Determining Bond Strength of Micro-surfacing Mixes

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16. Abstract

This report summarizes Phase 1 research work that was completed to document the current state-of-the-practice for using tack coat with micro-surfacing projects by state and provincial transportation agencies, summarize studies on the evaluation of bond strength between micro-surfacing mixes and existing pavement surface, and identify available tests that are used for measuring the interface bond strength to determine the most appropriate one to use in micro-surfacing applications. A national survey of transportation agencies was conducted to collect information from those agencies on using tack coat for micro-surfacing applications. The survey results indicated that there is no consensus among responding transportation agencies about the importance of using tack coat for micro-surfacing applications. Most agencies that use tack coat with micro-surfacing believe that it is critical for providing adequate bonding with the underlying surface, while the majority of the agencies that do not use tack coat believe that it is not needed, as adequate bonding can be provided by the emulsion in the micro-surfacing mix. However, some agencies that stopped using tack coat with micro-surfacing (such as Indiana DOT and Michigan DOT) have noted some debonding issues and decided or are considering adding a requirement for tack coat usage. The survey results also indicated that none of the responding agencies are performing field tests to evaluate the bonding strength of micro-surfacing mixes.

The results of the literature review conducted in Phase 1 of this project indicated that achieving adequate bonding between the micro-surfacing mix and the existing pavement is important to ensure full load transfer between the micro-surfacing layer(s) and the existing pavement. In addition, some studies suggested that the agencies that do not require using tack coat with micro-surfacing assume that the consistency of the micro-surfacing mix permits it to be evenly spread over the pavement surface, forming an adequate bond to the surface. The literature review was used to identify several candidate tests for the evaluation of the bond strength of micro-surfacing mixes.

Based on the results of Phase 1 it was recommended that the testing matrix for Phase 2 include the following variables: Existing surface conditions, micro-surfacing mix type, micro-surfacing mix residual binder content, tack coat application rate, and tack coat material type. It was also recommended that the variables be evaluated through a field-testing program. Furthermore, it was recommended to consider two types of field bond strength tests for Phase 2: pull-off and torque bonding tests.

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Executive Summary

This report summarizes Phase 1 research work that was completed to: (1) document the current state-of-the-practice for using tack coat with micro-surfacing projects by state and provincial transportation agencies in the United States and Canada, (2) summarize studies on the evaluation of bond strength between micro-surfacing mixes and existing pavement surface, and (3) identify available tests that are used for measuring the interface bond strength to determine the most appropriate one for use in micro-surfacing applications, and (4) develop a testing matrix for Phase 2 to improve the current practices for using tack coat for micro-surfacing applications. To achieve the first objective, a national survey of transportation agencies was conducted to collect information on using tack coat for micro-surfacing applications. The results of this survey indicated that ODOT and ten other transportation agencies responded to the national survey are currently using tack coat on all surfaces with micro-surfacing. In addition, ten agencies indicated using tack coat on some but not all surfaces with micro-surfacing, such as concrete surfaces or surfaces that are heavily raveled or oxidized. Finally, 18 agencies indicated that they do not use tack with micro-surfacing application. The survey results indicated that there is no consensus among responding transportation agencies about the importance of using tack coat for micro-surfacing applications. Most agencies that use tack coat with micro-surfacing believe that it is critical for providing adequate bonding with the underlying surface, while the majority of the agencies that do not use tack coat believe that it is not needed, as adequate bonding can be provided by the emulsion in the micro-surfacing mix. However, some agencies that stopped using tack coat with micro-surfacing (such as Indiana DOT and Michigan DOT) have noted some debonding issues and decided or are considering adding a requirement for tack coat usage. The survey results also indicated that none of the responding agencies are performing field tests to evaluate the bonding strength of micro-surfacing mixes. Furthermore, four agencies indicated that they do perform tests to evaluate bonding strength between asphalt layers. The used tests included either a pull-off test on milled surfaces (Kansas) or a direct shear bond test (Tennessee, Texas, and West Virginia).

The results of the literature review conducted in Phase 1 of this project indicated that achieving adequate bonding between the micro-surfacing mix and the existing pavement is important to ensure full load transfer between the micro-surfacing layer(s) and the existing pavement. In addition, some studies suggested that agencies that do not require using a tack coat with micro-surfacing assume that the consistency of the micro-surfacing mix permits it to be evenly spread over the pavement surface; forming an adequate bond to the surface. The results of the literature review also showed that the optimum tack coat for micro-surfacing applications also depends on the existing pavement surface type, texture, and condition. The testing modes that have been utilized to characterize the bond strength are: direct shear, direct tension, torque and flexural bending. Currently, the testing modes that have been used by state DOTs for measuring the bond strength between asphalt layers are direct shear and direct tension. Although direct shear tests have been commonly used by many state DOTs to evaluate bonding between asphalt layers, these tests are very difficult to conduct on thin lifts such as micro-surfacing and cannot be conducted in the field as they require a loading frame. The literature review was used to identify several candidate tests for the evaluation of the bond strength of micro-surfacing mixes.

Based on the results of Phase 1, it was recommended that the testing matrix for Phase 2 include the following variables:

1. Existing surface conditions:
   - Old: existing surfaces with different raveling and aging levels
   - New: Between micro-surfacing leveling course and micro-surfacing surface course
2. Micro-surfacing mix type:
   - Leveling course mix
   - Surface course mix
3. Micro-surfacing mix residual binder content
   - Typical residual binder content used by ODOT
   - 0.5-0.75% higher/lower than the typical asphalt emulsion content used. The highest/ lowest asphalt emulsion content values will be determined based on the results of lab tests.
4. Tack coat application rate:
   - 0 (no tack coat)
   - 0.03 gallons per square yard (diluted)
   - 0.06 gallons per square yard (diluted)
   - 0.1 gallons per square yard (diluted)
5. Tack coat material type:
   - CSS-1hm (same as the emulsion used in micro-surfacing mix)
   - SS-1h/CSS-1h

It was also recommended that the variables be evaluated through a field-testing program, which include two projects: one that uses only micro-surfacing surface course; and another that utilizes leveling and surfacing micro-surfacing layers. It was also recommended to consider two types of field bonding strength tests for Phase 2: pull-off and torque bonding tests. These tests cover the two main modes of interface bond failure observed in the field: tension (separation) and shear. Two candidate pull-off tests, namely, Com-Ten and Proceq DY 206, were recommended to be used in Phase 2. A torque bonding strength test device was also recommend to be developed and used in Phase 2 to evaluate the shear interface bond strength.

1. Project Background

Micro-surfacing has been widely used by several transportation agencies including the Ohio Department of Transportation (ODOT) as a preventive maintenance treatment in order to extend the service life of a pavement structure. The mixture used for micro-surfacing consists of a polymer-modified asphalt emulsion, aggregates, mineral fillers, water, and additives (Gransberg, 2010). A specialized equipment is used to produce the micro-surfacing mix, which is placed on a continuous basis by mixing the different constituents simultaneously in a pug mill. No compaction is typically required, and the finished surface is generally open to traffic soon after placement. The specifications for micro-surfacing are documented in ODOT Construction and Material Specifications (C&MS) Item 421. The current specifications require placing a tack coat on the existing pavement surface prior to the application of the micro-surfacing mix in order to improve the bond strength along the interface between the two materials. The tack coat shall consist of one part asphalt emulsion and three parts water and be applied at a rate of 0.06 to 0.12 gallon per square yard (0.25 to 0.45 L/m^2).

The International Slurry Surfacing Association (ISSA) suggests that tack coat is not needed for micro-surfacing applications unless the existing asphalt pavement surface to be treated is extremely dry and raveled or the existing pavement is surfaced with concrete or brick (International Slurry Surfacing Association, 2010). Some industry professionals also argue that using tack coat in micro-surfacing applications is not necessary to provide an adequate bond at the interface and that if used it may cause flushing in the newly placed micro-surfacing mix. However, the risk of not using a tack coat may include premature failure due to poor bonding between the micro-surfacing mix and the pre-existing pavement surface. Therefore, research is needed to evaluate the bond strength between micro-surfacing mixes and existing pavement surfaces with and without the application of tack coat in order to determine if tack coat is needed in micro-surfacing applications. In addition, there is a need to evaluate the impact of the tack coat materials, application rates, micro-surfacing mix properties, and pavement surface condition on the interface bond strength.

ODOT does not currently have a standard test method to measure the interface bond strength for asphaltic materials. However, a recently completed ODOT research project proposed a standard test procedure for evaluating the interface bond strength between asphalt layers. The proposed test procedure in that project uses direct shear mode. While this test could be useful for measuring the interface bond strength between asphalt surface and intermediate courses, it may not be applicable for evaluation of the interface bond strength between micro-surfacing mixes and treated pavement surfaces due to the relatively small thickness used in micro-surfacing and the properties of micro-surfacing mixes.

This objective of this project is to determine the bond strength between micro-surfacing mixes and existing asphalt surfaces with and without tack coat. In addition, it will also examine the effects of tack coat material type, and application rate as well as micro-surfacing mix type (leveling course and surface course), and existing surface type and condition (on existing pavement or on micro-surfacing leveling course) on the bond strength. This project will also identify and develop a bond strength test procedure to be used for field micro-surfacing mixes or lab-prepared specimens. The outcome of this project is anticipated to improve the performance of micro-surfacing applications and reduce the life cycle cost of pavements treated with micro-surfacing. If the outcome of this project suggests that tack coat is not needed for micro-surfacing applications, ODOT could save approximately $900,000 a year as close to 9 million square yards of micro-surfacing were during the 2017 construction season and the cost for the tack coat for micro-surfacing projects was about $0.10 per square yard.

2. Research Context

The main objective of this project is to evaluate and improve the current practice for using tack coat in micro-surfacing applications. Specific objectives of this project include:

- Determine the benefits and drawbacks of using tack coat in micro-surfacing applications.
- Identify the tack coat application rate that will result in the optimum interface bond strength and better long-term performance for micro-surfacing applications using SS-1h and other possible tack coat materials.
- Develop a standard test procedure and sample preparation technique for measuring the interface bond strength for micro-surfacing applications after construction.
- Develop a long-term monitoring plan to be used by ODOT in evaluating the performance of micro-surfacing applications.
- Evaluate the cost-effectiveness of using different tack coat materials and application rates with different micro-surfacing mixes on different types of pavement surfaces.

Phase 1 of this study included conducting the following tasks to achieve the outlined objectives:

Task 1. Document Experience and Practice in using Tack Coats with Micro-Surfacing
Task 2. Conduct Literature Review
Task 3. Compare the Outcome of Tasks 1 and 2 to ODOT's Current Practice
Task 4. Develop a Testing Matrix to be used in the Evaluation in Phase 2
Task 5. Prepare Interim Report and Present Findings

A summary of the comprehensive literature review performed in this study is presented in Appendix C. The results of previous studies indicated there is no consensus regarding the use of tack coat prior to applying micro surfacing treated to pavements. In addition, no previous research has been conducted to evaluate the interface bond strength between micro-surfacing mixes and existing pavement surfaces. Therefore, currently there is a need to examine this bond strength and identify factors that affect it. Several test methods and equipment have been proposed in the past and used to measure the interface bond strength between asphalt layers. Pull-off and torque type of tests have been used to evaluate the bond strength between surface treatments and existing pavement layers. However, the ability of those test methods for evaluating the bonding strength of micro-surfacing mixes was not examined in previous studies.

3. Research Approach

The following subsections summarize the research approach that was followed in this study.

3.1 Literature Review

A comprehensive literature review of pertinent studies on the evaluation of the bond strength between micro-surfacing mixes and existing pavement surface was conducted. The literature review covered: 1-construction and mix-related factors that affect the performance of micro-surfacing; 2- failure mechanisms due to poor bonding between micro-surfacing and existing pavement surfaces; 3- factors that influence the bond strength between micro-surfacing mixes and existing pavement surfaces, including tack coat material, application rate, properties of the micro-surfacing mix and the condition of the existing surface; 4- the test methods and equipment that can been utilized to evaluate the performance of tack coat materials as well as the interface bond strength between micro-surfacing mixes and the existing pavement surface; 5- micro-surfacing mix design procedure; and 6- quality control/quality assurance practices for micro-surfacing projects.

The results of the comprehensive literature review conducted in this conducted indicated that delamination is one of the main distresses in micro-surfacing projects. Delamination may be a subsequent distress to either fatigue cracking or slippage. It is mainly caused by the poor bonding between the micro-surfacing mix and the existing pavement surface. The results of previous studies suggested that bonding of a pavement micro-surfacing layer may be directly related to tack coat practices. Currently, there is no consensus regarding the use of tack coat prior to applying micro-surfacing treated to pavements. While some DOTs apply tack coat prior to the placement of the micro-surface mix to ensure a good bond between the micro-surface mix and the existing pavement surface, other DOTs do not require the use of tack coat with micro-surfacing. The states that do not require using tack coat with micro-surfacing assume that the consistency of the micro-surfacing mix permits it to be evenly spread over the pavement surface, forming an adequate bond to the surface. The micro-surfacing mixture can be also designed to ensure that the emulsion will wet the existing pavement surface to create the required bond (Gransberg, 2010). However, no research has been conducted to evaluate and verify that adequate interface bond strength is achieved when no tack coat is used.

The selection of an optimum tack application rate may also be critical for achieving a proper interface bond between the micro-surfacing mix and the underlying surface. An insufficient tack coat application rate may cause debonding, leading to various pavement distresses. On the other hand, excessive amounts of tack coat may result in slippage at the interface, which may lead to cracking and new mix flushing. Tack coats are typically installed at a specific application rate, which is different than the residual application rate. The tack coat application rate is the amount of diluted asphalt (asphalt and water) applied in the field, while the residual application rate is the amount of asphalt residue remaining after the water evaporates. ODOT requires that tack coat applied prior to micro-surfacing should consist of one part asphalt emulsion and three parts water and be applied at a rate of 0.06 to 0.12 gallon per square yard. NCHRP Synthesis 411 (Gransberg, 2010) indicated that the tack coat application rate specified for micro-surfacing applications by different transportation agencies ranged from 0.05 gallon per square yard to 0.25 gallon per square yard diluted with one part water to one part asphalt emulsion. ISSA also suggests applying tack coat at a rate of 0.05 to 0.10 gallon per square yard for micro-surfacing applications using a standard distributor (ISSA, 2010). The optimum tack coat application rate to be used during construction also depends on the existing pavement surface type, texture, and condition. In general, lower application rates can be used on new asphalt layers or asphalt surfaces in good condition, while higher application rates might be needed for old, oxidized, cracked, pocked, or milled asphalt surfaces as well as tined concrete surfaces (Mohammad et al., 2012). Some transportation agencies such as Caltrans do not require the use of a tack coat prior micro-surfacing unless the existing pavement surface is extremely dry and raveled or is surfaced with concrete (California DOT, 2009).

The type of tack coat material may also affect the micro-surfacing mix bond strength. Currently, asphalt emulsions are the most widely used tack coat material for micro-surfacing applications (Gransberg, 2010). An asphalt emulsion consists of an asphalt binder mixed with water and an emulsifying agent. There are several types of emulsions that have been used as tack coats including slow set, medium set, rapid set, and quick set emulsions (with and without polymer modification). The ISSA recommends using CSS-1h as a tack coat with micro-surfacing (ISSA, 2010). However, some state transportation agencies, including ODOT, utilize the same emulsion used in the micro-surfacing mix for tack coat.

Different testing modes that have been utilized to characterize the bond strength between asphalt layers: direct shear, direct tension, torque and flexural bending. Although direct shear tests have been extensively used by many state DOTs, including ODOT, to evaluate bonding between asphalt layers, these tests are very difficult to conduct in thin lifts, which is the case in micro-surfacing, and it cannot be conducted in the field as it requires a loading frame. Two direct tension (pull-off) tests, namely, the Com-Ten tester and the Proceq DY-206 tester, have been successfully used (Mealiff et al., 2017; Estakhri et al., 2015) to evaluate the bonding strength between asphalt layers. In addition, a field torque testing device was developed as part of a study funded by Texas DOT to evaluate the adhesion of surface treatment to primed and unprimed base layers (Freeman et al., 2010). The literature review results also indicated that ISSA A143 is the most popular method for designing micro-surfacing mixes.

Based on the review of DOTs materials and construction manuals, it was found that several DOTs have QC/QA specifications for micro-surfacing; these included: Indiana, Maine, Michigan, Minnesota, Missouri, Tennessee West Virginia, California, and Florida. Field sampling of the micro-surfacing mix is required as part of the QC/QA used by most of those agencies. The testing of the QC/QA samples primarily includes examining the aggregate gradation, quantifying the amount of fine dust and clay-like particles, as well as determining the residual asphalt binder content in the micro-surfacing mix.

3.2 Current Practices for Using Tack Coats with Micro-Surfacing

A national survey was conducted in this study to document the current state-of-the-practice for using tack coat with micro-surfacing projects by state and provincial transportation agencies in the United States (US) and Canada. A draft survey questionnaire was prepared by the research team and sent to ODOT Technical Advisory Committee (TAC) of this project for review at the beginning of September 2017. Modifications were made and some questions were added/deleted based on comments received from the advisory committee. The revised survey was implemented in SurveyMonkey (a copy of the survey is provided in Appendix A) for distribution to the other departments of transportation. The survey questionnaires were sent on September 21, 2017, and the due date for completing the survey was October 20, 2017.

The micro-surfacing survey questionnaire included a total of 32 questions organized into nine sections. In the first section, department of transportation personnel were asked to provide their contact information to be used for follow-up purposes if needed. In the second section, respondents were asked how often micro-surfacing is used by their agency. For agencies not using micro-surfacing, the respondent was directed to the end of the survey and was not required to answer the remaining questions. For agencies that do use micro-surfacing, the survey proceeded to the next section, which collected information about typical micro-surfacing applications, traffic level for roads where micro-surfacing is used, and whether tack coat is used or not with micro-surfacing. In the fourth section, information was collected about the type of tack coat(s) used with micro-surfacing, as well as the application rate and dilution rate for the tack coat. The section that followed collected information about mix design of micro-surfacing mixes. Information was collected in the sixth and seventh sections about construction and quality control/quality assurance practices for micro-surfacing. Various questions were included in the eighth section regarding the performance of micro-surfacing applications and the typical distresses observed with micro-surfacing. In the final section, respondents were asked to comment on their overall experience with using tack coat for micro-surfacing and discuss the reasons why they did or did not use tack coat with micro-surfacing. The respondents were also asked for permission to be contacted in the future with follow-up questions or requests for additional information.

3.3 Comparison to Current ODOT Practice

Current ODOT practices regarding the use of tack coat with micro-surfacing and relevant construction and material specifications were compared to those used by other transportation agencies. This included examining the differences in micro-surfacing mix design limits between ODOT and other transportation agencies and exploring the effect of changing the mix design limits on the interface bond strength. It noted that this comparison was included in the summary of responses to micro-surfacing questionnaire appendix (Appendix B) and the literature review appendix (Appendix C). A comprehensive evaluation of available bond strength tests was performed to determine the most appropriate one for use in micro-surfacing applications. Special consideration was given to the testing mode used in each test and the applicability of the testing mode to micro-surfacing applications. The failure mechanism in micro-surfacing applications was considered in the recommendation of the interface bond strength test methods.

3.4 Develop a Testing Matrix to be used in the Evaluation in Phase 2

The information collected and analyzed in Phase 1 was used to identify factors that need to be included in the testing matrix for Phase 2 of this project to improve the current practices for using tack coat in micro-surfacing project. In addition, candidate testing devices that can be used to measure bond strength between micro-surfacing and existing pavement surface were identified and recommended to be evaluated in Phase 2. Consultation with ODOT technical liaisons guided the final selection of the testing matrix and bond strength test(s)/method(s). The potential cost benefits were considered in the selection of the various factors that will be included in the testing matrix.

4. Research Findings and Conclusions

Appendices B and C present a detailed summary of responses to the national survey, and outcome of literature review conducted in Phase 1 of this study, respectively. Below is a summary of the main findings of Phase 1 of the study:

4.1 National Survey

- Majority of surveyed agencies reported that they use micro-surfacing for roads with moderate traffic levels (ADT between 5,000 and 20,000). ODOT currently uses micro-surfacing for all traffic levels.
- ODOT and ten other transportation agencies responding to the national survey indicated using tack coat on all surfaces with micro-surfacing. In addition, ten agencies indicated using tack coat on some but not all surfaces with micro-surfacing, such as concrete surfaces or surfaces that are heavily raveled or oxidized. Finally, 18 agencies indicated that they do not use tack with micro-surfacing application.
- Asphalt emulsions most frequently used with micro-surfacing mixes are CQS-1hM and CSS-1hM. CSS-1hM is the asphalt emulsion used in micro-surfacing mixes in Ohio.
- The majority of the surveyed agencies reported using a residual asphalt emulsion contents that range between 6.5% to 9% in micro-surfacing mixes; with 8% being the most common. Several agencies indicated using around 8% residual asphalt emulsion in the micro-surfacing mix. The residual asphalt emulsion content in ODOT specifications ranges between 7% and 8.5% for leveling and surface courses micro-surfacing mixes and between 6.5% and 8% for rut filling micro-surfacing mixes.
- Thirty two agencies indicated that the quality of the micro-surface mix is monitored during construction by visual inspection (cure time and smoothness) and mix design verification (aggregate gradation, residual asphalt content, aggregate properties, emulsion properties, aggregate moisture content). Currently, ODOT does not monitor the quality of the micro-surface mix during construction.
- None of the responding agencies indicated using field tests to evaluate the bonding strength of micro-surfacing mixes.
- Only four agencies indicated that they do perform field tests to evaluate bonding strength between traditional asphalt layers. The used tests included either a pull-off test on milled surfaces (Kansas) or a direct shear bond test (Tennessee, Texas, and West Virginia).
- While the majority of transportation agencies indicated that the expected service life for micro-surfacing is 6 to 8 years, ODOT reported as part of survey conducted in this study an expected service life of more than 8 years.
- The majority of transportation agencies indicated crack reflection as the most common distress observed in micro-surfacing projects. More than a quarter of the respondents indicated that raveling, debonding and streaking as other distresses commonly observed in micro-surfacing projects. Other types of distresses that were reported by some agencies include: corrugation, bleeding, debonding when tack coat was used, roughness, wearing through the wheel path, moisture-related issues, cracking, and rutting. Micro-surfacing distresses observed by ODOT include crack reflection, raveling, and debonding (in applications where tack coat was used).
- There is no consensus among responding transportation agencies about the importance of using tack coat for micro-surfacing applications. Most agencies that use tack coat with micro-surfacing believe that it is critical for providing adequate bonding with the underlying surface.

