GEORGIA DOT RESEARCH PROJECT 07 - 07

FINAL REPORT

ASSESSING TECHNIQUES AND PERFORMANCE OF THIN OGFC/PEM OVERLAY ON MICRO-MILLED SURFACE

Georgia Department of Transportation

OFFICE OF MATERIALS & RESEARCH
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16. Abstract:

The practice of placing an open-graded friction course (OGFC) or a porous European mix (PEM) directly on top of a conventional milled surface has rarely been done in Georgia due to concerns that this rehabilitation method could potentially cause delamination of the surface layer due to poor bonding between the OGFC/PEM layer and the conventional milled surface. This report presents the research study for evaluating the quality of two micro-milling operations (one on I-75 and one on I-95) designed to reduce the potential for these issues.

Results obtained from the I-75 project indicated that based on four years of satisfactory performance of the PEM overlay the use of a 95-percentile ridge-to-valley texture depth (RVD) parameter as the threshold value for compliance with the correction 3.2 mm RVD acceptance requirement could be too restrictive. Alternatively, Mean RVD was tentatively adopted on the I-95 project for compliance with the correction 3.2 mm RVD acceptance criteria. The research team concluded that the ultimate decision for selecting an appropriate RVD parameter for compliance with the correction 3.2 mm RVD acceptance requirement should be based on the long-term performance of the OGFC/PEM layer placed on the micro-milled surface.

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FINAL REPORT

ASSESSING TECHNIQUES AND PERFORMANCE OF THIN OGFC/PEM OVERLAY ON MICRO-MILLED SURFACE

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In cooperation with

U.S. Department of Transportation

Federal Highway Administration

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EXECUTIVE SUMMARY

Background and Research Need

Conventional milling with thin resurfacing is one of the most common asphalt pavement preservation methods. A typical application of this method on open-graded friction course (OGFC) over dense-graded or stone matrix asphalt (SMA) involves several steps. The first step is to mill out the total thickness of the pavement, including both the OGFC layer and the in-place dense-graded mix below the OGFC. The next step is to place a typical layer thickness of dense-graded (12.5 mm Superpave or gap-graded SMA) asphaltic concrete mixture on top of the milled surface. The final step is to overlay with OGFC.

Placing an OGFC layer directly over the milled surface has rarely been done because of the concern for potentially poor bonding between the OGFC and the rough-milled surface. There is also a possibility that surface water entering the OGFC could become trapped within the valleys created by the spacing of the milling teeth on the conventional-milled surface. Each of these events could potentially cause delamination of the OGFC layer. Another concern is that the reduced thickness of the asphalt mixture beneath the OGFC could result in the deficiency of the pavement structural capacity.

Replacing the conventional milling operation with the micro-milling technique could allow the OGFC or the new porous European mix (PEM) to be placed directly on the milled surface without encountering the potential problems mentioned above. This would result in significant savings when compared with the conventional milling and mixture replacement operation. A micro-milling operation using much finer teeth on the milling drum, together with an improved milling operation, could precisely control the milling

depth to $^{1}/_{16}$ in. and would produce a much finer, smoother textured surface. Due to the concern for potential delamination of the thin OGFC/PEM on the micro-milled surface, the need for the micro-milled surface to meet stringent requirements is much more critical.

Objective and Proposed Research Scope

The objective of the originally proposed research study was to conduct investigations in conjunction with the micro-milling and PEM overlay rehabilitation project on I-75 near Perry, Georgia. The study would evaluate the quality of the micro-milling and paving operations, assess the long-term performance of the PEM overlay pavement, and validate or offer suggestions for revising Georgia Department of Transportation (GDOT) Specification Section 432, "Mill Asphaltic Concrete Pavement," which includes the micro-milling specified requirements. The originally proposed research program consisted of four specific tasks (Tasks 1–4). Toward the end of the original research study, a second micro-milling and OGFC overlay rehabilitation project began on I-95 near Savannah, Georgia. This new micro-milling project could provide additional information for this research study; therefore, the researchers incorporated additional studies as Task 5, allowing the research findings from this study to be more readily implementable for the asphalt pavement milling and overlay construction operations of GDOT.

Major Findings

1. Results obtained from the I-75 project were based on four years of satisfactory performance of the PEM overlay placed on the micro-milled surfaces. These

results indicated the use of a 95 percentile ridge-to-valley texture depth (p95 RVD) parameter as the threshold value for compliance with the correction index of 3.2 mm RVD acceptance requirement could be too restrictive. Results from the I-95 project indicated that the Mean RVD of the micro-milled surface can meet the correction 3.2 mm RVD acceptance requirement. However, the appropriateness of using this parameter as the threshold value for compliance with the correction 3.2 mm RVD acceptance requirement, as tentatively adopted by the I-95 project, cannot be determined at this time. The ultimate test for selecting an appropriate RVD parameter should be based on long-term performance of the OGFC/PEM layer placed over the milled surface.

2. The underlay asphalt mixture on the I-95 project was an SMA, while that on the I-75 project was a dense-graded 12.5 mm mix. The appearance of the micro-milled surfaces on these two projects was quite different, with “pockets of holes” created by small aggregate pop out appearing on the milled surface on the I-95 project, while no such phenomenon was evident on the I-75 project.

3. The Laser Road Profiler (LRP) retrofitted with WinPRO® software developed by International Cybernetics Corporation (ICC) proved to be a viable and practical instrument for collecting the RVD data on the milled surface.

4. Milling operations should completely remove the original OGFC/PEM layer. No OGFC/PEM scabs should be left on the milled surface, even if they appear to be intact and bonded to the underlay material.

5. The cleanness of the milled surface should be closely inspected, particularly when pockets of holes are present on the milled surface.

Recommendations

The following recommendations are offered based on the results obtained from this research study.

1. GDOT Special Provision Section 432, "Mill Asphaltic Concrete Pavement (Micro-Mill)" stipulates that, "Any areas exceeding ⅛ in. (3.2 mm) between the ridge and valley of the mat surface…shall require that the underlying layer be removed and replaced with material as directed by the Engineer at no additional cost to the Department." Results obtained from the I-75 project indicated that based on four years of satisfactory performance of the PEM overlay, the use of p95 RVD parameter as the threshold value for compliance with the correction 3.2 mm RVD acceptance requirement could be too restrictive. Alternatively, Mean RVD was tentatively adopted on the I-95 project as the threshold value for compliance with the correction 3.2 mm RVD acceptance criterion. The ultimate decision for selecting an appropriate RVD parameter, whether it is the Mean RVD, p75, p80, p90, p95, or other RVD parameter, for compliance with the correction 3.2 mm RVD acceptance requirement, should be based on the long-term performance of the OGFC/PEM layer placed on the micro-milled surface.

2. In performing the quality control for the micro-milled surface at the I-95 project, the micro-milled surface texture raw data were collected by the LRP in ½-mile segments for the entire project. It is recommended that these raw data be safely

kept as they can be used to generate various RVD parameters (Mean RVD, p75, p80, p90, p95, or other RVD parameter) for ½-mile or longer segments. These RVD values generated at various locations can be used to correlate with the long-term performance and any observed distresses in the OGFC overlay at the same locations. This information can be used for establishing the appropriate RVD parameter for compliance with the correction index of 3.2 mm RVD acceptance criteria, or developing new acceptance criteria.

3. Researchers recommend a tack coat rate of 0.08 gal/yd^2 be used on micro-milled surfaces for PEM overlay paving. Results from this research study showed that using a 0.08 gal/yd^2 tack rate produced noticeably higher bond strength between the micro-milled surface and the PEM overlay than that using 0.06 gal/yd^2 tack rate.

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ACKNOWLEDGMENTS

The Georgia Department of Transportation (GDOT) Office of Materials and Research sponsored this research. The testing performed on the I-75 project, including the testing for measuring the milled surface texture depths and determining the bond strength, was conducted by the National Center for Asphalt Technology.

The author thanks the GDOT Office of Materials and Research and the personnel from the District 3 and District 5 Offices for their support and assistance and for their participation in the field testing activities. Special appreciation is expressed to Reeves Construction Co. and PP&S Co., and to Plant Improvement Co., Inc. of Brunswick, Georgia, for their cooperation and assistance.

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PART 1: BACKGROUND

CHAPTER 1 Introduction

1.1 Background and Needs

1.1.1 Current Method and Issues

Conventional milling with thin-resurfacing is one of the most common asphalt pavement preservation methods. A typical application of this method on open-graded friction course (OGFC) over dense-graded or stone matrix asphalt (SMA) involves several steps. The first step is to mill out the total thickness of the pavement, including both the OGFC layer and in-place dense-graded mix below the OGFC. The next step is to place a typical layer thickness of dense-graded (12.5 mm Superpave or gap-graded SMA) asphaltic concrete mixture on top of the milled surface. The final step is to overlay with OGFC.

Placing an OGFC layer directly over the milled surface has rarely been done because of the concern for potentially poor bonding between the OGFC and the rough-milled surface. There is also a possibility that surface water entering the OGFC could become trapped within the valleys created by the spacing of the milling teeth on the conventional-milled surface. Each of these events could potentially cause delamination of the OGFC layer. Another concern is that the reduced thickness of the asphalt mixture beneath the OGFC could result in the deficiency of the pavement structural capacity.

In the mid-to-late 1990s, a common asphalt pavement rehabilitation practice used by GDOT involved placing 1½ in. of dense-graded 12.5 mm or SMA mix and then covering it with ¾ in. of OGFC. This typical rehabilitation method performed well during GDOT’s planned maintenance cycle of 10 years. The OGFC surface then started to deteriorate, even though the underlying SMA layer was still in good condition and could last for another 10 years. Unfortunately, while desirable to mill out only the OGFC, conventional milling operation mills out not only the OGFC layer but also the entire 1½ in. of SMA or other dense-graded mix HMA layer beneath it, regardless of conditions. This required a new SMA or dense-graded asphaltic concrete (DGAC) layer be placed on the milled surface before a new OGFC or porous European mix (PEM) surface course could be placed on top of it. This was very expensive, but unfortunately, cannot be avoided when using conventional milling on this type of asphalt pavement structure.

1.1.2 Proposed Solution and Considerations

The micro-milling operation, sometimes referred to as "carbide grinding," uses much finer teeth on the milling drum together with an improved milling operation. Thus, it produces a much finer and smoother milled surface texture. Micro-milling could precisely control the milling depth down to 1/16 in. This precision allowed the operation to mill out only the existing OGFC or PEM layer, plus perhaps up to ¼ in. of the SMA or DGAC layer. An OGFC or PEM layer could then be placed directly on top of the micro-milled surface. This would result in significant savings when compared with the milling and overlay using the conventional milling operation described above.

The use of micro-milling, in conjunction with asphalt pavement overlay, is not completely new, although it is still a relatively innovative technique. Maryland and Colorado have used micro-milling and overlay with dense-graded HMA; however, placing a thin OGFC or PEM directly on top of the micro-milled surface has never been done before. The absence of this practice is due to the concern of potential delamination that could occur with the thin OGFC or PEM overlay on the micro-milled surface with reasons similar to that of OGFC or PEM placed over a conventional milled surface. The need for the micro-milled surface to meet the stringent requirements is much more critical for overlay with the thin OGFC or PEM layer than with thick dense-graded HMA. With regards to the quality of the OGFC or PEM paved on the milled surface, in addition to the smoothness requirement, adequate bonding between the OGFC or PEM and the milled surface is very important and needs to be evaluated to ensure its long-term performance.

It is important that researchers thoroughly investigate such issues so that proper construction techniques may be developed and the associated construction specifications can be validated. This new technique was used in Georgia for the rehabilitation projects at I-75 near Perry and at I-95 near Savannah. It is important to evaluate the quality of the micro-milling and paving operations and to assess the long-term performance of the OGFC and PEM overlay pavement on these projects. The results of these research studies can be used to validate established thresholds for the product acceptance or to evaluate any possible modifications of the GDOT Specification Section 432, "Mill Asphaltic Concrete Pavement," which includes the micro-milling operation.

1.2 Significance of Research

The use of micro-milling would allow milling out only the existing OGFC or PEM layer, plus perhaps up to ¼ in. of the underlying asphalt layer (either dense-graded HMA or SMA). Then a ⅝- to ¾-in. thick OGFC[1] or a 1¼-in. thick PEM layer could be placed directly on top of the micro-milled surface. The conventional milling operation would

[1] Editor's Note: Typical GDOT practice is to use thicker surface coats. Normal GDOT minimum pavement applications are 90-100 pounds/square-yard for OGFC and 135 pounds/square-yard for PEM. For typical void volumes, these depth values are roughly double those stated in the text.

require removal of the OGFC or PEM layer and the entire thickness of the asphalt layer beneath. A new SMA or DGAC layer would have to be placed on top of the milled surface before placing an OGFC or PEM layer on top of it. Thus, use of micro-milling and overlay operation would result in significant savings when compared to the conventional milling and overlay of OGFC or PEM.

At the I-75 project, the estimated cost savings for not placing 1½ in. of SMA was about $8.25 per square yard. This amount was based on the $100/ton cost for SMA in 2007. While the additional cost for micro-milling over the conventional milling is unknown, a 100% increase of the micro-milling cost over the conventional milling cost, which is about $2.00 per square yard, is assumed here as a conservative estimation. The direct cost savings per lane mile is estimated at $50,000. Thus, for the I-75 pavement rehabilitation project near Perry, Georgia, the direct cost savings was $4.7 million.[2] With the continuous escalation of asphalt paving costs, cost savings for using this new micro-milling and overlay method for rehabilitation of asphalt pavements in Georgia could be very significant.

1.3 Objective and Proposed Research Program

The objective of the research study, as originally proposed, was to conduct investigations in conjunction with the micro-milling and PEM overlay rehabilitation project on I-75 near Perry, Georgia. These investigations evaluated the quality of the micro-milling and paving operations, assessed the long-term performance of the PEM overlay pavement, and validated or offered suggestions for revising GDOT Specification

[2] Editor's note: The original cost estimate was significantly higher as more extensive rehabilitation was planned. The cost included in this report is for the SMA layer only. Reported savings thus represent a minimum.

Section 432, “Mill Asphaltic Concrete Pavement,” which includes the micro-milling specified requirements. The original proposed research program consisted of Tasks 1–4, as described below. Toward the end of the original research study, a second micro-milling and OGFC overlay rehabilitation project at I-95 near Savannah, Georgia, began. This new micro-milling project could provide additional information for this research study; therefore, additional studies were incorporated as Task 5. This supplement allowed the research findings from this study to be available for use with the asphalt pavement milling and overlay construction operations of GDOT.

Task 1: Pre-construction Research Activities. This work task consisted of two major research efforts. The first phase was to investigate the potential use of the Circular Track Meter (CTM) and other mobile laser-based devices suitable for measuring pavement surface texture, as well as to investigate such equipment as the Ultra-Light Inertial Profiler (ULIP), for evaluating the micro-milled surface quality. The second phase was to develop an appropriate laboratory method for evaluating the bond between the PEM layer and the micro-milled surface, as well as establishment of appropriate thresholds related to the long-term performance of the PEM layer against slippage failure.

Task 2: Research during the Construction of the Test Section. This work task consisted of two parts. The first part was to evaluate the quality of the micro-milled surface texture on the test section to meet the acceptance requirements in accordance with the GDOT Specification Section 432, “Mill Asphalt Concrete Pavement (Micro Mill).” The second part was the performance of laboratory bond strength testing of the cores taken from the test section to assess the bond strength between the PEM and the DGAC layer.

Task 3: Research during the Mainline Pavement Construction. This work task consisted of three parts. The first part was observation of the milling and overlay operations during the mainline construction to identify problems and methods that could improve the construction quality. The second part was evaluation of the quality of the micro-milled surface texture on the DGAC surface. The third part was performance of laboratory bond strength testing on the cores taken from the mainline pavement to determine the bond strength between the PEM and the DGAC layer.

Task 4: Post Construction Evaluation. The post-construction evaluation of the performance of the PEM surfacing on the micro-milled surface was conducted for two years to assess the viability of using the micro-milled technique in lieu of the conventional milling technique.

Task 5: Evaluation of Micro-milling Operation and Results on the I-95 Project. This work task consisted of three major efforts. The first stage was evaluation of the use of the LRP for measuring the RVD for pavement surface textures. The second stage was observation of the micro-milling operation and evaluation of the milled surface textures and the RVD data obtained on the micro-milled SMA surface. The third stage was the assessment of the use of a 95 percentile ridge-to-valley texture depth (p95 RVD) parameter as the threshold value for compliance with the correction index of 3.2 mm RVD acceptance requirement for micro-milled pavement surface textures.

1.4 Research Studies at I-75 Project and I-95 Project

Tasks 1, 2, 3, and 4 were intended for evaluating the micro-milling operations on the I-75 project near Perry, Georgia, while Task 5 was for evaluating the micro-milling operation on the I-95 project near Savannah, Georgia. Task 4 was proposed originally for the post-construction evaluation of the micro-milling and PEM overlay performance on the I-75 project. With the additional research studies in Task 5, the post-construction evaluation will also include the micro-milling and overlay long-term performance on the I-95 project. Some differences between the research studies performed on the I-75 project and on the I-95 project include the following:

1. Enforcement of the micro-milled surface texture quality: As the I-75 project was the first project using the micro-milling operation, the RVD requirements stipulated under GDOT Specification Section 432, "Mill Asphaltic Concrete Pavement" were used as guidelines for construction quality control and were enforced during I-95 project quality control.

2. Coverage of the micro-milling monitoring: Only ten (10) 150-ft segments from 7½ miles of milling sections were selected for monitoring the ridge-to-valley milled pavement surface texture depth during the I-75 project. For the I-95 project, the entire project, including the three northbound lanes and the three southbound lanes, totaling 81 lane-miles, was monitored.

3. Measurement of the milled surface texture: For the I-75 project, a special ULIP was used to measure the milled surface textures. The GDOT Laser Road Profiler (LRP) was used to measure the milled surface textures for the I-95 project. The

GDOT LRP, which is used routinely for pavement smoothness quality control, was retrofitted with software for generating the various ridge-to-valley depth parameters. It would be practical to use the LRP for monitoring the micro-milled surface textures as a routine pavement construction quality control.

4. Selection of the underlay asphalt mixture: The underlay asphalt mixture for the I-75 project was a 12.5 mm dense-graded HMA; the I-95 project used a 12.5 mm SMA. These two different types of underlay asphalt mixtures significantly affected the micro-milled surface textures characteristics.

1.5 Organization of Report

This report is divided into four parts. Part I consists of Chapters 1, 2, and 3. Chapter 2 presents the results of the literature review of the various instruments that have been used for evaluating pavement surface macrotexture. In addition, it identifies the use of the CTM and ULIP for measuring the micro-milled surface textures on the I-75 project and the use of GDOT's LRP for measuring the micro-milled surface textures on the I-95 project. Chapter 3 presents the findings of the literature review of the methods and threshold values for testing bond strength against asphalt pavement delamination and slippage cracking distresses.

Part 2, which includes Chapters 4–8, presents the work completed for the I-75 project. Chapter 4 presents the testing and the results obtained using the CTM and ULIP for measuring surface textures of a conventionally (rough) milled pavement surface. Chapter 5 presents the operations and the test results of the micro-milling surface textures of three initial trial test sections on the I-75 project. Chapter 6 presents the testing of micro-milled surface textures for Test Section 4 through Test Section 8 on the I-75 project after the contractors resumed the micro-milling and paving operations in August 2007. Chapter 7 presents the analyses and assessments and summarizes the findings of the micro-milled surface textures obtained on the I-75 project. Chapter 8 presents the testing and the results of the tack coat application rates and the bond strength on the I-75 project.

Part 3 contains Chapter 9, which presents the work completed for the I-95 project.

Part 4 presents the conclusions and recommendations.

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CHAPTER 2 Review and Assessment of Asphalt Pavement Surface Texture Measurement

GDOT Section 432, Special Provision, "Mill Asphaltic Concrete Pavement (Micro Mill)," stipulates the following requirements for the micro-milled surface texture as part of the acceptance criteria for the asphalt pavement mill and overlay construction project on I-75 near Perry, Georgia, and on I-95 near Savannah, Georgia:

- Section 432.2.02—Equipment, C. Micro-milling Equipment: "Capable of removing pavement to an accuracy of $^{1}/_{16}$ in. (1.6 mm)."
- Section 432.3.06—Quality/Acceptance: "Any areas exceeding ⅛ in. (3.2 mm) between the ridge and valley of the mat surface or failing to meet pavement surface acceptance testing using the Laser Road Profiler shall require that the underlying layer be removed and replaced with material as directed by the Engineer at no additional cost to the Department."
- The indices for the smoothness of the milled surface measured by the Laser Road Profiler must meet target 825 mm/km and not exceed the correction index of 900 mm/km.

The milled pavement texture depth acceptance criteria stipulated above requires having an instrument that is capable of measuring texture depth between ridge and valley of micro-milled surfaces to the specified accuracy in the field. This chapter is focused on evaluating the instruments and the test procedures currently available for such purposes, and identifying those that are suitable for this research study.

2.1 Asphalt Pavement Surface Texture Measurement Methods and Apparatus Review

The following are the most commonly used methods for measuring pavement surface macrotexture:

1. Sand Patch Method: ASTM E-965 and GDT – 72 [1]
2. Circular Track Meter: ASTM E-2157 [2]
3. International Cybernetics Corporation's (ICC) Laser Road Profiler System
4. Other Laser-Based Methods

Originally, these pavement surface texture measuring methods were developed for (1) measuring concrete pavement surface textures and (2) measuring surface textures of asphalt and concrete pavements. These methods were *related* to the noise due to tire–pavement interaction for studying segregation of asphalt pavements or for studying skid resistance.

Pavement surface macrotexture refers to road–tire contact area with wavelengths of 0.5 mm to 51 mm (0.02 to 2.01 in.) and vertical amplitudes between 0.2 mm to 50 mm (0.01 to 1.97 in.). Pavement surface microtexture, on the other hand, refers to the surface texture of single aggregate surfaces with wavelengths of 1 μm to 0.5 mm and vertical amplitudes less than 0.2 mm.

2.1.1 Sand Patch Method

The Sand Patch Method is used to determine the average depth of pavement surface macrotexture by application of a known volume of sand (or glass beads) on the surface and subsequent measurement of the total area covered (Figure 2-1).

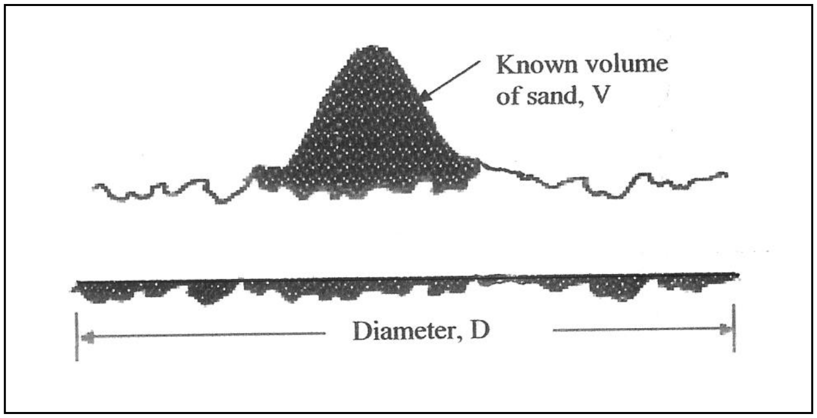


Figure 1: Concept of Sand Patch Method

The mean texture depth (MTD) of the surface can be calculated by

$$\text{MTD} = \frac{4V}{\pi D^2} \quad \text{(Eq. 2.1)}$$

Where:

MTD = mean texture depth of pavement macrotexture, mm. (in),

V = sample volume of sand used, mm.^{3} (in^3), and

D = average diameter of the area covered by the material, in. (mm).

This method has been used extensively. The test is relatively simple to perform; however, it is time consuming and its results are operator dependent. Another problem in using this method for measuring surface texture on micro-milled surfaces is that the sand particles (or glass beads) used to fill the testing surface need to be completely removed so that bonding between the milled surface and the overlay asphalt mixture are not affected.

2.1.2 Circular Track Meter

The Circular Track Meter utilizes a laser displacement sensor mounted on an arm at a radius of 142 mm (5.6 in). that rotates clockwise at a fixed elevation from the surface being measured (Figure 2-2 [2]). The device is controlled by a notebook computer. When initiated by the computer, a DC (direct current) motor drives the arm to rotate for a full 360-degree revolution, producing the measurement. The surface texture profile along the path of the traversed arm is recorded in the computer memory. The profile data are divided into eight segments for analysis (Figure 2-3). The computer software processes the data to report the mean profile depth (MPD) in accordance with ASTM E-1845 [3], the root mean square (RMS), or both for each segment, or the average of all eight segments. The length of each segment is about 100 mm (4 in.). The concept behind the calculation of the MPD by the CTM is illustrated in Figure 2-4. The apparatus is lightweight and portable, and it can be used in the laboratory and in the field. It generates an MPD reading in approximately 30 seconds.

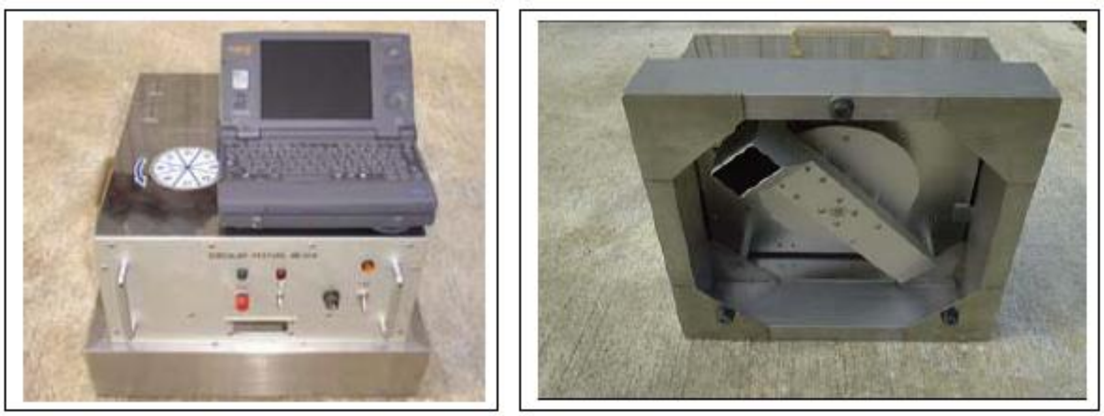


Figure 2-2 Circular Track Meter

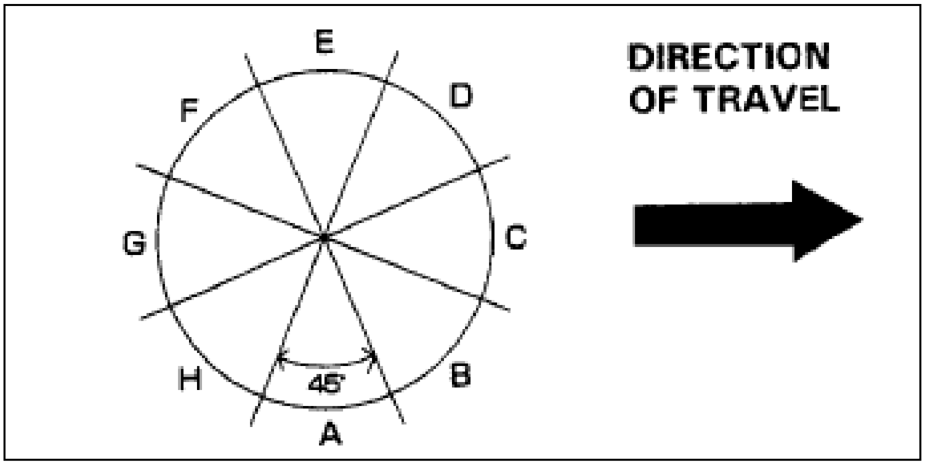


Figure 2-3 Segments of Circular Track Meter

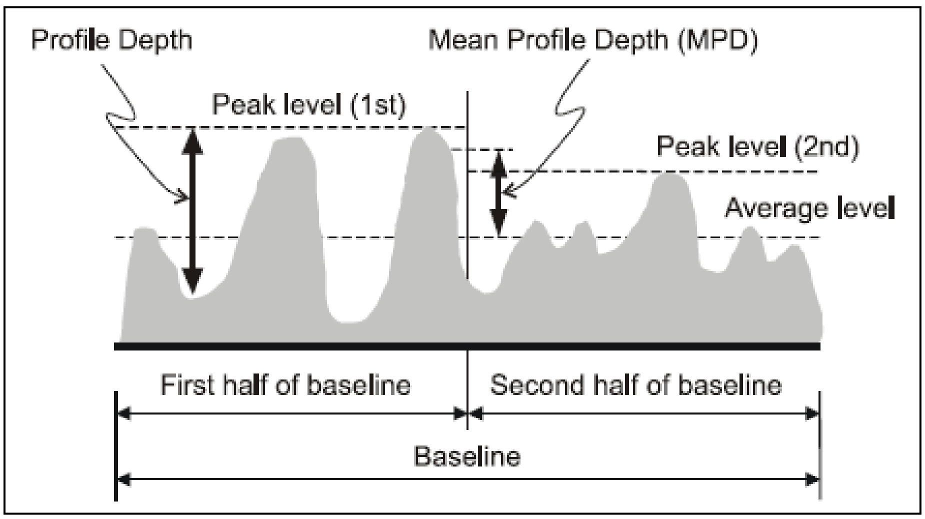


Figure 2-4 Calculation of Mean Profile Depth

2.1.3 ICC's Laser Road Profiler System

The Laser Road Profiler (LRP) System (Figure 2-5) routinely used by GDOT for measuring pavement surface profile smoothness, was retrofitted with software developed by International Cybernetics Corporation. The LRP generates ridge-to-valley pavement surface texture depth parameters as presented in Figure 2-6. Use of the LRP would be practical for monitoring the micro-milled surface textures, along with the pavement smoothness, as a routine pavement construction quality control. The GDOT LRP is equipped with a 32 kHz laser, resulting in a sampling spacing of about 0.6 mm (175 samples per 100 mm distance) when traveling at 40 mph. The accuracy for measuring the vertical depth is at least 0.025 mm.

Figure 2-5 GDOT's Laser Road Profiler

	(Miles)			IRI -- (mm/km)			Texture Depth -- (mm)			(mm)
				Rou		Hcs	(mm		Mean	95%
Date	From	To	Dist	IRI 1	IRI 2	IRI	MPD	% Error	RVD	RVD
11/19/2010: 12:15		[I-23]								

Figure 2-6 RVD and International Roughness Index (IRI) Report Generated by the WinPRO® Software

2.1.4 Other Laser-based Methods

Other methods for measuring pavement surface macrotexture include various laser-based systems, such as the Road Surface Analyzer (ROSAN) [4, 5], the Ultra-Light Inertial Profiler [6], the Automatic Road Analyzer (ARAN) Profile System [7], and the Laser Crack Measurement System (LCMS) [8]. Each of those systems is introduced below.

ROSAN

The Road Surface Analyzer shown in Figure 2-7 [4] is a mobile laser-based automated system for measuring pavement texture at highway speeds along a linear path. With the exception of the computer, the entire unit fits in one case and is transportable. The unit can be mounted on vehicles with a step bumper or any vehicle on which mounting brackets can be installed. ROSAN is capable of measuring pavement surface texture at sampling speeds ranging from 24 km/h (15 mi/h) to 104 km/h (65 mi/h) and sample intervals ranging from 0.25 mm (0.00975 in.) to 25 mm (0.975 in.), depending on the sampling speed. The laser resolution is about 0.03 mm. Figure 2-8 shows the typical readout from ROSAN.

