Determining Bond Strength of Micro-surfacing Mixes-Phase 2

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16. Abstract

This report summarizes results of a project that was completed to determine the benefits and drawbacks of using tack coat in micro-surfacing applications and identify the tack coat application rate that will result in the optimum interface bond strength and better performance for micro-surfacing applications using different tack coat materials. The project included conducting comprehensive field and laboratory testing programs. The field-testing program constructing a total of 25 test sections in two micro-surfacing projects to examine the effect of different factors on the bond strength between micro-surfacing mixes and existing asphalt surfaces. The evaluated effects included: the tack coat material type and application rate, the micro-surfacing mix residual binder content, and the existing surface type and condition (on existing pavement or on micro-surfacing leveling course). The laboratory testing program included preparing samples using materials collected from the field during the construction of test sections. The program was focused in examining the effect of the tack coat type, application rate, the residual asphalt binder content of the micro-surfacing mix, and existing pavement texture on micro-surfacing bond performance. The results of bond strength tests conducted on the samples obtained from the field test sections indicated that the sections with no tack coat had significantly lower bond strength than those with tack coat with at least 0.042 gsy total application (0.0068 gsy residual application rate). Furthermore, the results indicated that the use of 0.75% lower residual asphalt binder content in micro-surfacing mixes resulted in significantly lower bond strength between the micro-surfacing and existing pavement. Based on the results of this study, it is recommended that ODOT continue using the current specification for micro-surfacing (Item 421) that requires placing a tack coat with a total application rate of 0.06 to 0.12 gallon per square yard (0.25 to 0.45 L/m²) on existing pavement surfaces prior to the application of a micro-surfacing layer.

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Executive Summary

This report summarizes the results of a project that was completed to determine the benefits and drawbacks of using tack coat in micro-surfacing applications and identify the tack coat application rate that will result in the optimum interface bond strength and better performance for micro-surfacing applications using different tack coat materials. This project included conducting comprehensive field and laboratory testing programs. The field-testing program involved constructing a total of 25 test sections in two micro-surfacing projects to examine the effect of different factors on the bond strength between micro-surfacing mixes and existing asphalt surfaces. The evaluated effects included: the tack coat material type and application rate, the micro-surfacing mix residual binder content, and the existing surface type and condition (on existing pavement or on micro-surfacing leveling course). The first project was located on the eastbound lane of State Route (SR) 274 in Shelby County. The project included installing a single micro-surfacing layer for 11 test sections. The second project was located on SR 03 in Wayne County. This project included installing 14 test sections: 7 sections with a single micro-surfacing layer on the southbound of SR 03, and 7 sections with double micro-surfacing layers on the northbound of SR 03. Core lane samples were obtained from the different sections one week, 4 months, and 12 months after construction. The cores were tested in the laboratory using two varieties of pull-off tests and a torque bond strength test, which was developed as part of this project. The field performance of the test sections was also evaluated after 12 months of construction. The laboratory testing program included preparing samples using materials collected from the field during the construction of test sections on SR 03. The program was focused in examining the effect of the tack coat type, application rate, the residual asphalt binder content of the micro-surfacing mix, and existing pavement texture on micro-surfacing bond performance.

The results of bond strength tests conducted on the samples obtained from the field test section indicated that the sections with no tack coat had significantly lower bond strength than those with tack coat with at least 0.042 gsy total application (0.0068 gsy residual application rate). Furthermore, the results indicated that the use of 0.75% lower residual asphalt binder content in micro-surfacing mixes resulted in significantly lower bond strength between the micro-surfacing and existing pavement. The results also suggested that increasing the application rate of tack coat resulted in improving the bond strength. However, the improvement was not significant when the total application of tack coat was higher than 0.06 gsy (0.01 gsy residual application rate). The results indicated that using a CSS-1hM emulsion for tack coat might result in higher bond strength than a SS-1h emulsion. The results of the torque bond strength tests conducted on the samples obtained from the field test sections with double micro-surfacing layers indicated that sections with a tack coat application rate of at least 0.03 gsy between the first and second layer resulted in significantly improving the interlayer bonding strength. However, the pull-off tests showed that there was no significant improvement in interlayer bond strength due to applying tack coat between the micro-surfacing layers.

Based on the results of this study, it was recommended that ODOT continue using the current specification for micro-surfacing (Item 421) that requires placing a tack coat with a total application rate of 0.06 to 0.12 gallon per square yard (0.25 to 0.45 L/m²) on existing pavement

surfaces prior to the application of a micro-surfacing layer with a minimum of 15% asphalt residue content. It is recommended to monitor the long-term performance of the test sections constructed in this project by annually evaluating them for the first five years after construction. It is also recommended that the torque bond strength and Proceq pull-off tests be conducted on core samples obtained at least two months after the installation of micro-surfacing as part of future performance-based specifications for tack coat in micro-surfacing applications. The average value of three Proceq pull-off tests should be 125 lbf or greater. In addition, the average value of three torque bond strength tests should be 220 lbf.in or greater.

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 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 piece of 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 then immediate placed using a spread box. 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 existing pavement surface prior to the application of a micro-surfacing mix to improve the bond strength along the interface between the two materials. The tack coat shall consist of a minimum of 15% asphalt residue and be applied at a rate of 0.06 to 0.12 gallon per square yard (0.25 to 0.45 L/m^2) achieved by diluting with water.

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 aged 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, if used, it may cause flushing in the newly placed micro-surfacing mix. However, the risk of not using a tack coat may include delamination of the micro-surfacing mix from the existing pavement surface. Further, no previous research study has examined the bond strength of micro-surfacing mixes or the effect of tack coat on this bond. Therefore, research was needed to evaluate the bond strength between micro-surfacing mixes and existing pavement surfaces with and without the application of tack coat to determine if tack coat is needed in micro-surfacing applications. In addition, there was a need to evaluate the impact of the tack coat materials, application rates, micro-surfacing mix properties, and pavement surface conditions on the interface bond strength. Therefore, this project is the first research study to be done to evaluate the bond strength between micro-surfacing mixes and existing pavement and understand the effects of different factors on this strength.

ODOT initiated the project entitled "*Determining Bond Strength of Micro-surfacing Mixes -Phase 1*" (referred to as Phase 1 hereinafter) 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, summarize studies on the evaluation of bond strength between micro-surfacing mixes and existing pavement surfaces, and identify available tests that are used for measuring the interface bond strength to determine the most appropriate to use in micro-surfacing applications. 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, which included two projects: one that uses only micro-surfacing surface course and another that utilizes leveling and surfacing micro-surfacing layers. Furthermore, it was also recommended to consider two types of field bonding strength tests: 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.

The objective of Phase 2 of this project is to examine the bond strength between micro-surfacing mixes and existing asphalt surfaces with and without tack coat. In addition, it also examines the effect 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 also develops 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 per year, as close to 9 million square yards of micro-surfacing were placed 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.

The results of the comprehensive literature review conducted in Phase 1 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. Different factors can affect the bonding strength between micro-surfacing mix and existing surface: tack coat application rate, tack coat material type, micro-surfacing mix emulsion content, and existing surface conditions. In addition, 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. This is the case in micro-surfacing, further, direct shear tests cannot be conducted in the field as they require 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).

Phase 2 of this study included conducting the following tasks to achieve the outlined objectives:

Task 1. Purchase/Fabricate Bond Strength Test Devices
Task 2. Conduct Laboratory Testing
Task 3. Recommend Test Procedure for Measuring Bond Strength
Task 4. Construct Field Test Sections
Task 5. Field Evaluation of Test Sections
Task 6. Laboratory Testing of Field Samples
Task 7. Analysis of Test Results
Task 8. Make recommendations on Tack Coat Specifications for use with Micro-surfacing Applications
Task 9. Prepare and Submit Final Report

3. Research Approach

The following subsections summarize the research approach that was followed in this Phase 2 to evaluate and improve the current practice for using tack coat in micro-surfacing applications.

3.1 Purchase/Fabricate Bond Strength Test Devices

Two types of bonding strength tests were considered in this study: 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 (Figure 1) and Proceq DY 206 (Figure 2), were selected to be used in examining the different factors affecting the bond strength of micro-surfacing mixes. It is noted that Com-Ten pull-off test is a displacement-controlled test while the Proceq DY-206 is a load-controlled test. The research team purchased the two pull-off test devices. A low-cost laboratory torque device was developed in this study to characterize the bond strength in shear mode. The assembly of the device is shown in Figure 3. As can be seen from this figure, the torque device is comprised of several parts including a split mold with set screws attached to it, a torque adapter to measure the applied torque, a torque multiplier, a converter, and a torque wrench. The torque specimen was partially cored through the top layer and up to half an inch into the bottom layer. A metal disk was glued to the top of the surface. The specimen was then moved into the split mold and was fixed with the set screw in order to prevent any movement while applying torque. Torque was then applied by turning both handles of the wrench by hand with a consistent motion until failure occurred. During the application of the torque, the torque wrench was kept parallel with respect to the top surface of the specimen to avoid any effect of bending. A torque application rate of 4 rev/min was maintained throughout the study to avoid a variation due to an inconsistent application rate. The torque was applied until the failure occurred.

3.2 Conduct Preliminary Laboratory Testing

A limited lab testing program was conducted to determine the variables to be used in the field-testing program. An approved job mix formula (JMF) of a micro-surfacing mix was obtained. The bonding strength between micro-surfacing mixes with three asphalt emulsion contents and a typical asphalt surface mix was evaluated: optimum emulsion content in the JMF as well as 0.75% above and below the optimum emulsion content. The testing program also included evaluating four different tack coat application rates for mixtures with: 0 (no tack coat), 0.03 gallons per square yard (diluted), 0.06 gallons per square yard (diluted), and 0.10 gallons per square yard (diluted).


Figure 1. Com-Ten Pull-off Tester

Figure 2. Proceq Dy-206 Pull-off Testing Device

A sample preparation procedure was first developed. In this procedure, the micro-surfacing mix was prepared following the instructions provided in ISSA TB 113. The mixing temperature was maintained at 25°C, as specified in ISSA TB 113. The prepared mix was then poured on top of a hot mix asphalt (HMA) sample that was compacted to a target air void level of 7.0 ±1.0% and a height of 57 mm using a Superpave gyratory compactor (SGC). A plastic ring with a thickness of 0.25 inch and an inside diameter of 150 mm was used to maintain a thickness of 0.25 inches. Before the micro-surfacing mix was poured onto the HMA, tack coat was applied on the surface of the HMA sample base at the target tack application rate. The tack coat was allowed to cure before the micro-surfacing mix was placed on top of the sample. After allowing the mix to dry for at least 72 hours, the mix was compacted using a Hamburg wheel track device (HWTD) with 1000-wheel passes. The compaction using the HWTD was done to 1) simulate the compaction due to traffic load in the field and 2) make the micro-surfacing mix stiff enough so that the failure location would be at the interface between the micro-surfacing mix and the HMA substrate. Finally, two 2-inch diameter cores were drilled through the micro-surfacing mix and about half an inch into the HMA substrate along the compacted zone. All samples were tested exactly 21 days after preparing the micro-surfacing mix in order to exclude any variability associated with aging.

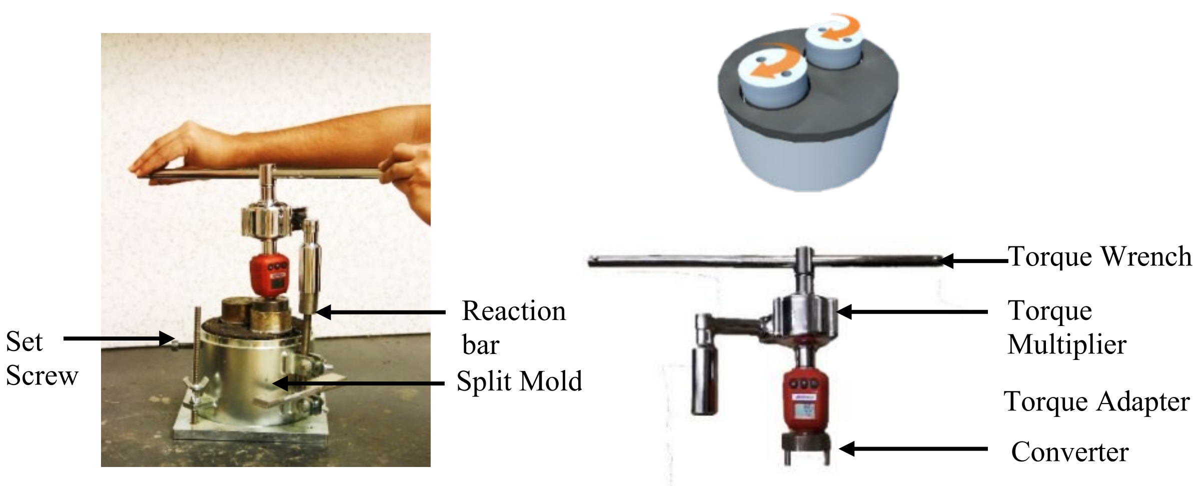

Figure 3. Torque Bonding Test

The Com-Ten and Proceq DY-206 pull-off tests as well as the torque bonding strength test were used to evaluate the bond strength of the micro-surfacing mix. Replicate samples were prepared to evaluate the repeatability of the three tests.

This task evaluated the performance of micro-surfacing mixes prepared with the three different emulsion contents. Three tests were used in this evaluation: the wet track abrasion test (WTAT) (ISSA TB 100), excess asphalt by loaded wheel test (LWT) test (ISSA TB 109) and lateral displacement test (ISSA TB 147- Method A). The WTAT was used to determine if the lowest emulsified asphalt content is enough to provide a proper coating with the aggregate. In addition, the excess asphalt test was conducted to ensure the higher emulsion content will not cause bleeding under traffic loading. Finally, the lateral displacement test (ISSA TB 147- Method A) was used to evaluate the rutting resistance of the different micro-surfacing mixes.

3.3 Field-Testing Program

A preliminary laboratory testing field-testing matrix was developed. This matrix included examining the bond strength between micro-surfacing mixes and existing asphalt surfaces with and without tack coat. In addition, it also evaluated the effects of tack coat material type and application rate as well as micro-surfacing mix binder content and existing surface type and condition (on existing pavement or on micro-surfacing leveling course) on the bond strength. The field-testing matrix included the following factors:

1. Existing surface conditions:

- Old: Existing surfaces with different levels of raveling and aging.
- New: Between micro-surfacing leveling course and micro-surfacing surface course.

2. Micro-surfacing mix residual binder content:
   - The design residual binder content in the JMF.
   - 0.75% lower than the design residual binder content in the JMF.
3. Tack coat application rate:
   - 0 (no tack coat)
   - 0.03 gallons per square yard (diluted)
   - 0.06 gallons per square yard (diluted)
   - 0.10 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

3.3.1 Description of Field Test Section

The field-testing program included the installation of micro-surfacing test sections in two field projects. The first project was located on the eastbound of State Route (SR) 274 in Shelby County between mileposts 10.73 and 13.35. The project included installing a single micro-surfacing layer for 11 test sections. Table 1 presents the details for each of the constructed test sections. As shown in Table 1, the test sections had different tack coat types, tack coat application rates, micro-surfacing mix residual binder content, and existing pavement surface conditions. It is noted that the length of test sections was about 1000 ft to 1600 ft. It is also worth mentioning that during the installation of section 1, the tack coat material type was changed from CSS-1hM to SS-1h for the last 300 feet.

The second project was located on SR 03 in Wayne County between mileposts 26.13 and 27.25. This project included installing 14 test sections: 7 sections on the southbound of SR 03, and 7 test sections on the northbound of SR 03. Tables 2 and 3 present the details for each installed test section. As shown in the tables, the first 7 sections included installing a single course micro-surfacing placed on an existing pavement surface. In addition, sections 8 through 14 included installing leveling micro-surface courses on the existing pavement. As shown in Tables 2 and 43, the effects of different variables were evaluated in SR 03 project, which included: tack coat type, tack coat application rate, and micro-surfacing mix residual binder content. It is noted that the length of each test section in the second project was about 900 ft. It is also worth to mention that during placing of the second layer at section 9, the emulsion content was changed from 11.6% to 10.4% for the last 317 feet from section length. It is worth noting that the lower residual asphalt binder content limit in the micro-surfacing mix used in some test sections in SR 274 project was 0.7% lower than the residual asphalt binder content in the JMF (7.7%). In addition, the lower limit was 0.75% lower than the residual binder content in the JMF (7.8%) for some sections in SR 03 project.

3.3.2 Evaluation of Test Sections prior to Construction

The pavement condition for the two selected projects was assessed. To this end, the Light Weight Deflectometer (LWD) test was conducted on different points along the projects to examine the uniformity in structural capacity of pavement structure. Different tests were also conducted to measure the pavement surface texture at different locations within the test sections. The conducted tests included: the circular track meter (CTM) (ASTM E2157), the AMES texture scanner, sand patch test (SPT) (ASTM E 965) and Dynamic Friction Tester (DFT) (ASTM E 1911-98). Field cores were also obtained from different locations within some test sections. The AMES texture scanner was used on those cores to examine the test sections. It is worth noting that these cores were used to prepared samples in the laboratory to examine the effect of existing pavement surface condition on bond strength of micro-surfacing mixes. Figure B.3 presents some of the photographs taken while measuring surface texture profile as well as evaluating the structural capacity of test sections in both selected projects using the different tests.

3.3.3 Construction of Test Sections

The test sections in the first project (SR 274) were constructed on June 7, 2019. The first 7 test sections in the second project (SR 03) were constructed on July 2, 2019, and, the rest of the test sections were constructed on July 9, 2019. Meetings with the designated personnel in the ODOT District offices and the contractors' representatives were held prior to installation of micro-surfacing mix to coordinate the construction activities and discuss the field sampling and testing plans. Prior to micro-surfacing installation, the tack coat distributor trucks were calibrated according to ASTM D2995 (Standard Practice for Estimating Application Rate of Bituminous Distributors) to ensure that the distributors could uniformly apply the tack coat at the selected application rate. Based on the calibration experiments, the rates to be used for each distributor truck was selected for every application rate considered. Figure A.4 presents pictures taken during the calibration of the distributor trucks.

Table 1. Test Section Matrix for Project 1

Section	**Tack Coat Material Type**	**Tack Coat Application Rate (gsy)**	**Residual Asphalt Binder Content of Micro-Surfacing Mix**	**Road Condition**	**Milepost**	
					Begin	**End**
1-A	CSS-1H/SS-1H	0.03	0.7% lower than JMF residual binder content (7.0%)	Typical Aging	10.73	10.79
1-B	CSS-1hM	0.03			10.79	10.92
2		0.06			10.92	11.10
3	CSS-1hM	0.06	JMF residual binder content (7.7%)	Highly aged	11.10	11.4
4		0.10			11.40	11.70
5		0.03			11.70	12.00
6		0.03		Typical Aging	12.00	12.20
7		0.10			12.20	12.40
8	CSS-1H/SS-1H	0.10			12.40	12.60
9		0.03			12.60	12.80
10		0.06			12.80	13.15
11	None	None			13.15	13.35

Table 2. Test Section Matrix for Project 2 (Single Course Micro-Surfacing Test Sections)

Section	Tack Coat Material Type	Tack Coat Diluted Application Rate (gsy)	Residual Asphalt Binder Content of Micro-Surfacing Mix	Milepost	
				Begin	End
1	Same as micro-surfacing mix (CSS-1hM)	0.03	0.75% lower than JMF residual binder content (7.05%)	26.13	26.30
2	None	None	JMF residual binder content (7.8%)	26.30	26.45
3	Same as micro-surfacing mix (CSS-1hM)	0.03		26.45	26.61
4		0.06		26.61	26.77
5		0.10		26.77	26.93
6	SS-1h/CSS-1h	0.10		26.93	27.09
7		0.03		27.09	27.25

Table 3. Test Section Matrix for Project 2 (Double Course Micro-Surfacing Test Sections)

Section	Sections on Existing Pavement Surface			Sections on New Leveling Course		Milepost	
	Tack Coat Material Type	Tack Coat Diluted Application Rate (gsy)	Residual Binder Content of Surfacing Mix	Tack Coat Material Type	Tack Coat Diluted Application Rate (gsy)	Begin	End
8	Same as micro-surfacing mix (CSS-1hM)	0.03	0.75% lower than JMF residual binder content (7.05%)	Same as micro-surfacing	0.03	26.13	26.30
9-A	None	None	JMF residual binder content (7.8%)	None	None	26.30	26.39
9-B	None	None	0.75% lower than JMF residual binder content (7.05%)	None	None	26.39	26.45
10	Same as micro-surfacing	0.06	JMF residual binder	None	None	26.45	26.61
11		0.06			0.03	26.61	26.77

12	mix (CSS-1hM)	0.06	content (7.8%)	CSS-1hM)	0.06	26.77	26.93
13	SS-1h/CSS-1h	0.06		SS-1h	0.03	26.93	27.09
14		0.06			0.06	27.09	27.25

During construction, the application rate was measured for each test section according to ASTM D2995. This was done by fixing a pre-weighed 1 ft^2 roofing paper on top of a steel plate and placing the steel plate on the pavement immediately prior to spaying the tack coat. The roofing paper with tack coat were collected after tack coat spraying and re-weighed. Figure A.5 presents pictures taken during the measurements of tack coat application rate for test sections in each project.

Videos and photographs were also taken to document the installation process. Figure A.6 presents some of the photographs taken during the installation process. Samples of each tack coat material were collected from each distributor truck. In addition, samples of the emulsion and aggregate used in the micro-surfacing mix(es) were collected during construction. It is noted that all micro-surfacing mixes met ODOT specifications.

3.3.4 Field Evaluation and Testing of Installed Test Sections

Field evaluations of the constructed test sections were conducted along the wheel path areas one week, 4 months, and twelve months after construction. The field evaluation involved assessing the road surface condition and examining the severity and extent of any type of distress that occurred in the test sections. Videos and photographs of the surface condition of each test section were obtained to document the road condition. The field evaluation also included obtaining at least six 6-inch core samples from each test section in the two projects. Coring was performed at a very slow and steady speed to avoid any damage to the obtained samples. Samples were carefully labeled and transported to laboratory for testing.

3.5 Lab Testing of Samples Collected in the Field

3.5.1 Testing of Field Cores

Com-Ten and Proceq DY-206 pull-off tests, as well as torque tests were conducted on the cores to examine the interlayer bond strength of the micro-surfacing mixes for the different test sections installed in both projects. The testing included making three 2-inch diameter cores in each field core sample. After coring, the surface of each small 2-inch diameter samples were prepared using sand paper and grinder (if needed) to prepare for gluing the metal disc with epoxy needed for testing. Figure A.7 in Appendix A shows an example of field core samples that were prepared in the lab for testing. All samples were conditioned for at least three hours at a temperature of 25 ^{o}C prior to testing. The results of the lab testing of the field cores obtained from both projects are discussed in section B.2 of Appendix B.

3.5.2 Testing of Lab Prepared Samples

Based on the results of bonding tests conducted in the lab for field samples, further lab testing was conducted to evaluate the effect of the tack coat application rate on bond strength and validate the test results obtained for field samples in a more controlled environment. The lab testing plan included examining the effect of the tack coat type, application rate, and the residual asphalt binder content of the micro-surfacing mix. Table 4 presents the lab testing matrix. Moreover, the lab testing plan included evaluating the effect of existing pavement surface texture on bond strength. To this end, the surface texture of the field cores obtained prior to construction of test sections in the SR 03 project was evaluated using an AMES scanner. The cores were divided into three groups: low, medium, high MDP value, and given group names as 1, 2, and 3, respectively. A tack coat application rate of 0.06 gsy was used in all samples used to examine the surface texture effect. Finally, the effect of tack coat curing time was also evaluated. The results of lab testing of the lab prepared samples are discussed in section B.4 of Appendix B.

A sample preparation procedure similar to that described in Section 3.2 was used to prepare lab specimens. Specimens were prepared using the aggregates and emulsion samples obtained from the field according to the proportion in the job mix design and tack coat rates shown in Table 4. It is worth to mention that in the case of double layers of micro-surfacing mix, the first layer was let to set for seven days before applying the second layer. This waiting period was selected to simulate the field conditions since there was a gap period of seven days between the application of the two micro-surfacing layers in the second project. -Com-Ten and Proceq DY-206 pull-off tests, as well as torque tests were conducted to examine the bond interlayer strength for the different samples. At least 4 samples were tested for each bond strength test.

Table 4. Laboratory Testing Matrix

Sample ID	First layer			Second layer		
	Emulsion content	Tack material	Tack coat app rate (gsy)	Emulsion content	Tack material	Tack coat app rate(gsy)
S1	Low	CSS-1hM	0.025			
S2	Regular	None	0			
S3	Regular	CSS-1hM	0.025			
S4	Regular	CSS-1hM	0.060			
S5	Regular	CSS-1hM	0.108			
S6	Regular	SS-1h	0.108			
S7	Regular	SS-1h	0.025			
S8	Low	CSS-1hM	0.025	Low	CSS-1hM	0.025
S9	Regular	None	0	Regular	None	0
S10	Regular	CSS-1hM	0.060	Regular	None	0
S11	Regular	CSS-1hM	0.060	Regular	CSS-1hM	0.025
S12	Regular	CSS-1hM	0.060	Regular	CSS-1hM	0.060
S13	Regular	SS-1h	0.060	Regular	SS-1h	0.025
S14	Regular	SS-1h	0.060	Regular	SS-1h	0.060
S15	Low	None	0	Low	None	0

3.5.2 Testing of Tack Coat

Basic material characterization tests on the tack coat materials were conducted, which included: residue by distillation, and the softening point test. In addition, dynamic shear rheometer (DSR) tests were conducted in accordance with AASHTO T315 (Determining the Rheological Properties of Asphalt Binder Using Dynamic Shear Rheometer -AASHTO, 2010) on the tack coat materials residual asphalt binder to determine the Superpave higher performance grade (PG) as well as the master-curve for each type of the tack coat residual binder. Results of lab testing for tack coat residue samples are discussed in section B.4.6 of Appendix B.

3.6 Analysis of Test Results

A statistical analysis was performed on the results of the field and lab samples testing to evaluate the effect of different factors considered on the bonding strength of micro-surfacing mixes. To this end, analysis of variance (ANOVA) and post ANOVA least square mean (LSM) statistical analyses were conducted using Statistical Analysis Software (SAS) on the obtained data. A 95% confidence level (α-value of 0.05) was used in the analyses. Based on the results of this statistical strength of micro-surfacing mixes were determined.

3.7 Evaluation of the Relationship Between Field Performance and Bond Strength

The ability of the selected bond strength tests to identify sections with good and poor performance as related to debonding and delamination was evaluated in this study. To this end, the performance information for all micro-surfacing projects that were constructed in the last four years were obtained from the ODOT Office of Pavement Engineering. The information included the pavement condition rating (PCR) data for the pavement before and after installing micro-surfacing treatments. The PCR data were examined to identify micro-surfacing sections that had distress code 4 (SDD - Surface disintegration or debonding) with high severity and extent. The results of the analysis of PCR data of micro-surfacing projects are discussed in section B.5.1 of Appendix B.

The bond strength of several micro-surfacing sections including the test sections constructed in this study were evaluated few months after construction. The sections were located on SR 274, SR 03, SR 97, and SR 598. This was done by obtaining cores from these sections and testing the same using the Proceq pull-off and torque tests. District 3 had a micro-surfacing section on SR 89 that debonded and delaminated a few months after construction. This section was located between State Line Mile (SLM) 15.58 and SLM 18.42. Delamination and debonding also occurred in various areas on SR 89. These included:

- Northbound: SLM 16.60, 16.76, 16.78, 17.08, 17.23, 17.35, and 17.91-17.99.
- Southbound: SLM 16.60, 16.91-16.96, 18.25.

A field evaluation was conducted on this route to investigate the delamination. Several cores were obtained from the following locations from the micro-surfacing section on SR 89 to relate the field performance to bond strength values:

- SLM 16.91 on southbound which had severe delamination issues.
- SLM 16.60 on northbound which had some delamination issues.
- SLM 15.60-16.00 on southbound which had no delamination issues, coring was done at SLM 15.71.

Proceq pull-off testing and torque testing were conducted on the field cores obtained from the deteriorated locations with SR 89 micro-surfacing section. Results of lab testing for field cores obtained from sections with known performance are discussed in section B.5.2 of Appendix B.

4. Research Findings and Conclusions

Appendices A and B present details of field and laboratory testing programs conducted in of this study and analyses of testing results, respectively. The main findings of this study are summarized below.

- The results of bond strength tests conducted on the samples obtained from the field test section indicated that, at 95% confidence level, the sections with no tack coat had significantly lower bond strength than those with tack coat with at least 0.042 gsy total application (0.0068 gsy residual application rate).
- The results indicated that increasing the application rate of tack coat results in improving the bond strength. However, the improvement was not significant when total application rate was higher than 0.06 gsy (0.01 gsy residual application rate).
- The results indicated that, at 95% confidence level, the use of 0.75% lower residual asphalt binder content in micro-surfacing mix than that in JMF mix design resulted in significantly lower bond strength between the micro-surfacing and existing pavement.
- The results indicated that using CSS-1hM emulsion for tack coat might result in higher bond strength than the SS-1h emulsion.
- The results indicated that the minimum value to ensure no debonding or delamination is 125 lbf in the Proceq and 220 lbf.in in the torque test.
- The results of the torque bond strength tests conducted on the samples obtained from the field test sections with double micro-surfacing layers indicated that sections with tack coat application rate of at least 0.03 gsy between the first and second layer resulted in significantly improving the interlayer bond strength.
- The results of the Com-ten and Proceq tests conducted on the samples obtained from the field test section with double micro-surfacing layers indicated that sections with tack coat application rate of at least 0.03 gsy between the first and second layers resulted in improving the interlayer bond strength; however, this improvement was not statistically significant.
- The micro-surfacing interlayer bond strength increased with time and traffic during the first year of service. However, the most significant increase in the bond strength occurred during the first few months of service.

5. Recommendations for Implementation

Based on the results of the of this study, the following recommendations are made:

- ODOT continue using the current specification for micro-surfacing (Item 421) that requires placing a tack coat with a total application rate of *0.06 to 0.12 gallon per square yard (0.25 to 0.45 L/m²)* on existing pavement surfaces prior to the application of a micro-surfacing layer. The asphalt residue content of the tack coat should be at least 15%. In addition, the contractor should apply tack coat that provides uniform coverage without excess run-off and allow tack to break before releasing to construction traffic.
- The initial performance of the all test sections was evaluated and documented in this study; however, it is recommended to monitor the long-term performance of these sections. To this end, it is recommended that the sections be evaluated annually for the first five years after construction.

- It is recommended that ODOT consider in the future changing the current specifications for double micro-surfacing layers by requiring the applications of tack coat with a total application rate of 0.03 to 0.06 gallon per square yard (0.12 to 0.25 L/m²) on top of a leveling course prior to placing the surface course. However, this decision should be based on the long-term performance of test sections with double micro-surfacing layers on SR 03.
- It is recommended that ODOT consider changing the current specifications for micro-surfacing (Item 421) by requiring that the minimum residual asphalt binder content by dry weight of aggregate to be 7.5 percent instead of 7.0 percent for leveling and surface courses.
- If ODOT decides in the future to use performance-based specifications, it is recommended that the torque bond strength and the Proceq pull-off tests be conducted on core samples obtained at least two months after the installation of micro-surfacing layer(s). Appendix C provides the procedures for conducting the torque and pull-off tests on core samples. The average pull-off force value for three samples should be 125 lbf or greater. In addition, the average torque value for three samples should be 220 lbf.in or greater.

6. References

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Appendix A Testing Program

A.1 Description of Field Test Section

The field-testing program included examining the bond strength between micro-surfacing mixes and existing asphalt surfaces with and without tack coat. In addition, it also evaluated 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. The field-testing matrix included the following factors:

2. Existing surface conditions:
   - Old: Existing surfaces with different levels of raveling and aging
   - New: Between micro-surfacing leveling course and micro-surfacing surface course
3. Miro-surfacing mix type:
   - Leveling course mix
   - Surface course mix
4. Micro-surfacing mix residual binder content:
   - Residual binder content in the JMF.
   - 0.75% lower than the residual binder content in the JMF.
5. Tack coat application rate:
   - 0 (no tack coat)
   - 0.03 gallons per square yard (diluted)
   - 0.06 gallons per square yard (diluted)
   - 0.10 gallons per square yard (diluted)
6. Tack coat material type:
   - CSS-1hM (same as the emulsion used in micro-surfacing mix)
   - SS-1h/CSS-1h

The field-testing program included the installation of micro-surfacing test sections in two field projects. The first project was located on the East Bound of State Route (SR) 274 in Shelby County between mileposts 10.73 and 13.35. The project included installing a single micro-surfacing layer for 11 test sections. Figure A.1 presents the location of the project as well as the layout of the test sections installed in this project. In addition, Table A.1 presents the details for each of the constructed test sections. As shown in Table A.1, the test sections had different tack coat types, tack coat application rates, micro-surfacing mix residual binder content, and existing pavement surface conditions. It is noted that the length of test sections was about 1000 ft to 1600 ft. It is also worth to mention that during the installation of section 1, the tack coat material type was changed from CSS-1hM to SS-1h for the last 300 feet from section length.

The second project was located on SR 03 in Wayne County between mileposts 26.13 and 27.25. This project included installing 14 test sections: 7 sections on the South Bound of SR 03, and 7 test sections on the North Bound of SR 03. Figure A.2 presents the location of the project as well as the layout of test sections installed in the second project on SR 03. Tables A.2 and A.3 present the details for each installed test section. As shown in the tables, the first 7 sections included installing a single course micro-surfacing placed on the existing pavement surface. In addition, sections 8 through 14 included installing leveling micro-surfacing courses on the existing pavement. As shown in Table A.2, the effect of different variables was evaluated in SR 03 project, which included: tack coat type, tack coat application rate, and micro-surfacing mix residual binder content. It is noted that the length of each test section in the second project was about 900 ft. It is also worth to mention that during the placing of the second layer at section 9, the emulsion content was changed from 11.6% to 10.4% for the last 317 feet from section length.