On the contrary, the majority of the agencies that do not use tack coat believe that it is not needed, as adequate bonding can be provided by the emulsion in the micro-surfacing mix. However, some agencies that stopped using tack coat with micro-surfacing (such as agencies in Indiana and Michigan) have noted some debonding issues and decided or are considering adding a requirement for tack coat.

- Several responding transportation agencies mentioned the importance of removing pavement markings prior to micro-surfacing as well as identifying the optimal timing for micro-surfacing.

4.2 Literature Review

- Achieving adequate bonding between the micro-surfacing mix and existing pavement is important to ensure full load transfer between the micro-surfacing layer(s) and the existing pavement.
- There are two modes of failure due to poor bonding between asphalt layers: shear and tension.
- States that do not require the use of tack coat with micro-surfacing assume that the consistency of micro-surfacing mix permits it to be evenly spread over the pavement surface, forming an adequate bond to the surface. The micro-surfacing mixture can be also designed to ensure that the emulsion wets the existing pavement surface to create the required bond.
- ODOT requires that tack coats applied prior to micro-surfacing should consist of one part asphalt emulsion and three parts water and be applied at a rate of 0.06 to 0.12 gallon per square yard. According to previous studies, the tack coat application rate specified for micro-surfacing applications by different transportation agencies ranged from 0.05 gallon per square yard to 0.25 gallon per square yard diluted with one part water to one part asphalt emulsion. The ISSA also suggests applying tack coat at a rate of 0.05 to 0.10 gallon per square yard diluted with one part asphalt emulsion to three parts water for micro-surfacing applications using a standard distributor.
- The optimum tack coat application rate for micro-surfacing applications depends on existing pavement surface type, texture, and condition. In general, lower application rates can be used on new asphalt layers or asphalt surfaces in good condition, while higher application rates might be needed for old, oxidized, cracked, pocked, or milled asphalt surfaces as well as tined concrete surfaces.
- The testing modes that have been utilized to characterize the bond strength are: direct shear, direct tension, torque and flexural bending. Currently, the testing modes that have been used by state DOTs for measuring the bond strength between asphalt layers are the direct shear and direct tension.
- Although direct shear tests have been used by many state DOTs including ODOT to evaluate bonding between asphalt layers, these tests are very difficult to conduct on thin lifts such as micro-surfacing and cannot be conducted in the field as they require a loading frame.
- Two pull-off tests that have been used in previous studies for evaluation of bond strength between asphalt layers are Com-Ten tester and Proceq DY-206 tester. While Com-Ten tester is strain controlled test, the Proceq DY-206 tester is load controlled test. Table 1 summarizes the pros and cons of these devices.
- A field torque testing device was developed by TxDOT to evaluate the adhesion between surface treatments to primed and unprimed base layers. Table 1 presents the pros and cons of this field torque testing device.

Table 1. Pros and Cons of Candidate Bonding Strength Tests

Test	Pros	Cons
Proceq DY-206 Pull-Off Test	• Positive experience was reported in previous studies. • Can be used in the field and lab • Inexpensive (<$10k) • Commercially available • Previous studies used ASTM C 1583 to conduct this test	• Cannot control failure location • No standard procedure to evaluate the bonding strength between asphalt layers • Does not capture mechanical component of bonding between layers. Thus, less sensitive to existing pavement conditions • Bonding energy cannot be calculated
Com-Ten Pull-Off Test	• Positive experience was reported in previous studies. • KS DOT has a standard procedure for this test • Can be used in the field and lab • Inexpensive (<$10k) • Commercially available • KS DOT has established an acceptance criteria • Bonding energy can be calculated	• Cannot control failure location • Does not capture the mechanical component of bonding between layers. Thus, less sensitive to existing pavement conditions
Texas Field Torque Test	• Measure shear bonding strength • Can be used in the field • Successfully used in a previous study • Can capture the mechanical component of bonding between layers. Thus, it is sensitive to existing pavement conditions	• Not available commercially • Not an absolute engineering measurement • Was not used to evaluate bonding strength between asphalt layers • Standard method has to be developed

5. Recommendations for Implementation

Based on the results of Phase 1 it is recommended that the testing matrix for Phase 2 include the following variables:

1. Existing surface conditions:
   - Leveling course mix
   - Surface course mix
2. Micro-surfacing mix emulsion content:
   - Typical residual binder content used by ODOT

- 0.5-0.75% higher/lower than the typical asphalt emulsion content used. The highest/ lowest asphalt emulsion content values will be determined based on the results of lab tests.

3. Tack coat application rate:
   - 0 (no tack coat)
   - 0.03 gallons per square yard (diluted)
   - 0.06 gallons per square yard (diluted)
   - 0.1 gallons per square yard (diluted)
4. Tack coat material type:
   - CSS-1hM (same as the emulsion used in micro-surfacing mix)
   - SS-1h/CSS-1h

The variables should be evaluated through a field-testing program, which will include two projects: one that uses only micro-surfacing surface course; and another that utilizes leveling and surfacing micro-surfacing layers. Tables 2 and Table 3 present the proposed testing plan for two projects. As shown in Table 2, the first project will include 12 test sections. These sections will be used to evaluate the effects of tack coat type, tack coat application rate, micro-surfacing mix residual binder content, and existing pavement surface conditions on bonding between the micro-surfacing surface course and the existing pavement. As shown in Table 3, the second project will include a total of 21 test sections; 12 sections on existing pavement surface and 9 test sections on new leveling course. The test sections on existing pavement surface will be used to evaluate the effect of tack coat type, tack coat application rate, micro-surfacing mix residual binder content, and existing pavement surface conditions on the bonding between micro-surfacing leveling course and existing pavement. In addition, test sections on the new leveling course will be used to evaluate effect of tack coat type and tack coat application rate on the bonding between micro-surfacing surface and leveling courses. In order to evaluate the effect of the pavement surface conditions, the two projects should be selected such that it will have sections with similar existing structural capacity but with different surface texture and condition. The circular track meter (ASTM E2157) (available at the ODOT office of Materials Management) and the Ames texture scanner (available at the ODOT office of technical services) can be used to measure the pavement surface texture in order to select the locations of the test sections.

It is recommended to consider two types of field bonding strength tests in Phase 2: pull-off and torque bonding tests. These tests cover the two main modes of bond failure observed in the field: tension (separation) and shear. Two candidate pull-off tests, Com-Ten and Proceq DY-206, are recommended to be used in Phase 2 to examine the aforementioned variables affecting the bond strength of micro-surfacing mixes. This will enable the research team to evaluate the viability of both devices and make final recommendations for their use by ODOT in the future. It is noted that Com-Ten pull-off test is displacement-controlled test while the Proceq DY-206 is load-controlled test. It is recommended that a torque bonding strength test device similar to the Texas torque tester be developed and used in Phase 2. Pull-off tests can examine the adhesion between the micro-surfacing mix and the underlying layer and to evaluate the susceptibility of the micro-surfacing mix to separate due tensile failure only. The torque tester should be used to evaluate the shear interfacial bond strength. In addition, pull-off tests do not evaluate the mechanical component of bonding strength between layers. Thus, the results of pull-off tests are less sensitive to the surface pavement frictional properties and conditions as compared to those of the torque test devise. It is estimated that the total cost of the parts and fabrication of the torque bond test device will be less than $10k. In addition, the research team should be able to design and fabricate the device within 2 months. It is recommended that all selected bonding strength tests be conducted directly after construction and at 2 and 12 months after construction.

Table 2. Proposed Testing Plan for Project 1-Single Course Micro-Surfacing

<table>
<tr><th>Tack Coat Material Type</th><th>Tack Coat Diluted Application Rate (g/sy)</th><th>Asphalt Emulsion Content of Micro-Surfacing Mix</th><th>Surface Condition</th></tr>
<tr><td>None</td><td>None</td><td>Typical Design</td><td rowspan="9">Typical aging and distresses</td></tr>
<tr><td>None</td><td>None</td><td>0.5-0.75% higher than typical design</td></tr>
<tr><td rowspan="4">Same as micro-surfacing mix (CSS-1hM)</td><td>0.03</td><td>0.5-0.75% higher than typical design</td></tr>
<tr><td>0.03</td><td rowspan="3">Typical Design</td></tr>
<tr><td>0.06</td></tr>
<tr><td>0.1</td></tr>
<tr><td rowspan="3">SS-1h/CSS-1h</td><td>0.1</td><td rowspan="3">Typical Design</td></tr>
<tr><td>0.06</td></tr>
<tr><td>0.03</td></tr>
<tr><td rowspan="3">Same as micro-surfacing mix (CSS-1hM)</td><td>0.03</td><td rowspan="3">Typical Design</td><td rowspan="3">Highly aged and distressed surface</td></tr>
<tr><td>0.1</td></tr>
<tr><td>0.06</td></tr>
</table>

Table 3. Proposed Testing Plan for Project 2-Leveling and Surface Course Micro-Surfacing

Sections on Existing Pavement Surface				**Sections on New Leveling Course***	
Tack Coat Material Type	Tack Coat Diluted Application Rate (g/sy)	Emulsion Content of Micro-Surfacing Mix	Surface Condition	Tack Coat Material Type	Tack Coat Diluted Application Rate (g/sy)
None	None	Typical Design	Typical aging and distress	None	None
None	None	0.5-0.75% higher than typical design		None	None
Same as micro-surfacing mix (CSS-1hM)	0.03	0.5-0.75% higher than typical design	Typical aging and distress	Same as micro-surfacing mx	0.03
	0.03	Typical Design			0.06
	0.06			None	None
	0.1				
SS1h/CSS-1h	0.1	Typical Design	Typical aging and distress	SS1h	0.06
	0.06	Typical Design			0.06
	0.03	Typical Design			0.03
Same as micro-surfacing mix	0.03	Typical Design	Highly aged and distressed	None	None
	0.06				
	0.1				

*Residual binder content in all surface course micro-surfacing mixes will be determined using the typical design method currently used.

6. References

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Appendix A Micro-surfacing Questionnaire

A national survey was conducted in this study to document the current state-of-the-practice for using tack coat with micro-surfacing projects by state and provincial transportation agencies in the United States (US) and Canada. A draft survey questionnaire was prepared by the research team and sent to ODOT Technical Advisory Committee (TAC) of this project for review at the beginning of September of 2017. Modifications were made and some questions were added/deleted based on comments received from the advisory committee. The revised survey was implemented in SurveyMonkey (a copy of the survey is provided below) for distribution to the other departments of transportation. The survey invitations were sent on September 21, 2017, and the due date for completing the survey was October 20, 2017.

The micro-surfacing survey questionnaire included a total of 32 questions organized into nine sections. In the first section, department of transportation personnel were asked to provide their contact information to be used for follow-up purposes if needed. In the second section, respondents were asked how often micro-surfacing is used by their agency. For agencies not using micro-surfacing, that was the end of the survey and the respondent was not required to answer the remaining questions. For agencies that do use micro-surfacing, the survey proceeded to the next section, which collected information about typical micro-surfacing applications, traffic level for roads where micro-surfacing is used, and whether tack coat is used or not with micro-surfacing. In the fourth section, information was collected about the type of tack coat(s) used with micro-surfacing, as well as the application rate and dilution rate for the tack coat. The section that followed collected information about mix design of micro-surfacing mixes, including mix tests, aggregate gradation, type of asphalt emulsion, asphalt emulsion modification, residual asphalt emulsion content, as well as the type of mineral fillers and additives used in the micro-surfacing mix. Information was collected in the sixth and seventh sections about construction and quality control/quality assurance practices for micro-surfacing. Various questions were included in the eighth section regarding the performance of micro-surfacing applications and the typical distresses observed with micro-surfacing. The respondents were also asked if they had encountered any performance issues (such as debonding) related to the use (or lack of use) of tack coat with micro-surfacing. In the final section, respondents were asked to comment on their overall experience with using tack coat for micro-surfacing and discuss the reasons why they did or did not use tack coat with micro-surfacing. The respondents were also asked for permission to be contacted in the future with follow-up questions or requests for additional information.

Determining Bond Strength of Micro-surfacing Mixes (Ohio Department of Transportation Research Study)

Ohio Department of Transportation

Contact Information

* 1. Please provide your contact information:

Name	
Title	
Agency	
State	-- select state --
Email Address	
Phone Number	

1

Determining Bond Strength of Micro-surfacing Mixes (Ohio Department of Transportation Research Study)

Use of Micro-surfacing

This survey is conducted as part of a study funded by the Ohio Department of Transportation to document current experience and practices in using tack coat in micro-surfacing applications. In this survey, micro-surfacing is defined as a cold-laid polymer-modified emulsified asphalt pavement course that is used to fill ruts, improve surface friction, or provide a leveling course or a surface course for existing pavements. If you have any question about the survey, please contact the principal investigator of this research study, Dr. Munir Nazzal, by email at nazzal@ohio.edu or by phone at 740-593-1080.

* 2. How often is micro-surfacing used by your agency?

- ◯ Not used
- ◯ Rarely
- ◯ Often
- ◯ Extensively

2

Determining Bond Strength of Micro-surfacing Mixes (Ohio Department of Transportation Research Study)

Ohio Department of Transportation

General Information

* 3. What are the most common applications for micro-surfacing in your state (check all that apply)?

- ☐ Rut filling
- ☐ Leveling course
- ☐ Surface wearing course
- ☐ Other. Please specify:

4. What is the typical Average Daily Traffic (ADT) for the roads where micro-surfacing is used (check all that apply)?

- ☐ ADT < 5,000 (< 500,000 ESALs)
- ☐ 5,000 < ADT < 20,000 (500,000 ESALs to 7 million ESALs)
- ☐ ADT > 20,000 (> 7 million ESALs)

* 5. Is tack coat required for micro-surfacing applications in your state?

- ◯ No (tack coat is not required for micro-surfacing)
- ◯ Yes (tack coat is always used with micro-surfacing)
- ◯ Yes (under certain conditions, e.g., on concrete surfaces). Please elaborate:

3

Tack Coat for Micro-surfacing

* 6. For micro-surfacing applications, what type of asphalt binder/emulsion is typically used for the tack coat?

* 7. For micro-surfacing applications, what tack coat application rate is specified?

* 8. For micro-surfacing applications, if tack coat dilution is allowed, what dilution rate is required?

Determining Bond Strength of Micro-surfacing Mixes
(Ohio Department of Transportation Research Study)

Micro-surfacing Mix Design

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* 9. Which of the following micro-surfacing mix design tests are specified by your agency (check all that apply)?

- [ ] None
- [ ] Wet track abrasion loss (1 hour) (ISSA TB 100)
- [ ] Wet track abrasion loss (six day soak) (ISSA TB 100)
- [ ] Excess asphalt by loaded wheel test (ISSA TB 109)
- [ ] Mix time @ 77F (ISSA TB 113)
- [ ] Mix time @ 100F (ISSA TB 113)
- [ ] Wet stripping (ISSA TB 114)
- [ ] Wet cohesion at 30 min (ISSA TB 139)
- [ ] Wet cohesion at 60 min (ISSA TB 139)
- [ ] Saturated abrasion compatibility (ISSA TB 144)
- [ ] Classification compatibility (ISSA TB 144)
- [ ] Vertical displacement (ISSA TB 147)
- [ ] Lateral displacement (ISSA TB 147)
- [ ] Specific gravity (ISSA TB 147)
- [ ] Modified Marshall stability (ISSA TB 148)
- [ ] Modified Marshall flow (ISSA TB 148)
- [ ] TTI mixing test
- [ ] Modified cup flow test
- [ ] Other. Please specify:

* 10. Which of the following aggregate gradations are used with micro-surfacing mixes (check all that apply)?

- [ ] Type II (Refer to Table 1 in ASTM D3910 Below)
- [ ] Type III (Refer to Table 1 in ASTM D3910 Below)
- [ ] Other. Please specify:

Table 1: Grading Requirements for Aggregates (ASTM D3910)

Sieve Size	Amount Passing Sieve, weight %		
	Type I	Type II	Type III
⅜ in. (9.5 mm)	100	100	100
No. 4 (4.75 mm)	100	90 to 100	70 to 90
No. 8 (2.36 mm)	90 to 100	65 to 90	45 to 70
No. 16 (1.18 mm)	65 to 90	45 to 70	28 to 50
No. 30 (600 µm)	40 to 60	30 to 50	19 to 34
No. 50 (300 µm)	25 to 42	18 to 30	12 to 25
No. 100 (150 µm)	15 to 30	10 to 21	7 to 18
No. 200 (75µ m)	10 to 20	5 to 15	5 to 15

* 11. Which of the following emulsions (M for Modified) are used with micro-surfacing mixes (check all that apply)?

- [ ] SS-1M
- [ ] CSS-1M
- [ ] QS-1M
- [ ] CQS-1M
- [ ] SS-1hM
- [ ] CSS-1hM
- [ ] QS-1hM
- [ ] CQS-1hM
- [ ] Other. Please specify:

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* 12. Of the asphalt emulsions listed above, which one(s) is/are the most commonly used (check all that apply)?

- [ ] SS-1M
- [ ] CSS-1M
- [ ] QS-1M
- [ ] CQS-1M
- [ ] SS-1hM
- [ ] CSS-1hM
- [ ] QS-1hM
- [ ] CQS-1hM
- [ ] Other. Please specify:

13. Which modifier is specified for asphalt emulsions used in micro-surfacing mixes (check all that apply)?

- [ ] Styrene Butadiene Rubber (SBR)
- [ ] Other. Please specify:

8

* 14. What range of percent residual asphalt emulsion is specified for micro-surfacing mixes (in your construction and material specifications)?

Example: In Ohio, a residual asphalt emulsion content of 7.0% to 8.5% by dry weight of aggregates is specified for leveling and surface course micro-surfacing mixes and a residual asphalt emulsion content of 6.5% to 8.0% is specified for rut filling micro-surfacing mixes.

Please list separately if varies by application:

* 15. What is the typical percent residual asphalt that is used in micro-surfacing mix designs?

Example: In Ohio, the residual asphalt emulsion content that is used in mix designs for leveling and surface course micro-surfacing mixes generally ranges between 7.5% and 8.0%, and the residual asphalt emulsion content that is used in mix designs for rut filling micro-surfacing mixes generally ranges between 6.5% and 7.0%.

Please list separately if varies by application:

* 16. Which of the following mineral fillers are used by your agency with micro-surfacing mixes (check all that apply)?

- [ ] Type I Portland Cement
- [ ] Type II Portland Cement
- [ ] Hydrated Lime
- [ ] Other. Please specify:

17. Which of the following additives are used by your agency with micro-surfacing mixes(check all that apply)?

- [ ] None
- [ ] Aluminum sulfate crystals (dry additive)
- [ ] Ammonium sulfate (dry additive)
- [ ] Liquid aluminum sulfate (liquid additive)
- [ ] Amines (liquid additive)
- [ ] Other dry or liquid additives. Please specify:

Determining Bond Strength of Micro-surfacing Mixes
(Ohio Department of Transportation Research Study)

Construction

18. What type of equipment is specified in your state for micro-surfacing (check all that apply)?

☐ Continuous self-propelled (variable pump)

☐ Continuous self-propelled (fixed pump)

☐ Truck mounted

19. What type of rollers is specified for micro-surfacing by your agency (check all that apply)?

☐ No rollers used

☐ Vibratory

☐ Static steel

☐ Pneumatic tired

☐ Combination pneumatic/steel

* 20. Have you encountered any issues during construction related to the use (or lack of use) of tack coat with micro-surfacing?

◯ No

◯ Yes. Please provide more detail:

Determining Bond Strength of Micro-surfacing Mixes
(Ohio Department of Transportation Research Study)

QC/QA

21. Do you require the contractor to submit a QC plan?

- ◯ No
- ◯ Yes. Is the QC plan submitted on a project-by-project basis, annually, or both?

22. Do you monitor the quality of the micro-surfacing mixes during construction?

- ◯ No
- ◯ Yes. Please provide more detail:

*** 23. Do you perform any field tests to evaluate the quality of bonding between the micro-surfacing mix and the pre-existing pavement surface?**

- ◯ No
- ◯ Yes. Please provide more detail:

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* 24. For non-micro-surfacing projects, do you perform any field tests to evaluate the quality of bonding for tack coat at the interface between various asphalt courses?

- ◯ No
- ◯ Yes. Please provide more detail:

Determining Bond Strength of Micro-surfacing Mixes
(Ohio Department of Transportation Research Study)

Performance

25. What is the expected service life of micro-surfacing applications in your state?

- ◯ Less than 2 years
- ◯ 2 to 4 years
- ◯ 4 to 6 years
- ◯ 6 to 8 years
- ◯ More than 8 years

26. How would you rate the overall performance of micro-surfacing in your state?

- ◯ Unacceptable
- ◯ Poor
- ◯ Good
- ◯ Excellent

* 27. What distresses are typically observed with micro-surfacing in your state (check all that apply)?

