GEORGIA DOT RESEARCH PROJECT 13-20

FINAL REPORT

EVALUATION OF THE LONG-TERM PERFORMANCE AND BENEFIT OF USING AN ENHANCED MICRO-MILLING RESURFACING METHOD

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1.Report No.:
FHWA-GA-18-1320

2. Government Accession No.:

3. Recipient's Catalog No.:

4. Title and Subtitle:
Evaluation of the Long-Term Performance and Benefit of Using an Enhanced Micro-Milling Resurfacing Method

5. Report Date:
January 2019

6. Performing Organization Code:

7. Author(s):
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8. Performing Organ. Report No.:
13-20

9. Performing Organization Name and Address:
Georgia Institute of Technology
790 Atlantic Drive
Atlanta, GA 30332-0355

10. Work Unit No.:

11. Contract or Grant No.:
PI#0011825

12. Sponsoring Agency Name and Address:
Georgia Department of Transportation
Office of Performance-Based Management and Research
15 Kennedy Drive
Forest Park, GA 30297-2534

13. Type of Report and Period Covered:
Final; July 2013 – January 2019

14. Sponsoring Agency Code:

15. Supplementary Notes:
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract:
The Georgia Department of Transportation (GDOT) has applied the environmentally friendly and cost-effective pavement preservation method, micro-milling and thin overlay, to Georgia's interstate highways since 2007. The objectives of this project were to critically assess the long-term performance of micro-milling and thin overlay and to quantitatively evaluate its economic and environmental benefits by conducting life-cycle cost analysis (LCAA) and life-cycle analysis (LCA). GDOT's projects on I-75, I-95, and I-285 were analyzed in the study. As an alternative, the conventional milling and overlay ("conventional method") was used for comparison. Results showed that the micro-milling and thin overlay method has 10-12 years of expected service life. It is comparable to the conventional method but reduces the costs by $65,600 per lane mile compared with the conventional method. The study also showed that micro-milling and thin overlay is a good crack relief treatment. In addition, it produces fewer greenhouse gases, and uses less water and energy than the conventional method. Overall, micro-milling and thin overlay is a promising, sustainable pavement preservation method that will save money for transportation agencies if it is applied adequately on the pavements with sound structural conditions.

17. Key Words:
Asphalt pavement; micro-milling; thin overlay; conventional milling; Life-Cycle Cost Analysis; Life-Cycle Analysis; service life;

18. Distribution Statement: No Restriction

19. Security Classification (of this report):
Unclassified

20. Security classification (of this page):
Unclassified

21. Number of Pages: 99

22. Price:

GDOT Research Project No. 13-20

Final Report

EVALUATION OF THE LONG-TERM PERFORMANCE AND BENEFIT OF USING AN ENHANCED MICRO-MILLING RESURFACING METHOD

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January 2019

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ACRONYMS AND ABBREVIATIONS

AADT	Annual Average Daily Traffic
GDOT	Georgia Department of Transportation
HMA	Hot Mix Asphalt
LCA	Life-Cycle Analysis
LCCA	Life-Cycle Cost Analysis
OGFC	Open-graded Friction Course
OM	Office of Maintenance
OMAT	Office of Materials and Testing
PACES	Pavement Condition Evaluation System
PaLATE	Pavement Lifecycle Assessment Tool for Environmental and Economic Effects
PEM	Porous European Mix
RAP	Reclaimed Asphalt Pavement
SMA	Stone Matrix Asphalt

EXECUTIVE SUMMARY

The Georgia Department of Transportation (GDOT) has applied the environmentally friendly and cost-effective pavement preservation method, micro-milling and thin overlay, to Georgia's interstate highways since 2007. The successful projects on I-75 and I-95 demonstrated that the performance of micro-milling and thin overlay is comparable to the conventional milling and overlay ("conventional method").

The objectives of this project are to critically assess the long-term performance of micro-milling and thin overlay, to quantitatively evaluate its economic benefits, and to quantitatively evaluate its environmental benefits over the conventional method by conducting life-cycle cost analysis (LCAA) to evaluate its cost-effectiveness and life-cycle analysis (LCA) to evaluate its long-term sustainability, including environmental and social impacts. The major research findings are as follows:

1. The long-term performance assessment of the micro-milling and thin overlay project on I-75 showed an expected service life of 10-12 years, similar to the conventional method. The detailed crack propagation study on the I-95 project showed that micro-milling and thin overlay is a good crack relief treatment, as evidenced by only 5% of the original cracks in total length reflected to pavement surface in 5 years.
2. The economic impact study using LCCA showed that micro-milling and thin overlay reduced the cost by 53% compared to the conventional method, which is equal to a net present value of more than $65,600 per lane mile. A break-even analysis shows that micro-milling and thin overlay has the same life-cycle costs as the conventional milling and overlay if it lasts 5 years.

3. The sustainability study using LCA demonstrated that micro-milling and thin overlay produces 61.7% fewer greenhouse gases, uses 61.8% less water, and uses 61.9% less energy than the conventional method. The qualitative evaluation of social impacts, such as the reduced construction time and increased flexibility, which improves the safety of drivers and workers, demonstrates the advantage of using micro-milling and thin overlay.

In summary, micro-milling and thin overlay is a promising, sustainable pavement preservation method. It will save money for transportation agencies and also provide environmental and social benefits if applied adequately on pavements with sound structural conditions. The research outcomes provide the quantitative evidence for transportation agencies, like GDOT and other state DOTs, to justify the use of micro-milling and thin overlay as a new, alternative pavement preservation method. It is recommended that GDOT work with the Federal Highway Administration (FHWA) to develop a set of national standards for this type of pavement preservation treatment.

ACKNOWLEDGMENTS

The work described in this final report was supported by the Georgia Department of Transportation (GDOT) Research Project 13-20. We would like to thank Mr. Andy Doyle (Jesse), Ms. Ernay Robinson, Mr. Larry Barnes, Mr. David Sparks, Mr. Sam Wheeler, and Mr. Michael Keene from the Office of Maintenance; Dr. Peter Wu and Ms. Sheila Hines from the Office of Materials and Testing; and Mr. David Jared, Mr. Binh Bui, and Mr. Brennan Roney from the Office of Performance-Based Management and Research for their strong support and heavy involvement in this project. We would also like to thank Mr. Greg Kelley and Mr. Van Truong from Los Angeles County and Mr. Andrea Latham of Keystone Engineering for sharing with us their practices and experiences. We would like to thank members of the research team (Yiching Wu, Georgene Geary, and Geoffrey Price) at the Georgia Institute of Technology for their diligent work.

CHAPTER 1: INTRODUCTION

1. Research Background and Research Need

Micro-milling and thin overlay has been applied to Georgia's interstate highways by the Georgia Department of Transportation (GDOT) since 2007 as an environmentally friendly and cost-effective pavement preservation method. Micro-milling removes only the surface friction course, such as the open-graded friction course (OGFC) or porous European mix (PEM); then, a thin OGFC or PEM layer is directly overlaid on top of the milled surface. This method has been successfully applied to some projects on I-75 and I-95. In the I-95 micro-milling resurfacing project, this method was proved to have saved approximately $65,600 per lane mile compared to the conventional milling and overlay method ("conventional method") in which the OGFC or PEM is overlaid on a dense-graded hot mix asphalt (HMA) layer that is placed on a conventionally-milled surface. Normally, micro-milling is intended for use when removing and replacing an aged thin open-graded surface layer on a structurally-sound pavement.

To cost-effectively maintain interstate highways, GDOT plans to use more micro-milling and thin overlay. When the conventional method is used, a new layer of dense-graded surface mix would have to be placed on the milled surface as a base for a new friction course. This is primarily due to the concern that if a friction course is placed directly on top of a conventionally-milled surface, it could potentially cause delamination of the friction course. The delamination of a friction course is caused by the surface water entering through the porous layer and being trapped in the valleys of the conventionally milled surface. On the other hand, the friction course could be placed directly on top of the micro-milled surface without such concerns.

Although literature shows micro-milling and thin overlay is a promising pavement preservation, there is a lack of a comprehensive and quantitative sustainability analysis, including economic, environmental, and social analyses, based on the long-term performance data. Thus, there is a need to critically assess the long-term performance of the application of OGFC or PEM directly on the micro-milled surface without any dense-graded intermediate layer. Second, the economic efficiency of micro-milling and thin overlay, which can be done by using life-cycle cost analysis (LCCA), needs to be studied. Third, life-cycle analysis (LCA) is needed to assess the environmental impact of using micro-milling and thin overlay.

2. Research Objectives

The objectives of this project are 1) to critically assess the long-term performance of micro-milling and thin overlay as a new and viable alternative for pavement preservation; 2) to quantitatively evaluate the economic benefit of micro-milling and thin overlay; and 3) to quantitatively evaluate the environmental sustainability benefits of micro-milling and thin overlay over the conventional method; LCCA will be used to evaluate micro-milling and thin overlay’s cost-effectiveness, and LCA will be used to evaluate long-term environmental and social sustainability. The research outcomes will enable GDOT to better justify its expanded use of micro-milling and thin overlay; it will also be useful for convincing the Federal Highway Administration (FHWA) of the method’s effectiveness.