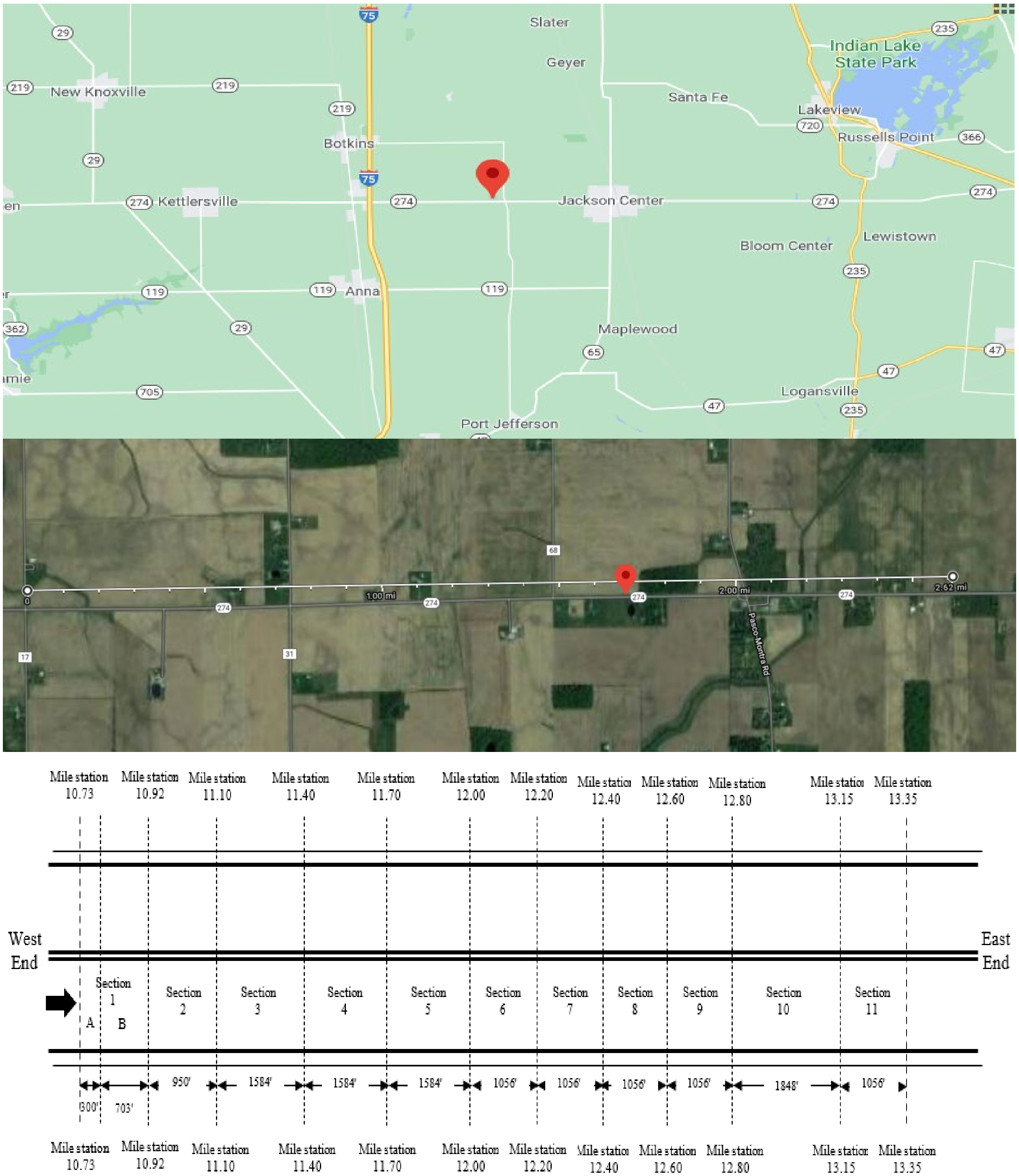
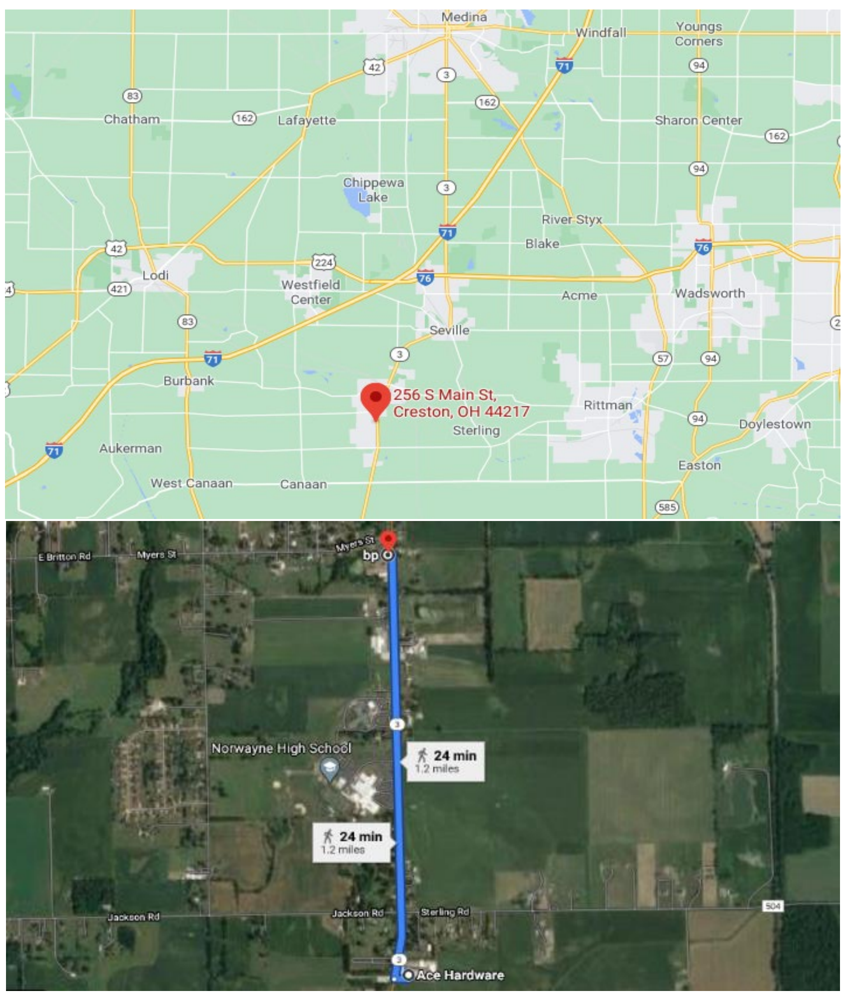


Figure A.1 Layout of Project 1 Test Sections on SR 274 in ODOT Shelby County

Table A.1 Test Section Matrix for Project 1 (Single Course Micro-Surfacing)

Section	Tack Coat Material Type	Tack Coat Application Rate (gsy)	Residual Asphalt Binder Content of Micro-Surfacing Mix	Road Condition	Milepost	
					Begin	End
1-A	SS-1h	0.03	0.7% lower than JMF residual binder content (7%)	Typical Aging	10.73	10.79
1-B	CSS-1hM	0.03			10.79	10.92
2		0.06			10.92	11.10
3	CSS-1hM	0.06	JMF residual binder content (7.7%)	Highly aged	11.10	11.40
4		0.10			11.40	11.70
5		0.03			11.70	12.00
6		0.03		Typical Aging	12.00	12.20
7		0.10			12.20	12.40
8	SS-1h	0.10			12.40	12.60
9		0.03			12.60	12.80
10		0.06			12.80	13.15
11	None	None			13.15	13.35



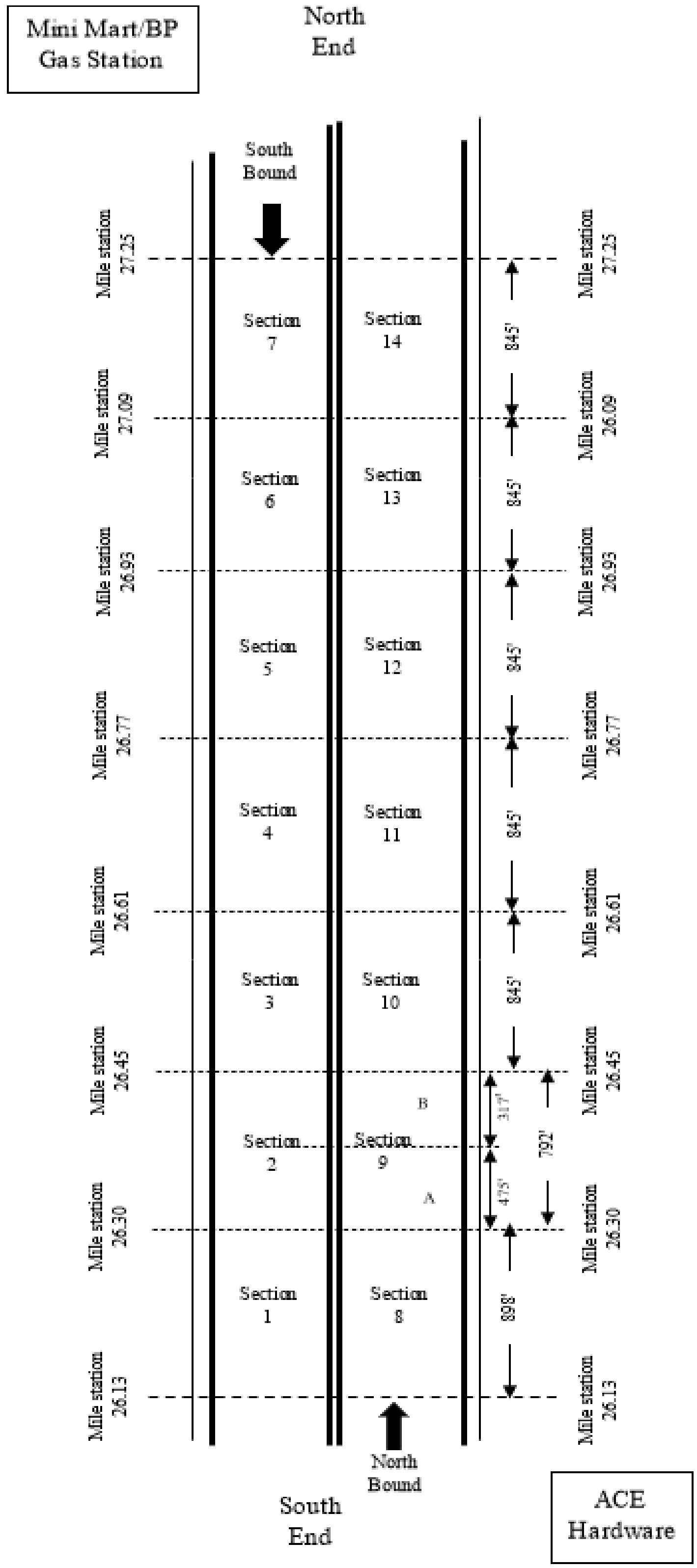


Figure A.2 Layout of Project 2 Test Sections on SR 03 in ODOT Wayne County

Table A.2 Test Section Matrix for Project 2 (single course micro-surfacing test sections)

Section	Tack Coat Material Type	Tack Coat Diluted Application Rate (gsy)	Residual Asphalt Binder Content of Micro-Surfacing Mix	Milepost	
				Begin	End
1	CSS-1hM	0.03	0.75% lower than JMF residual binder content (7.05%)	26.13	26.30
2	None	None	JMF residual binder content (7.8%)	26.30	26.45
3	CSS-1hM	0.03		26.45	26.61
4		0.06		26.61	26.77
5		0.10		26.77	26.93
6	SS-1h	0.10		26.93	27.09
7		0.03		27.09	27.25

Table A.3 Test Section Matrix for Project 2 (double course micro-surfacing test sections)

Section	Sections on Existing Pavement Surface			Sections on New Leveling Course		Milepost	
	Tack Coat Material Type	Tack Coat Diluted Application Rate (gsy)	Residual Binder Content of Surfacing Mix	Tack Coat Material Type	Tack Coat Diluted Application Rate (gsy)	Begin	End
8	CSS-1hM	0.03	0.75% lower than JMF residual binder content (7.05%)	CSS-1hM	0.03	26.13	26.30
9-A	None	None	JMF Residual binder content (7.8%)	None	None	26.30	26.39
9-B	None	None	0.75% lower than JMF residual binder content (7.05%)	None	None	26.39	26.45
10	CSS-1hM	0.06	JMF residual binder content (7.8%)	None	None	26.45	26.61
11		0.06		CSS-1hM	0.03	26.61	26.77
12		0.06			0.06	26.77	26.93
13	SS-1h	0.06		SS-1h	0.03	26.93	27.09
14		0.06			0.06	27.09	27.25

A.2 Evaluation of Test Section prior to Construction

The pavement condition for the two selected projects was assessed. To this end, the Light Weight Deflectometer (LWD) test was conducted on different points along the project to examine the uniformity in structural capacity of pavement structure along the project length. Different tests were also conducted to measure the pavement surface texture at different locations within the test sections. These tests included: the circular track meter (CTM) (ASTM E2157), AMES texture scanner, sand patch test (SPT) (ASTM E 965), and Dynamic Friction Tester (DFT) (ASTM E 1911-98). Field cores were also obtained from different locations within some test sections. The AMES texture scanner was used to scan the cores to examine their surface texture. It is worth noting that these cores were used to prepare samples in the laboratory to examine the effect of existing pavement surface texture on the bond strength of micro-surfacing mixes. Figure A.3 presents some of the photographs taken while measuring the surface texture profile as well as evaluating the structural capacity of test sections in both field projects using the different tests.

Figure A.3 Photographs taken during measuring the structural capacity and surface texture for both projects.

A.3 Construction of Test Sections

The test sections in the first project were constructed in June 7, 2019. In addition, while the first 7 test sections in the second project were constructed in July 2, 2019, the rest of the test sections were constructed on July 9, 2019. For each project, a pre-construction meeting with the designated personnel in the ODOT District office and the contractor representatives was held prior to the installation of micro-surfacing layer to coordinate the construction activities and discuss the field sampling and testing plans. Prior to micro-surfacing installation, the tack coat distributor trucks were calibrated according to ASTM D2995 (Standard Practice for Estimating Application Rate of Bituminous Distributors) to ensure that the distributors can uniformly apply the tack coat at the selected application rate uniformly. Based on the calibration experiments, the rates to be used for each distributor truck were selected for every application rate considered. Figure A.4 presents pictures taken during the calibration of the distributor trucks.

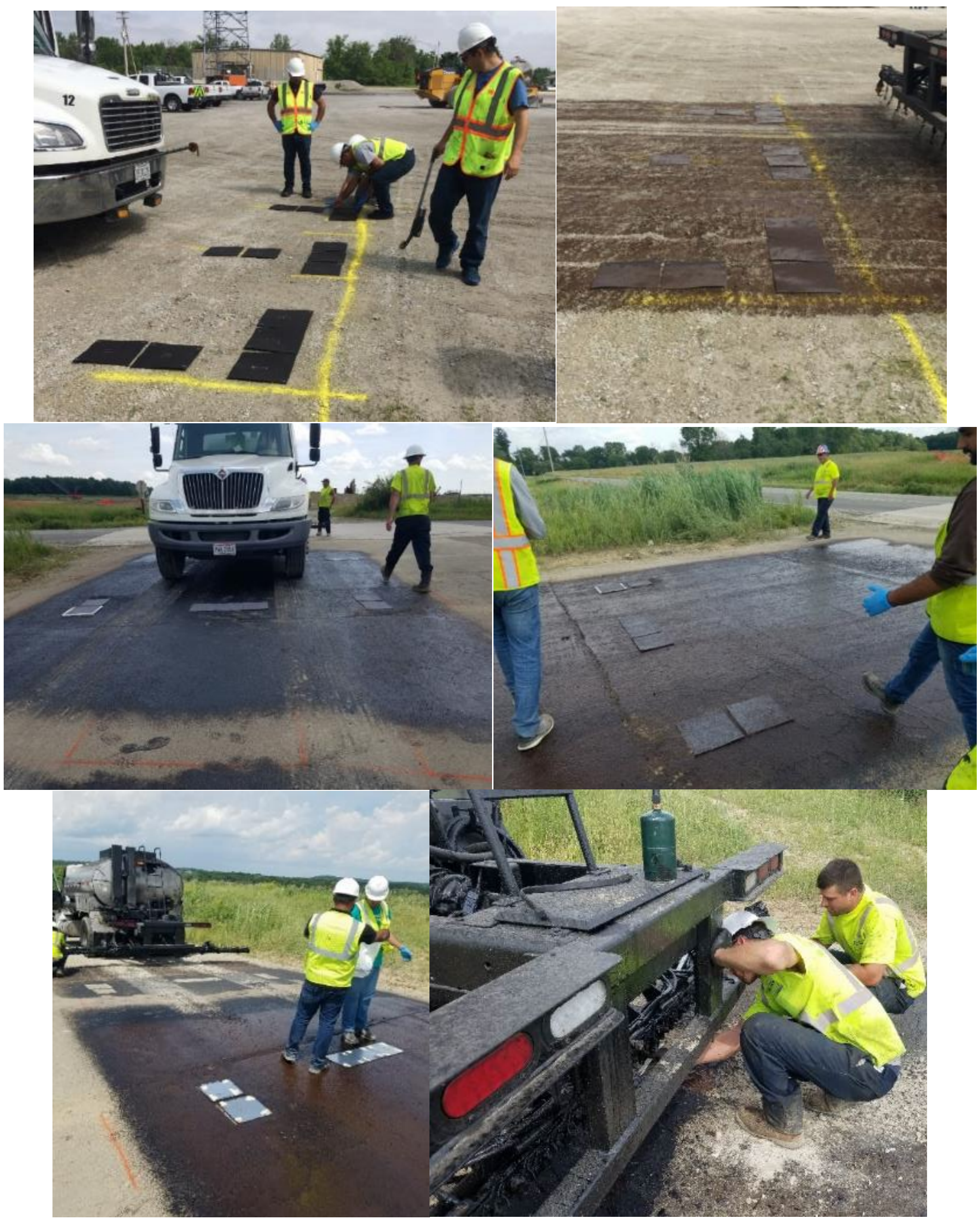


Figure A.4 Photographs taken during calibration of the tack coat application equipment.

During construction, the application rate was measured for each test section according to ASTM D2995. This was done by fixing a reweighed 1 ft^2 roofing paper on top of a steel plate and placing the steel plate on the pavement immediately prior to spaying the tack coat. The roofing paper with tack coat were collected after tack coat spraying and weighed. Figure A.5 presents pictures taken during the measurements of tack coat application rate for test sections in each project.

Figure A.5 Photographs taken during measuring the tack application rate.

The research team monitored the installation of the micro-surfacing mix to identify any problems that need to be addressed. Videos and photographs were also taken to document the installation process. Figure A.6 presents some of the photographs taken during the installation process. Samples of each tack coat material were collected from each distributor truck. In addition, samples of the emulsion and aggregate used in the micro-surfacing mix(es) were collected during construction. It is noted that all micro-surfacing mixes were constructed per ODOT specifications. Tables A.4 and A.5 present the properties of micro-surfacing mixes used in projects 1 and 2, respectively. Table A.6 presents the aggregate gradation selected for both projects. Table A.7 presents some properties of the emulsion used in both projects. It is worth noting that the aggregate type used in the installation of the micro-surfacing layer in both projects was limestone and was obtained from Shelly Materials-Forest. In addition, while the emulsion used in SR 274 project was obtained from Tri-State Asphalt, LLC, the emulsion used in SR 03 project was from Asphalt Materials, Inc. at Edison.

Figure A.6 Photographs taken during the installation of micro-surfacing course.

A.4 Field Evaluation and Testing of Installed Test Sections

Field evaluations of the constructed test sections were conducted along the wheel path area after one week, 4 months, and twelve months of construction. The field evaluation assessed the road surface condition and the severity and extent of any type of distress that occurred in the test sections. Videos and photographs of the surface condition of each test section were obtained to document the road condition. The field evaluation also included obtaining at least six 6-inch core samples from each test section in the two projects. Coring was performed at a very slow and steady speed to avoid any damage to the samples. Samples were carefully labeled and transported to the laboratory for testing. Com-Ten and Proceq DY-206 pull-off tests, as well as torque tests were conducted on the cores to examine the interlayer bond strength of the micro-surfacing mixes. The description of different bond strength tests is provided in the sections below. The testing included making three 2-inch diameter cores in each field core sample. After coring, the surface of each small 2-inch diameter sample was prepared using sandpaper and grinder (if needed) for gluing the metal disc with epoxy needed for testing. Figure A.7 shows an example of field core samples that were prepared in the lab for testing. All samples were conditioned for at least three hours at a temperature of 25 °C prior to testing.

Table A.4 Mix Design Properties for Micro-surfacing Mix in SR 274 Project.

Property	Value
Typical Emulsion Type	CSS-1hM
Residual Content in Emulsion (%)	63.6
JMF Residual Asphalt Binder Content (%)	7.7
JMF Emulsion Content (%)	12.1
Mineral Filler Content (%)	1.00 ± 0.25
Total Water Content (%)	7.0 ± 1.5
Undiluted Mix Set Additive (%)	0.00 ± 0.00
Water pH	7.5 ± 1.5

Table A.5 Mix Design Properties for Micro-surfacing Mix in SR 03 Project.

Property	Value
Typical Emulsion Type	CSS-1hM
Residual Content in Emulsion (%)	65.5
JMF Residual Asphalt Binder Content (%)	7.8
JMF Emulsion Content (%)	11.8
Mineral Filler Content (%)	1.50 ± 0.50
Total Water Content (%)	6.5 ± 1.5
Undiluted Mix Set Additive (%)	0.00 ± 0.20
Water pH	7.0 ± 5.0

Table A.6 Aggregate Gradation for Micro-surfacing Mixes in SR 274 and SR 03 Projects.

Sieve Size	% Passing (SR 274 project)	% Passing (SR 03 project)
3/8” (9.5 mm)	100	100
#4 (4.75 mm)	94	96
#8 (2.36 mm)	67	77
#16 (1.18 mm)	43	54
#30 (0.6 mm)	28	38
#50 (0.3 mm)	20	23
#100 (0.15 mm)	14	14
#200 (0.075 mm)	10.3	8.4

Table A.7 Basic Properties of the Supplied Emulsion used in Micro-surfacing Mixes in SR 274 and SR 03 Projects.

Property	Standard	Specifications	SR 274	SR 03
Viscosity at 77°F (25°C)	AASHTO T 59	20 to 100	-	30*
Storage Stability, 24-hr (% Difference)	AASHTO T 59	1 max.	-	0.0*
Distillation to 177°C, Residue % Solids	AASHTO T 59	62 min.	-	65.5*
Tests on Distillation Residue				
Penetration, 25°C, 100g, 5 sec (dmm)	AASHTO T 49	40-90	62	64.6
Ductility, 25°C, 5 cm/min (cm)	AASHTO T 51	40 min.		100.0*
Solubility in Trichloroethylene (%)	AASHTO T 44	97.5 min.		99.6*
Elastic Recovery, 10°C, 20 cm (%)	AASHTO T 301	50 min.	-	53.8*
Softening Point, Ring & Ball (°C)	AASHTO T 53	60 min.	64.8	62.5

*Reported by the supplier/mentioned in the JMF

Figure A.7 Field core samples prepared for testing in the lab.

A.5 Lab Testing

Based on the results of bonding tests conducted in the lab for field samples, further lab testing was conducted to evaluate the effect of the tack coat application rate on bond strength and validate the test results obtained for field samples in a more controlled environment. The lab testing plan included examining the effect of the tack coat type, application rate, the residual asphalt binder content of the micro-surfacing mix. Table A.8 presents the lab testing matrix selected to test the variables in the SR 03 project, respectively. Moreover, the lab testing plan included evaluating the effect of the existing pavement surface texture on the interlayer bond strength. To this end, the surface texture of the field cores obtained prior to construction of test sections in SR 03 project was evaluated using AMES laser texture scanner. Figure A.8 presents the mean profile depth (MDP) for the obtained field cores. Based on that the cores were divided into three groups: low, medium, high MDP value, and given group names as 1, 2, and 3, respectively. A tack coat application rate of 0.06 gsy was used in all samples used to examine the surface texture effect. The effect of curing time of tack coat material was also investigated. To this end, the bond strength was evaluated by comparing the bond strength tests at four different curing times (0 minutes, 15 minutes, 30 minutes, and 60 minutes).

A.5.1 Samples Preparation

The preparation of lab samples included first compacting 6-in gyratory samples to the same air void content of 7%. Tack coat was applied using a brush to the surface of the prepared 6-in gyratory samples specific according to the rates shown in Tables A.4 and A.5. The micro-surfacing aggregates and emulsion samples obtained from the field were then mixed according to the proportion in the job mix design in a bowl using a spatula for 2 to 3 minutes until the mixture was homogeneous. The micro-surfacing mix was then applied on the coated 6-in gyratory samples surface with a thickness of 6-7 mm to achieve a total thickness of 62-63 mm. It is noted that a silicon mold with a diameter of 6 inches and a thickness of 6.75 mm was used to achieve this purpose. A spatula was used to scrape the sample surface after applying the micro-surfacing mix and to smoothen it. Samples were kept to dry for at 2 days and became stiff enough to be compacted using a Hamburg Wheel Tracking (HWT) device. It is worth mentioning that in the case of double layers of micro-surfacing mix, the first layer was allowed to set for seven days before applying the second layer. This waiting period was selected to simulate the actual field installation conditions. Samples were then compacted using HWT device for 1,000 passes. This number of cycles was selected based on the results of Appendix A testing to simulate the compaction from traffic that is generated during one-week period. Figure A.9 presents pictures that illustrate the preparations of micro-surfacing samples in the lab.

Table A.8 Lab Prepared Samples for Project 2 (SR 03)

Sample ID	First layer			Second layer		
	Emulsion content	Tack material	Tack coat app rate (gsy)	Emulsion content	Tack material	Tack coat app rate(gsy)
S1	Low	CSS-1hM	0.025			
S2	Regular	None	0			
S3	Regular	CSS-1hM	0.025			
S4	Regular	CSS-1hM	0.060			
S5	Regular	CSS-1hM	0.108			
S6	Regular	SS-1h	0.108			
S7	Regular	SS-1h	0.025			
S8	Low	CSS-1hM	0.025	Low	CSS-1hM	0.025
S9	Regular	None	0	Regular	None	0
S10	Regular	CSS-1hM	0.060	Regular	None	0
S11	Regular	CSS-1hM	0.060	Regular	CSS-1hM	0.025
S12	Regular	CSS-1hM	0.060	Regular	CSS-1hM	0.060
S13	Regular	SS-1h	0.060	Regular	SS-1h	0.025
S14	Regular	SS-1h	0.060	Regular	SS-1h	0.060
S15	Low	None	0	Low	None	0

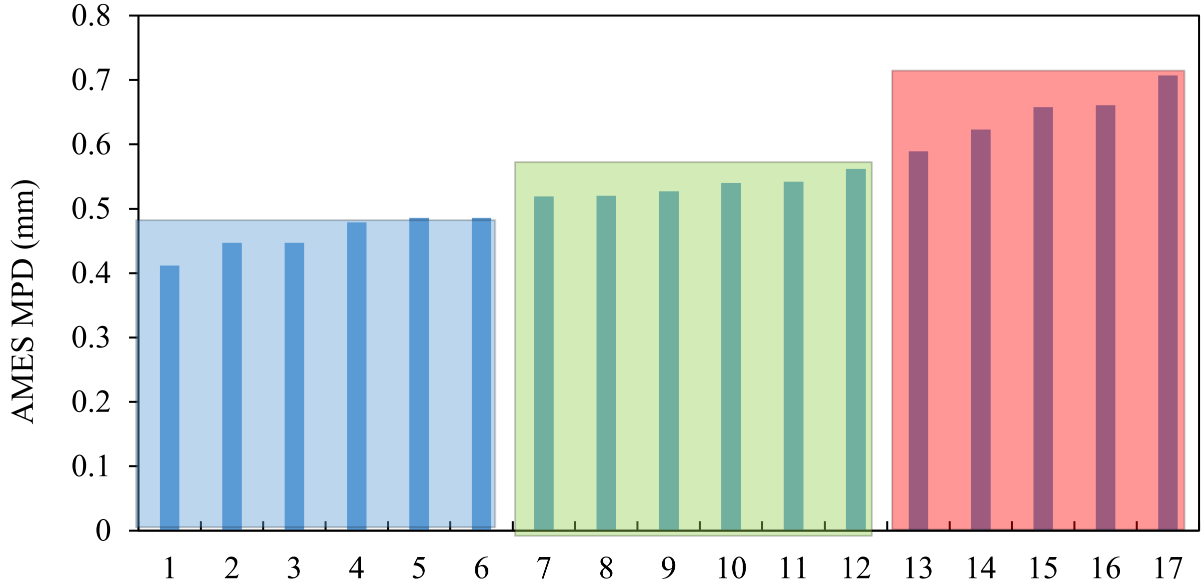
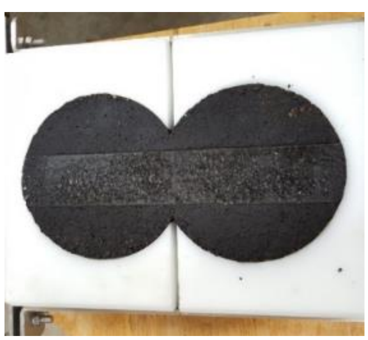


Figure A.8 MPD Values Obtained from AMES Testing on Field Cores of SR 03 Project


(a)


(b)


(c)


(d)


(e)


(f)

Figure A.9 Lab sample preparation: (a) application of tack coat, (b) leveling of micro-surfacing mix, (c) final lab specimen with a 6.5-mm top layer of micro-surfacing and 57 mm bottom layer of HMA, (d) Compacted sample using HWTD, (e) coring of the sample, and (f) lab specimens ready for testing tested.

After compaction, two 2-inch core samples were made in the compacted part of each sample to prepare them for bond strength tests. After coring, the surface of each small 2-inch diameter samples were prepared using sandpaper and grinder (if needed) for gluing the metal testing metal disc with epoxy. Com-Ten and Proceq DY-206 pull-off tests, as well as torque tests were conducted to examine the bond interlayer bond strength for the different samples. At least 4 samples were tested for each bond strength test.

A.5.2 Proceq Pull-off Test

The pull-off test was performed using an automated pull-off device called Proceq Dy 206. This device is specially designed to measure low strength typically associated with a thin surface. The device consists of three tripods, a pulling stub, a draw bolt, and a metal disk, as shown in Figure A.10. The test method involved coring through the micro-surfacing mix in the top layer and approximately half an inch into the bottom layer. A metal disk was then glued to the top of the specimen surface and a pulling stub was attached to the disk using a draw bolt. Finally, tensile loading was applied by pulling stub at a given loading rate until the bond between the micro-surfacing mix and the HMA surface failed. It is worth noting that more consistent results were obtained using a lower loading rate. Therefore, a loading rate of 2 lbf/sec was used to carry out the testing in this study. During the pull-off testing, the peak pull-off force was recorded. The average pull-off force presented in this study is the average of at least three specimens of each type.

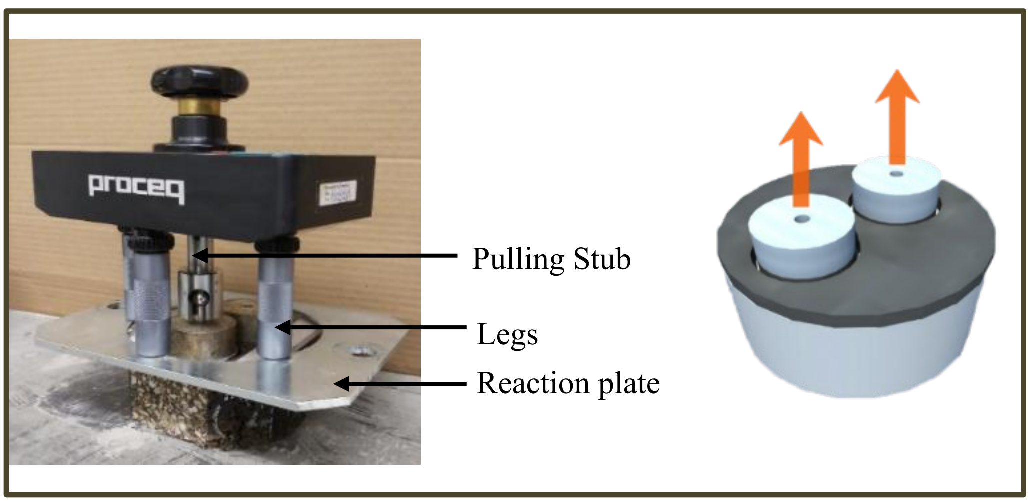


Figure A.10 Proceq Dy 206 pull-off device

A.5.3 Com-Ten Pull-off Test

The pull-off test was performed using an automated pull-off device called ANDILOG Com-Ten. This device is specially designed to measure low strength typically associated with a thin surface. The device consists of a frame body, load adapter, a pulling stub with a hook, and a metal disk with attached bolt, as shown in Figure A.11 The test method involved coring through the micro-surfacing mix in the top layer and approximately half an inch into the bottom layer. A metal disk with attached bolt was then glued to the top of the specimen surface and a pulling stub was attached to the disk using a hook. Finally, tensile loading was applied by pulling stub at a given displacement rate until the bond between the micro-surfacing mix and the HMA surface failed. It is worth noting that more consistent results were obtained using a lower displacement rate.

Therefore, a displacement rate of 0.4 in/min was used to carry out the testing in this study. During the pull-off testing, the peak pull-off force was recorded. The average bond strength presented in this study is the average of at least three specimens of each type. The average bond strength presented in this study is the average of at least three specimens of each type.

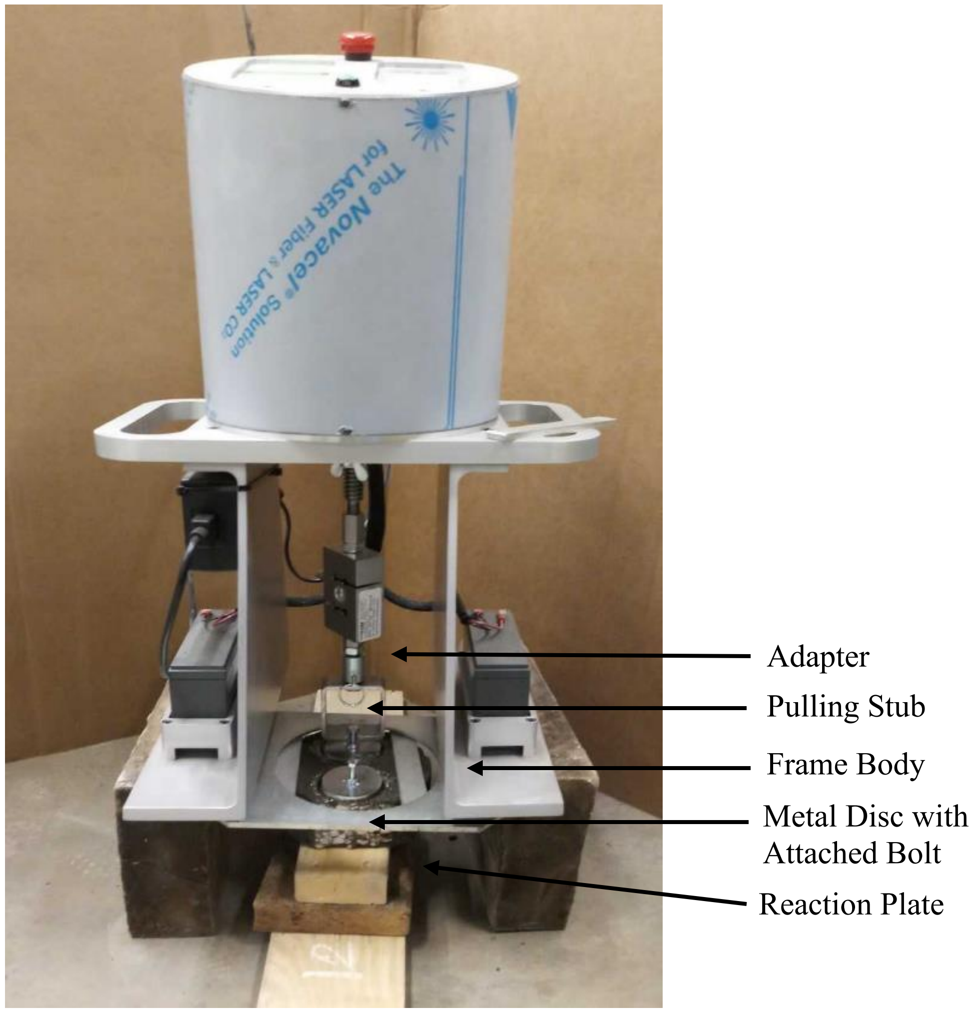


Figure A.11 Com-Ten pull-off device

A.5.4 Torque Test

A low-cost laboratory torque device was developed in the laboratory to characterize the bond strength in shear mode. The assembly of the device is shown in Figure A.12 As can be seen from this figure, the torque device is comprised of several parts including a split mold with set screws attached to it, a torque adapter to measure the applied torque, a torque multiplier, a converter, and a torque wrench. Similar to specimen preparation for the pull-off test, the torque specimen was partially cored through the top layer and up to half an inch into the bottom layer. A metal disk was glued to the top of the surface. The specimen was then moved into the split mold and was fixed with the set screw in order to prevent any movement while applying torque. Torque was then applied by turning both handles of the wrench by hand with a consistent motion until failure occurred. During the application of the torque, the torque wrench was kept parallel with respect to the top surface of the specimen to avoid any effect of bending. A torque application rate of 4 rev/min was maintained throughout the study to avoid a variation due to an inconsistent application rate. The torque was applied until the failure occurred and the peak torque was recorded.

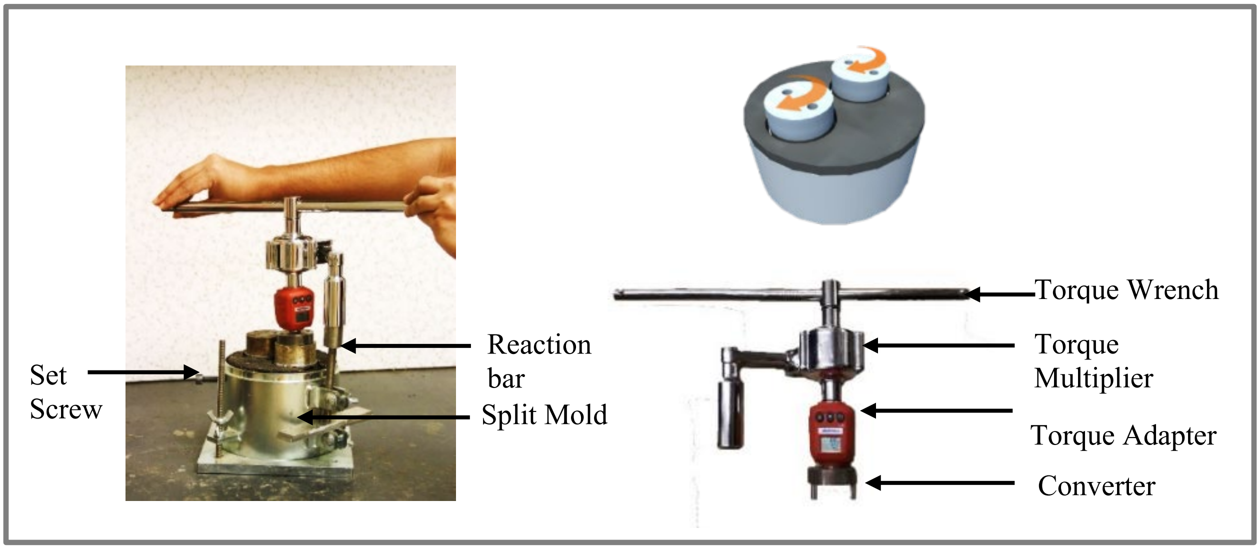


Figure A.12 Torque device

A.5.5 Testing of Emulsion Materials Properties

Basic material characterization tests were conducted on obtained emulsion, which included: residue by ignition oven, penetration, and softening point test. In addition, dynamic shear rheometer (DSR) test was conducted in accordance with AASHTO T 315 (Determining the Rheological Properties of Asphalt Binder Using Dynamic Shear Rheometer -AASHTO, 2010) on the obtained emulsion residual asphalt binder to determine the Superpave higher performance grade (PG) as well as the master-curve for each type of the emulsion residual binder. An Anton-Paar MCR 302 DSR shown in Figure A.13 was used to was used for all DSR testing.

A.6 Analysis of Test Results

Statistical analysis was performed on the results of the field and lab samples testing to evaluate the effect of different factors considered on the bonding strength of micro-surfacing mixes. To this end, analysis of variance (ANOVA) and post ANOVA least square mean (LSM) statistical analyses were conducted using Statistical Analysis Software (SAS) on obtained data. A 95% confidence level (α-value of 0.05) was used in the analyses.

Based on the results of this statistical analysis, the factors that significantly affect the bond strength of micro-surfacing mixes were determined, which helped in developing specifications for tack coat used in micro-surfacing applications as mentioned later.