- ☐ None
- ☐ Raveling
- ☐ Corrugation
- ☐ Streaking
- ☐ Bleeding
- ☐ Crack reflection
- ☐ Debonding (tack coat is used)
- ☐ Debonding (tack coat is not used)
- ☐ Other. Please specify:

* 28. Have you encountered any performance issues (such as debonding) related to the use (or lack of use) of tack coat with micro-surfacing?

- ◯ No
- ◯ Yes. Please elaborate:

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Determining Bond Strength of Micro-surfacing Mixes
(Ohio Department of Transportation Research Study)

Additional Information

29. Please comment on your experience with using tack coat for micro-surfacing (e.g., please comment on the reasons for using or not using tack coat with micro-surfacing):

30. Is there anything you would like to mention that was not covered in the questionnaire?

31. Please include links to relevant specifications to micro-surfacing:

* 32. If additional information is needed, do we have your permission to contact you in the future?

- ◯ Yes
- ◯ No

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Determining Bond Strength of Micro-surfacing Mixes
(Ohio Department of Transportation Research Study)

End of Survey

Thank you for your time and effort. If you have any question regarding the survey, please contact the principal investigator of this research study, Dr. Munir Nazzal, by email at nazzal@ohio.edu or by phone at 740-593-1080.

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Appendix B Summary of Responses to Micro-surfacing Questionnaire

The research team received a total of 57 responses to the micro-surfacing questionnaire. The survey respondents represented transportation agencies in 42 US states, the District of Colombia, and one Canadian province. These respondents came from a variety of backgrounds, including asphalt/material engineers, pavement design engineers, pavement management or maintenance engineers, and quality assurance/testing engineers. This appendix presents a summary of the responses for the various questions in the survey. It is noted that for some agencies, more than one respondent completed the survey; for these agencies, the research team combined the multiple responses into a single response to represent the state-of-the-practice in that agency. In addition, the research team reviewed the construction and material specifications for all agencies that reported using micro-surfacing in order to supplement the information collected from the survey.

Figures B.1 through B.19 and Tables B.1 through B.5 provide a summary of the responses to the survey questionnaire. These figures and tables are organized by topic and are presented in the same order as the questions listed in the survey. In each figure, the x-axis indicates a specific response to the question, while the y-axis indicates the percentage of respondents who chose the specific response. Labels on each bar indicate the exact percentage of respondents choosing a specific response and, in parentheses, the number of respondents that chose the specific response over the total number of agencies who responded to that question. A yellow star next to a response indicates ODOT's current practice, an orange star indicates that ODOT uses a modification of a particular specification, and a red star indicates that ODOT will adopt a certain specification in the near future.

B.1 General Questions

- Extent of use of micro-surfacing: The extent of use of micro-surfacing in transportation agencies is presented in Figure B.1. The survey provided four possible responses ("not used", "rarely", "often" or "extensively"). Each response is presented as a separate bar in the chart, and the height of the bar indicates the percentage of agencies selecting that response. As can be noticed from this figure, half of the transportation agencies that responded to the survey questionnaire reported using micro-surfacing "often" as is the case for ODOT. In addition, two out of 44 agencies (4.7%) (Kentucky and New York) reported using it "extensively," while 16 out of 44 (37.2%) reported that they "rarely" use micro-surfacing. Agencies in four states (Alaska, Maine, Oklahoma, and Washington State. Alaska, Maine, and Washington State) reported that they do not use this practice on roads in their jurisdiction, while Oklahoma reported that they only allow its use on shoulders.
- Micro-surfacing applications: In ODOT's current practice, micro-surfacing is used for rut filling, surface wearing courses, and providing a leveling course. Common applications reported by other agencies for micro-surfacing are presented in Figure B.2. As can be seen in this figure, micro-surfacing is reported to be used for providing a surface wearing course by 36 of the 39 agencies (92.3%) that responded to this question. A total of 25 agencies (64.1%) reported using it for rut filling, and 10 agencies (25.6%) reported that they use it for leveling courses. Eight agencies (20.5%) reported that they also use micro-surfacing for other

applications, including longitudinal joint sealing, filling in rumble strips, using it as a preventive maintenance practice, and using it to improve friction.

- Traffic level with micro-surfacing: ODOT currently uses micro-surfacing for all traffic levels. The survey results shown in Figure B.3 revealed that 25 out of 39 agencies (64.1%) indicated that their agencies use micro-surfacing for roads with average daily traffic (ADT) below 5,000. Thirty-two agencies (82.1%) reported that they use micro-surfacing for roads with moderate traffic levels (ADT between 5,000 and 20,000), while only 14 agencies (35.9%) use it on roads with high traffic levels (ADT greater than 20,000).

B.2 Tack Coat Questions

- Use of tack coat with micro-surfacing: When asked if tack coat is required by their agency for micro-surfacing applications, 18 out of 39 agencies (46.2%) indicated that no tack coat is required (Figure B.4). Eleven agencies (28.2%) reported that tack coat is always required with micro-surfacing, which is the current practice of ODOT. Ten agencies (25.6%) reported that tack coat is sometimes required under certain conditions, such as on concrete surfaces or on surfaces that are heavily raveled or oxidized.
- Tack coat information: Several survey questions prompted the respondents for more detailed information regarding the tack coats used by their agencies. Specific information from the responses for all agencies are listed in Table B.1. As can be noticed from this table, some agencies reported using standard tack coat materials with micro-surfacing applications as those used with traditional hot mix asphalt. Other agencies reported using specific tack coat emulsions, either the same emulsion as used in the micro-surfacing mix or a different one than used in the micro-surfacing mix. In Ohio, it was reported that most micro-surfacing contractors use CSS-1hM, which is the same emulsion specified for micro-surfacing mixes. As can be noticed from Table B.1, the tack coat application rate varied between 0.05 to 0.15 gallons per square yard. In contrast, a tack coat application rate of 0.06 to 0.12 gallons per square yard is specified in Ohio. The responses regarding tack coat dilution widely varied: some agencies allow no dilution, while others allow a 3:1 (water to emulsion) dilution, 2:1, or 1:1. Several state transportation agencies indicated that they use no dilution at the project site but allow dilution by the manufacturer. The tack coat dilution rate in Ohio is approximately 3 parts water to one part emulsion based on a minimum residual asphalt content of 15%.

B.3 Micro-surfacing Mix Design Questions

- Tests used in mix design of micro-surfacing mixtures: A total of 34 agencies provided the tests used for mix design of micro-surfacing mixes (Figure B.5). As can be noticed in this figure, the most commonly reported micro-surfacing mix tests were wet track abrasion loss (both one-hour and six-day soak), wet stripping, mix time at 77°F, wet cohesion (at 30 minutes and at 60 minutes), lateral displacement, classification compatibility, and specific gravity. ODOT is currently using most of these test and is planning to adopt the remaining tests with the exception of classification compatibility. Instead of the classification compatibility test, ODOT uses the saturated abrasion compatibility.
- Aggregate gradation: Of the 36 agencies that responded to this question, 26 (72.2%) reported using Type II aggregate gradation (as specified by ASTM D3910), while 27 agencies (75%)

reported using a Type III gradation (Figure B.6). Both of these gradations are used by ODOT. Only seven agencies (19.4%) reported using other state-specific aggregate gradations.

- Allowed and typical emulsions used in micro-surfacing mixes: As can be seen in Figures B.7 and B.8, the asphalt emulsions most frequently used with micro-surfacing mixes are CQS-1hM and CSS-1hM, followed by CQS-1M and CSS-1M. Emulsions infrequently used with micro-surfacing mixes included SS-1M, SS-1hM, and CSS-1mM.
- Residual asphalt emulsion content: A summary of responses regarding asphalt emulsion content in micro-surfacing mixes is presented in Table B.2. As can be noticed from this table, some agencies do not specify a range for asphalt emulsion content, while others specified a minimum residual emulsion (e.g., Kansas uses 8% minimum). Some agencies specify a narrow range for residual asphalt emulsion content (e.g., Montana uses a range of only 7.3% to 7.7%), while others specified a wide range (e.g., Iowa uses 6% to 12%). The specifications for residual asphalt emulsion content in Ohio ranges between 7% and 8.5% for leveling and surface courses and between 6.5% and 8% for rut filling. Regarding the typical range for residual asphalt emulsion, several agencies indicated using around 8%, with the majority of the responses falling in the range of 6.5% to 9%.
- Emulsion modification: A total of 28 agencies responded to the question about the type of modifier specified for use in asphalt emulsions with micro-surfacing mixes (Figure B.9). Of these, ten agencies (35.7%) indicated specifying the use of styrene butadiene rubber (SBR), as is the current practice by ODOT. A total of 22 agencies (78.6%) reported specifying a different modifier (e.g., latex or styrene butadiene styrene) or indicated that they do not specify which modifier to use.
- Mineral fillers: Agencies were asked which mineral fillers they use with micro-surfacing mixes (Figure B.10). Of the 36 agencies that responded to this question, 29 agencies (80.6%) indicated they use Type I Portland Cement, as is the current practice by ODOT. A total of 17 agencies (47.2%) indicated they use Type II Portland Cement, and 15 agencies (41.7%) reported using hydrated lime. Seven agencies (19.4%) reported using other mineral fillers, such as limestone dust, Type GU Portland cement, any non-air-entrained Portland cement, and any mineral filler conforming to ASTM D242.
- Additives: As shown in Figure B.11, 20 of the 30 agencies (66.7%) that responded to this question indicated that they do not require any additives to be used with micro-surfacing mixes. Six agencies (20.0%) also indicated that additives can be used as required to meet the mix performance tests. Only four agencies provided the type of additive that is typically used in their jurisdiction; one agency reported using liquid aluminum sulfate, two agencies – including ODOT – reported using liquid amines, and one agency reported using dry ammonium sulfate.

B.4 Quality Control and Monitoring during Construction Questions

- Quality control plan: As shown in Figure B.12, a total of 21 out of 36 agencies (58.3 %) indicated that they do not require contractors to submit a quality control plan, as is current ODOT practice. The remaining 15 agencies (41.7%) do require the submission of quality control plans. Of these, the quality control plan is submitted on a project-by-project basis (13), the quality control plan is set by the agency (1), or certification by the National Center for Pavement Preservation (NCPP) is required (1).

- Monitoring during construction: As shown in Figure B.13, a total of four out of 36 agencies (11.1%) indicated that they do not monitor quality of the micro-surface mixture during construction, as is the current practice by ODOT. The remaining 32 agencies (88.9%) indicated that the quality of the micro-surface mixture is monitored during construction by visual inspection (cure time and smoothness) and mix design verification (aggregate gradation, residual asphalt content, aggregate properties, emulsion properties, aggregate moisture content).
- Bonding test for micro-surfacing: Agencies were asked if they perform field tests to evaluate bonding between a micro-surfacing mix and the pre-existing pavement surface (Figure B.14). Based on the responses received from all agencies, no bonding test is currently specified for micro-surfacing, as is the current ODOT practice.
- Bonding test for hot mix asphalt (non-micro-surfacing projects): A total of 32 out of 36 agencies (88.9%) indicated that they do not perform any field tests to evaluate bonding for tack coat at the interface between various asphalt courses, as is the current practice by ODOT (Figure B.15). The remaining four agencies (11.1%) indicated that they do perform field tests, and these include either a pull-off test on milled surfaces (Kansas) or a test of shear strength of bonded layers (Tennessee, Texas, and West Virginia).

B.5 Overall Performance Questions

- Expected service life of micro-surfacing: When asked about the expected service life of micro-surfacing applications, the majority of agencies (23 out of 36 agencies, or 63.9%) indicated that they expect a service life of 6 to 8 years (Figure B.16). Eleven agencies (30.6%) expected a service life of 4 to 6 years, and one agency (2.8%) expected a service life of 2 to 4 years. One agency (ODOT) expected a service life of more than 8 years.
- Overall performance of micro-surfacing: When asked for an overall rating of micro-surfacing performance in their jurisdiction, the majority of the agencies (30 out of 36, or 83.3%), including ODOT, indicated "good" performance (Figure B.17). Three agencies (8.3%) rated the overall performance as "excellent", two agencies rated the overall performance as "poor", while one agency rated the overall performance as "unacceptable".
- Typical distresses for micro-surfacing: Distresses typically observed with micro-surfacing that were reported by the agencies surveyed are shown in Figure B.18. As can be noticed from this figure, the most common distress is crack reflection, which was reported by 29 out of 36 agencies (80.6%); followed by raveling and debonding (when no tack coat is used), which were both reported by 10 agencies (27.8%); and streaking, which was reported by 9 agencies (25%). Fewer agencies noted distresses such as corrugation (4), bleeding (6), or debonding when tack coat was used (7). Five agencies noted other distresses, which included roughness, wearing through the wheel path, moisture-related issues, cracking, and rutting. One agency reported observing no distresses. Micro-surfacing distresses observed by ODOT include crack reflection, raveling, and debonding (in applications where tack coat was used).
- Performance issues related to use (or lack of use) of tack coat with micro-surfacing: When asked if their agency had noted any performance issues related to the use (or lack of use) of tack coat with micro-surfacing (Figure B.19), 23 of 37 agencies (62.2%) reported that they did not encounter any issues. The remaining 14 agencies (37%) had encountered issues, and this

has been the experience of ODOT as well. Several agencies indicated that debonding might be a concern if no tack coat is used. A summary of the responses regarding performance issues observed by the responding agencies is presented in Table B.3.

- Experience with tack coat for micro-surfacing: Table B.4 provides a summary of the responses with regard to the overall experience with tack coat for micro-surfacing. As can be noticed from this table, there seems to be no agreement about the importance of using tack coat for micro-surfacing applications. Most agencies that use tack coat with micro-surfacing believe that it is critical for providing adequate bonding with the underlying surface, while the majority of the agencies that do not use tack coat believe that it is not needed, as adequate bonding can be provided by the emulsion in the micro-surfacing mix. However, some agencies that stopped using tack coat with micro-surfacing (such as agencies in Indiana and Michigan) have noted some debonding issues and decided or are considering adding a requirement for tack coat.

- Final comments: Final comments provided by the respondents are provided in Table B.5. As can be noticed from this table, respondents mentioned the importance of removing pavement markings prior to micro-surfacing and identifying the optimal timing for micro-surfacing, among other responses.

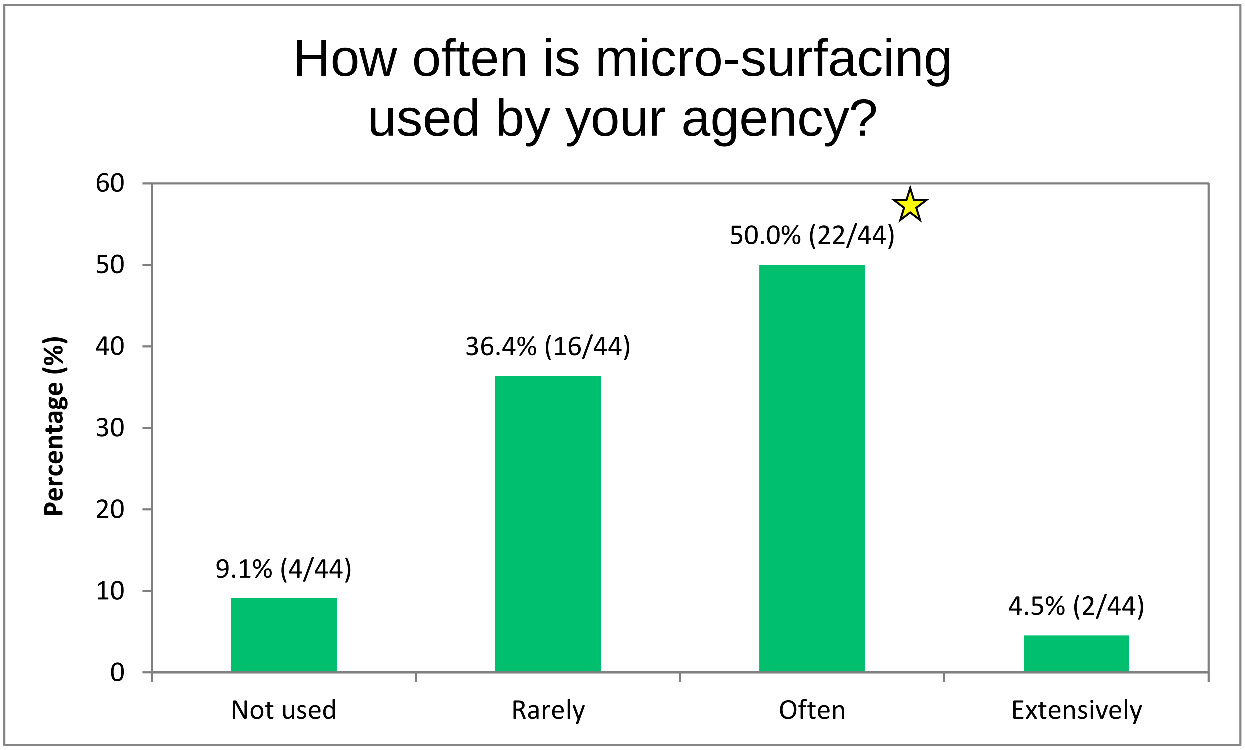


Figure B.1: Extent of use of micro-surfacing.

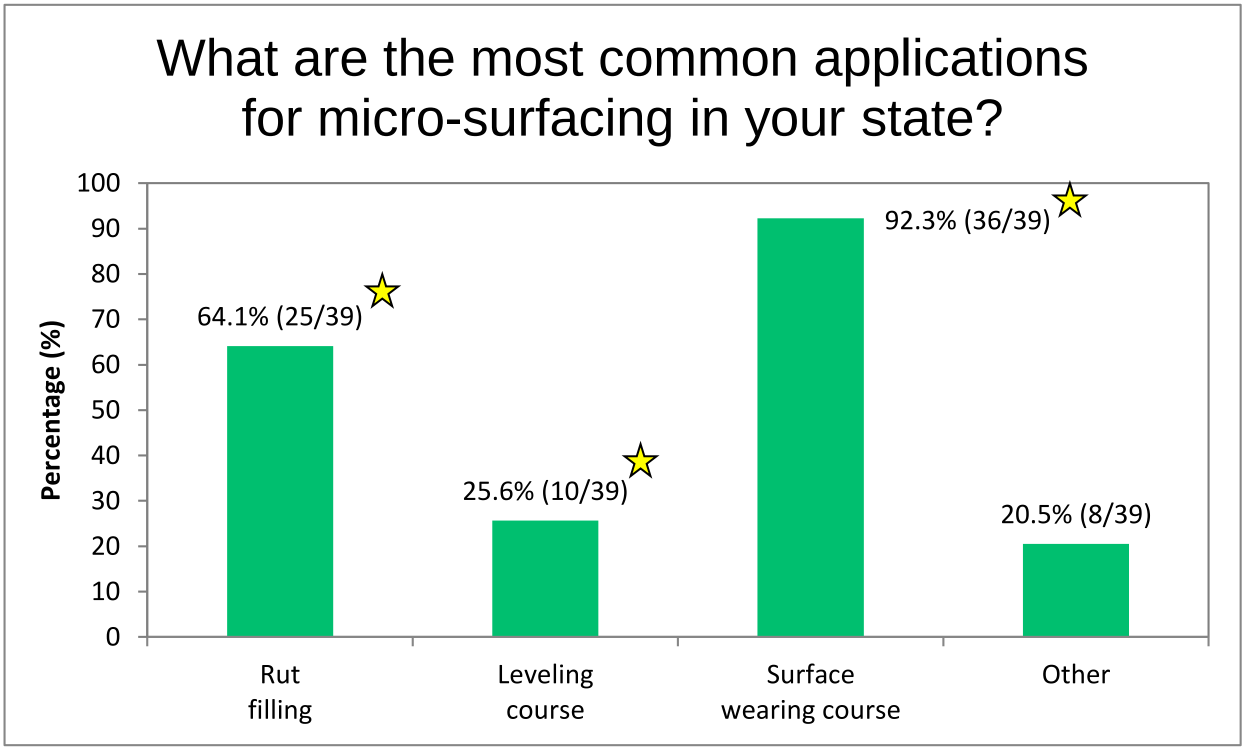


Figure B.2: Common applications of micro-surfacing.