Figure 2-7 Road Surface Analyzer

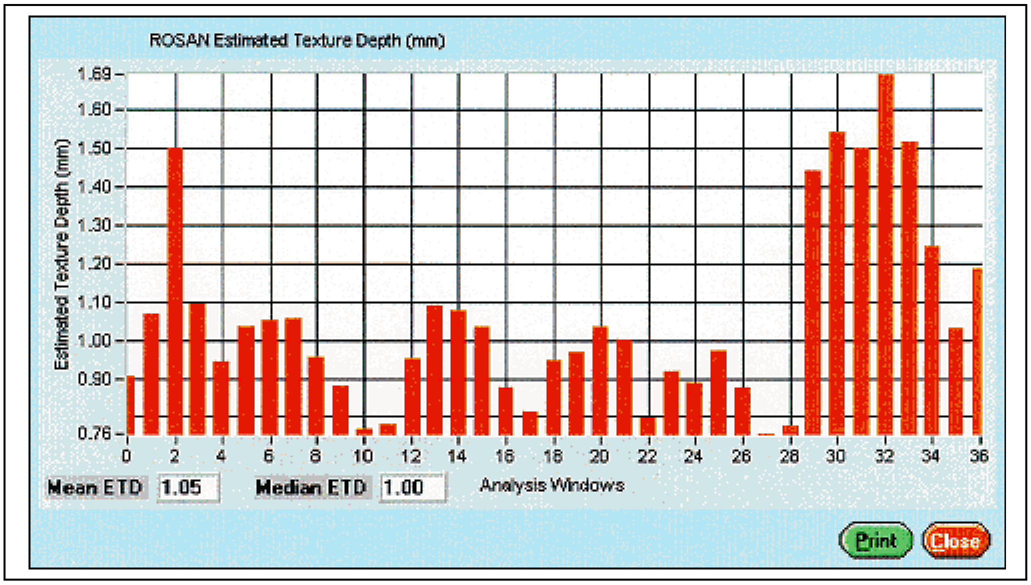


Figure 2-8 Typical Readout from ROSAN [5]

ULIP

The Ultra-Light Inertial Profiler is a laser-based device designed to measure surface profiles in order to evaluate surface texture or roughness. It consists of a Segway™ Human Transporter with a mounted sensor box attached to a laptop computer for data acquisition and analysis as shown in Figure 2-9. The sensor box is equipped with triggers, a laser, and accelerometers. Compared to the CTM and Sand Patch Method, the advantage of the ULIP for measuring surface macrotexture is that an entire length of pavement section can be evaluated. This allows better assessment of texture variability across the entire tested section, compared to spot measurements with the CTM and Sand Patch Method. The ULIP is capable of measuring pavement surface texture at sample intervals of 0.5 mm. More detailed information of the characteristics of the ULIP, including the accuracy of the measurements and the method for calculating the ridge-to-valley texture depth of a pavement surface profile, is presented later in this report.

Figure 2-9 Ultra-Light Inertial Profiler (ULIP) [6]

ARAN Profile System

The macrotexture measuring system using the ARAN Profile System [7] was developed for the New Jersey DOT to detect asphalt pavement segregation. Computer software similar to that used in ROSAN was developed to convert the pavement texture data collected by the ARAN Profile System into mean texture depth and root mean square values. The MTD calculation is based on the ASTM Specification E-965 (Sand Patch Method). Figure 2-10 shows the typical results of the MTD and RMS of an asphalt pavement [7]. The ridge-to-valley texture depth can also be generated in accordance with ASTM E-1845 [3].

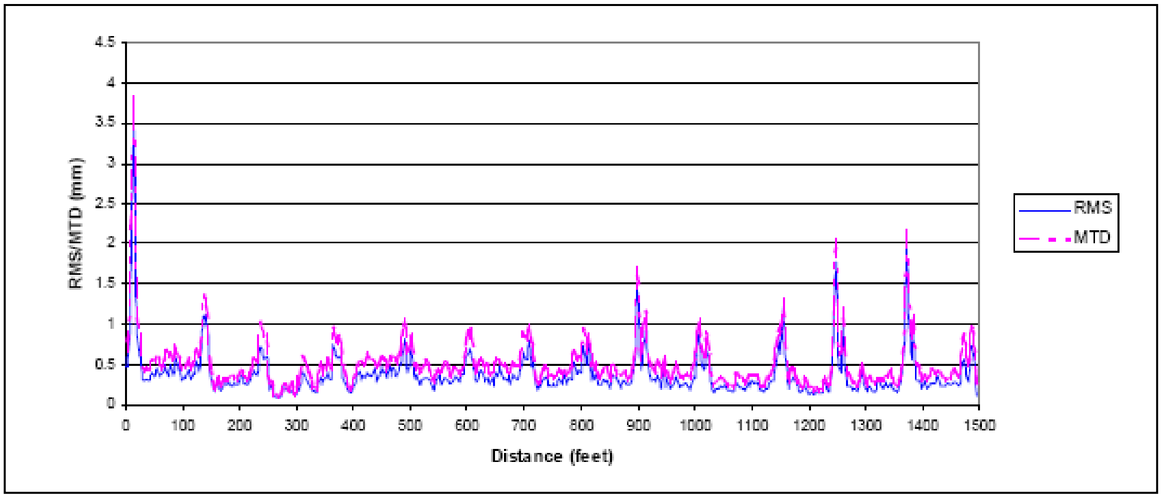


Figure 2-10 MTD and RMS of Asphalt Pavement Surface Texture from the ARAN Profile System

Georgia Tech's LCMS

The three-dimensional (3-D) pavement macrotexture measurement system (Figure 2.11), developed by Georgia Tech [8], consists of a laser crack measurement system and a high-resolution distance measurement instrument (DMI). The LCMS sensors are mounted on the back of the van to acquire 3-D continuous transversal profiles, and the high-resolution DMI is mounted on the rear wheel to control the interval between two consecutive transversal profiles. The LCMS sensors are designed to have a tilt angle to the transversal direction in order to prevent the acquired profiles from aligning with the transverse cracks and pavement joints.

When the sensors are mounted at a 12-degree clockwise tilt angle, approximately 150 profiles can be collected from a 12-ft standard lane width using a 5.0 mm (0.18-in.) interval between two consecutive profiles (Figure 2.12). The interval is controlled by the high-resolution DMI, which can provide an interval of 5.0 mm (0.20 in.) when the van travels at a speed of 100 km/hr. Both the tilt angle and spacing are adjustable. The LCMS provides a 1 mm (0.04-in.) resolution in the transverse direction (x-axis) and at least 0.5

mm (0.02-in.) resolution in the vertical direction (z-axis). The system can acquire more than 23 million 3-D data points per second of the detailed pavement macrotexture data.

Figure 2-11 Georgia Tech's Sensing Van

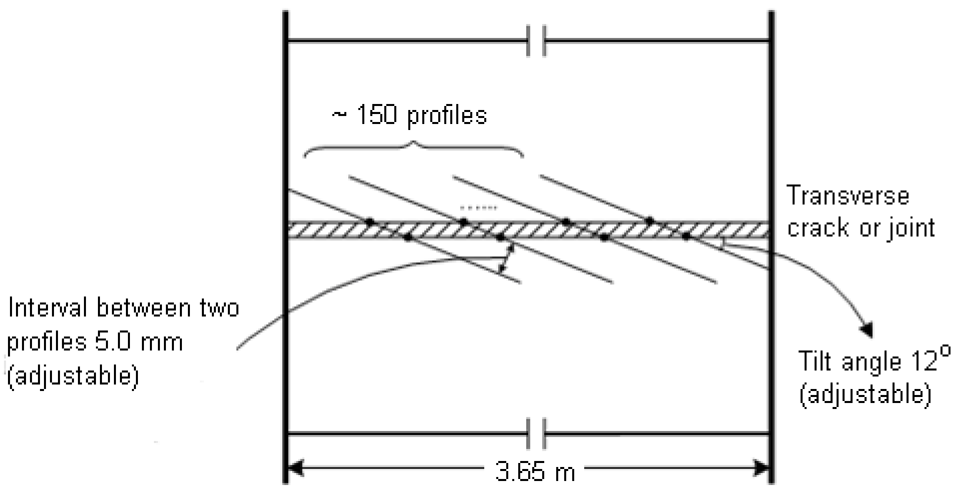


Figure 2-12 Illustration of the Alignment of the 3-D Continuous Laser Profiles

2.2 Correlation of Surface Texture from Different Methods

This section presents pertinent correlations of pavement surface texture data obtained by using various devices and methods discussed in Section 2.1. Researchers used these correlations to assess the viability of using some of these devices to measure micro-milled surface texture depths for this research project.

2.2.1 Correlation between Sand Patch Method and CTM

The mean pavement depth from the Circular Track Meter data, as illustrated in Figure 2-4, is equivalent to the mean texture depth determined from the Sand Patch Method. ASTM E-1845 [3] states, “the MPD can be used to estimate the result of a measurement of macrotexture depth using a volumetric technique according to E965.” The values of the MPD and MTD differ due to the finite size of the glass spheres used in the volumetric technique and because the MPD is derived from a two-dimensional profile rather than a three-dimensional surface. Therefore, a transfer equation must be used to relate these two parameters. The following is the transfer function recommended by ASTM E-2157 [2].

$$\text{MTD (mm)} = 0.947\text{MPD} + 0.069 \qquad \text{(ASTM E-2157)} \qquad \text{(Eq. 2.2)}$$

In 2000, the National Center for Asphalt Technology (NCAT) conducted a study for evaluating surface textures of 45 test sections constructed on the NCAT test track [9]. In this study, both MPD measurements from the CTM and MTD measurements from the sand patch test were obtained in five random locations in each of the 45 test sections. The NCAT test track provides a wide range of surface types, including: coarse and fine dense-graded Superpave mixes, OGFC, Hveem mixes, SMA, and Novachip. As shown in Figure 2-13, the results indicated that the CTM produced results comparable to the sand patch test. When open-graded mixtures were excluded, this study indicated that the offset was non-significant between the CTM and the sand patch test results [9].

NCAT conducted additional testing as part of a round robin in December 2003 at the test track. CTM and sand patch tests were conducted at ten random locations in each of six sections. These sections were selected to produce a range of surface textures. The results shown in Figure 2-14 indicate that the regression relation between the MPD and MTD is similar to that shown in Equation 2.2.

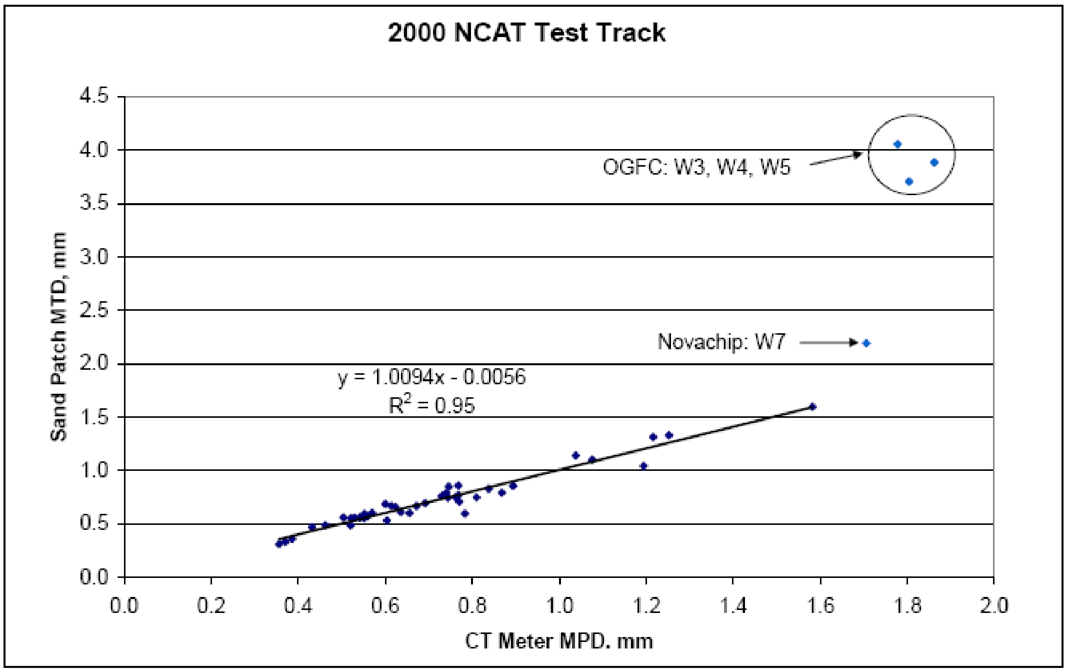


Figure 2-13 Relationship between CT Meter MPD and Sand Patch MTD from 2000 NCAT Test Track (45 test sections, newly constructed)

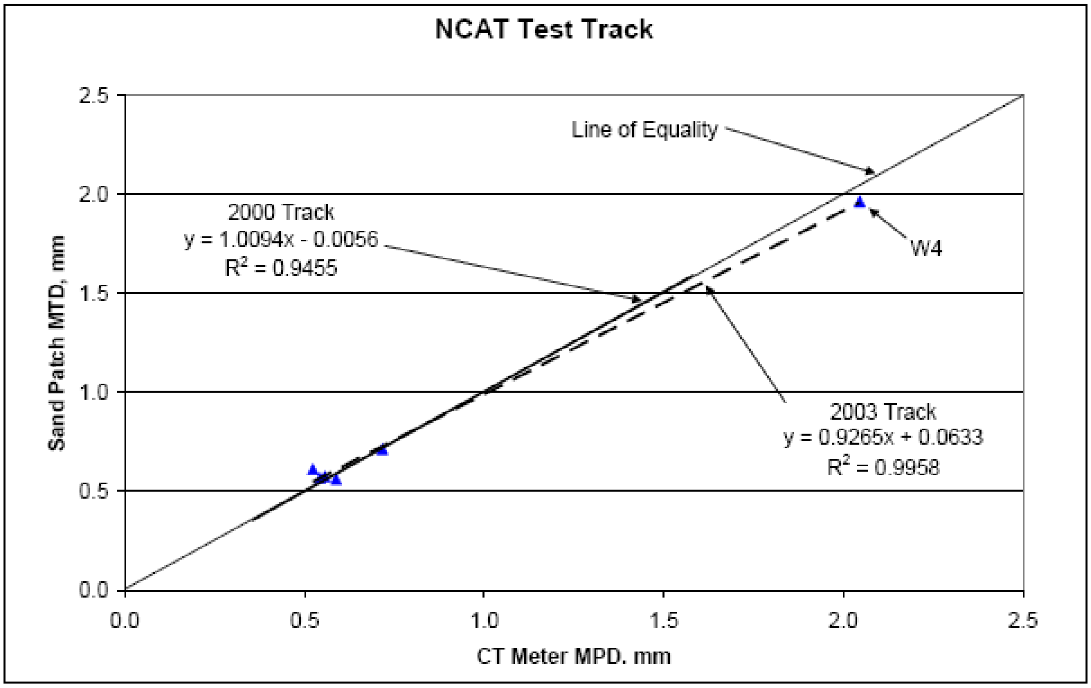


Figure 2-14 Relationship between CT Meter MPD and Sand Patch MTD from NCAT Test Tracks

A similar study conducted by the Virginia Transportation Research Council [10] on seven pavement surfaces from Virginia's Smart Road and 22 runway and taxiway test sections from the National Aeronautics and Space Administration's Wallops Flight Facility showed a similar regression relation between the MTD and MPD as that shown in Equation 2.2.

A slightly different regression equation (Equation 2.3) between the estimated texture depth (ETD) and MPD was given in ASTM E-1845 [3]. The ETD is comparable to the MTD value that results from the Sand Patch Method.

$$\text{ETD (mm)} = 0.2 + 0.8\ \text{MPD} \tag{2.3}$$

2.2.2 Correlation between ULIP and CTM

NCAT conducted a study in 2006 to compare the measurements of the surface texture obtained from the ULIP and those from the CTM and Sand Patch Method on the pavement sections at the NCAT test track [9]. Figure 2-15 shows an excellent correlation between the mean profile depth measured with the CTM and the ULIP devices.

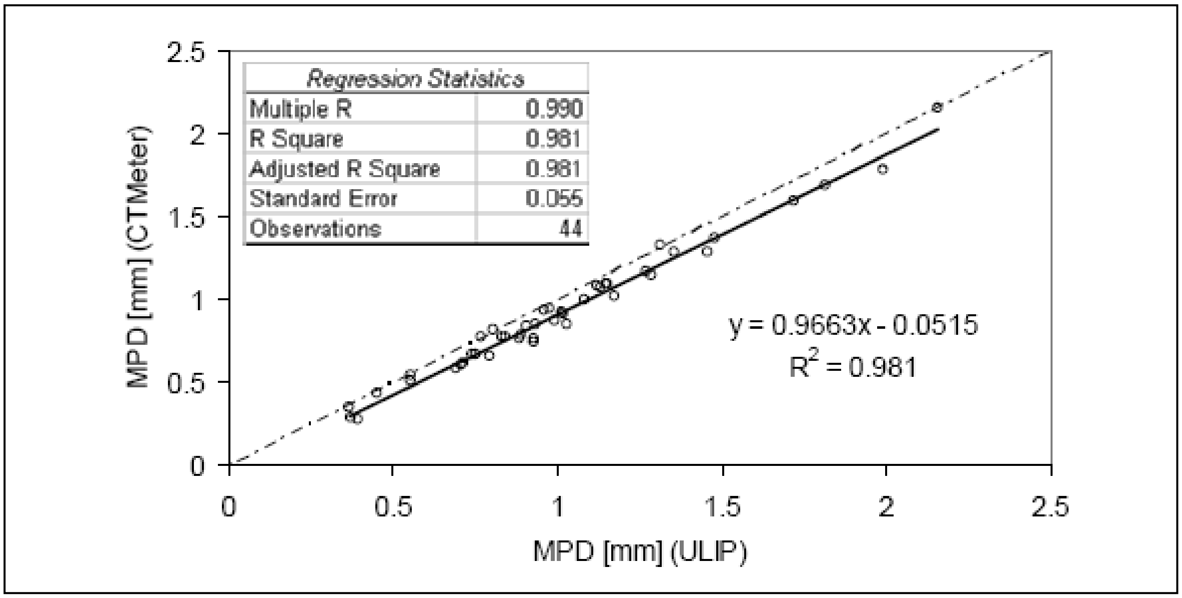


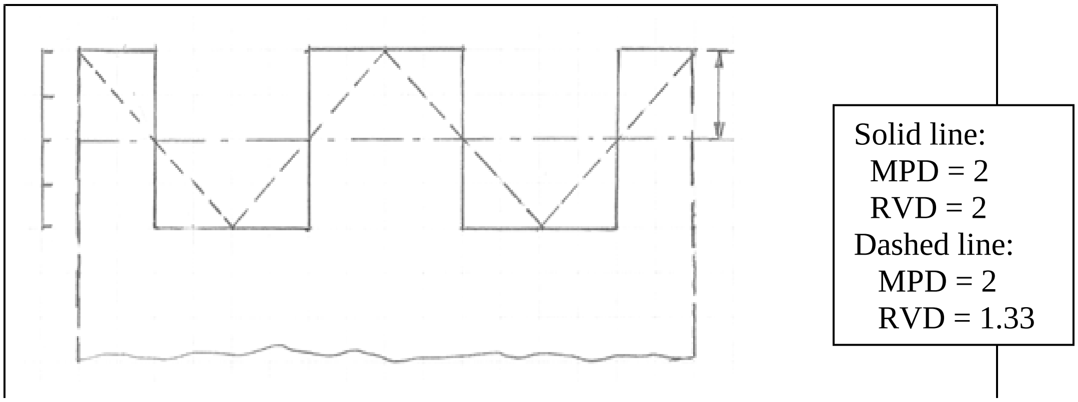
Figure 2-15. Relationship between ULIP and CT Meter Macrotexture Measurements of NCAT Test Track Pavement Sections

2.3 Issues Related to Use of MPD Data for Determining RVD for Pavement Texture

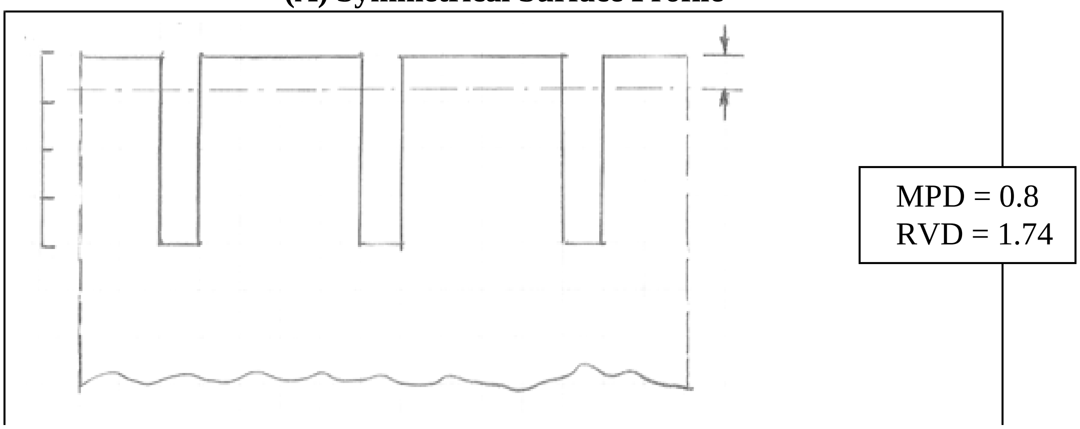
As noted in Section 2.1.1, the Sand Patch Method has a long history of being used to characterize pavement surface texture in terms of the mean texture depth. Recognizing the drawbacks for using the Sand Patch Method, various laser-based pavement surface texture measuring devices, such as those mentioned in Section 2.1.4, have been developed to replace the Sand Patch Method. The data obtained from these laser-based devices have been converted into mean profile depth in order to mimic MTD for pavement surface textures determined by the Sand Patch Method. Among those laser-based devices, the CTM has gained wide acceptance. The MTD or MPD values for pavement surface textures have been used to correlate with pavement surface friction and pavement–tire noise characteristics.

However, the acceptance criteria of GDOT on the micro-milled surface are not based on the MTD or MPD, but rather on the ridge-to-valley texture depth. It stipulates that the difference between the ridge and valley of the milled surface shall not exceed $^{1}/_{16}$ in. (1.6 mm) and corrective actions are required for any area exceeding ⅛ in. (3.2 mm) between the ridge and valley of the milled surface. Consequently, the MTD or MPD cannot directly be used to determine the acceptance of the milled surface quality as far as satisfying the maximum ridge-to-valley requirements is concerned. Therefore, there is a need to obtain RVD values directly from the milled surface or by establishing a correlation between the MPD and RVD values for the same milled pavement surfaces.

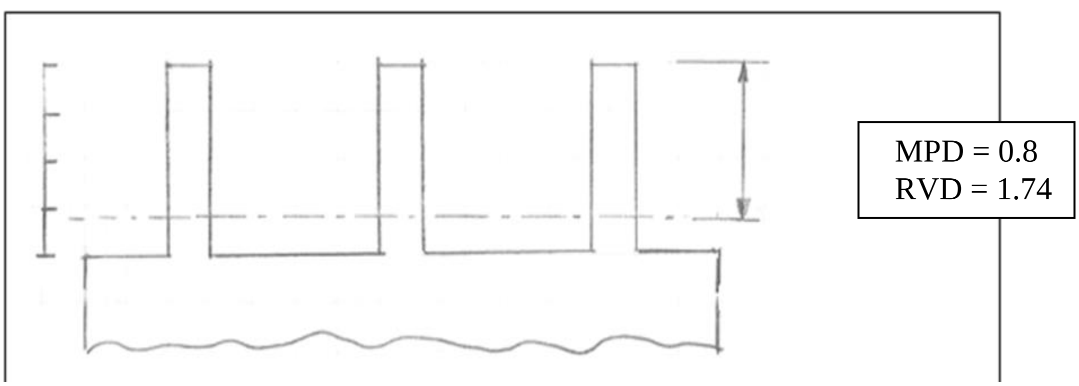
The need for obtaining RVD independently is due to the relationship between the average RVD and the MTD or MPD of a pavement surface, which depends on the characteristics of the surface texture as illustrated in Figures 2-16A, B, and C for different types of idealized texture profiles. For a symmetrical profile, such as that shown in Figure 2-16A, the RVD equals twice the MPD. For a negative unsymmetrical profile, such as the extreme case shown in Figure 2-16B, the RVD is much greater than two times the corresponding MPD. For a positive unsymmetrical profile, like that shown in Figure 2-16C, the RVD is much less than two times the corresponding MPD. The root mean square values for the different texture profiles shown Figure 2-16 do not provide useful information to discern whether a texture profile is symmetrical, or negative or positive unsymmetrical. Only when the surface texture profile is symmetrical, or close to symmetrical, does the RVD value approach two times the MPD value.



(A) Symmetrical Surface Profile



(B) Unsymmetrical Surface Profile (negative profile)



(C) Unsymmetrical Surface Profile (positive profile)

Figure 2-16 Surface Profiles

In the other studies, for which the main objectives for measuring the surface textures were to study skid resistance or pavement noise, or for studying segregation of asphalt pavements, the use of the MPD to quantify the pavement surface texture may be sufficient. However, for the purpose of this study, the ridge-to-valley texture depth value has to be accurately quantified. If the RVD values are to be determined from the corresponding MPD values, then a rigorous calibration program will have to be used to establish the correlation relation between the MPD and RVD values.

2.4 Instruments Used for Measuring Micro-milled Surface Texture Depth

2.4.1 Use of CTM and ULIP for Measuring Micro-milled Surface Texture Depth on the I-75 Project

As pointed out in Section 2.1.2, an advantage of using the CTM is that measurements from the CTM can provide mean profile depths of milled surface textures at different directions: parallel, perpendicular, and diagonal to the milling direction. The disadvantages of using the CTM are (1) that it can only measure pavement surface textures in small circular tracks (about 80 cm lengths) over a small number of locations, and (2) that the outputs of the measurements are in terms of the MPD, which is related to but cannot be directly converted to RVD surface texture depth. On the other hand, all the other laser-based instruments reviewed in Section 2.1.2, including the ULIP, can measure pavement surfaces over a large length and can directly provide the ridge-to-valley texture depth values. The disadvantage of all these instruments, with the exception of the 3-D LCMS system, is that they can only measure the texture depth in the milling direction. By combining the results of the measurements from the CTM and of those linear measurement instruments, it is possible to assess the surface texture depth in terms of RVD values on the micro-milled surface over a large surface area—not just that restricted to the RVD along the milling direction.

NCAT has both the CTM and the ULIP available and has the experience of using these two instruments to measure macro pavement textures from the previous research study [6]. Thus, in this research study the researchers decided to use the CTM and the ULIP to evaluate micro-milled surface texture depths at the I-75 project. Only a limited number of data were to be collected from the project to make such assessments, and the use of the CTM and the ULIP could achieve such objectives. More details for using the CTM and the ULIP for determining the micro-milled surface textures are presented in Part 2 of this report.

2.4.2 Use of Laser Road Profiler for Measuring Micro-milled Surface Texture Depth on the I-95 Project

Using the CTM and/or the ULIP would not be practical for pavement quality control purposes for enforcing the micro-milled surface texture requirements. In the second interim report for this project, after the completion of the I-75 micro-milling project, the researcher team recommended that the LRP routinely used by GDOT for pavement smoothness quality control be retrofitted with software for generating the various ridge-to-valley depth parameters. Use of the LRP with retrofitted software would make it practical for monitoring the micro-milled surface textures as a routine pavement construction quality control. Two LRPs were retrofitted with WinPRO® software by ICC and were used for measuring the RVD values on the I-95 micro-milling project. Details for the quality control of the micro-milled surface textures using the LRP are presented in Part 3 of this report.

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CHAPTER 3 Review of Bond Strength Testing Between Pavement Layers

3.1 Literature Review of Testing Bond Strength Between Pavement Layers

Many distresses of asphalt pavements can be directly attributed to the lack of proper bonding between HMA layers. Two of the most commonly occurring distresses due to poor bonding between the surface layer and its substrata are delamination and slippage cracking of an asphalt pavement surface layer. Slippage failure (Figure 3-1) is the most commonly observed problem related to poor bonding between layers; it often occurs at locations where traffic accelerates, decelerates, or turns.

Figure 3-1 Slippage Failure of Asphalt Surface due to Poor Bond

The literature review revealed that there have been several studies to investigate the bond strength between HMA layers [11, 12, 13]. Most of these studies were to assess bond strength between two layers of dense-graded HMA or a dense-graded HMA overlay on conventional milled surface. In this review, the author found no similar studies on evaluating the bond strength between a PEM overlay on a micro-milled DGAC surface.

Previous bond strength studies have found that the following parameters could affect bonding between asphalt pavement layers:

1. Types and rates of tack coat applied
2. Moisture on the surface of the tack coat
3. Different HMA types (fine-graded vs. coarse-graded HMA)
4. Interface characteristics (milled vs. non-milled surface)
5. Testing conditions, such as temperatures and rate of loading

In all of these studies, it was assumed no dust was present on the surfaces that could impede the development of proper bonding between the layers.

The literature review presented in this section is intended to identify proper testing apparatus and testing parameters that can be used in this research study for conducting bond strength testing to evaluate bond strength between the PEM and the micro-milled SMA surface.

3.2 Bond Strength Testing Apparatus

Two types of apparatus have been used for bond strength testing. The first type is the servo-hydraulic controlled testing machine, such as the Superpave simple shear tester. The second type is the universal testing machine or Marshall stability tester.

3.2.1 Servo-Hydraulic Testing Machine/SST

Mohammad et al. [13] evaluated the influences of tack coat types, application rates, and test temperatures on the interface shear strength using the Superpave Shear Tester (SST). NCAT [12] used a closed-loop servo-hydraulic material testing system (MTS) machine to study the bond strength while evaluating the effects of several material variables and test conditions. The MTS environmental chamber was used to maintain temperature during the test. FDOT [11] also used an MTS for performing the bond strength testing (Figure 3-2), as shown in Figure 3-3. The device is similar to the one several other researchers have used with some modifications, which allows for applying normal pressure (perpendicular to the direction of shear) to the test specimen. Use of this more sophisticated testing machine allows the bond strength testing to be performed under controllable loading rates and controllable testing temperatures.