A.7 Evaluation of the Relationship Between Field Performance and Bond Strength

The ability of the selected bond strength tests to identify sections with good and poor performance as related to debonding and delamination was evaluated in this study. To this end, the performance information for all micro-surfacing projects that was constructed in the last four years were obtained from ODOT Office of Pavement Engineering. The obtained information included the pavement condition rating (PCR) data for the pavement before and after installing micro-surfacing

treatments. The PCR data were examined to identify micro-surfacing sections that had distress code 4 (SDD - Surface disintegration or debonding) with high severity and extend.
The bond strength of several micro-surfacing sections in District 3 including the test section constructed in this study, were evaluated few months after construction. The sections were located on SR 274, SR 03, SR 97, and SR 598. This was done by obtaining cores from these sections and testing them using the Proceq pull-off and torque tests. District 3 had a micro-surfacing section on SR 89 that showed signs of debonding and delamination few months after construction. This section was located between State Line Limit (SLM) 15.58 and SLM 18.42. Delamination and debonding occurred in various areas within that section on SR 89. These included:

- Northbound: SLM 16.60, 16.76, 16.78, 17.08, 17.23, 17.35, and 17.91-17.99.
- Southbound: SLM 16.60, 16.91-16.96, 18.25.

Field evaluation was conducted on these sections to investigate the delamination that occurred at these locations. Several cores were obtained from the following locations from the micro-facing section on SR 89 to relate the field performance to bond strength values:

- SLM 16.91 on southbound which had severe delamination issues.
- SLM 16.60 on northbound which had some delamination issues.
- SLM 15.60-16.00 on southbound which had no delamination issues, coring was done at SLM 15.71.

Proceq pull-off testing and torque testing were conducted on the field cores obtained from the deteriorated locations with SR 89 micro-surfacing section. The results of these tests are discussed in section B.5.2 in Appendix B.

Figure A.13: Anton-Paar MCR 302 Dynamic Shear Rheometer (DSR) equipment used for measuring rheology of asphalt binder

Appendix B Results and Analysis

B.1 Results of Tack Coat Application Rate Measurements

The tack coat application rates for the different test sections in the two micro-surfacing projects in this study were measured according to ASTM D2995 (Standard Practice for Estimating Application Rate of Bituminous Distributors). Figure B.1 compares the average measured tack coat application rate values to the target application rates for the different sections in the SR 274 project. As seen in Figure B.1, the average value obtained in the field generally was lower than the targeted value for all test sections except section 9. More specifically, for sections with a target application rate of 0.03 gsy, the average measured application rate was close to the target value. For sections 9 and 10, (sections with SS-1h) the measured tack coat application rate was very close to the target value. However, for test sections 2, 3, 4, and 7, large differences were observed between the measured and the target values.

Figures B.2 and B.3 present the average measured tack coat application rates applied prior to installation of the levelling micro-surfacing layer at the different sections in SR 03 project. As seen in Figures, the average value obtained in the field was generally close than the targeted value for all test sections, except for test sections with 0.03 gsy target application rate, where the measured values of tack coat application rate were lower than the targeted value with higher difference than other test sections with higher tack coat application rates. Figure B.4 presents the average measured tack coat application rates applied prior to installation of surface micro-surfacing layer at the different sections that have double micro-surfacing layers. As seen in Figure B.4, the average value obtained in the field was very close to the targeted value for sections with 0.03 gsy target application rate, while it was higher than the targeted value for sections with higher targeted application rates, with a significant difference between the measured and the targeted values.

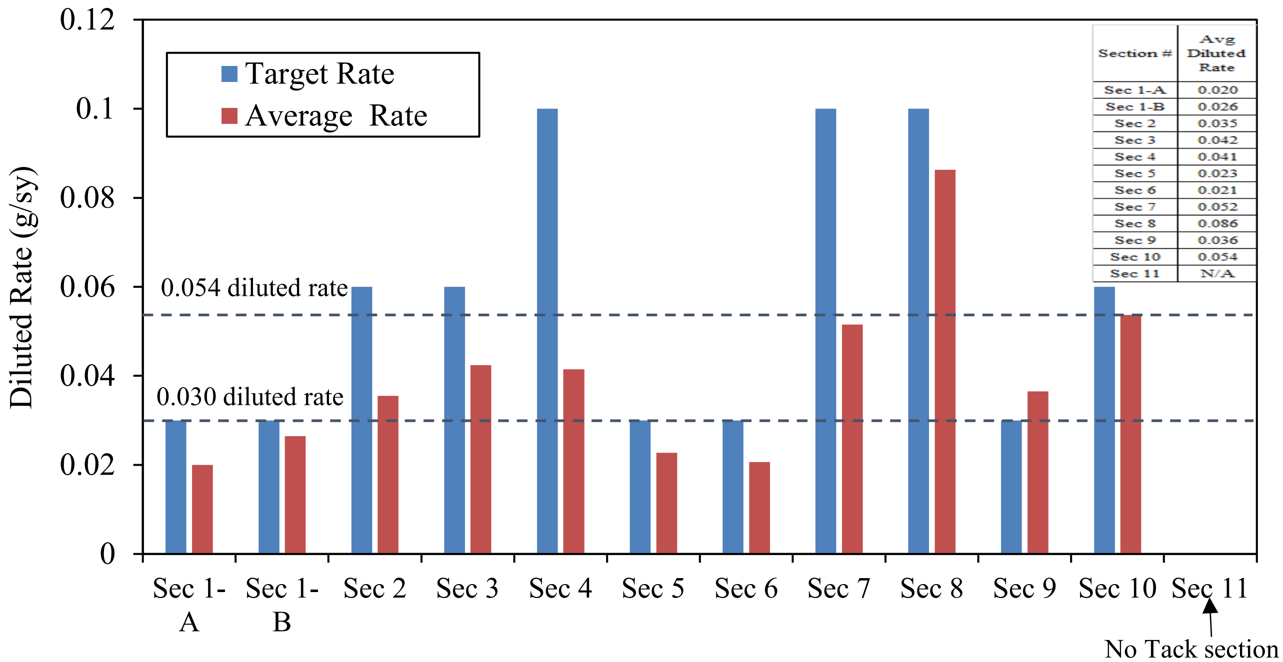


Figure B.1 Results of average measured tack coat application rate compared to target application rate values for SR 274 micro-surfacing project

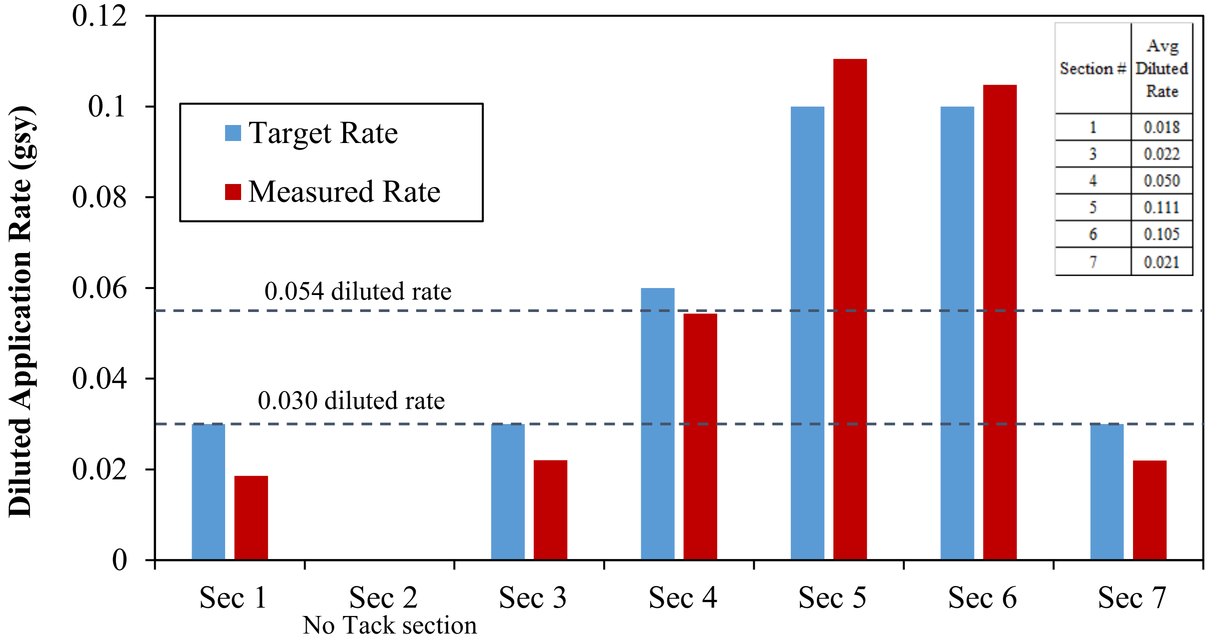


Figure B.2 Results of average measured tack coat application rate compared to target application rate values for the sections with single layer in SR 03 micro-surfacing project

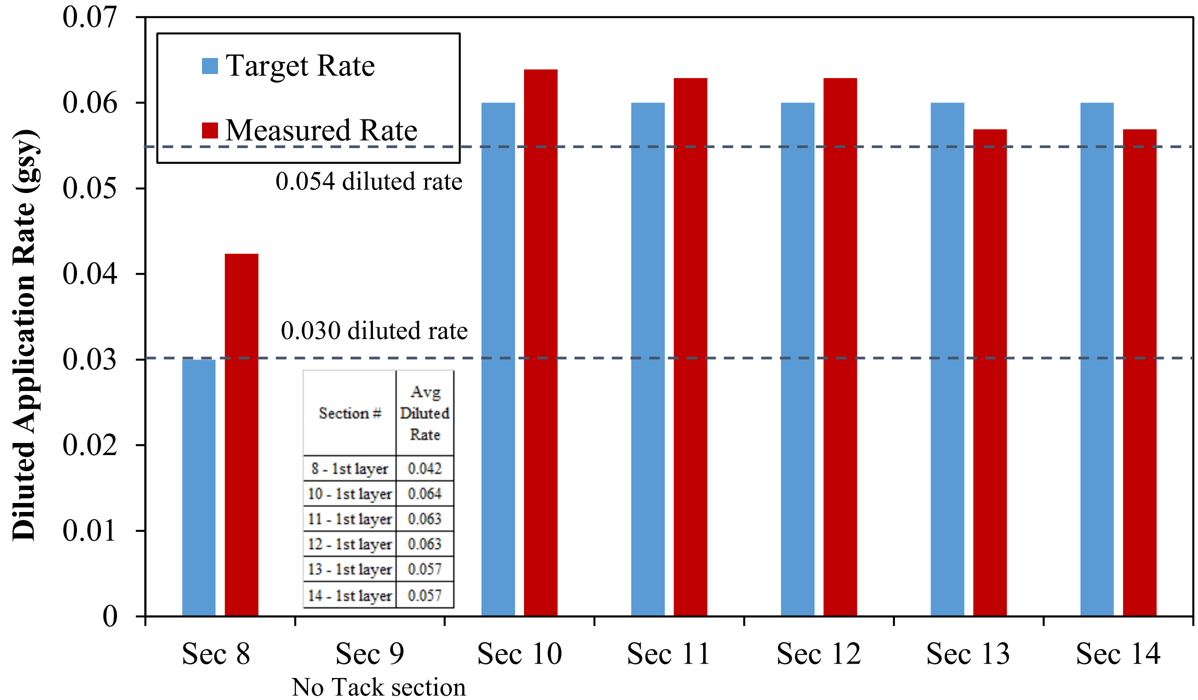


Figure B.3 Results of average measured tack coat application rate compared to target application rate values for the leveling layer at sections with double layers in SR 03 micro-surfacing project

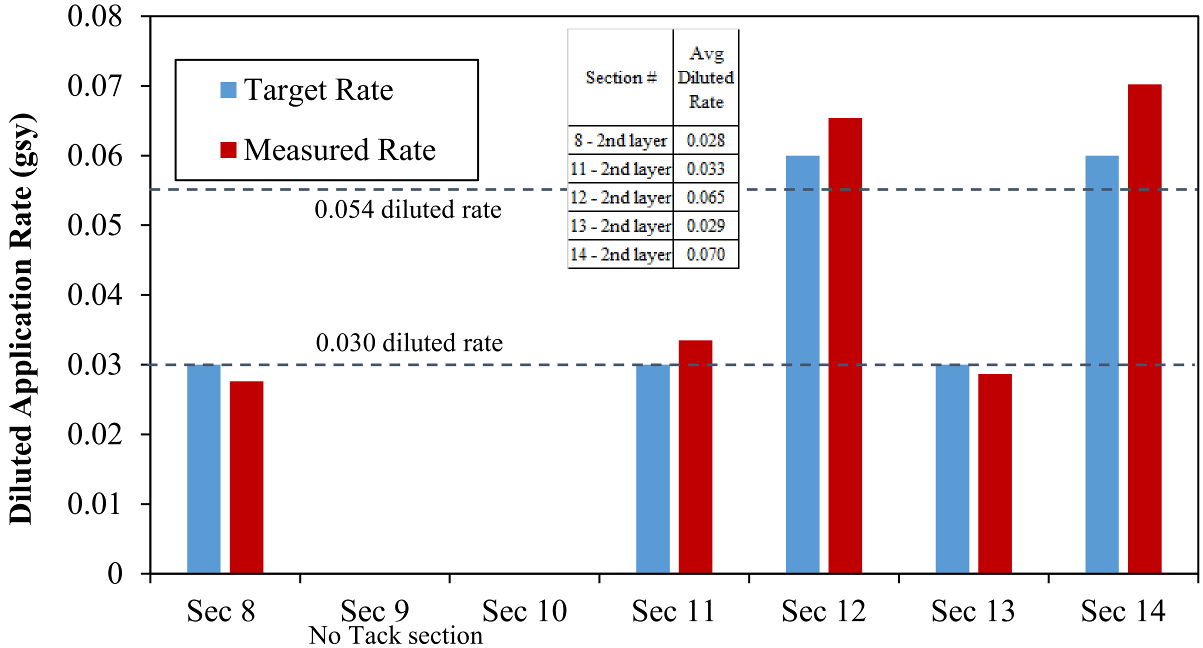


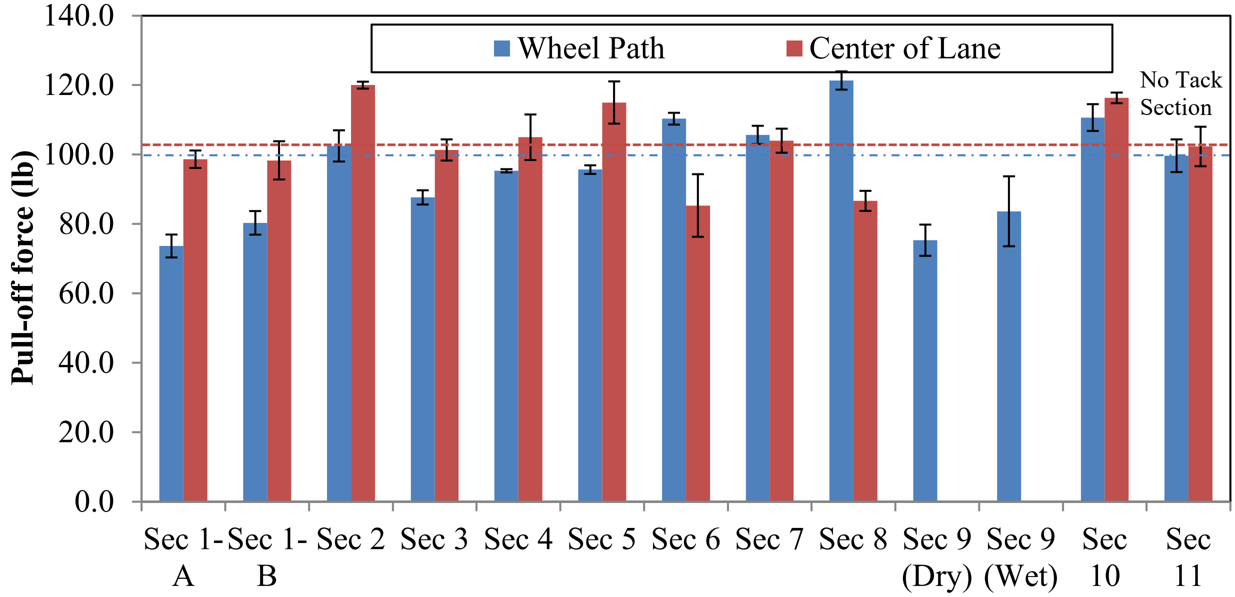
Figure B.4 Results of average measured tack coat application rate compared to target application rate values for the surface layer at sections with double layers in SR 03 micro-surfacing project.

B.2 Results of Bond Strength Tests on Cores Obtained from Field Test Sections

Pull-off tests including Proceq pull-off tester and Com-Ten pull-off tester, as well as Torque tests were performed in the laboratory on the field cores obtained from test sections in both projects to evaluate the interlayer bond strength after one week, 4 months, and 12 months after construction. The following section presents the results from the lab testing conducted on field cores.

B.2.1 Results of Bond Strength Tests on Cores Obtained after One Week - Project 1 (SR 274)

Figure B.5 presents the results of Proceq pull-off tester for field cores obtained along the wheel path and the center of the lane at test sections after one week of installing the micro-surfacing layer. Higher pull-off force values indicate a higher bond strength between the micro-surfacing layer and the existing pavement. It is noted that for the field cores obtained along the wheel path, test section 8 had the highest value of pull-off force compared to other test sections followed by section 10. In general, sections with tack coat application rate more than 0.054 gsy had required a higher pull-off force than that of the control section (section 11) with no tack coat material. These high values can be attributed to the higher tack coat application rate that was applied on sections 8 and 10. It is noted that the sections with tack coat application rate lower than 0.03 gsy and/or lower micro-surfacing mix residual binder content (sections 1-A, 1-B, 5, and 9) had the lowest value of pull-off force, which means a lower bond strength for these sections. In general, the effect of tack coat application rate was more pronounced in improving the bond strength of micro-surfacing mixes than the effect of tack coat type (SS-1h or CSS-1hM) for the field cores obtained along the wheel path after one week of construction. However, for the field cores obtained along the center of the lane after one week of construction, the effect of tack coat emulsion type was more significant than that of the tack coat application rate, as indicated by the higher pull-off force values obtained for sections 2, 4, and 5. The effect of application rate was more noticeable at section 10 since the pull-off force value was higher than that for the no tack section.

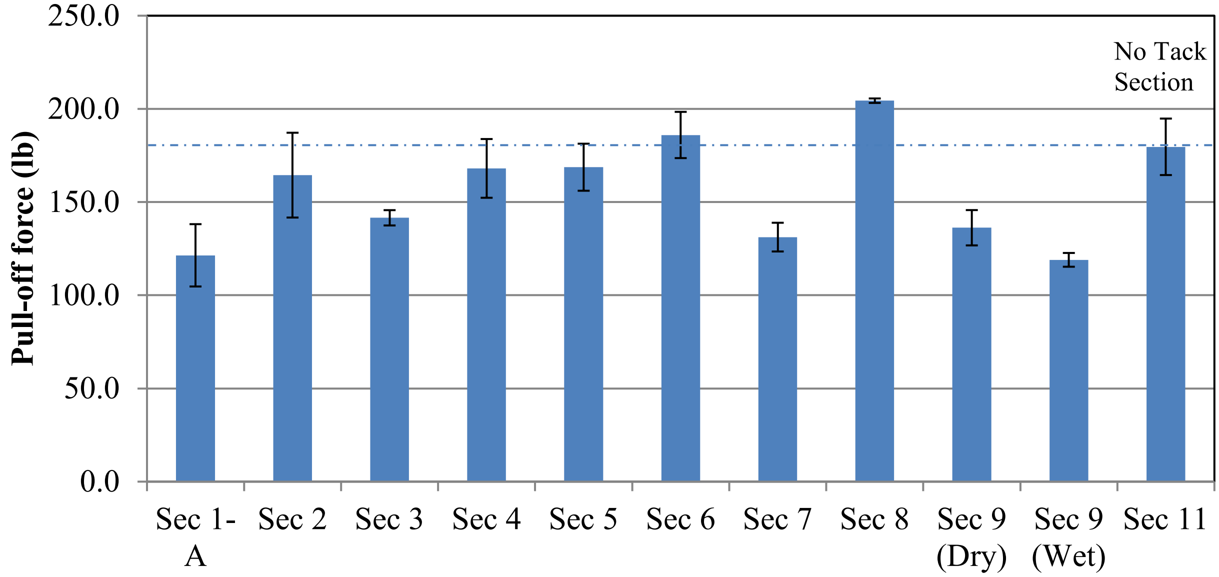


Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.054	0.0

Figure B.5 Results of Proceq Pull-off force Values for the Field Cores Obtained During the Installation of Micro-surfacing Layer in the First Project (SR 274), Tested After 7 Days of Installation

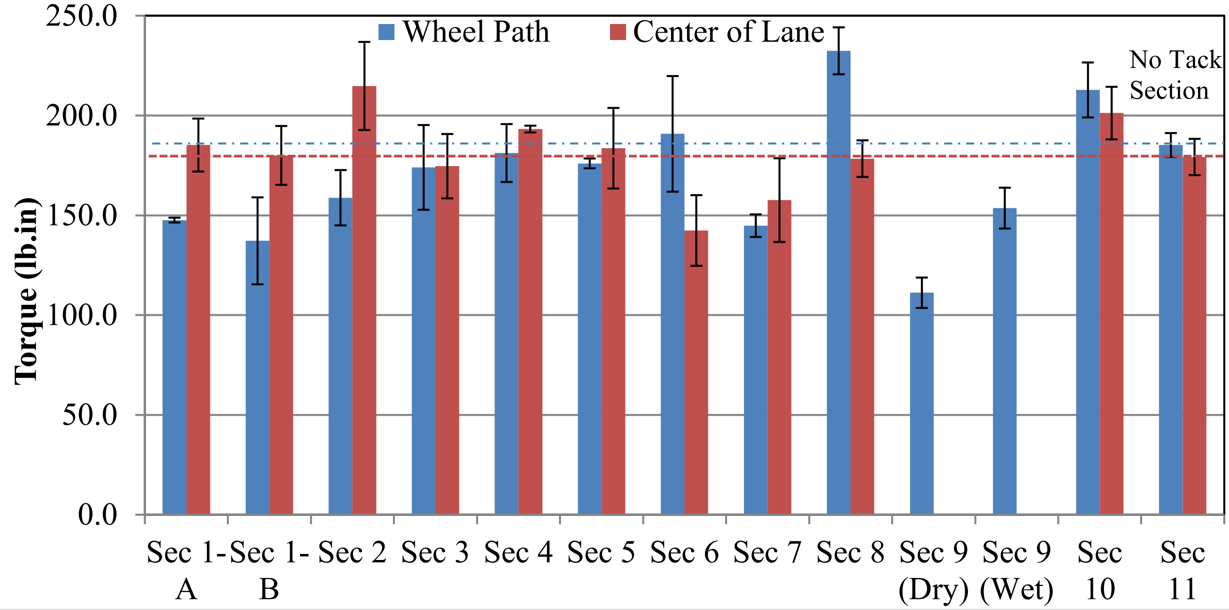
Figure B.6 presents the average pull-off force values obtained from the Com-Ten pull-off testing on wheel path SR 274 field cores. Section 8 had the highest value compared to all other test sections. While sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-A, and 9) had the lowest value of pull-off force. It was noticed that the effect of tack coat application rate and tack coat material type had no significant effect on bond strength, as the value of pull-off force for sections that exhibited these two factors showed lower pull-off strength than that for the no tack section.

Figure B.7 presents the torque values obtained from torque testing on field cores obtained along the wheel path and center of the lane at test sections on the SR 274 project. For the wheel path field cores, section 8 had the highest torque value among all other test sections, followed by section 10. Sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, 2, 9) had the lowest value of pull-off force. These results agree with the results obtained from pull-off testing on field cores along wheel path. The effect of tack coat was only observed for sections with tack coat application rate higher than 0.06 gsy (sections 8 and 10). For field cores obtained along the center of the lane, Figure B.7 shows that only sections 2 and 10 high higher torque bond strength than section 11 without tack coat. All other sections had similar or slightly lower torque bond strength than section 11 after one week of construction.



Avg Diluted Rate (gsy)	0.020	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.0

Figure B.6 Results of Com-Ten Pull-off force Values for the Field Cores Obtained Along Wheel Path During the Installation of Micro-surfacing Layer in the First Project (SR 274), Tested After 7 Days of Installation



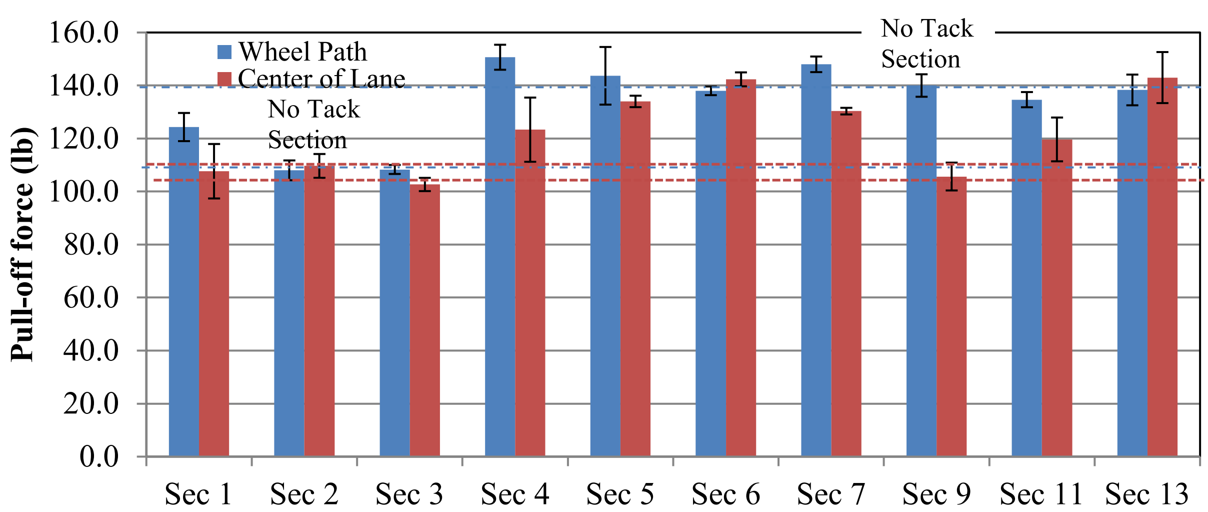
Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.054	0.0

Figure B.7 Results of Torque Values for the Field Cores Obtained During the Installation of Micro-surfacing Layer in the First Project (SR 274), Tested After 7 Days of Installation

B.2.2 Results of Bond Strength Tests on Cores Obtained after One Week- Project 2 (SR 03)

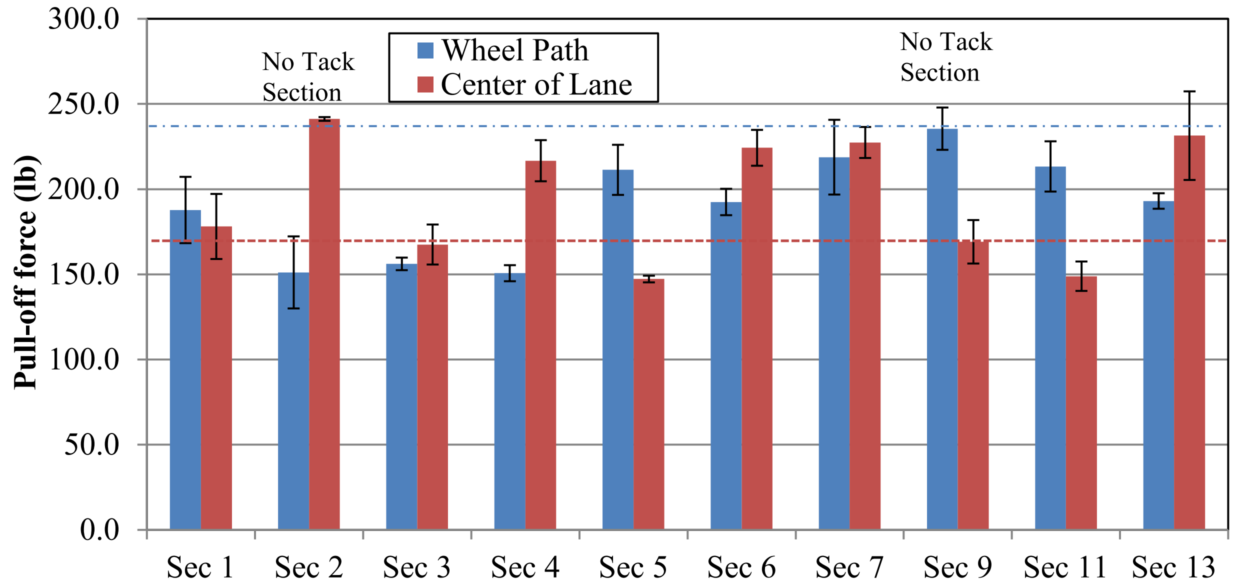
Figure B.8 presents the results of Proceq pull-off tester for field cores obtained along the wheel path and the center of the lane at test sections in the SR 03 project after one week of installing the micro-surfacing first layer. For the field cores obtained along the wheel path, all test sections had a higher pull-off force value than that of section 2, the control section without tack coat. This indicates that the effect of the tack coat was significant in improving the bond strength between the micro-surfacing layer and the existing pavement surface particularly when a tack application rate higher than 0.05 gsy was used. This confirms the results obtained in the SR 274 test sections. The results of pull-off force on field cores obtained from the center of the lane were consistent with those obtained from the testing of wheel path field cores. In both cases, the effect of using tack coat was significant in improving the bond strength particularly when a tack coat application rate higher than 0.054 gsy was used (sections 5, 6, 13).

Figure B.9 presents the results of Com-Ten pull-off test for field cores obtained along the wheel path and the center of the lane at test sections in the second project after one week of installing the micro-surfacing first layer. In general, the results of Com-Ten pull-off test for the single layer test sections (sections 1-7) were consistent with those obtained using the Proceq test. To this end, the tack coat had a significant effect on improving the pull-off force such that sections with tack coat had higher pull-off force than that of the no tack section (section 2). However, the effect of the tack coat was not evident for bonding of the leveling course in test sections that had double micro-surfacing layers (sections 9, 12, 13). It is noted that the section that had a micro-surfacing mix with lower residual binder content showed a lower pull-off force value compared to other test sections, but it was higher than that for the no tack section. This may suggest that the effect of applying a tack coat material has a significant effect on improving the interlayer bond strength of these mixes. Figure B.9 shows that for cores obtained along the center of the lane at sections with single micro-surfacing layer, the tack coat did not affect pull-off force for sections after one week of construction.



Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021	0.0	0.063	0.057

Figure B.8 Results of Proceq Pull-off force Values for the Field Cores Obtained During the Installation of Leveling Micro-surfacing Layer in the Second Project (SR 03), Tested After 7 Days of Installation



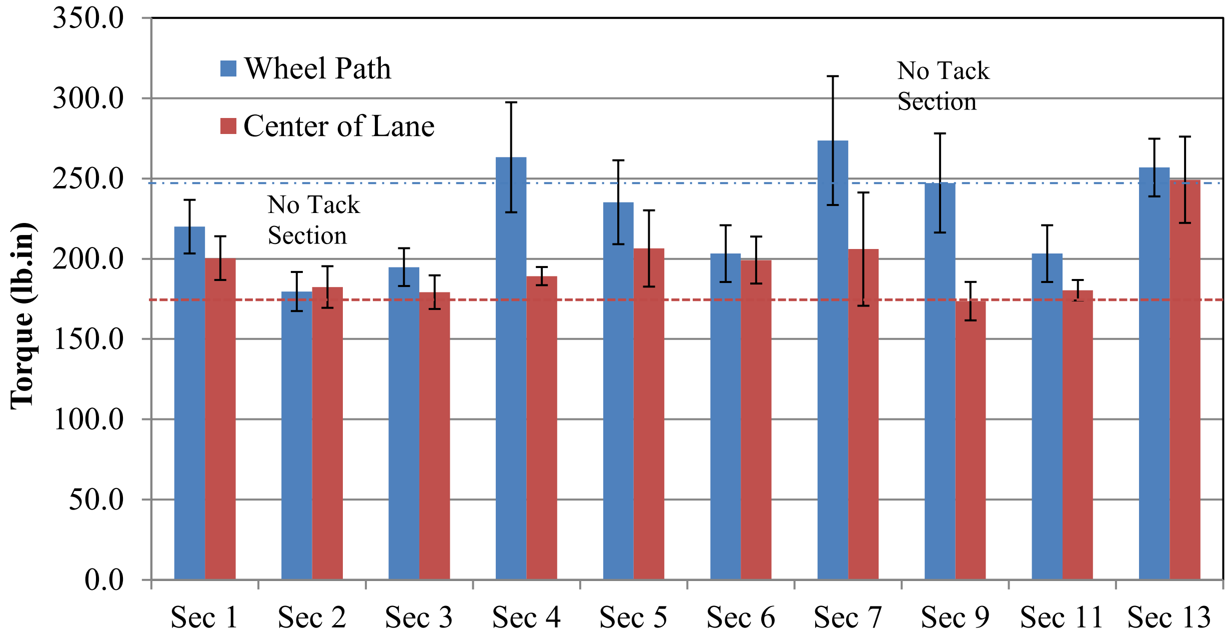
Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021	0.0	0.063	0.057

Figure B.9 Results of Com-Ten Pull-off force Values for the Field Cores Obtained During the Installation of Leveling Micro-surfacing Layer in the Second Project (SR 03), Tested After 7 Days of Installation

Figure B.10 presents the results of torque testing for field cores obtained along the wheel path and the center of the lane of the test sections in the SR03 project after one week of installing the micro-surfacing first layer. It is clear that for test section with single micro-surfacing layer applying tack coat resulted in higher interlayer bond strength as cores from all sections that included using tack coat had higher torque values than the no tack test section (section 2). It is noted that the section with micro-surfacing mix that had lower residual binder content showed a lower pull-off force value compared to other test sections, but it was higher than that for the no tack section without tack coat. It is noted that, in general, the results of torque test were consistent with those obtained from Proceq and Com-Ten pull-off tests.

Figure B.11 presents the results of Proceq pull-off test for field cores obtained along the wheel path and the center of the lane for test sections with double micro-surfacing layers in SR 03 project after a week of installing the second micro-surfacing layer (surface course layer). For field cores obtained along the wheel path and the center of the lane, the value of pull-off force was higher for all test sections with tack coat and micro-surfacing mixture that had residual binder content mentioned in the JMF than that that for the no tack section (section 9-B). This may indicate that applying tack coat resulted in improving the interlayer bond strength after one week of installing the micro-surfacing layer. It is noted that test section 8 which had a micro-surfacing mixture with lower residual binder content had the lowest value of Proceq pull-off force among all test sections with double micro-surfacing layer, which means that lowering the residual binder content in the mix resulted in lower interlayer bond strength after one week of construction.

For cores obtained along the center of the lane, the effect of application rate and material type was also significant in improving the bond strength, as the value of pull-off force for sections having tack coat was higher than that for no tack section (section 9-B). Similarly, the effect of the type of material used for tack coat application was more significant for the cores obtained along the center of the lane at test sections having double Micro-surfacing layers, as sections 13 and 14 had higher pull-off force values than other test sections, which means that the effect of unmodified residual binder (SS-1h) was more significant for these sections than that for the modified residual binder (CSS-1hM).

