75% Low: 45%	Rate decreases with increasing humidity level; relative effect is temperature dependent.
Curing Temperature	High: 60˚C Low: 10˚C	Rate increases with increasing temperature.
Dilution Rate	Undiluted, 50% Residue, and 1:1	Rate decreases with increasing dilution level; dilution can change ranking of materials.

3.2 Residue Resistance to Tracking

Based on the mass loss study, it was discovered that curing as defined by mass loss takes a relatively short time with a maximum of about 120 minutes. It was therefore decided that if a minimum of two hours of curing in the field is implemented, then tracking is mainly affected by the residue properties rather than the water in the emulsions. The testing for tracking proceeded with a minimum of one hour of curing before testing. As mentioned earlier two test types (Modified BBS and Wheel tracking) were used in the study. The following sections describe the details of the results collected in the study.

3.2.1 Modified BBS Results

The modified BBS test was used in this study to asses tracking potential of cured emulsion residue. A relationship between the POTS and moisture loss in the sample was developed to assess whether POTS alone can adequately predict tracking behavior or whether observation of the failure mode was also required. Table 7 lists the testing factors that were included in the testing.

Table 7. Initial Modified BBS Test Matrix

Factor	Level	Description
Emulsion Type	3	Trackless (Control) CSS-1h CRS-2
Curing Temp/Humidity	1	10°C/45% RH
Curing Time	4	0.5, 1, 2, 4 hours
Residual Application Rate	1	0.05 gal/yd^2

Table 8 shows the results of the initial testing in terms of the POTS values, the Cohesion Failure Percentage (CFP%), and when the emulsion became trackless. At the curing condition of 10ºC and 45% humidity, all the three tack coats became trackless within 30 minutes and remained trackless afterward, which is reasonable since the mass loss testing showed that the emulsions were nearly cured at 30 minutes under this condition. It would therefore be expected that the emulsion residue should show similar POTS at 30 minutes if POTS is able to accurately predict tracking potential. The POTS results and mass loss measured for this testing is shown in Figure 17.

Table 8. Results of Initial Modified BBS Testing

Type	Property	Curing time, hour			
		0.5	**1**	**2**	**4**
Trackless	POTS (psi)	0.0	0.0	0.0	0.0
	CFP (%)	0	0	0	0
	Trackless?	**Yes**	Yes	Yes	Yes
CSS-1h	POTS (psi)	33.3	93.3	98.3	131.7
	CFP (%)	0	0	0	0
	Trackless?	**Yes**	Yes	Yes	Yes
CRS-2	POTS (psi)	28.3	50.0	56.7	63.3
	CFP (%)	0	0	0	0
	Trackless?	**Yes**	Yes	Yes	Yes

It can be observed in Figure 17 that even though the three tack coats were all trackless at the condition of 10ºC and 45% humidity, the POTS values were significantly different. For Trackless tack coat there was no strength measured between the stub and the tack coat, which is expected because if a binder is not tacky (lower POTS), it will not stick to the BBS stub and will not have any resistance to the pull-of load. By contrast, the CSS-1h showed highest POTS followed by the CRS-2, however both of these emulsions were still trackless at the set condition. This suggests that tack coats can be tacky and can adhere to the stub and give higher POTS, but this does not necessarily mean that they are tracking (be picked on the stub) as the cohesive strength can overcome the adhesion to the stub and prevent the tracking. Therefore, the tracking performance of tack coat material is not predominately a function of its POTS value. This finding points out that the judgment of trackless behavior using this test should be based on the observation of failure modes of the test (cohesive or adhesive) instead of the POTS values measured in the modified BBS test.

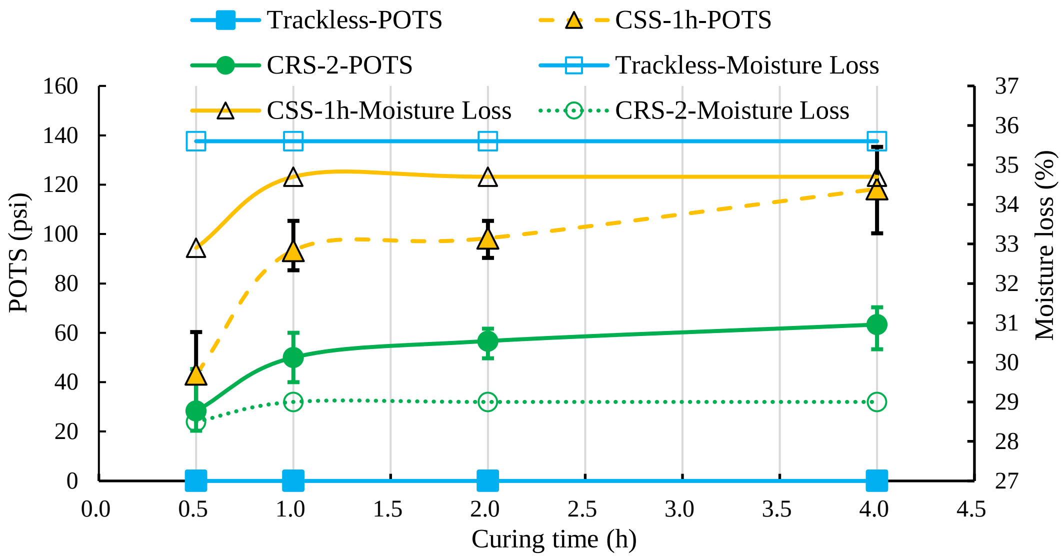


Figure 17. POTS and moisture loss versus curing time.

3.2.2 Effect of residue application rate on the tracking performance

To study the effect of residual application rate on the tracking performance, the modified BBS test was performed on two levels of application rates at 10ºC and 75% humidity (most severe condition for the effects of temperature and humidity as related to curing). Three emulsion types were evaluated with the results shown in Table 9.

Table 9. Effect of Residual Application Rate on Modified BBS

Residual Application rate (gal/yd^2)	Trackless time (hour)		
	Trackless tack coat	CSS-1h	CRS-2
0.02	0.5	1.0	0.5
0.05	0.5	1.0	0.5

It is observed in Table 9 that all the three tack coats showed the same tracking performance at different residual application rates. Therefore, the residual application rate has little effect on the tracking performance of the tack coat for the range of application rates used in this study. This finding suggests that the optimum residue application rate should be decided based on other considerations such as shear strength. For further testing in this study, the residual application rate was fixed at 0.05 gal/yd^2.

3.2.3 Effect of humidity on the tracking performance

Although humidity is not expected to affect residual asphalt rheological properties, the relative humidity does affect the curing rate of the emulsion and the amount of water left in the emulsion even after terminal loss is achieved. To study the effect of humidity on the tracking performance, the modified BBS test was performed on two levels of humidity at 10ºC. The 10ºC condition was used as a worst-case scenario to delay the moisture evaporation as much as possible. Testing conditions and results are shown in Table 10.

Table 10. Effect of Humidity on Modified BBS Results

Humidity at 10°C (%)	Tack coat type					
	Trackless		CSS-1h		CRS-2	
	Trackless time (h)	Loss as % of terminal loss at trackless time	Trackless time (h)	Loss as % of terminal loss at trackless time	Trackless time (h)	Loss as % of terminal loss at trackless time
45	0.5	100	0.5	81	0.5	98
75	0.5	100	1.0	90 (79 at 0.5h)	0.5	100

Table 10 shows that all the three types of tack coat can become trackless at 10ºC with 45% humidity or 75% humidity; however, at 75% humidity, it takes one hour for the CSS-1h to become trackless. Therefore, the humidity can affect the time when the tack coat becomes trackless because humidity can delay curing (water evaporation).

It is interesting to note that the effect of humidity is mainly due to the moisture loss delay as it is seen that longer time is needed for a tack coat to become trackless when moisture loss is significantly lower than 100%. At 10ºC with 75% humidity for the CSS-1h the loss percentage after 30 minutes was 79% and the emulsion was tracking at his time, while the loss at one-hour was 90% and the emulsion was trackless. Therefore, the trackless time for the tack coat is related to its water evaporation time. At the same temperature but 45% humidity, the emulsion was trackless at the half-hour mark and 81% loss. It is not known if the effect of water in the emulsion is affecting tracking due to the softening effect or due to changes in adhesion to the stub. There may be a "cutoff" in mass loss when the emulsion residue transitions from tracking to trackless; in other words, the emulsion does not need to be fully dried prior to exhibiting trackless behavior, but the cutoff does depend on curing time. The relationship between the moisture loss and the adhesion requires further evaluation as the cutoff mass loss may change between different emulsions.

3.2.4 Effect of tack coat type, temperature and dilution rate on the tracking performance

Based on previous literature it was found that the tracking of tack coats is related to the softening point or stiffness of the residue (Mohammed, et al. 2012). Therefore, it was expected that by changing testing temperature, all emulsion residues could become trackless because as temperature decrease the stiffness and cohesion of all residues will increase.

The six emulsion types were tested, using the modified BBS, at temperatures varying from 22ºC to 58ºC to compare their tracking performance and verify this expectation. Based on the prior testing, all samples were applied at 0.05 gal/yd^2 residual and cured at the specified test temperature and 45% RH. Testing was conducted beginning at 0.5 hours and each subsequent half hour until the tack either became trackless or four hours was reached. The tack coats were also diluted at three levels: original residue rate, diluted to 50% residue, and 1:1 diluted (half of the original residue rate).

The trackless temperature was defined as the highest temperature at which the tack coat was track-free (trackless) and the tracking temperature was the lowest temperature at which the tack coats were tracking. For the purposes of this study, the trackless temperature for a certain tack coat is considered equal to its tracking (transition) temperature minus 6ºC. Results for the emulsions tested are shown in Table 11, which also shows the results when each emulsion was diluted to 50% residue and when it was at 1:1 emulsion to water.

Table 11. Modified BBS Test Results for Various Tack Coats at Different Temperatures and Dilution Rates

Temp-erature (ºC)	Time for emulsion to become trackless (hours)															
	Trackless			CSS-1h			CSS-1hL			CQS-1h	CSS-1			CRS-1		
	Dilution Level															
	None	50% Res.	1:1	None	50% Res.	1:1	None	50% Res.	1:1	None	None	50% Res.	1:1	None	50% Res.	1:1
22											0.5	2.0	2.0	0.5	1.0	2.0
28				0.5	2.0	2.0				0.5	>4.0	>4.0	>4.0	>4.0	>4.0	>4.0
34				>4.0	>4.0	>4.0	0.5	1.0	2.0	>4.0						
40							>4.0	>4.0	>4.0							
46																
52	0.5	0.5	1.0													
58	>4.0	>4.0	>4.0													

Note: "> 4.0" means the tack coat is still tracking even after 4 hours curing time.

Based on Table 11, it can be concluded that decreasing testing temperature (representing pavement temperature), changes the tracking performance of tack coat from tracking to trackless for all emulsion. By comparison, the dilution rate can delay the time at a given temperature for an emulsion to become trackless. However, above a certain temperature, the dilution rate cannot change the "tracking status" as it appears the residue remains too soft with low cohesive strength to resist tracking even after four hours of curing.