Figure 3-2 MTS for Bond Strength Testing

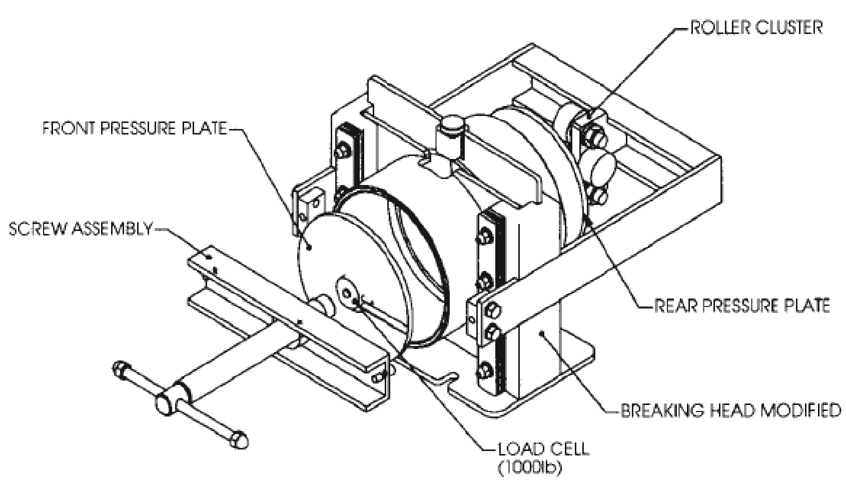

Figure 3-3 NCAT Bond Strength Device

3.2.2 Universal Testing Machine/Marshall Stability Tester

FDOT initially used a universal testing machine (Tinius Olsen), but found the test procedure cumbersome and the test results unsatisfactory. As a result, FDOT researchers switched to the MTS system. Although NCAT and FDOT successfully used the MTS system in the bond strength studies, both recommended using the Marshall Tester for bond strength testing (Figure 3-4) [10, 11]. Molenaar et al. [14] also used this device to evaluate shear resistance between HMA layers with several treatments, including a stress-absorbing interlayer with and without a tack coat. The Marshall Tester is readily available in most highway materials testing laboratories, and the testing procedure is quite simple. This is the principal reason the FDOT and NCAT studies recommend using this equipment for bond strength testing. However, there are some limitations for using the Marshall Tester, such as the fixed strain rate (2.0 in./min). The effects of these limitations on the bond strength are discussed later in this chapter.

Figure 3-4 FDOT Bond Strength Testing Device

3.3 Findings from Previous Bond Strength Testing

3.3.1 Bond Strength Testing Parameters

The objective of the FDOT study [11] was to develop an apparatus and testing procedure that could be used to evaluate bond strength between HMA layers. The following five testing parameters were examined: (1) specimen diameter, (2) mode of loading, (3) rate of loading, (4) testing temperature, and (5) gap width between shearing platens. In the assessment of the testing parameters, FDOT researchers focused on the selection of the final version of the testing parameters so that they could obtain the most meaningful data related to the performance, while maintaining practicality and simplicity in the test procedure. The final testing parameters selected in that study are listed below:

1. Specimen diameter: 6 in.
2. Mode of loading: strain controlled
3. Rate of loading: 2 in./min
4. Testing temperature: 77°F
5. Gap width between shearing platens: $^{3}/_{16}$ in.

3.3.2 Primary Findings from FDOT Study

The FDOT study [11] indicated that water applied to the surface of the tack coat significantly reduced the bond strength of the specimens when compared to equivalent sections without water application. Varying tack coat application rates within the range of 0.02 to 0.08 gal/yd^2 had a lesser effect on the bond strengths. The use of a tack coat to increase bonding strength was more effective for fine-graded mixtures compared to coarse-graded mixtures. Aggregate gradations of the mixtures played a critical role in the magnitude of the bond strengths achieved. Fine-graded mixtures achieved significantly lower bond strengths than the coarse-graded mixtures. A field project containing a milled interface achieved the greatest bond strengths of the projects tested.

Another finding from the FDOT study that provided useful information for this research study was the effect of curing time of the test specimens on the bond strength. For the US 90 project, the bond strengths were increased with curing time between 7, 15, 42, and 105 days (the cores were taken from the pavements at 1, 13, 40, and 99 days respectively) for all six test sections. Alternatively, for the I-95 project, the effect of curing time between 6, 18, and 39 days on the bond strength for all three dry sections with different tack coat application rates (0.02, 0.05, and 0.08 gal/yd^2) was negligible. For the micro-milled and overlay test sections, the effect of curing time between 7 and 13 days (the cores were taken from the pavement at 1 and 8 days, respectively) on the bond strength was also negligible.

3.3.3 Primary Findings from NCAT Study

In the NCAT study [12], the primary objective was to develop a test for measuring the bond strength between pavement layers while also evaluating tack coat materials and application rates for the Alabama Department of Transportation (ALDOT). The project included a laboratory and field phase. For the laboratory work, the experiment included two types of emulsion (CRS-2 and CSS-1) and PG 64-22 paving asphalt that are allowed by ALDOT specifications. Bond strengths were measured at three temperatures and at three normal pressure levels. Three application rates that encompassed the specification range were investigated for each tack coat. The laboratory prepared mixture samples included a coarse-graded blend and a fine-graded blend, representing two different surface textures. The effects of tack coat type, application rate, mixture type, testing temperature, and normal pressure on the bond strength were evaluated. The factors in the laboratory study are summarized in Table 3-1 below.

Table 3-1 Experimental Factors Used in the NCAT Study [12]

Factors	Levels
Mix Type	19.0 mm NMAS coarse graded, 4.75 mm NMAS fine graded
Tack Material	CRS-2, CSS-1, PG 64-22
Application Rate	0.02, 0.05, 0.08 gal/yd^2 (based on residual asphalt)
Normal Pressure	0, 10, 20 psi (0, 69, and 138 kPa)
Temperature	50, 77, 140°F (10, 25, 60°C)

In the laboratory phase, it was found that all of the factors used in the test plan affected bond strength. Testing temperature had the most significant impact on bond strength. As the temperature increased, bond strength decreased significantly. The normal pressure applied to the test samples affected bond strength differently for high, intermediate, and low temperatures. The use of PG 64-22 paving asphalt as tack coat resulted in higher bond strength than the two emulsion types used, especially for the fine-graded mixture tested at high temperature. For the range studied, tack coat with low application rates generally provided high bond strength for the fine-graded mixture. However, for the coarse-graded mixture, bond strength did not change much with varying application rates. The influences of tack coat type and application rate on bond strength were different for the fine-graded and coarse-graded mixtures.

Based on the laboratory work, a draft procedure to determine the bond strength between pavement layers was developed. An easy-to-use procedure that was believed to provide a good indication of the quality of the bond was selected. The procedure utilizes the simple shear device developed by NCAT with the Marshall Tester as the loading device. The draft procedure was based on a test temperature of 77ºF and a loading rate of 2.0 in./min. The reasons for recommending the 77ºF test temperature and use of the simple Marshall Tester with a loading rate of 2.0 in./min were similar to those of the FDOT bond strength study.

3.4 Typical Bond Strength between Pavement Layers

In the NCAT study [12], bond strengths were determined for seven field projects. Table 3-2 summarizes the key results obtained from these field projects. The following are some of the conclusions from this study. The average bond strength for the test sections, based on at least three samples, was 103.7 psi. The standard deviation for bond strengths calculated for each of the sections was 28.7 psi.

From the available data, there were no clear ranges of good and poor bond strengths. As a preliminary range for the bond strength test results, low bond strengths could include results up to around 50 psi. This value was approximately two standard deviations below the average bond strength for the test sections. Only a few test sections had average bond strengths below this value, and these sections had very low tack coat application rates. Most of the field sections had bond strengths above 100 psi, and the range of bond strengths between 50 and 100 psi was considered marginal. These preliminary ranges were based on the results for the various sections and not on performance information. In other words, the link between a minimum bond strength and slippage failure has not been established. One of the more interesting observations was from the projects with the high bond strengths measured on milled surfaces (projects 3, 4, and 7). These indicate that texture of the surface has a significant impact on bond strength. The irregular surface created by milling seems to significantly enhance the bonding.

Table 3-2 Summary of the Results for the Seven Field Projects [14]

Project	Type of Under-lying Surface	Tack Coat Type	Optimum App. Rate Based on Residual Asphalt (gal/yd^2)	Highest Bond Strength (psi)	Results/Observations
1	New HMA	Emulsion	N/A	37.1	No or very poor bond due to very low tack application rates (<0.01 gsy). Dusty surface may have contributed to poor bond.
2	New HMA	Paving Grade Asphalt	0.020 to 0.063	158.2	Very good bond strengths for each section, even area where no tack was applied. Bond strengths were not sensitive to application rate.
3	Milled HMA	Emulsion	0.014	273.5	Good bond strengths for all sections, even area where no tack was applied. Highest bond achieved for section with light tack.
4	Milled HMA	Paving Grade Asphalt	0.028	133.0	Good bond strengths for all sections, even area where no tack was applied. Highest bond achieved for section with light tack.
5	New HMA	Emulsion	0.054	124.5	Weak bond strengths were measured for lowest section at 0.029 gsy. Good bond strengths for application rates of 0.54 to 0.58 gsy.
6	Concrete	Polymer-modified Emulsion		86.7	The highest bond strengths were for section placed with Novachip spreader.
7	Milled HMA	Emulsion	0.017 to 0.060	148.7	Good bond strengths were measured for all sections, even area where no tack was applied. Highest bond achieved for section with heavy tack.

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PART 2: I-75 MICRO-MILLING PROJECT NEAR PERRY, GEORGIA

CHAPTER 4 Measurement of Rough-Milled Surface Texture Depth

Table 4-1 summarizes the initial testing performed on the I-75 micro-milling project near Perry, Georgia. These tests were conducted prior to the formal testing of micro-milled surface texture using the Ultra-light Inertial Profiler and the Circular Track Meter and evaluation of the software used to determine MPD and RVD from these measurements. Test Section 0 was a conventional (rough) milled surface. The work performed and the results obtained from this test section are presented in this chapter.

Table 4-1 Summary of Tests Performed

Test Section ID	**Location**	**Test Performed**	**Remarks**
Section 0	I-75 MP-78-S	Measure surface texture	Conventional milling
Section 1-1	MP 142.0 S L1	Measure surface texture	
Section 1-2	MP 142.0 S L1	Measure surface texture	
Section 2-1	MP 142.0 S L1	Measure surface texture	
Section 2-2	MP 142.0 S L1	Measure surface texture	
Section 3	MP 142.0 S L1	Measure surface texture	
Section 4-1	MP 133.0 S L1	Measure surface texture, Test tack rate, bond strength	Tack coat rate 0.06 gal/yd.
Section 4-2	MP 133.0 S L1		
Section 5-1	MP 130.0 N L1	Measure surface texture	
Section 5-2	MP 130.0 N L1	Measure surface texture	
Section 6	MP 135.0 S L2	Measure surface texture	
Section 7	MP 128.9 N L3	Measure surface texture	
Section 8	MP 129.4 N L3	Measure surface texture	
Section 9	MP 132.5 S L3	Test bond strength	Tack coat rate 0.08 gal/yd.

Test Section 1-1 to Test Section 8 were micro-milled surfaces at I-75 near Perry, Georgia. Researchers conducted surface texture measurements to assess the micro-milled surface textures using the CTM and the ULIP. The work performed and the results obtained from these test sections are presented in Chapters 5 and 6. Chapter 7 summarizes and evaluates the results of the micro-milled textures obtained in Chapters 5 and 6. Researchers assessed the bond strength between the micro-milled surface and the PEM overlay on Test Section 4 (4-1, 4-2) and Test Section 9; those results are presented in Chapter 8.

4.1 Measurement of Surface Texture by Ultra-Light Inertial Profiler

Before the formal testing of micro-milled surface textures at I-75 near Perry, Georgia, began, a trial test for measuring surface texture depths of rough (conventional) milled asphalt pavement surfaces using the CTM and the ULIP was performed. A 150-ft pavement section was selected at Milepost (MP) 78 of I-75 in a southbound lane (see Figure 4.1). The test was conducted on May 1, 2007.

Figure 4-1 Conventional Milled Surface on I-75 at Milepost 78

The ULIP was first used for measuring the milled surface texture, as shown in Figure 4-2. Three runs were performed over nearly the same wheel path (within about ±5 in.). The ULIP measured the surface profile depth at every 0.5 mm interval. The typically measured profile is shown in Figure 4-3. Figure 4-4A and Figure 4-4B show the surface profiles at 100 mm and 500 mm base lengths. Base length is the length of the profile segments used in the analysis of pavement texture. Selection of base length plays an important role in computing mean profile depths and ridge-to-valley texture depths. According to ASTM E-1845 [3], 100 mm was specified as the base length for calculating the mean profile depth (see Figure 2-4).

Figure 4-2 Measuring Milled Surface Texture by ULIP

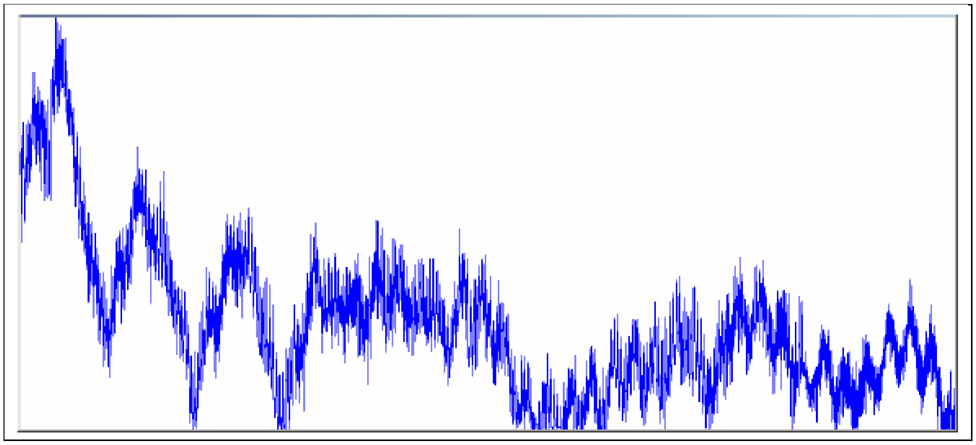
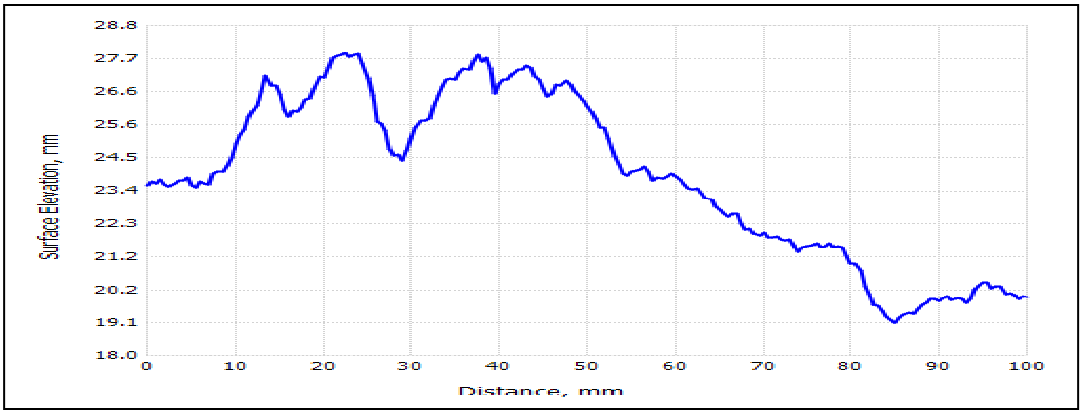
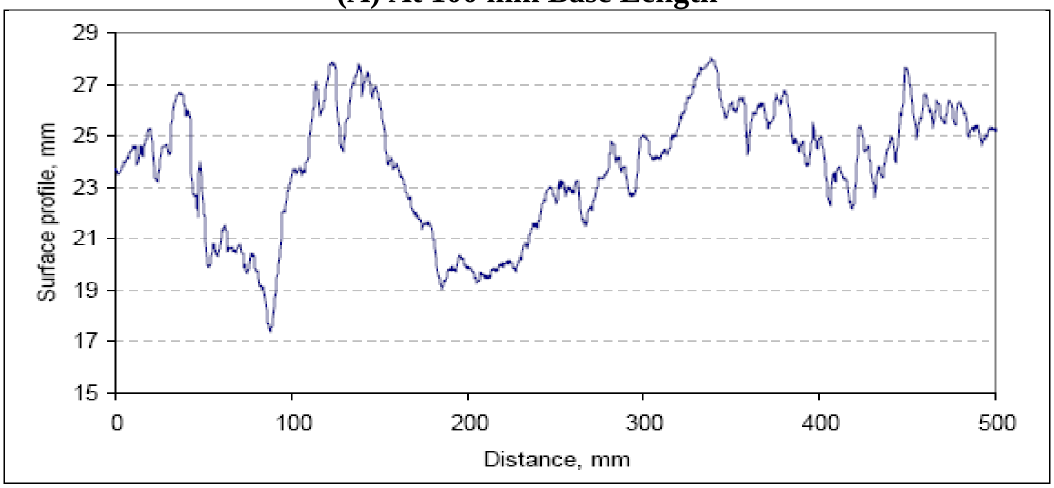


Figure 4-3 Milled Surface Texture Profile Measured by ULIP



(A) At 100 mm Base Length



(B) At 500 mm Base Length

Figure 4-4 Conventional Milled Surface Profiles

The GDOT Special Provision Section 432, "Mill Asphaltic Concrete Pavement (Micro Mill)," stipulates "Any areas exceeding ⅛ in. (3.2 mm) between the ridge and valley of the mat surface…shall require that the underlying layer be removed and replaced." Therefore, a clear definition for calculating the "depth between the ridge and valley" of a milled surface is needed. Unfortunately, no such definition is available. In developing the software, the height between the maximum ridge and minimum valley within the base length was defined for calculating "the depth between ridge and valley" on the milled surface. This measurement is referred to as the ridge-to-valley depth.

Different base length unit, such as 100 mm, 200 mm, 500 mm, or others, could be selected for calculating the RVD. The RVD values obtained using different base length units in the total measuring paths (3 × 150 ft.) were used to calculate the corresponding Mean RVD and the 50 to 99 percentile (p50 to p99) RVD values for the milled surface, and the results are shown in Table 4-2.

Use of longer base length consistently results in higher RVD values in the Mean RVD, and p50 to p99 RVD values of the surface texture profile, as clearly shown in Table 4-2 and Table 4-3. These consistent trends could be explained from the surface profile shown in Figure 4-4A and Figure 4-4B. To be consistent with ASTM E-1845, RVD results based on 100 mm base length units were used in the analyses and comparison of the results obtained from the CTM measurements and with the other data.

Table 4-2 Ridge-to-Valley Texture Depth of Conventional Milled Surface (Section S-0)

Run Path	Base Length, mm	No. of Units	Ridge-to-Valley, mm						
			Mean	St dev	p50	p75	p90	p95	p99
1	50	1760	2.24	1.17	2.13	2.95	3.71	4.27	5.71
1	100	862	3.32	1.43	3.22	4.2	5.18	5.91	6.95
1	200	419	4.75	1.51	4.71	5.67	6.79	7.23	7.96
1	500	153	6.72	1.78	6.79	7.73	8.6	9.39	10.4
2	50	1624	2.22	1.18	2.07	2.96	3.79	4.34	5.65
2	100	800	3.31	1.45	3.2	4.16	5.17	5.75	7.58
2	200	390	4.85	1.47	4.71	5.72	6.85	7.08	9.13
2	500	147	7.25	1.45	7.41	8.21	8.83	9.32	10.1
3	50	1832	2.36	1.12	2.24	3.05	3.86	4.39	5.54
3	100	908	3.43	1.33	3.33	4.3	5.16	5.75	6.87
3	200	440	5	1.38	4.94	5.8	6.9	7.55	8.17
3	500	160	7.19	1.45	7.03	7.98	9.14	9.8	11.81
Average=	50		2.27	1.16	2.15	2.99	3.79	4.33	5.63
	100		3.35	1.40	3.25	4.22	5.17	5.80	7.13
	200		4.87	1.45	4.79	5.73	6.85	7.29	8.42
	500		7.05	1.56	7.08	7.97	8.86	9.50	10.77

Table 4-3 Ratio of RVD to RVD at 100 mm Base Length

Base Length (mm)	Average 150-ft Section of Ridge-to Valley (RVD, mm)					
	Mean	p50	p75	p90	p95	p99
50	0.68	0.66	0.71	0.73	0.75	0.79
100	1.00	1.00	1.00	1.00	1.00	1.00
200	1.45	1.47	1.36	1.32	1.26	1.18
500	2.10	2.18	1.89	1.71	1.64	1.51

The MPD from the ULIP measurements were also calculated. Table 4-4 shows the comparison of the RVD and the MPD calculated from the ULIP measuring results based on the 100 mm base length. Ratios of RVD to MPD, as shown in Table 4-4, were between 2.36 and 2.65, all greater than 2, indicating that the milled surface profiles are positively unsymmetrical.

Table 4-4 Comparison of RVD and MPD from ULIP Data

	150-ft Measuring Section with 100 mm Base Length					
	Mean	p50	p75	p90	p95	p99
RVD, mm	3.35	3.25	4.22	5.17	5.80	7.13
MPD, mm	1.30	1.23	1.64	2.08	2.39	3.02
RVD/MPD	2.58	2.65	2.57	2.49	2.43	2.36

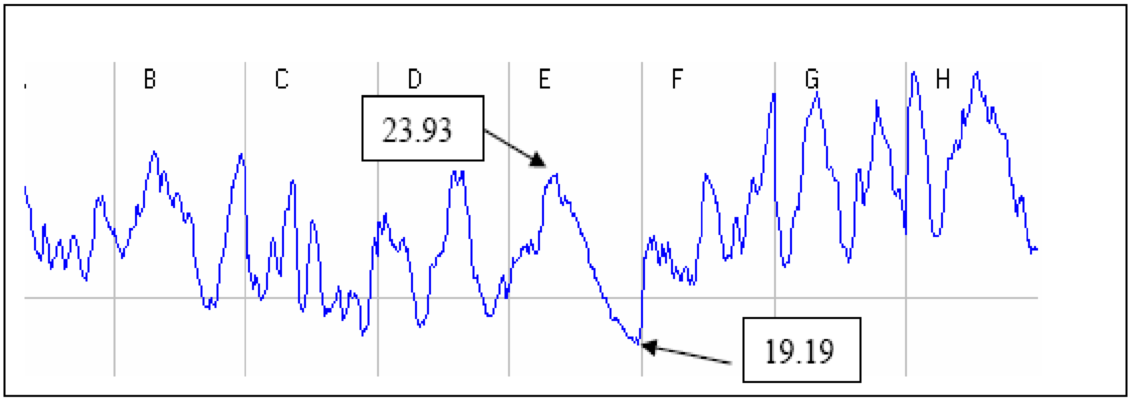
4.2 Measurement of Surface Texture by Circular Track Meter

The CTM described in Section 2.1.2 was also used to measure the milled surface texture profile. Measurements were performed at three random positions on each 150-ft measuring path, whereas the surface texture was measured on one path by the ULIP as described in Section 4.1 above. Three measurements were performed at each of the three random locations. Table 4-5 presents the summarized MPD values of the CTM test results. As indicated by the table, the surface texture measurements at the three random locations varied from location to location and from segment to segment of the eight CTM measurement segments (A–H). This could be expected given the irregular directional texture pattern of the milled surface shown in Figure 4-1 and Figure 4-2. If one considers that circular Segments A and E are parallel to the direction of milling and Segments C and G perpendicular, then the mean profile depth in the direction of milling is 1.99 mm and that perpendicular to the direction of milling is 2.87 mm. The researchers note that 1.99 mm MPD in the milling direction is greater than the 1.30 mm Mean MPD value determined from the ULIP data, as shown in Table 4-4.

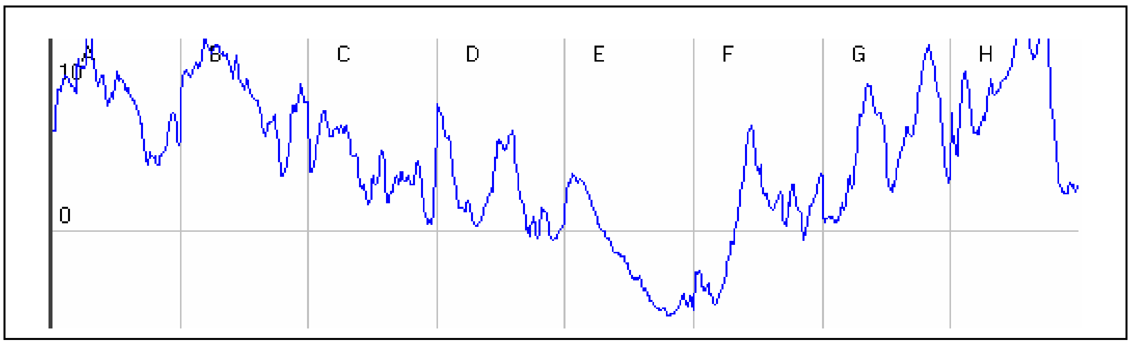
Table 4-5 MPD (mm) from CTM Measurements

	A	B	C	D	E	F	G	H
1	2.24 2.25 2.26	3.07 3.12 3.17	3.16 3.19 3.25	2.61 2.64 2.63	2.30 2.44 2.48	2.83 2.92 2.86	3.63 3.46 3.54	3.17 2.93 2.95
2	2.43 2.46 2.45	1.98 1.96 1.96	2.29 2.29 2.26	3.21 3.16 3.20	1.48 1.5 1.51	4.08 4.01 4.02	3.71 3.63 3.63	3.73 3.66 3.62
3	2.03 2.04 1.97	2.78 2.78 2.77	2.58 2.58 2.55	1.94 1.96 1.93	1.33 1.29 1.30	1.85 1.84 1.84	1.98 1.98 2.01	1.64 1.64 1.64
AVG STDEV	2.24 0.19	2.62 0.51	2.68 0.41	2.59 0.54	1.74 0.51	2.92 0.95	3.06 0.81	2.78 0.90

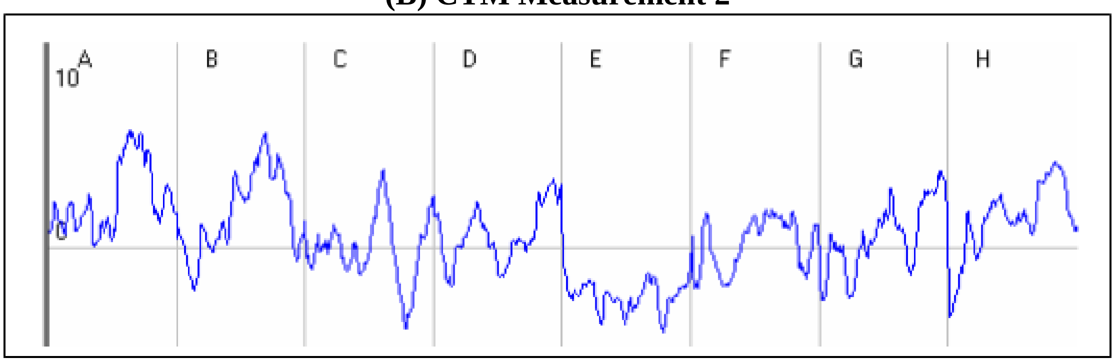
The surface profiles measured using the CTM at the three random locations are shown in Figures 4-5A through 4-5C. The CTM outputs shown in these three graphics did not provide the horizontal scale displayed, but this could be inferred from the raw data files that were generated during the measurements. The Ridge and Valley readings for Segment E were 23.93 and 19.19 mm as indicated in Figure 4-5A. Thus, the maximum total ridge-to-valley depth is approximately 4.7 mm (23.93 − 19.19) in the direction of milling, which is comparable to the values determined by ULIP with 100 mm base length as shown in Table 4-2.



(A) CTM Measurement 1



(B) CTM Measurement 2



(C) CTM Measurement 3

Figure 4-5 Surface Texture Profiles

4.3 Estimation of Maximum Ridge-to-Valley Texture Depth

From the CTM results presented in Table 4-5, the maximum MPD occurred in the direction of Segments C and G, with an average value of 2.87 mm. This would imply that the maximum RVD of the milled surface would most likely occur in the direction perpendicular to the milling direction. Since the RVD values for the milled surface determined by ULIP were only available in the milling direction, the following approaches were used to estimate the maximum Mean and p95 RVD values for the milled surface. The estimation was based on the assumption that the RVD in the directions transverse and diagonal to the milling directions, if measured by ULIP, were proportional to the MPD values determined by the CTM. Thus, the Mean RVD and p95 RVD values along the transverse and diagonal to the milling directions could be calculated accordingly and are presented in Table 4-6 below. From this table, it can be seen that the estimated maximum Mean RVD of 4.82 mm and estimated maximum p95 RVD of 8.35 mm occurred along the direction transverse to the milling direction.

Table 4-6 Estimation of Maximum RVD Values (using 100 mm Base Length)

	Milling Dir. A, E	**Trans. Dir. C, G**	**Diag. Dir. B, D, F, H**	**CG/AE**	**Diag./AE**
MPD (mm) from CTM					
Average	1.99	2.87	2.73	2.87 / 1.99 = 1.44	2.73 / 1.99 =1.37
RVD (mm) from ULIP					
Mean RVD	3.35	3.35 × 1.44 = 4.82	3.35 × 1.37 = 4.59		
P95 RVD	5.80	5.80 × 1.44 = 8.35	5.80 × 1.37 = 7.95		

4.4 Discussion

The main purpose for performing the testing presented in this chapter was, first, to verify that the CTM and the ULIP could produce comparable results. This was confirmed as indicated in the results presented in Sections 4.1 and 4.2. The maximum ridge-to-valley depth measured by the CTM was approximately 4.7 mm (23.93 − 19.19) in the direction of milling, which is comparable to the values determined by ULIP with 100 mm base length. Second, the testing was performed to ensure that the software written for analyzing the ULIP surface profiles could report the summary statistics for both mean profile depth and ridge-to-valley estimates. This objective was achieved as indicated from the statistical results generated and presented in Table 4-3 and Table 4-4. Third, the testing was done to identify potential operational problems that could be encountered. The operations of both the CTM and the ULIP were quite smooth, and no problems were encountered. The trial tests described in this chapter were completed in about 90 minutes.

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CHAPTER 5 Initial Micro-milling of Test Sections on I-75 Project

Since the milling and paving rehabilitation project on I-75 near Perry was the first time the micro-milling technique was used on an asphalt pavement surface in Georgia, the comprehensive monitoring program presented in Section 5.1 of this chapter was devised to monitor the micro-milled surface texture to ensure compliance with the stringent requirements described in Chapter 2. Sections 5.2, 5.3, and 5.4 present the monitoring of the micro-milled surface textures and the results for the first, second, and third trial test sections on this construction project, which were conducted on May 13, May 14, and May 21, 2007. Discussions of the results are presented in Section 5.5.

5.1 Plans for Evaluating Micro-milled Surface Texture Depths

The following two sets of micro-milling surface texture data were collected on the micro-milled surfaces for evaluation and validation of the micro-milled surface texture depths:

1. Mean profile depth and the ridge-to-valley depths data using the Ultra-Light Inertial Profiler on one or two 150-ft segments in each test section
2. Mean profile depth data from the CTM at several locations along the 150-ft ULIP measuring paths in each test section

The following analyses were performed to assess the milled surface texture depths from the data collected by the CTM and the ULIP in the field:

1. Determine the Mean RVD and p95 RVD values from the ULIP measurement data on the milled surfaces in the milling direction

2. Determine the MPD values from the CTM data in all directions (0°, ±45°, and 90° from the milling directions) and use those to estimate the maximum estimated Mean RVD and maximum estimated p95 RVD of the milled surfaces

In this study, the maximum estimated Mean RVD and maximum estimated p95 RVD obtained from the ULIP measurements were used to *tentatively* represent the two micro-milled surface texture acceptance criteria, namely, "Capable of removing pavement to accuracy of $^{1}/_{16}$ in. (1.6 mm)," and, "Any areas exceeding ⅛ in. (3.2 mm) between the ridge and valley of the mat surface…require that the underlying layer be removed..." More discussions on using these parameters to represent the acceptance criteria are presented in Chapter 7 and Chapter 9 of this report.