3. Report Organization

This report is organized into four chapters. Chapter 1 introduces the project background, need, objectives, and tasks. Chapter 2 presents a literature review. Chapter 3 presents the comprehensive data analysis (using the collected 3D laser data and the COPACES data acquired from GDOT) to study pavement deterioration and crack propagation. Chapter 4 presents the LCCA performed to study the economic impact of micro-milling and thin overlay. Chapter 5 presents the LCA performed to study the environmental impact of micro-milling and thin overlay. Chapter 6 summarizes research findings and offers recommendations for future research. Appendix I presents the experimental design for studying the performance of micro-milling and thin overlay.

CHAPTER 2: LITERATURE REVIEW

The most recent American Society of Civil Engineers (ASCE) report card has given America’s roads a “D”, calling them “chronically underfunded” (ASCE, 2017). According to the report, 20% of the nation’s highways were in poor conditions in 2014, which costs motorists $112 billion/year in extra vehicle repairs and operating costs. Overall, there is a need of $836 billion in capital investment for America’s highway system. Therefore, transportation agencies are looking at cost-effective alternatives to sustainably maintain roadway systems.

GDOT recognized the need to maintain its deteriorating pavements despite a limited budget. In 2007, GDOT decided to test a new pavement preservation technique involving micro-milling a thin open-graded wearing course and replacing it with a thin overlay of an open-graded wearing course. Micro-milling had been used by other agencies to address their pavement maintenance needs. However, GDOT was the first to use micro-milling with a thin overlay of an open-graded wearing course.

1. Micro-Milling in the United States

Micro-milling is sometimes called fine milling or, more infrequently, surface planning (PI, 2017). There is a distinction between fine milling and micro-milling. Micro-milling uses a drum with 5 mm bit spacing, which is three times the number of bits on a conventional milling drum, whereas fine milling has 8 mm bit spacing, which is approximately twice the number of bits on a conventional drum (Latham, 2016). However, these are often used interchangeably, making it difficult to distinguish the two when looking at their use across the country. An effort was made to distinguish between agencies using micro-milling from those using fine milling, but this was not always possible. Georgia uses micro-milling with the 5 mm bit spacing.

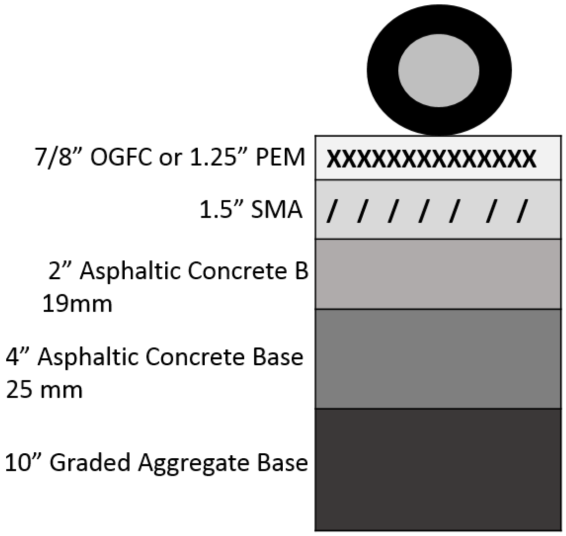
Though 19 states are using micro-milling, few of them are using it for the same purpose as Georgia. Generally, micro-milling is used for improving skid resistance, restoring a road's profile, or for milling and overlaying operations with varying overlay thicknesses. The most common quality control measure used is the sand patch test, but a different one is used in Georgia and will be discussed in the next section. As an example of a state that uses micro-milling in a manner similar to Georgia, Massachusetts uses micro-milling to mill and apply a thin leveling course followed by an open-graded friction course (Brown, 2012). Massachusetts takes advantage of the flexible construction to open the milled surface to traffic in the winter and overlays in the spring to avoid the extra patching and traffic control costs caused by the winter weather. Massachusetts isn't the only state that leaves the micro-milled surface open to traffic. Typically, states that use micro-milling for improving skid resistance leave the surface open to traffic, a use similar to diamond grinding use on concrete. Some states that use micro-milling for this purpose include Michigan, Nevada, and Ohio (AFR, 2013).

Different states use micro-milling to address different pavement distress issues. For example, Georgia uses micro-milling to correct raveling issue on the surface layer. But, some states, such as Nebraska (FCP-1, 2017) uses it to remove minor rutting. And, California uses it to remove other pavement deformation problems (Cook, et al., 2004). Only a handful of states have implemented micro-milling as a major part of their roadway maintenance strategy, such as Georgia, Massachusetts, Rhode Island, and Washington (Brown, 2012; FCP-2, 2017). In 2013, FHWA published a report concerning how pavement treatments impact roadway safety and determined that micro-milling was not widely used enough to consider it in their report (Merritt, et al., 2013).

Overall, micro-milling is still fairly new, but it is growing in popularity. Thus far, the only scholarly articles regarding micro-milling of asphalt pavements have been published by GDOT and Georgia Tech. These studies will be discussed in the following section.

2. Micro-Milling and Thin Overlay in Georgia

The typical interstate pavement design in GDOT is shown in FIGURE 1. The surface layer is a thin open-graded wearing course, either open-graded friction course (OGFC) or porous European mix (PEM). OGFC and PEM are very similar, but PEM has a higher air void content (18-22% as compared to 15% for OGFC) and PEM is more gap graded, and thus more permeable, than OGFC (Kline, 2010). These layers allow water to drain through them and out between the surface layer and the stone matrix asphalt (SMA) layer, reducing splash and spray and improving visibility and safety in rain. The SMA is a gap-graded mix with a high number of coarse aggregates that create an interlocking matrix that is stronger than in a typical dense-graded pavement. The SMA layer can still be sound when the OGFC layer fails after 10-12 years (Tsai, et al., 2016). It is important to note that OGFC is used in Georgia on all interstates paved with asphalt pavement, but it can also be used on state roads with high traffic. The design for the state routes is not shown because they are highly dependent on the specific traffic conditions. This report focuses on interstates. However, the findings can be applied to state routes in most cases.



“X” labels the layers removed by both micro-milling and conventional milling and “/ / /” labels the layer removed by conventional milling only

FIGURE 1: ***Typical GDOT Interstate Pavement Design***

Conventional milling and overlay (“conventional method”) removes both the OGFC and SMA layers after the OGFC fails, which means that about half of the life of the SMA is lost in this process. However, concerns about water entrapment due to the flow of water between the porous and SMA layers during rain leading to delamination led GDOT to choose conventional milling as a standard practice (Tsai, et al., 2016) in the past. In 2007, GDOT decided to challenge this standard practice by using micro-milling and thin overlay to preserve the remaining life of the SMA, which appeared to be both a financially and environmentally beneficial decision. However, many innovations and changes were needed to ensure that this method would be successful, including a new quality control specification, a measurement tool for the specified measurement, and new construction practices.

The developments in this pavement preservation technique were primarily made during the first two micro-milling projects. The first project occurred in 2007 on I-75 south of Macon, Georgia, on 15.3 miles with 3 lanes in each direction for a total of 91.8 lane-miles. This section had an average annual daily traffic (AADT) of approximately 50,100 vehicles and 25% truck traffic (GDOT, 2017). It was constructed in 1969 and resurfaced in 1997. In 2005, the pavement condition evaluation showed that the top layer had deteriorated with visible raveling and load cracking (Tsai, et al., 2016). After testing cores with an asphalt pavement analyzer, it was determined that the underlying layer, a dense-graded hot mix asphalt (HMA) pavement, was still sound. To delay a full-depth repair and thus save money (approximately $4.7 million on this project), a micro-milling and thin overlay process was devised. The project commenced in 2007 with micro-milling and a PEM overlay.

Following the success of the I-75 project, micro-milling and thin overlay was again chosen to preserve the pavement on I-95 near Savannah, Georgia. This project was 14 miles long with 3 lanes in each direction, or 84 lane-miles. It was last widened and resurfaced in 1995. The top layer was OGFC with an underlying 1.5” layer of SMA. In 2007, the pavement condition evaluation showed severe raveling and some longitudinal and transverse cracking. After testing cores with an asphalt pavement analyzer, it was determined that the SMA was still in good condition and construction commenced in 2010 and, due to weather concerns, finished in 2011. This project had an estimated cost savings of $5.7 million.

2.1 Development of RVD Measurement

Conventional milling uses a drum with wider, larger teeth and a larger separation between teeth than the drum used for micro-milling, which uses many small, tightly-spaced teeth. These smaller, more tightly-spaced teeth create a smoother surface after milling and reduce water entrapment between layers. However, even with micro-milling, water entrapment was still a concern, so a new construction quality measurement was devised: ridge to valley depth (RVD). This measures the difference between the highest and lowest points in the pavement over a specified distance, typically 100 mm, as shown in FIGURE 2. Several papers and reports have been published in regard to this measurement (Lai, et al., 2009; Tsai, et al., 2013; Lai, et al., 2012; Tsai, et al., 2012).