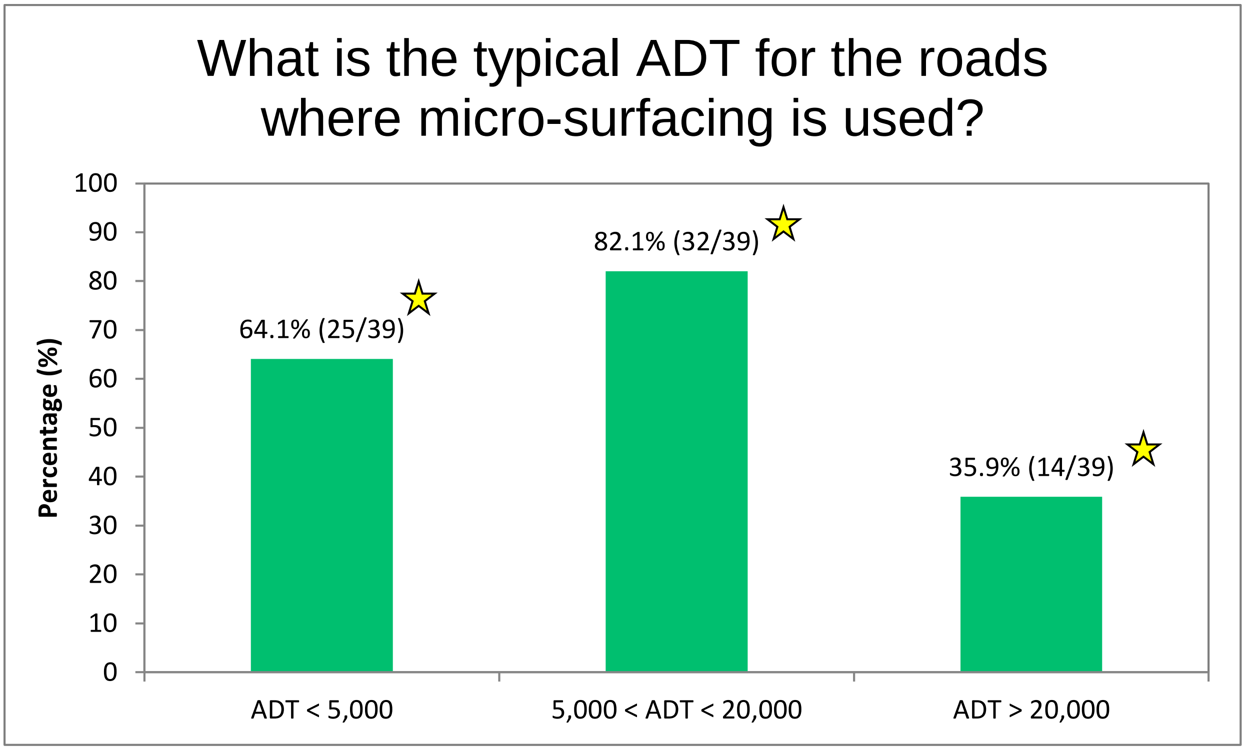


Figure B.3: Traffic levels for roads where micro-surfacing is used.

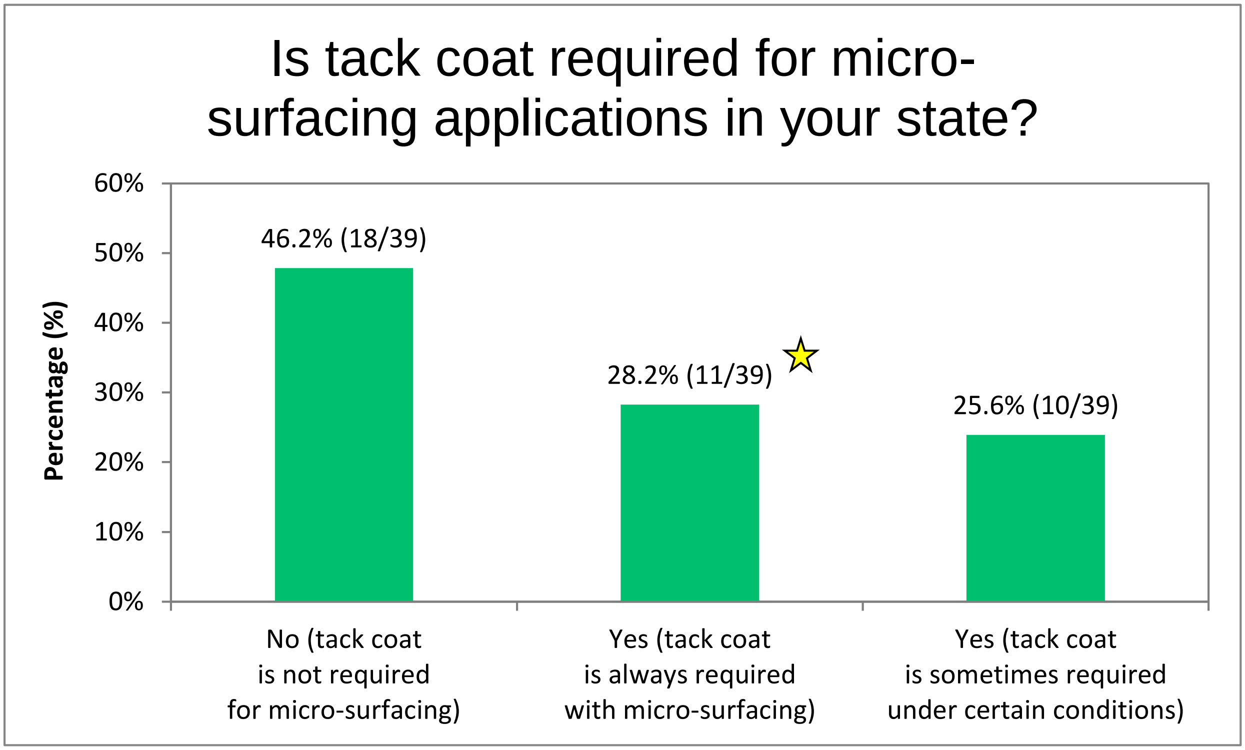


Figure B.4: Tack coat requirement for micro-surfacing applications.

Table B.1: Tack Coat Information.

State	Type of Asphalt Binder/Emulsion used for Tack Coat	Tack Coat Application Rate	Tack Coat Dilution
AR	Any standard emulsion	0.03 to 0.10 gallons per square yard	3:1 water to emulsion
CO	SS or CSS (CSS-1h is usually used)	0.1 gallons per square yard	50% dilution is required
DC	Trackless Tack SS-1 or SS-1h	0.01 to 0.05 gallons residual asphalt per square yard	3 parts emulsion to 1 part water by volume
DE	CSS-1h	0.1 gallons per square yard	60% emulsion
FL	SS, CSS, or the micro surfacing emulsified asphalt	0.05 to 0.15 gallons per square yard	One part emulsified asphalt to three parts water.
GA	CSS-1h or CQS-1h	0.05 to 0.10 gallons per square yard	No dilution on the project
KY	CSS-1h, SS-1h, CQS-1h	0.05 gallons per square yard	Our tack oils are about 67 to 28% in AC content depending upon applications
MD	Any emulsion type and grade that is compatible with the asphalt emulsion seal	0.05 to 0.10 gallons per square yard	one part asphalt emulsion to two or three parts water
MI	PG 64-22	0.035 to 0.070 gallons per square yard	One part emulsion to two parts water
MN	CSS-1 or CSS-1h	0.05 to 0.10 gallons per square yard	62% or greater residual after dilution required
MT	CQS-1hP	0.05 gallons per square yard	Not allowed
NC	CSS, CQS, or CRS	0.08 to 0.15 gallons per square yard	One part emulsified asphalt to two or three parts water, as approved by the Engineer
NH	CSS-1h	0.06 to 0.07 gallons per square yard	3:1 required

Table B.1: Tack Coat Information (Continued).

State	Type of Asphalt Binder/Emulsion used for Tack Coat	Tack Coat Application Rate	Tack Coat Dilution
NJ	CSS-1h	0.05 to 0.15 gallons per square yard	We do not allow any dilution of any of our emulsions
Ontario	CQS-1hP	Type II (low traffic volume) - 5 to 11 kg per square meter and Type III (high traffic volume) - 8 to 16 kg per square meter	1 part emulsion to 3 parts water by volume
OH	Most contractors will use the CSS-1hM emulsion used in the micro-surfacing mix	0.06 to 0.12 gallons per square yard	15% min residual, which is about 3 parts water to one part emulsion.
PA	SS-1h or CSS-1h materials are usually used but the specification is broad enough to allow other faster setting emulsions to be used	0.04 to 0.07 gallons residual asphalt per square yard	No dilution is allowed
SC	CSS-1	0.05 to 0.010 gallons per square yard	1:3
TN	SS-1h, CQS-1h, or CQS-1hP	0.10 to 0.15 gallons per square yard	50%
VA	CSS-1h	0.05 gallons per square yard	75% (water 3: asphalt 1)
WV	We require the tack emulsion to match the emulsion used in the micro-surfacing mix.	0.1 gallons per square yard	1:1, only at the manufacture

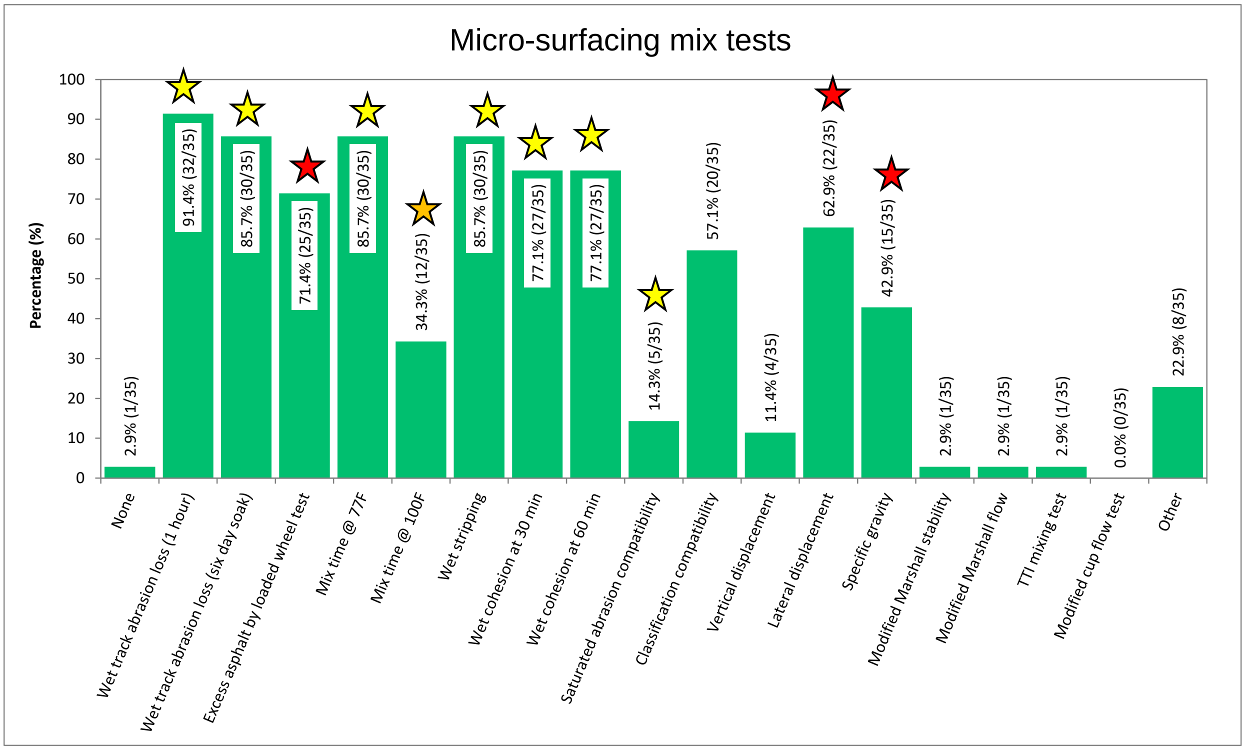


Figure B.5: Tests used for micro-surfacing mix design.

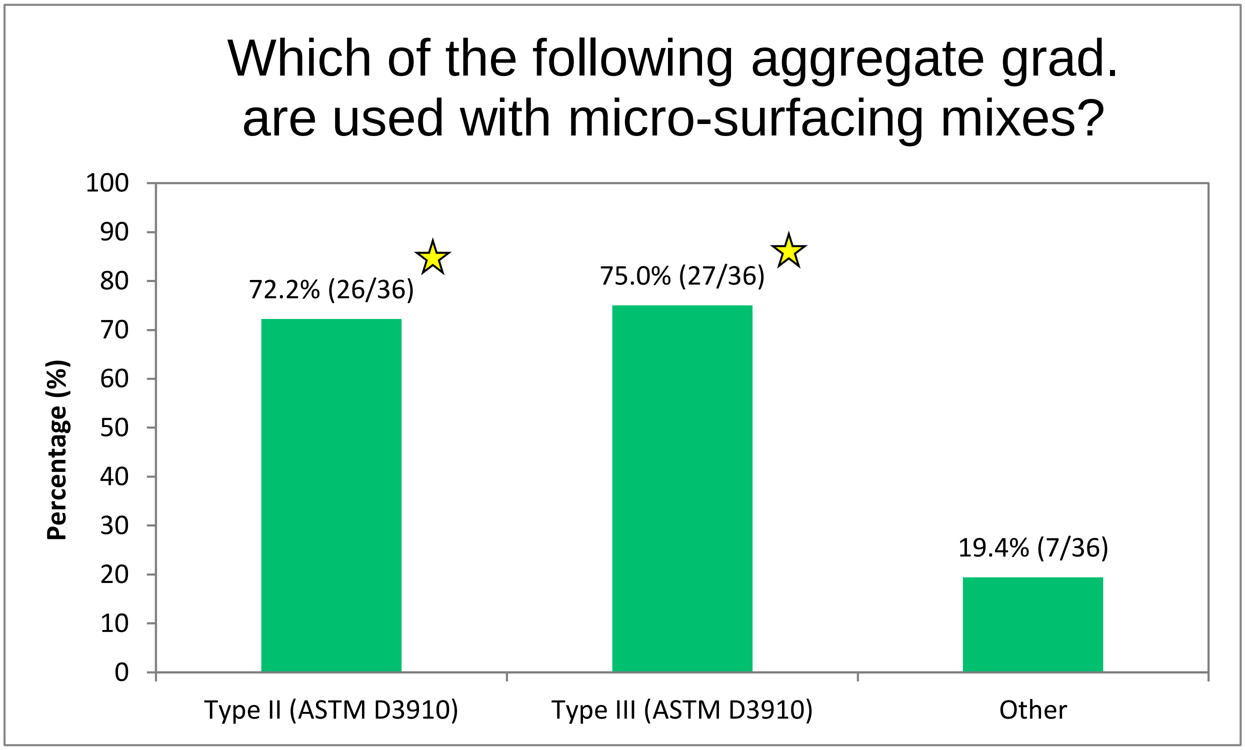


Figure B.6: Aggregate gradations for micro-surfacing mixes.

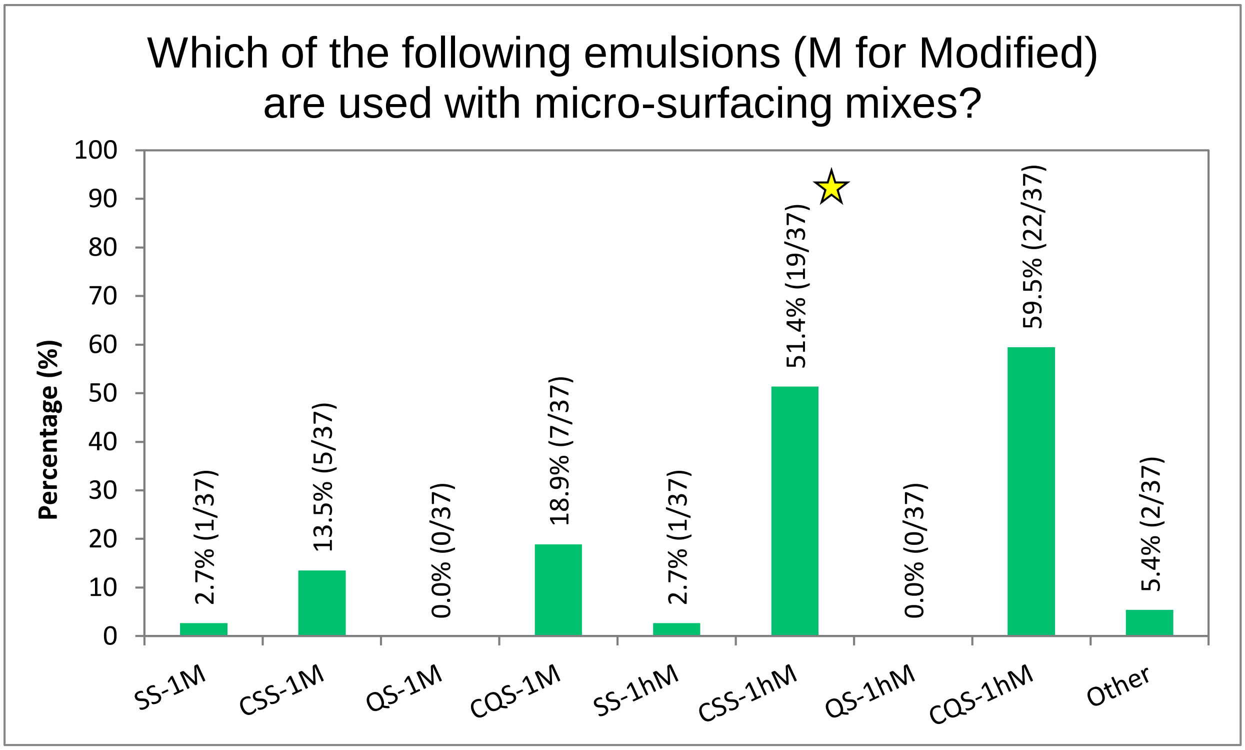


Figure B.7: Emulsions permitted with micro-surfacing mixes.

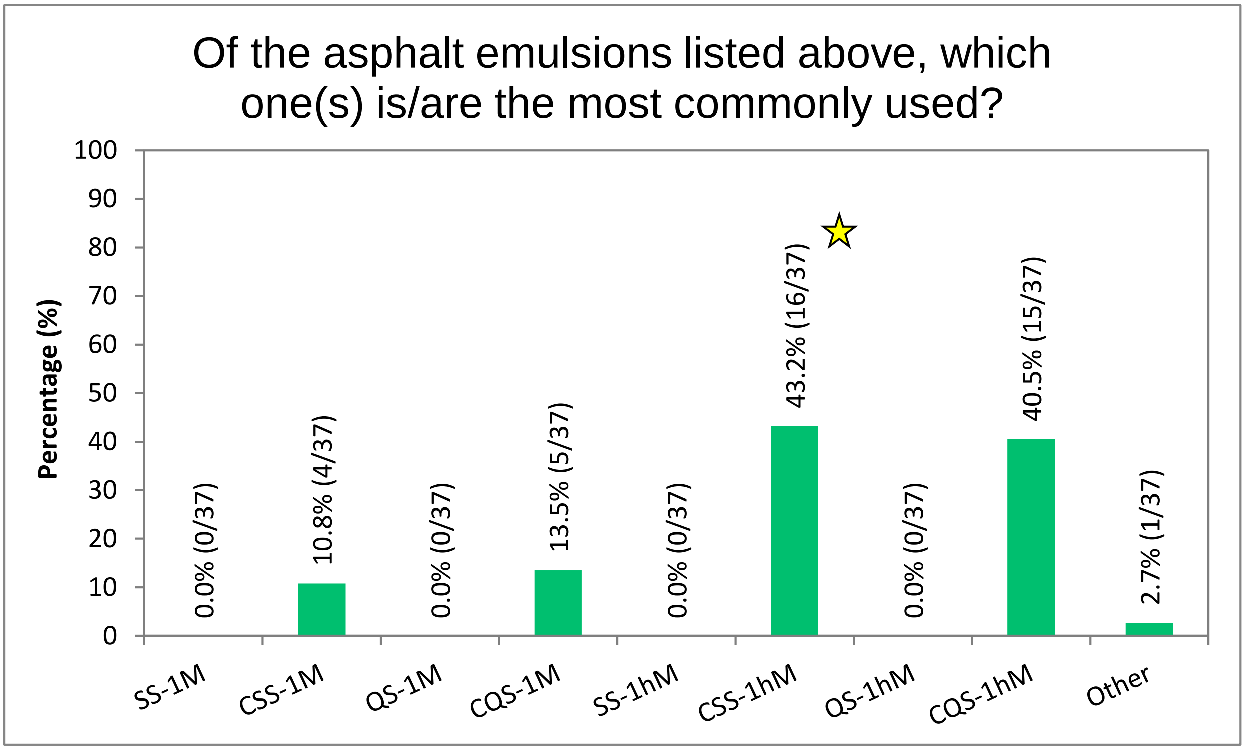


Figure B.8: Emulsions commonly used with micro-surfacing mixes.

Table B.2: Asphalt Emulsion Content in Micro-surfacing Mixes.

State	Specified Range for Residual Asphalt Emulsion	Typical Range for Residual Asphalt Emulsion
AL	Type II 6-10%, Type III 5-9%	Type II and Type III 8%
AR	6%-9%	We have just started using micro-surfacing, so we don't have any data for a typical rate.
AZ	6%-11.5%	8%
CO	No range is specified	The few micro-surfacing designs we have used have been around 8% residual asphalt (~13% CQS-1hP)
DE	11% but it depends on the aggregate. A test determines this ratio and is not fixed.	The same as above for all applications
FL	5.5%-10.5%	8.8%
GA	Type I 6%-9%, Type II 6%-9%	We have not used micro-surfacing for several years so I can not answer this question
IA	6%-12%	7%-9%
IL	5.5%-10.5%	Information unavailable
IN	No range is specified	7%-8.7%
KS	8% minimum	8%-8.5%
MD	5.5%-10.5%	I don't know
MI	7.0%-8.5% for 2FA aggregate, 6.5%-8.0% for 3FA aggregate, same as Ohio	Same as Ohio
MN	13%-16% emulsion	5.5%-10.5%
MO	5.5%-10.5%	6%-9%
MT	7.3%-7.7%	7.3%-7.7%
NC	Type II 7.5-13.5%, Type III 6.5-12%	Type II 6.7%-8%, Type III 8%-8.5%
ND	5.5%-10.5%	6.5%-10.5%
NH	No range is specified	8.1%-8.8%
NJ	5.5%-11.5%	5.5%-11.5%
NV	5.5%-9.5%	7.5%-8.5%
Ontario	6%-11.5%	Around 8%
NY	5.5%-10.5%	5.5%-10.5%

Table B.2: Asphalt Emulsion Content in Micro-surfacing Mixes (Continued).