5.2 First Trial Test Section

5.2.1 Test Section Site and Milling Operations

The initial 1000-ft test section for this project was located on I-75 at MP 142 in southbound lane 1 (SB1). Figure 5-1 shows the three-track Roadtec milling machine used for the milling. Figure 5-2 shows the differences between the micro-milling drum and the conventional milling drum. The micro-milling drum has a width of 12 ft. 6 in. and has about 560 teeth, which is approximately three times more teeth than the conventional milling drum.

Figure 5-1 Roadtec Milling Machine

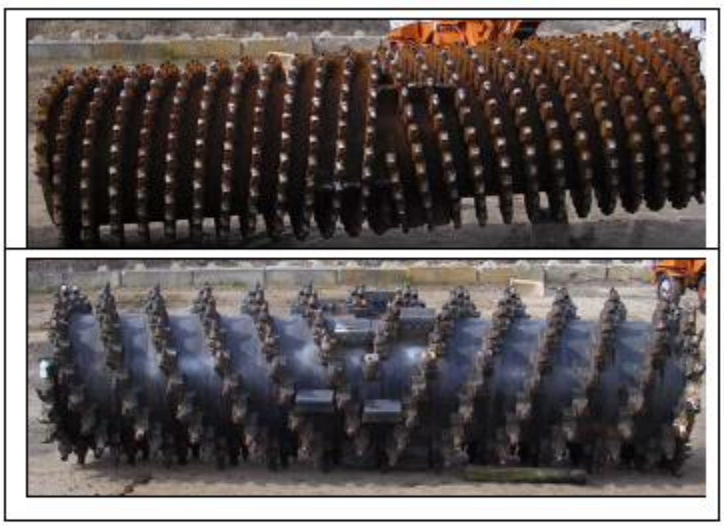

Figure 5-2 Micro-milling Drum (top) and Conventional Milling Drum (bottom)

5.2.2 First Trial Test Section Milling Operation

The micro-milling operation of the test section started at about 8:30 p.m. on May 13, 2007. The milling speed was about 18–20 ft./min. The micro-milled surface textures (Figure 5-3 and Figure 5-4) showed rather irregular patterns.

Figure 5-3 Micro-milled Surface Texture

Figure 5-4 Irregular Milled Surface Texture

According to the cores cut from the pavement prior to the milling, the typical thickness of the open-graded friction course on top of the dense-graded HMA was between ⅝ in. and ¾ in. The asphalt mixture under the OGFC was initially identified as an SMA, which was incorrect. The milling depth of 1.0 in. was specified for this project. It appeared that the milling machine was operated too fast and the milling was not quite deep enough. This contributed to the large scabs of OGFC left on the milled surface, as shown in Figure 5-4. Several factors could have contributed to the coarser milled surface texture, resulting in deeper than the allowed ridge-to-valley depth shown in Figure 5-3, and could also contribute to the irregular milled textures shown in Figure 5-4.

5.2.3 ULIP and CTM Data Collection Schemes and Results

Figure 5-5 shows the CTM and the ULIP measurement scheme. Two data collection sections were selected within the 1000-ft test section. The first data collection section (Section 1-1) was between 0+100 ft. and 0+250 ft., and the second collection section (Section 1-2) was between 0+600 ft. and 0+750 ft. The typical length used for the ULIP for collecting pavement surface texture data was 150 ft.

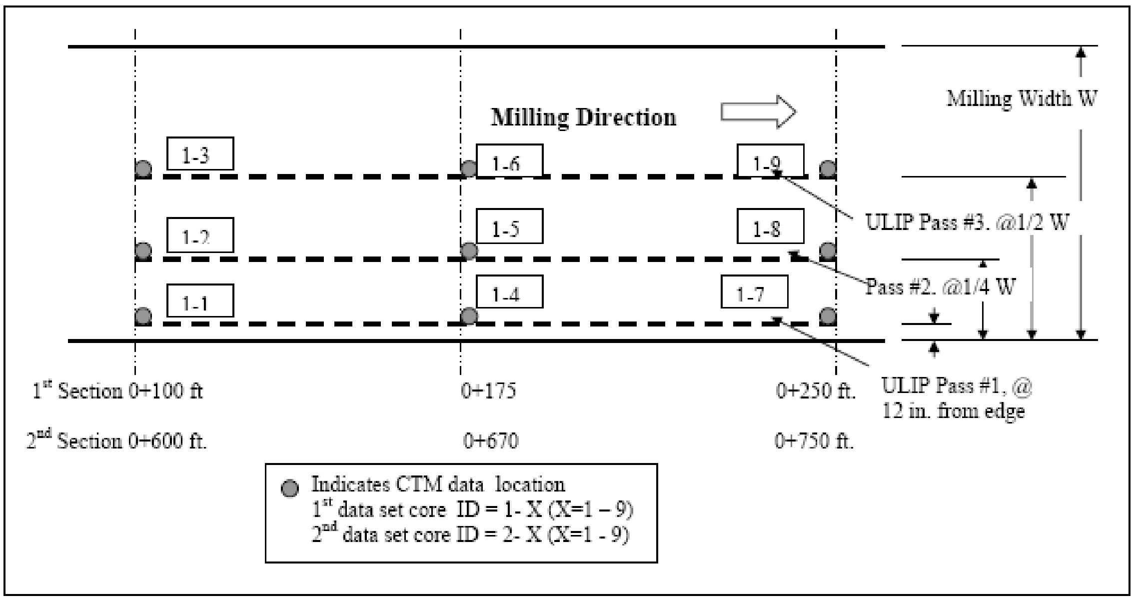

Figure 5-5 ULIP and CTM Data Collection Scheme

5.2.4 Collection of ULIP and CTM Field Data

The milled surface textures were measured by the ULIP first. The ULIP data were collected along Path 1, 2, and 3 as indicated in Figure 5-5. Three runs were performed on Path 1 and Path 2, and two runs were made on Path 3. The same 0.5 mm interval, similar to that used for measuring the rough-milled surface textures described in Chapter 4, was used by the ULIP for measuring the micro-milled surface textures. The typical surface texture profiles for Test Section 1-1 are shown in Figure 5-6.

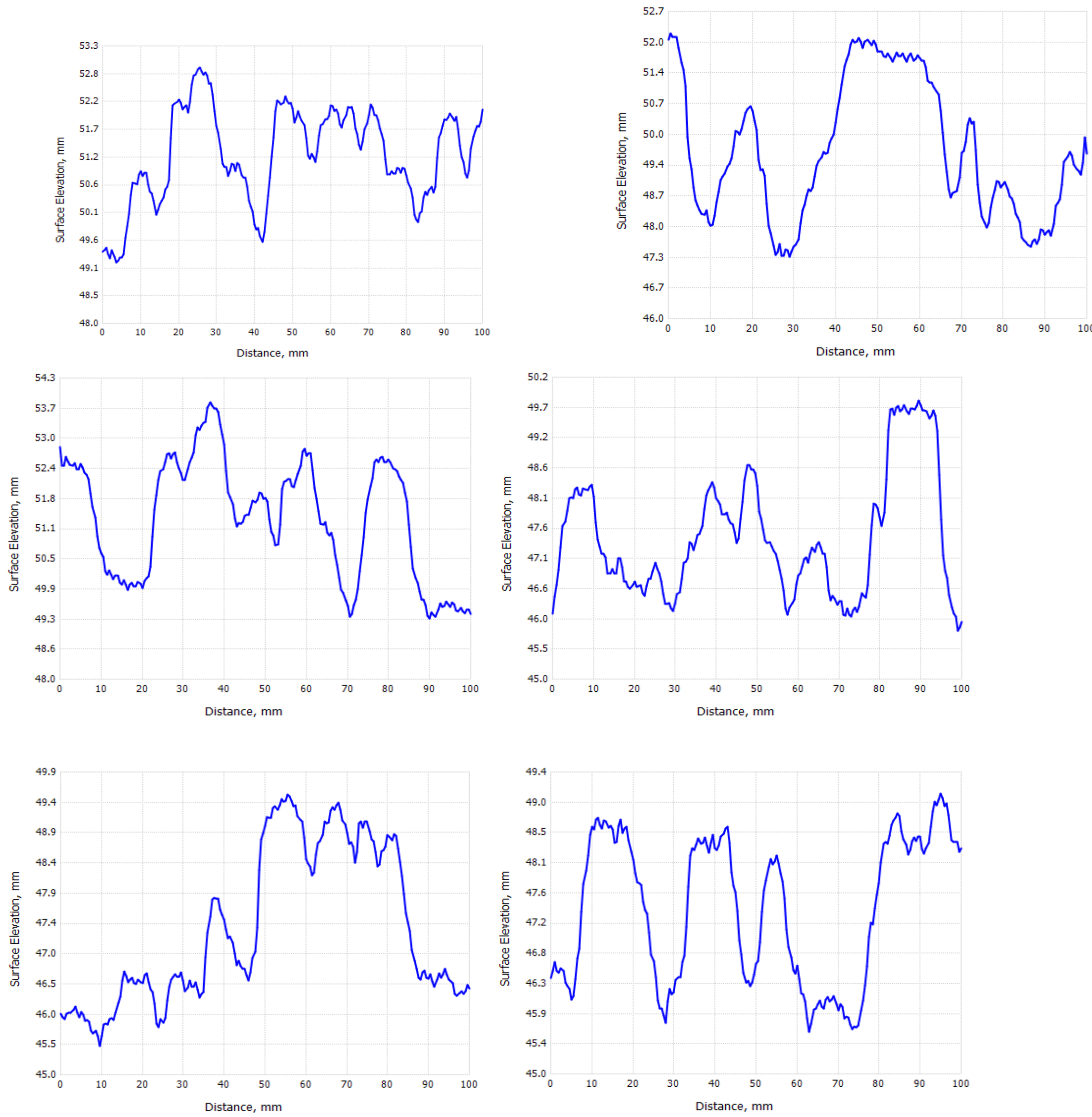

Figure 5-6 Typical Surface Texture Profiles for Test Section 1-1

As mentioned in Section 4.1, selection of the base length plays an important role in computing the MPD and RVD. Also mentioned in Chapter 4, the software developed in this research project used the maximum ridge and minimum valley within the base length unit to determine the RVD value. The MPD value within the base length was determined according to ASTM E-1845. The RVD values obtained in each of the base length units in the total measuring paths (8 × 150 ft.) were used to calculate the Mean, p50 (50 percentile) to p99 RVD values and the Mean and p50 to p99 MPD values. For example, the actual number of individual RVD values used for computing the RVD values shown in Table 5-1 for Sections 1-1 and 1-2 using 100 mm base length unit was approximately 3600. Results of the Mean RVD and p50 to p99 RVD values using different base length units for Sections 1-1 and 1-2 are summarized in Table 5-1.

The results presented in Table 5-1 indicate that for Test Section 1-1 the Mean RVD and p95 RVD values exceeded the target index of 1.6 mm ($^1/_{16}$ in.) averaged RVD and the correction index of 3.2 mm (⅛ in.) maximum RVD allowed by the specifications. The use of Mean RVD and p95 RVD parameters, respectively, for determining the compliance of the targeted 1.6 mm milling accuracy and for determining the requirement for corrective actions when the RVD exceeded correction 3.2 mm is discussed in Chapter 7.

Table 5-1 Summary of RVD Values for Sections 1-1 and 1-2

Section	Base Length (mm)	Average 150-ft Section of RVD, mm					
		Mean	p50	p75	p90	p95	p99
S 1-1	50	1.51	1.30	1.99	2.74	3.20	4.14
	100	**2.24**	**2.02**	**2.98**	**3.90**	**4.46**	**5.56**
	200	3.02	2.88	4.03	5.14	5.65	6.83
	500	3.93	3.91	5.34	6.24	6.73	7.66
S 1-2	50	1.01	0.89	1.26	1.71	2.02	2.75
	100	**1.43**	**1.29**	**1.77**	**2.31**	**2.73**	**3.50**
	200	1.81	1.67	2.20	2.83	3.28	4.12
	500	2.29	2.15	2.75	3.45	3.95	4.51

The MPD from the ULIP measurements were also calculated. Table 5-2 shows the comparison of the RVD and the MPD calculated from the ULIP measuring data based on

100 mm base length. The ratios of RVD to MPD, as shown in Table 5-2, were between 2.21 and 2.55, all greater than 2. This indicated that the milled surface profiles were positively unsymmetrical.

Table 5-2 Comparison of RVD and MPD from ULIP Data (S1-1 & S1-2)

Section		150-ft Section with 100 mm Base Length					
		Mean	**p50**	**p75**	**p90**	**p95**	**p99**
S 1-1	RVD, mm	2.24	2.02	2.98	3.90	4.46	5.56
	MPD, mm	0.91	0.79	1.21	1.66	1.96	2.52
	RVD/MPD	2.46	2.55	2.47	2.35	2.27	2.21
S1-2	RVD, mm	1.43	1.29	1.77	2.31	2.73	3.50
	MPD, mm	0.59	0.52	0.73	0.98	1.16	1.53
	RVD/MPD	2.42	2.45	2.42	2.36	2.35	2.28

After the ULIP measurements were completed, measurement of surface textures by the CTM was performed on the 150-ft ULIP measuring Paths 1, 2, and 3, following the data collection scheme shown in Figure 5-5. Triplicate tests were performed at each of the nine locations. The results are summarized in Table 5-3 below. After the CTM testing was performed on Test Section 1-1, the LRP testing of the milled surface smoothness was performed by the GDOT Quality Control team; the results indicated that the Smoothness Index (SI) for the entire Test Section 1 (including S1-1 and S1-2) exceeded the maximum allowable value of 900 mm/km. Therefore, the collection of the CTM data for the second data collection Section S1-2 was suspended.

Table 5-3 Summary of CTM Measurement Data for Test Section 1-1

		Path 1 (12 in.)	Path 2 (36 in.)	Path 3 (72 in.)	Average
Data Collection Section 1-1					
	AE (↑)	0.50	1.09	1.90	1.16
	CG (↔)	0.63	1.89	2.18	1.56
	Diagonal	0.71	1.61	2.23	1.51
	CG/AE	1.25	1.73	1.15	1.35
Data Collection Section 1-2	Not tested				

5.2.5 Estimation of RVD from CTM Data

Similar to that presented in Section 4.3, estimations of the maximum Mean RVD and p95 RVD values for the micro-milled surface were determined using the ULIP data and the CTM data from Test Section S1-1 and are presented in Table 5-1 and Table 5-3 above. Table 5-4 summarizes the results of the maximum estimated RVD values obtained. The results indicate that the highest RVD of the micro-milled surface occurred along the direction transverse to the milling direction with Mean RVD and p95 RVD of 3.02 mm and 6.01 mm, respectively.

Table 5-4 Estimation Maximum RVD Values for First Trial Test Section

	Milling Dir. A, E	Trans. Dir. C, G	Diag. Dir. B, D, F, H	CG / AE	Diag. / AE
MPD (mm) from CTM					
Average	1.16	1.56	1.51	1.56 / 1.16 = 1.35	1.51 / 1.16 = 1.30
RVD (mm) from ULIP, @100 mm base length					
Mean RVD	2.24	2.24 × 1.35 = 3.02	2.24 × 1.30 = 2.91		
p95 RVD	4.46	4.46 × 1.35 = 6.01	4.46 × 1.30 = 5.80		

5.2.6 Summary of First Trial Test Section

Results of the micro-milled surface texture depths obtained in Test Section 1 indicated that the highest RVD of the micro-milled surface occurred transverse to the milling direction with Mean RVD and p95 RVD of 3.02 mm and 6.01 mm, respectively. Both exceeded the targeted 1.6 mm and correction 3.2 mm allowed as stipulated in the specifications. It was obvious the milling depth was not quite enough to remove the entire thickness of the OGFC layer, which resulted in patches of the OGFC material remaining on the milled surface. In addition, the LRP test results indicated that the Smoothness Index exceeded the maximum 900 mm/km allowed by the specification.

5.3 Second Trial Test Section

5.3.1 Second Trial Test Section Site and Milling Operation

Location of the second test section was on the same southbound lane (SB1) immediately following the first trial test section. The micro-milling operation started at about 8 p.m. on May 14, 2007, using the same milling machine. The milling speed was reduced to 13–15 ft./min and the milling depth was increased. These changes resulted in improved quality of the micro-milled surface textures, as shown in Figure 5-7, over that of the first trial test section. Patches of scabs still appeared on the milled surface, as shown in Figure 5-8, indicating that the milling was still not quite deep enough. Results of the micro-milled surface texture depth measurements are presented in Section 5.3.2 below.

5.3.2 Collection of ULIP Field Data and Results

Two 150-ft–long data collection sections were selected. The first data collection section (Data Collection Section 2-1) was near the beginning of the test section and included some scrappy areas that appeared on the left side of the milled surface (see Figure 5-8). The second data collection section (Data Collection Section 2-2) started at 600 ft. from the beginning of the test section and showed rather uniform milled surface textures (see Figure 5.7). Locations of the measuring paths were similar to that shown in Figure 5-5. The ULIP data were collected along Path 1 and Path 3 on Data Collection Section 2-1; and along Paths 1–3 on Data Collection Section 2-2. Three runs were performed for each path.

Results of the RVD and MPD values obtained from the ULIP measurements using 100 mm base length are summarized in Table 5-5 below. The Mean RVD and p95 RVD along the milling direction as shown in Table 5-5 are less than the corresponding targeted 1.6 mm and correction 3.2 mm allowed by the specification. Estimations of the "maximum" Mean RVD and p95 RVD values for the milled surface are presented in Section 5.3.4 below.

Figure 5-7 Typical Micro-milled Surface Texture for the Second Trial Test Section

Figure 5-8 Scabbed Milled Surface on Second Trial Test Section

Table 5-5 Summary of ULIP Measurement Results for Test Section 2 (S2-1 & S2-2)

Section		150-ft Measuring Section with 100 mm Base Length					
		Mean	p50	p75	p90	p95	p99
S2-1	RVD, mm	1.22	1.05	1.50	2.07	2.47	3.32
	MPD, mm	0.46	0.39	0.56	0.80	0.95	1.30
	RVD/MPD	2.64	2.67	2.67	2.59	2.58	2.56
S2-2	RVD, mm	0.84	0.75	1.01	1.34	1.58	2.10
	MPD, mm	0.32	0.30	0.39	0.50	0.58	0.78
	RVD/MPD	2.61	2.53	2.63	2.70	2.70	2.70

5.3.3 Collection of CTM Field Data and Results

The CTM data were collected only on the Data Collection Section 2-2 following the data collection scheme shown in Figure 5-5. No CTM data were collected on Data Collection Section 2-1 due to scabs being present on the milled surface. The results are summarized in Table 5-6 below.

Table 5-6 Summary of CTM Measurement Data for Data Collection Section 2-2

MPD Results (mm)		Path 1 (12 in.)	Path 2 (36 in.)	Path 3 (72 in.)	Average
Data Collection Section 2-2					
	AE (↑)	0.74	0.65	0.64	0.68
	CG (↔)	0.76	0.82	0.73	0.77
	BDFH (Diag)	0.84	0.91	0.80	0.85
	Avg All	0.80	0.82	0.74	0.79
	CG/AE	1.03	1.25	1.14	1.14
	Diag/AE	1.14	1.39	1.24	1.26

The results shown in Table 5-6 indicate that the largest MPD values among all the CTM measurements in this data collection section occurred in the directions other than along the milling direction (A-E). Ratios of the MPD values perpendicular to the milling and diagonal to the milling directions over that along the milling direction, CG/AE and Diag/AE, as shown in Table 5-6, indicate that the ratio varied from 1.03 to 1.39.

5.3.4 Estimation of Maximum RVD Values

Estimation of maximum estimated Mean RVD and maximum estimated p95 RVD values for Test Section 2-2 in the three measuring paths could be made by multiplying the correction factor (the higher value between CG/AE or Diag./AE ratios shown in Table 5-6) to the Mean RVD and p95 RVD values obtained from the ULIP measurements along the milling direction (Table 5-5). The estimated maximum estimated Mean RVD of 1.06 mm and the maximum estimated p95 RVD values of 1.99 mm, thus obtained as shown in Table 5-7, are less than the allowable targeted 1.6 mm and correction 3.2 mm, respectively (except Section 2-1 Path 1). This indicates that lowering the milling speed from 18–20 ft./min to 13–15 ft./min and using appropriate milling depth could successfully meet the tentatively established ridge-to-valley surface texture depth requirements.

Table 5-7 Estimation of Maximum RVD Values for Test Section 2-2

	Milling Dir. A, E	Trans. Dir. C, G	Diag. Dir. B, D, F, H	CG/AE	Diag./AE
MPD (mm) from CTM					
Average	0.68	0.77	0.85	0.77 / 0.68 = 1.14	0.85 / 0.68 = 1.26
RVD (mm) from ULIP					
Mean RVD	0.84	0.84 × 1.14 = 0.96	0.84 × 1.26 = 1.06		
p95 RVD	1.58	1.58 × 1.14 = 1.80	1.58 × 1.26 = 1.99		

5.3.5 Summary of Second Trial Test Section

The results of the milled surface texture depths obtained in Test Section 2-2 indicated that the highest RVD of the micro-milled surface occurred diagonally to the milling direction with maximum estimated Mean RVD and maximum estimated p95 RVD of 1.06 mm and 1.99 mm, respectively. Both were within the targeted 1.6 mm and correction 3.2 mm allowed as stipulated in the specifications. However, the LRP test results indicated that the Smoothness Index exceeded the maximum 900 mm/km allowed for the smoothness of the micro-milled surface.

5.4 Third Trial Test Section

5.4.1 Third Trial Test Section Site and Milling Operation

Location of the third test section was on the same SB1 immediately following the second trial test section. The micro-milling operation started at about 9:30 p.m. on May 21, 2007. A four-track Wirtgen W2200 milling machine (see Figure 5-9) was used. The milling speed was about 17 ft./min, and the milling depth was increased to approximately 1¼ in. The quality of the micro-milled surface textures was quite uniform, and no scabs were present on the milled surface. Results of the micro-milled surface texture depth are presented in Section 5.4.2.

Since both of the last two trial test sections failed the smoothness requirement, the LRP smoothness tests were performed immediately on the milled surface after the milled surface was dried and swept clean. The averaged Smoothness Index from the LRP tests was 740 mm/km, less than the maximum SI allowable of 900 mm/km required by the specification.

Figure 5-9 Wirtgen W2200 Four-Track Milling Machine

5.4.2 Collection of CTM Field Data and Results

Due to a scheduling problem, ULIP was not available and only the CTM field data were collected in this third trial test section. The Figure 5-5 CTM data collection scheme was followed, and the CTM data were collected at nine locations. The only deviation from the scheme shown in Figure 5-5 was that Path 1 was 15 in. from the left edge instead of 12 in. from the left-milled edge to avoid a wide longitudinal crack present at approximately 6 in. from the left edge. Triplicate runs were performed at each position, and the results were averaged as presented in Table 5-8 and Table 5-9. The MPD values shown in these tables are comparable to that of the MPD values obtained from Test Section 2-2 in the second Trial Test Section.

Table 5-8 CTM Test Results for Test Section 3

CTM Location (in.)			**MPD Value (mm) at Diff. Segment, average of 3 runs**								
ID	**LONG**	**TRANS**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**Average**
3-1	0	15	0.95	0.90	1.50	1.19	1.16	1.19	1.01	0.92	1.10
3-2	0	36	1.27	1.27	2.02	1.16	0.77	1.41	1.61	1.10	1.33
3-3	0	72	1.09	1.18	0.95	0.85	0.83	1.01	1.19	0.97	1.01
3-4	75	15	0.90	1.37	1.38	1.17	1.01	0.87	1.07	0.95	1.09
3-5	75	36	0.95	1.03	1.76	1.63	1.02	1.50	1.85	1.13	1.36
3-6	75	72	0.92	1.03	0.84	1.07	0.69	1.03	1.15	0.97	0.96
3-7	150	15	0.51	0.63	0.83	1.15	0.69	1.37	0.84	1.10	0.89
3-8	150	36	0.71	1.20	1.39	0.79	1.05	1.02	1.74	1.65	1.19
3-9	150	72	0.72	1.33	0.95	0.98	0.70	1.21	1.13	1.45	1.06
Average			0.89	1.10	1.29	1.11	0.88	1.18	1.29	1.14	1.11

Table 5-9 Summary of CTM Data Collected from Section 3

MPD Results (mm)	**Direction**	**Path 1 (15 mm)**	**Path 2 (36 mm)**	**Path 3 (72 mm)**	**Average**
	AE	0.87	0.90	0.82	0.87
	CG	1.10	1.73	1.03	1.29
	BDFH (Diag)	1.06	1.24	1.09	1.13
	CG/AE	1.27	1.91	1.26	1.48
	Diag/AE	1.22	1.37	1.32	1.30

5.4.3 Estimation of RVD from CTM Data

Since no ULIP data were collected in this trial test section, preventing direct determination of the RVD values along the milling direction, the following prediction scheme was developed for estimating RVD values from the MPD data collected from the CTM testing in this trial test section.

Regression equations were initially developed for estimating Mean, p90, and p95 RVD using the RVD results obtained from the ULIP data and the MPD data obtained from the CTM from data collection Test Section S1-1 and S2-2. The estimated Mean RVD and p95 RVD values from these initial regression equations indicated that they were less than the allowed targeted 1.6 mm and correction 3.2 mm, respectively, by the specification.

After additional RVD results from the ULIP measurements and the MPD data from the CTM were available from Test Sections 5, 6, 7, and 8 (presented in Chapter 6 in this report); statistical analyses were performed again and the following regression equations, Equation 5.1, Equation 5.2, and Equation 5.3, were obtained. Figure 5-10 shows the data used and the regression equations obtained from these data.

$$\text{Mean RVD (mm)} = 2.56 * \text{MPD (AE, mm)} - 0.65 \qquad R^2 = 0.85 \qquad \text{(Eq. 5.1)}$$

$$\text{p90 RVD (mm)} = 4.611 * \text{MPD (AE, mm)} - 1.56 \qquad R^2 = 0.91 \qquad \text{(Eq. 5.2)}$$

$$\text{p95 RVD (mm)} = 4.83 * \text{MPD (AE, mm)} - 1.30 \qquad R^2 = 0.85 \qquad \text{(Eq. 5.3)}$$

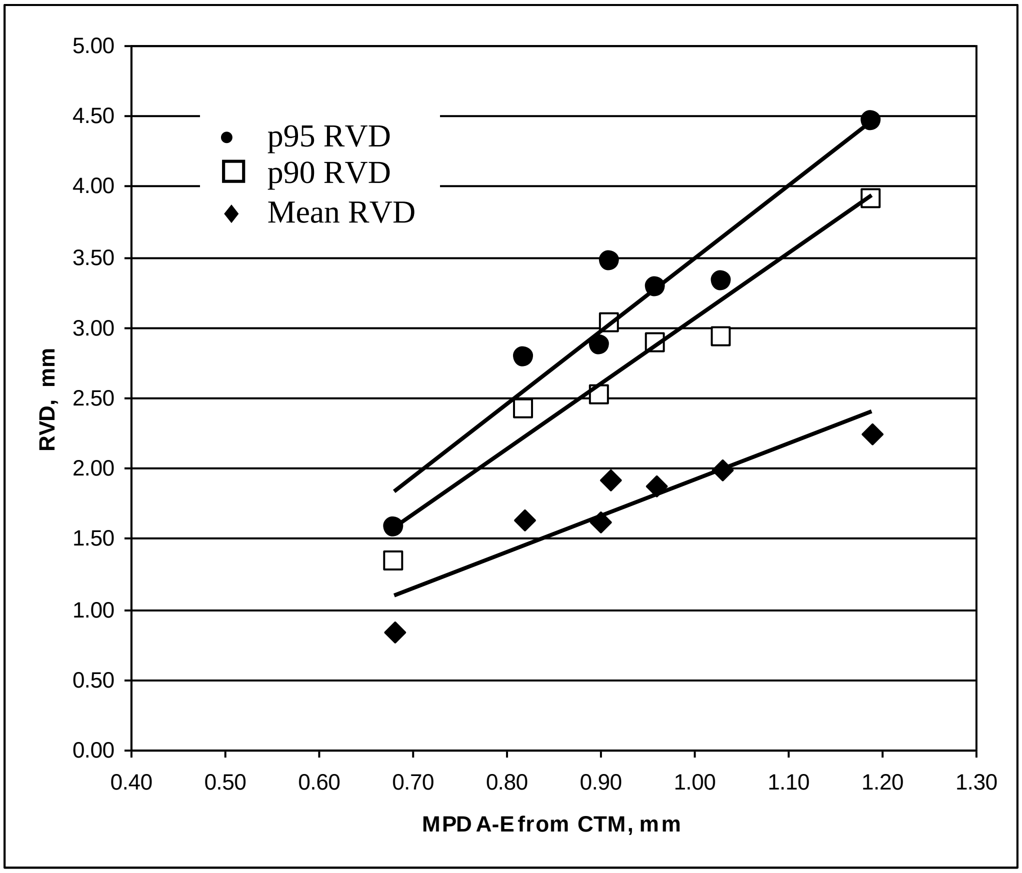

Figure 5-10 Correlation between Mean RVD and p95 RVD with MPD (AE) from CTM

The Mean RVD and p95 RVD values for this test section were estimated using Equation 5.1 and Equation 5.3 and the averaged MPD value from Segments A and E from the CTM results (Table 5-9). The estimated Mean RVD and p95 RVD along the milling direction at the locations where the CTM data were collected are presented in Table 5-10. Since the maximum texture depth for this test section, according to the CTM results shown in Table 5-9, occurred in the perpendicular direction, and the ratio of CG/AE was 1.48, the corresponding maximum estimated Mean RVD and estimated maximum p95 RVD could be determined by multiplying 1.48 to the Mean RVD and p95 RVD shown in Table 5-10. Thus, the maximum estimated Mean RVD and maximum estimated p95 RVD for this test section were 2.39 mm and 4.41 mm, respectively. Both exceeded the allowed amount stipulated in the specification.

Table 5-10 Estimated Mean and p95 RVD

Date:	**5/21/07**	**CTM Reading (mm)**			**Est. RVD Value**	
SEC	**LOCATION**	**A**	**E**	**Avg A-E**	**Mean**	**p95**
Section 3	Path 1-1	0.95	1.16	1.06	2.05	3.80
	Path 1-2	1.27	0.77	1.02	1.96	3.63
	Path 1-3	1.09	0.83	0.96	1.81	3.34
	Path 2-1	0.90	1.01	0.96	1.79	3.31
	Path 2-2	0.95	1.02	0.99	1.87	3.46
	Path 2-3	0.92	0.69	0.81	1.41	2.59
	Path 3-1	0.51	0.69	0.60	0.89	1.60
	Path 3-2	0.71	1.05	0.88	1.60	2.95
	Path 3-3	0.72	0.70	0.71	1.17	2.13
	Average (mm)				**1.62**	**2.98**
	Maximum (mm)				**2.39**	**4.41**

5.5 Summary of Third Trial Test Section

The estimated RVD results shown in Table 5-10 indicate that the estimated Mean RVD of 1.62 mm and p95 RVD of 2.98 mm along the milling direction are very close to the allowed amount (targeted 1.6 mm and correction 3.2 mm, respectively). However, the maximum estimated Mean RVD of 2.39 mm and maximum estimated p95 RVD of 4.41 mm occurred in the direction perpendicular to the milling direction, exceeding the amount allowed by the specification. The Smoothness Index measured on the milled surface was 740 mm/km, less than the 825 mm/km target and 900 mm/km maximum allowed values.

When the original paving contractor first started the PEM paving over the micro-milled surface on May 22, 2007, quality control testing performed at the asphalt plant showed the PEM mixtures produced could not meet the gradation requirements, and the paved surface was subsequently removed. The micro-milling and PEM paving operations for this project were suspended for several months.