Table 11 clearly indicates that different tack coats show different trackless temperatures: the trackless temperature ranking of the six tack coats is: Trackless > CSS-1hL > CSS-1h and CQS-1h > CRS-1 and CSS-1. It is interesting to note that this ranking is the same as the high-temperature PG of the six tack coat residues: trackless tack coat (PG 88) > CSS-1hL (PG70) > CSS-1h and CQS-1h (PG 64) > CRS-1 and CSS-1 (PG 58). These results show that the tracking performance of the tack coat is related to, or more controlled by, the rheological properties of the residue of the tack coat than by the curing time. In other words, the tracking performance of the tack coat is a temperature dependent property due to the change in the rheological behavior of the emulsion residue. The detailed relationship between the rheological property of the residue binder and the tracking performance is discussed in the following sections.

3.2.5 Rheological Properties and Relationship to Tracking performance

To validate whether the tracking behavior of tack coats can be estimated from rheological testing of their residue, the emulsion residues were subjected to a DSR temperature sweep test to measure the change in G*/sinδ with temperature. The relationship between the tracking propensity in the modified BBS test and G*/sinδ of the emulsion residues is shown in Figure 18.

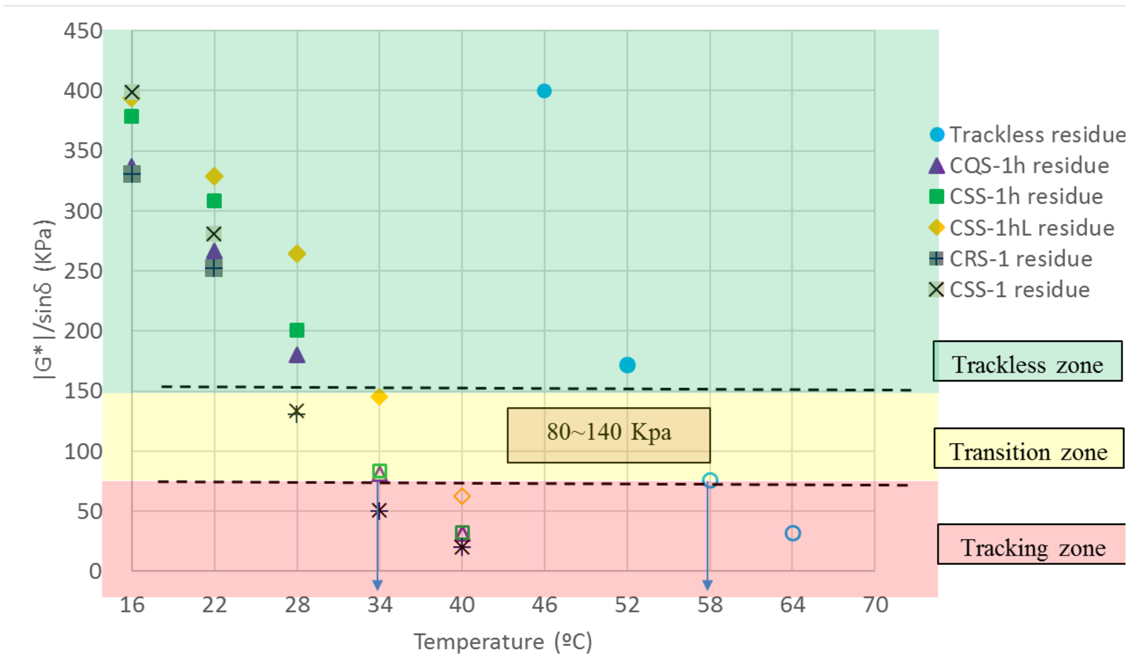


Figure 18. Relationship between tracking performance in the modified BBS test and G*/sin(δ) of the residue.

In Figure 18 the solid markers indicate the tack coat was trackless at this temperature while the hollow markers indicate that the tack coat was tracking at the test temperature. Based on the data shown, all emulsion residue appears to be transitioning from tracking to trackless between the G*/sinδ values of 80 kPa and 140 kPa. If the G*/sin δ of the residue at a given temperature is higher than 140 kPa, then the residue would be expected to be trackless at this temperature. Conversely, if the G*/sinδ of the residue at a given temperature is lower than 80 kPa, and the residue would be expected to track unless the temperature is reduced to exceed this limit. Any G*/sinδ value between 80 to 140 kPa means that the tack coat is in the transition zone and may be either trackless or tracking.

From a practical point of view, pavement temperatures in Wisconsin during the paving season can vary considerably, but in peak summer are expected to be between 46°C and 64°C during the daytime. All of the standard emulsions would therefore be expected to track during this time. Interestingly, the Trackless product would not be expected to track until pavement temperatures reach between 52°C and 64°C. However, the successful use of this type of material in the Southern U.S. where pavement temperatures often exceed 64°C suggests that the modified BBS test may be more conservative than practice. There is also a concern that the BBS is applying a direct tension (pull) on the residue, while the mechanism of tracking in the field involves more shearing by tires moving on the surface of the tack coat. It was therefore decided that a better representation of the rolling of a tire could give a more realistic simulation of the problem in the field.

3.2.6 Verification of Tracking Behavior using the Loaded Wheel Tracking Test

The LWTT was used to further validate the relationship between residue properties and tracking propensity. For this portion of the study, only the Trackless and CSS-1 emulsions were tested because they show the widest range in residual asphalt properties. The LWTT was conducted at 6 °C intervals and the wheel evaluated for tracking after each test. In the LWTT, the cycle frequency is fixed, but user controls the effective tire pressure by adding or removing standard weights to the top of the device. In this study two initial pressures (15 psi, 100 psi) were evaluated to determine whether tire pressure had a significant effect on the results. Results show that higher tire pressures result in greater propensity to track at a given temperature; the use of higher tire pressures is therefore more conservative and represents field conditions more closely. These results, and results comparing the tracking temperatures between the LWTT and modified BBS are shown in Table 12.

Table 12. Comparison between LWTT and Modified BBS Tracking Temperatures

	Loaded Wheel Tracking Test		**Loaded Wheel Tracking Test**		**Modified BBS test**	
Pressure	15 psi		100 psi		100 psi	
Tack coat type	CSS-1 (PG 58)	Trackless (PG 88)	CSS-1 (PG 58)	Trackless (PG 88)	CSS-1 (PG 58)	Trackless (PG 88)
Trackless Temperature	46°C	82°C	40°C	76°C	22°C	52°C
Transition Temperature	52°C	88°C	46°C	82°C	28°C	58°C

The tracking temperatures based on the LWTT are found to be higher than the tracking temperature based on the modified BBS test. This is not surprising as the two tests have different load application mechanisms and could impose different rates as well as values of pressure on the tack coat. The modified BBS test is found to be more conservative (require lower trackless temperatures) than the LWTT. There might exist a shift factor between the temperatures from the modified BBS test and LWTT which needs more investigation. In addition, field tracking performance of different tack coats should be acquired to verify the tracking which of the two tests are more realistic in simulating field conditions. However, it should be acknowledged that the loading mechanism of the LWTT is more realistically simulating a moving tire in the field than the BBS Pull-Off Mechanism. The trackless temperatures using the LWTT also appear to be more reasonable given what is known of the Trackless emulsion product performance in the Southern U.S.

A similar relationship between the tracking performance in the LWTT test and G*/sinδ of the residue was generated for the two emulsions and shown in Figure 19. Again, the solid markers in Figure 19**.** indicate the tack coat is trackless at this temperature while the hollow markers indicate that the tack coat was tracking at this temperature. Similar to the result from the modified BBS test, a tracking upper limit of (18 kPa) and a trackless lower limit (10 kPa) for the G*/sinδ can be identified in Figure 19**.** Therefore, the LWTT results similarly confirm that rheological properties of the emulsion residue can be used to predict the tracking behavior of a tack coat.

By comparison, the minimum threshold for the G*/sinδ determined from the LWTT (10-18 KPa) is much lower and was nearly one-eighth of the minimum threshold determined from the modified BBS test (80-140 KPa). Further investigation and field validation are needed to select which limit for the G*/sinδ of residue should be used to ensure the satisfactory tracking performance of tack coats although the findings using the LWTT appear reasonable.

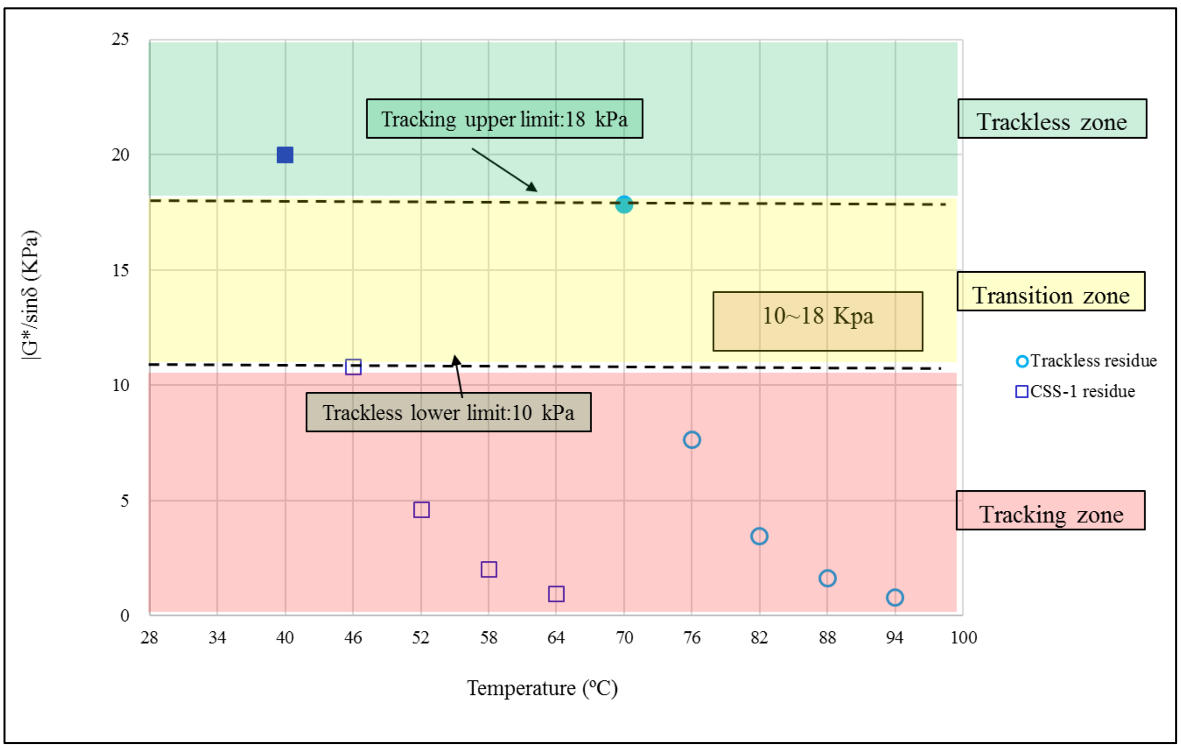


Figure 19. Relationship between tracking performance in the LWTT test and G*/sin(δ) of the residue.