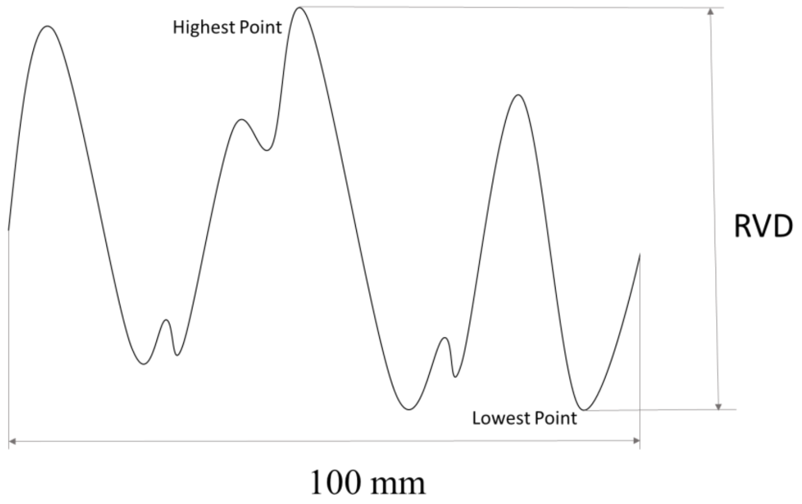


FIGURE 2: ***Simplified Demonstration of RVD Computation***

RVD was initially developed by James Lai from Georgia Tech to reflect the need to reduce potential water entrapment (Lai, et al., 2009). The measurement was compared to mean texture depth (MTD) and mean profile depth (MPD) to determine the correlations and the possibility of converting one value to another. It was found that the relationship between MTD or MPD and RVD is dependent on the macrotexture characteristics, which can be symmetrical, negative symmetrical, or positive symmetrical; however, these characteristics are not easily determined (Lai, et al., 2009). Therefore, RVD must be directly measured, which is possible with a retrofitted laser road profiler such as the one used for GDOT's first micro-milling project. Later, it was determined that RVD could be measured using 3D sensing technology (Tsai, et al., 2013).

As with any measurement, a threshold was needed to give meaning to the measurement. A threshold of 1.6 mm Mean RVD for compliance and 3.2 mm P95 RVD for corrective actions were chosen based on discussion with statisticians and pavement engineers (Lai, et al., 2009). They also recommended that P95 be used over P90 after analysis of measurements from the first micro-milling project. The analysis determined that P90 and P95 were quite close, so the more rigid option, P95, was chosen as the requirement. On the next micro-milling project, however, the P95 RVD of 3.2 mm was too difficult to meet, and the requirement was relaxed to a mean of 3.2 mm after some further research to determine if this could be acceptable. It was determined to be acceptable based on a good 3-year performance (Lai, et al., 2012).

A further study by Tsai et al. (2013) looked at the statistical distributions of RVD on smooth and rough segments. This research further demonstrated that a mean RVD of 3.2 mm is adequate to differentiate between a rough and a smooth segment. This research showed that rough segments follow an approximately normal distribution, and smooth segments follow a similar distribution but with a substantial positive skew in comparison to a rough section (Tsai, et al., 2012). This research reassessed the original 100 mm base length set for measuring the RVD, which was chosen to be consistent with ASTM E1845 for calculating MPD.

In the initial analysis, it was determined (based on circular track meter (CTM) results on the initial micro-milling project) that maximum surface texture depths are higher when they are either perpendicular or diagonal to the milling direction (Lai, et al., 2009). Laser road profilers only work in the parallel direction to the milling direction, which would have meant that to get the highest measured values, a CTM may have been necessary. However, work by Tsai et al. showed that it is possible to measure full-lane coverage RVD using 3D sensing technology (Tsai, et al., 2013). Using the full lane enables the identification of isolated spots of poor macrotexture. The 3D sensing process further allows for measuring the RVD in any direction. The transverse direction was chosen because it best represents the path of water runoff.

2.2 Construction Practices

Construction practices employed also impact the long-term performance of the thin overlay. These have been refined as projects were performed and are described by Tsai (Tsai, 2018). For example, a field investigation showed the “fixed” depth of 7/8 in. specified in the construction contract was not sufficient to remove the entire depth of OGFC at some locations, especially at locations approaching bridges. A change order was issued to use “variable” mill depth to remove the entire OGFC to ensure a clean, smooth, micro-milled surface for good bonding between the milling surface and the OGFC. The use of a variable milling depth has been subsequently adopted as a standard for the new method (Tsai, 2018). Pre-treatments are performed prior to construction. For sections showing damage to the layers deeper than the micro-milling depth, deep patching is performed. The I-95 project distresses requiring deep patching included high severity raveling (Tsai, 2015). This operation consisted of milling 2 inches deep, placing a 3/8 inch mat to prevent any crack propagation, and then repaving with SMA. Prior to the full commencement of the micro-milling operation, a 1,000-ft test section is micro-milled to ensure that the micro-milled surface conforms to the requirements specified in GDOT Special Provision Section 432 (GDOT, 2009). If the section fails, as it did in both the I-75 and I-95 projects, then the contractor will submit a plan that must be approved by the GDOT engineer to adjust the operation, such as adjusting milling speed and drum speed, to meet the requirements (Tsai, 2018). A second test section is then micro-milled and assessed, and the failed section is re-milled. Once appropriate settings are chosen, the micro-milling operation can commence.

The surface is frequently checked to ensure the operation still meets the requirements; the average RVD is measured every ½ mile. On the I-75 project, a 7/8-in micro-milling was specified in the contract. However, it was discovered through the course of construction that this depth could not guarantee the full removal of the OGFC, especially approaching bridges. As a result, the specification was changed to variable depth micro-milling for the rest of the project and future projects. It was also determined that a combination of appropriate milling machine speed, cutting drum speed, teeth pattern, and underlying material is needed to produce a smooth micro-milled surface. On the I-95 project, the material was sticking to the teeth, leading to a poor surface. This was addressed by adding a soap solution to the water spray to clean the milling drum. Additionally, worn-out micro-milling teeth were causing poor results. This was addressed by replacing the worn out teeth on a daily basis (Tsai, 2018).

It was also discovered on the I-95 project that some large aggregates in the SMA were dislodged, creating pockets in the surface and increasing the RVD. A clean surface would be necessary to fix this and to create an adequate bonding strength. A power broom was used to clear the smaller particles produced in the micro-milling process. It had to be operated more slowly than after conventional milling. The micro-milled surface is very smooth after cleaning, so it can be left open to traffic. GDOT allows this for up to 5 days, if needed, providing flexibility to the contractor. The traffic help blow out the dust left on the road surface after the brooming operation, further cleaning the surface. However, exposure time to traffic needs to be limited to avoid smoothing of ridges, which can skew RVD measurement.

Quality control of this pavement was performed using GDOT's laser road profiler for both projects. The I-95 project was the first to explore the use of full-coverage measurement of the micro-milled surface using 3D sensing technology, which is applicable to future projects (Tsai, 2018).

After the cleaning and quality control are complete, the paving operation can commence. First, a tack coat is applied to the freshly cleaned surface. Based on experimental tests on the I-75 project, a tack coat application rate of 0.08 gal/yd^2 is recommended. Following the tack application, the open-graded wearing layer is placed on top and compacted using a rubber roller. The paved surface is tested for acceptance using GDOT's laser road profiler to measure the Half Car Simulated International Roughness Index (HCS IRI), which must meet a target value of 825 mm/km and not exceed 900 mm/km.

2.3 Sustainability

With long-term data, we can accomplish the assessment of the overall sustainability of the practice. Sustainability is typically modeled as a 3-legged stool. The three legs of the stool are environmental, social, and economic sustainability. Altogether, these hold up a sustainable society. There is much debate about the definition of sustainability. For this report, the ASCE definition of sustainability will be used: "*a set of economic, environmental, and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely without degrading the quantity, quality, or the availability of economic, environmental, and social resources*" (ASCE, 2016). In terms of pavement maintenance, all the three aspects of stainability are applicable.

The sustainability analysis of micro-milling and thin overlay was begun by Tsai et al. (2016). It assessed the performance of the pavement after micro-milling on the I-75 project and the economic sustainability through a life-cycle cost assessment. The findings showed that a micro-milled and thin overlaid pavement has an approximate service interval of 10-11 years, comparable to that of the conventional method, which is 10-12 years. Also, the analysis showed that micro-milling and thin overlay can save $27,000 per lane-mile. However, this study can be expanded with more performance data and with more recent cost data to reflect more up-to-date micro-milling costs. An introduction to the process of assessing the environmental sustainability of micro-milling and thin overlay was presented at the MAIREINFRA conference (Tsai & Gadsby, 2017). A more complete life-cycle assessment is included here with a section discussing the social sustainability.