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CHAPTER 6 Second Stage Micro-milling of Sections on I-75 Project

The research team did not return to the project site for more than three months following the testing on May 21, 2007. The project engineer was concerned that both the quality of the micro-milling operation and the PEM paving operation were inconsistent. The determination was made to let the contractors work out the problems without the presence of the research team. The research team did not resume the testing until September 10.

During this period, Reeves Construction Company took over as prime contractor from Folsom Construction Co., the original prime contractor, in late July. The field paving operation was resumed in August. The milling sub-contractor had made changes for improving the procedures to control the milling operation.

It is worth pointing out that the length of time the micro-milled surface was exposed to traffic had been extended from three days to as long as eight days before the surface was paved over. With the high daytime temperatures in the summer, the pavement surface temperature often exceeded 100°F; also, the milled surface texture could have been affected under the prolonged exposure to the heavy traffic. The effect of the heat and traffic could be important from the quality control point of view. Table 6-1 summarizes the tests performed in Work Test 2 and 3.

Table 6-1 Field Testing Performed in Work Test 2 and Work Task 3

Test Section ID	Location	Milling Op	Measure Texture	PEM Paving	Coring	Test Performed	Remark
Section 0	I-75 MP-78-S		5/1			MU, MC	Rough milled surface
Section 1-1	MP 142.0 S L1	5/13	5/13			MU, MC	
Section 1-2	MP 142.0 S L1	5/13	5/13			MU	
Section 2-1	MP 142.0 S L1	5/14	5/14			MU	
Section 2-2	MP 142.0 S L1	5/14	5/14			MU, MC	
Section 3	MP 142.0 S L1	5/21	5/21			MC	
Section 4-1	MP 133.0 S L1	9/2	9/10	9/10	10/25	MC, TC, B	Tack rate 0.06 gal/yd.
Section 4-2	MP 133.0 S L1	9/2	9/10			MC, TC, B	
Section 5-1	MP 130.0 N L1	9/9	9/17			MU, MC	
Section 5-2	MP 130.0 N L1	9/9	9/17			MU, MC	
Section 6	MP 135.0 S L2	9/16	9/17			MU, MC	
Section 7	MP 128.9 N L3	9/17	9/17			MU, MC	
Section 8	MP 129.4 N L3	9/17	9/17			MU, MC	
Section 9	MP 132.5 S L3	10/15	No	10/16	11/29	TC, B	Tack rate 0.08 gal/yd.

MU = Measure surface texture using ULIP; MC = Measure surface texture using CTM
TC = Testing tack coat rate; B = Coring and testing bond strength

The research team returned to the construction site on September 10 to resume monitoring the micro-milled surface texture and to determine the tack coat application rates for the PEM overlay paving. Table 6-1 summarizes the field testing performed for this project. The testing and the results of the micro-milled surface textures for Test Section 1, Test Section 2, and Test Section 3 were presented in Chapter 5. The testing and the results of the micro-milled surface textures for Test Section 4 to Test Section 8 are presented in this chapter. The testing of tack coat application rates and testing of the bond strength for Test Section 4 and Test Section 9 are presented in Chapter 8.

6.1 Test Plan for Fourth Test Section

The fourth test section was located at the beginning of Milepost 133 in Southbound Lane 1 (SB1). The research work planned for this test section included measuring milled surface texture depths, determining tack coat application rates, and testing the bond strength between the PEM overlay and the micro-milled surface. The test section was divided into two segments for testing two different tack coat application rates. The first segment (Section 4-1) began at MP 133 marker, located at south of the Exit 134 on-ramp, and ended at the north edge of the Flat Creek Bridge. The second segment (Section 4-2) was about 1500 ft. long and began at the south edge of the bridge.

6.1.1 Layout of the Test Section

As shown in Figure 6-1, these two segments were designated as TCR-1 (Tack Coat Rate 1) and TCR-2. Two tack coat application rate testing assemblies, Pad Row #1 and #2, were installed in the first segment and two pad assemblies, Pad Row #3 and #4, in the second segment for testing the accuracy and uniformity of the tack coat spray. More detailed information concerning the pads and the installation of the pad assembly, as well as the testing, is presented in Chapter 8.

Two surface texture measuring sections (ST-1 and ST-2), each 150-ft–long were selected for this test section. ST-1 was located between the Pad Row #1 and #2, and ST-2 between Pad Row #3 and #4.

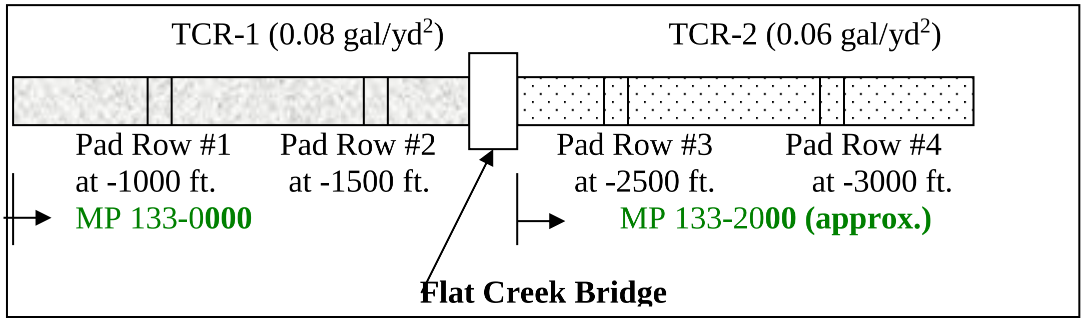

Figure 6-1 Location and Layout for Fourth Test Section

6.1.2 Description of the Milled Surface

The entire section from MP 133 to MP 132 was milled on September 2. The milled surface was exposed to normal Interstate traffic for eight days before the measuring of the surface texture was performed on September 10. The milled surface was visually inspected in the evening prior to performing both the surface texture measurements and the tack coat application rates testing. It was found that the milled surface was very clean and the surface texture was uniform.

6.2 Milled Surface Texture Depth Test Results for Fourth Test Section

6.2.1 ULIP and CTM Data Collection Schemes and Results

Two 150-ft–long data collection sections were selected. The first section was located in TCR-1 between Pad Row #1 and Pad Row #2, and the second section was located in TCR-2 between Pad Row #3 and Pad Row #4.

ULIP data were collected in the first section along three measuring paths as shown in Figure 6-2. Three runs were performed for each path. Unfortunately, due to an instrumentation problem, surface texture profile data from the ULIP could not be obtained during the testing. The problem could not be corrected in time, and no ULIP data were obtained.

Collection of the CTM data was conducted at four locations as indicated in Figure 6-2 at both data collection sections. At each location, three runs were performed and the MPD data were collected. The averaged MPD values for each of the segments at the eight locations are presented in Table 6-2. Researchers noticed that the differences of the MPD results among the eight CTM segments shown in Table 6-2 were quite small compared with those from the previous CTM test results shown in Chapter 5.

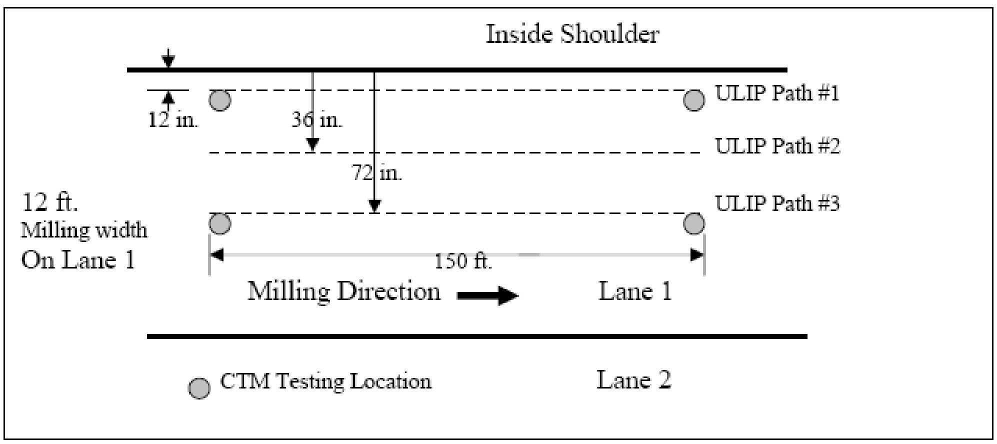

Figure 6-2 ULIP and CTM Data Collection Scheme

Table 6-2 CTM Test Results for Fourth Test Section

Test SECTION	Test Location (ft.) LONG	TRANS	MPD from Different CTM Segments (mm), average of 2 runs A	B	C	D	E	F	G	H	AVG
S4-1	0	12	1.30	1.10	0.77	1.09	1.17	0.98	0.75	0.96	1.01
	0	72	0.89	0.99	1.11	0.99	0.87	1.06	0.86	1.23	1.00
	150	12	0.79	0.70	0.88	0.81	0.74	0.92	0.85	0.78	0.81
	150	72	0.92	1.35	1.09	0.99	0.91	1.25	1.55	1.62	1.21
S4-2	0	12	0.95	0.97	1.03	0.84	1.27	1.25	1.00	1.65	1.12
	0	72	1.00	1.23	1.13	1.11	0.65	0.89	1.47	1.17	1.08
	150	12	0.86	0.96	1.09	1.24	0.73	1.53	1.08	1.25	1.09
	150	72	1.01	0.86	1.02	0.99	0.97	1.02	0.96	1.09	0.99
	AVERAGE, mm		0.96	1.02	1.01	1.00	0.91	1.11	1.06	1.22	1.04

From the results shown in Table 6-2 the average MPD values along the milling direction (A-E), perpendicular to milling direction (C-G) and in the diagonal direction (Diag. B-D-F-H), as well as the ratios of CG/AE and Diag./AE for Section 4-1 and Section 4-2 were computed and the results are summarized in Table 6-3.

Table 6-3 Average MPD at Different Directions on the Milled Surface

Section	Average A-E	Average C-G	Average Diag.	Average All Segmt	CG/AE	Diag./AE
Section 4-1	0.95	0.98	1.05	1.01	1.03	1.11
Section 4-2	0.93	1.10	1.11	1.07	1.18	1.20

6.2.2 Estimation of RVD from CTM Data

Since no ULIP data were collected in this test section for directly determining the RVD values along the milling direction, regression equations, Eq. 5.1 and Eq. 5.3, developed in Section 5.4.3, were utilized to estimate the RVD values from the MPD data collected from the CTM testing in this test section. The Mean RVD and p95 RVD values along the milling direction were computed using these equations, and the results are presented in Table 6-4. The estimated RVD results shown in Table 6.4 indicate that the estimated Mean and p95 RVD values for both sections along the milling direction are very close to the allowable limits (targeted 1.6 mm and correction 3.2 mm, respectively). The estimated maximum Mean RVD and maximum p95 RVD were computed by multiplying the Diag./AE ratios shown in Table 6-3 by the estimated Mean RVD and p95 RVD along the milling direction shown in Table 6-2. The results shown in Table 6-4 indicate that they slightly exceeded the Target amount allowed by the specifications.

Table 6-4 Estimated Avg RVD and p95 RVD for Fourth Test Section

Test Section	Test Path	CTM / MPD A-E AVG	Estimated RVD Est. Mean RVD	Est. p95 RVD
Section 4-1	12	1.24	2.51	4.67
	72	0.88	1.60	2.95
	12	0.76	1.30	2.38
	72	0.91	1.68	3.10
Average			1.77	3.27
Estimated Max			1.97	3.63
Section 4-2	12	1.11	2.19	4.06
	72	0.83	1.46	2.68
	12	0.80	1.39	2.54
	72	0.99	1.87	3.46
Average			1.73	3.19
Estimated Max			2.07	3.82

6.3 Fifth Test Section

The fifth test section was located at Milepost 130 in Northbound Lane 1. This section was milled on September 9, and testing of the micro-milled surface texture was performed on September 17. The operating speed of the milling machine was approximately 28 ft./min. Results of the micro-milled surface texture depth measurements are presented in Section 6.3.1 and 6.3.2.

6.3.1 Collection of ULIP Field Data and Results

Two 150-ft–long data collection sections were selected for testing the milled surface texture. The first segment (Section 5-1) began at MP 130.3 and the second segment (Section 5-2) began at MP 130.3+500 ft. ULIP data were collected along three data collection paths similar to those shown in Figure 5-5.

Results of the Mean RVD and p50 to p99 RVD values from the ULIP data for these two data collection sections are summarized in Table 6-5. Results presented in Table 6-5 include only the RVD and MPD values calculated from the ULIP data using 100 mm base lengths. The Mean RVD and p95 RVD along the milling direction shown in Table 6-5 are greater than the corresponding Target 1.6 mm and Correction 3.2 mm allowed in the specification. Results of the estimated maximum Mean RVD and estimated maximum p95 RVD values for the milled surface are presented in Section 6.3.3.

Table 6-5 Summary of ULIP Test Results for Fifth Test Section

Test Section		**150-ft Measuring Section with 100 mm Base Length**					
		Mean	**p50**	**p75**	**p90**	**p95**	**p99**
S5-1	RVD, mm	1.87	1.75	2.28	2.87	3.28	4.04
	MPD, mm	0.66	0.61	0.80	1.00	1.14	1.45
	RVD/MPD	2.84	2.85	2.84	2.88	2.88	2.79
S5-2	RVD, mm	1.92	1.77	2.35	3.02	3.47	4.42
	MPD, mm	0.68	0.62	0.83	1.06	1.21	1.64
	RVD/MPD	2.83	2.84	2.81	2.85	2.86	2.70

6.3.2 Collection of CTM Field Data and Results

The CTM data were collected on Sections 5-1 and 5-2 on Paths 1, 2, and 3 following the data collection scheme shown in Figure 5-5. At each of the nine locations, three tests were performed. The results are summarized in Table 6-6. The MPD of the milled surface determined from the CTM along the milling direction (A-E), perpendicular to the milling direction (C-G), and diagonal to the milling direction are summarized in Table 6-7.

Table 6-6 CTM Test Results for Fifth Test Section

CTM Location (FT)			MPD from Different CTM Segments (mm), Avg of 3 runs								
SECT	**LONG**	**TRANS**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**AVG**
S5-1	0	12	1.04	1.36	1.17	1.41	1.32	1.29	1.49	1.20	1.29
	75	12	0.89	1.22	1.20	3.38	1.34	2.53	4.71	1.07	2.04
	150	12	0.56	1.00	1.16	1.19	0.95	1.03	1.34	1.25	1.06
	0	36	0.61	1.23	1.15	1.58	0.96	1.51	1.13	0.93	1.14
	75	36	1.19	1.47	0.79	1.12	0.73	0.98	0.94	1.21	1.05
	150	36	1.02	1.47	1.13	0.75	0.88	1.17	1.24	1.49	1.14
	0	72	0.77	1.13	1.44	0.94	0.94	0.73	1.48	1.08	1.06
	75	72	1.13	0.88	1.22	0.67	0.81	0.79	1.49	0.83	0.98
	150	72	0.89	1.25	0.90	1.36	1.19	1.22	1.15	1.43	1.17
AVG S5-1			0.90	1.22	1.13	1.38	1.01	1.25	1.66	1.17	1.21
S5-2	0	12	0.96	1.03	1.04	1.18	0.51	1.34	1.32	1.01	1.05
	150	12	1.20	1.09	0.79	1.12	0.68	0.96	1.00	1.11	0.99
	0	36	0.78	1.27	1.51	1.33	0.95	0.80	0.94	1.36	1.12
	150	36	1.05	1.00	1.45	1.00	1.06	0.73	1.41	1.59	1.16
	0	72	0.91	1.19	1.06	0.75	1.11	0.83	1.09	1.21	1.02
	150	72	0.82	1.08	1.36	0.69	0.93	1.56	0.91	1.18	1.06
AVG S5-2			0.95	1.11	1.20	1.01	0.87	1.04	1.11	1.24	1.07
AVERAGE S5-1 & S5-2			0.93	1.17	1.17	1.19	0.94	1.14	1.39	1.20	1.14

Average of 5-1 = 1.22 mm; Average of 5-2 = 1.07 mm

Table 6-7 Summary of CTM Results for Section 5-1 and Section 5-2

Mean Texture Depth MPD (mm)		**Path 1 (12 in.)**	**Path 2 (36 in.)**	**Path 3 (72 in.)**	**Average**
Data Collection Section 5-1					
	AE (↑)	1.02	0.90	0.96	0.96
	CG (↔)	1.85	1.06	1.28	1.39
	Diag.	1.49	1.25	1.05	1.26
	CG/AE	1.81	1.18	1.34	1.46
	Diag./AE	1.47	1.39	1.10	1.32
Data Collection Section 5-2					
	AE (↑)	0.84	0.96	0.94	0.91
	CG (↔)	1.04	1.33	1.10	1.15
	Diag.	1.10	1.14	1.06	1.10
	CG/AE	1.23	1.38	1.17	1.26
	Diag./AE	1.31	1.18	1.12	1.20

The results shown in Table 6-7 indicate that the largest MPD values among all the CTM measurements in these data collection sections occurred in directions other than along the milling direction (A-E). Among the six sets of the measuring data, five of the maximum MPD occurred perpendicular to the milling direction, while one occurred diagonal to the milling direction. The ratios of the maximum MPD over that along the milling direction, CG/AE and Diag./AE, as shown in Table 6-7, indicate that the ratio varied from 1.10 to 1.81.

6.3.3 Estimation of Maximum RVD Values

Estimation of maximum Mean RVD and maximum p95 RVD values for the milled surfaces of the two data collection sections were made by multiplying the correction factor (the higher value of CG/AE and Diag./AE ratios) shown in Table 6-7 by the Mean RVD and p95 RVD values obtained from the ULIP measurements along the milling direction. The estimated maximum Mean RVD and estimated maximum p95 RVD values thus obtained are shown in Table 6-8. The results indicate that both the estimated maximum Mean RVD and maximum p95 RVD values of the micro-milled surfaces of these two data collection sections exceeded the allowable target 1.6 mm and correction 3.2 mm, respectively. This could be attributed to the high milling speed of 28 ft./min.

Table 6-8 Estimation of Maximum RVD in All Directions

	Section 5-1	Section 5-2	Remarks
MPD from CTM Testing			
Avg AE (mm)	0.96	0.91	Table 6.7
Max Ratio (CG or Diag)/AE	1.46	1.26	Table 6.7
RVD from ULIP Testing			
Mean RVD (mm)	1.87	1.92	Table 6.5
p95 RVD (mm)	3.28	3.47	Table 6.5
Estimated Max RVD			
Mean RVD (mm)	1.87 × 1.46 = 2.73	1.92 × 1.26 = 2.42	Table 6.7
p95 RVD (mm)	3.28 × 1.46 = 4.79	3.47 × 1.26 = 4.37	Table 6.6

6.4 Sixth Test Section

The sixth test section was located at Milepost 135 in Southbound Lane 2. This section was milled on September 16, and the testing of the micro-milled surface texture was performed on September 17. The operating speed of the milling machine was approximately 24 ft./min. Results of the micro-milled surface texture depth measurements are presented in Section 6.4.1 and 6.4.2.

6.4.1 Collection of ULIP Field Data and Results

One 150-ft–long data collection section was selected for testing the milled surface texture. ULIP data were collected along three data collection paths similar to that shown in Figure 5-5.

Results of the Mean RVD and p50 to p99 RVD values computed from the ULIP data using 100 mm base lengths for this test section are summarized in Table 6-9. The Mean RVD and p95 RVD along the milling direction shown in Table 6-9 are very close to the corresponding targeted 1.6 mm and correction 3.2 mm allowed in the specifications.

Estimations of the maximum Mean RVD and maximum p95 RVD values for the milled surface are presented in Section 6.4.3.

Table 6-9 Summary of ULIP Test Results for Sixth Test Section

	150-ft Measuring Section with 100 mm Base Length					
	Mean	**p50**	**p75**	**p90**	**p95**	**p99**
RVD, mm	1.63	1.52	1.94	2.41	2.78	3.63
MPD, mm	0.61	0.57	0.72	0.90	1.02	1.34
RVD/MPD	2.68	2.64	2.68	2.69	2.71	2.71

6.4.2 Collection of CTM Field Data and Results

The CTM data were collected on Paths 1, 2, and 3 at two locations (0 and 150 ft.). At each of the six locations, three tests were performed. The results are summarized in Table 6-10. The MPD of the milled surface determined from the CTM along (A-E), perpendicular to (C-G) and diagonal to the milling direction are summarized in Table 6-11.

Table 6-10 CTM Test Results for Sixth Test Section

CTM Location (FT)			MPD from Different CTM Segments (mm), Avg of 3 runs								
SECT	**LONG**	**TRANS**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**AVG**
6	0	12	0.77	1.03	1.11	1.00	0.67	1.07	1.06	1.00	0.96
	150	12	0.75	1.26	0.84	1.05	0.89	1.10	1.31	1.09	1.04
	0	36	0.71	0.98	0.82	1.04	1.05	1.16	0.96	0.94	0.96
	150	36	0.85	1.10	0.84	0.82	0.63	0.97	0.95	1.06	0.90
	0	72	0.71	0.85	1.24	1.30	0.79	1.02	1.45	0.78	1.02
	150	72	0.86	0.86	1.20	1.78	1.05	1.07	1.07	0.86	1.09
			0.78	1.01	1.01	1.17	0.85	1.06	1.13	0.96	1.00

Table 6-11 Summary of CTM Results for Sixth Test Section

Mean Texture Depth MPD (mm)		Path 1 (12 in.)	Path 2 (36 in.)	Path 3 (72 in.)	Average
	AE (↑)	0.77	0.81	0.85	0.81
	CG (↔)	1.06	0.89	1.24	1.06
	Diag.	1.08	1.01	1.06	1.05
	CG/AE	1.38	1.10	1.46	1.31
	Diag./AE	1.40	1.24	1.25	1.29

Again, the results shown in Table 6-10 indicate that the largest MPD values among all the CTM measurements in this data collection section occurred in the directions other than along the milling direction (A-E). The ratios of CG/AE and Diag./AE, as shown in Table 6-10, indicate that the ratio varied from 1.29 to 1.31.

6.4.3 Estimation of Maximum RVD Values

Estimated maximum Mean RVD and estimated maximum p95 RVD values for the milled surfaces of the test sections were computed using the same approach that was used previously in this chapter by multiplying the correction factor (the higher value between CG/AE or Diag./AE ratios shown in Table 6-11) by the Mean and p95 RVD values obtained from the ULIP data along the milling direction. The estimated maximum Mean RVD and estimated maximum p95 RVD values obtained are shown in Table 6-12. The results indicated that the estimated maximum Mean RVD of about 2.12 mm and the estimated maximum p95 RVD of about 3.61 for this test section exceeded the allowable correction 3.2 mm, respectively. Again, this could be attributed to the high milling speed of 28 ft./min.

Table 6-12 Estimation of Maximum Mean RVD and p95 RVD

	Milling Dir. A, E	**Trans Dir. C, G**	**Diag. Dir. B, D, F, H**	**CG/AE**	**Diag./AE**
MPD (mm), CTM					
Average	0.81	1.06	1.05	1.31	1.29
RVD (mm), ULIP					
Mean RVD	1.63	$1.63 \times 1.31 = 2.14$	$1.63 \times 1.29 = 2.10$		
p95 RVD	2.78	$2.78 \times 1.31 = 3.63$	$2.78 \times 1.29 = 3.59$		

6.5 Seventh and Eighth Test Sections

The researchers noted that in the fifth and sixth test sections the measured ridge-to-valley texture depth of the micro-milled surfaces exceeded the allowable values, and one of the possible causes was that the milling speed was too fast. These two additional test sections were added to assess the potential effect of the milling machine's operating speed on the milled surface texture quality.

The seventh test section was about 0.5 mile in length and was located on NB3 starting at MP 128.9. The milling speed was about 22–23 ft./min. The eighth test section was also about 0.5 mile in length and was located north of the seventh test section, starting at about MP 129.4 on NB3. The milling speed for the eighth test section was about 19 ft./min. Results of the micro-milled surface texture depth are presented in Section 6.5.1 and 6.5.2.

6.5.1 Surface Texture for Seventh Test Section

Both the ULIP data and the CTM data were collected on the milled surfaces of this test section. One 150-ft–long data collection section was selected for testing the milled surface texture. ULIP data were collected along three data collection paths similar to the one shown in Figure 5-5. In addition, three test runs were performed on all three paths, three more runs were performed on Path 1, and one additional run was performed on Path 2. Results of the Mean RVD and p95 RVD values from these tests are presented in Table 6-13. The CTM data were collected on Paths 1, 2, and 3 at two locations (0 and 150 ft.). Additionally, the CTM data were collected at two more locations (0 and 150 ft.) on a path 9 ft. (108 in.) from the left side of the lane. At each of the eight locations, three tests were performed. The results are summarized in Table 6-14.

Results of the RVD and MPD presented in Table 6-13 were computed from the ULIP data using 100 mm base lengths. The Mean RVD and p95 RVD along the milling direction, as shown in Table 6-13, are very close to the corresponding target 1.6 mm and correction3.2 mm allowed in the specification. Estimation of the maximum Mean RVD and maximum p95 RVD values for the milled surface as shown in Table 6-15 indicate that both were only about 0.40 mm over the allowed values.

Table 6-13 Summary of ULIP Test Results for Seventh Test Section

	150-ft Measuring Section with 100 mm Base Length					
	Mean	**p50**	**p75**	**p90**	**p95**	**p99**
RVD, mm	1.89	1.76	2.30	2.93	3.33	4.23
MPD, mm	0.68	0.63	0.83	1.06	1.21	1.55
RVD/MPD	2.79	2.77	2.76	2.76	2.76	2.73

Table 6-14 Summary of CTM Test Results for Seventh Test Section

CTM Location (FT)			MPD from Different CTM Segments (mm), Avg of 3 runs								
SEC	LONG	**TRANS**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**Average**
S7	0	108	0.76	1.07	1.00	1.54	0.69	1.13	1.15	0.87	1.03
	150	108	0.85	1.38	1.39	1.30	0.81	1.18	0.73	0.79	1.06
	0	72	1.53	0.79	1.24	0.95	1.04	1.01	1.15	0.81	1.06
	150	72	1.74	1.35	1.19	1.16	1.17	0.98	0.95	1.25	1.22
	0	36	1.07	1.31	1.03	1.62	0.80	1.12	1.07	1.13	1.14
	150	36	1.01	0.96	1.32	1.53	0.78	1.48	1.09	1.58	1.22
	0	12	1.15	1.02	1.02	0.96	1.10	0.93	0.86	1.19	1.03
	150	12	0.58	1.20	1.27	1.35	1.30	1.40	1.15	0.94	1.15
Overall AVERAGE			1.09	1.14	1.18	1.30	0.96	1.15	1.02	1.07	1.11

Table 6-15 Estimation of Maximum Mean RVD and p95 RVD

	Milling Dir. A, E	**Trans. Dir. C, G**	**Diag. Dir. B, D, F, H**	**CG/AE**	**Diag./AE**
MPD (mm), CTM					
Average	1.03	1.05	1.17	1.02	1.14
RVD (mm), ULIP					
Mean RVD	1.89	1.89 × 1.02 = 1.93	1.89 × 1.14 = 2.16		
p95 RVD	3.33	3.33 × 1.02 = 3.40	3.33 × 1.14 = 3.80		

6.5.2 *Surface Texture for Eighth Test Section*

Both the ULIP data and the CTM data were collected on the surface texture of this test section. One 150-ft–long data collection section was selected for testing the milled surface texture. ULIP data were collected along three data collection paths similar to that shown in Figure 5-5. The typical surface texture profiles are shown in Figure 6-3. In comparison with the typical surface texture profiles shown in Figure 5-6 for Test Section 1-1, the typical RVD shown in Figure 6-3 is smaller than that in Figure 5-6, which is consistent with the actual calculated RVD values shown in both Table 6-16 and Table 5-2.

Results of the Mean RVD and p95 RVD values along the milling direction are presented in Table 6-16. The CTM data were collected on Paths 2, 3, and 4 (3 ft., 6 ft., and 9 ft. from left pavement edge) at two locations (0 and 150 ft.). At each of the six locations, triplicate tests were performed. The results are summarized in Table 6-17.

Table 6-16 Summary of ULIP Test Results for Eighth Test Section

	150-ft Measuring Section with 100 mm Base Length					
	Mean	**p50**	**p75**	**p90**	**p95**	**p99**
RVD, mm	1.62	1.51	2.01	2.52	2.87	3.59
MPD, mm	0.61	0.56	0.75	0.95	1.09	1.38
RVD/MPD	2.66	2.69	2.67	2.65	2.64	2.61

Table 6-17 Summary of CTM Test Results for Eighth Test Section

CTM Location (FT)			MPD from Different CTM Segments (mm), Avg of 3 runs								
SEC	**LONG**	**TRANS**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**Average**
S8	0	108	0.81	0.62	1.21	0.81	1.00	1.65	0.73	0.88	0.96
	150	108	0.94	1.00	1.32	0.94	0.76	1.30	0.90	0.47	0.95
	0	72	0.79	0.76	0.99	1.13	0.97	0.82	0.81	1.00	0.91
	150	72	0.73	1.61	0.98	0.79	0.81	0.88	0.91	0.91	0.95
	0	36	0.88	0.69	1.03	0.93	0.86	0.97	0.69	0.74	0.85
	150	36	1.40	1.12	0.66	0.92	0.90	0.81	0.88	0.95	0.96
Overall AVERAGE			0.92	0.97	1.03	0.92	0.88	1.07	0.82	0.82	0.93

Again, results of the RVD and MPD presented in Table 6-16 were computed from the ULIP data using 100 mm base lengths. The Mean RVD and p95 RVD along the milling direction as shown in Table 6-16 are very close to the corresponding target1.6 mm and correction 3.2 mm allowed in the specification. The estimated maximum Mean RVD and the estimated maximum p95 RVD for the milled surface shown in Table 6-18 are also very close to the allowed values.