State	Specified Range for Residual Asphalt Emulsion	Typical Range for Residual Asphalt Emulsion
OH	Leveling and surface course 7.0%-8.5%, rut filling 6.5%-8%	Leveling and surface course 7.5% and 8.2%, rut filling 6.5% and 7.0%
OR	5.5%-10.5%	Projects too rare to see a trend
PA	1/4 inch 6%-8.5%, 3/8 inch 5.5%-7.5%, rut filling 5.5%-7.5%	Not sure I understand the question.
SC	5%-10.5%	8%-8.5%
SD	5.5%-10.5%	8%-9%
TN	5%-9% for surface course	Approximately 8% based on the last few years designs
TX	6%-9%	6%-9%
UT	7% minimum	7.5%
VA	Type A & B 6.5-8.5%, Type C 5%-7.5%, Rutfilling 4.5%-6.5%	Type A & B 7.2%-8.1%, Type C 7.3%-7.5%, Rutfilling 7.3%-7.5% (Districts report using Type C for rutfilling). Typical values based on brief survey to District QA personnel. No statewide dataset for these items.
VT	5.5%-10.5%	7%-7.5%
WV	2FA 7%-8.5%, 3FA 6.5%-8%	Around 8%
WY	11%-14.5% emulsion rate for top course, 10%-13.5% for longitudinal rut and crack filling, specified 65% residual asphalt	11%-14.5% emulsion rate for top course, 10%-13.5% for longitudinal rut and crack filling, specified 65% residual asphalt

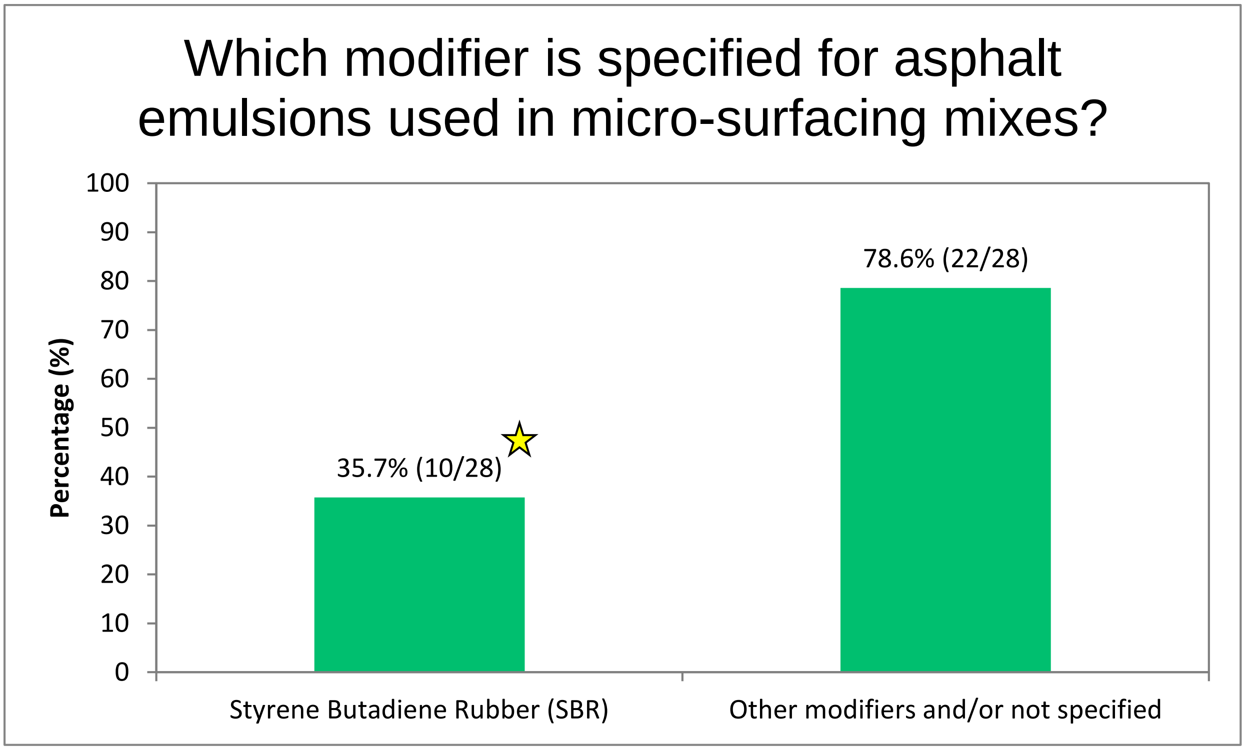


Figure B.9: Asphalt emulsion modification used with micro-surfacing mixes.

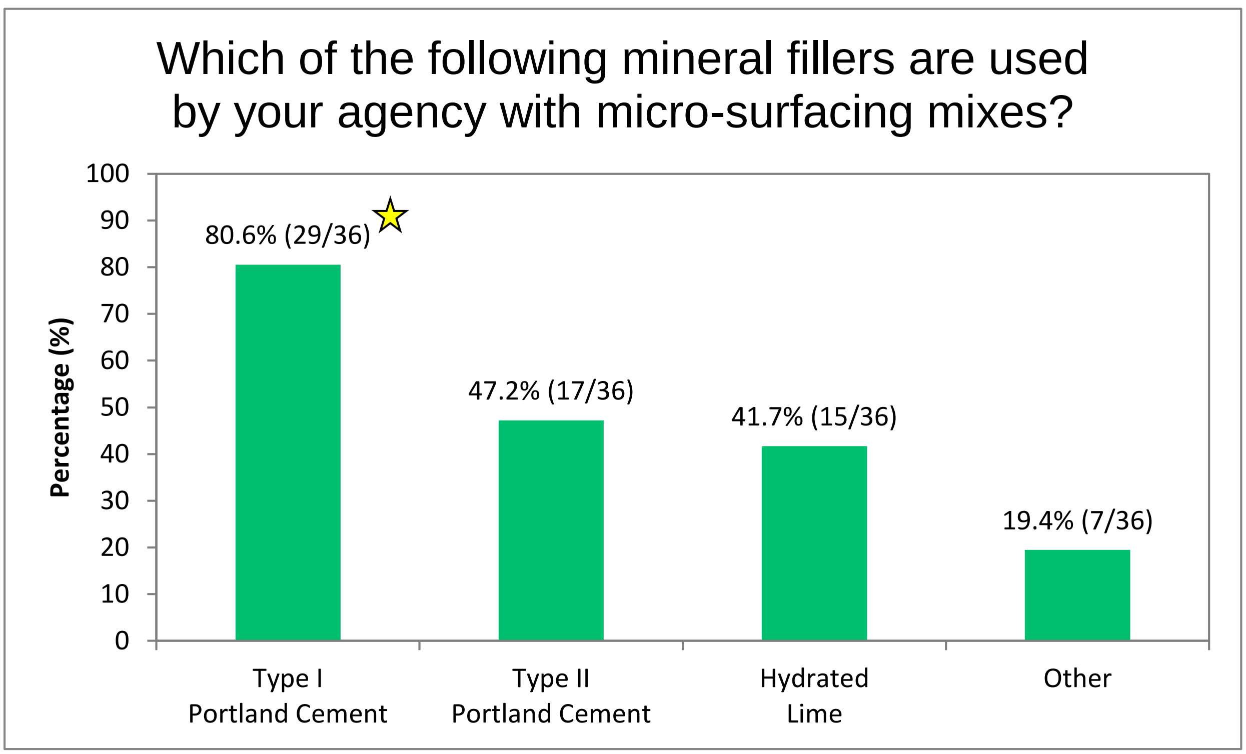


Figure B.10: Mineral fillers used with micro-surfacing mixes.

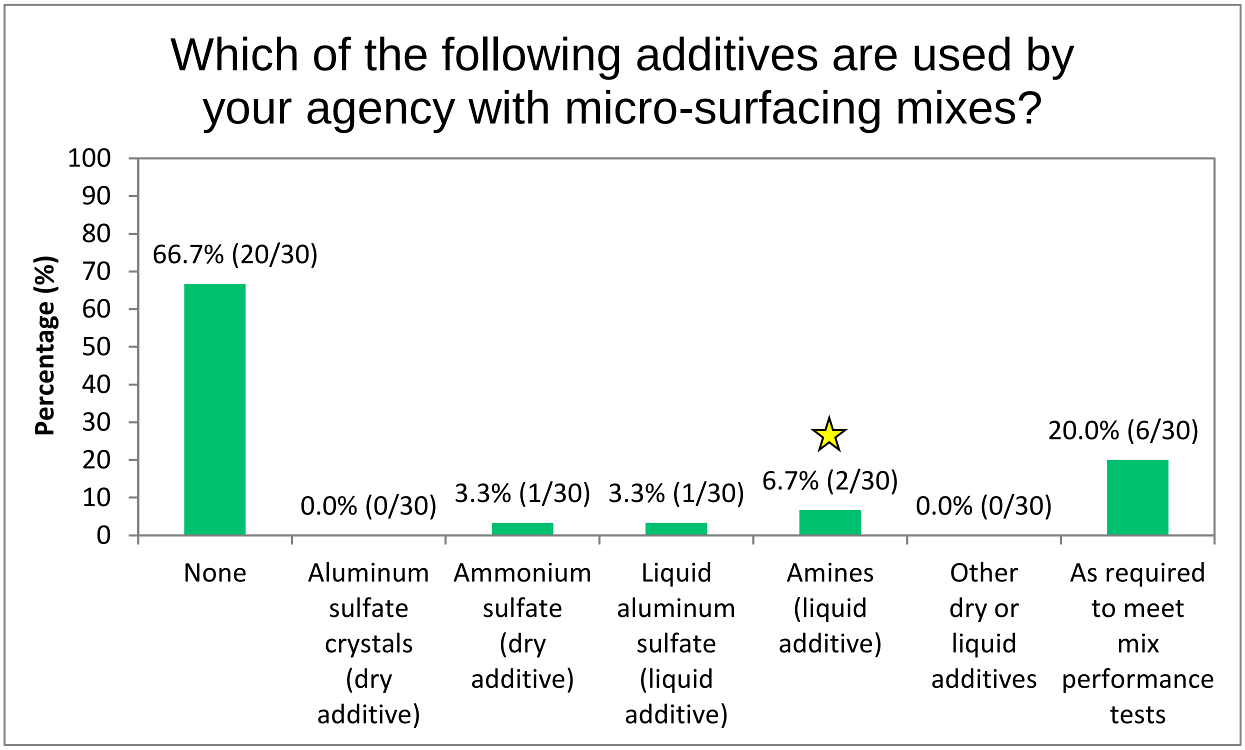


Figure B.11: Additives used with micro-surfacing mixes.

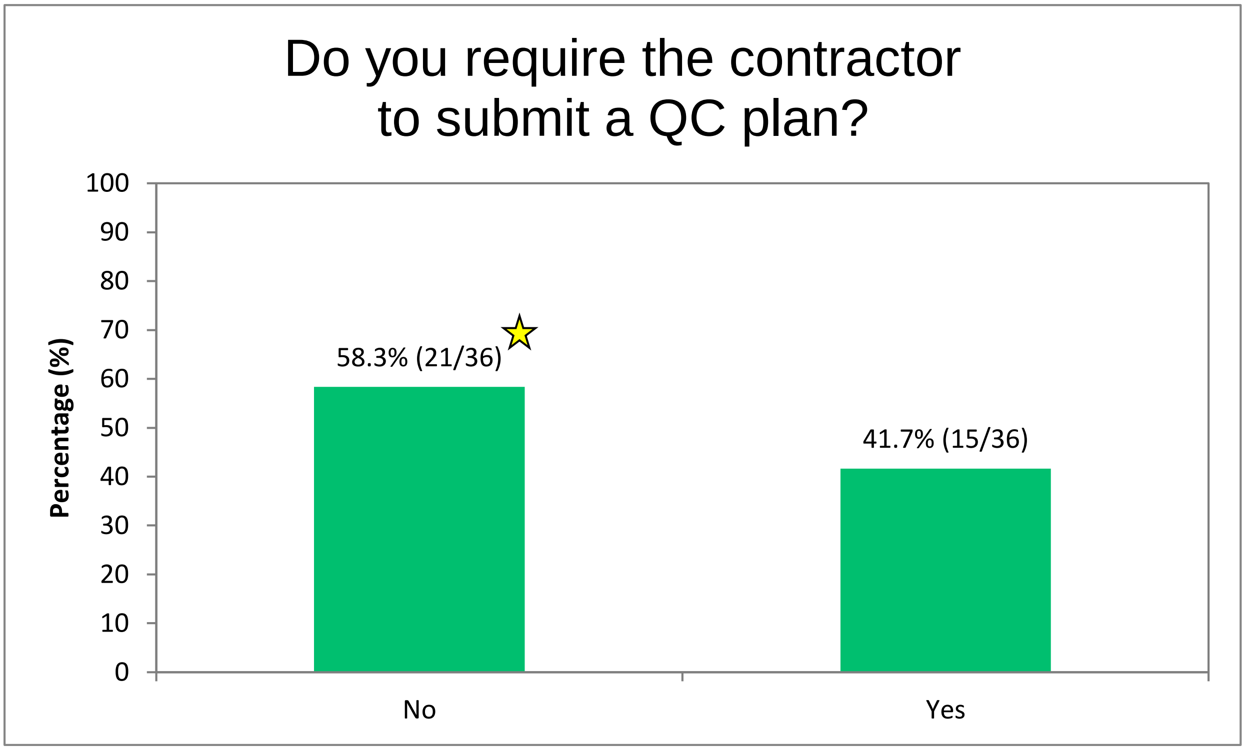


Figure B.12: Quality control plan for micro-surfacing applications.

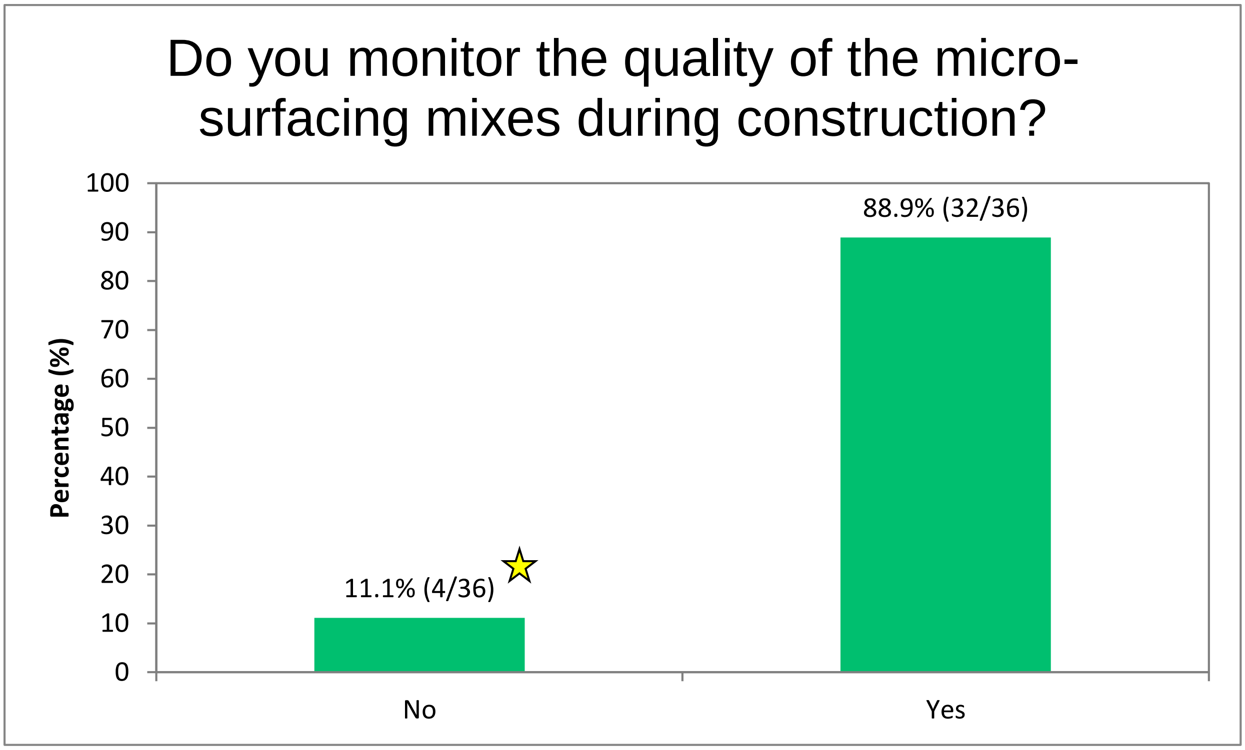


Figure B.13: Quality monitoring during construction for micro-surfacing applications.

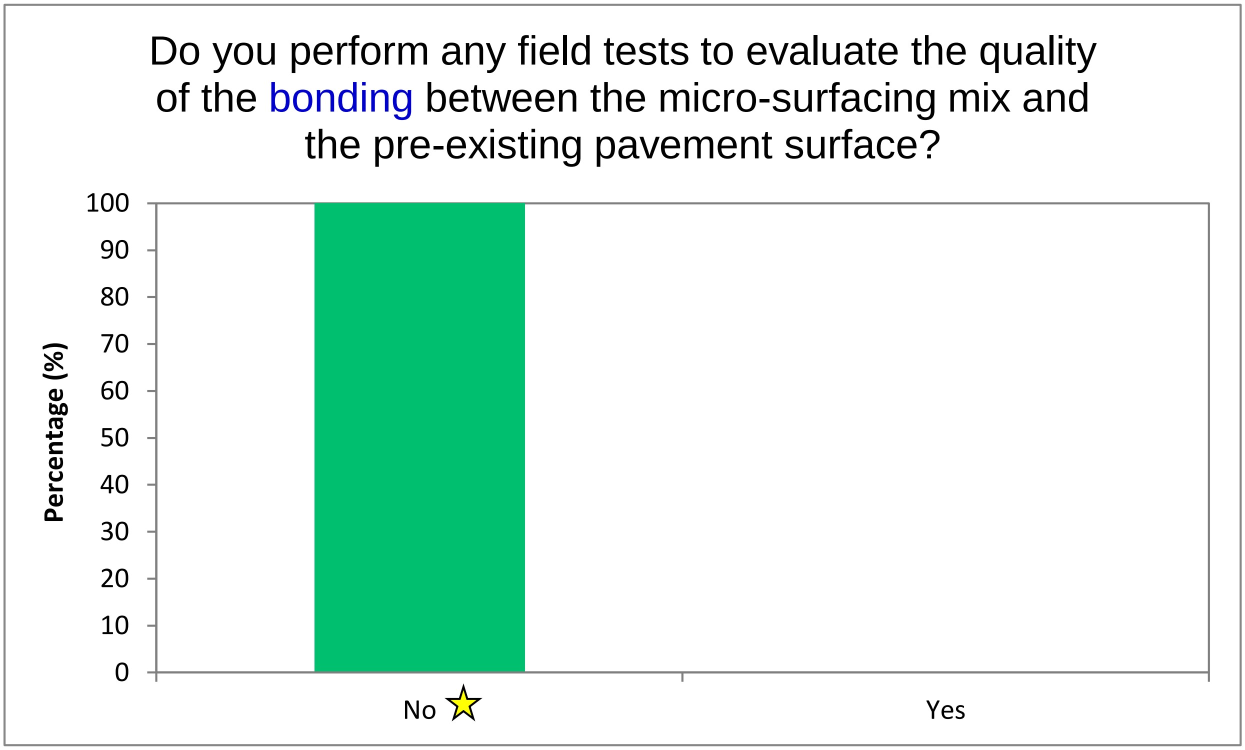


Figure B.14: Field tests to evaluate bonding for micro-surfacing applications.

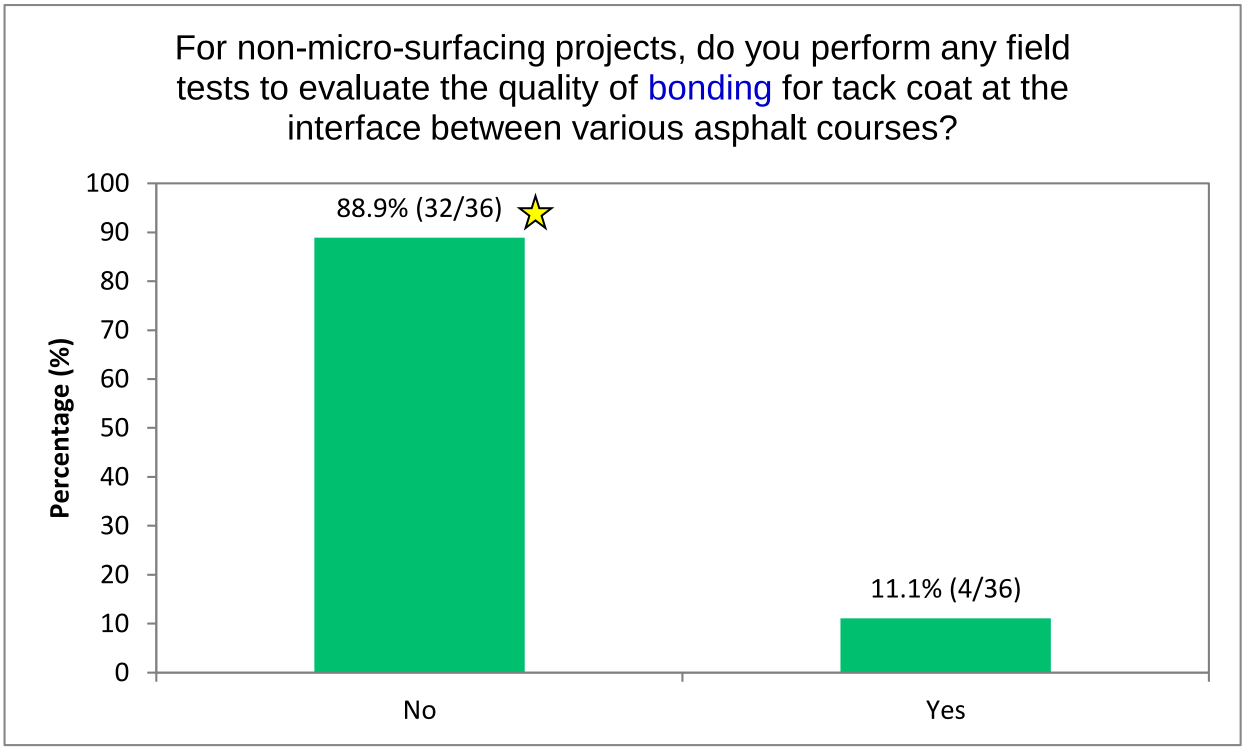


Figure B.15: Field tests to evaluate bonding for non-micro-surfacing projects.