2.4 3D Sensing Technology

In recent years, 3D sensing technology that employs the laser triangulation principle has gained widespread interest from researchers, industry and highway agencies, and has been successfully used for collecting pavement surface distresses such as pavement cracking, rutting, and texture. FIGURE 3 (a) shows the Georgia Tech Sensing Vehicle (GTSV) equipped with 3D laser system, mobile LiDAR system, and digital video logging system, which was developed and integrated by our research team at Georgia Tech. In comparison to 2-dimensional (2D) digital image data, 3D laser data has its intrinsic advantage for pavement crack detection. FIGURE 3 (b) shows an example 2D pavement image, and the corresponding 3D laser data is shown in FIGURE 3 (c). Our previous study has comprehensively validated that 3D laser data is much more robust in crack detection (Tsai and Wang, 2015).

In this research project, GTSV was employed to collect 3D laser data on some micro-milling and thin overlay project. The 3D laser data were then processed and analyzed for crack detection and rutting measurement.

(a) Sensing Vehicle **(b) 2D Image** **(c) 3D Laser Data**

FIGURE 3: ***3D Sensing System and Sensing Data***

CHAPTER 3:   PAVEMENT PERFORMANCE ANALYSIS

As mentioned in Chapter 2, the first micro-milling and thin overlay project in Georgia has been in service for 10 years. With this long-term data, it is possible to study the long-term performance of this pavement preservation technique. This chapter will consider three of the early micro-milling and thin overlay projects: one on I-75, completed in 2007; one on I-95, completed in 2012; and one on I-285, completed in 2012. The three projects will be analyzed from three different perspectives. The I-75 project occurred prior to the existence of the GTSV, so GDOT's performance data, i.e., COPACES data, will be used for the assessment. This data is aggregated on segment (one segment is typically one-mile long) and project level, so it can provide a high-level view of the pavement performance. 3D laser data is available on the micro-milled surface in the I-95 projects, so a detailed analysis of the precondition of the pavement and how it performed over time is feasible. In particular, it is possible for us to assess where, when and which types of cracks reflect. The project on I-285 has no precondition data, but it was in a poor condition when micro-milling and thin overlay was applied due to money concerns. This makes the I-285 project a relevant subject in assessing how the pre-condition impacts performance. The project on I-285 has 3D laser data available after the micro-milling was conducted. Thus, the cracking and raveling can be assessed.

1. Project Descriptions

The first project considered is on I-75 just south of Macon, Georgia. It had an AADT of 50,100 with 25% trucks in 2007. The AADT decreased in the following years, but increased to 50,200 in 2016, 25% of which was trucks. The project covered 91.8

lane-miles on a stretch of 15.3 miles with 3 lanes in each direction. The I-75 project location, lane configuration and traffic are shown in FIGURE 4 (A). The pavement design is shown in FIGURE 5 (a). This pavement has an older mix, Asphaltic Concrete E, instead of SMA, and PEM as the open-graded surface layer.

The I-75 pavement section was originally constructed in 1964 using jointed plain concrete pavement (JPCP). It was overlaid with asphaltic concrete in 1994, and micro-milling and thin overlay was performed in 2007. FIGURE 5 shows the existing pavement design. This design has been in service for 10 years now and has not yet needed replacement. Initial expectations for this project, due to the newness, were that it would last 3-4 years (Tsai, et al., 2016), but it has lasted as long as a conventional milling and overlay project.

The second project considered is on I-95 near Savannah, Georgia. The project was approximately 14 miles long with 3 lanes in each direction (84 lane-miles). Construction began in 2011 and, due to weather concerns (minimal temperature requirement), finished in 2012. It had an AADT of 67,810 in 2011, which increased to 84,500 in 2016, as shown in FIGURE 4. The truck traffic is roughly 14%, equivalent to a total daily count of 11,000 in 2016, about 1,000 less per day than I-75. FIGURE 4 (B) shows the location of the project, lane configuration, and traffic counts since 2011.

The I-95 pavement section was originally constructed in 1971 using 8.5” continuously reinforced concrete pavement with a 6” pre-mixed soil cement sub base. However, the pavement has since been topped by asphaltic concrete, as shown in FIGURE 5 (b). The OGFC layer is from the thin overlay, replacing an older open-graded surface layer, asphaltic concrete D mod, which is no longer used. This design has been in service for 6 years now with only a few miles showing cracking.

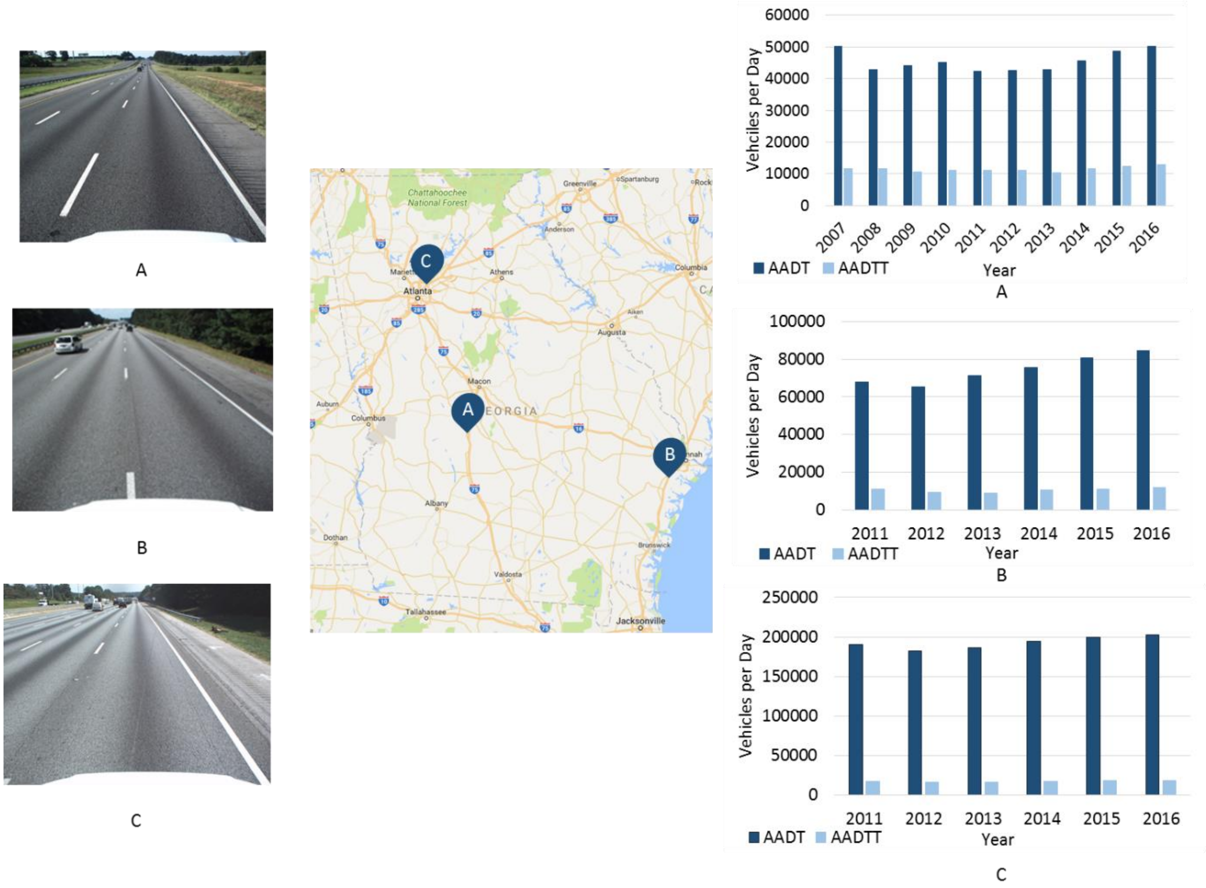
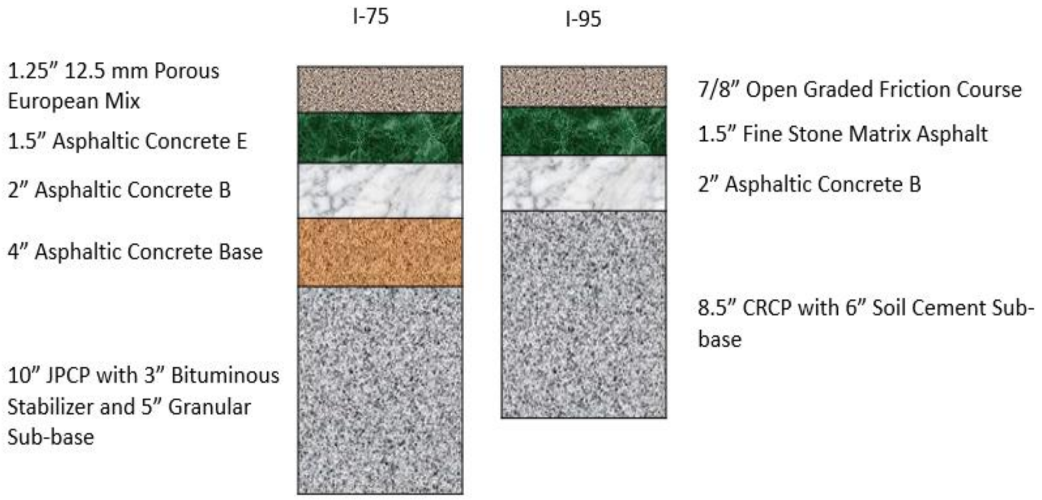