Table 6-18 Estimation of Maximum Mean RVD and p95 RVD for Eighth Test Section

	Milling Dir. A, E	**Trans. Dir. C, G**	**Diag. Dir. B, D, F, H**	**CG/AE**	**Diag./AE**
MPD (mm), CTM					
Average	0.90	0.93	0.95	1.03	1.06
RVD (mm), ULIP					
Mean RVD	1.62	$1.62 \times 1.03 = 1.67$	$1.62 \times 1.06 = 1.72$		
p95 RVD	2.87	$2.87 \times 1.03 = 2.96$	$2.87 \times 1.06 = 3.04$		

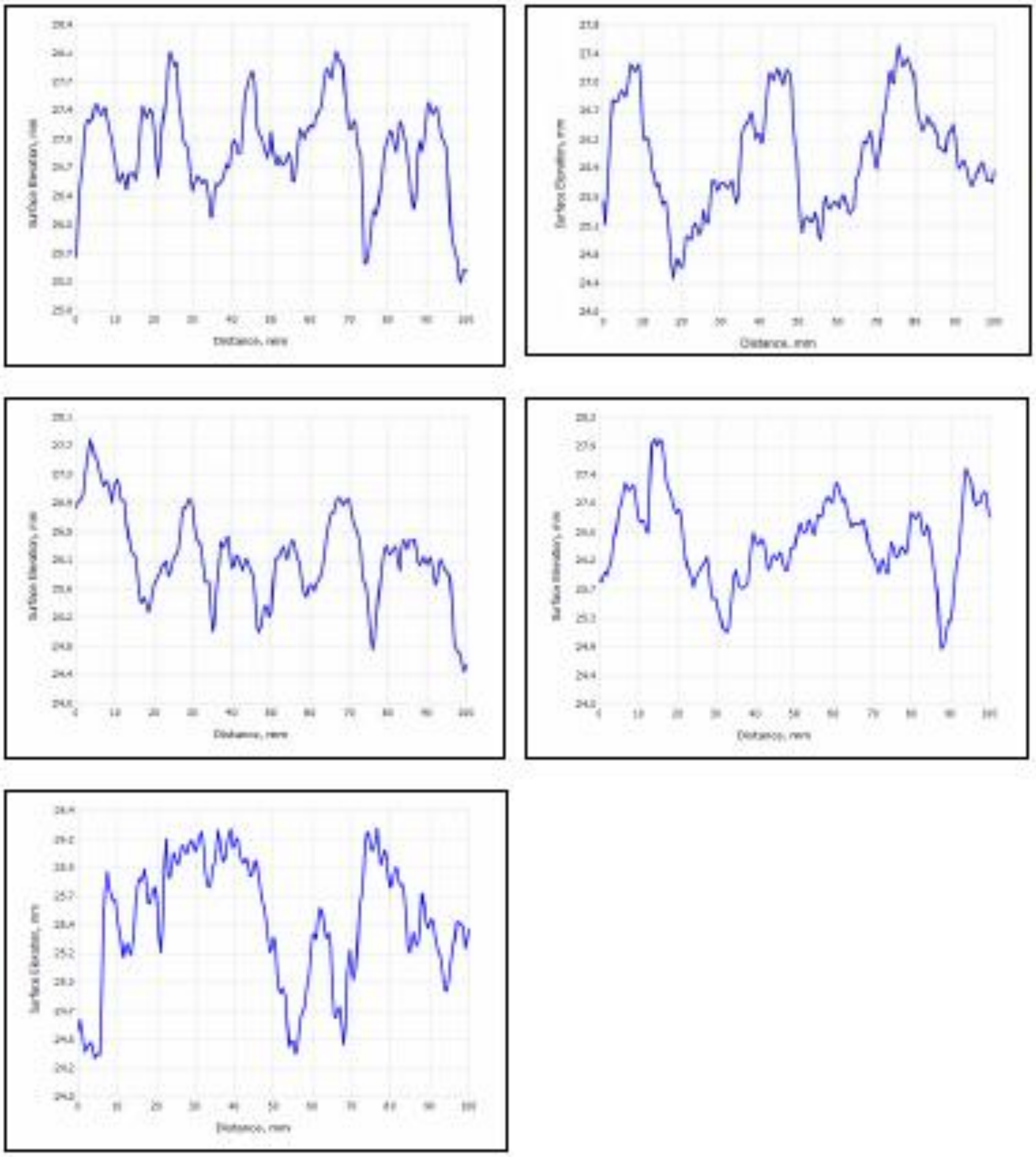

Figure 6-3 Typical Micro-milled Surface Textures for Eighth Test Section

CHAPTER 7 Assessment of Micro-milled Surface Texture Quality on I-75 Project

Evaluation of the micro-milled surface texture quality performed for this project was conducted on eight test sections using the CTM and the ULIP. The objectives of this part of the study were to assess if micro-milling could produce milled surfaces capable of meeting the ridge-to-valley surface texture depth requirements stipulated for this construction project, to offer suggestions for modifications of the specifications, and to make recommendations for the micro-milling operation in light of the results obtained from this study. Results for each of the test sections are presented in Chapters 5 and 6. Analyses and summaries of the results obtained from the eight test sections are presented in this chapter.

The following requirements for the micro-milled surface texture were stipulated according to GDOT Special Provision Section 432, "Mill Asphaltic Concrete Pavement (Micro Mill)," as a part of the acceptance criteria for the asphalt pavement mill and overlay construction project on Interstate 75 near Perry, Georgia:

1. Section 432.2.02 Equipment, C. Micro-milling Equipment: "Capable of removing pavement to an accuracy of $^{1}/_{16}$ in. (1.6 mm)."

2. Section 432.3.06 Quality/Acceptance. "Any areas exceeding ⅛ in. (3.2 mm) between the ridge and valley of the mat surface or fail to meet pavement surface acceptance testing using the Laser Road Profiler shall require that the underlying layer be removed and replaced with material as directed by the Engineer at no additional cost to the Department."

In Chapters 5 and 6, the mean ridge-to-valley surface texture depth (Mean RVD) measured by the ULIP and the estimated maximum Mean RVD values were used to relate to the requirement stipulated in (1) above, and the 95 percentile ridge-to-valley surface texture depth (p95 RVD) and the estimated maximum p95 RVD values were used to relate to the requirement stipulated in (2) above. There are several issues that are related to and could potentially affect the RVD values and, thus, affect the compliance of the micro-milled surface texture depth requirements. These include selection of an appropriate base length unit for calculating RVD from the ULIP data and selection of appropriate RVD parameters, Mean RVD, p90, p95, or others to relate to the milled texture depth requirements. These two issues are presented in Section 7.1 and Section 7.4. Other factors that could potentially affect the micro-milled surface textures include the milling speed and the duration of the milled surfaces' exposure to traffic before the surface texture depth measurements were performed and evaluated. The results are presented in Section 7.6.

7.1 Effects of Base Length on RVD from ULIP Data

As presented in Chapters 5 and 6, a 150-ft length was selected from the test sections for measuring surface textures by the ULIP. The ULIP measured the surface profile depth at every 0.5 mm interval in this entire 150-ft measuring length. There are over 90,000 data points for each of the 150-ft measuring paths. The ULIP measuring was conducted on two to four measuring paths for each of the test sections, and a minimum of three runs were performed for each 150-ft–long measuring path. Thus, a large amount of data were collected for each test section.

When calculating the RVD values from the ULIP data, a base length unit was selected and the height between maximum ridge and minimum valley within the base length unit was captured by the software as being the RVD value. The RVD values obtained from each base length units in each measuring path were used to calculate the Mean RVD and p50 to p99 RVD values for each measuring path. The values obtained for each measuring path were then averaged to obtain the corresponding Mean, RVD and p50 to p99 RVD values for the test section.

Selection of base length units plays an important role in computing RVD values. Table 7-1 summarizes the Mean RVD, p50 to p99 RVD values with 50 mm, 100 mm, 200 mm, and 500 mm base length units for the eight test sections measured by the ULIP. The effects of base length on the RVD are clearly shown in this table. The summary of the averaged ratios of the RVD values obtained from 50 mm, 200 mm, and 500 mm base length units to that from 100 mm base length unit for all eight test sections are presented in Table 7-2 and Figure 7-1. The results indicate that use of longer base length units would consistently result in higher RVD values in the Mean RVD and p50 to p99 RVD values of the surface texture depths.

Table 7-1 Summary of RVD Calculated from Different Base Lengths for All Sections

Section	Date Testing	Location	Base Length (mm)	Average 150-ft Section of RVD, mm					
				Mean	p50	p75	p90	p95	p99
S-0	05/01/07	Trial							
		Conventional	50	2.27	2.15	2.99	3.79	4.33	5.63
		Milling	100	3.35	3.25	4.22	5.17	5.80	7.13
			200	4.87	4.79	5.73	6.85	7.29	8.42
			500	7.05	7.08	7.97	8.86	9.50	10.77
S1-1	05/13/07	MP142 S1							
			50	1.51	1.30	1.99	2.74	3.20	4.14
			100	2.24	2.02	2.98	3.90	4.46	5.56
			200	3.02	2.88	4.03	5.14	5.65	6.83
			500	3.93	3.91	5.34	6.24	6.73	7.66
S1-2	05/13/07	MP142 S1							
			50	1.01	0.93	1.34	1.81	2.14	2.86
			100	1.43	1.36	1.89	2.46	2.88	3.66
			200	1.81	1.79	2.38	3.02	3.46	4.30
			500	2.29	2.35	2.98	3.68	4.18	4.74
S2-1	05/14/07	MP142 S1							
			50	0.88	0.75	1.08	1.52	1.86	2.54
			100	1.22	1.05	1.50	2.07	2.47	3.32
			200	1.55	1.34	1.93	2.59	3.04	3.97
			500	2.00	1.75	2.46	3.19	3.56	4.42
S2-2	05/14/07	MP142 S1							
			50	0.61	0.54	0.74	1.00	1.18	1.66
			100	0.84	0.75	1.01	1.34	1.58	2.10
			200	1.03	0.94	1.24	1.59	1.81	2.37
			500	1.32	1.28	1.56	1.85	2.09	2.58
S5-1	09/17/07	MP130 N1							
			50	1.35	1.23	1.71	2.28	2.66	3.47
			100	1.87	1.76	2.29	2.89	3.30	4.06
			200	2.30	2.21	2.74	3.33	3.68	4.46
			500	2.73	2.68	3.20	3.70	4.07	4.42
S5-2	09/17/07	MP130 N1							
			50	1.37	1.22	1.73	2.30	2.72	3.61
			100	1.92	1.77	2.35	3.02	3.47	4.42
			200	2.41	2.25	2.85	3.54	3.98	5.04
			500	2.85	2.74	3.28	3.84	4.21	4.65
S6	09/17/07	MP135 S2							
			50	1.19	1.09	1.45	1.87	2.18	2.96
			100	1.63	1.52	1.94	2.41	2.78	3.63
			200	2.02	1.94	2.34	2.76	3.06	3.72
			500	2.46	2.40	2.78	3.19	3.46	4.15
S7	10/02/07	MP128.9 N3							
			50	1.36	1.24	1.69	2.24	2.63	3.50
			100	1.89	1.76	2.30	2.93	3.33	4.23

Section	Date Testing	Location	Base Length (mm)	Average 150-ft Section of RVD, mm					
				Mean	p50	p75	p90	p95	p99
			200	2.39	2.27	2.80	3.36	3.80	4.58
			500	2.85	2.77	3.26	3.83	4.16	4.87
S8	10/02/07	MP129.4 L3							
			50	1.14	1.03	1.44	1.90	2.21	2.91
			100	1.62	1.51	2.01	2.52	2.87	3.59
			200	2.03	1.95	2.47	2.96	3.26	3.96
			500	2.47	2.42	2.87	3.38	3.63	4.07
Grand Total					1.86	2.40	2.98	3.36	4.13

Table 7-2 Ratios of RVD at Different Base Lengths to 100 mm Base Length (Section 1-1 to Section 8)

Base Length (mm)	Average 150-ft Section of Ridge-to Valley (RVD, mm)					
	Mean	p50	p75	p90	p95	p99
50	0.71	0.70	0.72	0.75	0.77	0.80
100	1.00	1.00	1.00	1.00	1.00	1.00
200	1.26	1.30	1.24	1.20	1.17	1.13
500	1.56	1.65	1.51	1.39	1.33	1.20

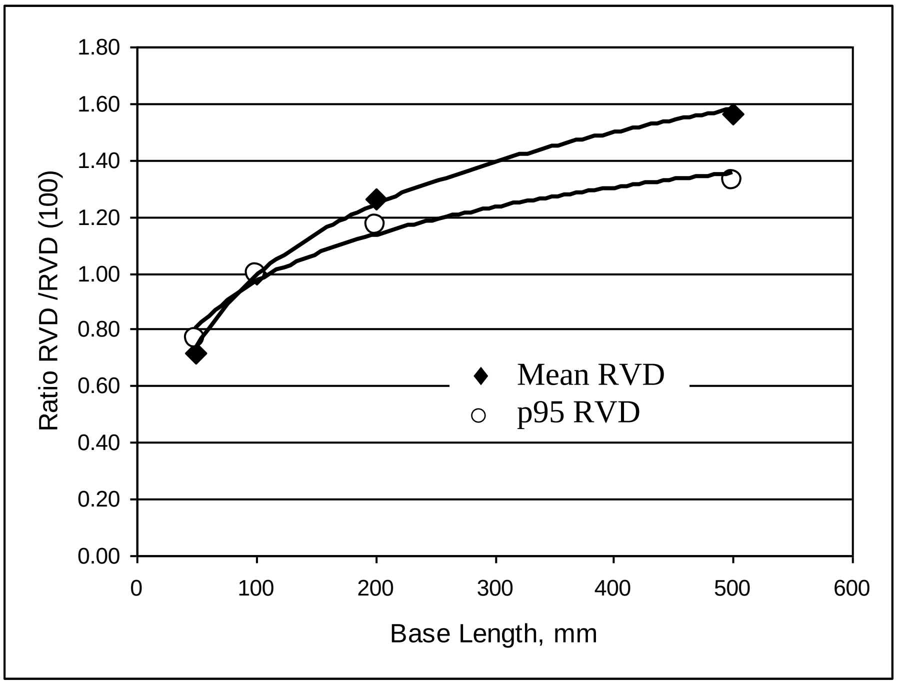

Figure 7-1 Variation of RVD Ratios with Base Length

In the NJDOT study [7], the effects of base length on the mean segment depth (MMSD) were also investigated. The ratios of MMSD obtained at different base lengths (25 mm to 200 mm) to that obtained at 100 mm from the study are shown in Figure 7-2. The trend shown in Figure 7-2 is quite similar to that shown in Figure 7-1.

According to ASTM E-1845 [3], 100 mm was specified as the base length when calculating mean profile depth. Therefore, to be consistent with that specified in ASTM E-1845, the RVD values calculated based on 100 mm base length were used in this research study for assessing the compliance of the ridge-to-valley milled surface texture depths with that allowed by the specification and for comparison with the results obtained from the CTM measurements.

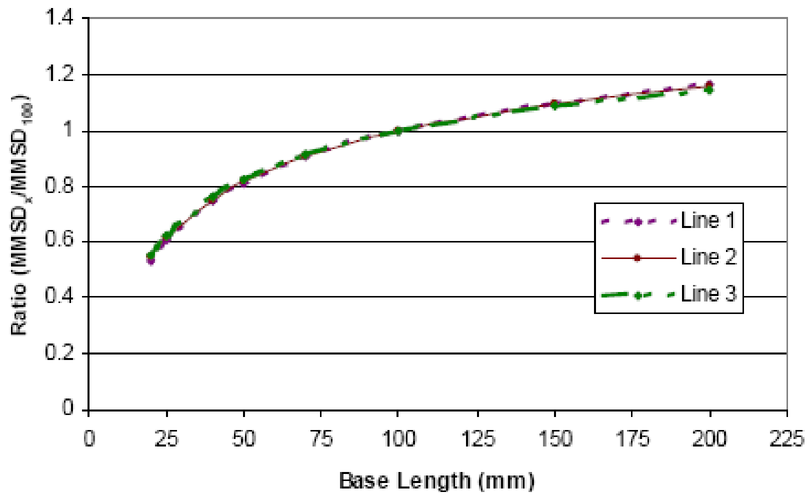

Figure 7-2 Variation of Texture Depth Ratios with Base Length [6]

7.2 Summary of MPD Obtained from CTM Data

As illustrated in Fig 2-3, the CTM can generate the mean profile depth for each individual segment (A–H), as well as the averaged MPD for all eight segments. Table 7-3 summarizes the MPD values of the micro-milled surface textures obtained from the CTM data along the milling direction (Segments A and E) and that perpendicular (Segments C and G) and diagonal (the other four segments) to the milling direction for all eight test sections. The results shown in Table 7-3 indicate that the maximum texture depths in terms of the MPD values in all eight test sections occurred in the direction either diagonal or perpendicular to the milling direction. The ratios of CG/AE and Diag./AE to that along the milling direction, as shown in Table 7-3, varied between 1.03 and 1.45 with an average of 1.21. However, no definitive trends existed between the MPD along the milling direction and that from the other directions, as indicated in Figure 7-3.

Table 7-3 Summaries of MPD Data in All Directions for Eight Test Sections

Section	Date		MPD Values, mm				Ratios to Milling Direction		
	Milled	Tested	A-E	C-G	Diag.	ALL	CG/AE	Diag./AE	Average Ratio
S1-1	5/13	5/13	1.19	1.56	1.51	1.44	1.31	1.27	1.28
S2-2	5/14	5/14	0.68	0.77	0.85	0.79	1.13	1.25	1.21
S3	5/21	5/21	0.89	1.29	1.13	1.11	1.45	1.27	1.33
S4-1	9/2	9/10	0.95	0.98	1.05	1.01	1.03	1.11	1.08
S4-2	9/2	9/10	0.93	1.10	1.11	1.07	1.18	1.19	1.19
S5-1	9/9	9/17	0.96	1.39	1.25	1.22	1.45	1.30	1.35
S5-2	9/9	9/17	0.91	1.15	1.06	1.07	1.26	1.16	1.19
S6	9/16	9/17	0.82	1.07	1.05	1.00	1.30	1.28	1.29
S7	10/2	10/2	1.03	1.10	1.14	1.11	1.07	1.11	1.10
S8	10/2	10/2	0.90	0.93	0.95	0.93	1.03	1.06	1.05
Average							**1.22**	**1.20**	**1.21**

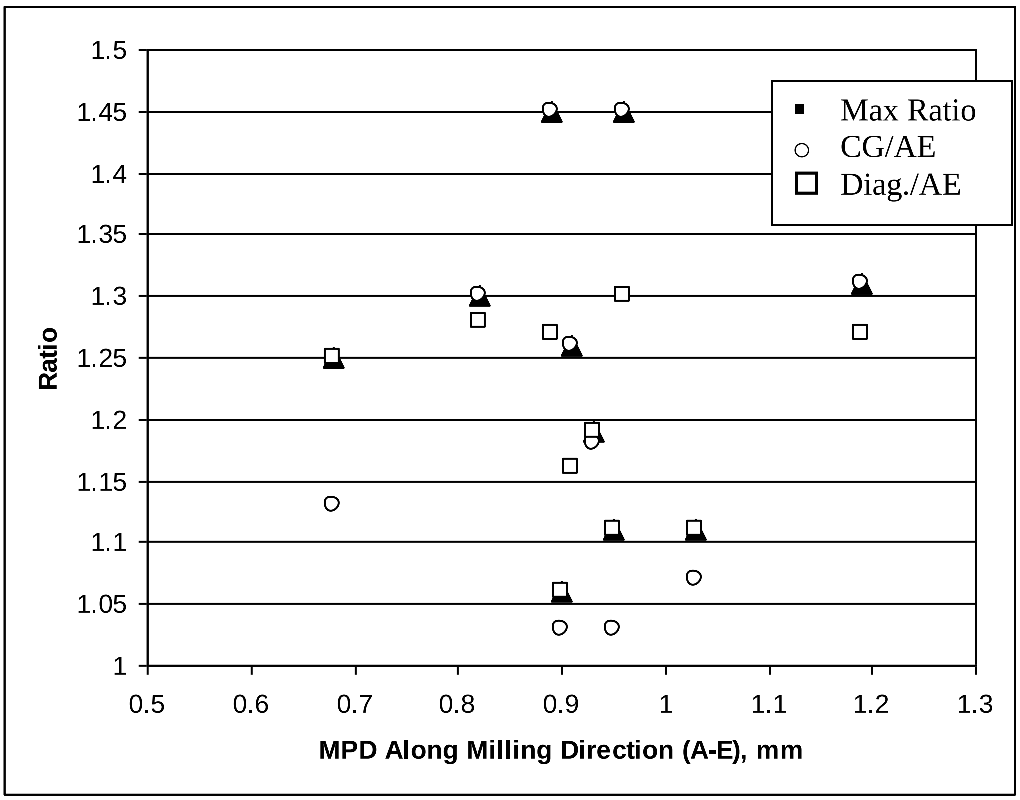

Figure 7-3 Relations between MPD (A-E) with MPD in other Directions

7.3 Estimation of Maximum RVD Values

According to the CTM test results presented in Table 7-3, the maximum surface texture depths for all the test sections occurred either in the directions perpendicular or diagonal to the milling direction. This would infer that the maximum RVD of the milled surface would most likely occur in the directions perpendicular or diagonal to the milling direction. Since the ULIP could only measure the surface texture in the milling direction, the RVD values determined from the ULIP data represented only the texture depth in the milling direction and did not represent the maximum texture depth on the entire milled surface. Estimations of the maximum RVD values were made by multiplying the RVD values obtained from the ULIP by the maximum direction ratios obtained from the CTM data (occurred in CG, or Diag. direction) shown in Table 7-3. This approach was based on the assumption that the RVD in the directions transverse and diagonal to the milling directions, if measured by the ULIP, would be proportional to the corresponding MPD values determined by the CTM. Results of the estimated maximum Mean, p90, and p95 RVD values obtained by this approach are presented in Table 7-4 for the eight test sections.

Table 7-4 Estimation of "Maximum" RVD Values

Section	RVD Data, mm			Max Dir	Est. Max RVD, mm		
	Mean	p90	p95	Ratio	Mean	p90	p95
S1-1	2.24	3.90	4.41	1.31	2.93	5.11	5.78
S2-2	0.84	1.34	1.58	1.25	1.05	1.68	1.98
S3	1.62	2.54	2.98	1.45	2.35	3.68	4.32
S4-1	1.77	2.82	3.27	1.11	1.96	3.13	3.63
S4-2	1.73	2.73	3.19	1.19	2.06	3.25	3.80
S5-1	1.87	2.89	3.30	1.45	2.71	4.19	4.79
S5-2	1.92	3.02	3.47	1.26	2.42	3.81	4.37
S6	1.63	2.41	2.78	1.30	2.12	3.13	3.61
S7	1.89	2.93	3.33	1.11	2.10	3.25	3.70
S8	1.62	2.52	2.87	1.06	1.72	2.67	3.04

Note: For Section 3 and Sections 4-1 and 4-2 the RVD values in the milling direction were estimated using Equation 5.1, Equation 5.2, and Equation 5.3.

7.4 Suitable RVD Parameters for Assessing Milled Texture Depth Requirements

There is a need to determine a set of RVD parameters that could best represent the specifications related to the targeted 1.6 mm milling accuracy requirement and to the requirement for corrective actions when RVD exceeded 3.2 mm. The parameters that could be selected from include Mean RVD, p50 to p99 RVD, and the corresponding estimated maximum Mean RVD, p50 to p99 RVD values. In Chapters 5 and 6, both Mean RVD and estimated maximum Mean RVD values were used tentatively to relate to the targeted 1.6 mm milling accuracy requirement, and both p95 RVD and estimated maximum p95 RVD values were used tentatively to relate to the requirement for corrective actions when RVD exceeded 3.2 mm.

An important consideration to bear in mind is the ease in the implementation in the quality control during the milling operation. It is important that the RVD parameters selected can be easily obtained shortly after the milling operation is completed so that the compliance of the milled surface quality can be determined immediately. An ideal case would be similar to current GDOT pavement surface smoothness quality control operations. The Smoothness Index of the entire length of the milled surface was obtained shortly after the milling operation was completed using the LRP.

A preliminary investigation conducted in this research study indicated that it is feasible to incorporate the ridge-to-valley pavement surface texture measuring capability into the LRP currently used by GDOT. This would allow RVD values to be acquired by the same LRP currently used for acquiring the profile Smoothness Index. However, the RVD values obtained by LRP are in the milling direction only, similar to those obtained by the ULIP. Although the CTM measurements could be made on selected locations and the data would be used to estimate maximum RVD values similar to the approach presented in Section 7.3. This would require additional efforts, however. The only other instrument that has the potential for acquiring the RVD values over the entire milled surface, not just along the milling direction, and the data can be obtained at high speed is the Laser Crack Measurement System developed by Tsai [8].

Regarding the targeted 1.6 mm milling accuracy requirement, it seems that using the Mean RVD would be reasonable. It represents the average of the RVD along the milling direction. While using the estimated maximum Mean RVD would seem more reasonable, the use of this parameter would require taking the CTM measurements. The average value and the standard deviation of the ratios of the estimated Mean RVD to the corresponding Mean RVD for the eight test sections shown in Table 7-4 are, respectively, 1.25 and 0.13. Since the targeted 1.6 mm milling accuracy requirement is not as critical as that of the requirement for corrective actions when the RVD exceeded 3.2 mm, using the Mean RVD for determining the targeted 1.6 mm milling accuracy requirement would be reasonable.

The requirement for corrective actions when the RVD exceeded 3.2 mm is more critical from the quality control and acceptance point of view. Originally, using *estimated maximum p90 RVD*, which represents the 90 percentile RVD in all directions on the milled surface, was considered. Again, use of this parameter would require taking the CTM measurements. An alternative would be to use the p95 RVD in the milling direction so that it would not require taking the CTM measurements. The average value and the standard deviation of the ratios of the estimated maximum p90 RVD to the corresponding p95 RVD (in the milling direction) for the eight test sections shown in Table 7-4 are, respectively, 1.08 and 0.11. The RVD values between these two parameters among the eight test sections are quite close. Therefore, the p95 RVD in the milling direction was considered in this project for determining the requirement for corrective actions when the RVD exceeded 3.2 mm.

Using these two parameters, the Mean RVD for the targeted 1.6 mm milling accuracy requirement and p95 RVD for determining the requirement for corrective actions, the summarized results shown in Table 7-4 indicated that Test Sections S2-2, S3, S6, and S8 could meet the requirements; Test Sections S1-1, S5-1, S5-2, and S7 failed the requirements; and Test Sections S4-1 and S4-2 are borderline.

It should be emphasized that no matter what RVD values were selected in this project to be the threshold values for representing these two acceptance requirements, such threshold RVD values should be viewed only as being tentative. The ultimate test to the appropriateness of the selected threshold RVD values should be based on the long-term performance of the OGFC/PEM layer placed on top of the micro-milled surface.

7.5 Comparison of MPD Obtained from ULIP and CTM Measurements

Table 7-5 summarizes the Mean, p50 to p99 MPD values calculated from the ULIP data for all the test sections. Also presented in this table are the MPD values along the milling direction (average of A and E segments) from the CTM testing (from Table 7-3). It is worth noting that among all the test sections in which both the ULIP data and the CTM data were collected, the Mean MPD obtained from the ULIP data are consistently less than that of the MPD obtained from the CTM data in the milling direction. Although the MPD values determined from both the CTM and the ULIP measurements were determined according to ASTM E-1845 using 100 mm base length, the number of units used for calculating the averaged MPD were significantly different: 24 to 54 individual MPD values for the CTM data and 2700 to 5400 for the ULIP data. This could be one of the reasons contributing to the differences.

Table 7-5 MPD Values Determined from ULIP Data (100 mm Base Length)

Section	Date Measure	MPD from ULIP (mm) at 100 mm base length						MPD /CTM A-E (mm)	Remarks
		Mean	p50	p75	p90	p95	p99		
S0	05/01/07	1.30	1.23	1.64	2.08	2.39	3.02	1.99	
S1-1	05/13/07	0.91	0.79	1.21	1.66	1.96	2.52	1.19	
S1-2	05/13/07	0.59	0.52	0.73	0.98	1.16	1.53		No CTM
S2-1	05/14/07	0.46	0.39	0.56	0.80	0.95	1.30		No CTM
S2-2	05/14/07	0.32	0.30	0.39	0.50	0.58	0.78	0.68	
S3	05/21/07							0.89	No ULIP
S4-1	09/10/07							0.95	No ULIP
S4-2	09/10/07							0.93	No ULIP
S5-1	09/17/07	0.66	0.61	0.80	1.00	1.14	1.45	0.96	
S5-2	09/17/07	0.68	0.62	0.83	1.06	1.21	1.64	0.91	
S6	09/17/07	0.61	0.57	0.72	0.90	1.02	1.34	0.82	
S7	10/02/07	0.68	0.63	0.83	1.06	1.21	1.55	1.03	
S8	10/02/07	0.61	0.56	0.75	0.95	1.09	1.38	0.90	

7.6 Effect of Milling Speed and Exposure to Traffic on Milled Surface Textures

7.6.1 Milling Speed

The effect of milling speed on the milled surface texture in terms of Mean RVD and p95 RVD are presented in Table 7-6 and Figure 7-4. Data from Test Section 1-1 was not used in the comparison because it was considered that during the initial trial testing consistent micro-milling operation was not yet properly established. Data from Test Section S3 and S4 were not used because no direct RVD data from the ULIP were obtained. The two curves shown in Figure 7.4 clearly show definitive trends between the milling speed and the Mean RVD and p95 RVD values. With the milling equipment used for this construction project, by keeping the milling speed to about 20 ft./min or slower the milled surface texture depths could meet the targeted 1.6 mm and correction 3.2 mm requirements.

Of course, there are other factors that could also affect milled surface texture depths in addition to the milling speed. The characteristics of the milling equipment and the characteristics and the conditions of the micro-milling drum are perhaps the most important factors other than the milling speed that can affect milled surface texture depths. Types of underlying HMA surface (see the I-95 project presented in Chapter 9) and perhaps types of coarse aggregates used in the existing HMA could also affect the milled surface textures

Table 7-6 Ridge-to-Valley Milled Surface Texture vs. Milling Speed

Test Section	Date		Milling Speed (ft./min)	Est. Max RVD, mm		Remarks
	Milled	Tested		Mean	p95	
S1-1	5/13	5/13		2.24	4.41	Data not used
S2-2	5/14	5/14	14	0.84	1.58	
S3	5/21	5/21				No direct RVD data
S4-1	9/2	9/10				No direct RVD data
S4-2	9/2	9/10				No direct RVD data
S5-1	9/9	9/17	28	1.87	3.30	
S5-2	9/9	9/17	28	1.92	3.47	
S6	9/16	9/17	24	1.63	2.78	
S7	10/2	10/2	23	1.89	3.33	
S8	10/2	10/2	19	1.62	2.87	

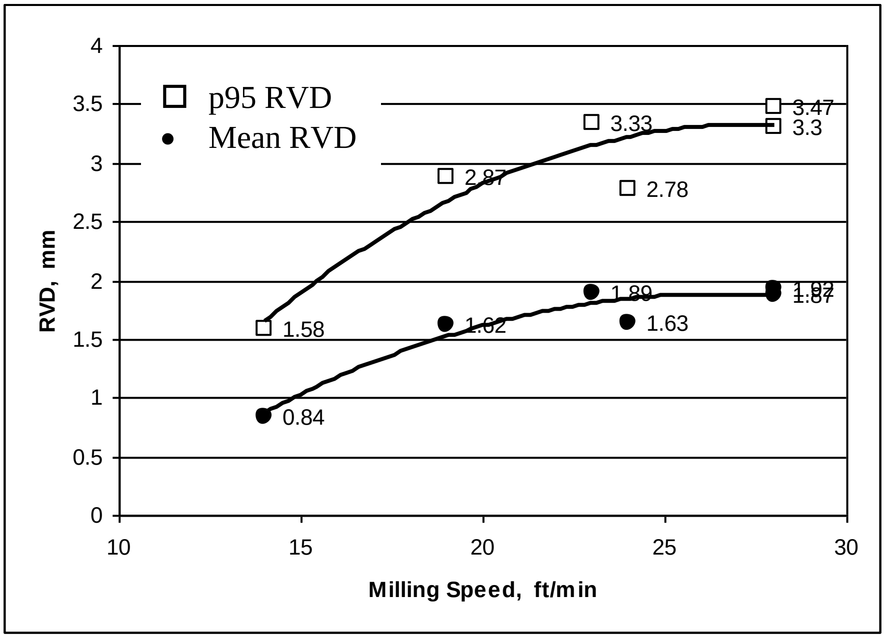

Figure 7-4 RVD Surface Textures Depth vs. Milling Speed

7.6.2 Length of Time Exposed to Traffic

Length of time the milled surfaces exposed to highway traffic could conceivably also affect milled surface texture depths. Table 7-7 summarizes the length of time the milled surfaces of the eight test sections were exposed to traffic. For Test Sections S1, S2, S3, S7, and S8, measuring of the surface textures was performed immediately after the milling was completed and the surface was swept clean; Test Section S6 was exposed to traffic for 1 day; while Test Sections S4 and S5 were exposed to traffic for 8 days before measurement of the surface textures was performed. The abrasion actions of heavy wheel loading and tire pressure from the highway traffic could conceivably cause the ridges of the milled surface textures to be smoothed out and, thus, reduce the ridge-to-valley depths. Such effect could conceivably be even more obvious in the summer when the high daytime temperature could soften the milled asphalt pavement surfaces and, thus, reduce the ridge-to-valley depths.