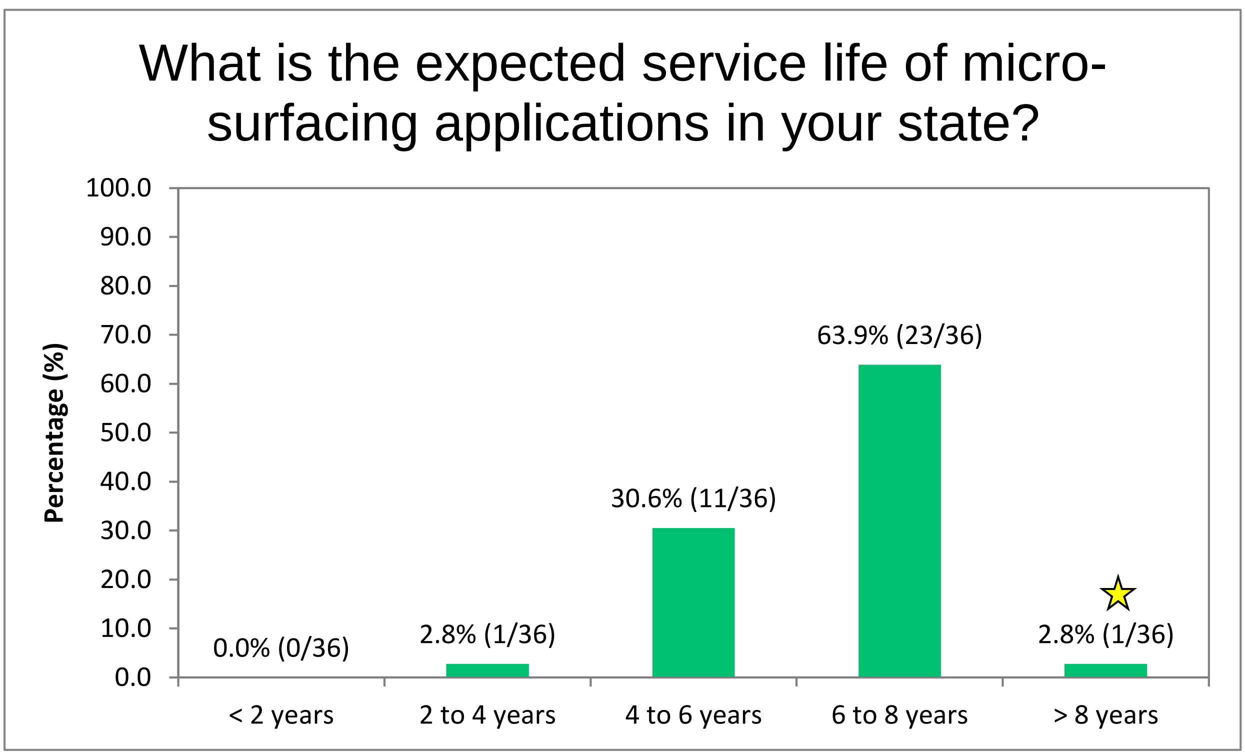


Figure B.16: Expected service life of micro-surfacing applications.

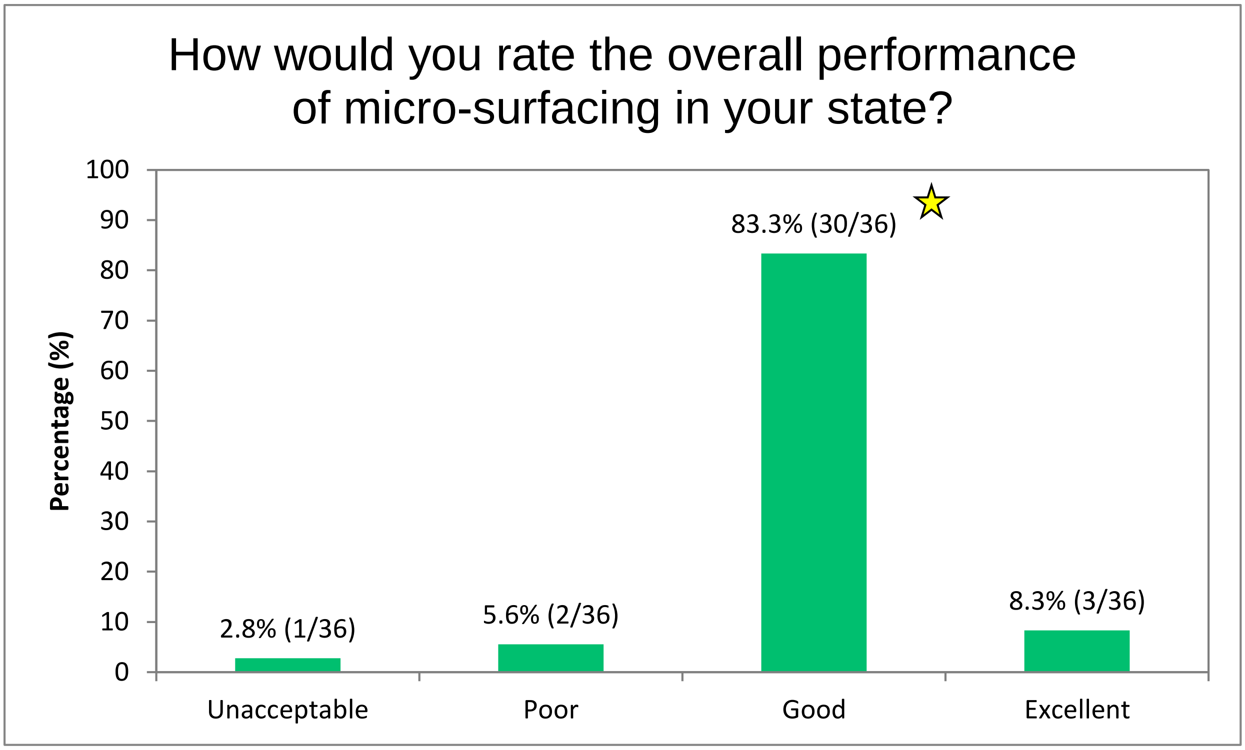


Figure B.17: Overall Performance of micro-surfacing applications.

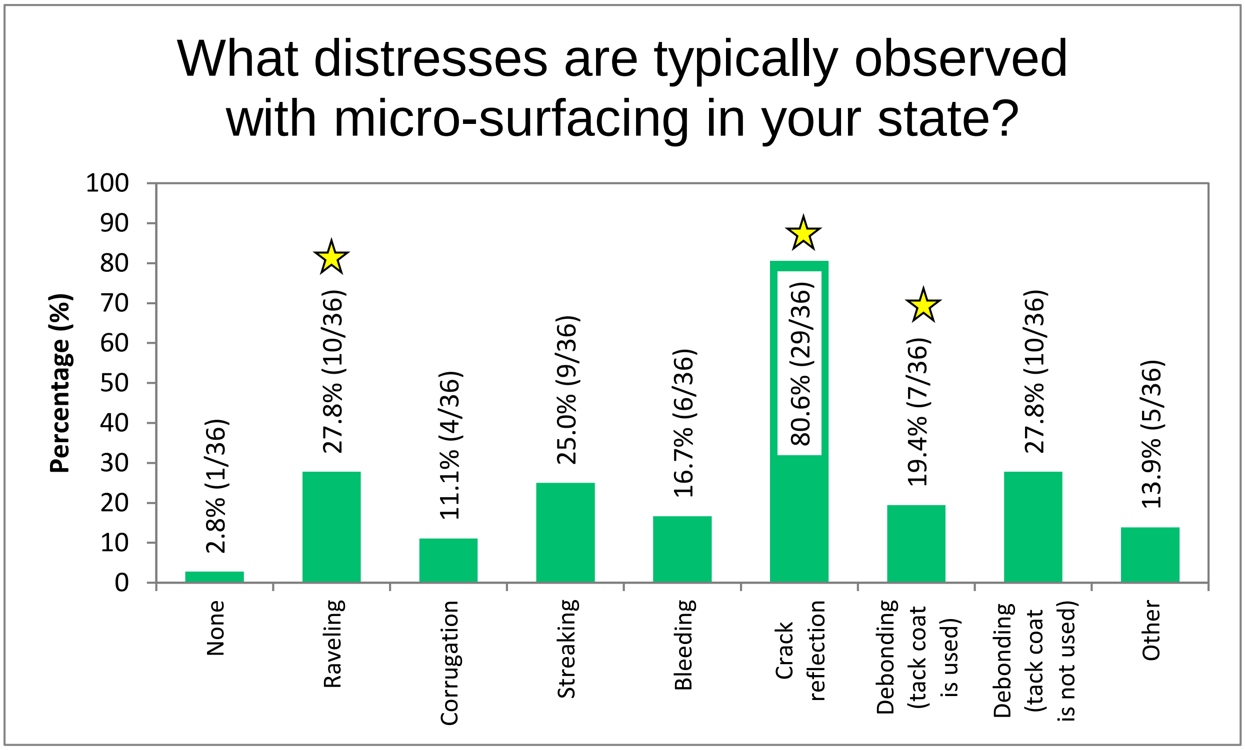


Figure B.18: Distresses typically observed with micro-surfacing.

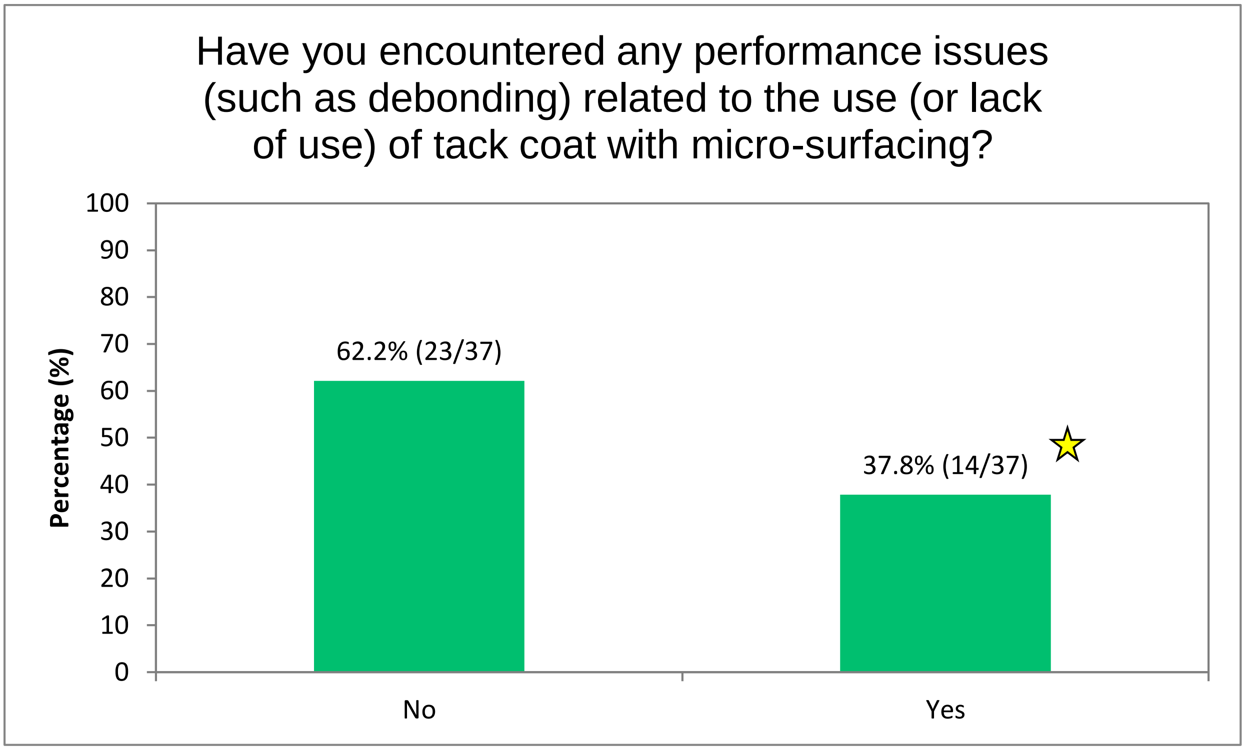


Figure B.19: Performance issues related to the use
(or lack of use) of tack coat with micro-surfacing.

Table B.3: Summary of performance issues related to the use (or lack of use) of tack coat with micro-surfacing.

State / Province	Have you encountered any performance issues (such as debonding) related to the use (or lack of use) of tack coat with micro-surfacing? If "Yes", please elaborate:
CO	Some areas have debonded and popped off the underlying layer.
DC	Some roadways have unraveled due to heavy rainfall. Unsure if tack coat was applied and at what rate.
DE	Debonding.
FL	Minor areas within overall project. However, FDOT does not have a lot of micro-surfacing experience.
MI	Michigan has seen delamination occurring usually after 5 or 6 years. Recently some within 1 to 2 years (2 year warranty). More study needed.
MN	Not a common issue if tack coat is used in the appropriate circumstance. If not used on concrete or raveled surfaces, de-bonding can be an issue.
NH	Yes. delams have been seen even with tack.
OH	There was a project we suspected no or little residual in tack and there were spots of delamination. Debonding has happened years after but may or may not be related to tack.
SC	Some limited cases, likely from existing spots on road - motor oil, fuel, etc. Ensure road is pre-wet or not too hot prior to placement, the MS could set-cure to fast and not bond properly.
SD	Some debonding.
TN	In some cases there has been debonding that may have been a result of no tack.
TX	Debonding.
TX	Not sure. We think a lot of the issues were related to excessive moisture.
VA	Debonding is likely when tack was not used.
VT	Debonding.

Table B.4: Summary of comments on experience with tack coat with micro-surfacing.

State / Province	Please comment on your experience with using tack coat for micro-surfacing (e.g., please comment on the reasons for using or not using tack coat with micro-surfacing):
Yes (tack coat is always used with micro-surfacing)	
DC	Tack coat is used to bond the leveling course to the course below.
DE	Better results than when we did not use tack coat.
GA	We use tack coat for all bituminous material applications.
IN*	Tack coat is a low-cost item, but can significantly improve the life of the microsurface course.
MD	We use it because it is relatively inexpensive, and identified as a good practice to have.
MT	We use tack, however waive the requirement if no traffic is on the surfacing below and the prior lift is less than 7 days old.
NH	all thin lift treatments should be tacked
NJ	Obviously bonding is a major concern when you are dealing with very thin material. Without the use of tack the proper bond may not be achieved and your micro-surfacing would fail.
OH	We like using it. More pain to ensure contractors put the tack down uniformly and at the proper spray rate.
VA	When tack isn't used the risk of debonding increases. Tack is specified on micro projects and debonding is an isolated issue if and when it occurs.

* Indiana DOT has a 3-year warranty specification for micro-surfacing. They do not specifically require tack coat, but it was observed that most contractors use tack coat with micro-surfacing.

State / Province	Please comment on your experience with using tack coat for micro-surfacing (e.g., please comment on the reasons for using or not using tack coat with micro-surfacing):
Yes (under certain conditions, e.g., on concrete surfaces)	
CO	We have not had issues with debonding, areas with tack (concrete and raveled/oxidized asphalt) are performing adequately.
FL	No issues. Use it to assure a better bond.
KY	In our experience, tack provides added adhesion benefit, especially in cases of dryer pavements.
MI	2 year warranty allows the contractor option to tack. All have chosen not to tack in recent years. MI has experienced more debonding in recent years.
Ontario	Tack coating of existing pavement surfaces is typically required. New pavements or flushed pavements to be micro-surfaced may not require tack coating. When a thick scratch coat micro-surfacing is anticipated, tack coating may not be required.

PA	We have not seen debonding of micro-surfacing much at all except where pavement markings have not been removed.
TN	It is required by spec, but some of the regions left it of their plans for various perceived reasons. I think you get a better product with it in.
WV	Only a few of our project have used tack. We have not had any issues either way.

State / Province	Please comment on your experience with using tack coat for micro-surfacing (e.g., please comment on the reasons for using or not using tack coat with micro-surfacing):
No (tack coat is not required for micro-surfacing)	
AL	Haven't seen the need for it.
AZ	No issues with debonding.
IA	No recent problems resulting from not using tack coat.
MO	To my knowledge, we have not experience any bonding issues by not utilizing a tack coat.
ND	Tack will sometimes be used on bare concrete under overpasses on interstate applications. Tack is not used because the emulsion in the micro-surfacing is of sufficient quantity to bond to the underlying road.
UT	It is a good surface treatment. Sometimes the ride is poor and we have talked about using a ride spec with it.
VT	We just don't seem to achieve the expected level of performance.

Table B.5: Final comments provided by respondents.

State / Province	Is there anything you would like to mention that was not covered in the questionnaire?
DE	We remove striping before Micro helps with debonding.
IN	We require a warranty bond for 3 years.
MI	There are ongoing discussions with industry partners related to National recommendations and current asphalt requirements. May increase residual requirements.
MO	We use micro-surface as a preventative maintenance treatment. It is critical to use this treatment at the right time to get the optimal service life. If applied late, the micro-surfacing won't perform as well.
NV	Verify the application rate is important.
PA	Our biggest problems were encountered when the test strip was waived and the emulsion did not break properly and needed to be removed.
SC	Ensure radar is working on machine to accurately measure ground distance on equipment- common issue.
UT	We measure our micro by the square yard and industry wants us to go to the ton. We are looking at that possibility.

Appendix C Literature Review

C.1. Introduction

Different pavement preservation treatments have been used by transportation agencies to enhance the quality of pavement condition and extend the pavement service life time. Micro-surfacing is one of the most common pavement preservation treatments that are used in the US (Rajagopal, 2010). Micro-surfacing was first developed in Germany in the late 1960s and early 1970s and was used as a conventional slurry in layers thick enough to fill deep wheel ruts (Broughton et al., 2012). It was introduced to the US in the late 1980s after Dr. Fredrick Raschig presented his new slurry system to the International Slurry Surfacing Association (ISSA).

Micro-surfacing is a cold laid polymer-modified asphalt mix containing crushed aggregate, asphalt emulsion (about 7% by weight), water, polymer additives (about 3% by weight of asphalt) and mineral filler (about 1% by weight of total dry mix) to fill ruts, improve surface friction, or provide a leveling course or a surface course for existing pavements (Hein et al. 2003). While a coarser aggregate gradation is typically specified for rut filling applications, a finer aggregate gradation is typically specified for leveling and surface course applications. Micro-surfacing can be applied in a single layer that may be as thin as 3/8 inch (9.5 mm). In addition, it can be applied in multiple layers to fill wheel ruts up to 2 inches (50.8 mm) deep. One of the main benefits of micro-surfacing over other pavement treatments is its rapid breaking due to the use of polymer-modified cationic asphalt emulsion that chemically speeds the evaporation of moisture. In most instances, micro-surfacing can set in less than one hour, requires no rolling, and allows the road to be opened to traffic quickly (Broughton and Lee, 2012).

C.2. Micro-surfacing Performance

Micro-surfacing has been found to be effective in slowing raveling and oxidation, sealing cracks, filling potholes, enhancing the skid resistance and improving the longevity of the pavement structure (Rajagopal, 2010). Previous studies found that micro-surfacing service life typically range between 5 to 9 years depending on its function. In general, micro-surfacing was found to be most effective when it is used for rut filling. In a research study funded by ODOT, Rajagopal (2010) found that micro-surfacing was cost-effective when used to treat pavements on the general system routes with a Pavement Condition Rating (PCR) of 61 to 70 prior to installation. The service life of micro-surfacing treatments on these pavements was reported to be approximately nine years.

Different distresses develop in micro-surfacing during its service life. These distresses include: crack reflection, delamination, raveling, segregation, corrugation potholes, bleeding, longitudinal and transverse joint cracking, and streaking (Gransberg, 2010; Broughton and Lee, 2012). A research study sponsored by California DOT also indicated that segregation is also common in micro-surfacing. While some of these distresses might develop immediately after construction, others develop after 3 to 5 years of service. According to surveys conducted as part of studies funded by the NCHRP and Texas DOT, the most commonly observed distresses that might develop immediately after construction are: crack reflection, delamination, and streaking.

C.3. Factors Affecting Micro-surfacing Performance

Several factors affect the development of the distresses in micro-surfacing. As mentioned earlier, one of the most common distresses in micro-surfacing is crack reflection. This distress is mainly caused by existing conditions such as fatigue cracking of the treated pavement structure (Broughton and Lee, 2012). Therefore, proper project selection for micro-surfacing is very important to avoid the development of this distress.

Another common type of distress that is observed in micro-surfacing is raveling. The development of raveling is related to the properties of the micro-surfacing mix. Poor asphalt quality, poor quality aggregate, lack of fines to fill up the voids in the mixture can all result in raveling. In addition, improper micro surface mix design resulting in too much or too little water in the mix, too many fines, improper amounts of emulsion and additives, and incompatibility of the aggregate-emulsion combination can also cause raveling. Raveling can also result from construction related issues such as installing the micro-surfacing in layers that are too thin to hold the large aggregates, premature opening to traffic, and insufficient curing due to cooler temperatures (Gransberg, 2010; Broughton and Lee, 2012).