FIGURE 4: ***Project Location, Lane Configuration, and Traffic on I-75 (A), I-95 (B), and I-285 (C)***



(a) I-75 **(b) I-95**

FIGURE 5: ***Pavement Structure on I-75 and I-95***

I-285 is an interstate that goes around Atlanta, and this project took place on the northeast part of it. The project was completed in 2012. It is approximately 6.6 miles long, and the number of lanes varied during the project with a minimum of 3 lanes in each direction. It had an AADT of approximately 200,000 VPD with 8% truck traffic, as shown in FIGURE 4 (C). Half of the section has underlying Portland cement concrete (PCC) overlaid with hot mix asphalt pavement. The other half is full-depth asphalt pavement with a 1.5" Asphaltic Concrete E layer under the PEM, similar to the pavement design on I-75. PEM was the overlaid layer for this project.

2. Performance Studies

The following sections will assess the performance of each of the three projects.

2.1 Performance of I-75 Micro-milling and Thin Overlay Project

The performance of the micro-milling and thin overlay project on I-75 is assessed using GDOT's PACES data (GDOT, 2011). PACES evaluates pavement condition and assesses 10 types of pavement distresses. Each pavement distress is rated by severity and extent. Most distresses have three levels of severity; Severity Level 1 represents low severity, and Severity Level 3 represents high severity. These ratings are converted to an overall rating on a scale of 0 to 100, with 100 being a perfect pavement and 70 being the cutoff for an acceptable pavement. This data is given on the project level, typically 7-10 miles, and the segment level, typically 1 mile. Cracking is assessed in a representative 100-foot segment where detailed measurements are taken, and most other distresses are assessed over the entire mile using a windshield survey.

Prior to micro-milling and thin overlay on this section of I-75, the pavement was in poor condition, indicated by its PACES rating of 65 (out of 100). The poor rating was primarily attributable to raveling, reflective cracking, and some load cracking. There was extensive Severity Level 2 reflective cracking, which means that all joints had reflected, and the cracks were wide enough that they could require sealing. In PACES, there are two types of transverse cracking: block and reflective cracking. Without prior knowledge of the pavement construction, it is easy for raters to mistake reflective cracking as block cracking. Prior to 2007, it was often recorded as block cracking. Since this was the case in 2006, the 2005 ratings had to be used. In 2005, there were 148 feet of Severity Level 2 reflective cracking. There was extensive Severity Level 1 raveling with 93% of the section raveled in 2006. There was also some minor load cracking first recorded in 2006.

Nine years after the overlay, the project is still in fair condition, having a rating of 77 in 2016. The 2016 rating was created based on the 3D laser data. Although the results seem reasonable after looking at images of the pavement, they may be lower than the results of a manual survey because the automatic detection of raveling tends to be more accurate than visual inspection, especially for low-severity raveling.

FIGURE 6 shows the project's PACES rating by age before and after milling with the years 1994 and 2007 being at age 0. PACES is a manual rating system that can produce some inconsistencies, and the PACES survey is not performed in some years, so there may be gaps in the data. Despite the gaps, the PACES data is good enough to support the performance study. Although the trends of ratings appear to be very similar before and after construction, some differences can be attributed to the different surface layers and construction. In 1994, a full-depth reconstruction was performed, which means the surface layer was laid on a perfect asphalt pavement, whereas the surface layer after micro-milling was laid on a 14-year-old asphalt pavement layer. The 1994 pavement had an older design, called asphaltic concrete D, but this was replaced with porous European mix in 2007. The mixes were of different design and had the same purpose, but the performance, especially raveling, could have been impacted by the different mixes.

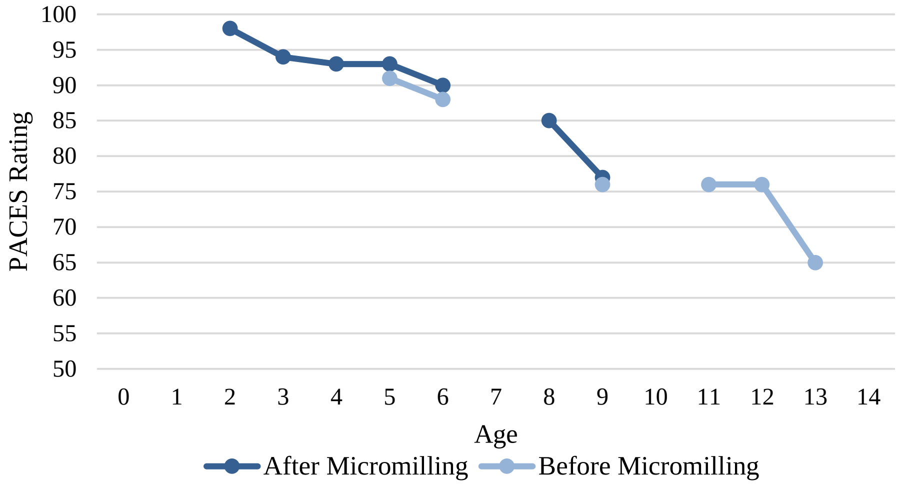


FIGURE 6: ***Project Rating before and after Micro-milling and Thin Overlay***

FIGURE 7 shows the raveling and reflective cracking extent before and after micro-milling by age. As previously mentioned, the reflective cracking prior to micro-milling was sometimes recorded as block cracking, which is measured using a different type of extent, so it was excluded here. Transverse cracking of any kind was first recorded in 1999 at age 5. This was also the first year that a survey was performed. Reflective cracking started on the post-micro-milling surface at age four, so the reflective cracking began at similar ages before and after. Raveling began for both at age six. It progressed rapidly, but the year-nine data from the post-micro-milling are from the automated PACES data, which, as discussed, tends to detect raveling earlier than manual rating.

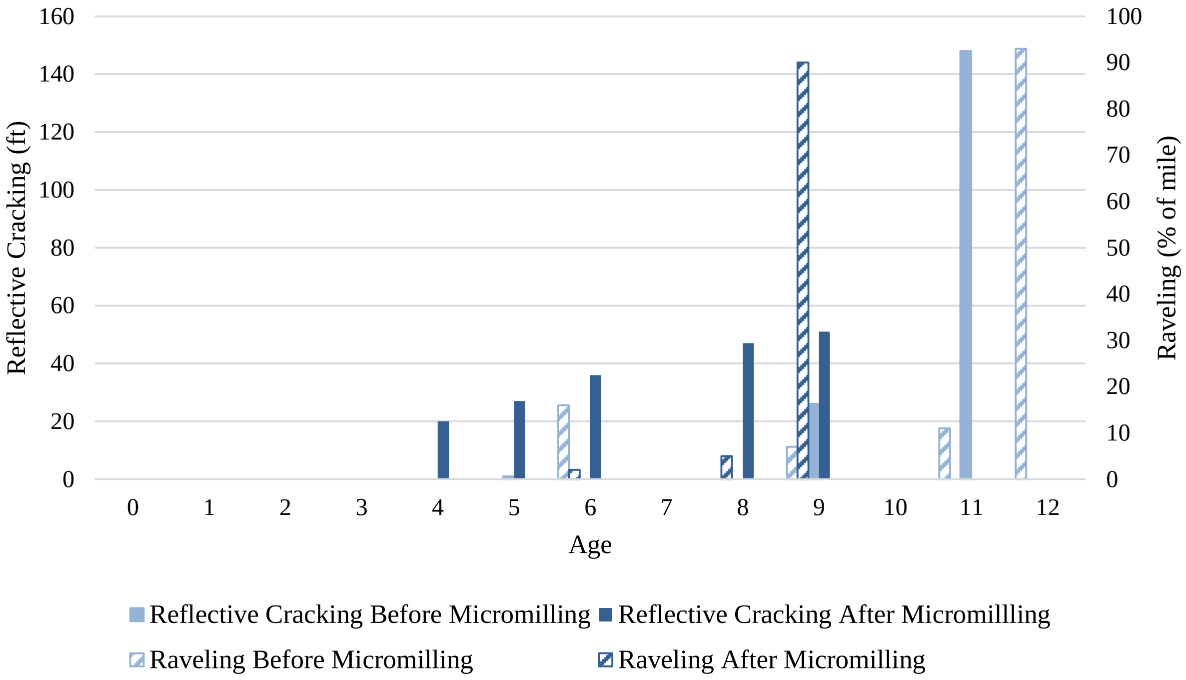


FIGURE 7: ***Project-Level Reflective Cracking and Raveling before and after Micro-milling***

Based on the pavement performance on the I-75 project and the similarity in performance before and after micro-milling, an approximate service interval of 10-12 years can be concluded. This is higher than the 10-11-year service interval found in 2016, which was adjusted to accommodate the current state of the pavement and the added knowledge of the before and after conditions from this assessment (Tsai, et al., 2016).