A field experiment to assess the effect of traffic exposure was considered. However, due to tight construction scheduling facing the contractors and other concerns, such an experiment was not carried out. The only data that could point to such effects was from the Mean RVD and p95 RVD data for Test Sections S5-1 and S5-2, the data points on the far right of the curves, as shown in Fig 7-4. One could speculate that if the surface textures for S5-1 and S5-2 were measured immediately after the milling, the Mean RVD and p95 RVD values for these two sections could be higher, resulting in the curves shown in Fig 7-4 to trend upward instead of leveling off.

The effects of prolonged exposure to traffic on the micro-milled surface characteristics could have some implications in the quality control and in developing micro-milling specifications.

Table 7-7 Effect of Duration of Milled Surfaces Exposure to Traffic

Section	Date			RVD, mm	
	Milled	Tested	Duration	Mean	p95
S1-1	5/13/2007	5/13/2007	0	2.24	4.41
S2-2	5/14/2007	5/14/2007	0	0.84	1.58
S3	5/21/2007	5/21/2007	0		
S4-1	9/2/2007	9/10/2007	8		
S4-2	9/2/2007	9/10/2007	8		
S5-1	9/9/2007	9/17/2007	8	1.87	3.30
S5-2	9/9/2007	9/17/2007	8	1.92	3.47
S6	9/16/2007	9/17/2007	1	1.63	2.78
S7	10/2/2007	10/2/2007	0	1.89	3.33
S8	10/2/2007	10/2/2007	0	1.62	2.87

7.7 Conclusions

Evaluation of the micro-milled surface texture quality performed on the I-75 micro-milling project was conducted on eight test sections using the CTM and the ULIP. The objectives of this part of the study were to assess whether or not micro-milling could produce the milled surfaces capable of meeting the ridge-to-valley surface texture depth requirements stipulated for this construction project. The two requirements were: (1) capable of removing pavement with milling accuracy of targeted 1.6 mm, and (2) requiring corrective actions when RVD exceeds 3.2 mm. Results for each of the test sections are presented in Chapters 5 and 6. Analyses and summaries of the results obtained from the eight test sections are presented in this chapter.

The overall conclusion based on the results obtained from this project is that with the milling equipment used for this construction project and by keeping the milling speed to about 20 ft./min or slower, the Mean RVD can meet the targeted 1.6 mm milling accuracy requirement, and the 95 percentile RVD can meet the not-to-exceed correction 3.2 mm requirement. Based on the 4 years of satisfactory performance of the PEM overlay placed on the micro-milled surface, the use of the Mean RVD and p95 RVD to represent the threshold values for compliance with the two requirements stipulated in the specification are adequate, but could be too conservative.

The following are some specific conclusions.

7.7.1 Effects of Base Length on RVD from ULIP Data

Selection of base length units plays an important role in computing RVD values. Use of longer base length units for computing the RVD values consistently results in higher RVD values in the Mean and 50 to 99 percentile of the surface texture depths. Based on ASTM E-1845, 100 mm was specified as the base length for calculating mean profile depth. To be consistent with ASTM E-1845, the RVD results calculated based on 100 mm base length were used in this research study to assess the compliance with the two requirements stipulated by GDOT for the construction project.

7.7.2 MPD Obtained from CTM Data

Testing using the CTM to measure micro-milling surface textures was conducted on the eight test sections. Mean profile depth values for the micro-milled surface textures obtained from the CTM data along the milling direction (Segments A and E) and that are perpendicular (Segments C and G) and diagonal (the other 4 segments) to the milling direction were determined. The results indicated that the maximum texture depths in terms of the MPD values in all eight test sections occurred in the direction either diagonal or perpendicular to the milling direction. The ratios of CG/AE and Diag./AE to that along the milling direction varied between 1.03 and 1.45 with an average of 1.21.

7.7.3 Estimation of Maximum RVD Values

Estimations of maximum RVD values were made by multiplying the RVD values obtained from the ULIP by the maximum direction ratios of the MPD values (occurred in CG, or Diag. direction) from the CTM data in the same test section. This approach for estimating maximum RVD was based on the assumption that the RVD in the directions transverse and diagonal to the milling directions, if measured by ULIP, would also be proportional to the corresponding MPD values determined by the CTM.

7.7.4 Suitable RVD Parameters for Assessing Milled Texture Depth Requirements

The parameters that were selected from included Mean RVD, p50 to p99 RVD, and the corresponding estimated maximum Mean RVD, and p50 to p99 RVD values. After analyzing the results and consideration of the ease of implementation of the quality control during the milling operations, *Mean RVD* and *p95 RVD*, both in milling direction, were recommended for determining the compliance of the targeted 1.6 mm milling accuracy requirement and the requirement for corrective actions when RVD exceeds 3.2 mm, respectively. This consideration was based on the milling equipment used for this construction project traveling at a milling speed of 20 ft./min or slower, milled to surface texture depths capable of meeting the requirements. Use of these two parameters would require using a linear laser-based surface profile measuring instrument, such as the ULIP or a modified LRP alone and would not require additional data from the CTM. This would expedite the quality control during the milling operations.

It should be emphasized that no matter which RVD values were selected in this project to be the threshold values for representing these two acceptance requirements, such threshold RVD values should be viewed as only the tentative values. The ultimate test for the appropriateness of the selected threshold RVD values should be based on the long-term performance of the OGFC/PEM layer placed on top of the micro-milled surface.

The pavement conditions of this project have been monitored since the PEM overlay paving was completed in November 2007. The last time the author visited the project site on November 7, 2010, three years after the PEM overlay paving was completed, no slippage failure or delamination due to poor bonding or other distresses was observed on any of the PEM surfaces of this project. This seems to indicate that, among other factors that can also affect the pavement performance, the micro-milling operation used and the characteristics of the micro-milled surface textures generated on this project were adequate. Among the test sections measured by the ULIP, the results indicated that the Mean RVD and p95 RVD values of several test sections exceeded the targeted 1.6 mm and correction 3.2 mm requirements, respectively (see Table 7-4). Since the test sections represent only a very small portion of the entire project, and had the micro-milled surface textures been monitored on the entire project, the Mean RVD and the p95 RVD of the milled surface textures of a significant portion of the project would also fail to meet the targeted 1.6 mm and correction 3.2 mm RVD requirements, yet no delamination occurred on the PEM overlay on the entire project. This seems to indicate that the use of p95 RVD for determining the 3.2 mm threshold for requiring corrective action is too conservative, in so far as relating to the long-term pavement performance is concerned.

7.7.5 Summary of the Micro-milled Surface Texture Depths of Eight Test Sections

Using these two parameters, the Mean RVD for the targeted 1.6 mm milling accuracy requirement and p95 RVD for determining the requirement for corrective actions, the results from the eight test sections indicated that Sections S2-2, S3, S6, and S8 could meet the requirements; Sections S1-1, S5-1, S5-2, and S7 failed the requirements; and Sections S4-1 and S4-2 were borderline.

7.7.6 Effect of Milling Speed on Milled Surface Textures

The milling speed for the micro-milling operations in the eight test sections varied from 14 ft./min to 28 ft./min. Comparison between the milling speed and the Mean RVD and p95 RVD values among the test sections clearly showed definitive trends with higher milling speed producing higher RVD values. With the milling equipment used for this construction project, keeping the milling speed to about 20 ft./min or slower, the Mean RVD and the p95 RVD of the milled surface texture depths could meet the targeted 1.6 mm and correction 3.2 mm requirements.

7.7.7 Effect of Exposure to Traffic on Milled Surface Textures

The length of time the milled surfaces are exposed to highway traffic could conceivably also affect milled surface texture depths. Among the eight test sections, five were measured immediately after the milling was completed and the surface was swept clean, one test section was exposed to traffic for one day, and two test sections were exposed to traffic for eight days. The abrasion actions of heavy wheel loading and tire pressure from the highway traffic could possibly have caused the ridges of the milled surface textures to be smoothed out and reduced the ridge-to-valley depth. Such an effect could conceivably be even more obvious in the summer when the high daytime temperature could soften the milled asphalt pavement surfaces and reduce the ridge-to-valley depth. No specific field experiment was conducted to directly assess such an effect, but the available data from the eight test sections indicated the possibility that such an effect occurred. Such effects could have some implications in specifying when the quality control testing of the RVD should be performed, immediately after milling or allowing the measurements to be taken just before the overlay paving.

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CHAPTER 8 Evaluation of Bond Strength at I-75 Project

8.1 Bond Strength Testing Procedure

Based on the literature review of the subjects of testing bond strength between pavement layers presented in Chapter 3, and after discussion with the engineers at the GDOT Office of Materials and Testing (OM&T), it was decided that the following parameters be adopted for testing bond strength between the PEM and the micro-milled surface for the test sections:

- Specimen diameter: 6 in.
- Mode of loading: strain controlled
- Rate of loading: 2 in./min
- Testing temperature: 77°F
- Confining stress: No normal stress applied on the test specimen

The testing of bond strength for the cores taken from the test sections for this research project was performed by NCAT using the Marshall Tester with the bond strength device shown in Figure 3.4.

8.2 Trial Testing of Bond Strength

The bond strength testing was performed on seven cores cut from pavement on Interstate 20 located on the west side of Atlanta, Georgia. The pavement surface was a PEM placed on an SMA under-layer that had been constructed for approximately 1 year prior to testing. The purpose for this trial testing was to determine the bond strength between the PEM and the SMA under-layer. Experience indicated that this type of pavement performs well; thus, the bond strength from this testing could serve as a useful reference for establishing the bond strength threshold value for PEM over a micro-milled surface.

The testing procedure and parameters described in Section 8.1 were followed, and the results are shown in Table 8-1.

According to the NCAT study [12], most of the field test sections had bond strengths above 100 psi. It suggested that an average bond strength of 100 psi is representative of bond strength between typical HMA pavement layers against slippage failure. This statement is supported by the results shown in Table 8-1.

As indicated in the FDOT study [10], curing time could have varying effects, ranging from significant to negligible, on the bond strength between asphalt pavement layers (see Section 3.3). This should be taken into consideration when using the results obtained from this trial bond strength testing to establish the bond strength acceptance threshold value for PEM over a micro-milled surface.

Table 8-1 Bond Strength Test Results

Sample #	Diameter, in.	Load to Failure, lbs.	Bond Strength, psi
1	5.91	2200	80.2
2	5.89	2300	84.4
3	5.93	3000	108.6
4	5.91	6200	226.0
5	5.91	3100	113.0
6	5.93	3400	123.1
7	5.85	2500	93.0
Average	5.90	3243	118.3
Std Dev	0.03	1377	50.0

8.3 Evaluation of Tack Coat Application Rate

Based on the literature review for the tack coat application rates for different pavement surfaces [10–13] and the typical PG 64-22 tack coat application rates used for asphalt pavement construction in Georgia, the Office of Materials and Testing has recommended using 0.06 and 0.08 gal/yd^2 application rates on the micro-milled surfaces of the test sections to evaluate bond strength between the PEM overlay on the micro-milled surface. Table 8-2 summarizes the results of two tack coat application tests and the bond strength obtained. The testing programs and the bond strength test results are presented in the following.

Table 8-2 Summary of Tack Coat Rate and Bond Strength Test Results

Test	#1	#2
Location	MP133 -132.3 SB1	MP132.5 -130.5 SB3
Tack Coat Rate	0.06 gal/yd^2	0.08 gal/yd^2
Date Tack Appl	09/10/07	10/16/07
Date Coring	10/21/07	11/29/07
Date Tested	10/23/07	11/30/07
Bond Strength (psi)		
Average	63.0	85.6
High-Low	82.7 - 59.3	98.3 - 75.0

8.3.1 Tack Coat Application Rate Testing Scheme for Test #1

Originally, two Tack Coat Application Sections, TCR-1 and TCR-2, as shown in Figure 8-1, were planned for testing tack coat application rates at 0.08 gal/yd^2 (TCS-1) and 0.06 gal/yd^2 (TCS-2). Each section was approximately 2000 ft. long.

Two rows consisting of twelve 12″× 12″ pieces of thin metal pads were installed per TCR section at the locations shown in Figure 8-1. For this test setup, thin metal pads instead of heavy geotextile pads, as specified by ASTM D-2995, were used. Due to the fact that PG 64-22 paving asphalt was used as tack coat in this construction project, it was believed that using thin metal pads should not affect the test results. Actually, using the metal plates instead of geotextile pads simplified the testing process.

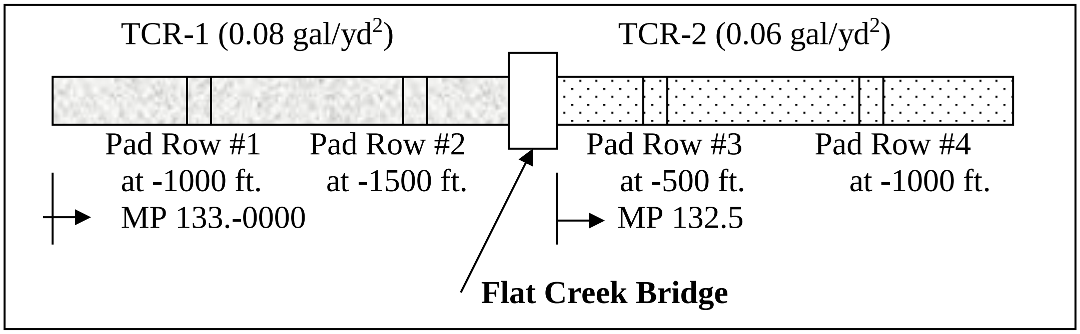

Figure 8-1 Locations and Layout for Tack Coat Rates Testing Plan

Figures 8-2 and 8-3 show the pad assembly placed on the test section before and after the asphalt tack coat was sprayed. As soon as the asphalt distributor had sprayed the tack coat over the pad assemblies, the pads were removed one by one in sequence from the pavement surface and were weighed to the nearest 0.1 gram and recorded on the data sheets. The results are summarized in Table 8-3. Detailed data and results are shown in Table 8-4A to Table 8-4D. Unfortunately, the actual tack coat application rates tested (see Table 8.3) indicated that the actual tack coat applied on both test sections was about 0.06 gal/yd^2 instead of 0.08 and 0.06 gal/yd^2 as originally planned. Instructions for applying 0.08 gal/yd^2 tack coat for TCS-1 and 0.06 gal/yd^2 for TCS-2 were conveyed to the contractor. It was not clear what caused the actual tack rate applied on TRC-1 section to be incorrect.

Figure 8-2 Pad Assembly before Tack Coat is Sprayed

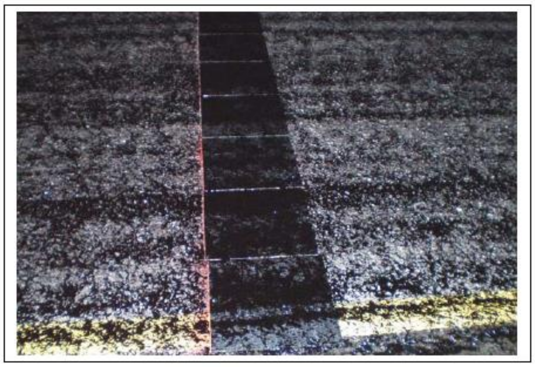

Figure 8-3 Pad Assembly after Tack Coat is Sprayed

Table 8-3 Summary of Tack Coat Rate Test Results

Pad Assembly	Design Rate (gal/yd^2)	Actual Results		No. of Pads Survived
		Mean (gal/yd^2)	CV	
1	0.08	0.066	17.1%	11/12
2	0.08	0.059	14.3%	12/12
3	0.06	0.061	15.1%	12/12
4	0.06	0.057	23.0%	10/12

Table 8-4 Tack Coat Rate Test Results

(A) TCR-1, Row #1

Row 1: Design Tack Rate = 0.08 gal/yd^2 Design Tack Wt. = 34.80 gr.

Plate	Plate Wt.	Combined Wt. (grams)	Tack Wt. (grams)	Deviation Actual-Design	Deviation % Dev
1	342.1	373.0	30.9	-3.9	-11.21%
2	344.4	366.0	21.6	-13.2	-37.93%
3	343.1	369.0	25.9	-8.9	-25.57%
4	342.9	370.0	27.1	-7.7	-22.13%
5	342.6	365.0	22.4	-12.4	-35.63%
6	342.9	368.0	25.1	-9.7	-27.87%
7	345.9	378.0	32.1	-2.7	-7.76%
8	342.7	373.0	30.3	-4.5	-12.93%
9	345.4	379.0	33.6	-1.2	-3.45%
10	344.2	382.0	37.8	3.0	8.62%
11	344.5	374.0	29.5	-5.3	-15.23%
12	343.0				
	Average		**28.8**	**-6.0**	**-17.37%**
	STDEV			**4.9**	
	CV			**17.0%**	

Design Tack Coat = 0.08 gal/yd^2; Actual Tack Coat = 0.066 gal/yd^2

(B) TCR-1, Row #2

Row 2: Design Tack Rate = 0.08 gal/yd^2 Design Tack Wt. = 34.68 gr.

Plate	Plate Wt.	Combined Wt. (grams)	Tack Wt. (grams)	Actual-Design	% Dev
13	343.1	365.0	21.9	-12.9	-37.20%
14	344.3	373.0	28.7	-6.1	-17.59%
15	345.6	366.0	20.4	-14.4	-41.52%
16	344.5	367.0	22.5	-12.3	-35.47%
17	345.9	371.0	25.1	-9.7	-27.97%
18	344.6	366.0	21.4	-13.4	-38.64%
19	345.0	369.0	24.0	-10.8	-31.14%
20	345.1	371.0	25.9	-8.9	-25.66%
21	345.4	372.0	26.6	-8.2	-23.64%
22	347.8	378.0	30.2	-4.6	-13.26%
23	346.1	375.0	28.9	-5.9	-17.01%
24	346.6	378.0	31.4	-3.4	-9.80%
	Average		**25.6**	**-9.2**	**-26.58%**
	STDEV			**3.7**	
	CV			14.3%	

Design Tack Coat = 0.08 gal/yd^2; Actual Tack Coat = 0.059 gal/yd^2

(C) TCR-2, Row #3

Row 3: DesignTack Rate = 0.06 gal/yd2 Design Tack Wt. = 26.01

Plate	Plate Wt.	Combined Wt. (grams)	Tack Wt. (grams)	Deviation Actual-Design	% Dev
25	344.6	370.0	25.4	-0.6	-2.35%
26	345.5	368.0	22.5	-3.5	-13.49%
27	346.2	369	22.8	-3.2	-12.34%
28	345.1	372.0	26.9	0.9	3.42%
29	345.8	368.0	22.2	-3.8	-14.65%
30	359.8	384.0	24.2	-1.8	-6.96%
31	341.7	369.0	27.3	1.3	4.96%
32	344.0	375.0	31.0	5.0	19.18%
33	343.0	374.0	31.0	5.0	19.18%
34	341.2	371.0	29.8	3.8	14.57%
35	343.0	375.0	32.0	6.0	23.03%
36	343.6	364.0	20.4	-5.6	-21.57%
	Average		**26.3**	**0.3**	**1.08%**
	STDEV			**4.0**	
	CV			15.1%	

Design Tack Coat = 0.06 gal/yd^2; Actual Tack Coat = 0.061 gal/yd^2

(D) TCR-2, Row #4

Row 4: Design Tack Rate = 0.06 gal/yd2 Design Tack Wt. = 26.01 gr.

Plate	Plate Wt.	Combined Wt. (grams)	Tack Wt. (grams)	Deviation Actual-Design	% Dev
37	344.1	372.0	27.9	1.9	7.27%
38	347.1	367.0	19.9	-6.1	-23.49%
39	346.5	369.0	22.5	-3.5	-13.49%
40	345.9				
41	341.3	362.0	20.7	-5.3	-20.42%
42	344.6	367.0	22.4	-3.6	-13.88%
43	342.6	371.0	28.4	2.4	9.19%
44	343.8	373.0	29.2	3.2	12.26%
45	342.4	374.0	31.6	5.6	21.49%
46	345.0	374.0	29.0	3.0	11.50%
47	345.7				
48	345.6	359.0	13.4	-12.6	-48.48%
	Average		**24.5**	**-1.5**	**-5.81%**
	STDEV			**5.6**	
	CV			23.0%	

Design Tack Coat = 0.06 gal/yd^2; Actual Tack Coat -= 0.057 gal/yd^2

8.3.2 Evaluation of Bond Strength for Tack Coat Test Section 1

Initially, coring was attempted one day after PEM was paved to cut cores from the pavement for testing the bond strength. However, the PEM surface was too tender to allow for cutting cores from the pavements, and coring was delayed. Coring was performed on October 21, 42 days after the PEM was paved. A total of 10 cores were cut from the pavement at random locations shown in Table 8-5. The first 5 cores were located between Pad Row #1 and Pad Row #2; the remaining 5 cores between Pad Row #3 and Pad Row #4. Bond strength testing was performed on October 23, two days after the cores were cut. The bond strength testing parameters stipulated in Section 8.1 were followed, and the test results are presented in Table 8-5.

Table 8-5 Bond Strength Test Results for Test Section 1

Sample ID	Location (ft.)		Bond Strength (psi)	Remarks
	Longitudinal	Transverse		
#1	MP133 -757	2.1	66.8	
#2	MP133 -757	5.6		Kept for GDOT
#3	MP133 -799	3.7	60.3	
#4	MP133 -792	7.1	59.3	Interface damp
#5	MP133 -743	9.8	41.6	Core disturbed
#6	MP132.5 -337	2.3	64.5	
#7	MP132.5 -321	4.1		Kept for GDOT
#8	MP132.5 -345	7.5	68.1	
#9	MP132.5 -300	6.0	82.7	
#10	MP132.5 -312	9.1	60.9	
AVG			63.0	

Note: Transverse location measured from the inside shoulder mark.

8.3.3 Plan for Tack Coat Test Section 2

Since the Tack Coat Test #1 described in Sections 8.3.1 and 8.3.2 resulted in applying about the same 0.06 gal/yd^2 in the two Tack Coat Application Sections (TCR-1 and

TCR-2) instead of applying 0.06 gal/yd^2 and 0.08 gal/yd^2 tack coat rates as originally intended, the research team scheduled another tack coat test section. Tack Coat Test #2 was set up to apply 0.08 gal/yd^2 tack rate. The section was located in Southbound Lane 3 between MP 132.5 (south end of Flat Creek Bridge) and MP 130.5. The tack rate of 0.08 gal/yd^2 was carefully controlled by the paving contractor, although testing of the actual tack coat application rate, similar to that described in Section 8.3.1, was not conducted. The tack coat application and the PEM paving were performed on September 16, 2007.

Coring of samples from the test section was performed on November 29, forty-five days after the PEM was paved. A total of 10 cores were cut from the pavement at random locations, as shown in Table 8-6. Bond strength testing was performed on November 30, 1 day after the cores were cut. The bond strength testing parameters stipulated in Section 8.1 were followed, and the test results are presented in Table 8-6.

8.4 Conclusions

The results shown in Table 8-5 and Table 8-6, and summarized in Table 8-2, indicate that the bond strength for the cores taken from Tack Coat Test Section 2, which used 0.08 gal/yd^2 tack rate, was significantly higher than that from Tack Coat Test Section 1, which used 0.06 gal/yd^2 tack rate. It is likely the bond strength will increase with pavement age.

The NCAT study [11] suggested that average bond strength of 100 psi is representative of bond strength between typical HMA pavement layers against slippage failure; a bond strength between 50 psi to 100 psi is considered marginal, and below 50 psi inadequate. Based on these criteria, the bond strength for the two tack coat test sections are marginal against slippage failure.

Table 8-6 Bond Strength Test Results for 0.08 gal/yd^2 Tack Coat Rate

Sample ID	Location (ft.)		Bond Strength (psi)	Remarks
	Longitudinal	Transverse		
#1	MP132.5-737	2.1		Kept for GDOT
#2	MP132.5-712	3.7	89.1	Interface dry
#3	MP132.5-722	6.2	98.3	
#4	MP132.5-703	8.1	88.1	
#5	MP132.5-732	10.1	74.7	Interface damp
#6	MP132.5-1209	2.3	86.2	
#7	MP132.5-1235	4.1		Kept for GDOT
#8	MP132.5-1205	4.5	76.7	
#9	MP132.5-1240	7.5	96.4	Interface dry
#10	MP132.5-1227	9.3	75.0	Interface damp
AVG			85.6	

Note: Transverse location measured from the outside shoulder mark.

The pavement conditions of this project have been monitored since the PEM overlay paving was completed in November 2007. The last time the writer visited the project site on November 7, 2010, three years after the PEM overlay paving was completed, no slippage failure or other distresses was observed on any of the PEM surfaces for this project.

PART 3: I-95 MICRO-MILLING PROJECT NEAR SAVANNAH, GEORGIA

CHAPTER 9 Micro-milling at I-95 Project

The objectives of the research studies carried out at the I-75 micro-milling project near Perry, Georgia, were to evaluate the micro-milled surface texture characteristics and to assess whether the tentative acceptance criteria were attainable and practical. The results obtained from the project indicated that the tentative acceptance criteria were attainable. At the I-75 project, only ten 150-ft segments from eight ½-mile micro-milling sections were selected for monitoring the ridge-to-valley texture depth. However, if the micro-milling technique and the specifications are to be adopted as a viable alternative to the conventional milling; additional data generated from micro-milling operations under different construction conditions, such as different types of pavement structure, different milling machines and operation conditions, etc., should be collected and analyzed to refine and revise the micro-milling specifications. This would ensure that the specifications are practical and implementable.

The use of micro-milling techniques for removing the existing OGFC surface at the I-95 project near Savannah, Georgia, was the second time such a technique was used by GDOT. The micro-milling operation at the I-95 project was performed by a different contractor and used a different milling machine equipped with a different milling drum. The underlying asphalt mixture at the I-95 project was an SMA, while that at the I-75 project was a dense-graded 12.5 mm mixture. Different techniques for measuring the micro-milled surface textures were used at the I-95 project. More importantly, monitoring the micro-milled surface textures was an integral part of the construction quality control program for the I-95 project. Monitoring of the micro-milled surface texture for each ½-mile segment was performed using the GDOT Laser Load Profiler, the same apparatus routinely used by GDOT for the quality control of pavement ride quality

Section 9.1 presents the information about the project and the micro-milling operations. Section 9.2 presents the use of the LRP for collecting the micro-milled surface textures and analyzing the data for Northbound Lane 1 (NB1) and Southbound Lane 1 (SB1). Section 9.3 presents the analyses of the micro-milling data collected for Lane 2 and Lane 3 in both Northbound and Southbound Lanes. Conclusions are presented in Section 9.4.

9.1 Overview of the Micro-milling Project and Operations

9.1.1 Location of the Project Site

The project was performed on six lanes of I-95/SR 405, beginning at US 17/SR 25 and extending north to I-16/SR 404 located between Chatham County and Bryan County near Savannah (see Figure 9-1 and Figure 9-2). The total length of the project was approximately 14.095 miles. The project included micro-mill of roadway mainline to remove the existing OGFC overlay of about ⅝ in. to ⅞ in. thickness and resurfacing with 90 lb/yd^2 of 12.5 mm OGFC. The Plant Improvement Co. Inc. of Brunswick, Georgia, was the contractor.

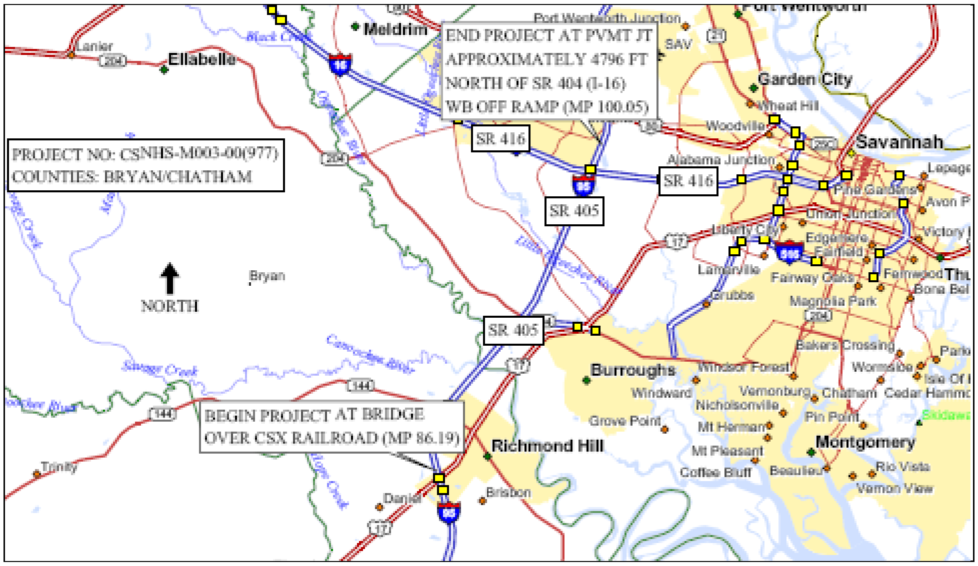

Figure 9-1 Location of the Project Site

Figure 9-2 Six Lane I-95 near Savannah, Georgia

9.1.2 Micro-milling Operations

Figure 9-3 shows the four-track Roadtec® milling machine used for the milling[3]. Figure 9-4 shows the micro-milling drum used in this milling machine. The arrangement of the milling teeth on this milling drum is very different from that on the milling drum used at the I-75 project, as shown in Figure 5-2.

[3] Editor's Note: While the tractor was a Roadtec®, the milling head was not.

Figure 9-3 Milling Machine used on the I-95 Project

Figure 9-4 Milling Drum and Micro-milling Teeth Used in the Milling Machine

9.2 Micro-milling Operations and Results for Lane 1

The micro-milling operation started on November 8, 2010. Micro-milling operations started at the south end of Northbound Lane 1. The milling depth was between ⅝ in. and ⅞ in. as stipulated in the contract for this project.

9.2.1 Initial Test Sections

The micro-milling operations were initially tried out on three test sections at the south end of NB1. The milling speed was approximately 40 ft./min for Test Section 1 and Test Section 2, and was reduced to 32 ft./min for Test Section 3. Table 9-1 summarizes the results of the micro-milled surface texture depths and the IRI values obtained by the GDOT LRP for these three test sections.

The results shown in Table 9-1 indicate that the micro-milled surface textures of all three test sections exceeded the Mean RVD target of 1.6 mm.tentatively recommended for the acceptance threshold values established from the I-75 project (see Section 7.4). However, the ride quality of the milled surface for the three test sections was excellent. Lowering the milling speed from 40 ft./min to 32 ft./min slightly improved the milled surface textures.