Bleeding and segregation are distresses that are typically associated with micro-surfacing mix proportion issues. The use of excess amount of asphalt binder in the micro-surfacing mix is the primary reason for these distresses (ISSA, 2010). Longitudinal and transverse joints cracking are also common distresses in micro-surfacing application. Improper construction of joints may result in excessive overlap or uncovered areas, which may lead to unwanted bumps in the pavement. Contractor inexperience is the main reason for improper joints.

Delamination is another common distresses in a micro-surfacing project. In this distress, the pavement layer is completely detached from the existing surface as shown in Figure C.1. Delamination may be a subsequent distress to either fatigue cracking or slippage. It is mainly caused by improper bonding between the micro-surfacing mix and the existing pavement surface or between two micro-surfacing layers.

(a) (b) (c)

Figure C.1: Distresses Associated with Poor Bonding: (a) Fatigue Cracking, (b) Slippage Failure, and (c) Delamination.

C.4. Bonding Between Micro-Surfacing and Existing Pavement Surface

Achieving an adequate bond between the micro-surfacing mix and the existing pavement significantly affects the long-term and short-term performance of treated pavement. Bonding between new and existing asphalt layers is important to ensure that the pavement system behaves as one structure. This is critical for very thin asphalt overlays and treatments such as micro-surfacing, as they are designed primarily for functional and not structural purposes. Thus, proper load transfer should be maintained between the micro-surfacing layer(s) and the existing pavement. A study conducted by Raab and Partl (2004) indicated that there are two modes of failure occur due to poor bonding: shear and tension (Figure C.2). However, Chun et al. (2017) in their study on prime coat indicated shear as the main mode of failure. Crovetti et al. (2012) concluded that the rotational shear is the main failure mode in the field.

Poor bonding between asphalt layers causes re-distribution of stress such that large tensile stresses will occur at the interface between the newly paved layer and the existing asphalt surface (Zhang, 2017) as shown in Figure C.3. This may lead to the development of fatigue cracking; especially in thin micro-surfacing layers. In addition, re-distribution of stresses due to poor bonding will also lead to the development of compressive stresses at the top of the existing layer. This results in relative movement between the two layers at the interface, leading to weaker bond slippage (Shahin et al. 1986). It is noted that slippage failure typically develops at locations where frequent braking and acceleration of traffic occur. Since at these locations the vehicles induce a high lateral shear force on the pavement surface. When applied shear forces exceed the bond strength, slippage failure occur.

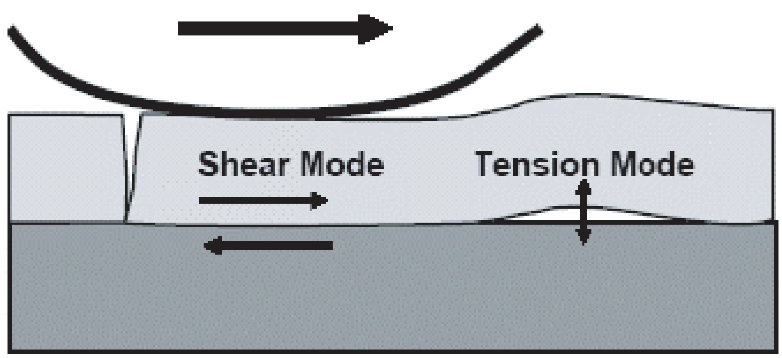
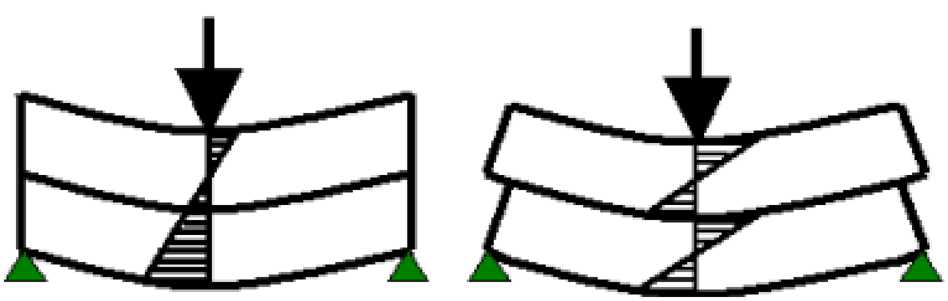


Figure C.2: Distress modes at pavement interface under service condition (after Raab & Partl, 2004).



(a) (b)

Figure C.3: Stress distribution: (Gomba et al., 2004): (a) Fully Bonded Pavement Acting as One Structure (b) Debonded Pavement Acting as Two Systems.

C.5. Factors Affecting Micro-Surfacing Bonding Strength

Bonding of a pavement micro-surfacing layer is a directly related to tack coat practices. While some DOTs apply tack coat prior to the placement of the micro-surface mix to ensure a good bond between the micro-surface mix and the existing pavement surface, other DOTs do not use tack coat with micro-surfacing. In NCHRP synthesis 411, Gransberg (2010) sampled the specifications of 18 DOTs and reported that DOTs in seven states (Alabama, Georgia, Michigan, Minnesota, Ohio, Pennsylvania, and Tennessee) required the use of tack coat prior to micro-surfacing. The states that do not require using tack coat with micro-surfacing assume that the consistency of the micro-surfacing mix permits it to be evenly spread over the pavement surface, forming an adequate bond to the surface. The micro-surfacing mixture can be also designed to ensure that the emulsion will wet the existing pavement surface to create the required bond (Gransberg, 2010). However, no research has been conducted to evaluate and verify that adequate interface bond strength is achieved when no tack coat is used. A study sponsored by Texas DOT found that delamination is more frequent in Texas than in other states. The study attributed that to the lack of use of tack coat and to high temperatures in Texas that cause the micro-surfacing emulsion to break quickly (Broughton, 2012).

The selection of an optimum tack application rate is also critical for achieving a proper interface bond between the micro-surfacing mix and the underlying surface. An insufficient tack coat application rate may cause debonding, leading to various pavement distrexxsses. On the other hand, excessive amounts of tack coat may result in slippage at the interface, which may lead to cracking and new mix flushing. Tack coats are typically installed at a specific application rate, which is different than the residual application rate. The tack coat application rate is the amount of diluted asphalt (asphalt and water) applied in the field, while the residual application rate is the amount of asphalt residue remaining after the water evaporates. ODOT requires that tack coat applied prior to micro-surfacing should consist of one part asphalt emulsion and three parts water and be applied at a rate of 0.06 to 0.12 gallon per square yard. NCHRP Synthesis 411 (Gransberg, 2010) indicated that the tack coat application rate specified for micro-surfacing applications by different transportation agencies ranged from 0.05 gallon per square yard to 0.25 gallon per square yard diluted with one part water to one part asphalt emulsion. ISSA also suggests applying tack coat at a rate of 0.05 to 0.10 gallon per square yard for micro-surfacing applications using a standard distributor (ISSA, 2010). The optimum tack coat application rate to be used during construction also depends on the existing pavement surface type, texture, and condition. In general, lower application rates can be used on new asphalt layers or asphalt surfaces in good condition, while higher application rates might be needed for old, oxidized, cracked, pocked, or milled asphalt surfaces as well as tined concrete surfaces (Mohammad et al., 2012). Some transportation agencies such as Caltrans does not require the use of a tack coat prior micro-surfacing unless the existing pavement surface is extremely dry and raveled or is surfaced with concrete (California DOT, 2009).

The type of tack coat material may also affect the micro-surfacing mix bond strength. Currently, asphalt emulsions are the most widely used tack coat material for micro-surfacing applications (Gransberg, 2010). An asphalt emulsion consists of an asphalt binder mixed with water and an emulsifying agent. There are several types of emulsions that have been used as tack coats including slow set, medium set, rapid set, and quick set emulsions (with and without polymer modification). The ISSA recommends using CSS-1h as a tack coat with micro-surfacing (ISSA, 2010). However, some state transportation agencies, including ODOT, same emulsion used in the micro-surfacing mix for tack coat.

C.6. Bond Strength Tests

Over the last four decades, several test methods have been proposed to evaluate tack coat quality and interface bond strength. Table C.1 provides a summary of these test methods. As can be noticed from this table, the testing modes that have been utilized to characterize the bond strength are: direct shear, direct tension, torque and flexural bending. Currently, the testing modes that have been used by state DOTs for measuring the bond strength between asphalt layers are the direct shear and direct tension. Direct shear tests are the most common and are performed by applying a vertical shear force along the interface of a dual-layered sample until failure occurs. The maximum bonding shear stress or the bonding energy (area under the stress-strain curve) obtained in these tests is used to evaluate bond strength at the layers' interface. Although direct shear tests have been extensively used by many state DOTs (including ODOT) to evaluate bonding between asphalt layers, these tests are very difficult to conduct in thin lifts, as in the case of the micro-surfacing, and they cannot be conducted in the field as they require a loading frame.

C.6.1 Direct Tension Bonding Strength Tests

Tensile bond strength tests are often called pull-off tests. These tests can be conducted in the field or lab. Pull-off tests are typically performed by coring through the upper layer and partway through the bottom layer in the field (or cored sample in the lab) and gluing a metal disk to the surface and applying a tensile force in a direction perpendicular to the interface until failure. It is noted that these tests evaluate the adhesive bond strength at the interface. Different tensile bond strength tests have been developed and used by state DOTs. The section below describes different pull-off bond tests evaluated in previous studies.

C.6.1.1 Switzerland Pull-Off Test (Proceq DY-206 testing device)

The Proceq DY-206 testing device (Figure C.4a), also referred to as the Switzerland pull-off test, is one of the direct tensile tests that have been used to evaluate bond strength between asphalt layers. Proceq DY-206 is an automated pull-off tester. It has a working load range of 0.3 to 3.1 MPa (44 to 443 psi) and can exert a tensile force of 0.6 to 6 kN (135 to 1349 lbf). Proceq DY-206 has an increased accuracy for low-strength applications such as testing the adhesive strength of mortars. The maximum pulling speed of this device is 4.65 mm/min (0.183 inch/min). This device incorporates a comprehensive range of test discs plus an adjustable foot configuration to cover a wide range of applications. The test is performed by coring first through the new asphalt layer and partway into the existing layer with a 2-in. diameter core barrel. The testing device disk is then glued to the top surface and is pulled in tension at a rate of 5 psi/sec until failure. The sample is then evaluated to see if failure occurred at the bond, in the upper or lower layers, or at the glue interface as shown in Figure C.4b. It is noted that a manually operated version of this device called Dyna Proceq Z16 (Figure C.4c) is available, and has been used in previous studies.

Texas DOT has used this test in a number of studies. Scullion et al. (2012) used the Dyna Proceq Z16 in a study funded by Texas DOT to assess the quality of bond bonding of the surface treatment to full-depth reclaimed roadways. The authors used a modified version of the ASTM C 1583 standard test method for determining the bond strength. Scullion et al. (2012) also suggested to compare laboratory results to field bonding strengths. In another study, Estakhri et al. (2015) recommended using this test device for the evaluation of the bond strength when using thin surface mixes for pavement preservation.

Table C.1: Summary of Testing Devices for Tack Coat Evaluation (modified After Mohammad et al., *2012*)).

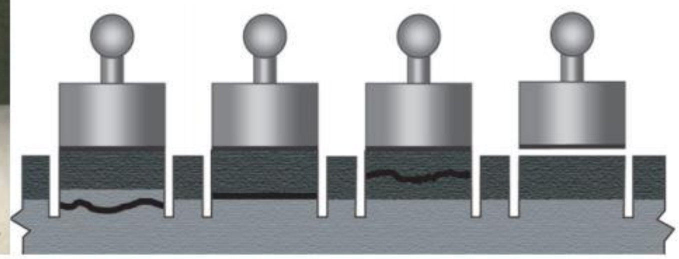
Apparatus	Procedure	Test Results	Type	Remark
Interface Shear Test Device (ISTD)	A vertical monotonic or cyclic load is applied and the maximum shear load and its corresponding shear displacement are measured to evaluate interface strength.	Shear Strength	Lab	Developed by Illinois Center for Transportation
Pull-off test based on Modified ACI 506.4R and ASTM C 1583-04 method	Test specimen is prepared by a shallow core drilling into and perpendicular to the surface. A steel disk is then glued to the top surface of the test specimen and a tensile load is applied to the steel disk until tensile failure occurs.	pull-off tensile strength	Field	Proposed by Purdue University
Louisiana Interlayer Shear Strength Tester (LISST)	A vertical shear force is applied to dual - layered specimens along the interface with 0.1 in./min. until failure.	Shear strength	Lab	Product of NCHRP 9-40
Louisiana Tack Coat Quality Tester (LTCOT)	A pull-off test device. A vertical tensile load is applied to a specimen with a strain controlled mode.	Tensile strength and vertical deformation	Lab or field	Product of NCHRP 9-40. Improved ATacker™ Tester
Leutner Shear Test	A vertical shear load is applied to a double-layered specimen with a strain controlled mode at a constant rate of 2.0 in/min at 21.1°C until failure.	(1) Maximum shear load (2) Corresponding maximum displacement	Lab	No normal load is applied
LTRC Direct Shear Test	A horizontal shear load is applied to a dual-layer specimen of asphalt concrete with a stress control mode at a constant rate of 50 lbs/min at a given temperature until the sample is separate. With a climate chamber, the temperature can be set in the range from –20 to 80°C.	Shear stress at failure	Lab	(1) Normal load is optional (2) Developed by Louisiana Transportation Research Center (LTRC)
TTI Torsional Shear Test	A twisting moment with constant rate of 2.9 E-04 radian/sec and a normal load is applied on the top of a double-layered cylinder specimen at a constant rate until failure.	(1) Shear strength (2) Construct Mohr-Coulomb failure envelopes to get the cohesion and the tangent of internal friction angle	Lab	Developed by Texas Transportation Institute (TTI)

Apparatus	Procedure	Test Results	Type	Remark
Florida Direct Shear Test	A vertical shear load is applied to dual-layer asphalt concrete specimen with strain control mode at a constant rate of 2.0 in/min at 25°C until failure.	Shear strength at failure	Lab	(1) No normal loads can be applied during the test (2) Developed by Florida DOT
Virginia Shear Fatigue Test	Cyclic shear load [a 0.015- in. deflection was applied to the specimen in the form of a 0.10-s half-sine wave, followed by a relaxation period of 0.9 s (the total cycle is 1s)] is applied at the geocomposite membrane interface of dual-layer sample composed of concrete and HMA specimens until failure at ambient temperature.	(1) Maximum shear stress of each cycle (2) Maximum shear stress against the number of cycles of failure (3) Optimal tack coat application rate	Lab	Developed by Virginia Polytechnic Institute & State University and the Virginia Tech Transportation Institute
ASTRA Interface Shear Test	Horizontal load is applied along the interface of dual layered sample at constant rate until failure; meanwhile, a constant normal load is applied on top of the specimen.	Shear stress at failure	Lab	If carried out at different normal load, a Mohr-Coulomb failure envelope can be obtained.
Layer-Parallel Direct Shear (LPDS)	Vertical shear load is applied to a composite specimen with strain control mode at constant rate.	Tensile strength	Lab	(1) Shear-plane can be along interface or within the layers (2) Modified by EMPA, Swiss Federal Laboratory for Materials Testing and Research
Switzerland Pull-Off Test	A tensile load is applied to asphalt concrete specimen composed of two layers at constant rate.	Tensile strength	Lab	Test is carried out according to German testing specification ZTV-SIB 90
Loboratorio de Caminos de Barcelona Shear Test (LCB)	The dual-layer specimen with tack coat interlay is used as a beam located over two supports and a vertical load is applied to the specimen at a constant deformation speed of 0.05 in/min in the middle of the two supports until failure.	(1) Shear strength (2) Shear modulus and the specific cracking energy	Lab	(1) No normal load can be applied during this test (2) Developed by DOT, Technical University of Catalonia, Spain
Wedge-Splitting Test	A vertical load is applied through a wedge to a dual layered specimen with a groove and starter notch along the interface at a constant rate until complete separation of the specimen.	(1) Maximum horizontal force (2) Specific fracture energy	Lab	Developed by Technical University, Austria

Apparatus	Procedure	Test Results	Type	Remark
Dynamic Interaction Test	A sinusoidal shear force is applied to dual-layered specimen at particular temperature and given load frequency.	The norm of Interlayer reaction complex modulus *KI** and phase angle	Lab	Developed by University of Naples, Italy
NCAT Shear Test	A vertical shear force is applied to dual - layered specimens along the interface with strain control mode at constant rate until failure.	Bond shear strength	Lab	Developed by National Center for Asphalt Technology (NCAT)
HasDell EBSTTM Emulsion Shear Test	A shear force is applied along the interface until failure.	Bond shear strength	Lab or field	Marketed by R/H Specialty and Machine, Terre Haute, Indiana
Traction Test	A tensile force is applied at constant rate of 54 lb/s to a cylindrical sample until failure	Bond tensile strength	Lab or field	Developed by Ministère des Transports du Québec, Canada
The ATacker™ Test	A pull and/or torque force is applied to detach the tack - coated plates or detach the contact plate and tack - coated pavement.	Tensile strength and/or shear strength	Lab or field	Developed by Instrotek , Inc .
UTEP Pull - Off Test	A torque force is applied to detach the tack - coated plates or detach the contact plate and tack - coated pavement	Tensile stress at the point of failure	Lab or field	Developed by University of Texas at El Paso
UTEP Simple Pull - Off Test	A tensile force is applied directly to pull off the contact plate from the tack - coated surface.	Tensile stress at failure	Lab or field	Developed by University of Texas at El Paso
Impulsive Hammer Test	An impu lsive loading is applied with a hammer to the pavement surface at particular locations and given loading frequency.	FD number	Field	Under development at Nottingham University
Torque Bond Test	A torque force is applied to core sample from pavement with a torque wrench to failure.	Bond strength	Field	Developed by Highway Agency, United Kingdom
In situ Shear Stiffness Test	A rotational force is applied to the pavement through a test plate, meanwhile a normal weight is provided by the test equipment.	Shear strength and shear modulus	Field	Developed by Carleton University, Canada

In another study, Freeman et al. (2010) used Dyna Proceq Z16 to assess the adhesion between surface treatments and prime-coated base course materials. According to their study, this test was able to differentiate between primed and unprimed bases such that the adhesion provided by a primed base course was significantly greater than without a prime coat. Wilson et al. (2016) used automated Proceq DY-206 testing device as a tool to carry out field testing as a part of a project with TxDOT. Bond strengths from field samples were considerably lower than those for labmolded samples. The authors also indicated that the bond strength measured using this device significantly varied between projects due to differences in pavement surface type, asphalt overlay design, and asphalt layer compaction temperature. Wilson et al. (2016) indicated that the results of this testing device was insensitive to the tack type. In addition, they also indicated that no exact determination of the bond strength can be made if the failure occurs in the new or existing asphalt layer, but the bond strength will be greater than the failed layer. The laboratory shear testing the variance was not that much high. Wilson et al. (2016) recommended to conduct more field studies to validate the results of this device.

(a)



(b)

(c)

Figure C.4: (a) Switzerland Pull-Off Tester (Proceq Dy-206 testing device) and Failure Modes. (b) Possible Failure Modes (c) Photo of Direct Tensile Bond Test Apparatus (Dyna Proceq Z16) (After Scullion et al. 2012)

C.6.1.2 Com-Ten Pull-off Tester

Another pull-off testing device is the Com-Ten tester. The Kansas DOT have used Com-Ten pull-off tester (Figure C.5) in the field to evaluate the bond strength of tack coat following the KT-78 test procedure. The Com-Ten pull-off tester has a wide load range that varies between 5kN and 25 kN. The pulling speed is adjustable between 2 and 500 mm/min. The device also includes an electronic control panel with a colored touch screen that displays the real time force reading and the peak force at the end of the test. KT-78 test method involves gluing aluminum pucks to the 2-inch (50-mm) diameter cores and pulling in direct tension at rate of 0.7 in/min (1.78 cm/min) until failure. The peak tensile stress obtained in this method is used to examine the bonding strength quality according to the criteria presented in Table C.2.

Mealif et al. (2017) used the com-ten pull-tester to evaluate the bond strength in field and compared it to pull-off tests performed in laboratory using a universal testing machine. Though the lab and field test results were not equal, they showed a similar trend for the different samples. Mealif et al. (2017) concluded that the Com-Ten pull-off tester data was reliable. They also indicated that the overall experience in using the Comp-Ten pull-off test with the KT-78 test method was very positive.

Figure C.5: Com-Ten Pull-off tester (After Mealiff et al. 2017).

Table C.2: Kansas DOT criteria for tensile bond strength based on KT-78.

Tensile Strength (psi)	**Bond Condition**
≥ 70	Good
35 – 69	Fair (minimum 35 psi)
< 35	Poor

C.6.1.3 Louisiana Tack Coat Quality Tester (LTCQT)

Mohammed et al. (2009) developed a modified version of the ATacker device called the Louisiana Tack Coat Quality Tester (LTCQT) as part of NCHRP Project 9-40. The LTCQT (Figure C.6) can be used in the field or laboratory to determine the tack coat quality of a tacked surface as measured by the tensile strength. The test involves applying the tack coat material at the prescribed residual application rate and application temperature to an area of 152.4 mm by 152.4

mm. A compressive preload stress of 10.8 kPa is applied for 3 min to the surface via the LTCQT loading plate. A tensile force is then applied at a displacement rate of 0.2 mm/s until failure. The tensile force is continuously recorded, and the tensile strength are computed and used in the analysis. The LTCQT was found to be a viable test for performing comparative evaluations of various tack coat materials and application rates in the field. Repeatability of measurements using the LTCQT was good, with an average coefficient of variation of less than 11%.