3.3 Laboratory Interlayer Shear Strength Performance

The purpose of this portion experimental program is to compare the interlayer shear strength on laboratory prepared samples using different asphalt emulsion types, residual application rates, and existing surface textures. Additionally, the effect of testing temperature was investigated for a subset of material combinations. The objective of this testing is to validate whether the ISS can be used to effectively screen materials in a laboratory setting and to provide a database of materials for comparison to testing of road cores later in this study.

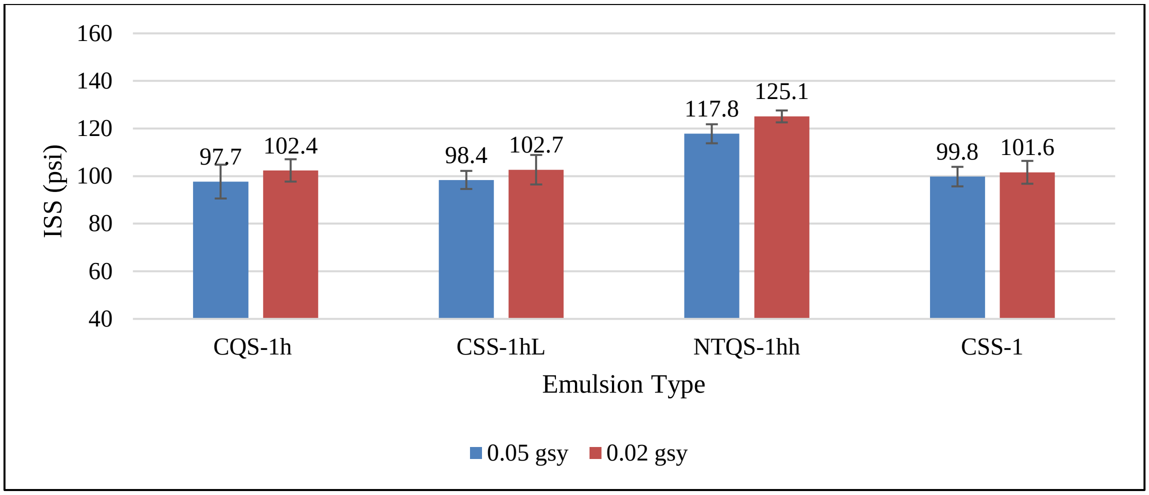
3.3.1 Effect of Emulsion Type and Residual Application Rate on ISS

The four emulsions chosen for this portion of the study (CSS-1, CQS-1h, CSS-1hL, and Trackless) were selected to encompass a wide range of residual asphalt properties. As such, one would expect that if residual asphalt properties significantly affect shear strength, a significant difference between the ISS for the emulsions would be noted. Figure 20 shows the results for the four emulsions for both the low texture and high texture surfaces and both residual application rates.

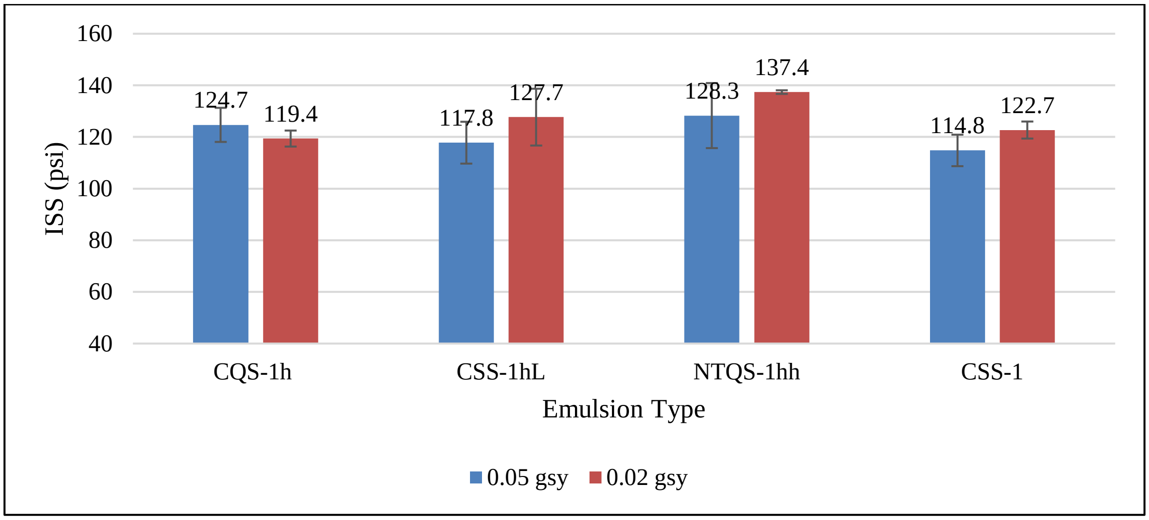
The results in Figure 20 show that emulsion type does not appear to have a practically significant effect on the ISS. The Trackless product (NTQS-1hh) shows slightly higher ISS values for the low texture mixture, but it gives very similar strength to the other three emulsions for the high texture mixture. Similar to emulsion type, there does not appear to be a significant effect of residual application rate on ISS for the two application rates evaluated. In all but one case, the higher residual application rate actually results in a lower average ISS value. These findings suggest that under these testing conditions other variables (such as surface texture) are dominating the ISS response.

Interestingly, comparing the findings of this project with those of the NCHRP 09-40 (Mohammed et. al. 2012), the materials tested during this study appear to show less differentiation when compared against laboratory compacted specimens produced during NCHRP 09-40 (Figure 21). In the NCHRP study, for example, the difference between CRS-1 and the Trackless product was found to be approximately 55 psi, whereas the maximum difference observed during this study is approximately 22 psi. It is noted that the NCHRP study used a confinement level of zero pressure of the samples and found inconsistent trends when increasing the residual application rate in the laboratory, with one emulsion exhibiting increased ISS with increasing residual application rate, one exhibiting decreased ISS, and three exhibiting an initial increase then decrease. For SS-1h, Trackless, and PG 64-22 (hot applied), it was found that the optimum rate—at which the greatest ISS was achieved is 0.062 gal/yd^2. 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 gal/yd^2. Note that the NCHRP study covered a wider range of residual application rates (0.031 to 0.155 gal/yd^2) than what is used in this project. In addition, a research project recently presented in the SPTC-ODOT Workshop (Ghabchi et al., 2017) also concluded that in general the interlayer shear strength decreased as an increase in the residual application rate (Figure 22). Only the two Non-Tracking tack coats (NTHAP and NTQS-1HH) showed slightly higher ISS values when their application rates increased. Aside from the CRS-1 emulsion, the ISS values reported in the NCHRP study are similar to the ISS values reported for this project when comparing similar application rates. The NCHRP study also found that the Trackless tack product produced the highest average ISS for the lower application rates.

The ISS values reported in the Oklahoma's study (Ghabchi et al., 2017) are generally lower than the ISS values reported for this project. This may be due to the normal force applied during the ISS tests for this project. A 7.0 psi normal force was applied during this study while in the Oklahoma's study, it is not mentioned whether a normal force was applied during the ISS tests.



(a) Low texture existing surface



(b) High Texture existing surface

Figure 20. Effect of emulsion type and residual application rate for low texture (top) and high texture (bottom) existing surfaces.

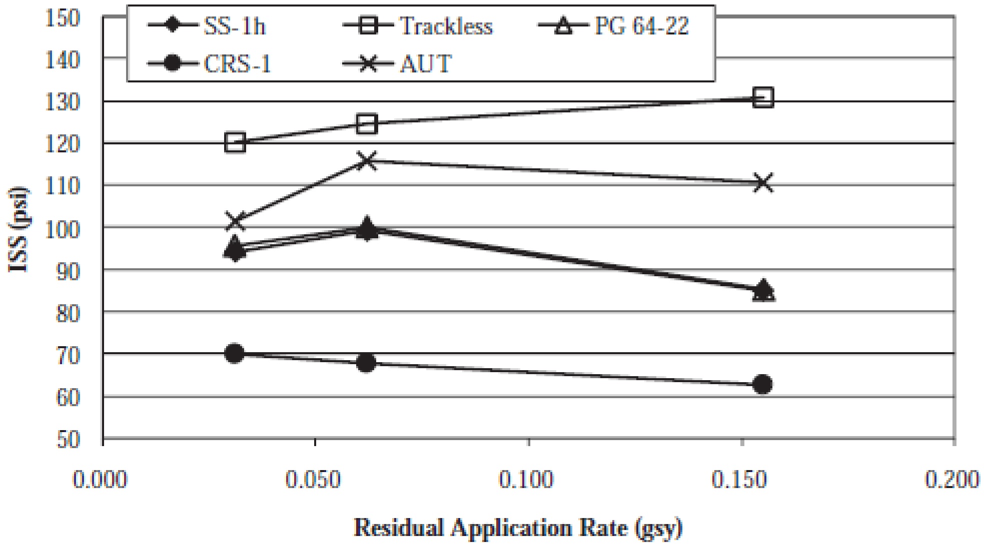


Figure 21. Effect of emulsion type and residual application rate on laboratory compacted specimens during NCRHP 09-40.

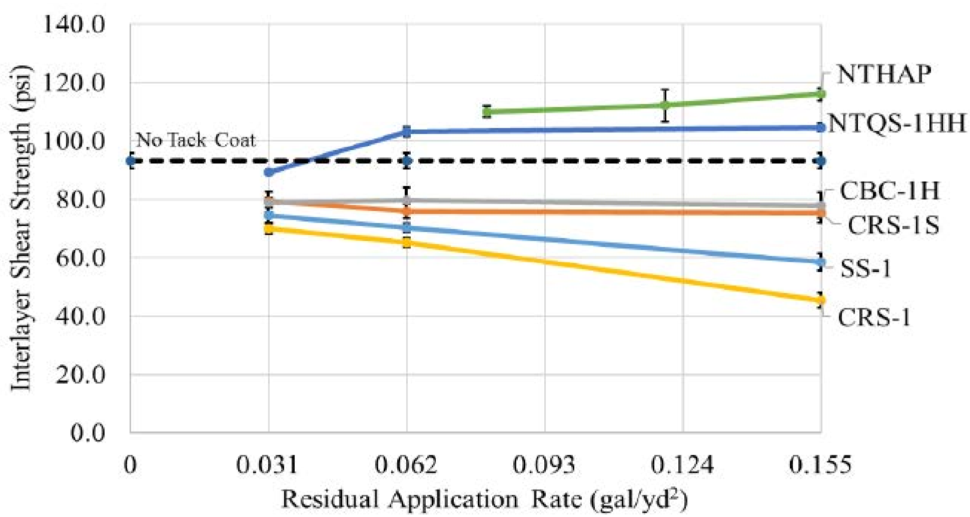
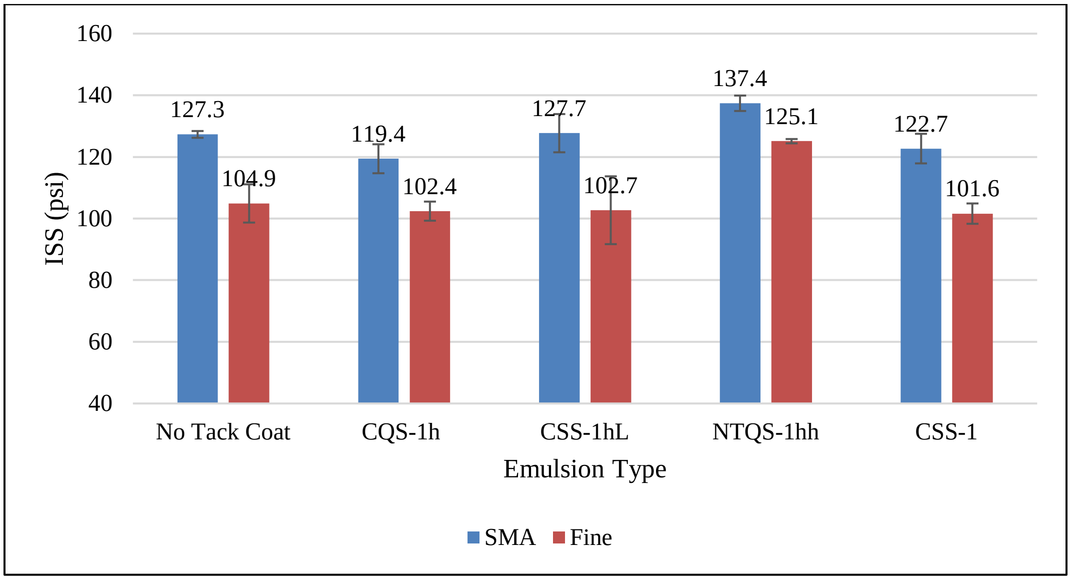