Table 9-1 IRI and Micro-milled Textures for Test Sections 1–3

Test Section	Length (mile)	Milling Speed (ft./min)	IRI (mm/km)	Measured Surface RVD	
				Mean (mm)	p95 (mm)
#1	0.18	40	712 / 558	2.71/2.73	4.48/4.59
#2	0.18	40	587 / 553	2.78/2.44	4.53/3.62
#3	0.10	32	423 / 492	2.59/2.19	3.69/3.46

<u>Characteristics of the Milled Surface</u>

The milling depth on these three test sections was approximately between ⅝ in. and ⅞ in. At some portions of the pavement, this milling depth was not deep enough to remove all the OGFC on top of the SMA underlying layer. This contributed to OGFC scabs left on the milled surface, as shown in Figure 9-5. As shown in Figure 9-6, when the OGFC layer was completely removed, the micro-milled surface was smoother and the Mean RVD value on the micro-milled surface was significantly lower when compared with the micro-milled surface with OGFC scabs left on the surface. Those data were obtained using the LCMS instrument [8], which has the capability to measure micro-milled surface textures on small areas.

The appearance of the micro-milled surface of these three test sections (see Figure 9-7), was quite different from that of the I-75 project (see Figure 9-8). A close inspection of the micro-milled surface of these three test sections revealed that pockets of holes appeared on the milled surface (see Figure 9-6 and Figure 9-7), while no such phenomenon was evident on the I-75 project (see Figure 9-8). The presence of the holes can be explained by the following. The underlying asphalt mix on the I-75 project was a 12.5 mm HMA, while that on the I-95 project was a 12.5 mm SMA. When the milling teeth struck the SMA surface, the coarse aggregates in the SMA underlying layer were more susceptible to being dislodged by the milling teeth and leaving pockets of holes on the surface than if the underlying material was a dense-graded HMA. The effects of the holes left on the milled surface textures are discussed later in this section.

Figure 9-5 Scabby Area on Micro-milled Surface

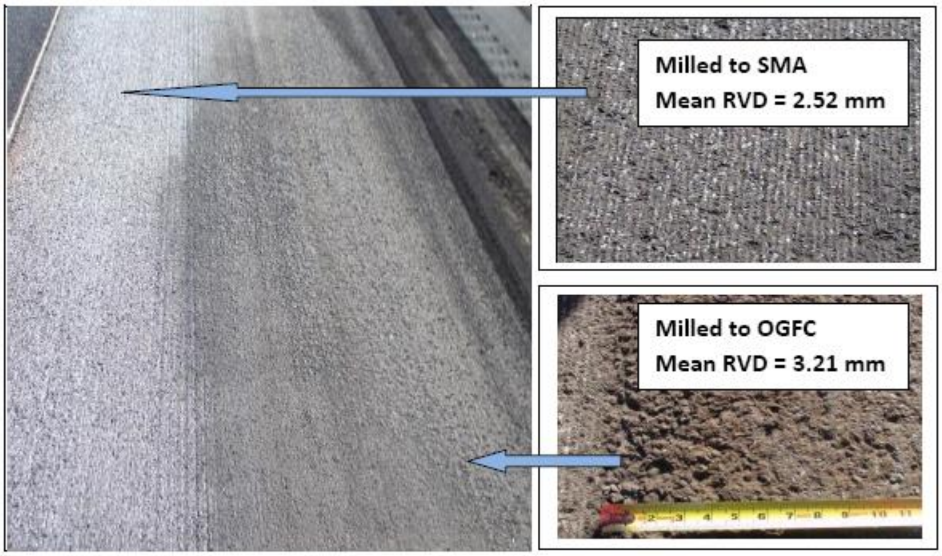

Figure 9-6 Detailed Milled Surface Texture

Figure 9-7 Micro-milled Surface on the I-95 Project

Figure 9-8 Micro-milled Surface on the I-75 Project

Selection of Appropriate RVD Value for Acceptance Parameter

As mentioned in Section 7.7, the p95 RVD was tentatively selected as the parameter for representing the 3.2 mm threshold value requiring corrective action. The ultimate test for selecting an appropriate RVD parameter to represent this threshold value should be based on the long-term performance of the OGFC/PEM layer placed on top of the micro-milled surface. After four years of satisfactory performance history of the PEM surface on the I-75 project, it seems reasonable to conclude that the use of the p95 RVD as the threshold value for compliance with the correction 3.2 mm RVD acceptance requirement is adequate, but may be too restrictive. Although there were many sections, including the four test segments, in which the p95 RVD values were indeed less than correction 3.2 mm, there were many more segments on the I-75 project, including several sections that were monitored, in which the p95 RVD values exceeded correction 3.2 mm. No delamination of the PEM overlay was observed on any of the pavement areas at this project.

After discussing with GDOT State Bituminous Construction Engineer and with the representative from the FHWA, it was tentatively agreed that Mean RVD, instead of p95 RVD, be used as the threshold value for compliance with the correction 3.2 mm RVD acceptance requirement.

9.2.2 Micro-milled Surface Textures for Lane 1

The micro-milling and OGFC overlay paving proceeded on November 9, 2010. The micro-milling operations started at the south end (Milepost 86.2) in the Northbound Lane 1. The initial three test sections were also re-milled. The micro-milling proceeded northward until it reached the north end (Milepost 100.0) of the project. The milling operation then moved to the Southbound Lane 1 and proceeded from the north end of the project until it reached the south end. The micro-milling and OGFC overlay paving on both NB1 and SB1 were completed in early December 2010. The construction operation was suspended due to the cold weather.

According to the field engineer monitoring the construction, the milling depth for the entire lane 1 was between ⅝ in. and ⅞ in., as specified in the construction contract. The results from the three test sections and other segments in Lane 1 showed that the milling depth was insufficient and resulted in some original OGFC material left on the milled surface, as shown in Figure 9-5.

During the milling operation, the milled surface was swept clean immediately after the milling and the milled surface quality was measured for smoothness and for ridge-to-valley surface texture depths at every ½-mile segment using the GDOT LRP. Table 9.2 summarizes the IRI and the Mean RVD values obtained for every ½-mile segment for NB1 and SB1.

As shown in Table 9-2, the Average Mean RVD values for the NB1 is 2.6 mm with the range between 3.4 mm and 1.8 mm; the Average Mean RVD for the SB1 is 2.4 mm with the range between 3.2 mm and 1.8 mm. These values are significantly higher than the Mean RVD values obtained at the I-75 micro-milling project near Perry (see Figure 9-9). As already mentioned in Section 9.2.1, one of the possible causes contributing to the higher RVD values on the I-95 project, as compared with that on the I-75 project, was the pockets of holes left on the milled surface due to the coarse aggregates in the SMA under layer being dislodged by the milling teeth. However, the riding quality between these two types of micro-milled surfaces was comparable. It is important to evaluate whether the holes left on the milled surface would cause adverse effects on the performance of the PEM (or OGFC) overlay, such as delamination of the OGFC surface due to the surface water seeping through the OGFC layer and staying in the holes.

Table 9-2 Quality of Micro-milled Surface – Lane 1

Milepost	Northbound IRI (mm/km)	Northbound Mean RVD (mm)		Southbound IRI (mm/km)	Southbound Mean RVD (mm)
86.5-87.0	546	3.1		575	2.5
87.0-87.5	638	2.7		643	2.6
87.5-88.0	564	2.0		574	3.2
88.0-88.5	563	2.9		429	2.8
88.5-89.0	498	2.4		429	3.0
89.0-89.5	513	2.6		455	2.8
89.5-90.0	590	2.5			
90.0-90.5	532	3.4		426	1.9
90.5-91.0	642	3.2		482	2.7
91.0-91.5	688	1.8		635	2.7
91.5-92.0	677	2.6		620	2.9
92.0-92.5	717	2.0		742	2.7
92.5-93.0	595	2.9		474	2.9
93.0-93.5	574	2.9		502	3.0
93.5-94.0	724	2.8		477	2.1
94.0-94.5				382	2.0
94.5-95.0	537	2.3		477	2.2
95.0-95.5	501	1.9		545	1.8
95.5-96.0	586	2.0		561	3.0
96.0-96.5	624	2.2		413	2.0
96.5-97.0	722	2.8		473	1.9
97.0-97.5	618	2.2		504	2.3
97.5-98.0	510	2.0		494	2.0
98.0-98.5	657	2.1		538	1.9
98.5-99.0	563	3.2		596	1.8
99.0-99.5	718	3.0		549	2.1
99.5-100.0	566	3.1		383	1.9
Average	**602**	**2.6**		**515**	**2.4**
High	724	3.4		742	3.2
Low	498	1.8		383	1.8

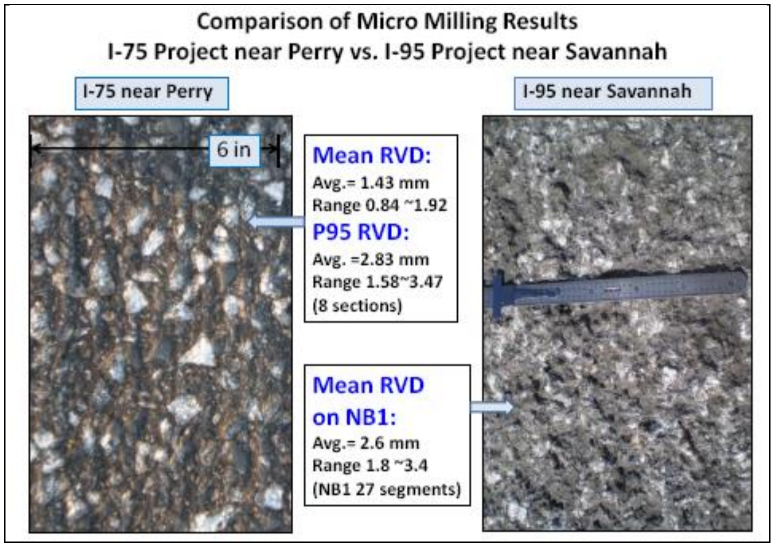

Figure 9-9 Comparison of Mean RVD between I-75 Project and I-95 Project

9.3 Micro-milling Operations and Results for Lane 2 and Lane 3

The micro-milling and OGFC overlay construction on I-95 resumed in March 2011. Lanes 2 and 3 in both the northbound and southbound direction were milled and overlaid as follows.

9.3.1 Micro-milling Operations

The micro-milling operations started at the north end of the Southbound Lane 3 (SB3) and proceeded southward until it reached the south end of the project. The milling operation then moved to the NB3 and proceeded from the south end of the project until it reached the north end. The operation was then moved to SB2 and started at the north end and proceeded southward until it reached the south end of the project. The operation was then shifted to NB2 and started at the south end and preceded northward until it reached the north end of the project.

According to the field engineer monitoring the construction, the milling depth for the initial portion of SB3 (between Milepost 100.0 and 94.0) was between ⅝ in. and ⅞ in.

Recognizing the need for increasing the milling depth to prevent OGFC scabs left on the milled surface, a change order was issued for the contract, changing the milling depth from "⅝ in. to ⅞ in." to "variable depth." With this change order, the contractor started to adjust the milling depth to mill out the entire original OGFC layer, and the problem of the original OGFC scabs left on the milled surface was reduced.

9.3.2 Mean RVD Results

Table 9.3 summarizes the IRI and the Mean RVD values obtained for each ½-mile segment for the SB3 and NB3, and Table 9.4 provides those values for SB2 and NB2. Data shown in these two tables were collected before the milled surfaces were exposed to traffic, except the three data sets marked with "expo" in Table 9.3, which were collected after the milled surfaces were exposed to traffic. The Average Mean RVD values shown in Table 9.3 are 2.4 mm for both SB3 and NB3. The Average Mean RVD values shown in Table 9.4 are 2.3 mm and 2.6 mm, respectively, for SB2 and NB2. The IRI values shown in these two tables are all below the 900 mm/km threshold value requiring corrective action. The three Mean RVD values collected after the surfaces were exposed to traffic are significantly higher than the other Mean RVD values shown in Table 9.3. However, the IRI values of these three data sets are comparable with that collected without exposure to traffic.

Table 9-3 Quality of Micro-milled Surface – Lane 3

Milepost	Northbound IRI (mm/km)	Northbound Mean RVD (mm)		Southbound IRI (mm/km)	Southbound Mean RVD (mm)
86.5-87.0	699	2.0		555	2.0
87.0-87.5	646	2.6		667	2.1
87.5-88.0	661	2.0		567	2.2
88.0-88.5	488	2.1		579	2.0
88.5-89.0	472	2.2		542	2.4
89.0-89.5	694	2.5		602 expo	3.5 expo
89.5-90.0	620	2.4		569 expo	3.6 expo
90.0-90.5	610	2.2		430 expo	3.8 expo
90.5-91.0	638	2.4		519	1.8
91.0-91.5	715	2.0		572	1.9
91.5-92.0	728	2.4		606	2.6
92.0-92.5	676	2.3		713	2.2
92.5-93.0	631	2.3		609	2.2
93.0-93.5	635	2.6		512	2.2
93.5-94.0	585	2.2		617	2.4
94.0-94.5	842	2.3		671	2.2
94.5-95.0	715	2.0		606	2.0
95.0-95.5	633	2.2		712	2.5
95.5-96.0	689	2.1		642	2.3
96.0-96.5	474	2.3		622	2.6
96.5-97.0	540	2.5		761	2.3
97.0-97.5	559	2.4		753	2.2
97.5-98.0	657	2.5		732	2.3
98.0-98.5	724	2.4		810	2.4
98.5-99.0	719	3.0		611	2.2
99.0-99.5	727	3.0		638	2.4
99.5-100.0	607	2.6		584	2.6
Average	**644**	**2.4**		**622**	**2.4**
High	842	3.0		753	3.8
Low	472	2.0		430	1.8

Note: Data marked with "expo" were collected after exposed to traffic

Table 9-4 Quality of Micro-milled Surface – Lane 2

Milepost	Northbound			Southbound	
	IRI	Mean RVD		IRI	Mean RVD
	(mm/km)	(mm)		(mm/km)	(mm)
86.5-87.0	494	2.8		550	2.1
87.0-87.5	627	2.1		480	1.9
87.5-88.0	608	2.3		462	2.1
88.0-88.5	590	2.7		467	1.9
88.5-89.0	691	2.8		511	2.0
89.0-89.5	507	2.8		516	2.1
89.5-90.0	403	2.2		483	2.0
90.0-90.5	441	2.3		443	1.9
90.5-91.0	561	2.3		617	2.4
91.0-91.5	652	2.4		719	2.1
91.5-92.0	724	2.4		764	2.4
92.0-92.5	679	2.3		721	2.3
92.5-93.0	685	2.4		578	2.4
93.0-93.5	599	2.1		455	2.3
93.5-94.0	645	2.2		524	2.7
94.0-94.5	545	2.0		588	2.5
94.5-95.0	540	2.2		526	2.1
95.0-95.5	698	2.4		637	2.0
95.5-96.0	526	3.2		542	2.5
96.0-96.5	532	3.1		591	3.2
96.5-97.0	583	2.8		620	3.2
97.0-97.5	534	2.9		472	1.7
97.5-98.0	623	2.7		423	1.9
98.0-98.5	516	2.9		467	2.1
98.5-99.0	514	3.2		589	2.1
99.0-99.5	781	2.6		653	2.7
99.5-100.0	590	3.2		590	2.6
Average	**588**	**2.6**		**555**	**2.3**
High	781	3.2		719	3.2
Low	494	2.0		443	1.7

9.3.3 Comparison of Mean RVD Obtained "Before" vs. "After" Exposure to Traffic

There were seven ½-mile segments in SB3 in which both the IRI and the Mean RVD values were collected under both "before" and "after" the milled surfaces were exposed to traffic. The Mean RVD data are shown in Table 9.5. The values of Mean RVD after the measured surfaces were exposed to traffic are significantly higher than those before they were exposed to traffic condition.

Table 9-5 RVD "Before" and "After" Exposed to Traffic

Milepost	**Mean RVD (mm)**	
	Before	**After**
94.5-95.0	2.28	4.10
95.0-95.0	2.52	4.20
95.5-96.0	2.28	4.10
96.0-96.5	2.55	3.90
98.5-99.0	2.21	4.60
99.0-99.5	2.44	3.93
99.5-100.0	2.60	4.60
Average	**2.41**	**4.20**
High	2.55	4.60
Low	2.21	3.90

The following are some possible causes:

1. The OGFC remaining on the scabbed areas of the milled surface were intact after the surface was swept but before exposed to traffic. According to the field engineer, after the milled surface was exposed to traffic, some of the OGFC left on the scabbed areas were raveled under traffic, which could increase the RVD of the milled surface.

2. Before being exposed to traffic, the pockets of holes on the milled surface were still partially filled with milling dust even after the surface was swept clean and, thus, the true depth of the valleys was partially masked. After the surface was exposed to traffic for a day or longer, the dirt trapped in the holes could be blown out and the full depth of the valleys revealed.

The causes mentioned above could lead to the following implications. Under the first situation described above, if a new OGFC layer were placed before the milled surface was exposed to traffic, it is possible that the scabbed areas left on the milled surface could still be raveled under the traffic, even though the original OGFC scabs are protected by a thin new OGFC overlay. Potentially, this could lead to delamination of the OGFC overlay. Under the second situation described above, if a new OGFC layer were placed before the milled surface was exposed to traffic, the dirt present in and over the holes on the milled surface could prevent effective bonding of the new OGFC layer with the milled surface and potentially lead to delamination and other distresses on the OGFC overlay. Therefore, to ensure long-term performance of a new OGFC overlay on milled surface it is important that during the milling operation: (1) no OGFC scabs should be allowed to be left on the milled surface, even if they appear to be intact and bonded to the underlay material; and (2) cleanness of the milled surface, particularly when pockets of holes are present on the surface, should be closely inspected to ensure no dirt is left in or over the holes. Exposing the milled surface to traffic for few days before placing the OGFC on top of it could be an effective way to achieve such effects.

9.4 Conclusions

The use of micro-milling techniques for removing the existing asphalt pavement surface on I-95 near Savannah was the second time such a technique was used by GDOT. The following are the main conclusions from this portion of the study.

1. Laser Load Profiler retrofitted with WinPRO software developed by ICC was used for monitoring the micro-milled surface texture of each ½-mile segment on the entire project. It has proved to be a viable and practical instrument for collecting the RVD data on the milled surface.

2. The micro-milled surface textures, in term of Mean RVD and p95 RVD, on the I-95 project were significantly higher than those at the I-75 project. The average Mean RVD values for the six lanes (three northbound and three southbound lanes) ranged between 2.3 mm and 2.6 mm. However, the ride quality in term of IRI for these two projects was comparable. One of the causes of the higher RVD values on the I-95 project, as compared to that on the I-75 project, was the pockets of holes left on the milled surface as a result of the coarse aggregates in the SMA underlying layer being dislodged by the milling teeth. The coarse aggregates in the SMA were more susceptible to be dislodged when the milling teeth struck them than were the coarse aggregates in a dense-graded HMA. The holes left on the milled surface could increase the ridge-to-valley depths.

3. During the milling operation, the milled surface was swept clean immediately after the milling, and the riding quality and the milled surface quality was measured for smoothness and for ridge-to-valley surface texture depths. The IRI

and the RVD data were collected under this condition for all the 81 lane-miles of this project. However, seven ½-mile segments in Southbound Lane 3, in which both the IRI and the Mean RVD values were collected under this condition, as well as after the milled surfaces were swept clean and exposed to traffic for at least one day (sometimes as long as 3 days). The Mean RVD values obtained after the measured surfaces were exposed to traffic were significantly higher than those values obtained without being exposed to traffic. Two possible causes were identified: (1) after the milled surface was exposed to traffic, some of the OGFC scabs that remained on the milled surface were raveled under traffic, which could increase the RVD of the milled surface; and (2) before being exposed to traffic, the pockets of holes on the milled surface were still partially filled with milling dust and, thus, the true depth of the valleys of the holes was partially masked. After the surface was exposed to traffic for a day or longer, the dust trapped in the holes could be blown out and the full depth of the valleys exposed.

4. Under the situation described in (1) above, if a new OGFC layer were placed before the milled surface was exposed to traffic, it is possible that the scabbed areas left on the milled surface could still be raveled under the traffic, even though the original OGFC scabs are protected by a thin OGFC overlay. Potentially, this could lead to delamination of the OGFC overlay. Under the situation described in (2) above, if a new OGFC layer were placed before the milled surface was exposed to traffic, the dirt present in and over the holes on the milled surface could prevent effective bonding of the new OGFC layer with the milled surface and potentially lead to delamination and other distresses on the

OGFC overlay. Therefore, to ensure long-term performance of a new OGFC overlay placed on a micro-milled surface, it is important that during the milling operation: (1) no OGFC scabs should be allowed to be left on the milled surface, even if they appear to be intact and bonded to the underlay material; and (2) cleanness of the milled surface, particularly when pockets of holes are present on the surface, should be closely inspected to ensure no dirt is left in or over the holes. Exposing the milled surface to traffic for a few days before placing the OGFC on top of it could be an effective way to achieve such effects.

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PART 4: CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 10 Conclusions and Recommendations

10.1 Conclusions

The following conclusions can be drawn based on the results obtained from this research study.

10.1.1 General Conclusions

1. Results obtained from the I-75 project indicated that based on four years of satisfactory performance of the PEM overlay placed on the micro-milled surfaces, the use of 95 percentile RVD parameter as the threshold value for compliance with the correction index of 3.2 mm ridge-to-valley texture depth acceptance requirement could be too restrictive. Results from the I-95 project indicated that the Mean RVD of the micro-milled surface can meet the correction 3.2 mm RVD acceptance requirement. However, the appropriateness of using this parameter as the threshold value for compliance with the correction 3.2 mm RVD acceptance requirement, as tentatively adopted at the I-95 project, cannot be determined at this time. The ultimate test for selecting an appropriate RVD parameter should be based on long-term performance of the OGFC/PEM placed over the milled surface.

2. The underlay asphalt mixture on the I-95 project was an SMA, while that on the I-75 project was a 12.5 mm dense-graded HMA. The appearances of the micro-milled surface on these two projects were quite different, with pockets of holes

appearing on the milled surface on the I-95 project, while no such phenomenon was evident on the I-75 project.

3. The LRP retrofitted with WinPRO software developed by ICC proved to be a viable and practical instrument for collecting the RVD data on the milled surface.

4. Milling operation should completely remove the original OGFC/PEM layer. No OGFC/PEM scabs should be left on the milled surface, even if they appear to be intact and bonded to the underlay material.

5. Cleanness of the milled surface should be closely inspected, particularly when pockets of holes are present on the milled surface.

10.1.2 Specific Findings for I-75 Project Near Perry

1. Identification of Instruments for Measurement of Texture Depths: The literature review on measuring asphalt pavement surface macrotexture conducted as a part of this research program identified the Circular Track Meter and the Ultra-Light Inertial Profiler as instruments suitable for measuring micro-milled surface texture depths on the I-75 project. A trial-testing program for measuring conventional milled surface textures using the CTM and the ULIP was conducted; it confirmed that the use of these two instruments together could determine the RVD of micro-milled surfaces.

2. Measurement of Surface Texture Depths on Test Sections: The measuring of the micro-milled surface texture depths was conducted on eight test sections using the CTM and the ULIP. The objective of this part of the study was to assess if the

micro-milling operation could produce milled surfaces capable of meeting the ridge-to-valley surface texture depth requirements stipulated for this construction project, by achieving targeted 1.6 mm milling accuracy; and (2) requiring corrective actions when RVD exceeded 3.2 mm.

3. <u>Selection of Base Length for Calculating RVD</u>: When calculating the RVD from the ULIP data, a base length unit was selected, and the maximum ridge and minimum valley within the base length unit was the RVD value for this base length unit. These RVD values (from each base length unit) within each of the ULIP measuring paths were used to calculate the Mean RVD, p50 to p99 RVD, and the corresponding MPD values for the test section. Use of longer base length units for computing RVD values consistently resulted in higher RVD values. To be consistent with ASTM E-1845, a 100 mm base length was used for determining the RVD values in this research study.

4. <u>Measurement to Obtain MPD from CTM Data</u>: The CTM was used to measure micro-milling surface textures on the eight test sections. Mean profile depth values of the micro-milled surface textures were obtained from the CTM data along the milling direction and paths both perpendicular and diagonal to the milling direction. The results indicated that maximum texture depths in terms of MPD values in all eight test sections occurred either diagonal or perpendicular to the milling direction. Ratios of MPD values in the perpendicular and diagonal directions to that in the milling direction varied between 1.03 and 1.45 with an average of 1.21.

5. Estimation of Maximum RVD Values: Estimations of maximum RVD values were computed by multiplying the RVD values obtained from the ULIP by the maximum direction ratios for the MPD values from the CTM data in the same test section. This approach for estimating maximum RVD was based on the assumption that RVD values in the directions transverse and diagonal to the milling directions, if measured by the ULIP, were proportional to the corresponding MPD values determined by the CTM.

6. Selection of RVD Parameters for Assessing Milled Texture Depth Requirements: *Mean RVD* and *p95 RVD* parameters were tentatively recommended for determining the compliance of the targeted 1.6 mm milling accuracy and for determining the requirement for corrective actions when RVD exceeded 3.2 mm, respectively. Results from the eight test sections indicated that four met the requirements, three failed the requirements, and one was borderline.

7. Observation of Performance over Time: The ultimate test for selecting an appropriate RVD parameter for representing this threshold value should be based on the long-term performance of the PEM layer placed on top of the micro-milled surface. After four years of satisfactory performance history of the PEM surface on the I-75 project, it seems reasonable to conclude that the use of the p95 RVD as the threshold value for compliance with the correction 3.2 mm RVD acceptance requirement is adequate, but may be too restrictive. Although there were many sections, including the four test segments, in which the p95 RVD values were indeed less than correction 3.2 mm, there were many more segments

on the I-75 project, including several sections that were monitored, in which the p95 RVD values exceeded correction 3.2 mm. No delamination of the PEM overlay was observed on any of the pavement areas at this project.

8. Evaluation of Bond Strength between PEM and Micro-milled Surfaces: Two tack coat application rates were evaluated. Tack coat was applied at the rate of 0.06 gal/yd^2 in Test Section 1 and at the rate of 0.08 gal/yd^2 for Test Section 2. The averaged bond strength between the PEM overlay and the micro-milled surface for Test Section 2 was 85.6 psi, which was significantly higher than the average bond strength of 63.0 psi for Test Section 1. Available literature indicated that bond strength between 50 psi and 100 psi is considered marginal for dense-graded mixtures. As of the end of November 2010, three years after the PEM overlay was paved, no slippage failure was observed on the PEM surfaces of these two tack coat test sections or on any of the PEM surfaces of this project.

10.1.3 Specific Findings for I-95 Project near Savannah

1. Use of Viable Instrument for Collecting RVD Data: Laser Load Profiler retrofitted with WinPRO software developed by ICC was used for monitoring the micro-milled surface texture of each ½-mile segment on the entire project. It has proven to be a viable and practical instrument for collecting the RVD data on the milled surface.

2. Micro-Milled Surface Textures: The micro-milled surface textures, in terms of Mean RVD and p95 RVD, on the I-95 project were significantly higher than those

at the I-75 project. The average Mean RVD values for the six lanes (three northbound and three southbound lanes) ranged between 2.3 mm and 2.6 mm. However, the ride quality in term of IRI for these two projects was comparable. One of the causes of the higher RVD values on the I-95 project, as compared with that on the I-75 project, was the pockets of holes left on the milled surface as a result of the coarse aggregates in the SMA underlying layer being dislodged by the milling teeth. The coarse aggregates in the SMA were more susceptible to be dislodged when the milling teeth struck them than were the coarse aggregates in a dense-graded HMA. The holes left on the milled surface could increase the ridge-to-valley depths.

3. Impact of Traffic Exposure: During the milling operation, the milled surface was swept clean immediately after the milling and the riding quality and the milled surface quality was measured for smoothness and for ridge-to-valley surface texture depths. The IRI and the RVD data were collected under this condition for all the 81 lane-miles of this project. However, in seven ½-mile segments in Southbound Lane both the IRI and the Mean RVD values were collected under this condition, as well as after the milled surfaces were swept clean and exposed to traffic for at least one day (sometimes as long as three days). The Mean RVD values obtained after the measured surfaces were exposed to traffic were significantly higher than those values obtained without being exposed to traffic. Two possible causes were identified: (1) after the milled surface was exposed to traffic, some of the OGFC scabs that remained on the milled surface were raveled under traffic, which could increase the RVD of the milled surface; and (2) before

being exposed to traffic, the pockets of holes on the milled surface were still partially filled with milling dust and, thus, the true depth of the valleys of the holes was partially masked. After the surface was exposed to traffic for a day or longer, the dust trapped in the holes could be blown out and the full depth of the valleys exposed.

4. Elimination of OGFC Scabs: Under the situation described in (1) above, if a new OGFC layer were placed before the milled surface was exposed to traffic, it is possible that the scabbed areas left on the milled surface could still be raveled under the traffic, even though the original OGFC scabs are protected by a thin OGFC overlay. Potentially, this could lead to delamination of the OGFC overlay. Under the situation described in (2) above, if a new OGFC layer were placed before the milled surface was exposed to traffic, the dirt present in and over the holes on the milled surface could prevent effective bonding of the new OGFC layer with the milled surface and potentially lead to delamination and other distresses on the OGFC overlay. Therefore, to ensure long-term performance of a new OGFC overlay placed on a micro-milled surface, it is important that during the milling operation: (1) no OGFC scabs should be allowed to be left on the milled surface, even if they appear to be intact and bonded to the underlay material; and (2) cleanness of the milled surface, particularly when pockets of holes are present on the surface, should be closely inspected to ensure no dirt is left in or over the holes. Exposing the milled surface to traffic for a few days before placing the OGFC on top of it could be an effective way for achieving such effects.

10.2 Recommendations

The following recommendations are offered based on the results obtained from this research study.

1. GDOT Special Provision Section 432, "Mill Asphaltic Concrete Pavement (Micro Mill)," stipulates that, "Any areas exceeding ⅛ in. (3.2 mm) between the ridge and valley of the mat surface…shall require that the underlying layer be removed and replaced with material as directed by the Engineer at no additional cost to the Department." Results obtained from the I-75 project indicated that based on four years of satisfactory performance of the PEM overlay the use of a 95 percentile RVD parameter as the threshold value for compliance with the correction 3.2 mm RVD acceptance requirement could be too conservative. Alternatively, Mean RVD was tentatively adopted on the I-95 project as the threshold value for compliance with the correction 3.2 mm RVD acceptance criteria. The ultimate decision for selecting an appropriate RVD parameter, whether it is the Mean RVD, p75, p80, p90, p95, or other RVD parameter, for compliance with the correction 3.2 mm RVD acceptance requirement should be based on the long-term performance of the OGFC/PEM layer placed on the micro-milled surface.

2. In the course of performing the quality control for the micro-milled surface at the I-95 project, the micro-milled surface texture raw data were collected by the LRP in ½-mile segments for the entire project. It is recommended that these raw data be safely kept as they can be used to generate various RVD parameters (Mean RVD, p75, p80, p90, p95, or other RVD parameter) for each ½-mile

segment, or even areas. These RVD values so generated at various locations can be used to correlate with the long-term performance and the occurrence of distresses on the OGFC overlay at the same locations. This information can be used for establishing the appropriate RVD parameter for compliance with the correction index of 3.2 mm RVD acceptance criteria, or developing new acceptance criteria.

3. It is recommended that a tack coat rate of 0.08 gal/yd^2 be used on micro-milled surfaces for the PEM overlay paving. Results from this research study showed that using a 0.08 gal/yd^2 tack rate produced noticeably higher bond strength between the micro-milled surface and the PEM overlay than that from using 0.06 gal/yd^2 tack rate.

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