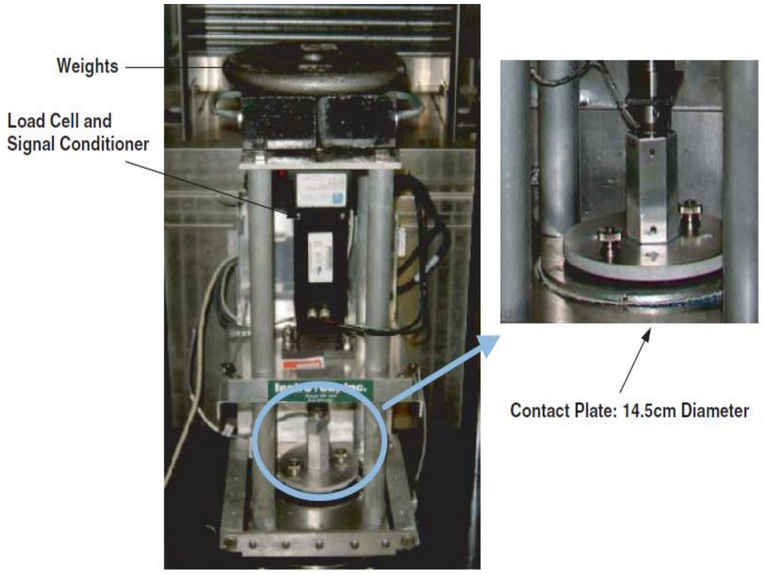


Figure C.6: Second generation of LTCQT (After Mohammad et al., 2012).

C.6.2. Torque Bond Strength Tests

Torque bond tests have been used to evaluate the bond strength between asphalt layers. These tests involves applying a torque load to a plate bonded to the surface of a sample until a twisting shear failure in the bond occurs. Torque tests can be used to evaluate the load needed to cause cohesive shear failure. Different bond tests have been reported in literature. Tashman et al. (2006) conducted torque bond tests according to the British Board of Agrément (BBA) procedure to determine the interlayer bond strength between the asphalt pavement layers in a study funded by Washington DOT. The tests were performed in the lab on core samples obtained from the field. In this study, the field cores were clamped below the interface using a gripping unit, as shown in Figure C.7a. A steel plate was then glued to the top surface of the specimen prior to the test (Figure C.7b). A torque wrench was then attached to the plate and a torque force was applied until the specimen failed. The force required for failure was recorded as well as the location of the failure (Figure C.7c). The manual bond test is generally limited to the interface between a thin surface and the lower layer material (Sutanto, 2010). This procedure results in difficulty to apply constant torque. Choi et al. (2005) used a constant torque rate of 6000 N.m/min, which is achieved by synchronizing the movement of the torque dial gauge with the second hand of an analogue clock. Again according to Babtie (2000), found it difficult to keep the application of the torque parallel to the interface resulting in axial bending on the specimen.

A field torque testing device (Figure C.8) was developed in a TxDOT study to compare the adhesion of the surface treatment to primed and unprimed base layers. The device imparts a horizontal torque to the surface at different vertical compressive loads and records the load required to cause shear failure at the surface. The device slips into a 2-inch, square tube hitch receiver and uses the weight of the vehicle to provide the reaction force. A pressure regulator and a tank of nitrogen gas control and provide the vertical load (30, 40, and 65 pounds per square inch (psi)) while a torque multiplier and torque wrench are used to apply and measure the torque required to rotate the rubber-coated foot pad through an angle of 120 degrees. Freeman et al. (2010) indicated that this test device is designed to be a measure of relative worth; a tool for ranking the performance, not an absolute engineering measurement. No work has been done in this limited study to determine the mechanical properties of the test or determine the engineering properties. Freeman et al. (2010) indicated that no comparisons were made between one test site and another due to differences in surface texture. It is worth noting that in the study conducted by Freeman et al. (2010), the foot pad was not attached to the pavement surface.

a. Torque Grip **b. Specimen Set-up** **c. Laboratory test**

Figure C.7: Laboratory torque bond test. (a) Torque Grip, (b) Specimen Set-up, and (c) Laboratory Test

Figure C.8: Texas Field Torque Device (After Freeman et al.2010)

C.7. Mix Design Methods for Micro-Surfacing

As indicated previously the performance of micro-surfacing treatments is greatly controlled by the micro-surfacing mix proportions, which are determined as part of the mix design procedure. There are currently several micro-surfacing mix design procedures; which include: ISSA A143 (ISSA Design Method For Micro-Surfacing), ASTM D 3910 (ASTM design method for slurry seals) ASTM D 6372-99a (ASTM design method for micro-surfacing), TTI 1289(Texas Transport Institute (TTI) design method), and California Department of Transportation (Caltrans) design method. According to a survey conducted by NCHRP Synthesis 411 (Gransberg, 2010), 12 out of 31 responding agencies used ISSA A143, three agencies use ASTM Design Method for Slurry

Seals (ASTM 2007a), two agencies used ASTM D 6372-99a, and only one of them used TTI 1289. Thus, ISSA A143 is the most popular method for designing micro-surfacing mixes.

C.7.1 ISSA Design Method for Micro-surfacing

Figure C.9 presents the main steps of the ISSA A143 procedure for designing micro-surfacing mix. The first step in the mix design is to select the mix components that satisfy the ISSA A143 specifications. According to ISSA A143, the aggregates must to conform one of two types of aggregate gradations: Type II or Type III. The gradations for the two types along with allowed tolerance are provided in Table C.3. The selection of the gradation type depends on the purpose for using micro-surfacing. Type II aggregate gradation is used to fill surface voids, address surface distresses, seal, and provide a durable wearing surface. On the other hand, Type III aggregate, which is relatively coarser, is appropriate for heavily traveled pavements, rut filling, or for placement on highly textured surfaces requiring larger size aggregate to fill voids. The selected aggregates used in micro-surfacing mixes must also to meet the properties shown in Table C.4. ISSA A143 does not specify the type of emulsion used in micro-surfacing, but it requires that the used emulsion meet the specifications presented in Table C.5. Portland cement, hydrated lime, fly ash or other approved filler can be used as a mineral filler, but it has to meet the requirements of ASTM D 242 “Standard Specification for Mineral Filler For Bituminous Paving Mixtures”. Water used for micro-surfacing must be free from harmful salts and contaminants. Additives are allowed to be used to accelerate or retard the break/set of the micro-surfacing mix but the appropriateness and their applicable use range should be approved as part of the mix design.

Once the mix components are selected, the proportions of the different components (i.e. aggregate, emulsion, water, and the mineral filers) are determined. Different tests shown in Table C.6 are used to achieve that. Mixing time test is first conducted following the procedure described in ISSA TB 113 to determine the optimum water content at which mixture can be mixed at room temperature (77ºF or 25ºC) for at least 120 seconds. Once the optimum water content is determined, mixes are prepared at three different asphalt contents. The other tests shown in Table C.6 are then conducted on the prepared mixes. The results of these tests are used to determine the emulsion content that will yield a micro-surfacing mix meeting the criteria in Table C.6. Wet track abrasion test (WTAT) is used to determine the minimum amount of emulsified asphalt content for the given mix to have a proper coating with the aggregate. In addition, the loaded wheel test (LWT) is conducted to establish the maximum asphalt content necessary for preventing bleeding under traffic loading. The wet cohesion test provides an estimate of the minimum time required for a mix before it can be subjected to traffic. The wet stripping test is used to examine the potential for stripping of a micro-surfacing mix. Since micro-surfacing can be used to fill ruts, it should have the proper resistance against vertical and lateral deformations under vertical loading (Robati, 2014). This can be examined using the lateral displacement test, which measures the amount of compaction or displacement of micro-surfacing under simulated rolling traffic compaction. After passing all the aforementioned tests, test for the compatibility of the mixes are done. The test result provides a rating system for abrasion loss, integrity and adhesion characteristics of a specified mix. The test values may relate to the field performance of paving mixtures. For a design to be acceptable, the mix must achieve a minimum of 11 grade points (i.e., AAA or AAB). Table C.7 shows the compatibility classification system.

As shown in Table C.8, ISSA A143 specifics limits for the percentages of micro-surfacing mix components. According to ISSA A143 specifications, the residual asphalt binder content in the mix should be 5.5-10.5% by dry weight of aggregates. In addition, mineral additives should be 0.0-3.0% by dry weight of the aggregate. Finally, polymer content should be at least 3% of the asphalt binder weight.

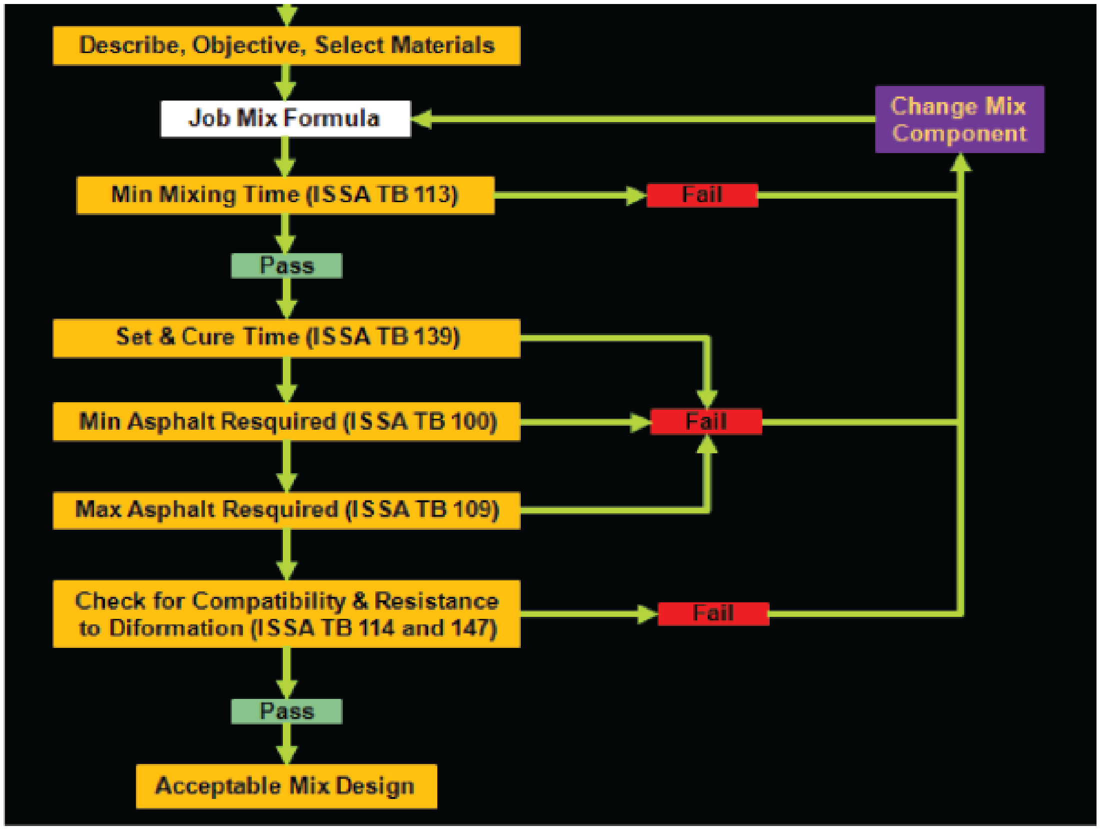


Figure C.9: ISSA A143 Procedure for Designing Micro-Surfacing Mix (Robati, 2014).

Table C.3: ISSA Type II and III aggregate gradation for Micro-surfacing (ISSA, 2010).

Sieve Size		**% Passing by Weight**		**Stockpile Tolerance,%**
in	**mm**	**Type II**	**Type III**	
3/8	9.5	100	100	
No. 4	4.75	90-100	70-90	+/- 5
No. 8	2.36	65-90	45-70	+/- 5
No. 16	1.18	45-70	28-50	+/- 5
No. 30	0.6	30-50	19-34	+/- 5
No. 50	0.3	18-30	25-Dec	+/- 4
No. 100	0.15	21-Oct	18-Jul	+/- 3
No.200	0.075	15-May	15-May	+/- 2

Table C.4: ISSA A143 Tests for Aggregate and Criteria for Micro-surfacing Mix (ISSA, 2010).

Test	Test Method		Specification
	AASHTO	ASTM	
Sand Equivalent Value of Soils and Fine Aggregate	T 176	D 2419	65 Minimum
Soundness of Aggregates by Use of Sodium Sulfate of Magnesium Sulfate	T 104	C 88	15% Maximum w/NA2SO4 25% Maximum w/MgSO4
Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine[1]	T 96	C 131	30% Maximum

[1]The abrasion test is run on the parent aggregate.

Table C.5: ISSA A143 Asphalt Emulsion Specifications for Micro-surfacing Mix (ISSA, 2010)

Test	Test Method		Specification
	AASHTO	ASTM	
Settlement and Storage Stability of Emulsified Asphalts, 24-h	T 59	D 6930	1% Maximum
Distillation of Emulsified Asphalt[1]	T 59	D 6997	62% Minimum
Tests on Emulsified Asphalt Residue			
Softening Point of Bitumen (Ring-and-Ball Apparatus)	T 53	D 36	135°F (57°C) Minimum
Penetration of Bituminous Materials at 77°F (25°C)	T 49	D 5	40-90[2]

[1] The temperature for this test should be held at 350°F (177°C) for 20 minutes.
[2] The climatic conditions should be considered when establishing this range.

Table C.6: ISSA A143 Mix Design Tests for Micro-surfacing Mix (ISSA, 2010).

ISSA Test No	Description	Specification
ISSA TB 113	Mix Time at 25°C	Controllable to 180 second Minimum
ISSA TB 139 (For Quick-Traffic)	Wet Cohesion 30 Minutes (Set) Wet Cohesion 60 Minute	12kg-cm Minimum 20kg-cm Minimum
ISSA TB 109 (For Heavy-Traffic)	Excess Asphalt by Loaded Wheel Test Sand Adhesion	538 g/m² Maximum
ISSA TB 114	Wet Stripping	Pass (90% Minimum)
ISSA TB 100	Wet Track Abrasion Lost, One-Hour Soak	538 g/m² Maximum
ISSA TB 100	Wet Track Abrasion Lost, Six-Days Soak	807 g/m² Maximum
ISSA TB 147	Lateral Displacement	5% Maximum
ISSA TB 144	Classification Test	Minimum 11 Points

Table C.7: Compatibility Classification system suggested by ISSA for Micro-surfacing Adapted from (ISSA, TB 144).

Grade Rating	Point Rating	Abrasion Loss, Grams	Integrity,% Retained	Adhesion,% Coated
A	4	0 – 0.70	90–100	90–100
B	3	0.71 – 1.00	75–89	75–89
C	2	1.01 – 1.30	50–74	50–74
D	1	1.31 – 2.00	10 – 49	10 – 49
0	0	2.01+	0	0

Table C.8: Limits for Micro-Surfacing Mix Components (After ISSA, 2010)

Component Materials	Suggested Limits
Residual Asphalt	5.5 - 10.5% by dry weight of aggregate
Mineral Filler	0.0 - 3.0% by dry weight of aggregate
Polymer Content	Minimum of 3.0% solids based on bitumen weight content
Additives	As needed
Water	As required to produce proper mix consistency

C.7.2. ASTM Design Method for Micro-Surfacing, ASTM D 6372-99a (ASTM, 1999)

ASTM D 6372-99a provides another method for the design of micro-surfacing mixes. The major difference between this method and ISSA A143 method is that the ASTM method specifies the use of only four out of the eight tests used in by ISSA A143 for mix design. The tests performed and their specifications are provided in Table C.9.

Table C.9: Mix design tests recommended by ASTM for micro-surfacing (ASTM, 1999).

ISSA TEST NO	DESCRIPTION	SPECIFICATION
ISSA TB 139 (For Quick-Traffic)	Wet cohesion 30 Minutes (Set) Wet cohesion 60 Minutes	12 kg-cm Minimum 20 kg-cm Minimum
ISSA TB 109 (For Heavy-Traffic)	Excess asphalt by loaded wheel test sand adhesion	538 g/m^2 Maximum
ISSA TB 100	Wet track abrasion lost, one-hour soak	807 g/m^2 Maximum
ISSA TB 144	Classification test	Minimum 11 points

C.8. Quality Control and Quality Assurance of Micro-surfacing

Proper field monitoring of the quality of micro-surfacing mixes is another important factor affecting the performance of these mixes. Field quality monitoring should include two primary activities: sampling of the field mix and correction of defects in workmanship. Sampling is used to verify that the mix conforms to the job mix formula. This is important due to variability in the aggregate and emulsion properties that might occur during construction, which can result in significant changes in the micro-surfacing mix properties and performance. Another major field quality management activity is monitoring and correction of defects in workmanship. This is very crucial to the success of the project since even if the mix meets all specifications it might not perform well if it is not properly installed (Gransberg, 2010).

Based on reviewing the materials and construction manuals of different DOTs, several DOTs have quality control/quality assurance specifications for micro-surfacing; these include: Indiana, Maine, Michigan, Minnesota, Missouri, Tennessee, West Virginia, California, and Florida. Field sampling of micro-surfacing mixes is required by most of these agencies. The testing of the samples primarily includes examining the gradation and detrimental fine dust or clay-like particles in the aggregate as well as determining the residual asphalt binder content in the micro-surfacing mix. Although the same tests are used, DOT have differences in the specified sampling frequency as shown in Table C.10. While most DOTs require obtaining one sample for aggregate testing every 500 tons or every day of construction, whichever is greater, California DOT requires obtaining a sample every 300 tons of mixture. In addition, most DOTs require determining residual binder content three times per day. Tolerances in the required tests also varies among the states requirements. Table C.10 presents the tolerances specified by different DOTs for QC/QA testing. For aggregate gradation, tolerance limits for most DOTs are $\pm 5\%$ for sieve No. 4, 8, 16, 30, and 50 and $\pm 3\%$ and $\pm 2\%$ for sieve no 100 and 200, respectively, from the Job Mix Formula (JMF). For the sand equivalent test, the tolerance limit is 7% from the JMF. The tolerance limit for residual binder content also differs between states. Michigan DOT requires the tolerance limit for single test is $\pm 0.5\%$ and for daily average the limit is $\pm 0.2\%$ from the JMF. Florida and Missouri DOT have tolerance limit for each test is $\pm 0.6\%$ and $\pm 0.3\%$ respectively, and do not require the average of the daily conducted test. The majority of the state DOTs rely on the contractor to perform the required quality control tests. Some DOTs like Missouri DOT have a QC and QA programs for micro-surfacing where QC tests are done contractor but there QA tests are performed by the DOT for verification. In QA program, tests for gradation, residual asphalt content, and deleterious material are done once per day and the tests results are compared with the test results found for the QC program done by the contractors. The difference between the gradation results form the QC and QA is supposed to conform to the values provided in Table C.11.

Table C.10: Frequency for the QC/QA tests.

States	Frequency for the tests			
	Gradation	Sand equivalency	Residual Asphalt Content	Application Rate
Florida[1]	One sample per day	One sample per day	One sample per day	
Indiana[2]	one per 500 T	one per 500 T	three times a day	three times a day
Maine[2]				
Michigan[2]	One per 500T	One per 500T	three times a day	three times a day
Minnesota				
Missouri[3]	one per 600 T of mixture	one per 600 T of mixture	one per 600 T of mixture	
	one per day	one per day	one per day	
Tennessee			three times a day	three times a day
West Virginia[2]	One per 500T	One per 500T	three times a day	three times a day
California	one per 300T	one per 300 T		

Table C.11: Tolerance for the QC/QA tests.

DOT	Aggregate Gradation Tolerance							Sand Equivalent	Determination Asphalt Content		Application rate
	#4	#8	#16	#30	#50	#100	#200		Single Test	Daily Average	
Florida[1]	±6%	±7%			±6%		±3%		±0.6%[6]		±2%
Indiana[2]	±5%	±5%	±5%	±5%	±4%	±3%	±2%	±7%	±0.5%[7]	±0.2%	±1%
Maine[2]	±7%	±4%				±3%	±2%				
Michigan[2]	±5%	±5%	±5%	±5%	±4%	±3%	±2%	±7%	±0.5%[7]	±0.2%	±2%
Minnesota	±5%	±5%	±5%	±5%	±4%	±3%	±2%	±7%	±0.5%[7]		
Missouri[4]	±4%	±4%					±1%		±0.3%[8]		
Missouri[3]	±4%	±3%	±3%	±3%	±2%	±2%	±2%		±0.3%[8]		
Tennessee									±0.5%[7]		±2%
West Virginia[5]	±5%	±5%	±5%	±5%	±4%	±3%	±2%	±7%	±0.5%[7]	±0.2%	±2%
California											

[1] The Engineer shall obtain one sample of micro-surfacing mixture for each day of production.
[2] The contractor shall sample fine aggregate from the project stockpile and test for gradation
[3] Testing shall be done by the contractor
[4] Testing shall be done by the DOT and the test results are compared with the tests done by the contractors
[5] Aggregate shall be randomly sampled from the composite cold feed belt or the hot bins and samples for determination of the asphalt binder content shall be retrieved from the hot elevator at the asphalt plant or from the transport truck at the plant by random sampling.
[6]FM 5-563: Quantitative Determination Of Asphalt Content From Asphalt Paving Mixtures By The Ignition Method
[7]From Equipment Counter Display
[8]AASHT O T 308: Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method& AASHTO T 287: Standard Method of Test for Asphalt Binder Content of Asphalt Mixtures by the Nuclear Method

C.9 References

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AASHTO T 104, Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate

AASHTO T 96, Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

AASHTO T 59, Standard Method of Test for Emulsified Asphalts: Settlement and Storage Stability of Asphalt Emulsion.

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