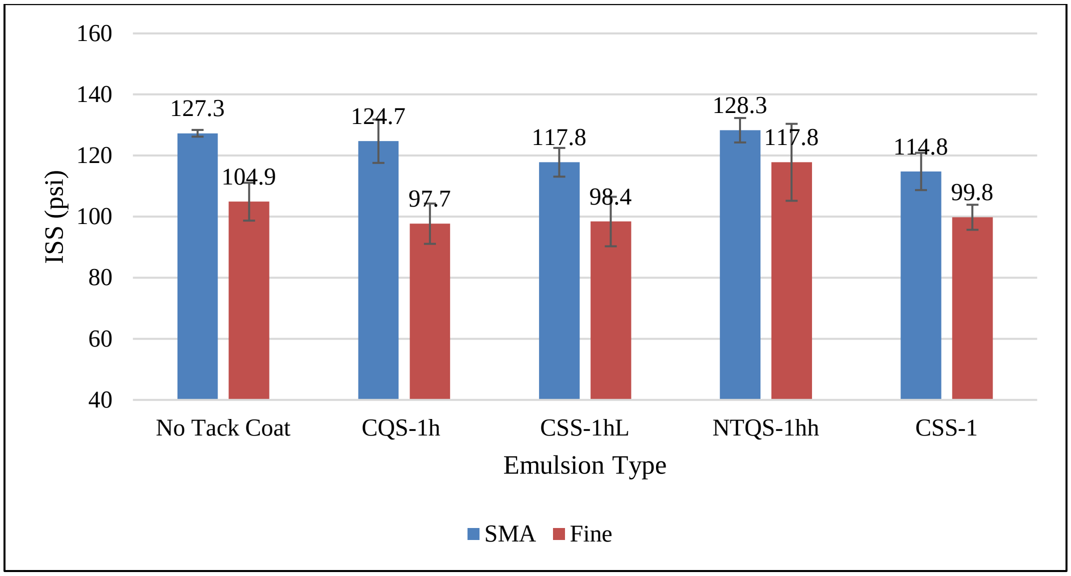
Figure 22. Effect of emulsion type and residual application rate on laboratory compacted specimens from the ODOT Study (Ghabchi et al., 2017).

3.3.2 Effect of Surface Texture on ISS

Results shown in Figure 20 suggest that factors other than application rate and emulsion type may be dominating ISS behavior in the laboratory. The mixture used to prepare the top half of all ISS specimens tested during this study is the same for all combinations of emulsion and residual application rate. Therefore, the direct effect of existing surface texture can be compared for the low texture and high texture existing surfaces. This data is shown in Figure 23. The effect of existing surface texture is clearly shown in Figure 23 with increasing texture resulting in increased ISS. Interestingly, the average spread between the high texture and low texture ISS value for a given emulsion at a given residual application rate is approximately 20 psi for most cases, which is the approximate largest spread in the data shown in Figure 20. This finding suggests that for newly compacted specimens in the laboratory, existing surface texture dominates ISS performance.



(a) 0.02 gal/yd^2 residual application rate



(b) 0.05 gal/yd^2 residual application rate

Figure 23. Effect of existing surface texture on ISS for 0.02 gal/yd^2 residual application rate (top) and 0.05 gal/yd^2 residual application rate (bottom).

Findings from NCHRP 09-40 using three surface texture conditions (Open Graded Friction Course (OGFC), Sand Mixture, and SMA) found a pronounced effect of texture, with a spread in ISS of approximately 20 psi between surface texture extremes and at relatively similar residual application rates to those used in this study. This is shown in Figure 24. The ODOT study has also confirmed the dominating effect of surface texture conditions on the ISS values, in which the HMA specimens showed significantly higher ISS values than the PCC cores (Figure 25). Besides, most of specimens with tack coats showed similar or slightly lower ISS values compared to the specimens with no tack coat, except for the specimens with Non-Tracking tack coats.

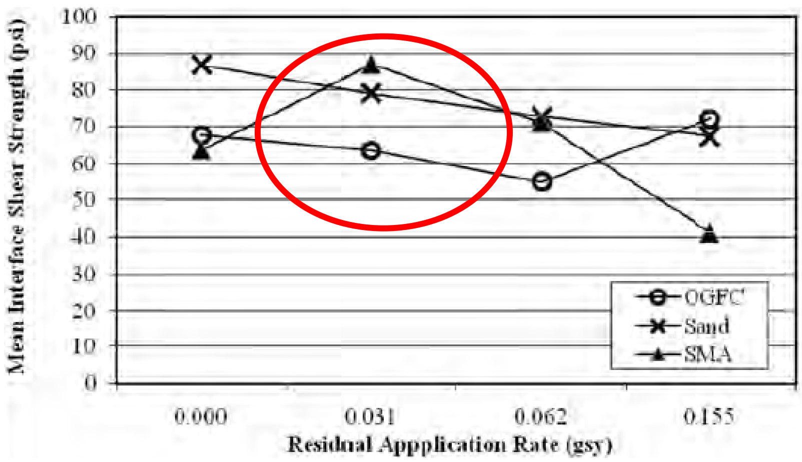


Figure 24. Effect of surface texture on ISS from NCHRP 09-40. Red circle shows the ISS for application rates similar to those used in this study (Mohammad et al., 2012).

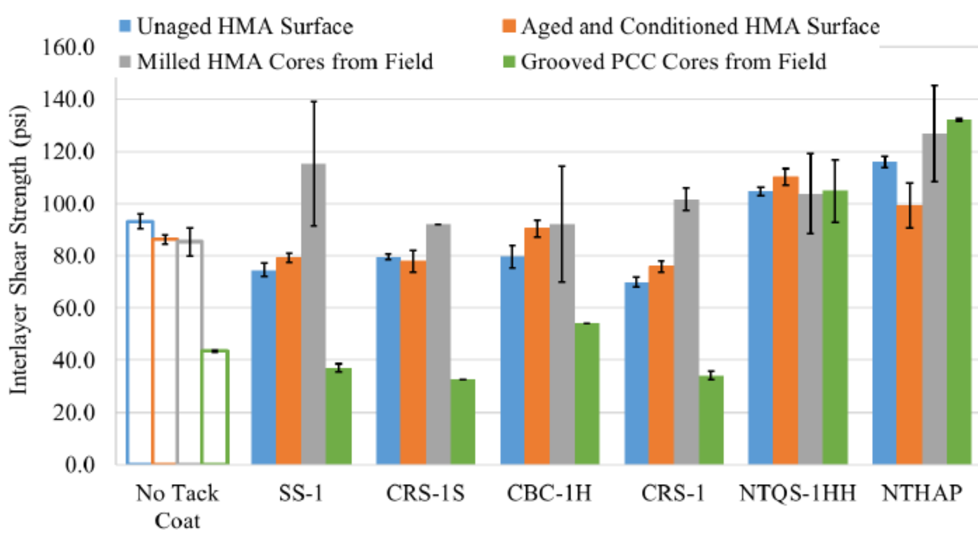


Figure 25. Effect of surface conditions on ISS at the optimum residual application rates (mostly 0.031 gal/yd^2 for SS-1, CRS-1S, CBC-1H, and CRS-1) from ODOT (Ghabchi et al., 2017).

To further illustrate the effect of existing surface texture, samples were prepared with no tack coat. The hot low texture mixture was compacted directly on top of the cooled, existing surface. Results indicate that the "No Tack Coat" samples performed at least similarly and, in many instances, better than the emulsion-tacked surfaces. In addition, for one emulsion (CSS-1hL), samples were prepared for both the low texture and high texture mixture by slicing the uppermost (exposed) surface using a wet saw to produce an effectively smooth surface. These samples resulted in a reduction in ISS of 27% for the low texture mix and 52% for the high texture mix (Figure). These findings clearly indicate that existing surface texture dominates ISS performance in the laboratory.

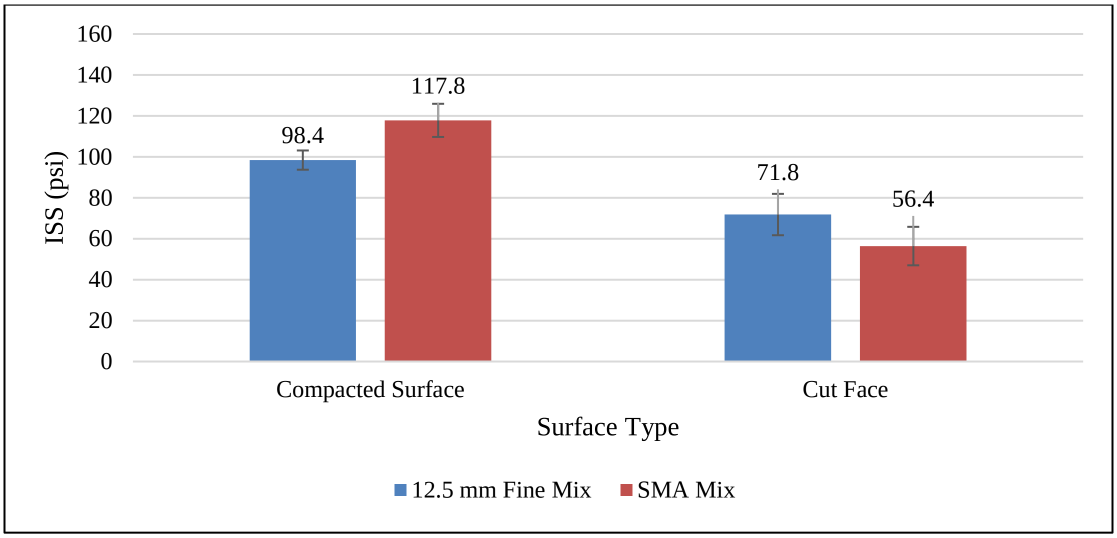


Figure 26. Effect of loss of texture on ISS for CSS-1hL.