2.2 Performance of I-95 Micro-milling and Thin Overlay Project

A PACES survey is performed using manual inspection methods; most cracks are assessed on a selected 100-foot pavement sample section that is chosen to be a representative section for the mile. This is a subjective measurement method. PACES also analyzes distresses in a lump sum approach, so it is impossible to determine if an individual crack has reflected from the underlying surface or is new. However, the 3D sensing methods can solve these problems. This section will demonstrate another way of assessing the impacts of the pre-condition of a micro-milled surface and the propagation of cracks following overlay by using 3D laser data to accurately measure the cracks.

In this study, one mile was chosen so that a detailed assessment of the cracks could be performed to utilize the strength of the 3D sensing technology. Using PACES data as an overview, milepost 96 to 95 in the southbound direction was chosen because it had the most cracking recorded. After selecting the mile for detailed analysis, a beginning and ending point had to be chosen that could be seen in the 3D images of the road both immediately after milling and in 2016. The chosen section, given this constraint, begins just after the Mile 96 marker and continues until the exit at Mile 94, making the distance longer than 1 mile (approximately 1.5 miles). Once the beginning and ending points are identified, cracks are detected along with the measurements of length and width of cracks. Next, the images and crack maps are manipulated to allow for a visualization that aligns the images so that cracks can be matched to assess which cracks are propagated or if the crack is new. With the aligned cracks, an analysis of the cracks can be performed.

There were 2,005 feet of cracks with an average width of 0.6 inches on the section in 2011 on the milled surface. TABLE 1 shows the cracks by type and year. As seen in TABLE 1, the majority of these cracks were transverse cracks, but some longitudinal cracks were present. Longitudinal cracking is separated into non-wheel path and wheel path because the wheel-path cracking is assumed to be caused by traffic loading, whereas non-wheel-path cracking is caused by weathering and aging.

TABLE 1: Total Crack Length from 2011 to 2016

Year	**Crack Length (ft.)**			
	Transverse	**Non-wheel-path Longitudinal**	**Wheel-path Longitudinal**	**Subtotal**
2011	1,556	331	118	2,005
2013	0	0	0	0
2014	22	1	0	23
2015	45	6	0	51
2016	94	32	28	154

FIGURE 8 shows some crack examples in the milled pavement. The right column shows the video-log images; the left column shows the corresponding rectified 3D laser images. Each 3D laser image covers 5 meters in the driving direction and 4 meters in the transverse direction. From FIGURE 8, 3D laser images show much less background noise. Thus, they are used for generating crack maps in this study. As seen in FIGURE 8, there is variation in the widths of the cracking. The right-side construction joints show significant deterioration and the joints are wide open. The third image shows an example of poor pavement conditions, which is located approximately ½ mile (850 m) from the starting of the selected pavement section.

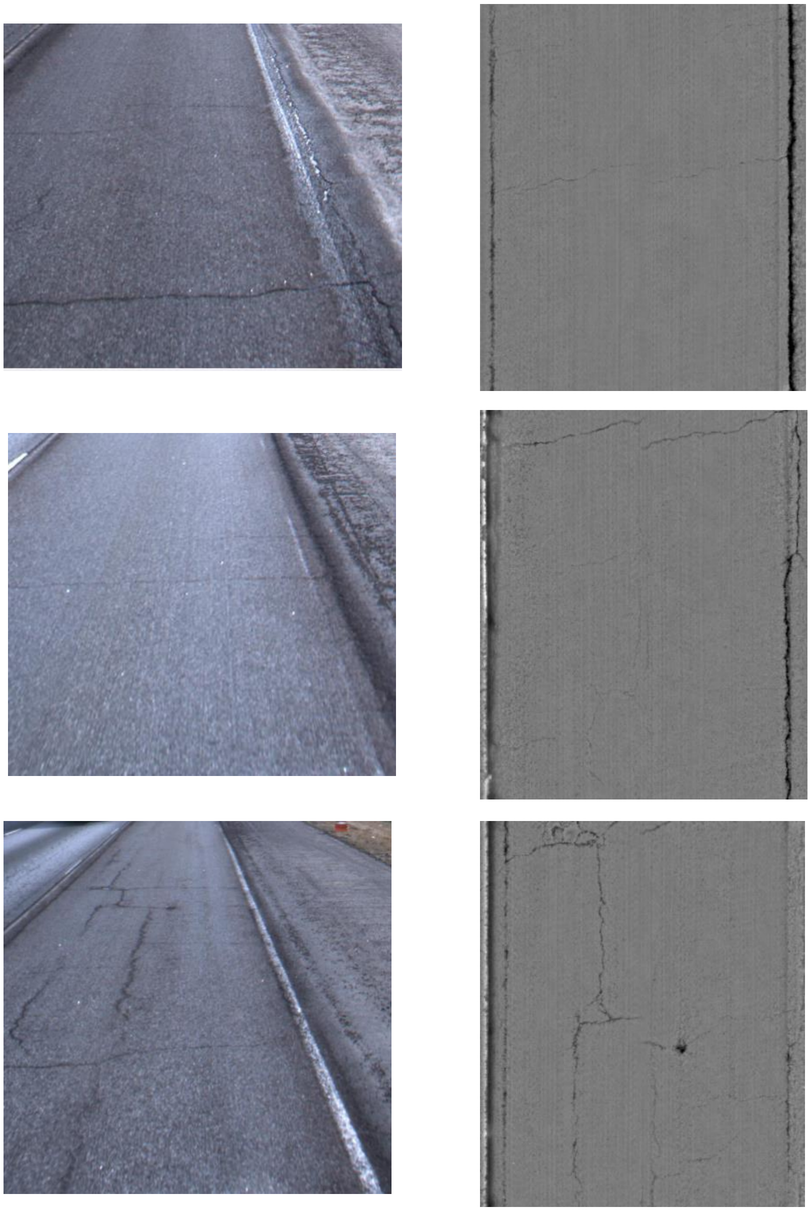


FIGURE 8: ***Video-Log Images and 3D Laser Data on Milled Surface in 2011***

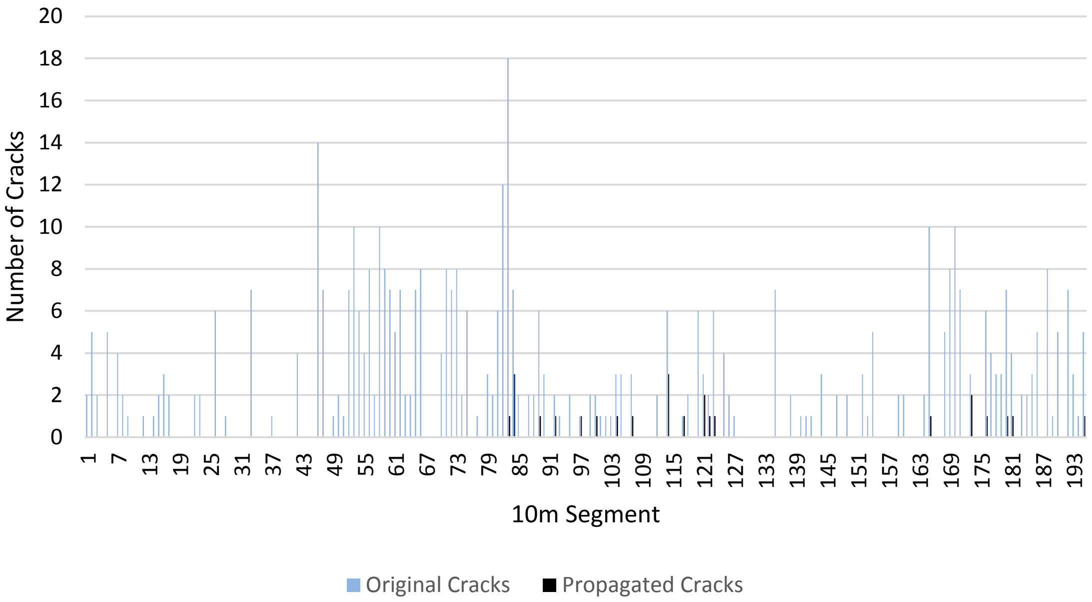
TABLE 2 lists the crack length by type in 2011 and 2016. For cracks identified in 2011 right after the micro-milling and before the thin overlay, the crack length of each crack type, as well as the total amount, are further categorized into “reflected in 2016” and “non-reflected in 2016” based on the registered cracks maps. “Reflected in 2016” indicates the amount of cracks that were reflected in 2016; otherwise, they are “non-reflected” cracks. From TABLE 2, it can be seen that 6% (94 ft.) of transverse cracks in the pre-construction pavements were reflected in 2016. In contrast, 4% (12 ft.) of non-wheel-path longitudinal cracks were reflected; and none of wheel-path longitudinal cracks were reflected. From this analysis, transverse cracks are more critical than other types of cracks for assessing pre-construction pavement conditions of micro-milling and thin overlay projects. This is because most transverse cracks are working ones. Thus, careful pretreatments are desired for transverse cracks before thin overlay. Nevertheless, the reflected percentage is still small in 4 years after the thin overlay. This means that the surface friction course is a good crack relief layer and the pre-construction conditions on I-95 was sufficient for micro-milling and thin overlay.