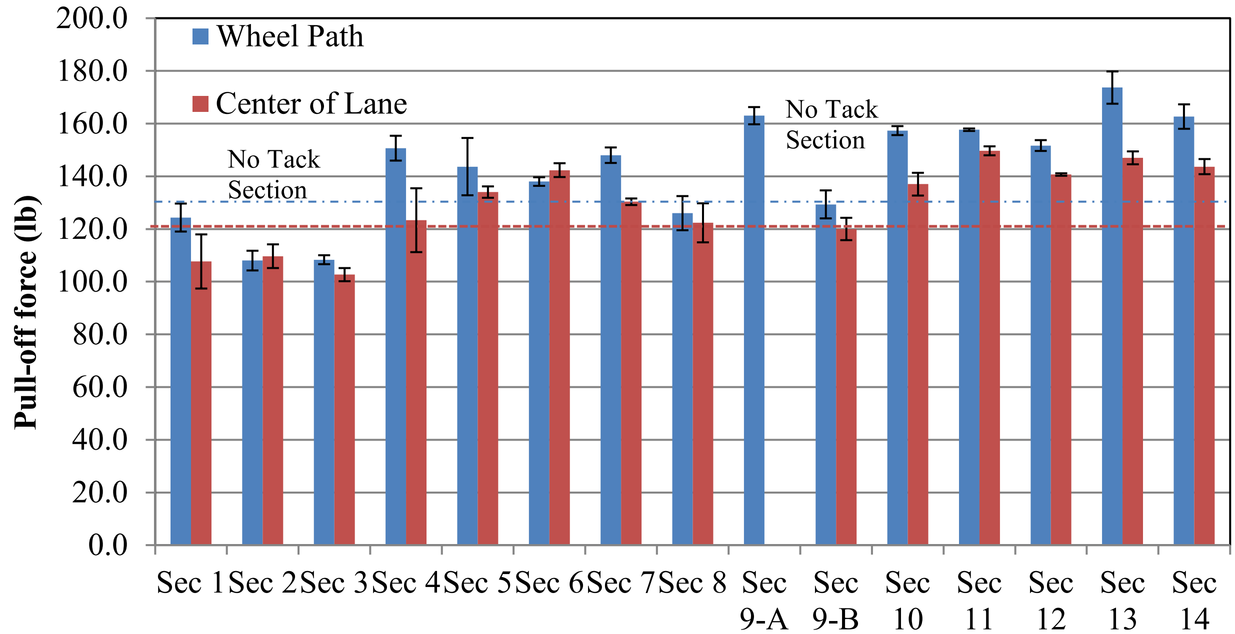


	Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	Sec 6	Sec 7	Sec 9	Sec 11	Sec 13
Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021	0.0	0.063	0.057

Figure B.10 Results of Torque Values for the Field Cores Obtained During the Installation of Leveling Micro-surfacing Layer in the Second Project (SR 03), Tested After 7 Days of Installation

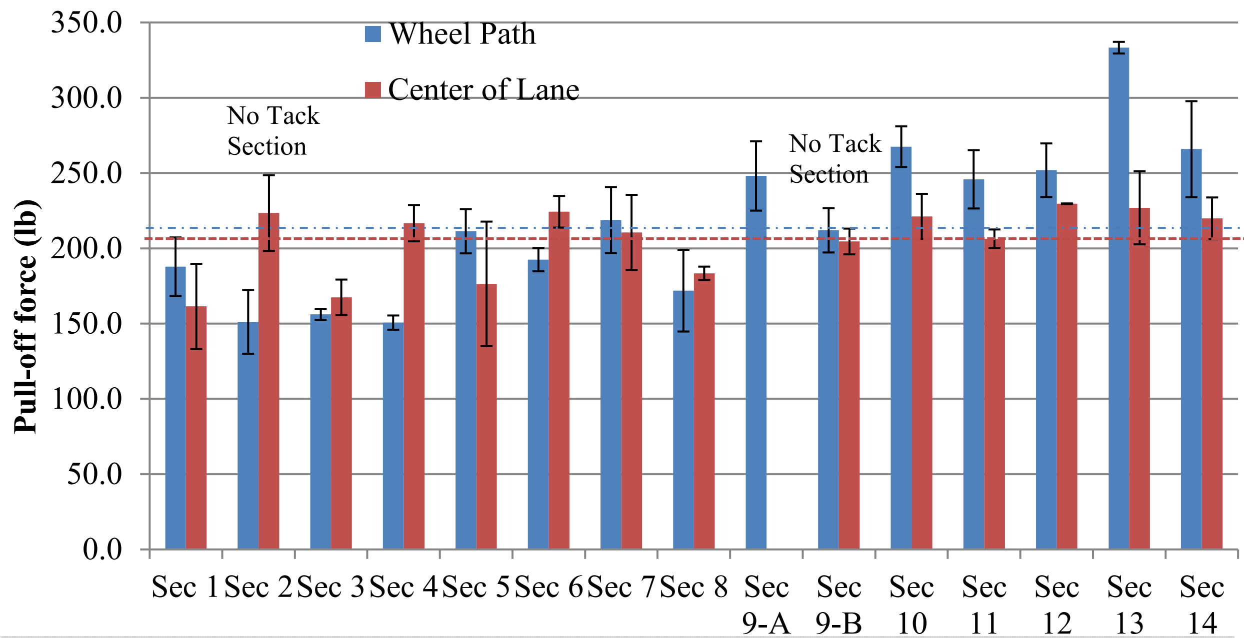
Figure B.12 presents the results of Com-Ten pull-off tester for field cores obtained along wheel path and the center of lane at for test sections with double micro-surfacing layers in SR 03 project after one week of installing the second micro-surfacing layer (surface course layer). The test sections that had tack coat between the first micro-surfacing layer and existing pavement showed a higher pull-off force as compared to the no tack one (section 9-B), except for test section 8 that had micro-surfacing mix with lower residual binder content.

Figure B.13 presents the results of Torque testing for field cores obtained along the wheel path and the center of lane at test sections in the second project after 7 days of installing the micro-surfacing second layer (surface layer). For wheel path cores, the effect of tack coat application rate and residual binder type on bond strength was significant as the torque values were higher for all test sections than that for the no tack section (section 9-B), except for test section 8 that had a lower residual binder content in the mix. Results of pull-off force for sections 10 to 14 indicate that the effect of the tack coat having unmodified residual asphalt binder (SS-1h) was more significant in improving the bond strength than that having the modified residual binder (CSS-1hM), as the pull-off values of sections 13 and 14 were higher than those for sections 10, 11 and 12.



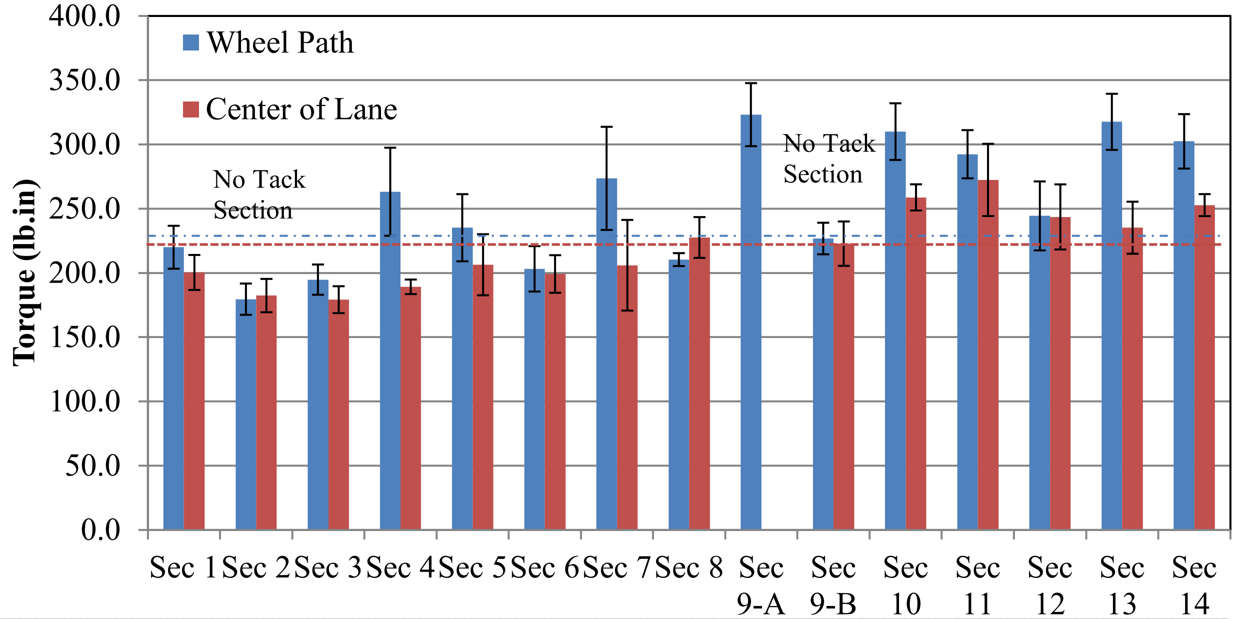
		Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	Sec 6	Sec 7	Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
Avg Diluted Rate (gsy)	1st layer	0.018	0.0	0.022	0.050	0.111	0.105	0.021	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer								0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.11 Results of Proceq Pull-off force Values for the Field Cores Obtained During the Installation of Surface Micro-surfacing Layer in the Second Project (SR 03), Tested After 7 Days of Installation



		Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	Sec 6	Sec 7	Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
Avg Diluted Rate (gsy)	1st layer	0.018	0.0	0.022	0.050	0.111	0.105	0.021	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer								0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.12 Results of Com-Ten Pull-off force Values for the Field Cores Obtained During the Installation of Surface Micro-surfacing Layer in the Second Project (SR 03), Tested After 7 Days of Installation



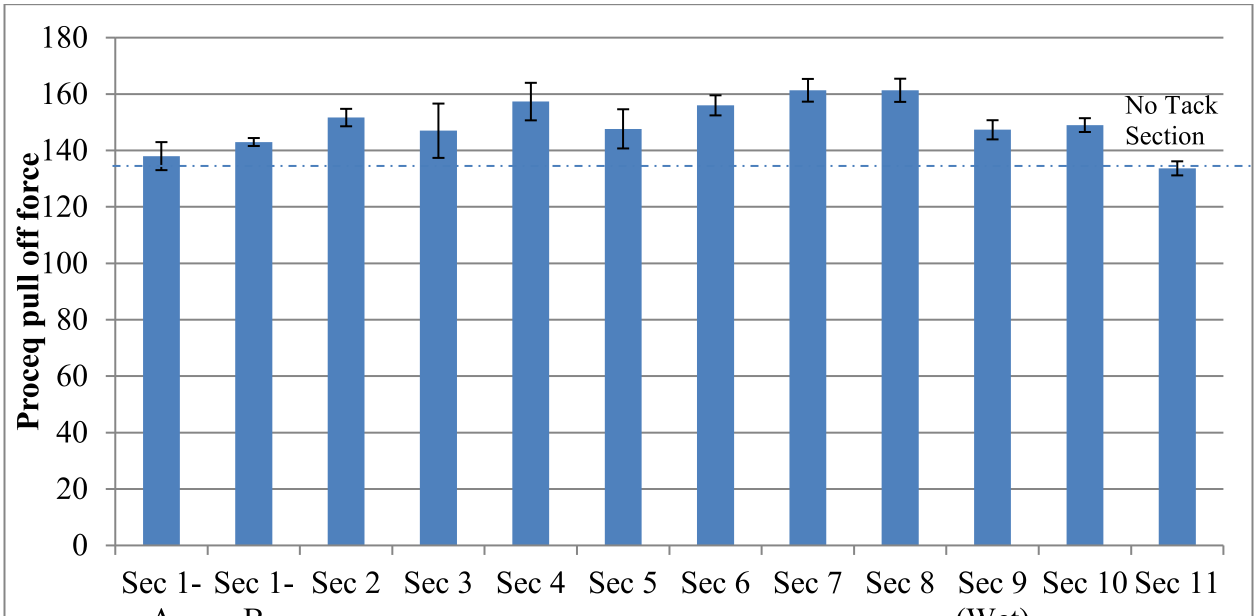
Avg Diluted Rate (gsy)		Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	Sec 6	Sec 7	Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
	1st layer	0.018	0.0	0.022	0.050	0.111	0.105	0.021	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer								0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.13 Results of Torque Values for the Field Cores Obtained During the Installation of Surface Micro-surfacing Layer in the Second Project (SR 03), Tested After 7 Days of Installation.

In general, it is evident that the effect of unmodified residual binder material used in tack coat application is more significant on bond strength of micro-surfacing mixes than that of the effect of modified residual binder for short term bond strength performance of the micro-surfacing layers (7 days after construction). Moreover, the failure mode or all test sections with double micro-surfacing layers was at the interface between the micro-surfacing leveling layer and the existing pavement surface. No failure was reported at the interface between the two adjacent micro-surfacing layers at any of the tested field cores and all failures were adhesive failures.

B.2.3 Results of Bond Strength Tests on Cores Aged for Four Months in the Laboratory-Project 1 (SR 274)

Figure B.14 presents the results of Proceq pull-off tester for field cores obtained along the wheel path at test sections in the first project after 7 days of installing the micro-surfacing surface layer, and tested after 4 months of laboratory aging. As seen in Figure B.14, section 8 had the highest value of pull-off force compared to other test sections, followed by section 7. Note that the value for control section (section 11) where no tack coat material was applied had the lowest pull-off value. The high values in Sec. 8 can be explained by the high actual tack coat application rate that was applied, which was the highest application rate among all sections. Sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, 5, and 9) had lower values of pull-off strength than other sections, but still higher than the no tack section. Pull-off force for sections that were installed on the pavement surface that had an applied tack coat with modified asphalt binder (CSS-1hM) or unmodified asphalt binder (SS-1h) showed higher values of pull-off force compared to the no tack section, which means a significant effect of tack coat application on bond strength improvement, with a slight advantage for the modified asphalt binder over the unmodified one.

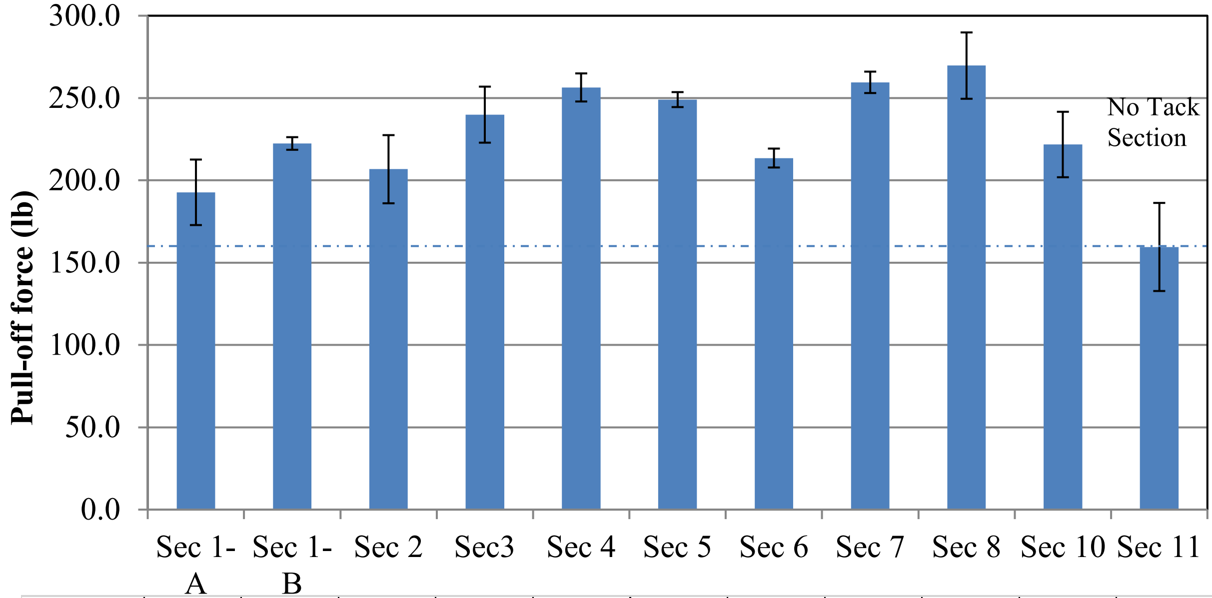


Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.054	0.0

Figure B.14 Results of Proceq Pull-off force Values for the Field Cores Obtained During the Installation of Micro-surfacing Layer in the First Project (SR 274) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation

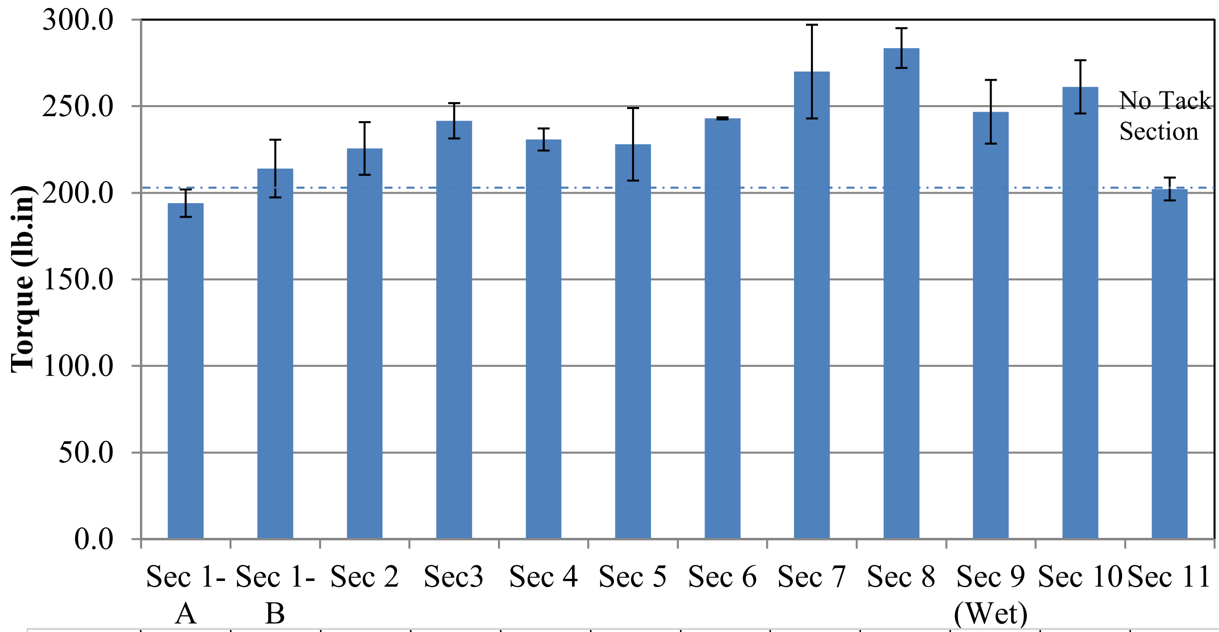
Figure B.15 presents the pull-off force values obtained from Com-Ten pull-off testing on wheel path field cores. Section 8 had the highest value compared to all other test sections. While sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, and 2) had lower values of pull-off force than other test sections, but still higher than the no tack section (section 11). It was noticed that the effect of tack coat material type had more effect on bond strength than the effect of tack coat application rate, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for the no tack section.

Figure B.16 presents the torque values obtained from torque testing on field cores obtained along the wheel path at test sections in the first project. Section 8 had the highest torque value among all other test sections, followed by section 7 and section 10. Sections with lower tack coat application rate and/or lower residual binder content in the Micro-surfacing mix (sections 1-A, 1-B, 2, 9) had lower values of pull-off force compared to other test sections, but still higher than the value for section 11 (no tack section). These results agree with the results obtained from pull-off testing on field cores along the wheel path. The effect of tack coat application rate or tack coat material type on bond strength was significant, as all test sections had higher torque values than that for the no tack section.



Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.054	0.0

Figure B.15 Results of Com-Ten Pull-off force Values for the Field Cores Obtained During the Installation of Micro-surfacing Layer in the First Project (SR 274) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation

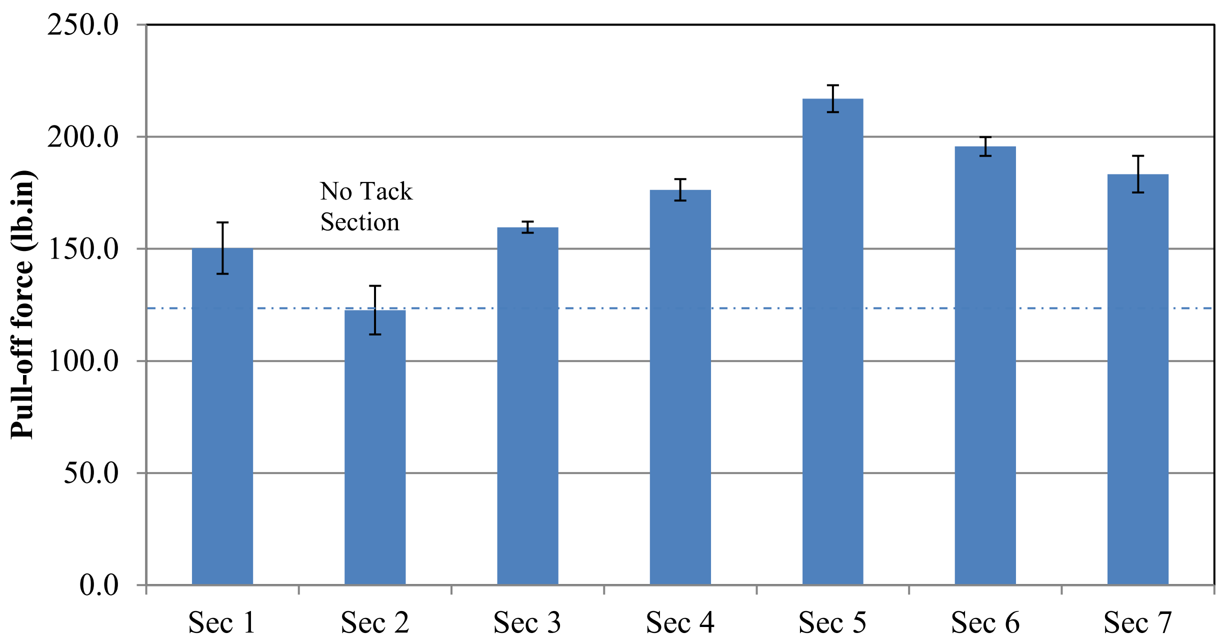


Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.054	0.0

Figure B.16 Results of Torque Values for the Field Cores Obtained During the Installation of Micro-surfacing Layer in the First Project (SR 274) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation

B.2.4 Results of Bond Strength Tests on Cores Aged for Four Months in the Laboratory-Project 2 (SR 03)

Figure B.17 presents the results of Proceq pull-off tester for field cores obtained along wheel path in the second project after 7 days of installing the micro-surfacing surface layer for sections with single micro-surfacing layer, and tested after 4 months of laboratory aging. As seen in Figure B.17, section 5 had the highest value of pull-off force compared to other test sections, followed by section 6. These high values can be explained by the high actual tack coat application rate that was applied on these two sections which was the highest application rate values among all sections. Furthermore, the better performance for modified residual binder as compared to that for unmodified residual binder was demonstrated by the higher pull-off force value obtained for section 5. However, the effect of the unmodified residual binder on bond strength was almost comparable to that for the modified residual binder, since the pull-off force value for section 6 was close to that for section 5 knowing that they had almost the same tack coat application rate, and the value for section 7 was also close to that for section 5 even though a lower tack coat application rate was sprayed at that section. The section with lower residual binder content in the micro-surfacing mix (sections 1) had a lower value of pull-off force than other sections, but still higher than the no tack section, which indicates that the effect of applying a tack coat on pavement surface was significant in improving bond strength.

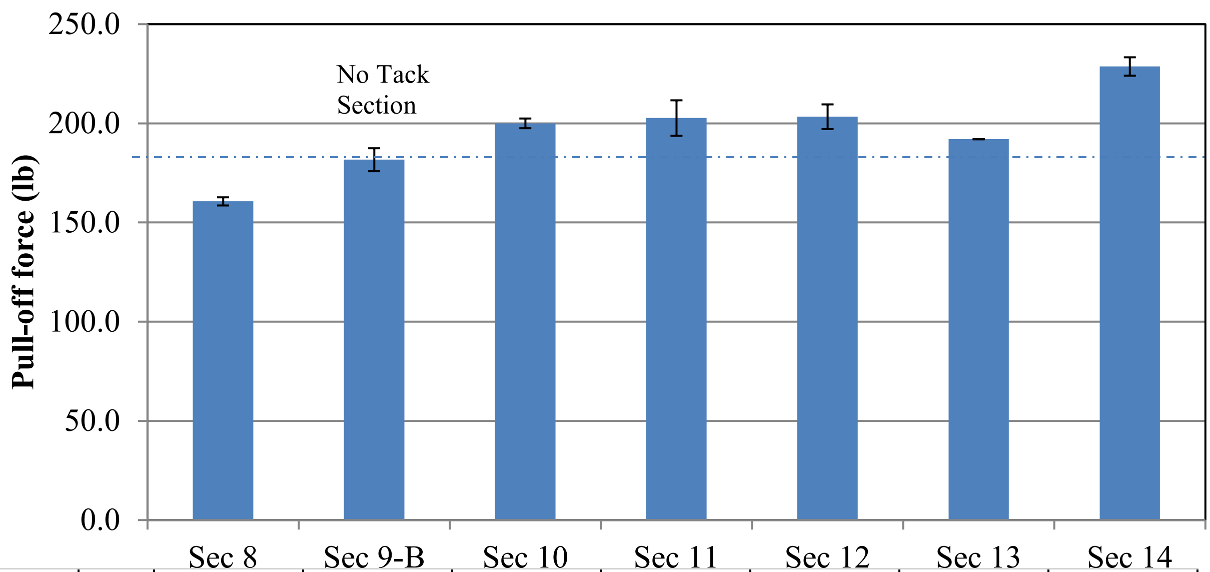


Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

Figure B.17 Results of Proceq Pull-off force Values for the Field Cores Obtained from Test Sections with Single Micro-surfacing Layer During the Installation of Micro-surfacing Layer in the Second Project (SR 03) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation

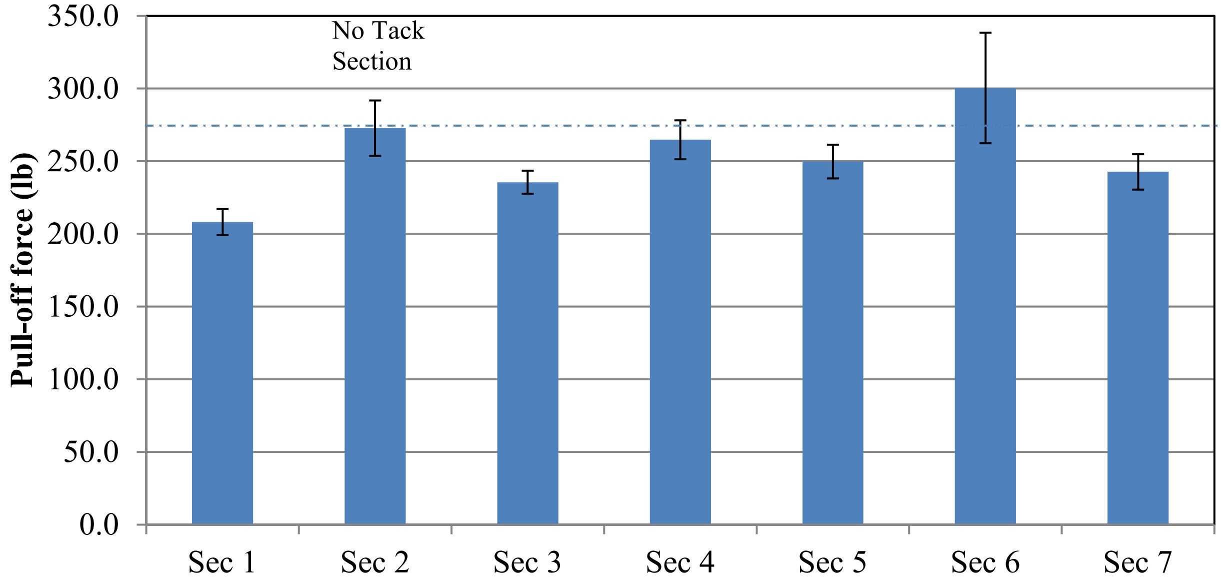
Figure B.18 presents the pull-off force values obtained from Proceq pull-off testing for field cores obtained along wheel path in the second project after 7 days of installing the micro-surfacing surface layer for sections with double micro-surfacing layer, and tested after 4 months of laboratory aging. Section 14 had the highest value compared to all other test sections, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one (sections 11 and 12), section 13 had slightly lower pull-off force value compared to that for sections 11 and 12 even though the unmodified residual binder was used in the tack coat material This can be explained by the lower tack coat application rate that was applied on the leveling micro-surfacing layer before installing the surface layer, which lowered the effect of the tack coat material on bond strength between micro-surfacing layers. The section with lower residual binder content in the micro-surfacing mix (sections 8) had lower values of pull-off force than other test sections, but still higher than the no tack section (section 9). It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for other sections.

Figure B.19 presents the results of Com-Ten pull-off tester for field cores obtained along the wheel path in the second project after 7 days of installing the micro-surfacing surface layer for sections with single micro-surfacing layer, and tested after 4 months of laboratory aging. As seen in Figure B.19, section 6 had the highest value of pull-off force compared to other test sections. This indicates a better effect for modified residual binder than that for unmodified residual binder. The section with lower residual binder content in the micro-surfacing mix (sections 1) had a lower value of pull-off force than other sections, even lower than the no tack section.



Avg Diluted Rate (gsy)	1st layer	0.042	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.18 Results of Proceq Pull-off force Values for the Field Cores Obtained from Test Sections with Double Micro-surfacing Layer During the Installation of Micro-surfacing Layer in the Second Project (SR 03) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation

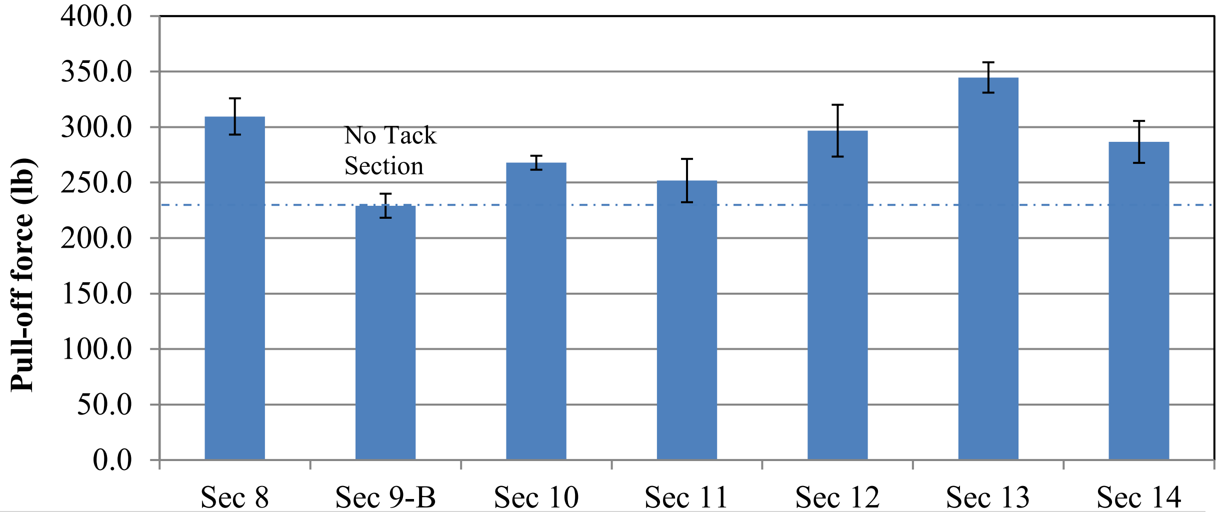


Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

Figure B.19 Results of Com-Ten Pull-off force Values for the Field Cores Obtained from Test Sections with Single Micro-surfacing Layer During the Installation of Micro-surfacing Layer in the Second Project (SR 03) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation

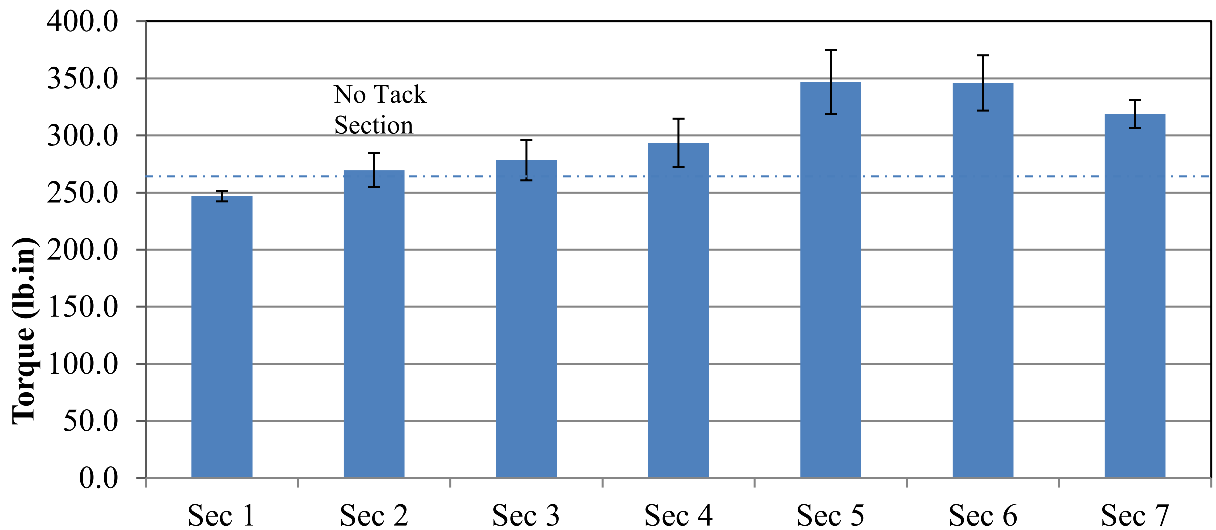
Figure B.20 presents the pull-off force values obtained from Com-ten pull-off testing for field cores obtained along wheel path in the second project after 7 days of installing the micro-surfacing surface layer for sections with double micro-surfacing layer and tested after 4 months of laboratory aging. Section 13 had the highest value compared to all other test sections, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one (sections 11 and 12. The section with lower residual binder content in the micro-surfacing mix (sections 8) had a higher value of pull-off force than other test sections, and the no tack section (section 9) had the lowest value of pull-off force among all other sections. It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for other sections.

Figure B.21 presents the results of Torque testing for field cores obtained along the wheel path in the second project after 7 days of installing the micro-surfacing surface layer for sections with single micro-surfacing layer and tested after 4 months of laboratory aging. As seen in Figure B.21, section 5 had the highest torque value compared to other test sections, followed by section 6 with a slightly lower torque value. These high values can be explained by the high actual tack coat application rate that was applied on these two sections which was the highest application rate values among all sections, this indicates almost similar effect for unmodified residual binder on bond strength to that for modified residual binder, which was also seen from the torque value for section 7 that was close to that for sections 5 and 6 even though a lower tack coat application rate was sprayed at that section. The section with lower residual binder content in the micro-surfacing mix (sections 1) had the lowest torque value among other sections, which implies that the effect of residual binder content in the micro-surfacing mix was also significant on the bond strength between micro-surfacing layer and the existing pavement surface.



Avg Diluted Rate (gsy)		Sec 8	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
	1st layer	0.042	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.033	0.065	0.029	0.070

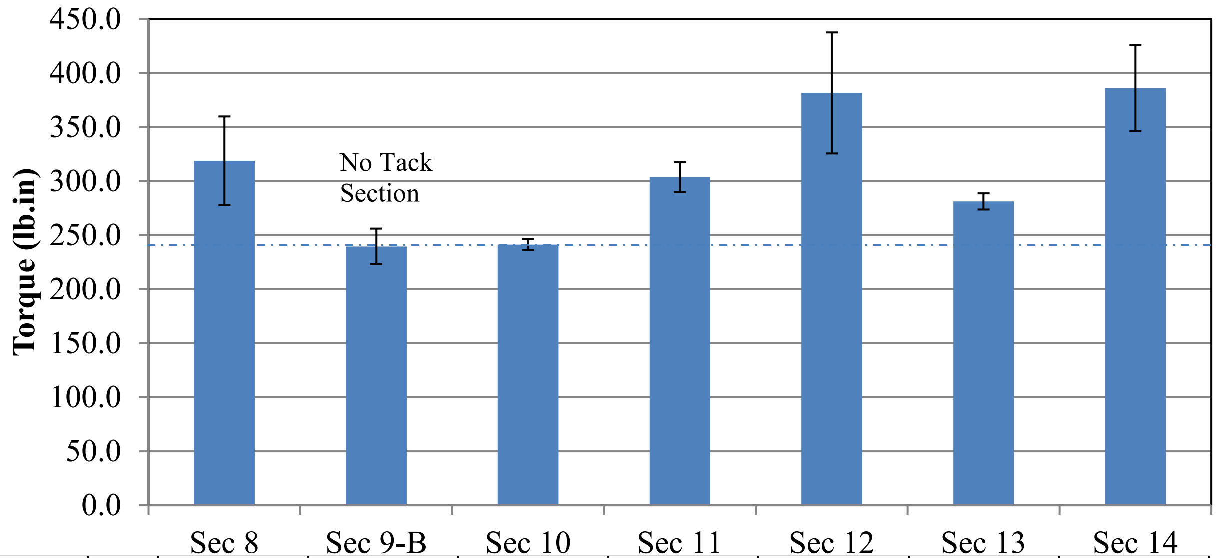
Figure B.20 Results of Com-Ten Pull-off force Values for the Field Cores Obtained from Test Sections with Double Micro-surfacing Layer During the Installation of Micro-surfacing Layer in the Second Project (SR 03) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation



	Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	Sec 6	Sec 7
Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

Figure B.21 Results of Torque Values for the Field Cores Obtained from Test Sections with Single Micro-surfacing Layer During the Installation of Micro-surfacing Layer in the Second Project (SR 03) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation

Figure B.22 presents torque values for field cores obtained along wheel path in the second project after 7 days of installing the micro-surfacing surface layer for sections with double micro-surfacing layer and tested after 4 months of laboratory aging. Section 14 had the highest value compared to all other test sections, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one (sections 11 and 12), section 13 had a lower torque value compared to that for sections 11 and 12 even though the unmodified residual binder was used in the tack coat material, this can be explained by the lower tack coat application rate that was applied on the leveling micro-surfacing layer before installing the surface layer, which lowered the effect of the tack coat material on bond strength between micro-surfacing layers. The section with lower residual binder content in the micro-surfacing mix (sections 8) had a higher value of torque than other test sections, and the no tack section (section 9-B) had the lowest torque value among all other sections. These results agree well with the results obtained from pull-off tests. It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the torque value for sections that had these two factors was higher than that for other sections.