This finding is supported in the findings of NCHRP 09-40. Figure 27, taken from that study, shows that for SS-1h the "No Tack" condition resulted in an ISS almost 20 psi higher than the next highest measurement for laboratory prepared samples. In the ODOT study, the findings of that no tack coat samples showed relatively better interlayer bonding performance than most of the samples with tack coats may also be explained by the dominating effect of existing surface texture (Figure 25). The reason for an exception of the samples with Non-Tracking tack coats is not clear. But it should be noted that the application rates for those two Non-Tracking tack coats were from 0.062 to 0.155 gal/yd^2, instead of the application rate of 0.031 gal/yd^2.

Note that by comparison in Figure 27, the "field prepared" specimens tested during the NCHRP 09-40 study exhibited substantially lower ISS values for the same application rate and the same mixture materials.

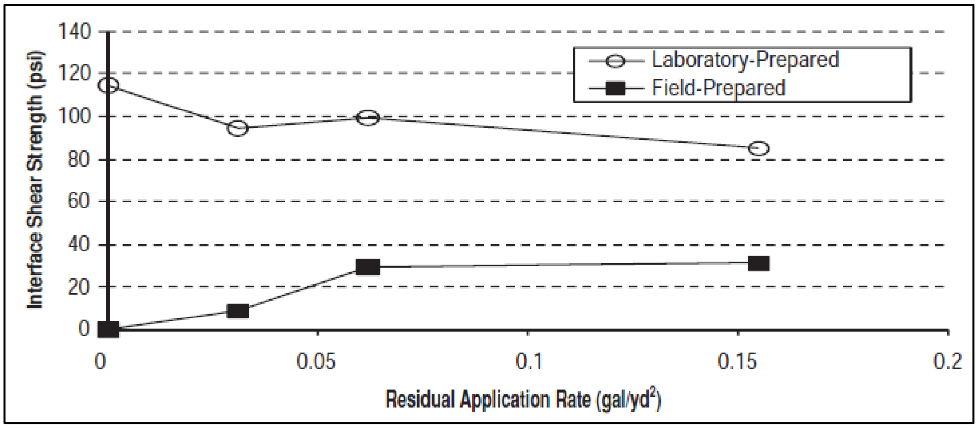


Figure 27. Effect of residual application rate of SS-1h for laboratory and field prepared specimens during NCHRP 09-40 project (Mohammad et al., 2012).

In a research study conducted by the Swiss Federal Laboratories for Materials Science and Technology (EMPA) (Raab and Partl, 2004), the effects of tack coat types and surface texture conditions on the interlay bonding performance were assessed. The main conclusion was that the use of tack coats does not necessarily result in a better interlayer shear strength, but the different surface textures do influence the interlayer shear strength. Besides, the results of maximum shear force from the laboratory tests on gyratory samples using nearly 20 different types of tack coats showed a range of values between 40 and 60 kN (equivalent to 328-492 psi), which was known to be much higher than the values from field samples. It should be mentioned here that in the Swiss standard for interlayer shear tes˚t a deformation rate of 50 mm/min is applied to testing specimen at a temperature of 20°C.

The field cores from test sites of another project from the EMPA's research (Raab and Partl, 2015) supported the finding of that interlayer bonding performance does not depend on the type and application rate of tack coats. The maximum shear force values of those field cores with tack coats varied in a range between 20 and 40 kN (equivalent to 164-328 psi) (Figure 28).

The researchers from EMPA believe that the gyratory compaction resulted in the higher interlay bonding strength than the field compaction. That is the reason they chose a roller compactor for preparing lab specimens in their research. In addition, they also investigated the effect of tack coats by means of employing tack coats on the surface of dirty and/or wet existing layer, which was claimed as a common phenomenon on construction sites (Raab and Partl, 2009). It was found that tack coats had a great potential to secure and improve the interlayer bonding performance in the case of dirt and moisture.

So, based on the findings from the NCHRP 09-40 study and EMPA's research it is clear that a better understanding of the gap between interlayer bonding performance of laboratory-prepared specimens and field cores is important. This confirms the necessity to conduct a field validation study in this project.

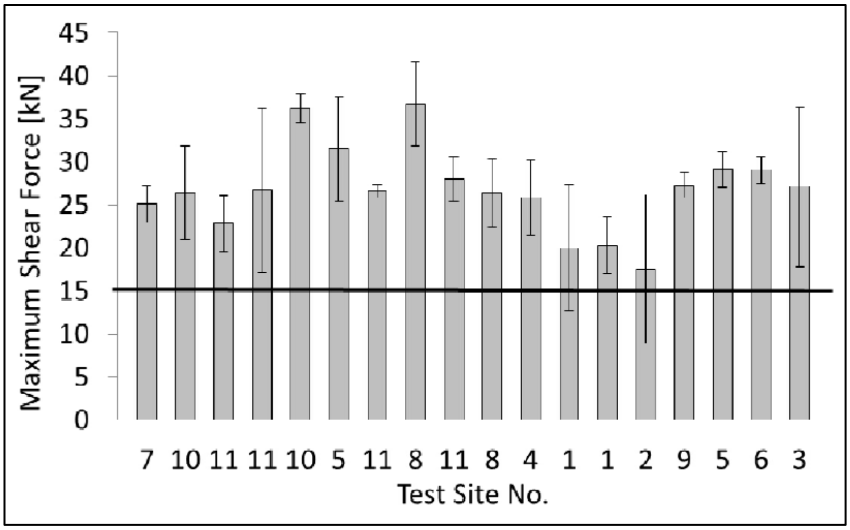
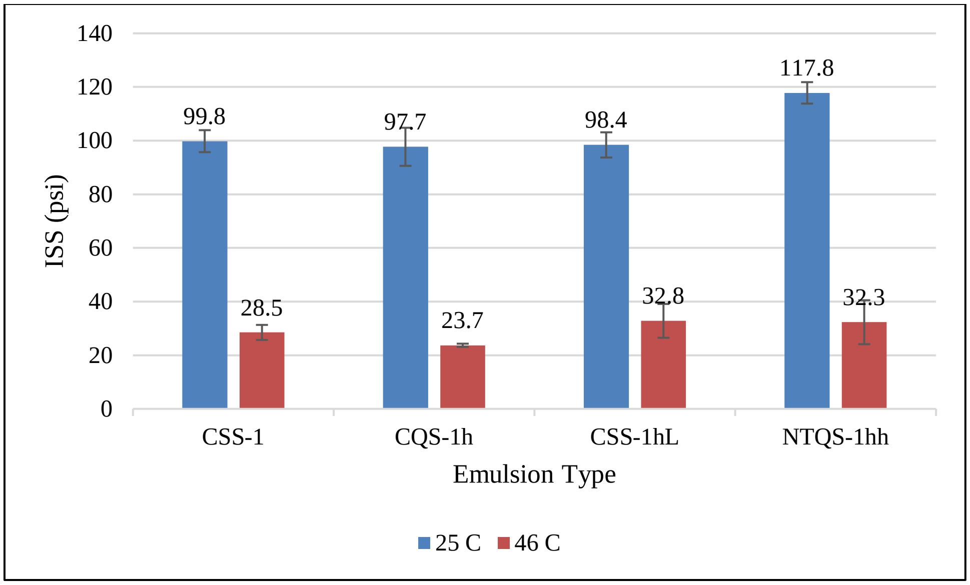


Figure 28. Examples of the interlay bonding performance of field samples from the EMPA's research (Raab and Partl, 2015).

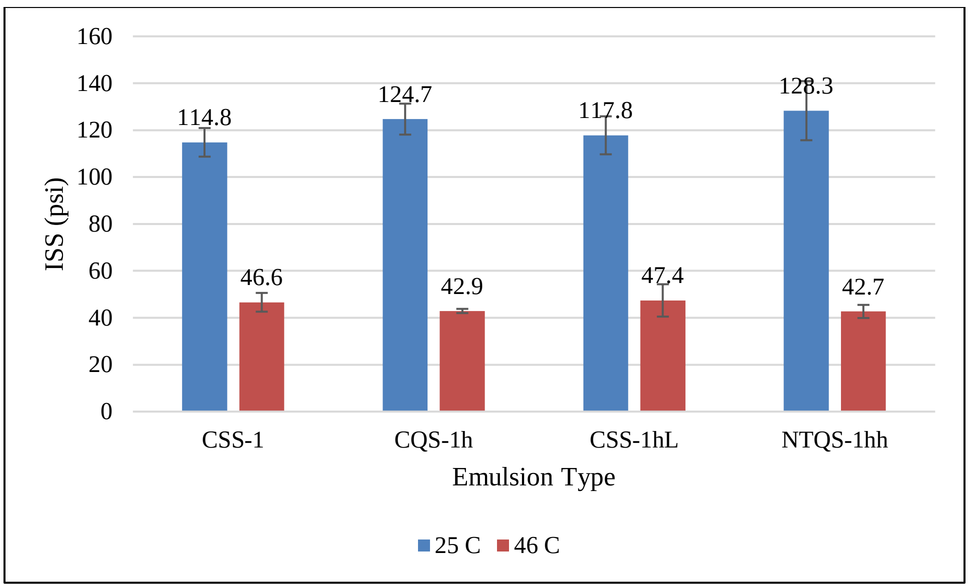
3.3.3 Effect of Testing Temperature on ISS

To evaluate the relative effect of testing temperature, which can be related to pavement temperature, compacted test samples were conditioned at 46˚C prior to testing; this temperature was specifically selected as the 50% reliability high pavement temperature in the State of Wisconsin at two inches below the pavement surface according to the Long-Term Pavement Performance (LTPP) database. All other testing conditions were held constant.

The effect of test temperature is pronounced for both levels of surface texture, but the relative ranking of ISS remains the same (high texture provides higher ISS) at the higher test temperature (Figure 29). The percent decrease in ISS with increased temperature is approximately the same for both mixtures and among asphalt emulsion types; this finding suggests surface texture is the again the most important factor controlling ISS, independent of temperature. For practical purposes, this finding also suggests that testing at 25°C alone is reasonable to screen emulsion or surface types.



a- Using a Fine Bottom layer



b- Using a SMA Bottom layer

Figure 29. Effect of test temperature on ISS using two surface textures for the bottom layer

3.3.4 Statistical Analysis of Laboratory ISS Testing

An Analysis of Variance (ANOVA) was conducted to determine the statistical significance of the ISS results presented above. To conduct the ANOVA, the emulsion type is quantified using the ER-DSR Test (AASHTO TP123) tested on the emulsion residue at 25°C. The ER-DSR subjects the emulsion residue to a monotonic shear strain rate while recording shear stress up to a predefined shear strain then applies a zero-stress condition while recording shear strain recovery. The log of the maximum observed shear stress was used in this study to quantify residual asphalt properties of the emulsion. Surface texture is quantified using the MTD as described in earlier sections of this report. The replicate factor was included to provide information regarding the reliability of the test method itself relative to varying other factors. The statistical software used to generate the ANOVA was JMP®. Results of the ANOVA are given in Table 13.