On the other hand, the cracks found in 2016, based on the most recent 3D laser data, are further categorized into “reflected from 2011” and “non-reflected from 2011”. “Reflected from 2011” indicates the cracks found in 2016 are the ones reflected from the preconstruction cracks; otherwise, they are newly generated cracks due to traffic loading and/or weathering. In TABLE 2, all transverse cracks in 2016 are reflected from 2011; there is no new transverse crack generated in 2016. In contrast, less than half (37%) of non-wheel-path longitudinal cracks are reflected from the cracks in 2011, but all of the wheel-path longitudinal cracks are newly generated. The percentage of newly generated cracks is about 31%, which is approximately half of the reflected cracks and could be used to quantify the performance of thin overlay if the pre-construction pavements have no cracking issue. Of course, the newly generated cracks could also be related to the pre-construction cracks because they cannot be isolated from the overall pavement structural conditions.

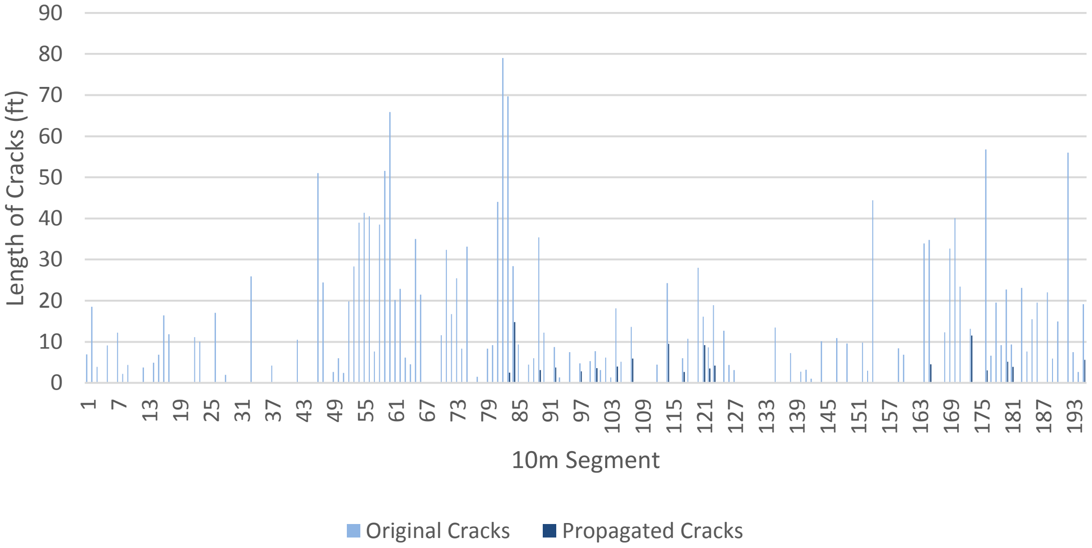
TABLE 2: Comparison of Total Crack Length in 2011 and 2016

	Cracks in 2011			**Cracks in 2016**		
	Subtotal	**Reflected in 2016**	**Non-reflected in 2016**	**Subtotal**	**Reflected from 2011**	**Non-reflected from 2011**
Transverse	1,556	94 (6%)	1462 (94%)	94	94 (100%)	0 (0%)
Non-wheel-path Longitudinal	331	12 (4%)	319 (96%)	32	12 (37%)	20 (63%)
Wheel-path Longitudinal	118	0 (0%)	118(100%)	28	0 (0%)	28 (100%)
Subtotal	2,005	106 (5%)	1900 (95%)	154	106 (69%)	48 (31%)

We divide the entire pavement section into 10-m segments and summarized the total number and total length of cracks in each, as shown in FIGURE 9 (a) and (b), respectively. In FIGURE 9, longitudinal cracks are not counted because they did not reflect. It can be seen that all the reflected cracks are clustered in the latter half of the test section. Actually, this section is the only one with cracking on the entire project and the majority of the cracking is after a transverse construction joint, which means all reflected cracks occur in continuously paved pavement. Therefore, the difference in performance might be attributed to the paving process or the HMA used.



(a) Count by Number



(b) Count by Length

FIGURE 9: ***Spatial Distribution of Cracks in 2011 and Reflected Cracks in 2016***

Using the 3D laser data, it is also convenient to trace the propagation of an individual crack. Because the increase in crack length is attributed to both lengthening of individual cracks and appearance of new cracks, it is useful to follow a selection of cracks to observe their propagation characteristics. Three cracks that had clear images each year were chosen. Their range images from 2014, 2015, and 2016 are shown in FIGURE 10. The increase of crack length and width can be visually seen and is listed in TABLE 3. The rate of change varies among cracks and from year to year, although crack length tended to increase more rapidly than width, as expected.

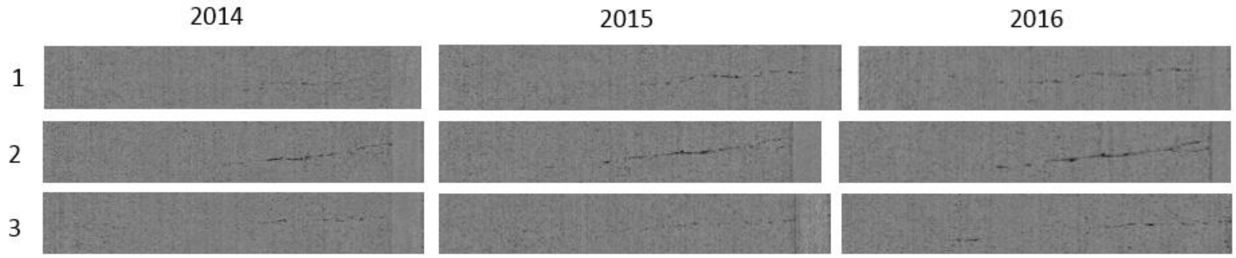


FIGURE 10: ***Propagation of Three Individual Cracks***

TABLE 3: Detailed Crack Length and Change for 3 cracks

	Crack 1		**Crack 2**		**Crack 3**	
Year	**Length (ft.)**	**Delta**	**Length (ft.)**	**Delta**	**Length (ft.)**	**Delta**
2014	1.94	--	3.63	--	2.52	--
2015	2.89	49%	3.92	8%	2.99	19%
2016	3.77	31%	4.64	18%	4.53	51%

The 3D laser data and the derived crack maps, which help with the issue of data variation in PACES data, make it possible to study the detailed level of crack propagation on I-95. Based on the study of a one-mile pavement section on I-95, transverse cracks are the ones that are most prone to be reflected into the thin overlay in comparison to non-wheel-path longitudinal cracks and wheel-path longitudinal cracks. However, the amount of reflected cracking is small (about 8%) in 4 years after thin overlay, which suggests good performance for crack relief. Using 3D laser data and the derived crack maps shows great potential and advantages over PACES data. Other than the crack propagation in terms of total crack length, each individual crack can also be traced. So, we can further study the micro-level crack propagation characteristics.

2.3 Performance of I-285 Micro-milling and Thin Overlay Project

There is no historical PACES data available for I-285, so the routinely collected 3D laser data is used for this analysis, as well. No precondition survey was performed for the I-285 project, so only the performance after micro-milling is used for assessment. 3D laser data was available for this section in 2013, one year after completion of the micro-milling, to 2017. Both cracking and rutting were observed for this section. After the visual inspection, a 1.75-mile-long section in the clockwise direction from exit 30 to 31A was chosen for analysis. Although no record was available of the pre-construction condition on I-285, engineers at GDOT stated that the condition on I-285 was poor, potentially lacking structural integrity for micro-milling and thin overlay, as shown by rutting. Micro-milling was used due to a lack of budget at the time and a need to remove rutting that was causing safety concerns. This project can show how effective micro-milling is on a pavement in poor condition and help differentiate between good and bad candidates for micro-milling and thin overlay.