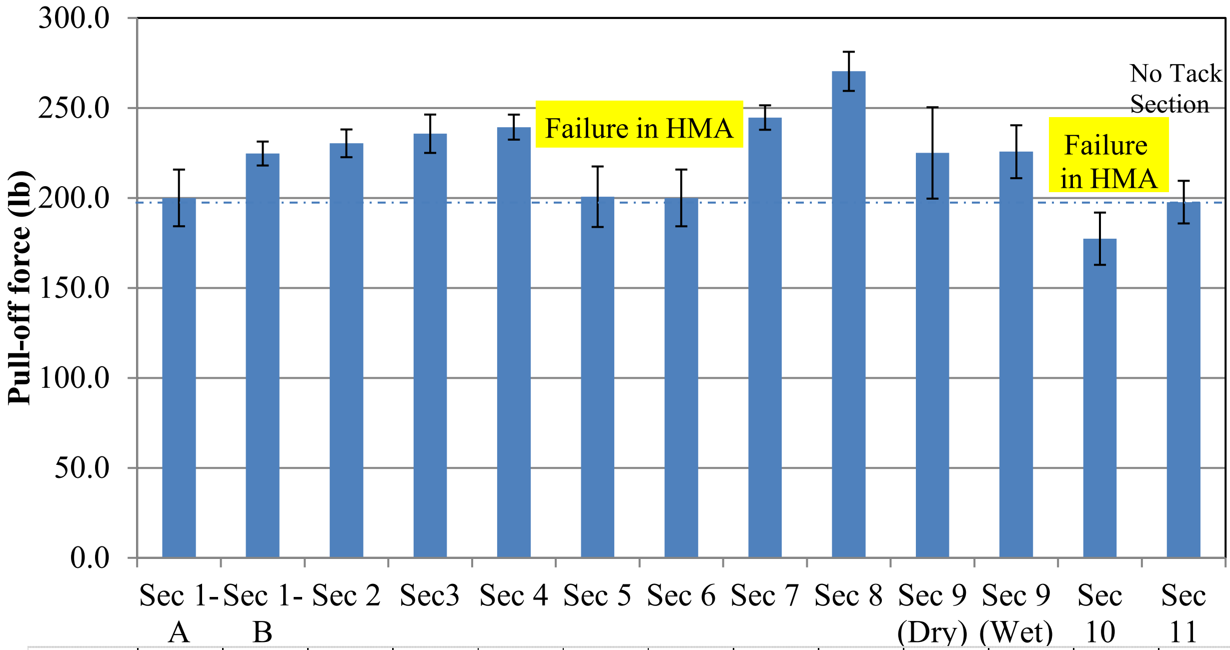


		Sec 8	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
Avg Diluted Rate (gsy)	1st layer	0.042	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.22 Results of Torque Values for the Field Cores Obtained from Test Sections with Double Micro-surfacing Layer During the Installation of Micro-surfacing Layer in the Second Project (SR 03) and Aged for 4 Months in the Lab, Tested After 4 Months of Installation

B.2.5 Results of Bond Strength Tests on Field Cores Obtained After Four Months of Construction- Project 1 (SR 274)

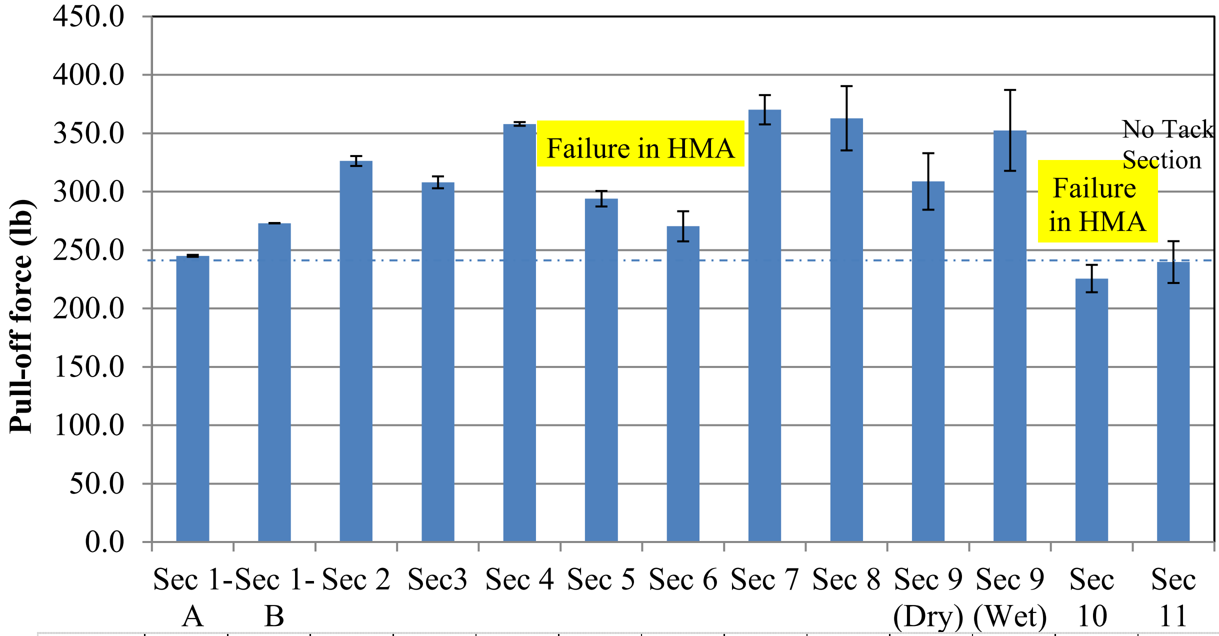
Figure B.23 presents the results of Proceq pull-off tester for field cores obtained along the wheel path at test sections in the first project 4 months after installation of micro-surfacing surface layer. As seen in Figure B.23, section 8 had the highest value of pull-off force compared to other test sections, followed by section 7, higher than the value for the no tack section (section 11). These high values can be explained by the high actual tack coat application rate that was applied on section 8 which was the highest application rate among all sections. Sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, and 9) had lower values of pull-off force than other sections, but still higher than the no tack section. Pull-off force for sections that were installed on the pavement surface that had an applied tack coat with modified asphalt binder (CSS-1hM) or unmodified asphalt binder (SS-1h) showed higher values of pull-off force compared to the no tack section, which means a significant effect of tack coat application on bond strength improvement, with a slight advantage for the modified residual binder over the unmodified one. These results are quite similar to the results of Proceq pull-off testing for field cores aged for 4 months in the lab. However, some field cores exhibited a failure in the existing old pavement layer (sections 5, 6, and 10) and the value of pull-off force could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower pull-off force values were reported for these sections, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer.



Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.054	0.0

Figure B.23 Results of Proceq Pull-off force Values for the Field Cores Aged for 4 Months in the Field in the First Project (SR 274), Tested After 4 Months of Installation

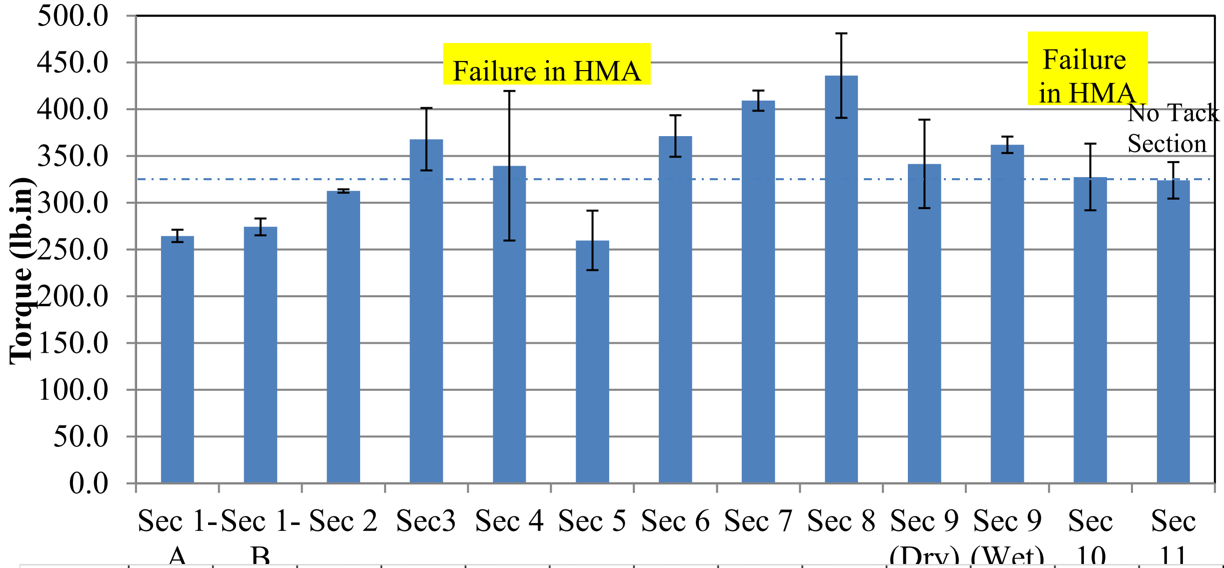
Figure B.24 presents the pull-off force values obtained from Com-Ten pull-off testing on wheel path field cores. Section 7 had the highest value compared all other test sections, followed by section 8 with a slightly lower pull-off force value. Sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, and 2) had lower values of pull-off force than other test sections, but still higher than the no tack section (section 11). It was noticed that the effect of tack coat material type had more significant effect on bond strength than the effect of tack coat application rate, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for the no tack section, with almost similar effect for unmodified residual binder used in tack coat material on bond strength to that for the modified one. These results agree with the results of Com-Ten pull-off testing for field cores aged for 4 months in the lab. However, some field cores exhibited a failure in the existing old pavement layer (sections 5, 6, and 10) and the value of pull-off force could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower pull-off force values were reported for these sections, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer.



Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.054	0.0

Figure B.24 Results of Com-Ten Pull-off force Values for the Field Cores Aged for 4 Months in the Field in the First Project (SR 274), Tested After 4 Months of Installation

Figure B.25 presents the torque values obtained from torque testing on field cores obtained along the wheel path at test sections in the first project. Section 8 had the highest torque value among all other test sections, followed by section 7. Sections with lower tack coat application rate and lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, and 2) had the lowest values of pull-off force compared to other test sections, with higher strength for section 2 than that for section 1-A and section 1-B, which indicates that applying a higher rate of same tack coat material resulted in improving bond strength. The effect of tack coat application rate or tack coat material type on bond strength was significant. These results agree with the results of torque testing for field cores aged for 4 months in the lab. However, some field cores exhibited a failure in the existing old pavement layer (sections 4, 5, 6, and 10) and the torque value could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower torque values were reported for these sections, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer.



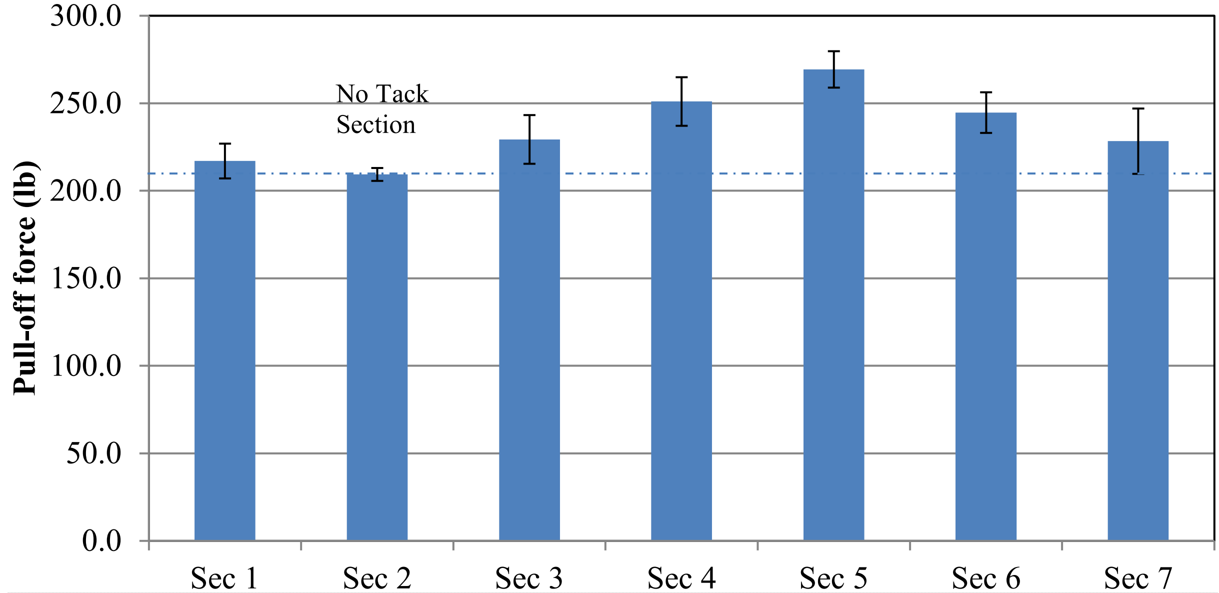
Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.054	0.0

Figure B.25 Results of Torque Values for the Field Cores Aged for 4 Months in the Field in the First Project (SR 274), Tested After 4 Months of Installation

B.2.6 Results of Bond Strength Tests on Field Cores Obtained After Four Months of Construction - Project 2 (SR 03)

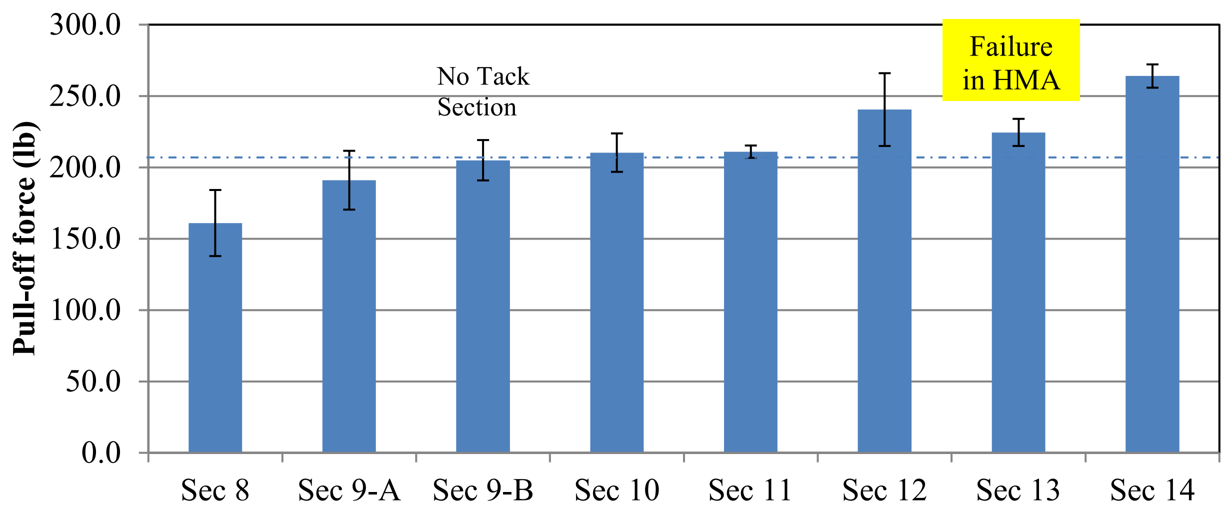
Figure B.26 presents the results of Proceq pull-off tester for field cores obtained along the wheel path in the second project 4 months after the installation of micro-surfacing surface layer at sections with single micro-surfacing layer. As seen in Figure B.26, section 5 had the highest value of pull-off force compared to other test sections, followed by section 4. Better effect for modified residual binder than that for unmodified residual binder was indicated as section 5 had the highest pull-off force value. However, the effect of the unmodified residual binder on bond strength was almost comparable to that for the modified residual binder, since the pull-off force value for section 6 was close to that for section 5 knowing that they had almost the same tack coat application rate. The section with lower residual binder content in the micro-surfacing mix (sections 1) had a lower value of pull-off force than other sections, but still higher than the no tack section, which indicates that the effect of applying a tack coat on pavement surface was significant in improving bond strength. These results are quite similar to the results of Proceq pull-off testing for field cores aged for 4 months in the lab.

Figure B.27 presents the pull-off force values obtained from Proceq pull-off testing for field cores obtained along wheel path in the second project 4 months after the installation of micro-surfacing surface layer at sections with double micro-surfacing layer. Section 14 had the highest value compared to all other test sections, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one (sections 11 and 12). Section 13 exhibited a failure in the existing old pavement layer, and the value of pull-off force could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. The section with lower residual binder content in the micro-surfacing mix (sections 8) had the lowest pull-off force value among other test sections. It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for other sections.



	Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	Sec 6	Sec 7
Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

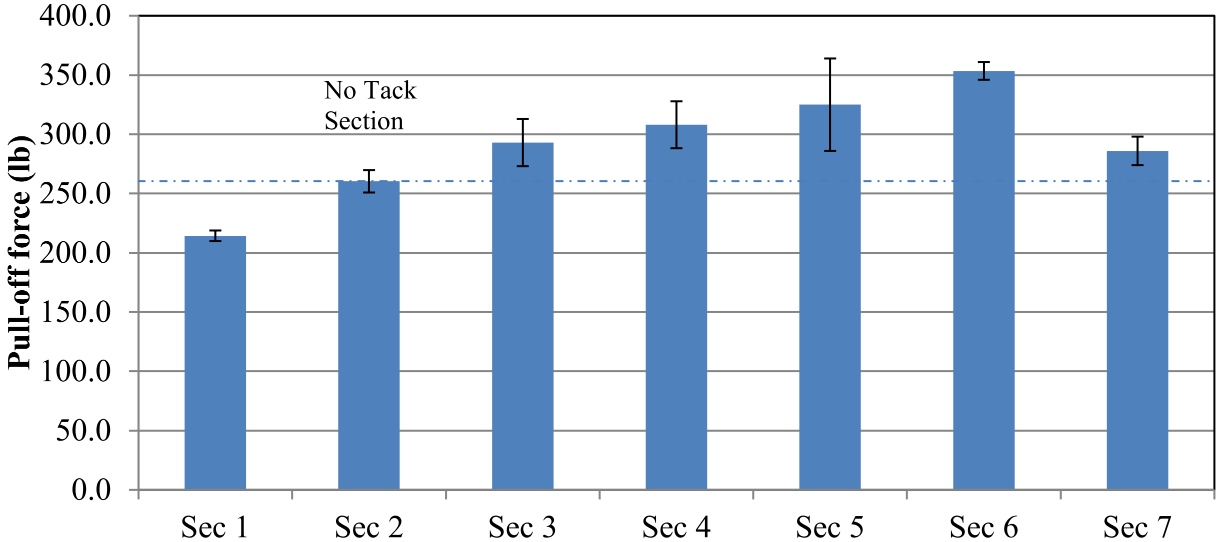
Figure B.26 Results of Proceq Pull-off Values for the Field Cores Aged for 4 Months in the Field for Sections with Single Micro-surfacing Layer in the Second Project (SR 03), Tested After 4 Months of Installation



		Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
Avg Diluted Rate (gsy)	1st layer	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.27 Results of Proceq Pull-off Values for the Field Cores Aged for 4 Months in the Field for Sections with Double Micro-surfacing Layer in the Second Project (SR 03), Tested After 4 Months of Installation

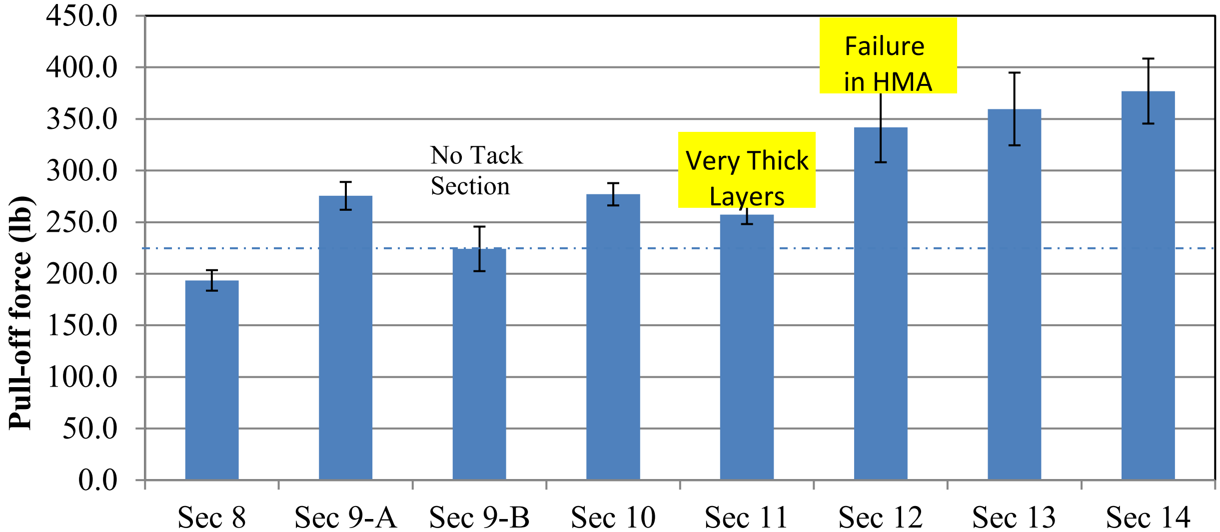
Figure B.28 presents the results of Com-Ten pull-off tester for field cores obtained along wheel path in the second project 4 months after the installation of micro-surfacing surface layer at sections with single micro-surfacing layer. As seen in Figure B.28, section 6 had the highest value of pull-off force compared to other test sections. This indicates a better effect for modified residual binder than that for unmodified residual binder. The section with lower residual binder content in the micro-surfacing mix (sections 1) had a lower value of pull-off force than other sections, even lower than the no tack section.



Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

Figure B.28 Results of Com-Ten Pull-off Values for the Field Cores Aged for 4 Months in the Field for Sections with Single micro-surfacing Layer in the Second Project (SR 03), Tested After 4 Months of Installation

Figure B.29 presents the pull-off force values obtained from Com-ten pull-off testing for field cores obtained along wheel path in the second project 4 months after installation of the micro-surfacing surface layer for sections with double micro-surfacing layer. Section 14 had the highest value compared to all other test sections, followed by section 13, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one. Section 12 exhibited a failure in the existing old pavement layer, and the value of pull-off force could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Section 11 pull-off force value was not also included in the comparison since its field cores had very thick micro-surfacing layers compared to other test sections, this high thickness made it very easy to pull-off the micro-surfacing layers since these layers were softer than they should be, which lowered the bond strength value, resulting in misleading bond strength. It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for other sections, except for the section with lower residual binder content in the micro-surfacing mix (sections 8) which had the lowest value of pull-off force among all other sections.

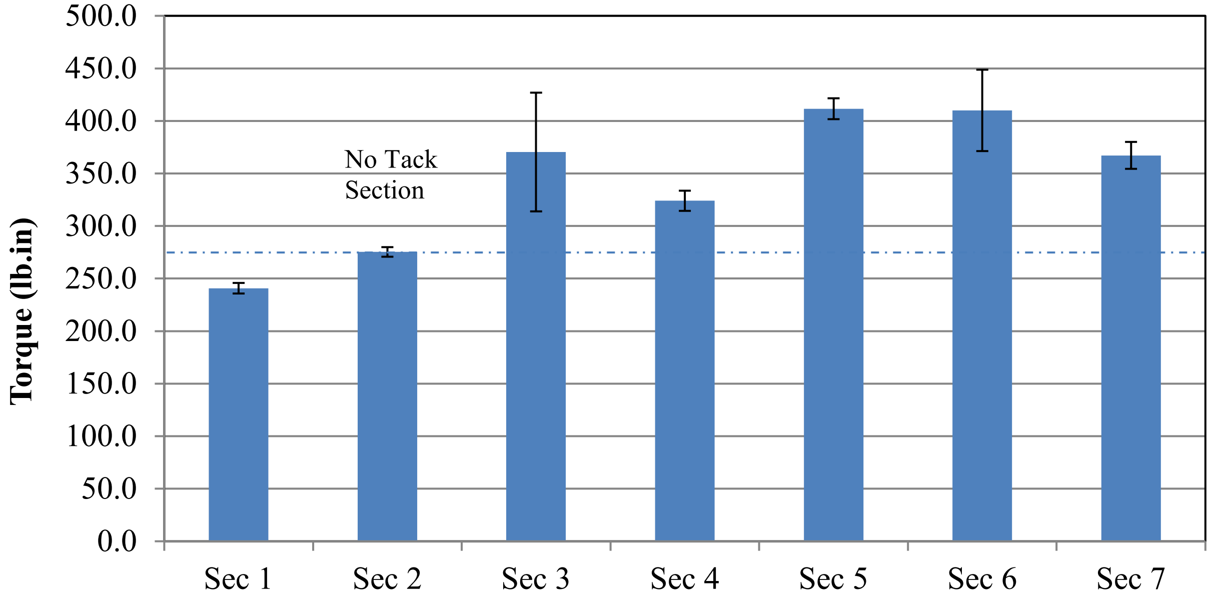


		Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
Avg Diluted Rate (gsy)	1st layer	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.29 Results of Com-Ten Pull-off Values for the Field Cores Aged for 4 Months in the Field for Sections with Double Micro-surfacing Layer in the Second Project (SR 03), Tested After 4 Months of Installation

Figure B.30 presents the results of Torque testing for field cores obtained along wheel path in the second project 4 months after installation of micro-surfacing surface layer at sections with single micro-surfacing layer. As seen in Figure B.29, section 5 had the highest value of pull-off force compared to other test sections, followed by section 6 with a slightly lower torque value. These high values can be explained by the high actual tack coat application rate that was applied on these two sections which was the highest application rate values among all sections, this indicates almost similar effect for unmodified residual binder to that for modified residual binder, which was also seen from the torque value for section 7 that was close to that for sections 5 and 6 even though a lower tack coat application rate was sprayed at that section. The section with lower residual binder content in the micro-surfacing mix (sections 1) had the lowest value of pull-off strength than among other sections, which implies that the effect of residual binder content in the micro-surfacing mix was also significant on the bond strength between micro-surfacing layer and the existing pavement surface.

Figure B.31 presents torque values for field cores obtained along wheel path in the second project 4 months after the installation of micro-surfacing surface layer at sections with double micro-surfacing layer. Section 14 had the highest value compared to all other test sections, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one (sections 11 and 12), which can also be seen from the relatively high torque value for section 13. The section with lower residual binder content in the micro-surfacing mix (sections 8) had the lowest torque value among all other test sections. These results agree well with the results obtained from pull-off tests. It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the torque value for sections that had these two factors was higher than that for other sections.

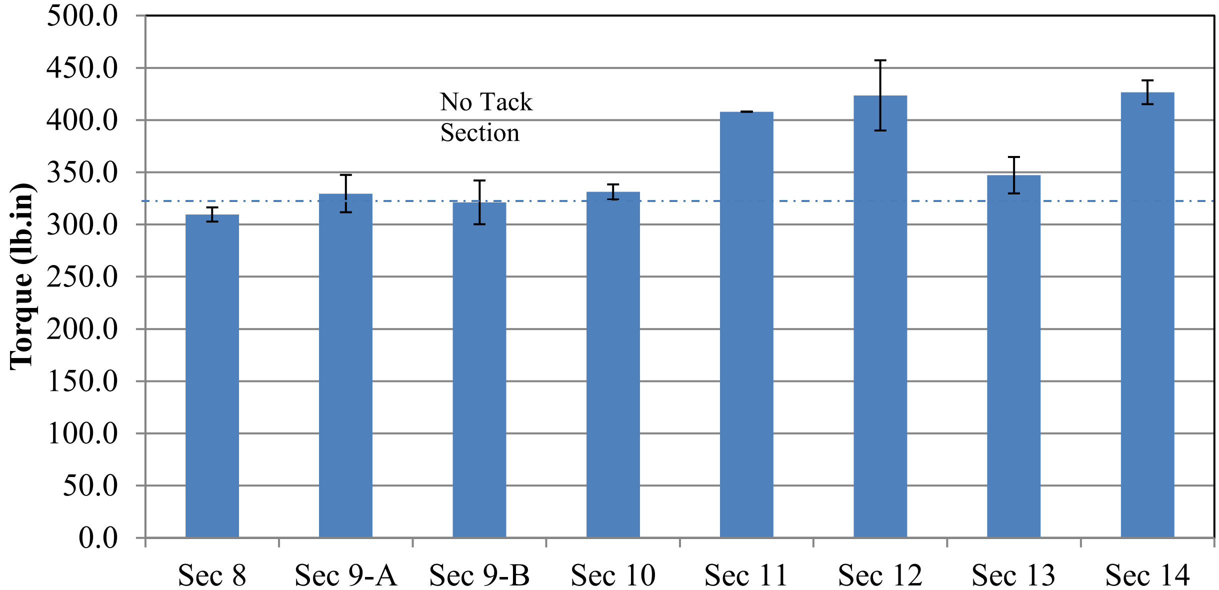


Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

Figure B.30 Results of Torque Values for the Field Cores Aged for 4 Months in the Field for Sections with Single Micro-surfacing Layer in the Second Project (SR 03), Tested After 4 Months of Installation

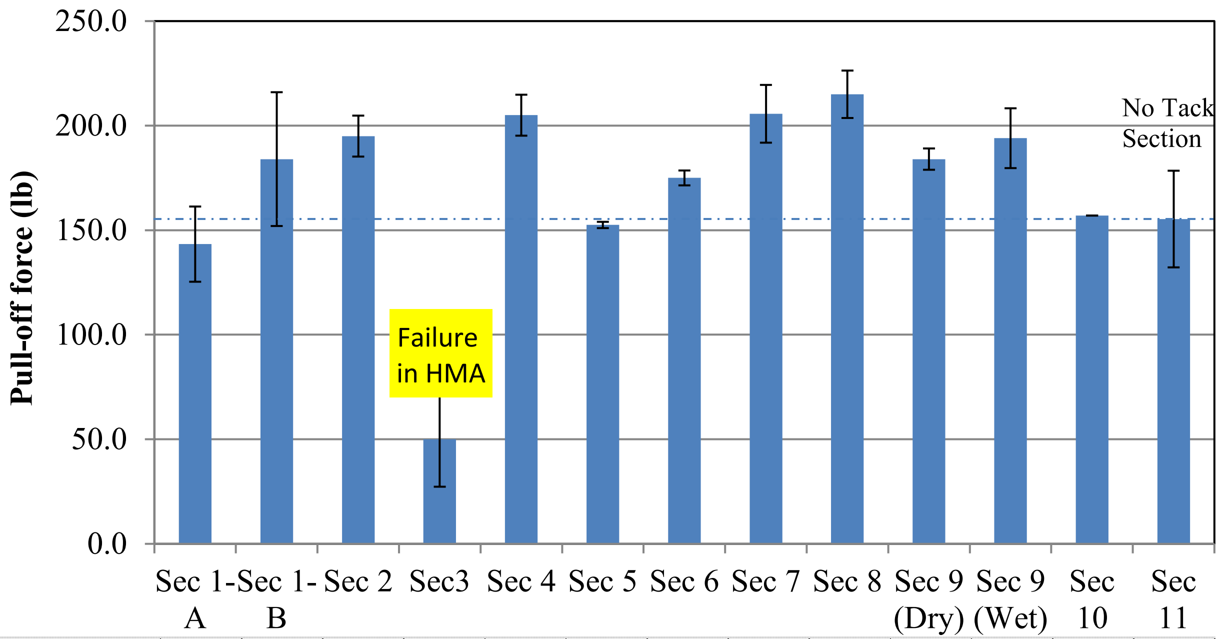
B.2.7 Results of Bond Strength Tests on Field Cores Obtained after Twelve Months of Construction - Project 1 (SR 274)

Figure B.32 presents the results of Proceq pull-off tester for field cores obtained along wheel path at test sections in the first project 12 months after installation of micro-surfacing surface layer. As seen in Figure B.32, section 8 had the highest value of pull-off force compared to other test sections, followed by section 7. These high values agree well with the results obtained from 4 months testing. Sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, and 9) had lower values of pull-off strength than other sections, but still higher than the no tack section. Pull-off force for sections that were installed on the pavement surface that had either types of tack coat with (CSS-1hM or SS-h) showed higher values of pull-off force compared to the no tack section, which indicates that there is a significant effect of tack coat application on bond strength improvement, with a slight advantage for the CSS-1hM over SS-1h tack coat. These results are quite similar to the results of Proceq pull-off testing for 4 months field cores and field cores that were aged for 4 months in the lab. However, a complete failure in the existing old pavement layer (section 3), or partial failure (sections 5, 6, and 10). The corresponding value of pull-off force for these sections could not be included in the comparison since it does not represent the bond strength on between the micro-surfacing layer and existing pavement surface. Much lower pull-off force values were reported for these sections, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer.



Avg Diluted Rate (gsy)		Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
	1st layer	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

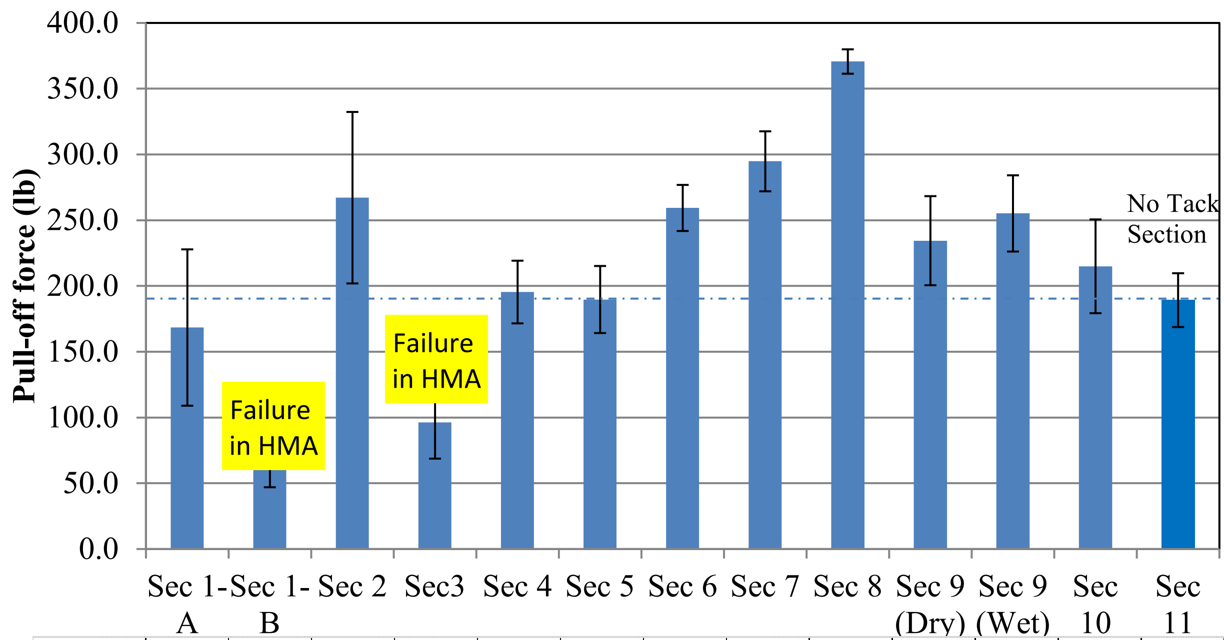
Figure B.31 Results of Torque Values for the Field Cores Aged for 4 Months in the Field for Sections with Double Micro-surfacing Layer in the Second Project (SR 03), Tested After 4 Months of Installation



	Sec 1-A	Sec 1-B	Sec 2	Sec3	Sec 4	Sec 5	Sec 6	Sec 7	Sec 8	Sec 9 (Dry)	Sec 9 (Wet)	Sec 10	Sec 11
Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.054	0.0

Figure B.32 Results of Proceq Pull-off force Values for the Field Cores Aged for 12 Months in the Field in the First Project (SR 274), Tested After 12 Months of Installation

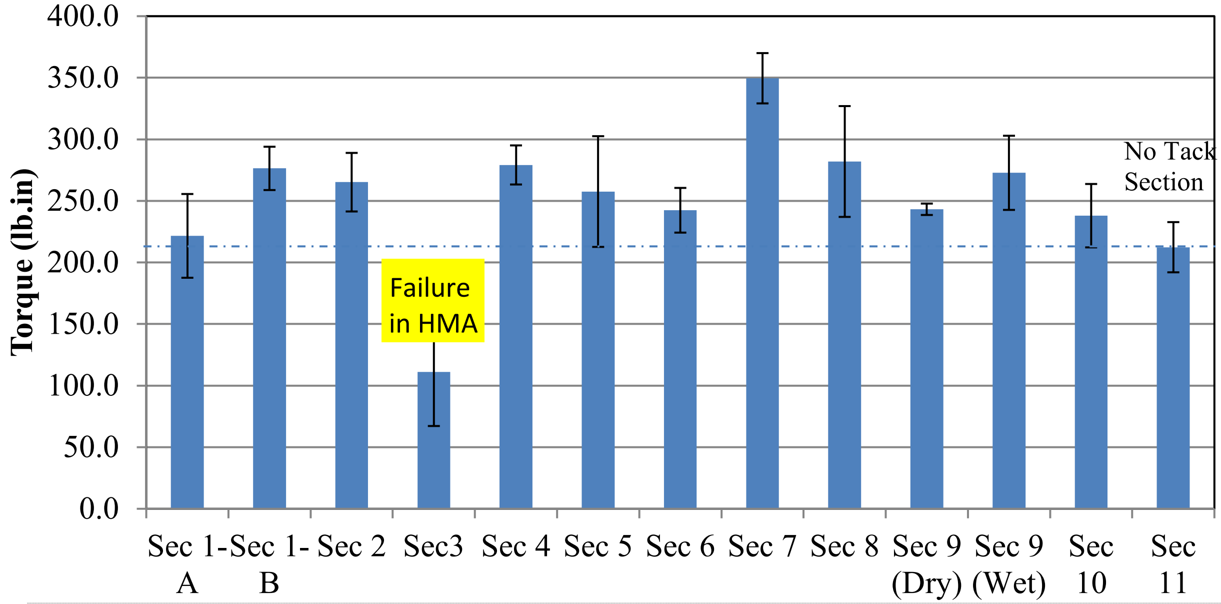
Figure B.33 presents the pull-off force values obtained from Com-Ten pull-off testing on wheel path field cores. Section 8 had the highest value compared all other test sections, followed by section 7. Sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, and 2) had lower values of pull-off force than other test sections, but still higher than the no tack section (section 11). It was noticed that the effect of tack coat material type had more significant effect on bond strength than the effect of tack coat application rate, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for the no tack section, with almost similar effect for unmodified residual binder used in tack coat material on bond strength to that for the modified one. These results agree with the results of Com-Ten pull-off testing for field cores obtained 4 months after installation and field cores aged for 4 months in the lab. However, some field cores exhibited a complete failure in the existing old pavement layer (sections 1-B, and 3), or partial failure (4, 5, 6, and 10). The torque value could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower pull-off force values were reported for these sections, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer.



Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.054	0.0

Figure B.33 Results of Com-Ten Pull-off force Values for the Field Cores Aged for 12 Months in the Field in the First Project (SR 274), Tested After 12 Months of Installation

Figure B.34 presents the torque values obtained from torque testing on field cores obtained along the wheel path at test sections in the first project. Section 7 had the highest torque value among all other test sections, followed by section 8. Sections with lower tack coat application rate and lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, and 2) had the lowest values of pull-off force compared to other test sections. The effect of tack coat application rate or tack coat material type on bond strength was significant since all test sections showed higher torque values than the no tack section (section 11). These results agree with the results of torque testing for field obtained 4 months after installation and field cores aged for 4 months in the lab. However, some field cores exhibited a complete failure in the existing old pavement layer (sections 1-B, and 3), or partial failure (5, 6, and 10). The torque value could not be included in the comparison since it does not represent the bond strength on between the micro-surfacing layer and existing pavement surface. Much lower torque values were reported for these sections, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer.



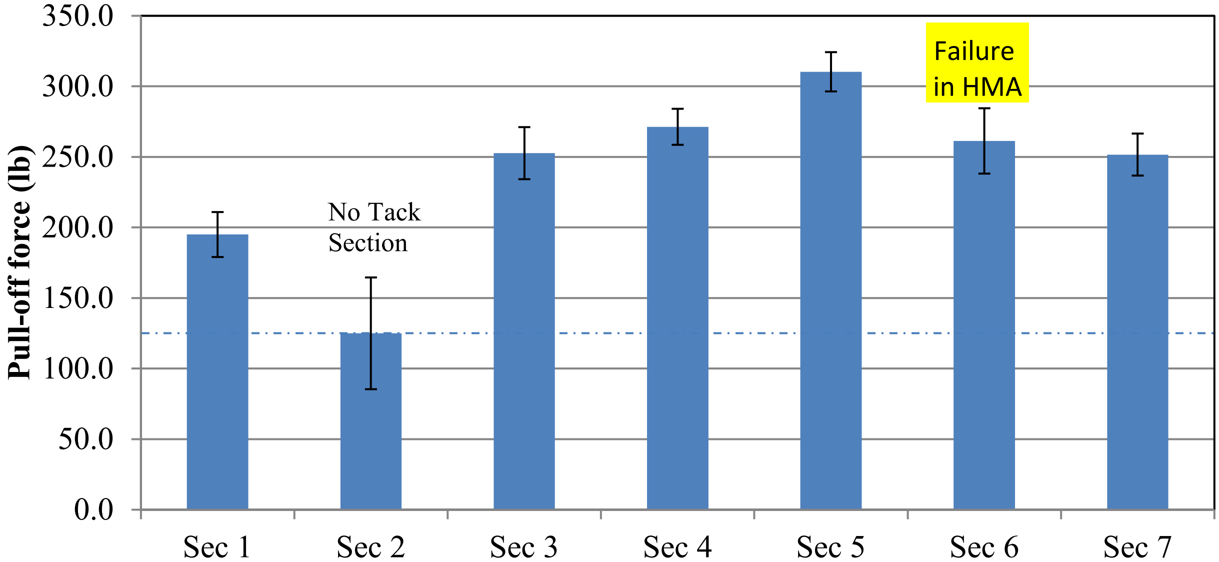
Avg Diluted Rate (gsy)	0.020	0.026	0.035	0.042	0.041	0.023	0.021	0.052	0.086	0.036	0.036	0.054	0.0

Figure B.34 Results of Torque Values for the Field Cores Aged for 12 Months in the Field in the First Project (SR 274), Tested After 12 Months of Installation

B.2.8 Results of Bond Strength Tests on Field Cores Obtained after Twelve Months of Construction - Project 2 (SR 03)

Figure B.35 presents the results of Proceq pull-off tester for field cores obtained along the wheel path in the second project 12 months after the installation of micro-surfacing surface layer at sections with single micro-surfacing layer. As seen in Figure B.35, section 5 had the highest value of pull-off force compared to other test sections, followed by section 4. Better effect for modified residual binder than that for unmodified residual binder was indicated as section 5 had the highest pull-off force value. However, field cores of section 6 exhibited a complete failure in the existing old pavement layer. The pull-off force value could not be included in the comparison between the effect of modified and unmodified residues since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower pull-off force values were reported for these sections, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer.

The section with lower residual binder content in the micro-surfacing mix (sections 1) had a lower value of pull-off strength than other sections, but still higher than the no tack section, which indicates that the effect of applying a tack coat on pavement surface was significant in improving bond strength. These results are quite similar to the results of Proceq pull-off testing for field cores obtained 4 months after installation of micro-surfacing surface layer and field cores aged for 4 months in the lab.

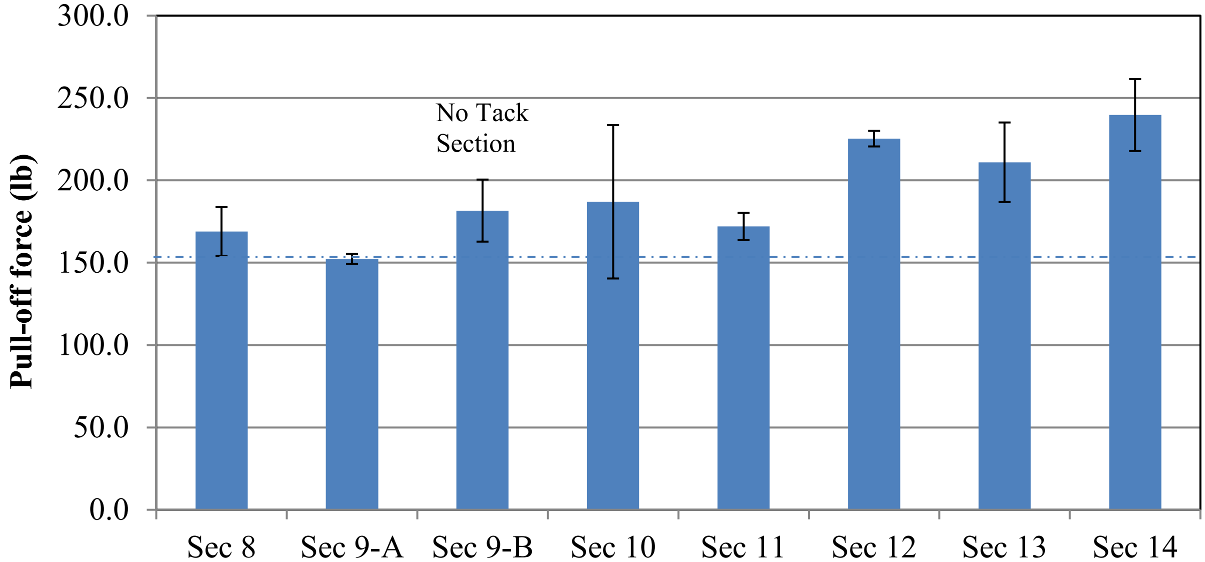


Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

Figure B.35 Results of Proceq Pull-off force Values for the Field Cores Aged for 12 Months in the Field for Sections with Single Micro-surfacing Layer in the Second Project (SR 03), Tested After 12 Months of Installation

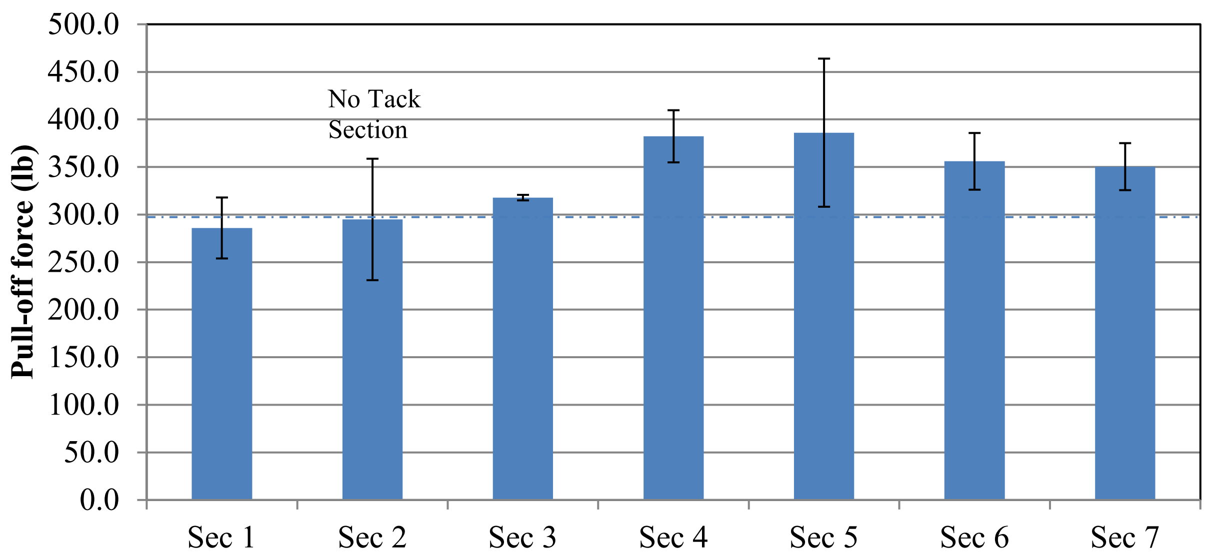
Figure B.36 presents the pull-off force values obtained from Proceq pull-off testing for field cores obtained along wheel path in the second project 12 months after the installation of micro-surfacing surface layer at sections with double micro-surfacing layer. Section 14 had the highest value compared to all other test sections, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one (sections 11 and 12), section 13 had slightly lower pull-off force value compared to that for section 12 even though the unmodified residual binder was used in the tack coat material, this can be explained by the lower tack coat application rate that was applied on the leveling micro-surfacing layer before installing the surface layer, which lowered the effect of the tack coat material on bond strength between micro-surfacing layers. The section with lower residual binder content in the micro-surfacing mix (sections 8) had lower pull-off force value than other test sections, but still higher than that for the no tack section (section 9-B). It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for other sections.

Figure B.37 presents the results of Com-Ten pull-off tester for field cores obtained along wheel path in the second project 12 months after the installation of micro-surfacing surface layer at sections with single micro-surfacing layer. As seen in Figure C.44, section 5 had the highest value of pull-off force compared to other test sections, followed by section 4. However, section 6 had a pull-off force value close to that for sections 4 and 5, which indicates that the effect of unmodified residual binder is comparable to that for the modified one. The section with lower residual binder content in the micro-surfacing mix (sections 1) had the lowest value of pull-off force among all other sections, even lower than the no tack section.



		Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
Avg Diluted Rate (gsy)	1st layer	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

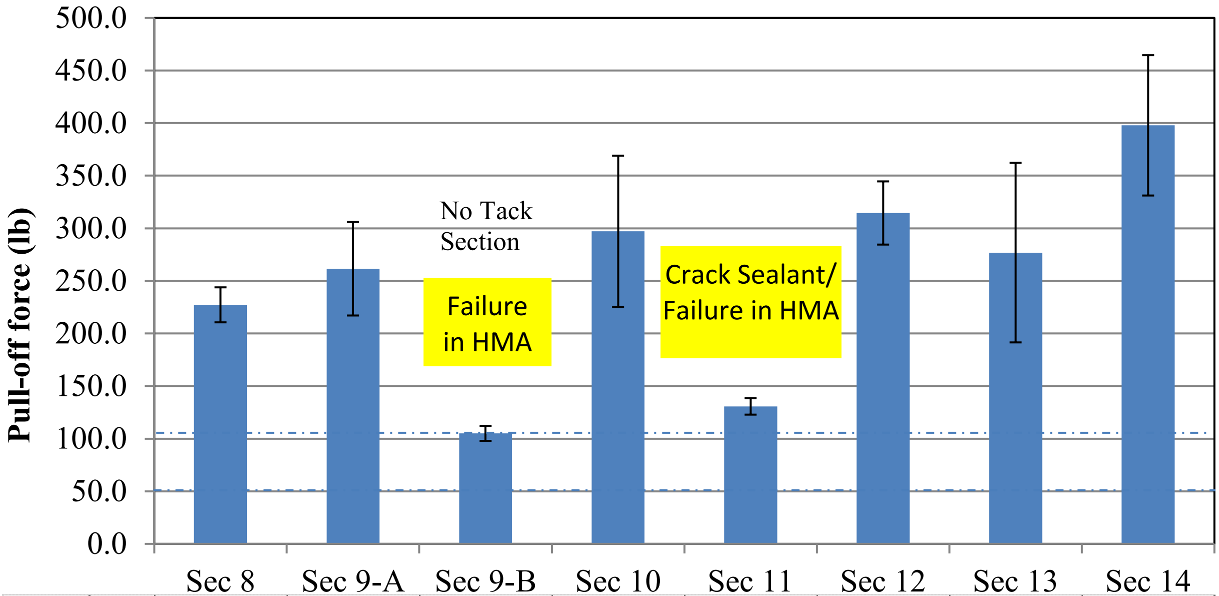
Figure B.36 Results of Proceq Pull-off force Values for the Field Cores Aged for 12 Months in the Field for Sections with Double Micro-surfacing Layers in the Second Project (SR 03), Tested After 12 Months of Installation



	Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	Sec 6	Sec 7
Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

Figure B.37 Results of Com-Ten Pull-off force Values for the Field Cores Aged for 12 Months in the Field for Sections with Single Micro-surfacing Layer in the Second Project (SR 03), Tested After 12 Months of Installation

Figure B.38 presents the pull-off force values obtained from Com-ten pull-off testing for field cores obtained along wheel path in the second project 12 months after installation of the micro-surfacing surface layer for sections with double micro-surfacing layer. Section 14 had the highest value compared to all other test sections, followed by section 12, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one.



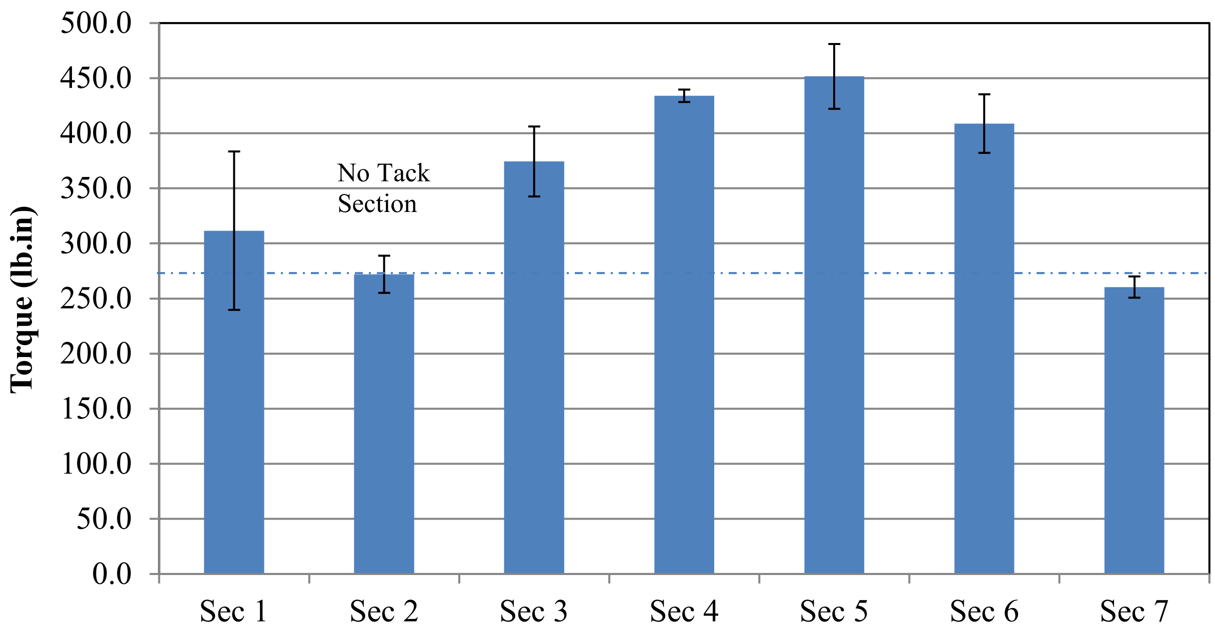
		Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
Avg Diluted Rate (gsy)	1st layer	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.38 Results of Com-Ten Pull-off force Values for the Field Cores Aged for 12 Months in the Field for Sections with Double Micro-surfacing Layers in the Second Project (SR 03), Tested After 12 Months of Installation

Section 9-B exhibited a failure in the existing old pavement layer, and the value of pull-off force could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Section 11 pull-off force value was not also included in the comparison since its field cores had a crack sealant in the existing old pavement layer, this crack sealant means that the old pavement surface was cracked which made it very easy to pull-off the micro-surfacing layers since the bond between those layers and the existing pavement surface was not sufficient, which lowered the strength value and led to a misleading bond strength. It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the value of pull-off force for sections that had these two factors showed higher pull-off force than that for other sections, except for the section with lower residual binder content in the micro-surfacing mix (sections 8) which had the lowest value of pull-off force among all other sections.

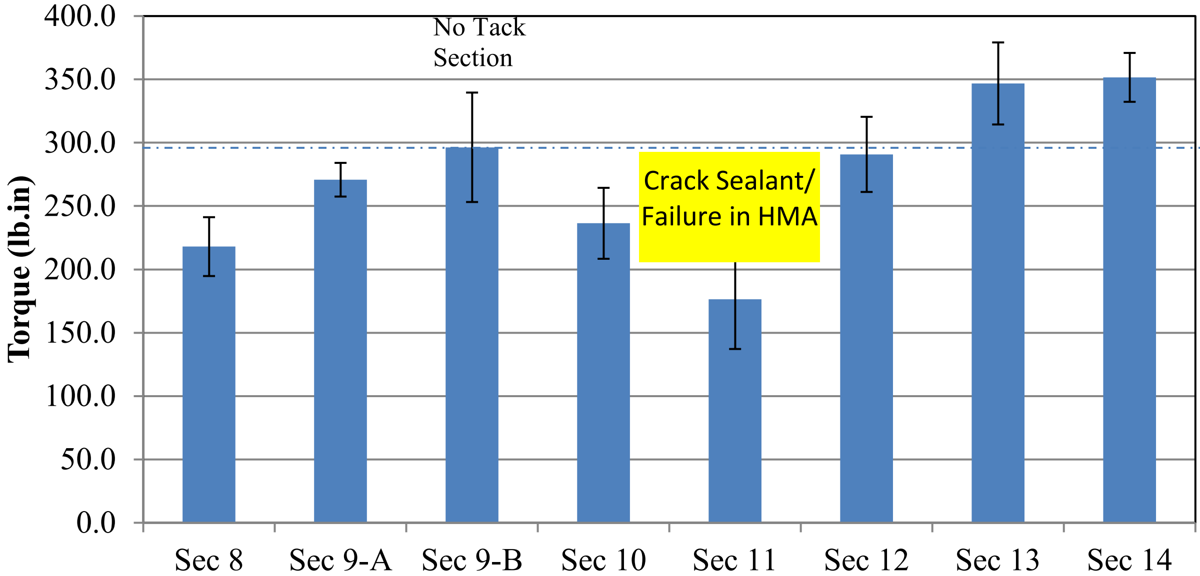
Figure B.39 presents the results of Torque testing for field cores obtained along wheel path in the second project 12 months after the installation of micro-surfacing surface layer at sections with single micro-surfacing layer. As seen in Figure B.39, section 5 had the highest torque value compared to other test sections, followed by section 4 with a slightly lower torque value. These high values can be explained by the high actual tack coat application rate that was applied on these two sections which was the highest application rate values among all sections, this indicates almost similar effect for SS-1h compared to that of CSS-1hM. The section with lower residual binder content in the micro-surfacing mix (section 1) had the lower torque value than other sections, but higher than that of no tack section.

Figure B.40 presents torque values for field cores obtained along wheel path in the second project 12 months after the installation of micro-surfacing surface layer at sections with double micro-surfacing layer. Section 14 had the highest value compared to all other test sections, which means a better effect for unmodified residual asphalt binder on bond strength compared to the modified one (section 12), which can also be seen from the high torque value for section 13, which was slightly lower than that for section 14. The section with lower residual binder content in the micro-surfacing mix (sections 8) had the lowest torque value among all other test sections. These results agree well with the results obtained from pull-off tests. Section 11 exhibited a failure in the existing old pavement layer, and the value of pull-off force could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. It was noticed that the effect of tack coat material type and tack coat application rate had a significant effect on bond strength, as the torque value for sections that had these two factors was higher than that for other sections.



Avg Diluted Rate (gsy)	0.018	0.0	0.022	0.050	0.111	0.105	0.021

Figure B.39 Results of Torque Values for the Field Cores Aged for 12 Months in the Field for Sections with Single Micro-surfacing Layer in the Second Project (SR 03), Tested After 12 Months of Installation



Avg Diluted Rate (gsy)		Sec 8	Sec 9-A	Sec 9-B	Sec 10	Sec 11	Sec 12	Sec 13	Sec 14
	1st layer	0.042	0.0	0.0	0.064	0.063	0.063	0.057	0.057
	2nd layer	0.028	0.0	0.0	0.0	0.033	0.065	0.029	0.070

Figure B.40 Results of Torque Values for the Field Cores Aged for 12 Months in the Field for Sections with Double Micro-surfacing Layers in the Second Project (SR 03), Tested After 12 Months of Installation

B.3 Statistical Analysis of The Field Cores Testing Results

Analysis of Variance (ANOVA) and post ANOVA Least Square Mean (LSM) analyses were conducted using Statistical Analysis Software (SAS) (SAS, 2004) to statistically evaluate the results of bond strength testing in the laboratory for field cores obtained from SR 274 project and SR 03 project twelve months after the installation of micro-surfacing layer(s) at each project, to evaluate the effect of tack coat material type and application rate on bond strength. A linear Completely Random Design (CRD) model was used in the analysis. Tables B.1, and B.2 present the results of ANOVA on the Proceq pull-off force, and torque values obtained from the bond strength tests performed on the 12 months field aged cores obtained from SR 274 project. It is noted that from both tables that the effects of tack coat material type and application rate on Proceq pull-off force and torque values were statistically significant at 95% confidence level, which can be indicated by the P-values in both tables.

Table B.3 presents the results of the ranking of test sections based on Proceq pull-off force values for SR 274, which were determined using the post ANOVA LSM analysis. In this table, the groups are listed in descending order with the letter "A" assigned to the highest mean followed by the other letters in an appropriate order. It is noted that section 8 had the highest value of pull-off force compared to other test sections, followed by section 7. Sections with lower tack coat application rate and/or lower residual binder content in the micro-surfacing mix (sections 1-B, and 9) had lower values of pull-off force than other sections, but still higher than the no tack section. Pull-off force for sections that were installed on the pavement surface that had CSS-1hM or SS-1h tack coat showed higher values of pull-off force compared to the no tack section, which means a significant effect of tack coat application on bond strength improvement, with a slight advantage for the unmodified residual binder over the unmodified one. However, a complete failure in the existing old pavement layer (section 3), or partial failure (sections 3, 5, and 10). The corresponding value of pull-off force for these sections could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower pull-off force values were reported for these sections, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer. Table B.4 presents the results of the ranking of test sections based on torque values, which was determined using the post ANOVA LSM analysis. Section 7 had the highest torque value among all other test sections, followed by section 8. Sections with lower tack coat application rate and lower residual binder content in the micro-surfacing mix (sections 1-A, 1-B, and 2) had lower values of pull-off force than other sections, but still higher than the no tack section. The effect of tack coat application rate or tack coat material type on bond strength was significant since all test sections showed higher torque values than the no tack section (section 11). However, some field cores exhibited a complete failure in the existing old pavement layer (sections and 3). The torque value could not be included in the comparison since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower torque values were reported for this section, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer.

Table B.1 Results of ANOVA Analysis on Proceq pull-off force Results for SR 274 test sections.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F-Value	P-Value
Section	9	19	4.25	0.0038

Table B.2 Results of Post ANOVA on Torque Results for SR 274 test sections.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F-Value	P-Value
Section	11	24	3.39	0.0059

Table B.3 Results of Post ANOVA Analysis on Proceq Pull-off force Results for SR 274 test sections.

Section	Estimate	Letter Group
8	215.00	A
7	205.67	AB
4	205.00	AB
2	195.00	AB
9-WET	194.00	AB
1-B	184.00	ABC
9-DRY	184.00	ABC
6	175.00	BCD
11	155.33	CD
1-A	143.33	D

Table B.4 Results of Post ANOVA Analysis on Torque Results for SR 274 test sections.

Section	Estimate	Letter Group
7	349.60	A
8	282.00	B
4	279.20	B
1-B	276.40	BC
9-WET	272.80	BC
2	265.20	BCD
5	257.60	BCD
9-DRY	243.20	BCD
6	242.40	BCD
10	238.00	BCD
1-A	221.60	CD
11	212.40	D

Tables B.5, B.6, and B.7 present the results of ANOVA on the Proceq pull-off force, Com-Ten pull-off force, and torque value obtained from the bond strength tests performed on the 12 months field aged cores obtained from test sections with single micro-surfacing layer at SR 03 project. It is noted that from all tables that the effects of tack coat material type and application rate on Proceq pull-off force and torque values were statistically significant at 95% confidence level, which can be indicated by the P-values in all tables.

Table B.8 presents the results of the ranking of test sections based on Proceq pull-off force values, which was determined using the post ANOVA LSM analysis. In this table, the groups are listed in descending order with the letter "A" assigned to the highest mean followed by the other letters in an appropriate order. As seen in Table B.8, section 5 had the highest value of pull-off force compared to other test sections, followed by section 4. Better effect for modified residual binder than that for unmodified residual binder was indicated as section 5 had the highest pull-off force value. However, field cores of section 6 exhibited a complete failure in the existing old pavement layer. The pull-off force value could not be included in the comparison between the effect of modified and unmodified residues since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower pull-off force values were reported for this section, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer. The section with lower residual binder content in the micro-surfacing mix (sections 1) had a lower value of pull-off force than other sections, but still higher than the no tack section, which indicates that the effect of applying a tack coat on pavement surface was significant in improving bond strength. Table B.9 presents the results of the ranking of test sections based on Com-Ten pull-off force values, which was determined using the post ANOVA LSM analysis. As seen in Table B.9, section 5 had the highest value of pull-off force compared to other test sections, followed by section 4. Better effect for modified residual binder than that for unmodified residual binder was indicated as section 5 had the highest pull-off force value. However, field cores of section 6 exhibited a complete failure in the existing old pavement layer. The pull-off force value could not be included in the comparison between the effect of modified and unmodified residues since it does not represent the bond strength between the micro-surfacing layer and existing pavement surface. Much lower pull-off force values were reported for this section, and the failure happened in that area because the micro-surfacing layer had much higher cohesive strength than that for the existing pavement layer. The section with lower residual binder content in the micro-surfacing mix (sections 1) had a lower value of pull-off strength than other sections, but still higher than the no tack section, which indicates that the effect of applying a tack coat on pavement surface was significant in improving bond strength. Table B.10 presents the results of the ranking of test sections based on Torque values, which was determined using the post ANOVA LSM analysis. As seen in Table B.10, section 5 had the highest torque value compared to other test sections, followed by section 4 with a slightly lower torque value. These high values can be explained by the high actual tack coat application rate that was applied on these two sections which was the highest application rate values among all sections, this indicates almost similar effect for unmodified residual binder to that for modified residual. The section with lower residual binder content in the micro-surfacing mix (sections 1) had a lower torque value than other sections, but higher than that of no tack section.

Table B.5 Results of ANOVA Analysis on Proceq pull-off force Results for SR 03 Test sections with Single Micro-surfacing Layer.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F-Value	P-Value
Section	5	12	18.64	<.0001

Table B.6 Results of ANOVA Analysis on Com-Ten pull-off force Results for SR 03 Test sections with Single Micro-surfacing Layer.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F-Value	P-Value
Section	5	9	1.72	0.2267

Table B.7 Results of ANOVA Analysis on Torque Results for SR 03 Test sections with Single Micro-surfacing Layer.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	P-Value
Section	5	11	15.61	0.0001

Table B.8 Results of Post ANOVA Analysis on Proceq Pull-off force Results for SR 03 Test Sections with Single Micro-surfacing Layer.

Section	**Estimate**	**Letter Group**
5	310.33	A
4	271.33	AB
3	252.67	B
7	251.67	B
1	195.00	C
2	125.00	D

Table B.9 Results of Post ANOVA Analysis on Com-Ten Pull-off force Results for SR 03 Test Sections with Single Micro-surfacing Layer.

Section	Estimate	Letter Group
5	386.07	A
4	382.27	A
7	350.37	AB
3	317.80	AB
1	307.60	AB
2	262.40	B

Table B.10 Results of Post ANOVA Analysis on Torque Results for SR 03 Test Sections with Single Micro-surfacing Layer.

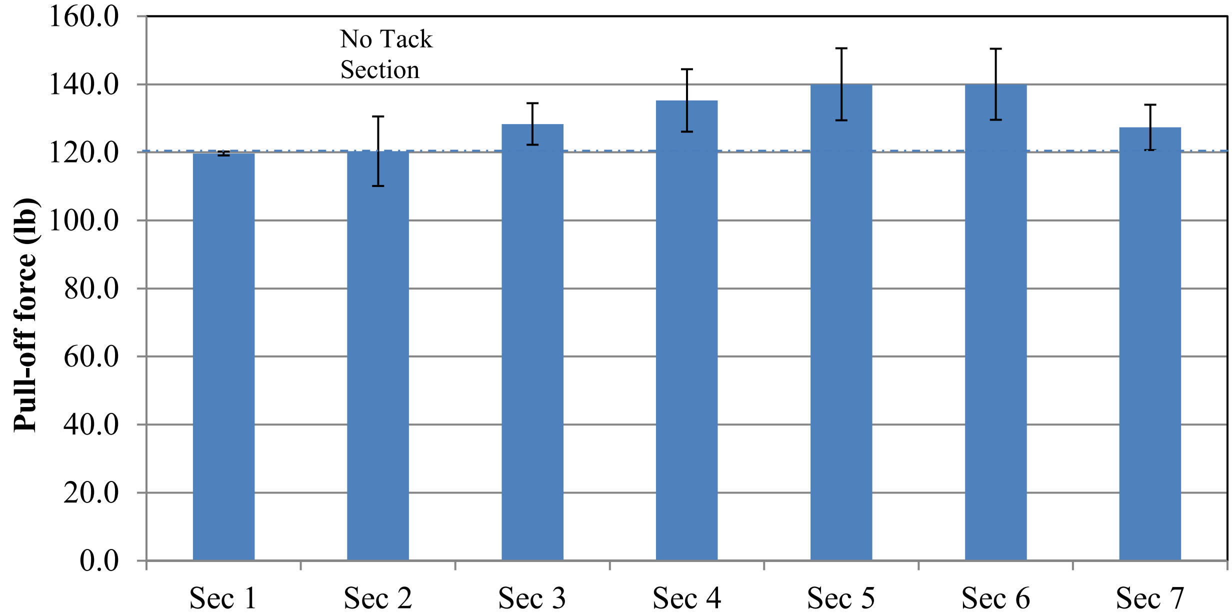
Section	Estimate	Letter Group
5	451.60	A
4	434.00	A
6	408.80	AB
3	374.40	B
1	362.40	B
2	272.00	C

B.4 Results of Lab Testing Program

As mentioned earlier in Appendix A of this report, further lab testing was conducted to evaluate the effect of the tack coat application rate on bond strength and validate the test results obtained for field samples and extend them to ranges outside those used in the test sections. The effect of existing pavement surface texture on bond strength was also evaluated by preparing lab micro-surfacing samples on the field cores obtained from the field during the evaluation of surface texture prior to micro-surfacing layers installation for both projects, AMES scanner was used in the laboratory to evaluate the surface texture of the existing pavement of the obtained field cores prior to preparing the lab micro-surfacing samples. Moreover, the effect of waiting time after applying tack coat material on the existing pavement surface and prior to installation of micro-surfacing layer, as well as the effect of traffic wheels on the bond strength of micro-surfacing mix was evaluated by simulating the tracking of vehicle tires on the existing pavement layer after applying tack coat and prior to installation of micro-surfacing layer.

B.4.1 Results of Testing on Lab Prepared Samples for SR 03 Project

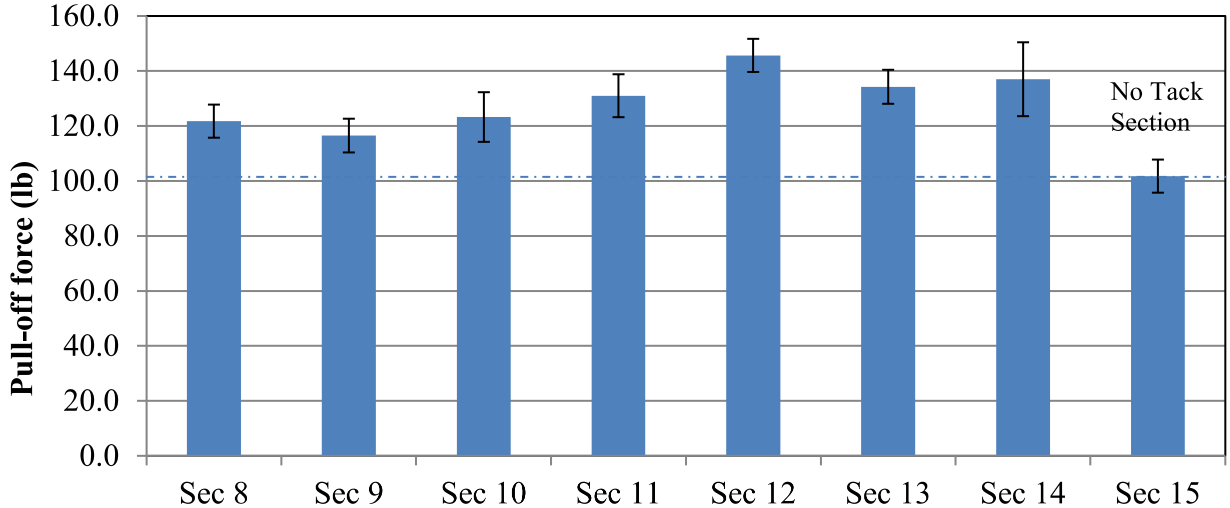
Figure B.41 presents the results of Proceq pull-off testing for laboratory prepared samples with single micro-surfacing layer. As seen in Figure B.41, sections 5 and 6 had the same highest value of pull-off force among all other sections, followed by section 4. The section with lower emulsion content in the mix and low tack coat application rate (section 1) had the lowest pull-off force value, even lower than no tack section (section 2). Sections with SS-1h tack coat type showed comparable pull-off force values to those with CSS-1hM tack coat type, as seen from the result obtained for section 6 which was similar to that obtained for section 5, knowing that the tack coat application rate was similar for both sections. Section 7 also showed comparable results to section 3 as the pull-off force value was slightly lower for section 7 than that for section 3, knowing that the tack coat application rate was similar for both sections. Variability was almost similar for all sections which can be seen from error bars that represent the standard deviation values between different tested samples from the same mix, except for section 1 that had the lowest standard deviation among all other test sections.



Avg Diluted Rate (gsy)	0.025	0	0.025	0.06	0.108	0.108	0.025

Figure B.41 Results of Proceq pull-off testing on lab prepared samples with single micro-surfacing layer.

Figure B.42 presents the results of Proceq pull-off testing for laboratory prepared samples with double micro-surfacing layers. Sections 12 had the same highest value of pull-off force among all other sections, followed by section 14. The section with lower emulsion content in the mix and no applied tack coat (section 15) had the lowest pull-off force value, even lower than the no tack section (section 9-B). The section with lower emulsion content in the mix and low tack coat application rate (section 8) had higher pull-off force value than the no tack section. Sections with SS-1h tack coat type showed comparable pull-off force values to those with CSS-1hM tack coat type, as seen from the result obtained for section 14 which was slightly lower than that obtained for section 12, knowing that the tack coat application rate was similar for both sections. Section 13 also showed comparable results to section 11 as the pull-off force value was slightly higher for section 13 than that for section 11, knowing that the tack coat application rate was similar for both sections. Variability represented by error bars that represent the standard deviation values between different tested samples from the same mix was almost similar for all sections, except for section 14 that had the relatively high standard deviation value.

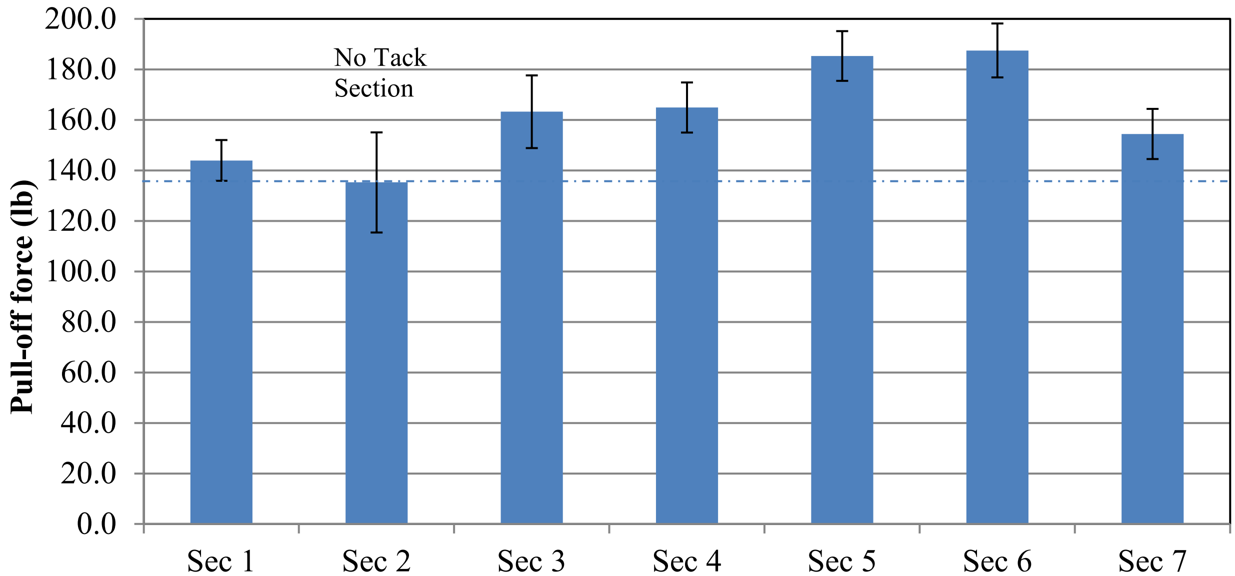


Avg Diluted Rate (gsy)	0.025	0	0.06	0.06	0.06	0.06	0.06	0
	0.025	0	0	0.025	0.06	0.025	0.06	0

Figure B.42 Results of Proceq pull-off testing on lab prepared samples with double micro-surfacing layers.