Table 13. ANOVA for ISS Main Factors

Main Factor	F Ratio	p-value	R^2_{ADJ}
Surface Texture	103.5	<0.0001	0.79
Emulsion Type	59.3	<0.0001	
Application Rate	7.6	0.0085	
Replicate	6.8	0.0123	

All controlled factors are found to be significant at the $\alpha = 0.05$ level. Based on the results in Table 13, it is found that surface texture is the most significant factor influencing ISS, as expected based on the results presented earlier in this section. Emulsion type shows the second highest influence on ISS, followed by application rate and the replicate factor. The R^2_{ADJ} for the regression equation including only these four main factors is relatively strong at 79%, indicating that 79% of the data variance can be explained with these four factors alone. Including interactive factors in the model improves the R^2_{ADJ} by only 1%, indicating interactive factors are not significantly influencing ISS. It should be noted that the replicate factor is found to be somewhat significant, indicating the test method variability should be considered when comparing results. The results of the regression model are shown in Figure 30.

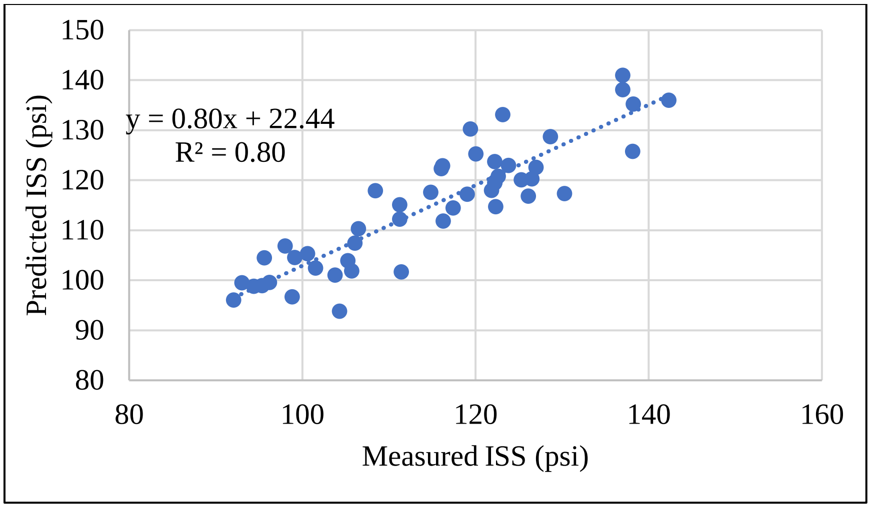


Figure 30. Regression fit for ISS using main factors.

Since the Trackless emulsion is not widely used in Wisconsin and the residue is considerably stiffer than the other three emulsion residues, the ANOVA was conducted again removing the Trackless data from the analysis. Results are shown in Table 14.

Table 14. ANOVA for ISS Main Factors (Without trackless emulsion)

Main Factor	F Ratio	p-value	R^2_{ADJ}
Surface Texture	114.11	<0.0001	0.78
Replicate	6.28	0.0177	
Application Rate	4.05	0.0530	
Emulsion Type	0.59	0.4468	

Interestingly, with the Trackless emulsion removed from the data, the effect of emulsion type on ISS is not found to be significant. Application rate is considered only marginally significant at the $\alpha = 0.05$ level. Surface texture again dominates the ISS response. The replicate factor is again found to be somewhat significant, indicating that the test method variability is relatively high compared to changing the other factors controlled in this study. The R^2_{ADJ} of the regression model for this analysis is almost identical to the model including the Trackless emulsion, meaning the Trackless emulsion itself is not fundamentally biasing the data.

Based on the results in Table 14, it is concluded that for emulsions currently allowed by WisDOT specification, ISS should not factor into the decision of emulsion type for tack coats. It is concluded that the ISS test is sensitive to application conditions and emulsion type and shows fairly good repeatability. Some critical challenges identified by the research team in using this test in the laboratory still need to be addressed however. For example, the samples prepared with no tack coat showed similar or in some cases higher ISS values relative to samples that have been tacked, which is in contrast to published findings using field data. This will be explored further in the next section.

3.4 Field ISS Validation Study

The ISS test was also used to test road cores and field materials sampled from active paving projects during the 2017 and 2018 paving seasons to validate the laboratory findings. For most of the projects, materials from the active paving project were collected to produce the laboratory prepared specimens for comparison, which include the field cores of the existing layer, emulsions for the interlayer bonding, and loose mixes of the new asphalt layers. A materials collection worksheet was requested for all projects to record relevant project information; an example of a completed field worksheet is given in Appendix B. After collection of these materials, the laboratory specimens were prepared by using the SGC. These samples were all tested at 25°C following AAHSTO TP 114.

Initially 16 combinations of surface type, application rate, and emulsion type were requested for this study. In all nine of 16 combinations were sampled from five projects. Table 15 shows the combinations tested for this study. Raw materials were not collected from the HWY 54 project on the milled existing surface and the application rate was also not specified at the time of coring. In addition, the DOT reported non-uniform coverage for one of the emulsion types on that project. Similarly, raw materials were also not collected for the STH 61 project and only one rate and emulsion type were used. The cores collected from these projects were tested and the data was reported during an interim presentation to the Project Oversight Committee on August 29th, 2018. For the following analysis, however, this data was not included for the reasons listed above.

It should also be noted that the "QS-1h" listed in the table is the same emulsion as the "SS-1h", only for the "QS" an additive was added to the emulsion tanker prior to applying the tack. Anionic quick-setting emulsion ("QS") is not a recognized AASHTO emulsion designation (cationic quick set is recognized: "CQS"). The actual residual application rates differed between projects and are listed in the associated data plots. For all combinations except the 25 mm new surface three road cores and three laboratory prepared specimens were tested for each combination; two samples were tested for each of the 25 mm surface combinations.

Table 15. Combinations Received and Tested for Field Validation Study.

Existing Surface Type	Application Rate	Emulsion Type		
		SS-1h	QS-1h	Third Emulsion
Milled	High	Hwy 54, Blk. Riv. Falls*[†] US 45, P&D	Hwy 54, Blk. Riv. Falls*[‡] US 45, P&D	x
	Low	US 45, P&D	US 45, P&D	x
12.5 mm New	High	x	STH 61, Lancaster*	x
	Low	x	x	x
19 mm New	High	US 45, P&D	US 45, P&D	N/A
	Low	US 45, P&D	US 45, P&D	N/A
25 mm New	High	I-39 Rock Road	I-39 Rock Road	N/A
	Low	I-39 Rock Road	I-39 Rock Road	N/A

* = road cores only, no raw materials collected

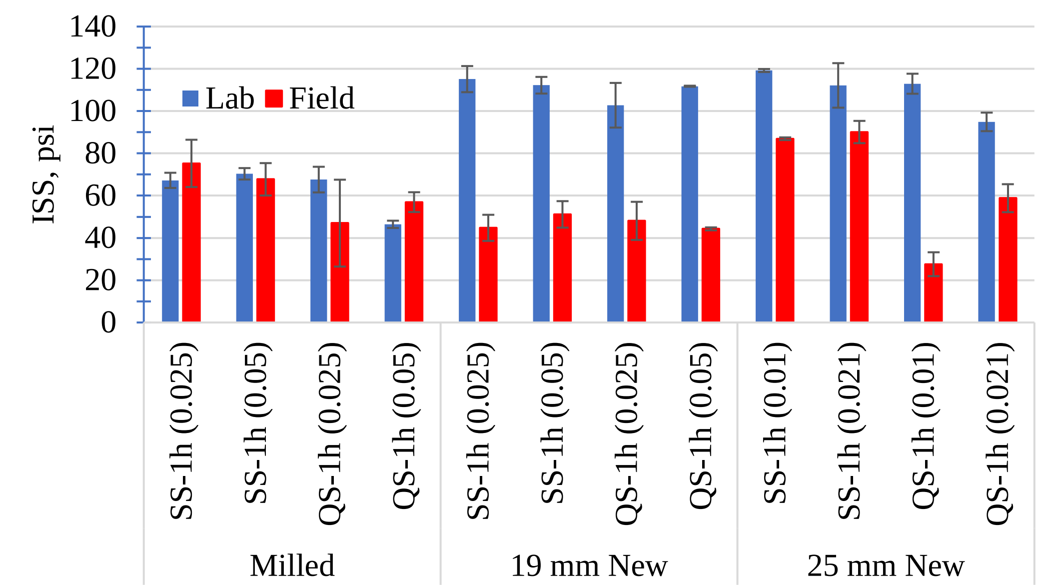
† = Application rate not specified or unknown
‡ = Non-uniform coverage of tack reported by DOT
x = combination requested but not received.
N/A = combination not requested

For some of the samples collected full data from the field including the pavement and air-temperatures were supplied by the contractor. Table 16 includes the summary for the Milled Surface and for the 19 mm new Surface on STH 45. As can be seen in the table the application pavement temperature varied between 67 and 90 for the Milled Surface and 72 to 89 for the 19-mm new surface. It is also noticed that the breaking time is shorter when the QS additive was used. However, the ratio of the breaking time of the QS to the CSS-1h is not consistent possibly because of the effect of pavement temperature variation.

Table 16. Air and Pavement Temperatures for the STH 45 Project.

	Milled HMA Surface (STH 45 Lower)				**New HMA Surface (STH 45 Upper)**			
	CSS-1h @ 0.025	**CSS-1h+QS @ 0.025**	**CSS-1h @ 0.05**	**CSS-1h+QS @ 0.05**	**CSS-1h @ 0.025**	**CSS-1h+QS @ 0.025**	**CSS-1h @ 0.05**	**CSS-1h+QS @ 0.05**
Residual Rate (x 10^{-3} gal/yd^2)	32	29	59	56	26	24	59	51
Air Temp (˚F)	65	70	67	70	69	76	69	78
Pavement Temp (˚F)	67	87	78	90	72	86	78	89
Time To Break (min)	20	5	20	9	10	8	16	13.5
QS/SS % of break time		25%		45%		80%		84%

The summary of the ISS results of the field validation study is shown in Figure 31. Samples are grouped by existing surface type. The intended (Target) residual application rate is listed with each sample; note that the actual residual rate may be different between existing surface types due to construction variability. The error bars represent ± 1 SD from the mean value. All samples were tested in one laboratory by one technician to eliminate testing bias from the analysis.



Labels: Emulsion Type (Target Residual App. Rate, gal/yd²)

Figure 31. Comparison of Lab and Field ISS for Field Validation Study.

For this data set it is clear that laboratory prepared samples cannot be used to reliably predict field ISS values using the same materials. A series of statistical t-tests were performed at the 95% confidence level to determine the significance of application rate, emulsion type, and compaction method on the ISS. The resulting p-values from this analysis are shown in Table 17; values that are bolded and in red are groupings that show statistical significance at the 95% confidence level.

Table 17. P-values from T-tests on Groupings of ISS Data for Field Validation Study

Grouping	Application Rate				Emulsion Type*				Lab to Field			
	Field		Lab		Field		Lab		SS-1h		QS-1h	
	SS-1h	QS-1h	SS-1h	QS-1h	Low	High	Low	High	Low	High	Low	High
Milled	0.390	0.460	0.299	**0.004**	0.901		0.299	**0.004**	0.302	0.609	0.171	**0.022**
19 mm	0.278	0.511	0.531	0.214	0.639		0.134		**0.000**	**0.000**	**0.002**	**0.000**
25 mm	0.360	**0.003**	0.445	0.058	**0.000**	**0.003**	0.127		**0.000**	**0.048**	**0.000**	**0.007**

*If application rate is not found to be significant, data from both application rates is used to compare emulsion type; if application rate is significant, the data is separated by application rate to compare emulsion type.

The following conclusions are drawn from the field study data:

- For all three existing surfaces, the effect of residual application rate is statistically similar for all combinations tested except the unique case of the lab-prepared milled surface using QS-1h (0.025 gal/yd^2 > 0.05 gal/yd^2) and the field core 25 mm surface QS-1h (0.021 gal/yd^2 > 0.01 gal/yd^2). Potential explanations are given below. It should be noted that range of residual application rates for all samples is relatively narrow and application rates significantly higher or zero could affect results, as was the case for the findings of the NCHRP 09-40 project.

- For combinations in which the application rate is not significant, the effect of tack coat material type is also statistically similar. This is expected since the residual asphalt used for both emulsions is the same. A liquid additive was added to the SS-1h to create a “QS” emulsion. In the cases where emulsion type is significant, it appears to be caused by the low values of ISS when using the QS-1h emulsion.
- The effect of compaction method is inconsistent, but statistically significant for nine of 12 combinations and all combinations for the 19 mm and 25 mm surfaces. For the milled surfaces the effect is not statistically significant for three of the four combinations. For the 19 mm and 25 mm surfaces, the lab ISS is statistically higher than the field ISS.
- The effect of surface type is pronounced, although the milled samples exhibited lower ISS relative to the new surfaces. This is unexpected as milled surfaces are expected to provide greater texture relative to the new surface. Several noteworthy observations were made during the testing of these samples that could provide some explanation for this finding. First, the direction of travel (milling) was not noted on the samples, so a bias could have been introduced based on the direction of milling. Second, it was noted that during the testing that several of the samples broke in the lower layer away from the tack interface. A picture of one such sample is shown in Figure 32. Although the effect of this observation on ISS cannot be quantified directly, it was noted for both laboratory and field samples.

Figure 32. Sample showing deformation/shear of lower layer in addition to tack layer; two shear planes are circled.

One sample combination (25 mm New, QS-1h, 0.01 gal/yd^2 residual) exhibited non-uniform tack coat coverage and dusty/dirty interface surfaces following testing. A picture of one of the samples is shown Figure 33. These samples exhibited an average reduction in ISS of over 50% relative to the next lowest field ISS value for this surface type, demonstrating the potentially severe negative impacts of non-uniform coverage and/or dirty surfaces during tack coat application. This finding agrees with the findings of NNCHRP 09-40 and is consistent with the language in the WisDOT Construction and Materials Manual (CMM) and Standard Specification.

Figure 33. Interface of field cores showing uniform coverage on clean surface (top) and non-uniform coverage on dusty surface (bottom) for 25 mm New, QS-1h.

4. Conclusions & Recommendations

The objective of WHRP Project 0092-17-06 is to perform a critical evaluation of the materials and application methods used in Wisconsin for asphalt emulsion tack coats in order to provide recommendations that make tack coat usage more efficient and effective. In support of this objective this research project was divided into two major phases. The first phase is a laboratory evaluation of five commonly used tack coat materials in Wisconsin and one commercially available Trackless tack coat product for curing, tracking propensity, and shear strength performance. The second phase of the project is a validation of shear strength of materials and application rates using field cores taken during the 2017 and 2018 paving seasons. The main findings of the study are summarized below:

4.1 Laboratory Evaluation of Tack Coat Materials

4.1.1 Evaluation of Curing Time using Mass Loss

- Type of emulsion is found to affect the time required to reach terminal mass loss at a given set of application and curing conditions, although the commonly used naming convention in the asphalt emulsion industry to designate reactivity (SS, MS, RS) can be misleading in terms of tack coat curing due to the thin films used during this process. Not considering the Trackless product, the five other emulsions were generally within 10% of each other in terms of mass loss at a given cure time; practically speaking this difference may not be significant.
- Within the range of residual application rates investigated during this study there is minimal effect of application rate on curing time although on average the curing rate decreased as application rate increased, most likely as a result of increased film thickness.
- Emulsion curing is sensitive to temperature and relative humidity; increasing curing temperature and decreasing humidity increase the curing rate and decrease the overall curing time. The relative effect of humidity is dependent on the curing temperature, with curing at lower temperatures being more sensitive to humidity.
- Dilution of emulsions is found to significantly affect the rate of curing and terminal curing time. The effect of dilution is found to be material dependent, and the level of dilution can also change the relative ranking of materials. In all cases dilution substantially increases the terminal curing time, in some cases almost doubling the time required to reach terminal mass loss.
- For undiluted emulsions, the total curing time observed in this study is between 30 and 60 minutes at the conditions studied. For diluted emulsions, curing time is between 90 and 120 minutes at the conditions listed. Allowing traffic on the emulsion before it has substantially cured will result in tracking of the wet emulsion and will compromise the coverage of the fresh emulsion on the substrate.

4.1.2 Evaluation of Tracking Propensity

- Tracking of asphalt emulsions can be divided into two stages: tracking of wet, uncured emulsion and pickup and tracking of the emulsion residue after curing. The first stage is mitigated by allowing the emulsion to substantially cure before allowing traffic on the tack coated surface. The second stage is found to be dependent on the residue properties of the emulsion at the prevailing climatic conditions. In this study a modified BBS (AASHTO T361) test and Loaded Wheel Test (LWT, ASTM D6372) were developed to measure tracking potential of the cured residue.
- The propensity of an emulsion residue to track is not found to be dependent on the residual application rate of emulsion within the range of residual application rates used in this study.
- It is found that the emulsion does not need to be 100% terminally cured before becoming track free, although the percent terminal loss required for trackless behavior is dependent on the emulsion residue properties. For the CSS-1 emulsion used in this study, the percent terminal loss required for trackless behavior at 10°C is found to be approximately 80%.
- Since dilution increases the curing time to reach a given percent terminal loss, the time required to reach trackless behavior at a given set of climatic conditions increases with increasing level of dilution. If the pavement temperature is too high, the emulsion residue will remain prone to tracking even after four hours of curing time for undiluted as well as diluted emulsions.
- Pavement temperature is the most important factor affecting tracking behavior after the emulsions have reached terminal mass loss. The residual asphalt properties of the emulsion appear to be good indicators of tracking potential, with increased residue stiffness at a given temperature resulting in greater resistance to tracking at that temperature. Based on the LWT results using the two extreme materials in terms of residue stiffness, the softest material (CSS-1) had an upper limit of tracking temperature of between 40°C and 46°C, meaning at any pavement temperature greater than approximately 40°C, the emulsion residue would be expected to track. By comparison, the hardest material (Trackless) had an upper limit of tracking temperature of between 70°C and 76°C, a difference of approximately 30°C.
- Based on the LWT, the proposed lower limit for $G^*/\sin(\delta)$ of the emulsion residue to limit tracking is 10-18 kPa at the design pavement temperature at the time of construction. These limits need to be verified in the field, but provide a starting point for future investigation.
- Based on the data collected, all emulsions specified and commonly used in Wisconsin are expected to track during periods of high pavement temperature (Summer). Use of hard base ("h") emulsion will allow greater reliability against tracking, but will still track in the warmest periods. Trackless emulsions are a viable solution, however concerns regarding their field bonding performance in cooler climates have been expressed by the Project Oversight Committee.

4.1.3 Evaluation of Laboratory Shear Strength using ISS

- The shear strength of laboratory prepared specimens is primarily a function of surface texture and emulsion residue properties. The effect of surface texture, quantified using volumetric techniques, is pronounced and appears to dominate shear response in the laboratory. The effect of emulsion residue properties is less pronounced; considering only tack coat materials currently specified by WisDOT there is not a significant effect of emulsion type on shear strength.
- Within the range of residual asphalt rates used in this study, the change in ISS due to application rate is not practically significant and no clear trend between residual application rate and ISS is observed.
- Testing temperature is found to significantly affect ISS, with higher temperatures resulting in lower ISS; surface texture, however, is still found to dominate ISS at higher testing temperature.
- Samples prepared with no tack coat exhibited similar, and in some cases higher ISS values compared to those prepared with tack coat. This finding agrees with prior literature, and is hypothesized to be the result of surface texture and compaction methods on the laboratory. This is a critical challenge associated with using the ISS in the laboratory to determine optimal application rates and emulsion types.
- Accounting for test method variability, all of the combinations of surface texture and emulsions tested during this study achieved ISS values of 100 psi or greater in the laboratory. Proposed limits in the literature vary between approximately 40 psi and 100 psi. This finding may suggest that a laboratory to field shift factor needs to be applied if evaluating ISS on laboratory compacted specimens.

4.2 Validation of Laboratory ISS using Field Cores

- There is not a clear relationship in ISS between field and laboratory prepared samples even when the same materials are used for both samples; if bond strength needs to be tested or verified in the field, cores must be taken.
- Field cores taken from various projects throughout the State of Wisconsin show that for un-milled surfaces, the ISS values of field cores are significantly lower than the ISS of laboratory compacted specimens. For the milled surface the ISS of the lab and field were found to be similar, although ratio between lab and field was inconsistent. It should be noted that residual application rate and surface texture were not measured and/or verified in the field portion of this study.
- Within the range of application rates reported, ISS is not significantly affected by application rate for nearly all of the combinations tested. If the NCHRP 09-40 recommended minimum ISS of 40 psi is considered, all combinations tested during this study except one met this requirement. The combination that did not meet the 40 psi minimum was found to be compromised (see below).

- Emulsion type is not found to significantly affect ISS for most combinations, although for this data set significant differences between the two emulsions were not expected as explained in earlier sections.
- There is evidence that poor construction practice can significantly reduce the ISS in the field, as evidenced by one sample which exhibited a reduction in ISS of over 50% relative to the next lowest value. After testing this sample, it was noted that the existing surface exhibited incomplete tack coat coverage and significant surface dust was present. This finding highlights the need for a clean surface and uniform coverage.
- Assuming existing surfaces in the field are clean and substantially dust-free, two prevailing theories explaining the lab-to-field shift are offered. Laboratory testing of laboratory-prepared, laboratory-cored specimens showed that coring can have a negative impact on ISS, with a reduction in ISS of approximately 25% noted in this study. The second cause of lower ISS values in the field is hypothesized to be a result of the difference in compaction method and effectiveness between the laboratory and field. Compaction in the laboratory is 100% confined and pore structure at the layer interface may be substantially different than what is observed in the field.

4.3 Recommendations for WisDOT Standard Specifications, Construction Materials Manual, and Facilities Development Manual regarding tack coat usage in Wisconsin

The final objective of this project is to develop recommendations for WisDOT Standard Specifications, Construction Materials Manual, and Facilities Development Manual regarding tack coat usage and best-practices. This section includes general commentary on specific sections of these manuals in Table 17 based on the conclusions drawn from this study.

Table 18. Commentary and Recommendations for WisDOT Standard Specifications, Construction Materials Manual, and Facilities Development Manual.