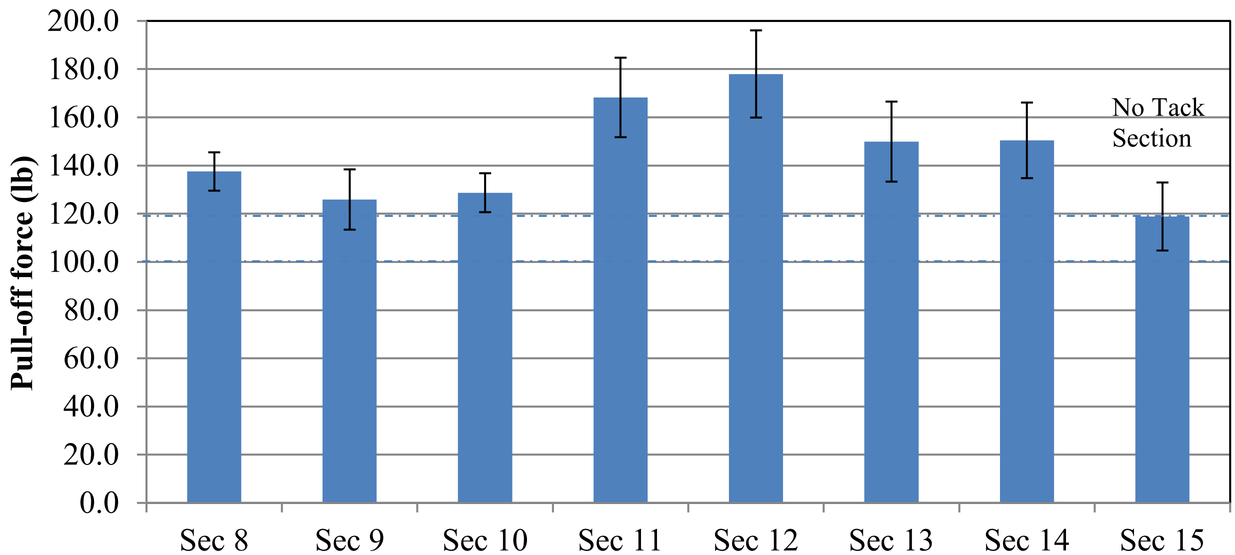
Figure B.43 presents the results of Com-Ten pull-off testing for lab prepared samples with single micro-surfacing layer. As seen in Figure B.43, section 6 had the highest value of pull-off force among all other sections, followed by section 5. The no tack section (section 2) had the lowest pull-off force value, even lower than the section with lower emulsion content in the mix and low tack coat application rate (section 1). Sections with SS-1h tack coat type showed comparable pull-off force values to those with CSS-1hM tack coat type, as seen from the result obtained for section 6 which was slightly higher than that obtained for section 5, knowing that the tack coat application rate was similar for both sections. Section 7 also showed comparable results to section 3 as the pull-off force value was slightly lower for section 7 than that for section 3, knowing that the tack coat application rate was similar for both sections. These results agree well with the results obtained from Proceq pull-off testing. Variability was almost similar for all sections which can be seen from error bars that represent the standard deviation values between different tested samples from the same mix, except for sections 2 and 3 that had relatively higher standard deviation among other test sections.

Figure B.44 presents the results of Com-ten pull-off testing for lab prepared samples with double micro-surfacing layers. Sections 12 had the same highest value of pull-off force among all other sections, followed by section 11. The section with lower emulsion content in the mix and no applied tack coat (section 15) had the lowest pull-off force value, even lower than the no tack section (section 9-B). The section with lower emulsion content in the mix and low tack coat application rate (section 8) had higher pull-off force value than the no tack section. Sections with SS-1h tack coat type showed relatively comparable pull-off force values to those with CSS-1hM tack coat type, as seen from the result obtained for section 14 which was slightly lower than that obtained for section 12, knowing that the tack coat application rate was similar for both sections. Section 13 also showed comparable results to section 11 as the pull-off force value was slightly higher for section 13 than that for section 11, knowing that the tack coat application rate was similar for both sections. These results agree with the results obtained from Proceq pull-off testing. Variability represented by error bars that represent the standard deviation values between different tested samples from the same mix was almost similar for all sections.



Avg Diluted Rate (gsy)	0.025	0	0.025	0.06	0.108	0.108	0.025

Figure B.43 Results of Com-Ten pull-off testing on lab prepared samples with single micro-surfacing layer.



Avg Diluted Rate (gsy)	0.025	0	0.06	0.06	0.06	0.06	0.06	0
	0.025	0	0	0.025	0.06	0.025	0.06	0

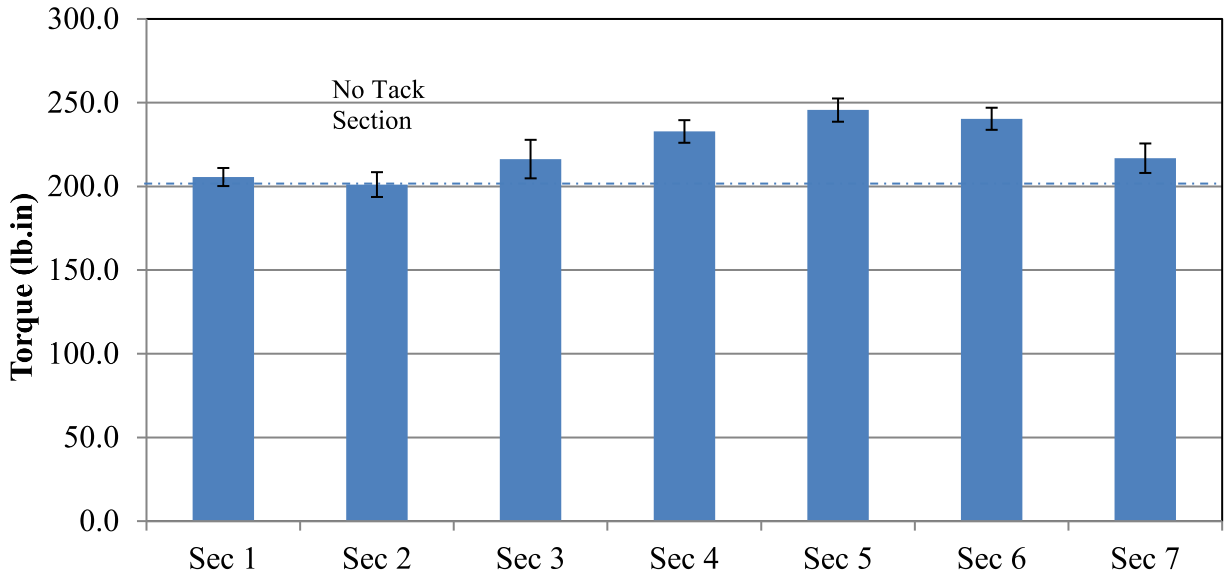
Figure B.44 Results of Com-Ten pull-off testing on lab prepared samples with double micro-surfacing layers.

Figure B.45 presents the results of torque testing for lab prepared samples with single micro-surfacing layer. As seen in Table B.45, section 5 had the highest value of pull-off force among all other sections, followed by section 6. The no tack section (section 2) had the lowest pull-off force value, even lower than the section with lower emulsion content in the mix and low tack coat application rate (section 1). Sections with SS-1h tack coat type showed comparable pull-off force values to those with CSS-1hM tack coat type, as seen from the result obtained for section 6 which was slightly lower than that obtained for section 5, knowing that the tack coat application rate was similar for both sections. Section 7 also showed comparable results to section 3 as the pull-off force value was slightly higher for section 7 than that for section 3, knowing that the tack coat application rate was similar for both sections. These results agree well with the results obtained from Proceq pull-off testing. Variability was almost similar for all sections which can be seen from error bars that represent the standard deviation values between different tested samples from the same mix.

Figure B.46 presents the results of torque testing for lab prepared samples with double micro-surfacing layers. Sections 12 had the same highest value of pull-off force among all other sections, followed by section 14. The section with lower emulsion content in the mix and no applied tack coat (section 15) had the lowest pull-off force value, even lower than the no tack section (section 9-B). The section with lower emulsion content in the mix and low tack coat application rate (section 8) had lower pull-off force value than the no tack section. Sections with SS-1h tack coat type showed relatively comparable pull-off force values to those with CSS-1hM tack coat type, as seen from the result obtained for section 14 which was slightly lower than that obtained for section 12, knowing that the tack coat application rate was similar for both sections. Section 13 also showed comparable results to section 11 as the pull-off force value was slightly higher for section 13 than that for section 11, knowing that the tack coat application rate was similar for both sections. These results agree with the results obtained from Proceq pull-off testing. Variability represented by error bars that represent the standard deviation values between different tested samples from the same mix was almost similar for all sections, except for section 10 that had relatively lower standard deviation compared to other test sections.
It is worth to mention that for all bond strength testing results, the value of pull-off force or torque was higher in the case of applying higher rate of same tack coat type, these results were seen for both tack coat types evaluated in this study (SS-1h and CSS-1hM). In general, it can be said that the bond strength between the micro-surfacing layer and the existing pavement layer increases when a higher rate of tack coat is applied on the existing pavement surface prior to installation of micro-surfacing layer, these results agree well with the results obtained from lab testing conducted on field cores obtained 4 months and 12 months after installation of the micro-surfacing surface layer at test sections in the second project (SR 03).

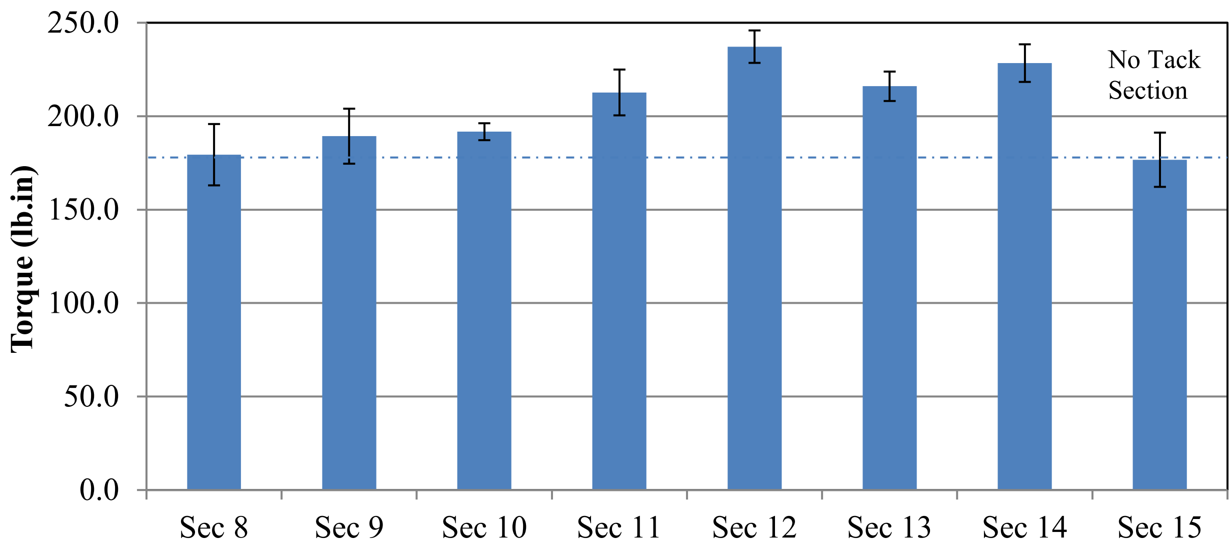
B.4.2 Statistical Analysis of Results of Testing on Lab Prepared Samples for SR 03 Project
Analysis of Variance and post ANOVA-LSM analyses were conducted using SAS (SAS, 2004) to statistically evaluate the results of Proceq pull-off force, Com-ten pull-off force, and torque for samples prepared in the lab with single micro-surfacing layer for the purpose of evaluating the effect of the tack coat application rate on bond strength and validate the test results obtained for field samples and extend them to ranges outside those used in the test sections of SR 03 project. Tables B.11, B.12, and B.13 present the results of ANOVA on the Proceq pull-off force, Com-ten pull-off force, and torque values, respectively. It can be seen from these tables that the effect of

section properties such as the tack coat material type, tack coat application rate, and emulsion content in micro-surfacing mix on Proceq pull-off force and torque values was statistically significant at 95% confidence level, which can be indicated by the P-values in all tables.



Avg Diluted Rate (gsy)	0.025	0	0.025	0.06	0.108	0.108	0.025

Figure B.45 Results of Torque testing on lab prepared samples with single micro-surfacing layer.



Avg Diluted Rate (gsy)	0.025	0	0.06	0.06	0.06	0.06	0.06	0
	0.025	0	0	0.025	0.06	0.025	0.06	0

Figure B.46 Results of Torque testing on lab prepared samples with double micro-surfacing layers.

Table B.14 presents the results of the ranking of micro-surfacing sections having single micro-surfacing-micro-surfacing layer based on Proceq pull-off force values, which was determined using the post ANOVA LSM analysis. In this table, the groups are listed in descending order with the letter "A" assigned to the highest mean followed by the other letters in an appropriate order. It is noted from Table B.14 that all sections showed higher value of Proceq pull-off force than that for the no tack section (section 2), except for the section that had a lower emulsion content in the mix (section 1). This implies that there was a significant effect for tack coat material type and application rate on bond strength of micro-surfacing mix. CSS-1hM tack coat type had a slightly higher significant effect on bond strength than the effect of SS-1h tack coat type as section 5 had the highest values of Proceq pull-off force compared to other test sections, followed by section 6. However, it can be said that the effect of SS-1h tack coat material on bond strength is almost comparable to the effect of CSS-1hM tack coat, which can be seen from the very close value of pull-off force for section 6 compared to that for section 5, knowing that similar tack coat application rate was applied on samples surface.

Table B.15 presents the results of the ranking of micro-surfacing sections having single-micro-surfacing layer based on Com-ten pull-off force values, which was determined using the post ANOVA LSM analysis. It is noted that all sections showed higher value of Proceq pull-off force than that for the no tack section (section 2) even the section that had a lower emulsion content in the mix (section 1). This implies that there was a significant effect for tack coat material type and application rate on bond strength as well as the emulsion content in the mix on bond strength. SS-1h tack coat type had more significant effect on bond strength than the effect of CSS-1hM tack coat type as section 6 had the highest values of Proceq pull-off force compared to other test sections, followed by section 5. This indicates that the effect of SS-1h tack coat material on bond strength is comparable to or even better than the effect of CSS-1hM tack coat, which can be seen from the very close value of pull-off force for section 6 compared to that for section 5, knowing that similar tack coat application rate was applied on samples surface.

Table B.16 presents the results of the ranking of micro-surfacing sections having single micro-surfacing layer based on torque values, which was determined using the post ANOVA LSM analysis. Table B.16 presents the results of the ranking of micro-surfacing sections having single micro-surfacing layer based on torque values, which was determined using the post ANOVA LSM analysis. It is noted that all sections showed higher torque values than that for the no tack section (section 2), even the section that had a lower emulsion content in the mix (section 1). This implies that there was a significant effect for tack coat material type and application rate on bond strength of micro-surfacing mix. CSS-1hM tack coat type had a slightly higher significant effect on bond strength than the effect of SS-1h tack coat type as section 5 had the highest values of Proceq pull-off force compared to other test sections, followed by section 6. However, it can be said that the effect of SS-1h tack coat material on bond strength is almost comparable to the effect of CSS-1hM tack coat, which can be seen from the very close value of pull-off force for section 6 compared to that for section 5, knowing that similar tack coat application rate was applied on samples surface.

Table B.11 Results of ANOVA Analysis on Proceq pull-off force Results for Lab Testing Plan Samples with Single Micro-surfacing Layer.

Effect	F-Value	P-Value
Section properties	3.13	<0.034

Table B.12 Results of ANOVA Analysis on Com-ten Pull-off force Results for Lab Testing Plan Samples with Single Micro-surfacing Layer.

Effect	F-Value	P-Value
Section properties	10.01	<.0001

Table B.13 Results of ANOVA Analysis on Torque Results for Lab Testing Plan Samples with Single Micro-surfacing Layer.

Effect	F-Value	P-Value
Section properties	16.51	<.0001

Table B.14 Results of Post ANOVA Analysis on Proceq pull-off force Results for Lab Testing Plan Samples with Single Micro-surfacing Layer.

Section	Letter Group	Emulsion Content	TC type	TC rate (gsy)
Sec 5	A	Regular	CSS-1hM	0.11
Sec 6	A	Regular	SS-1h	0.11
Sec 4	A	Regular	CSS-1hM	0.06
Sec 3	AB	Regular	CSS-1hM	0.025
Sec 7	AB	Regular	SS-1h	0.025
Sec 2	B	Regular	NA	0
Sec 1	B	Low	CSS-1hM	0.025

Table B.15 Results of Post ANOVA Analysis on Com-ten Pull-off force Results for Lab Testing Plan Samples with Single Micro-surfacing Layer.

Section	Letter Group	Emulsion Content	TC type	TC rate (gsy)
Sec 6	A	Regular	SS-1h	0.11
Sec 5	A	Regular	CSS-1hM	0.11
Sec 4	B	Regular	CSS-1hM	0.06
Sec 3	B	Regular	CSS-1hM	0.025
Sec 7	BC	Regular	SS-1h	0.025
Sec 1	CD	Low	CSS-1hM	0.025
Sec 2	D	Regular	NA	0

Table B.16 Results of Post ANOVA Analysis on Torque Results for Lab Testing Plan Samples with Single Micro-surfacing Layer.

Section	Letter Group	Emulsion Content	TC type	TC rate (gsy)

Sec 5	A	Regular	CSS-1hM	0.11
Sec 6	A	Regular	SS-1h	0.11
Sec 4	B	Regular	CSS-1hM	0.06
Sec 7	BC	Regular	SS-1h	0.025
Sec 3	BC	Regular	CSS-1hM	0.025
Sec 1	C	Low	CSS-1hM	0.025
Sec 2	C	Regular	NA	0

Analysis of Variance (ANOVA) and post ANOVA Least Square Mean (LSM) analyses were also conducted to statistically evaluate the results of Proceq pull-off force, Com-ten pull-off force, and torque for samples prepared in the lab with double micro-surfacing layers for the purpose of evaluating the effect of the tack coat application rate on bond strength and validate the test results obtained for field samples and extend them to ranges outside those used in the test sections of SR 03 project. Tables B.17, B.18, and B.19 present the results of ANOVA on the Proceq pull-off force, Com-ten pull-off force, and torque values, respectively. It can be seen from these tables that the effect of section properties as the tack coat material type, tack coat application rate, and emulsion content in micro-surfacing mix on Proceq pull-off force and torque values was statistically significant at 95% confidence level, which can be indicated by the P-values in all tables. It can be seen from these tables the effect of section properties as the tack coat material type, tack coat application rate, and emulsion content in micro-surfacing mix on Proceq pull-off force and torque values was statistically significant at 95% confidence level, which can be indicated by the P-values in all tables.

Table B.20 presents the results of the ranking of micro-surfacing sections having double micro-surfacing layer based on Proceq pull-off force values, which was determined using the post-ANOVA LSM analysis. In this table, the groups are listed in descending order with the letter "A" assigned to the highest mean followed by the other letters in an appropriate order. It is noted from Tables B.20 that all sections showed higher value of Proceq pull-off force than that for the no tack section (section 9-B), except for the section that had a lower emulsion content in the mix and no tack coat application on samples surface (section 15). This implies that there was a significant effect for tack coat material type and application rate on bond strength of micro-surfacing mix as well as the emulsion content in the mix on bond strength of micro-surfacing mix. CSS-1hM and SS-1h tack coat types had almost similar effect on Proceq pull-off force as section 12 with CSS-1hM tack coat had higher values of Proceq pull-off force compared to section 14, knowing that same application rate for both layers was applied in both sections. However, same ranking was observed for both sections, which means that the value of pull-off force was very close for section 14 compared to section 12 value. This similar effect for both tack coat types can also be seen from the higher rank obtained for section 13 compared to that for section 11 knowing that similar application rate was applied on samples surface in both sections, which indicates a better effect for SS-1h tack coat type on bond strength than that for CSS-1hM tack coat type on bond strength of micro-surfacing mix. CSS-1hM tack coat type had a slightly higher significant effect on bond strength than the effect of SS-1h tack coat type as section 5 had the highest values of Proceq pull-off force compared to other test sections, followed by section 6. However, it can be said that the effect of SS-1h tack coat material on bond strength is almost comparable to the effect of CSS-1hM

tack coat, which can be seen from the very close value of pull-off force for section 6 compared to that for section 5, knowing that similar tack coat application rate was applied on samples surface.
Table B.21 presents the results of the ranking of micro-surfacing sections having double micro-surfacing layer based on Com-ten pull-off force values, which was determined using the post-ANOVA LSM analysis. It is noted that all sections showed higher value of Proceq pull-off force than that for the no tack section (section 9-B), except for the section that had a lower emulsion content in the mix and no applied tack coat (section 15). This implies that there was a significant effect for tack coat material type and application rate on bond strength. of micro-surfacing mix. CSS-1hM and SS-1h tack coat types had almost similar effect on Proceq pull-off force as section 12 with CSS-1hM tack coat had higher values of Proceq pull-off force compared to section 14, knowing that same application rate for both layers was applied in both sections. However, same ranking was observed for both sections, which means that the value of pull-off force was close for section 14 compared to section 12 value. This similar effect for both tack coat types can also be seen from the pull-off force value obtained for section 13 compared to that for section 11 knowing that similar application rate was applied on the surface in both sections, which indicates a comparable effect for SS-1h tack coat type on bond strength than that for CSS-1hM tack coat type on bond strength. SS-1h tack coat type had more significant effect on bond strength than the effect of SS-1h tack coat type as section 6 had the highest values of Proceq pull-off force compared to other test sections, followed by section 5. Thich indicates that the effect of SS-1h tack coat material on bond strength is comparable to or even better than the effect of CSS-1hM tack coat, which can be seen from the very close value of pull-off force for section 6 compared to that for section 5, knowing that similar tack coat application rate was applied on samples surface.
Table B.22 presents the results of the ranking of micro-surfacing sections having double micro-surfacing layers based on torque values, which was determined using the post-ANOVA LSM analysis. It is noted that all sections showed higher torque values than that for the no tack section (section 9-B), except for the section that had a lower emulsion content in the mix (section 8), and the section that had a lower emulsion content in the mix and no applied tack coat (section 15). This implies that there was a significant effect for tack coat material type and application rate on bond strength of micro-surfacing mix. CSS-1hM tack coat type had a slightly higher significant effect on bond strength than the effect of SS-1h tack coat type as section 12 had the highest values of Proceq pull-off force compared to other test sections, followed by section 14. However, it can be said that the effect of SS-1h tack coat material on bond strength is almost comparable to the effect of CSS-1hM tack coat, which can be seen from the very close value of pull-off force for section 14 compared to that for section 12, knowing that similar tack coat application rate was applied on samples surface.

Table B.17 Results of ANOVA Analysis on Proceq pull-off force Results for Lab Testing Plan Samples with Double Micro-surfacing Layer.

Effect	F Value	P-Value
Section properties	10.67	<.0001

Table B.18 Results of ANOVA Analysis on Com-ten Pull-off force Results for Lab Testing Plan Samples with Double Micro-surfacing Layer.

Effect	F Value	P-Value
Section properties	12.76	<.0001

Table B.19 Results of ANOVA Analysis on Torque Results for Lab Testing Plan Samples with Double Micro-surfacing Layer.

Effect	F Value	P-Value
Section properties	12.20	<.0001

Table B.20 Results of Post ANOVA Analysis on Proceq pull-off force Results for Lab Testing Plan Samples with Double Micro-surfacing Layer.

Section	Letter Group	Layer 1 Emulsion Content	Layer 1 TC type	Layer 1 TC rate (gsy)	Layer 2 Emulsion Content	Layer 2 TC type	Layer 2 TC rate (gsy)
Sec 12	A	Regular	CSS-1hM	0.06	Regular	CSS-1hM	0.06
Sec 14	A	Regular	SS-1h	0.06	Regular	SS-1h	0.06
Sec 13	AB	Regular	SS-1h	0.06	Regular	SS-1h	0.025
Sec 11	BC	Regular	CSS-1hM	0.06	Regular	CSS-1hM	0.025
Sec 10	BC	Regular	CSS-1hM	0.06	Regular	NA	0
Sec 8	C	Low	CSS-1hM	0.025	Low	CSS-1hM	0.025
Sec 9	C	Regular	NA	0	Regular	NA	0
Sec 15	D	Low	NA	0	Low	NA	0

Table B.21 Results of Post ANOVA Analysis on Com-ten Pull-off force Results for Lab Testing Plan Samples with Double Micro-surfacing Layer.

Section	Letter Group	Layer 1 Emulsion Content	Layer 1 TC type	Layer 1 TC rate (gsy)	Layer 2 Emulsion Content	Layer 2 TC type	Layer 2 TC rate (gsy)
Sec 12	A	Regular	CSS-1hM	0.06	Regular	CSS-1hM	0.06
Sec 11	B	Regular	CSS-1hM	0.06	Regular	CSS-1hM	0.025
Sec 14	AB	Regular	SS-1h	0.06	Regular	SS-1h	0.06
Sec 13	BC	Regular	SS-1h	0.06	Regular	SS-1h	0.025
Sec 8	C	Low	CSS-1hM	0.025	Low	CSS-1hM	0.025
Sec 10	CD	Regular	CSS-1hM	0.06	Regular	NA	0
Sec 9	CD	Regular	NA	0	Regular	NA	0
Sec 15	D	Low	NA	0	Low	NA	0

Table B.22 Results of Post ANOVA Analysis on Torque Results for Lab Testing Plan Samples with Double Micro-surfacing Layer.

Section	Letter Group	Layer 1 Emulsion Content	Layer 1 TC type	Layer 1 TC rate (gsy)	Layer 2 Emulsion Content	Layer 2 TC type	Layer 2 TC rate (gsy)
Sec 12	A	Regular	CSS-1hM	0.06	Regular	CSS-1hM	0.06
Sec 14	A	Regular	SS-1h	0.06	Regular	SS-1h	0.06
Sec 13	AB	Regular	SS-1h	0.06	Regular	SS-1h	0.025
Sec 11	B	Regular	CSS-1hM	0.06	Regular	CSS-1hM	0.025
Sec 10	BC	Regular	CSS-1hM	0.06	Regular	NA	0
Sec 9	C	Regular	NA	0	Regular	NA	0
Sec 8	C	Low	CSS-1hM	0.025	Low	CSS-1hM	0.025
Sec 15	C	Low	NA	0	Low	NA	0

B.4.3 Effect of Existing Pavement Surface Texture on Bond Strength

Figure B.47 presents the results of Proceq pull-off force for lab samples prepared by installing the micro-surfacing layer on the AMES measured field cores obtained from SR 03 project. As seen from Figure B.47, group 2 had the highest value of pull-off force among the two other groups, followed by group 1 with a slightly lower pull-off force value. The lowest pull-off force value was recorded for group 3 samples, which indicates lower bond strength at higher MPD values. Variability represented by error bars that represent the standard deviation values between different tested samples from the same mix was relatively high for group 2 samples, while group 3 samples had the lowest variability among the other two groups.

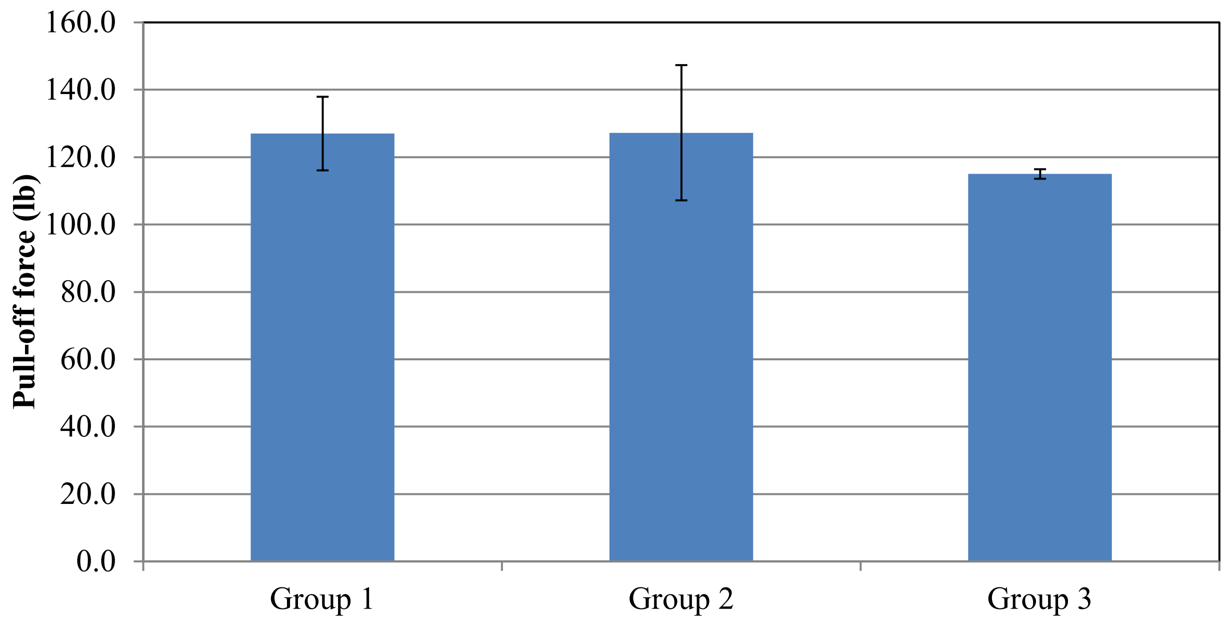


Figure B.47 Results of Proceq pull-off testing for lab prepared samples on AMES scanned field cores obtained from SR 03 project.

Figure B.48 presents the results of Com-Ten pull-off force for lab samples prepared by installing the micro-surfacing layer on the AMES measured field cores obtained from SR 03 project. As seen from Figure B.48, group 2 had the highest value of pull-off force among the two other groups, followed by group 1 with a slightly lower pull-off force value. The lowest pull-off force value was recorded for group 3 samples, which indicates lower bond strength at higher MPD values. Variability represented by error bars that represent the standard deviation values between different tested samples from the same mix was almost similar for all sections.

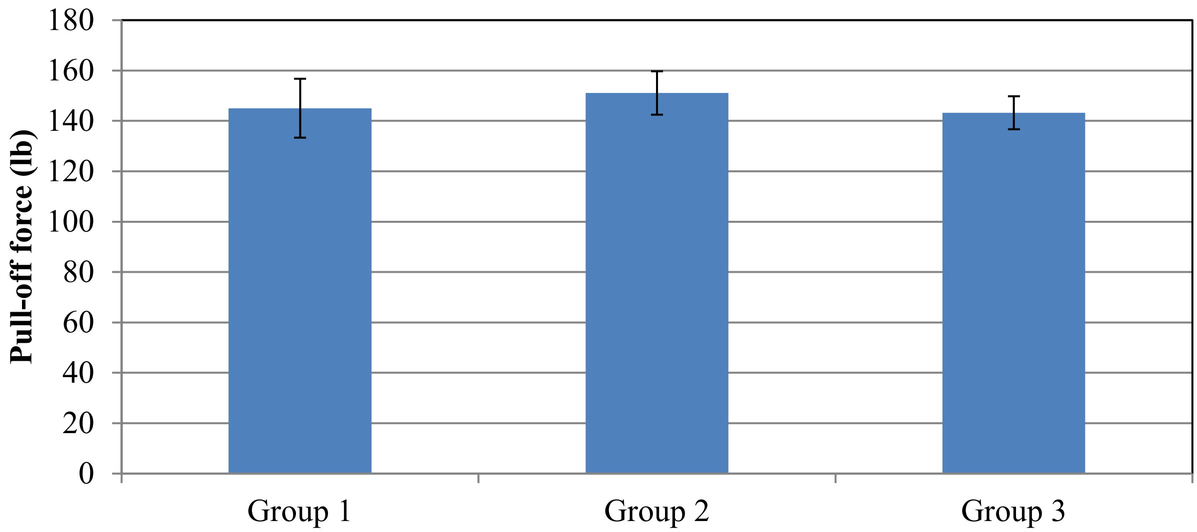


Figure B.48 Results of Com-Ten pull-off testing for lab prepared samples on AMES scanned field cores obtained from SR 03 project.

Figure B.49 presents the results of torque testing for lab samples prepared by installing the micro-surfacing layer on the AMES measured field cores obtained from SR 03 project. As seen from Figure B.49, group 3 had the highest value of pull-off force among the two other groups, followed by group 1 with a slightly lower pull-off force value. The lowest pull-off force value was recorded for group 2 samples. Variability represented by error bars that represent the standard deviation values between different tested samples from the same mix was high for groups 1 and 2, while a relatively lower variability was indicated for group 3 samples.

B.4.4 Statistical Analysis of Results to Evaluate Effect of Existing Pavement Surface Texture on Bond Strength

Analysis of Variance (ANOVA) was conducted to evaluate the significance of the effect of old pavement surface texture on torque, pull-off strength measured by Proceq, and pull-off force measured by Com-ten. Statistical Analyses software SAS was used to conduct all statistical analyses. A linear Completely Random Design (CRD) model was used in the analysis. Tables B.23, B.24, and B.25 present the results of ANOVA on the Proceq pull-off force, Com-ten pull-off force, and torque value obtained from the bond strength tests performed on lab prepared samples on top of AMES scanned field cores obtained from SR 03 project. It is noted that from all tables that the effects of old pavement surface texture on Proceq pull-off force, Com-ten pull-off force, and torque values were statistically significant at 95% confidence level, which can be indicated by the P-values in both tables.

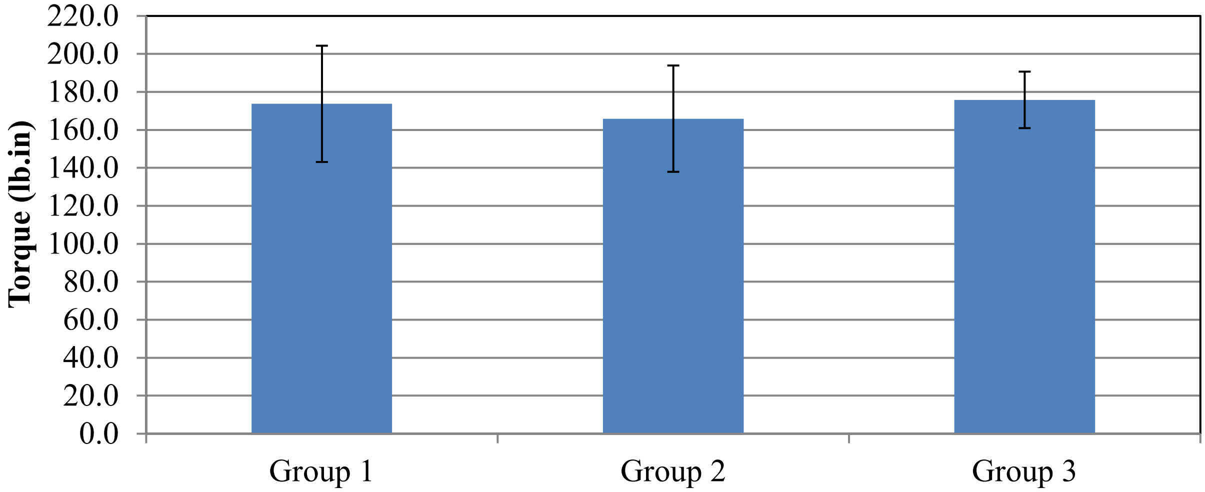


Figure B.49 Results of Torque testing for lab prepared samples on AMES scanned field cores obtained from SR 03 project.

Table B.23 Results of ANOVA Analysis on Proceq pull-off force Results for Lab prepared samples on AMES scanned field cores.

Effect	**F Value**	**P-Value**
Texture	0.53	0.6131

Table B.24 Results of ANOVA Analysis on Com-Ten pull-off force Results for Lab prepared samples on AMES scanned field cores.

Effect	**F-Value**	**P-Value**
Texture	0.80	0.4792

Table B.25 Results of ANOVA Analysis on Torque Results for Lab prepared samples on AMES scanned field cores.

Effect	**F-Value**	**P-Value**
Texture	0.17	0.8479

B.4.5 Effect of Curing Time on Bond Strength

Figure B.50 presents the Proceq pull-off force values for laboratory samples prepared using different tack coat curing times between tack coat application and installing the micro-surfacing layer, for CSS-1hM tack coat types curing times were selected as 0 minutes, 15 minutes, 30 minutes, and 60 minutes. As seen in Figure B.50, the value of pull-off force for samples having CSS-1hM tack coat material increased while the curing time was increased from 0 minutes to 15 minutes and from 15 minutes to 30 minutes, then it decreased when the curing time was changed to 60 minutes, which means lower bond strength in the case of 60 minutes curing time. However, the value of pull-off force was still higher than the case when there was no curing time. This suggests that this tack coat type has a setting time around 30 minutes which results in best bonding, and it will start to lose bonding efficiency if the curing time is increased before installing the micro-surfacing layer.