Comment Number	Relevant Section	Item	Commentary/Recommendations
Facilities Development Manual			
1	FDM 14-10-5 Section 5.12 Tack Coats	“The rate of application is provided in standard spec 455.3.2. Use the lower rates if tack coat will be placed over previously placed lower layers and use the higher application rates if placing over milled HMA, pulverized HMA, concrete or rubblized concrete, etc.”	Based on the limited data presented in this study, there is no justification for changing the application rate based on the surface type; however, there is evidence to suggest inadequate coverage can lead to low ISS values; therefore, it is suggested to use an application no less than that required to achieve uniform coverage. Using a higher rate will reliably ensure uniform coverage while not reducing ISS. Literature also shows that a higher rate can reduce risk of debonding/slippage.

Construction and Materials Manual			
2	4-54.6.2.1 General	"The surfaces to which the tack coat is to be applied must be clean and dry."	There is evidence that non-uniform coverage and/ or tack applied to dusty/dirty surfaces can reduce ISS significantly.
3	4-54.6.2.1 General	"The surface may be pre-wetted prior to applying tack coat material, though no standing water is permitted."	Dilution of tack is shown to significantly delay curing. Literature indicates that pre-wetting of the surface to a "damp" condition may result in a similar phenomenon (NAPA, 2013); light pre-wetting to aid in tack uniformity may not cause significant curing delays.
4	4-54.6.2.1 General	"Care must be taken that the water from the emulsion has evaporated before paving... Otherwise the resultant water vapor may inhibit the bond…and contribute to premature pavement failure."	This statement is not supported by the literature review conducted as part of this project and is the concept of spray-pavers. However, tracking will be a major concern if the tack coat is not allowed to dry before paving.
5	4-54.6.2.2 Distributor	"The spraying pattern should be checked regularly for full and even coverage."	See Comment 1 and 2
6	4-54.6.2.3 Asphaltic Material	"The asphaltic material shall be MS-2, SS-1, SS-1h, CSS-1, or CSS-1h emulsified asphalt unless otherwise specified in the contract."	All materials specified and commonly used in Wisconsin exhibited similar drying rates and did not result in significantly different ISS values. If tracking is to be reduced, use of hard-base emulsions ('h' grades) is recommended during all seasons; however, the data suggests that these emulsions will still tack in summer months or during periods of higher pavement temperature.
7	4-54.6.2.5 Rate	"A suggested initial application rate is 0.05 gal/SY on new surfaces and 0.07 gal/SY on older or milled surfaces."	See Comment 1 and 2
Standard Specification for Construction			
8	455.2.5 Tack Coat	"Under the Tack Coat bid item, furnish type MS-2, SS-1, SS-1h, CSS-1, CSS-1h, QS-1, QS-1h, CQS-1, CQS-1h, or modified emulsified asphalt..."	See Comment 6
9	455.3.2.1 General	"… ensure that the surface is reasonably free of loose dirt, dust, or other foreign matter."	See Comment 2 and 3
10	455.3.2.1 General	"The contractor may, with the engineer's approval, dilute tack material ... Provide calculations … to show that as-placed material has 50 percent or more residual asphalt content. Apply at 0.050 to 0.070 gallons per square yard, after dilution.... The engineer may adjust the application rate based on surface"	See Comment 2 and 3
11	455.3.2.3 Preparing the existing surface	"Immediately before applying tack material, sweep existing surfaces to remove dust, dirt, or other objectionable material."	See Comment 2 and 3

5. References

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6. Appendix A: Emulsion Certificates for Laboratory Study

sphalt Technologies GROUP

Modified Asphalt Research Center

UW Madison **CSS-1**

Certificate of Analysis

AASHTO M208 / ASTM D2397 Specification

July 30, 2018

ATG Sample #: 400-762

Pass / Fail

Production Date: 07/25/18

Testing Date: 07/26/18

PROPERTY		AASHTO / ASTM TEST METHOD	SPECIFICATIONS	RESULTS
Emulsified Asphalt				
Saybolt Furol Viscosity	25.0 °C	T59 / D7496	20 - 100	25.3 seconds
Storage Stability, 24 hour	-----	T59 / D6930	1.0 max	0.3 %
Particle Charge Test	-----	T59 / D7402	positive	positive
Sieve	-----	T59 / D6933	0.10 max	0.00 %
Cement Mixing Test	-----	T59 / D6935	2.0 max	0.0 %
Distillation, % Residue	260 °C	T59 / D6997	57 min	61.1 %
Distillation Residue				
Penetration, 100 g, 5 seconds	25.0 °C	T49 / D5	90 - 250	104 dmm
Ductility, 5 cm/minute	25.0 °C	T51 / D113	40 min	40+ cm
Ash Content	-----	T111	1 max	0.0 %

Page 1 of 1

These results are believed to be true and accurate to the best of my knowledge.
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Asphalt Technologies GROUP

Modified Asphalt Research Center
UW Madison **CSS-1h**

Certificate of Analysis
AASHTO M208 / ASTM D2397 Specification

May 24, 2018

ATG Sample #: 400-734 **Production Date: 05/15/18**
Pass / Fail **Testing Date: 05/18/18**

PROPERTY		AASHTO / ASTM TEST METHOD	SPECIFICATIONS	RESULTS
Emulsified Asphalt				
Saybolt Furol Viscosity	25.0 °C	T59 / D7496	20 - 100	30.9 seconds
Storage Stability, 24 hour	-----	T59 / D6930	1.0 max	0.0 %
Particle Charge Test	-----	T59 / D7402	positive	positive
Sieve	-----	T59 / D6933	0.10 max	0.01 %
Cement Mixing Test	-----	T59 / D6935	2.0 max	0.0 %
Distillation, % Residue	204 °C	T59 / D6997	57 min	61.7 %
Distillation Residue				
Penetration, 100 g, 5 seconds	25.0 °C	T49 / D5	40 - 90	79 dmm
Ductility, 5 cm/minute	25.0 °C	T51 / D113	40 min	40+ cm
Ash Content	-----	T111	1 max	----- %

Page 1 of 1

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Asphalt Technologies GROUP

Modified Asphalt Research Center

UW Madison **CRS-1**

Certificate of Analysis

AASHTO M208 / ASTM D2397 Specification

July 30, 2018

ATG Sample #: 400-760

Pass / Fail

Production Date: 07/20/18
Testing Date: 07/23/18

PROPERTY		AASHTO / ASTM TEST METHOD	SPECIFICATIONS	RESULTS
Emulsified Asphalt				
Saybolt Furol Viscosity	50.0 °C	T59 / D7496	20 - 100	64.5 seconds
Storage Stability, 24 hour	-----	T59 / D6930	1.0 max	0.0 %
Demulsibility, 35 mL 0.8% Dioctyl Sodium Sulfosuccinate	-----	T59 /D6936	40 min	57.2 %
Particle Charge Test	-----	T59 / D7402	positive	positive
Sieve	-----	T59 / D6933	0.10 max	0.00 %
Distillation, % Residue	260 °C	T59 / D6997	60 min	66.0 %
% Oil			3 min	0.5 %
Distillation Residue				
Penetration, 100 g, 5 seconds	25.0 °C	T49 / D5	90 - 150	105 dmm
Ductility, 5 cm/minute	25.0 °C	T51 / D113	40 min	40+ cm
Ash Content	-----	T111	1 max	0.1 %

Page 1 of 1

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Asphalt Technologies GROUP

Modified Asphalt Research Center
UW Madison **CSS-1hL**

Certificate of Analysis
AASHTO M316 (CQS-1hP)
Polymer-Modified Emulsified Asphalt Used for MicroSurfacing

May 24, 2018

ATG Sample #: 400-736 **Production Date: 05/15/18**
Testing Date: 05/17/18

Pass / Fail

PROPERTY		AASHTO / ASTM TEST METHOD	SPECIFICATIONS	RESULTS
Emulsified Asphalt				
Saybolt Furol Viscosity	25.0 °C	T59 / D7496	20 - 100	39.9 seconds
Particle Charge Test	-----	T59 / D7402	positive	positive
Sieve	-----	T59 / D6933	0.10 max	0.00 %
Distillation, % Residue	204 °C	T59 / D6997	62 min	66.7 %
Distillation Residue				
Penetration, 100 g, 5 seconds	25.0 °C	T49 / D5	40 - 90	57 dmm
Elastic Recovery, pull 20 cm, hold 5 minutes	10.0 °C	T301 / D6084	50 min	52.5 %
Softening Point, Ring and Ball	-----	T53 / D36	57 min	61 °C
Ash Content	-----	T111	1 max	----- %

Page 1 of 1

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Asphalt Technologies GROUP

Modified Asphalt Research Center
UW Madison **CQS-1h**

Certificate of Analysis

AASHTO M208 / ASTM D2397 Specification

May 24, 2018

ATG Sample #: 400-735 **Production Date: 05/15/18**
Pass / Fail (Pass circled) **Testing Date: 05/17/18**

PROPERTY		AASHTO / ASTM TEST METHOD	SPECIFICATIONS	RESULTS
Emulsified Asphalt				
Saybolt Furol Viscosity	25.0 °C	T59 / D7496	20 - 100	51.9 seconds
Particle Charge Test	-----	T59 / D7402	positive	positive
Sieve	-----	T59 / D6933	0.10 max	0.00 %
Distillation, % Residue	204 °C	T59 / D6997	62 min	64.9 %
Distillation Residue				
Penetration, 100 g, 5 seconds	25.0 °C	T49 / D5	40 - 90	77 dmm
Ductility, 5 cm/minute	25.0 °C	T51 / D113	40 min	40+ cm
Ash Content	-----	T111	1 max	----- %

Page 1 of 1

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7. Appendix B: Example Field Report for Validation Study

SITE INFORMATION

Location:	SS1	I 39 Widening @ Newville Rd		GPS Coord	42°47'48" N, 89°00'15"W
Section:	1 of 2		Date:	Time:	6:25 AM
Traffic Level	Closed to Traffic		Closest weather station	Milton, WI	
Air Temp.	55 F		Residual Rate	0.011 Gal/sqyd	Humidity 97%
Emusion Source	Tri-State Asphalt	Emulsion Type SS 1H 80-20	Application Rate	.025 Gal/sqyd	Emulsion Temp. 140
Contractor	Rock Roads		Supervisor	Steve Bloedow	

Pavement Condition prior to Tack Coat application

Cleaningness (presence of dust, water or other deleterious material) Material is clean and dry. Very little to no dust or dirt from tires

1. New surface	Yes	No
2. Old surface milled	Yes	No
3. Old milled surface condition		

General Appearance (alligator cracks, dry, flush, rut depth, raveling, patches etc..) Attach pictures

Surface Preparation Procedure: N/A

NMAS of existing mix: 2 HT (25mm NMAS)

Overlay Information

Plant Type: Counter Flow Dual Drum	NMAS 4HT (12.5 NMAS)	RAP Content 30%
Overlay Thickness 2.5"	Number of lanes 2	Design Air void Content 3%
Compaction Temp. 280 F	Paver Type CAT AP1000	Compactor Type: Sakai SW 800 Sakai SW 880HV

General Comments	Dilution rate 51% direction of Tack application North. 14' lanes. Sample collected 228' North from pavement break, 7' East of inside pvmt edge.