Figure B.51 presents the Com-Ten pull-off force values for laboratory samples prepared using different curing times between tack coat application and installing the micro-surfacing layer. As seen in Figure B.51, the value of pull-off force for samples having CSS-1hM tack coat material increased while the curing time was increased from 0 minutes to 15 minutes and from 15 minutes to 30 minutes, then it decreased when the waiting time was changed to 60 minutes, which means lower bond strength in the case of 60 minutes curing time. However, the value of pull-off force was still higher than the case when there was no curing time. This suggests that this tack coat type has a setting time around 30 minutes which results in best bonding, and it will start to lose bonding efficiency if the curing time is increased before installing the micro-surfacing layer.

Figure B.52 presents torque values for laboratory samples using prepared different curing times between tack coat application and installing the micro-surfacing layer. As seen in Figure B.52, the value of torque for samples having CSS-1hM tack coat material increased while the curing time was increased from 0 minutes to 60 minutes with 15 minutes time increment period. This suggests that even though the tack coat started to lose bonding efficiency when curing time was increased, this loss did not reflect on bond strength in case of Torque testing. However, further testing is needed to evaluate bond strength of micro-surfacing mixes with longer curing times after applying CSS-1hM tack coat material type on existing pavement surface and before installing the micro-surfacing layer.

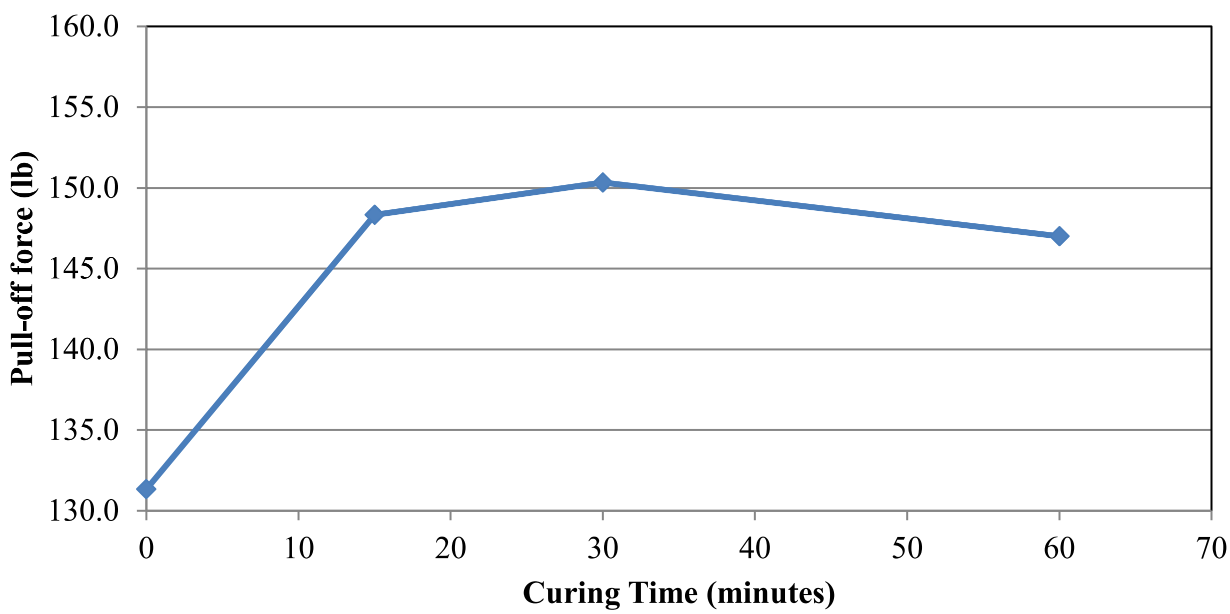


Figure B.50 Results of Proceq pull-off force for lab prepared samples at different curing times of CSS-1hM tack coat.

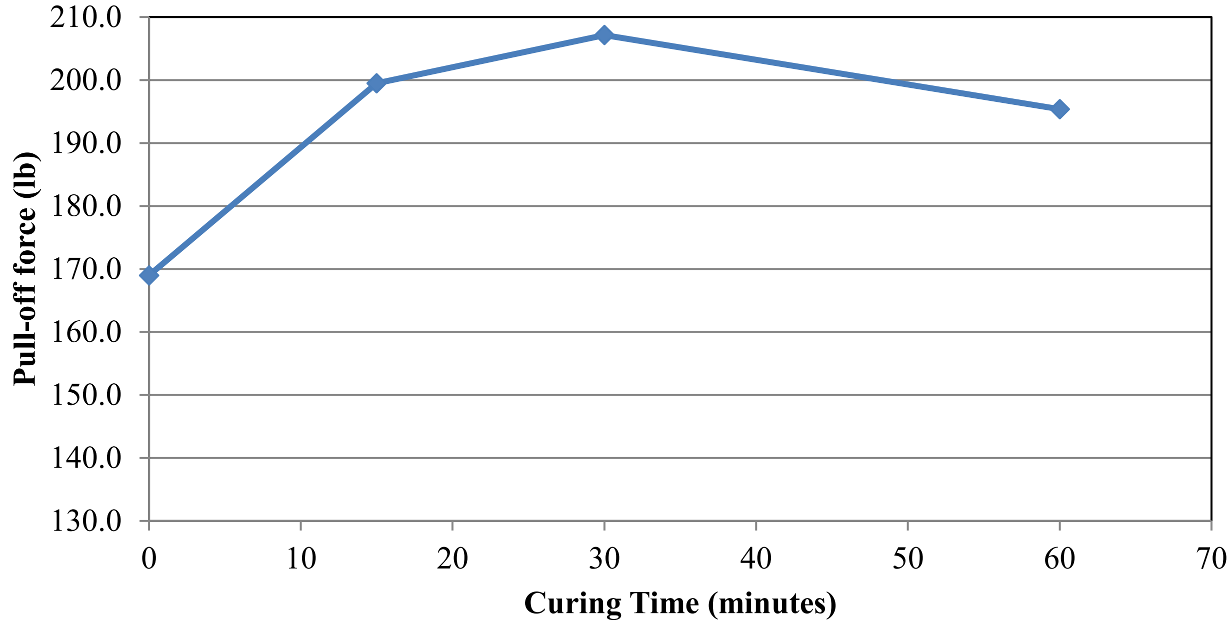


Figure B.51 Results of Com-Ten pull-off force for lab prepared samples at different curing times of CSS-1hM tack coat.

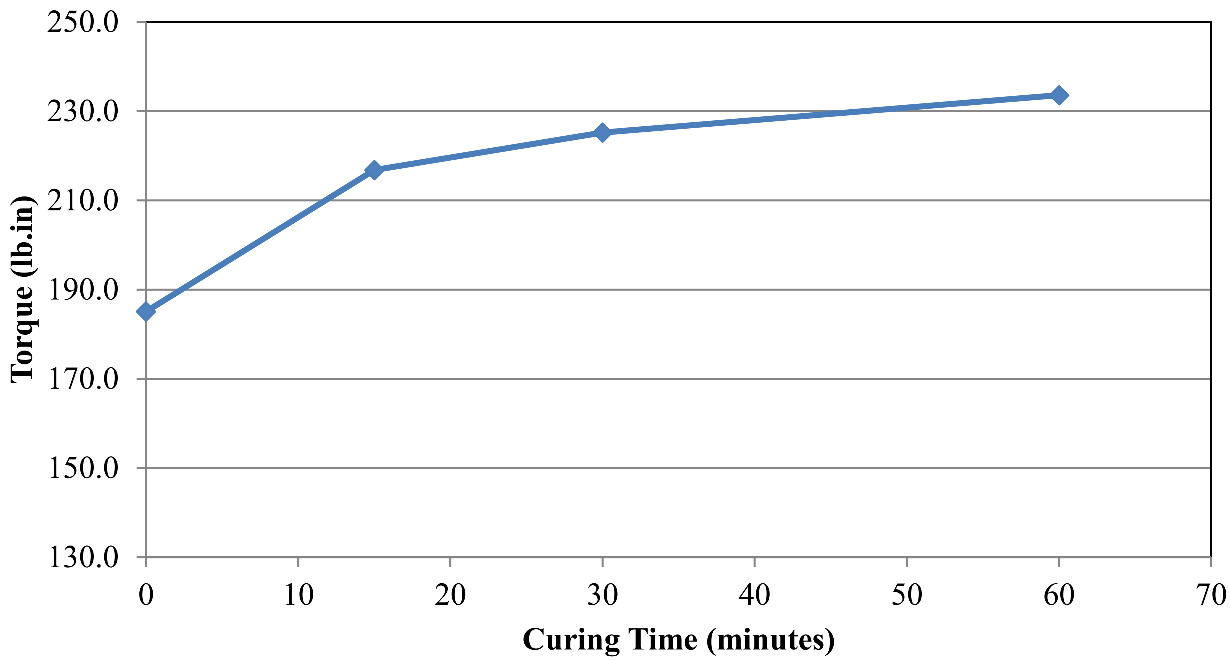


Figure B.52 Results of Torque testing for lab prepared samples at different curing times of CSS-1hM tack coat.

B.4.6 Testing Results for Emulsion Residues

As mentioned earlier in Appendix A, basic material characterization tests were conducted on tack coat materials. The conducted tests included: residue by evaporation method (ignition oven), residue by distillation method, penetration for evaporation residue, and softening point test for evaporation residue. Table B.26 presents the results of basic material characterization tests conducted on SS-1h and CSS-1hM emulsion materials. Dynamic shear rheometer (DSR) tests were conducted in accordance with AASHTO T 315 (Determining the Rheological Properties of Asphalt Binder Using Dynamic Shear Rheometer -AASHTO, 2010) on the residual asphalt binder of the tack coat material to determine the Superpave higher performance grade (PG) as well as the master-curve for each type of the emulsion residual binder. Table B.27 presents the results of high PG grade obtained for SS-1h and CSS-1hM emulsion residues. As expected, the CSS-1hM residue showed higher PG grade than SS-1h residue.

Table B.26 Results of basic material characterization tests for SS-1h and CSS-1hM emulsions Residues

Property	SS-1h Result	CSS-1hM Result
Residual Content (%)-Evaporation Method	26.77	19.93
Residual Content (%)-Distillation Method	26.35	19.94
Penetration, 25°C, 100g, 5 sec (dmm)	71.2	64.6
Softening Point, Ring & Ball (°C)-for Evaporation Residue	52.5	62.5

Table B.27 Results of DSR PG Grading for SS-1h and CSS-1hM emulsions Residues

Property	SS-1h Result	CSS-1hM Result
PG higher Grade-Distillation Method	64	70
PG higher Grade-Evaporation Method	70	70
Failure Temperature (°C)	66.5	78.9

B.5 Evaluation of the Relationship Between Field Performance and Bond Strength

The ability of the selected bond strength tests to predict performance as related to debonding and delamination was evaluated in this stud by analyzing PCR data of micro-surfacing project and evaluating the bond strength of micro-surfacing sections with known performance.

B.5.1 Results Analysis of PCR Data of Micro-Surfacing Project

Based on the information obtained from the office of pavement engineering for all projects that relate to the micro-surfacing treatment, PCR data for the pavement before and after installing micro-surfacing treatment were used to evaluate the micro-surfacing performance over service life. The focus was on the micro-surfacing projects that were open for traffic in 2017 and had a surface disintegration or debonding distress type. Table B.28 presents the PCR change over time for each selected project for the period from 2016 to 2017. It was noticed that very limited number of sections that had distress code 4, and those sections had low to medium severity surface disintegration or debonding. This might be attributed to the fact that ODOT specifies applying a tack coat with minimum application rate of 0.06 gsy prior to installing a micro-surfacing layer on an existing pavement.

B.28 PCR change over time for the projects with debonding or disintegration distress type - Code 4.

District	Road	From	To	PCR	Date Rated	Pavement Type	CODE_4 Surface disintegration or debond
12	SCUYIR00090**C	0	2.8	86	9/16/2020	Composite	LO (0.9)
12	SCUYIR00090**C	0	2.8	88	5/1/2019	Composite	LO (0.9)
12	SCUYIR00090**C	0	2.8	89	5/1/2018	Composite	
12	SCUYIR00090**C	0	2.8	92	5/3/2017	Composite	
12	SCUYIR00090**C	0	2.8	79	5/12/2016	Composite	LO (0.9)
7	SMOTIR00070**C	0	6.7	93	7/1/2020	Composite	LO (0.9)
7	SMOTIR00070**C	0	6.7	95	6/20/2019	Composite	LO (0.9)
7	SMOTIR00070**C	0	6.7	97	7/19/2018	Composite	
7	SMOTIR00070**C	0	6.6	74	8/7/2017	Composite	LO (0.9)
7	SMOTIR00070**C	0	6.6	74	11/1/2016	Composite	LO (0.9)
7	SMOTIR00070**C	0	6.7	93	7/1/2020	Composite	LO (0.9)
7	SMOTIR00070**C	0	6.7	93	6/14/2019	Composite	LO (0.9)
7	SMOTIR00070**C	0	6.7	97	7/19/2018	Composite	
7	SMOTIR00070**C	0	6.6	80	8/7/2017	Composite	
7	SMOTIR00070**C	0	6.6	80	11/1/2016	Composite	
8	SCLESR00032**C	0	1	84	6/17/2020	Composite	LO (0.9)
8	SCLESR00032**C	0	1	91	5/7/2019	Composite	
8	SCLESR00032**C	0	1	91	5/9/2018	Composite	
8	SCLESR00032**C	0	1	79	4/13/2017	Composite	
8	SCLESR00032**C	0	1	85	5/25/2016	Composite	

B.5.2 Results of The Bond Strength for Micro-Surfacing Sections with Known Performance

The bond strength of several micro-surfacing sections in District 3 with known performance was determined. This was done by obtaining cores from these sections few months after installing the micro-surfacing layer. Figure B.56 presents the values of Proceq pull-off force for field cores obtained from selected locations at SR 89 section in District 3 that have shown debonding and delamination few months after construction. As seen from Figure B.56, the location with no delamination 15.71-SB showed the highest pull-off force value among other tested locations, which indicates better bond strength at that location. The location with severe delamination problem (16.91-SB) had a higher pull-off force value than that for 16.6-NB location that had a medium severity delamination problem.

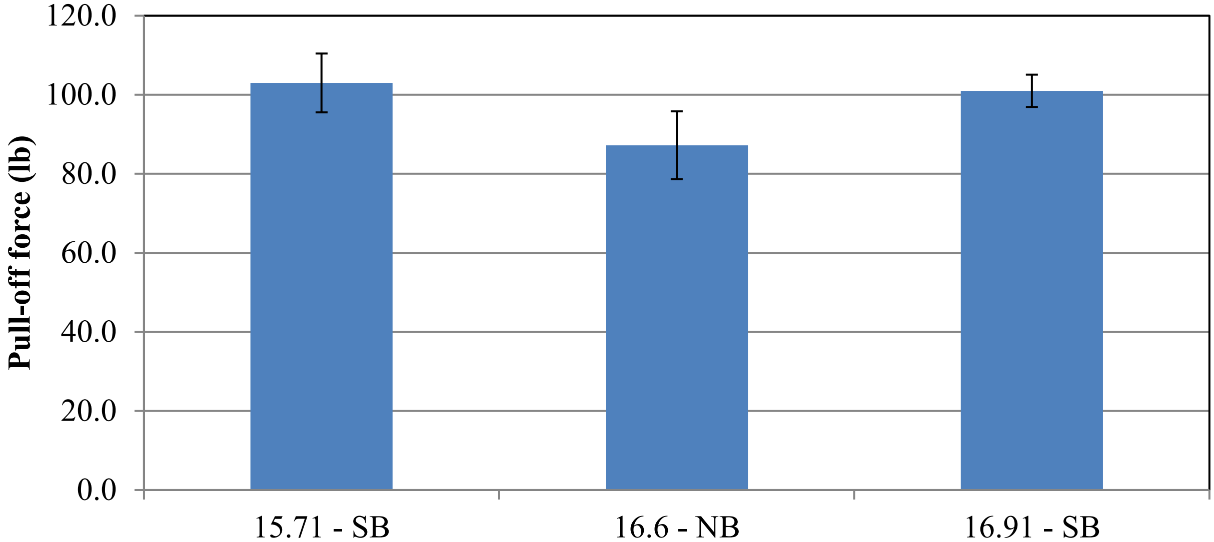


Figure B.56 Results of Proceq Pull-off Testing for Field Cores Obtained at selected locations at SR 89 section

Figure B.57 presents the results of torque testing conducted on field cores obtained from selected deteriorated and good locations at SR 89 section in District 3. The location with no delamination issues had the highest torque value compared to other two locations. Both locations that had delamination problems had almost similar torque values with a slightly higher value for the location with medium severe delamination problem (16.6-NB).

Figure B.58 presents some photographs taken during the evaluation of deteriorated micro-surfacing locations at SR 89 test section and obtaining field cores from these locations.

Results obtained from SR 89 field cores testing were compared to the results obtained from testing field cores samples on SR 274 project, SR 03 project, SR 598 project, and SR 97 project as part of field evaluation plan. The comparison focused on samples with JMF emulsion content and a tack coat application rate close to 0.06 gsy and CSS-1hM tack coat material type. Figure B.59 presents the results of Proceq pull-off force for field core samples obtained from selected sections in SR 274 project, SR 03 project, SR 598 project, and SR 97 project at aging period of around two to four months, and compared to the results of field cores obtained from SR 89 section two months after the installation of micro-surfacing surface layer. As seen in Figure B.59, pull-off force values obtained from testing the field cores of SR 89 section were much lower than the values obtained from other evaluated test sections at other projects.

Figure B.60 presents the results of torque value for field core samples obtained from selected sections in SR 274 project, SR 03 project, SR 598 project, and SR 97 project at aging period around two to four months, and compared to the results of field cores obtained from SR 89 section two months after the installation of micro-surfacing surface layer. As seen in Figure B.60, torque values obtained from testing the field cores of SR 89 section were much lower than the values obtained from other evaluated test sections other projects. These results agree well with the results obtained from Proceq pull-off testing. This suggests that there was a debonding problem at that section that resulted in loss of bond strength between the newly installed micro-surfacing layer and old pavement surface, which also agreed with the results obtained from field evaluation conducted on that section.

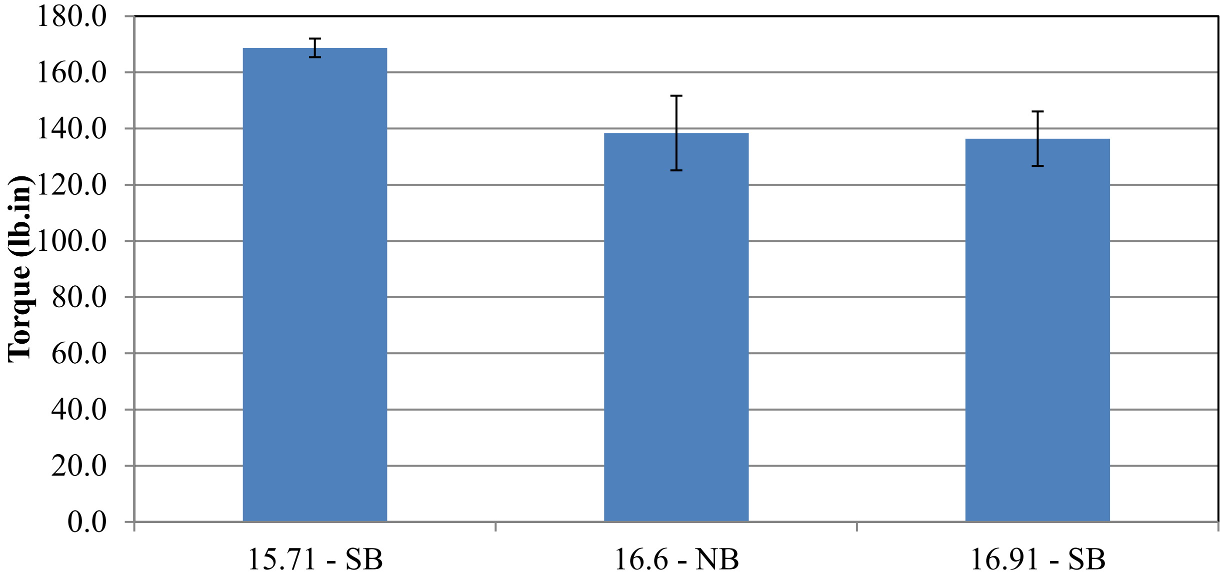


Figure B.57 Results of Torque Testing for the Field Cores Obtained at selected locations at SR 89 section.

Figure B.58 photographs taken during the evaluation of deteriorated and good micro-surfacing locations at SR 89 test section and obtaining field cores from these locations: a) 16.91-16.96 SB, b) 16.6-16.61 NB, c) 15.6-16.0 SB, and d) coring at one selected location.

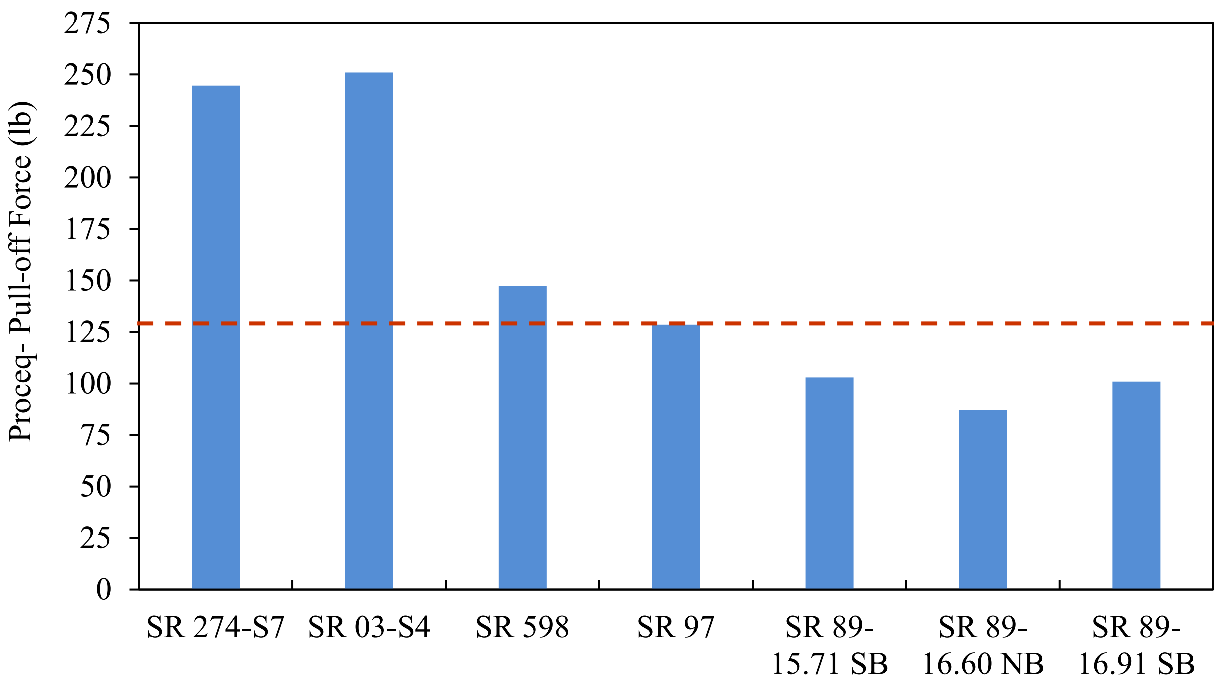


Figure B.59 Results of Proceq Pull-off force for the Three Projects Evaluate in this Study.

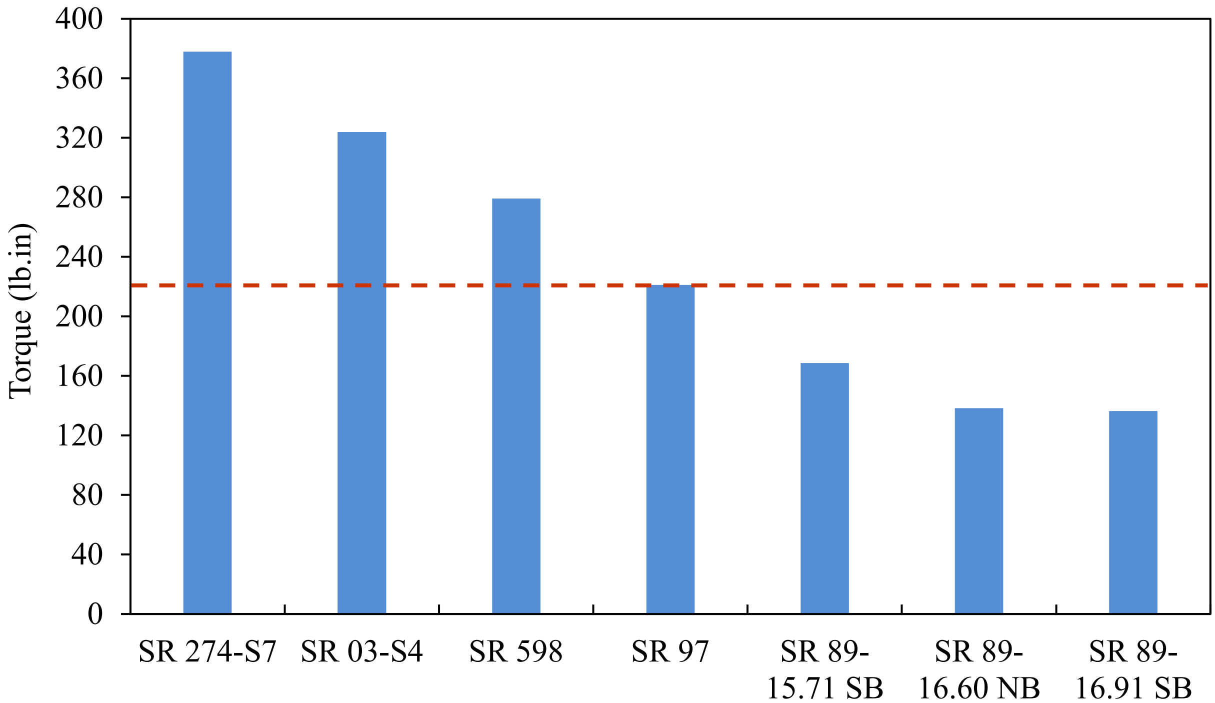


Figure B.60 Results of Torque Testing for the Three Projects Evaluate in this Study.

Analysis of Variance (ANOVA) and post ANOVA Least Square Mean (LSM) analyses were conducted using Statistical Analysis Software (SAS) (SAS, 2004) to statistically evaluate the results of bond strength from Proceq and Torque testing in the laboratory conducted on field cores obtained from each project, to evaluate the significance of testing results between different test sections. Tables B.29, and B.30 present the results of ANOVA on the Proceq pull-off force and torque values. It can be seen from both tables that the effects of section location on Proceq pull-off force and torque values were statistically significant at 95% confidence level, which can be indicated by the P-values in both tables.

Table B.31 and B.32 present the results of the ranking of micro-surfacing projects based on Proceq pull-off force values and torque values, which was determined using the post ANOVA LSM analysis. In this table, the groups are listed in descending order with the letter “A” assigned to the highest mean followed by the other letters in and appropriate order. It is noted from both tables that sections of SR 89 project had the lowest values of Proceq pull-off force and Torque compared to other Projects. Those sections have shown debonding and delamination few months after construction. This suggests that pull-off test and torque bond strength can be used to detect section that might develop debonding or delamination. The results in Table C.15 and C.16 also suggest that minimum average value of Proceq pull-off and torque bond strength tests should be 125 lbf and 220 lbf.in, respectively, to ensure adequate interlayer bonding between micro-surfacing layer and existing pavement.

Table B.29 Results of ANOVA Analysis on Proceq pull-off force Results for Several Evaluated Projects.

Effect	F-Value	P-Value
Section	122.53	<0.0001

Table B.30 Results of ANOVA Analysis on Torque Results for Several Evaluated Projects.

Effect	F-Value	P-Value
Section	41.01	<0.0001

Table B.31 Results of Post ANOVA Analysis on Proceq pull-off force Results for Several Evaluated Projects.

Section	Estimate	Standard Error	Letter Group
SR03-S4	251.00	5.5462	A
SR274-S7	244.67	5.5462	A
SR598	147.33	5.5462	B
SR97	128.67	5.5462	C
SR 89-SB15.7	103.00	4.8031	D
SR 89-NB16.6	101.00	4.8031	DE
SR 89-NB16.91	87.2500	4.8031	E

Table B.32 Results of Post ANOVA Analysis on Torque Results for Several Evaluated Projects.

Section	Estimate	Standard Error	Letter Group
SR274-S7	378.00	16.3533	A
SR3-S4	324.00	16.3533	B
SR 598	279.20	16.3533	B
SR 97	221.20	16.3533	C
SR 89-SB15.7	168.72	12.6672	D
SR 89-NB16.6	138.40	11.5635	D
SR 89-NB16.91	136.40	11.5635	D

Appendix C Testing Procedures for Evaluating Interlayer Bond Strength

Core samples should be obtained along the wheel path for evaluation of the interlayer bond strength between the micro-surfacing layer(s) and the existing pavement. Coring should be at least 1.5 inch into existing pavement layer. The testing procedures to evaluate the interlayer bond strength using the obtained cores are provided below.

C.1 Torque Testing Procedure for Evaluating Interlayer Bond Strength

Equipment

- The torque device (Figure C.1) is comprised of several parts including a 6-inch proctor test mold with set screws attached to it, a torque adapter to measure the applied torque, a torque multiplier, a converter (Figure C.2 provides details for the converter), and a torque wrench to apply torque.
- Sandpaper (60 and 100 grit)
- Epoxy Adhesive: Two-part, high strength, rapid curing Gel formula epoxy with at least a strength of 2,500 psi (Devcon 21045 or equivalent). This is used to affix the loading disks to the test sample. The epoxy adhesive must be capable of maintaining adhesion between metal and micro-surfacing mixture under direct shear loading.
- Water bath or enviromental chamber to condition sample at 25 ºC.

Testing Procdure

The following steps are provided to conduct the test on 6-inch diameter cores sampled from constructed micro-surfacing sections.

1. Make three 2-inch diameter cores in each sample obtained from the field (Figure C.3). The coring should be through the top micro-surfacing layer(s) and up to half an inch into the existing pavement layer.
2. Prepare the surface of each of the 2-inch cores using sandpapers and grinder (if needed) to remove any existing surface irregularities. Coarse sandpaper (60 grit) should be used first to remove any defects and prepare the sample surface. A fine sandpaper (100 grit) should be used to give a smoother surface for epoxy application.
3. Glue the 2-inch metal disk to the top of the surface using a two-part creamy phase epoxy that has a strength of at least 2500 psi. A thick layer of epoxy needs to be applied uniformly over the 2-inch core to achieve a good bonding between the metal disk and the surface of the substrate. Clean off excess epoxy with a tongue depressor or any other disposable flat tool.
4. Condition the samples for in a water bath or an environmental chamber at 25 ± 1°C for 2 hours ± 10 minutes. If water bath is used for conditioning, sample should be kept dry during the conditioning process.
5. Move the sample into the mold and fix it with the set screw in order to prevent any movement while applying torque.
6. Apply the torque with the torque wrench at a constant 4 rev/min rate by turning both ends of the handle by both hands until failure occurs. During the application of the torque, the

torque wrench should be kept parallel with respect to the top surface of the specimen to avoid any effect of bending.

7. Record the value of peak torque when the failure occurs.

Evaluation Criterion

The average peak torque value for three samples should be 220 lbf.in or greater for cores obtained along the wheel path at least two months after installing the micro-surfacing layer(s). In addition, no single test peak torque value should be less than 200 lbf.in.

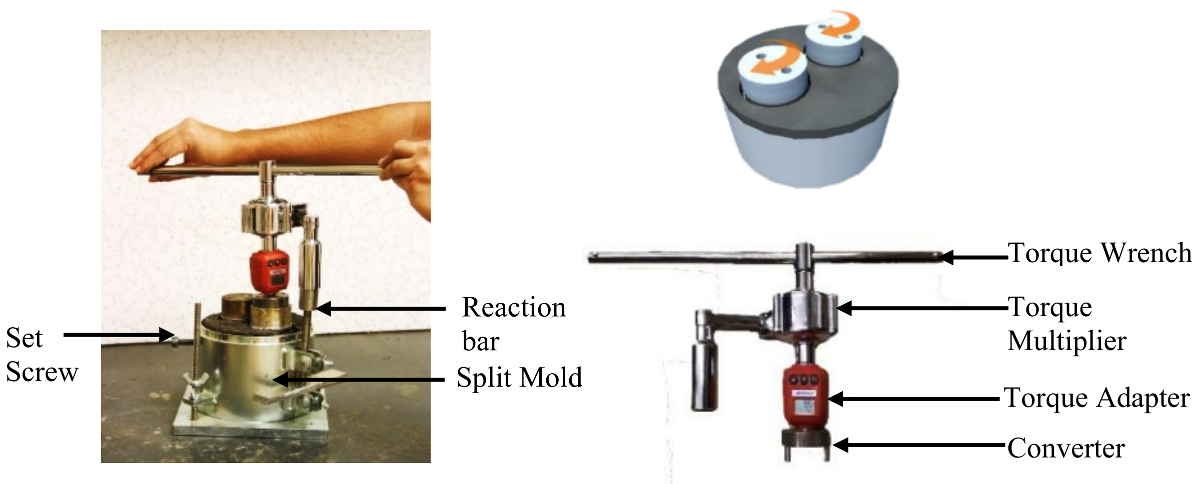


Figure C.1 Torque Testing Device

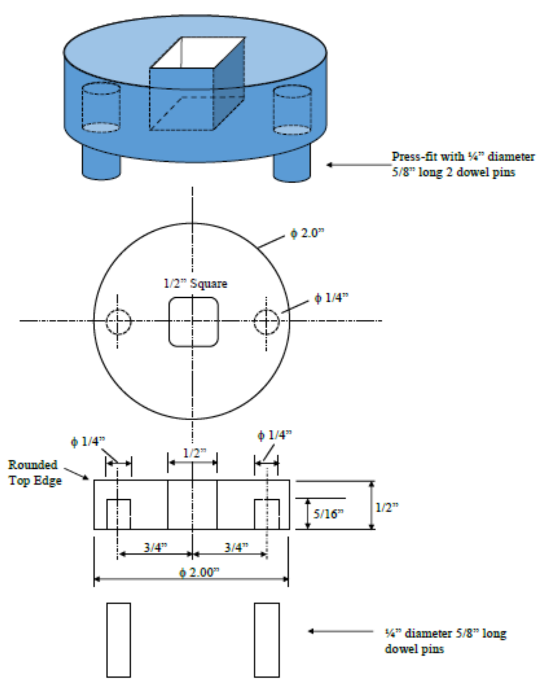


Figure C.2 Shop Drawings for The Torque Device Converter


Figure C.3 Field core samples prepared for interlayer bond strength testing

C.2 Pull-off Testing Procedure for Evaluating Interlayer Bond Strength

Equipment

- Use an automated pull-off tester with a working range of 0.6 to 6 kN (135 to 1349 lbf) and can apply a loading rate of 2 lbf/sec such as Dyna Proceq^{TM} Pull-off tester Dy 206 (Figure C.4). The used tester should be specially designed to measure low tensile bonding strength typically associated with a thin surface.
- Sandpaper (60 and 100 grit)
- Epoxy Adhesive: Two-part, high strength, rapid curing Gel formula epoxy with at least a strength of 2,500 psi (Devcon 21045 or equivalent). This is used to affix the loading disks to the test sample. The epoxy adhesive must be capable of maintaining adhesion between metal and micro-surfacing mixture under direct shear loading.
- Water bath or enviromental chamber to condition sample at 25 ^{o}C.

Testing Procdure

The following steps are provided to conduct the test on core samples obtained from constructed micro-surfacing sections.

1. Make three 2-inch diameter cores in each sample obtained from the field (Figure C.3). The coring should be through the top micro-surfacing layer(s) and up to half an inch into the existing pavement layer.
2. Prepare the surface of each of the 2-inch cores using sandpapers and grinder (if needed) to remove any existing surface irregularities. Coarse sandpaper (60 grit) should be used first to remove any defects and prepare the sample surface. A fine sandpaper (100 grit) should be used to give a smoother surface for epoxy application.
3. Glue the 2-inch metal disk to the top of the surface using a two-part creamy phase epoxy that has a strength of at least 2500 psi. A thick layer of epoxy needs to be applied uniformly over the 2-inch core to achieve a good bonding between the metal disk and the surface of the substrate. Clean off excess epoxy with a tongue depressor or any other disposable flat tool.

4. Condition the samples for in a water bath or an environmental chamber at 25 ± 1°C for 2 hours ± 10 minutes. If water bath is used for conditioning, sample should be kept dry during the conditioning process.
5. Place a reaction plate on the specimen. Then, place the device on the reaction plate. The reaction plate needs to be used for the proper transmission of the reaction force.
6. Using the pulling stub, bring the device in contact with the test bolt.
7. Apply a tensile load by pulling stub using a loading rate of 2 lbf/sec. The test should continue until the pull-off force reaches a peak value and drops down to a force value less than 25 lbf.
8. Record the peak pull-off force.

Figure C.4 Dyna Proceq Pull-off Testing Device

<u>Evaluation Criterion</u>

The average pull-off force value for three samples should be 125 lbf or greater for cores obtained along the wheel path at least two months after installing the micro-surfacing layer(s). In addition, no single test pull-off force value should be less than 110 lbf.