The cracking on the I-285 project looks to be reflective cracking from the underlying PCC. Near the beginning of the section, the old off-ramp can be seen reflected, as shown in the first row of images in FIGURE 11. FIGURE 11 shows a selection of cracking images from the assessed section in 2013 (left) and 2017 (right). The second image shows a reflected construction joint that runs near the wheel path; the positioning might have been causing more rapid deterioration. This cracking runs throughout most of the project and accounts for most of the longitudinal cracking. Many of the transverse cracks also appear to be reflected joints. The bottom images in FIGURE 11 show the most extreme example of this. Based on a visual assessment, it seems the cracking problems on I-285 project can be attributed to reflective cracking.

FIGURE 11: ***Examples of Cracking on I-285 in 2013 (Left) and 2017 (Right)***

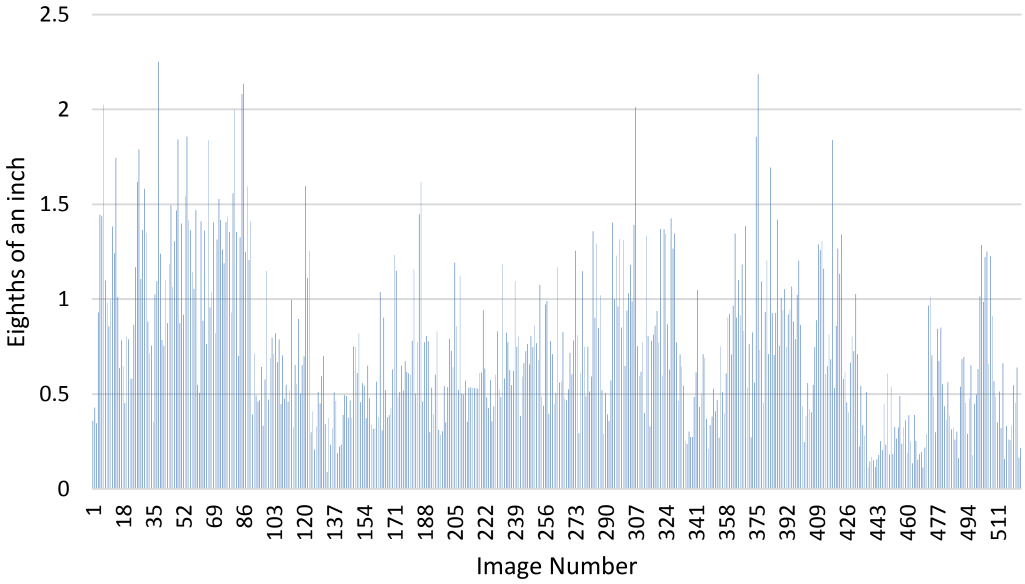
Cracking started earlier in the I85 project than it did in the I-95 project. On the I-285 project, cracking was already emerging in 2013 on a stretch of 351 ft., which is more than double the cracking in 2016 on the I-95 project. From 2013 to 2017, the cracking grew by 2,481 ft., 7 times the amount of cracking in 2013. This could be attributed to the higher traffic load or the condition of the road prior to micro-milling, which suggested a weakening of structural support in some of the deeper layers.

The average and maximum rutting for the left and right wheel paths is shown in TABLE 4. The rutting is calculated every 2 feet, and these statistics were found across the entire analysis section from each 2-foot reading. On average, the rutting across years remained at approximately 1/10 inch. This is not a concerning level of rutting, but the maximum rutting beginning in year 2014 is approximately ½ inch, which is an alarming level. The rutting situation improved in some years, which could be due to maintenance activities or variations in the data. Because the maximum is high but the average is acceptable, the location of the high rutting needs to be considered to see how long the sections of high rutting lasted.

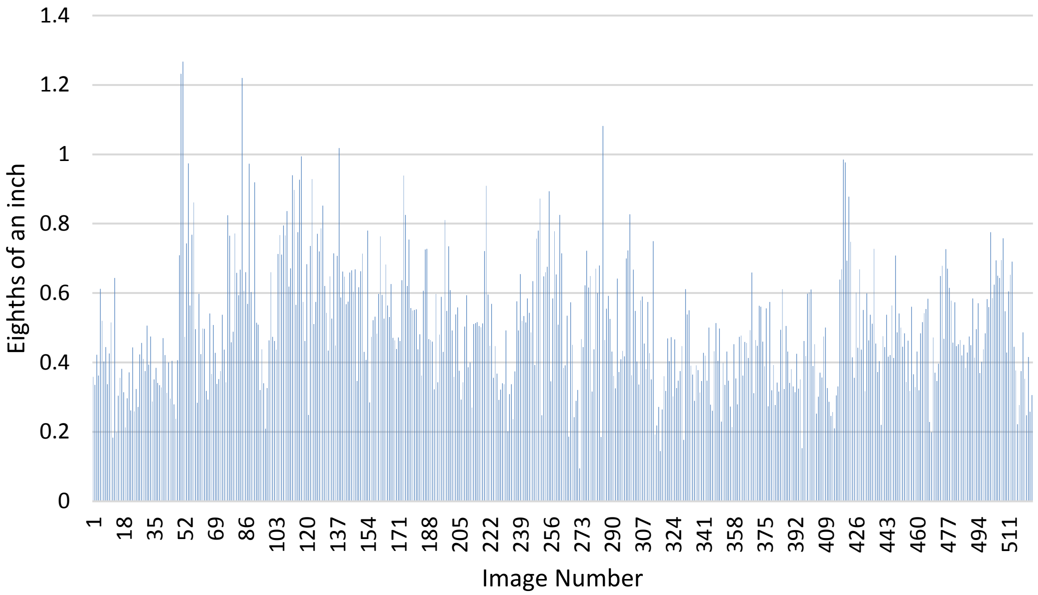
TABLE 4: Rutting in Left and Right Wheel Paths

	Mean (1/8”)		**Maximum (1/8”)**	
	Left	Right	Left	Right
2013	0.5	1.2	1.5	3.3
2014	0.8	1.2	1.9	3.8
2015	0.8	0.8	2.2	3.6
2016	0.9	0.8	2.2	3.6
2017	0.9	1.4	2.6	4.2

As for spatial distribution, the rutting was averaged per 5 m image, previously measured at one rutting value taken per foot. FIGURE 12 (a) and (b) show the rutting in eighths of an inch per 5-m image in 2017. Aggregated at the image level, the maximum rutting is approximately 2.3 and 1.3 eigths of an inch for the right and left wheel paths, respectively. This is still within an acceptable range, although the right wheel path is somewhat high. It can futher be shown that the highest rutting does tend to occur in clusters, which means it could be reduced by patching operations, but there are many of these clumps, so this may not be as effective as desired. This is especially true in the left wheel path, which has more uniform rutting throughout the section. Looking at the rutting aggregated in this way, it can be concluded that micro-milling and thin overlay can ameliorate rutting for five or more years as the rutting on a 5 m basis has not exceeded an acceptable value. However, due to the randomly distributed 1/2” of rutting in 2017, it is suggested the use of rutting amelioration on poor roads be limited to 4 years.



(a)



(b)

FIGURE 12: ***Spatial Distribution of Rutting in Right (a) and Left (b) Wheel Paths***

3. Summary

Based on above analyses on three projects on I-75, I-95, and I-285, respectively, micro-milling and thin overlay is shown to be an effective pavement preservation treatment. From the project on I-75, micro-milling and thin overlay has an expected service interval of 10-12 years. The I-95 project further supported this with its crack propagation after 5 years of service. The analysis of the I-95 project focused on cracking and reflection of cracks through the overlay. This analysis showed that only minor amounts of cracking had reflected (5% of the original cracking), suggesting this is an effective crack relief method. The I-285 project was considered for comparison because of the original poor condition of the pavement. The reflective cracking did progress more quickly than on I-95, but that could be related to traffic loading or the severity of the original condition. The micro-milling did ameliorate the rutting temporarily (for approximately 4 years), so it can be used as a temporary treatment for rutting.

CHAPTER 4: ECONOMIC ANALYSIS

Life-cycle cost analysis (LCCA) is a method of assessing and comparing the cost-effectiveness of a project over a lifetime, including materials, construction, maintenance, and end of life. This method can be used to assess the economic effectiveness of micro-milling and thin overlay. In deciding whether to use micro-milling and thin overlay or conventional method, the cost-effectiveness is of primary concern. An LCCA for micro-milling and thin overlay was previously done by Tsai et al. (2016). This study used 8 years of pavement performance data to look at the I-75 project and develop an expected service life for micro-milling and thin overlay. The service life, based on the condition of the pavement and engineering judgement, was approximated to be 10-11 years. This value was then used in an LCCA to determine the cost-effectiveness of micro-milling and thin overlay and compare it to the conventional method. This LCCA included material and construction costs only, assuming all other costs were the same for the two treatments. It concluded that micro-milling and thin overlay can save 11% compared to the conventional method.

Some limitations to this study will be addressed in this chapter. First, there is no existing micro-milling project that has reached the its end of service life. As detailed in Chapter 3, the I-75 project is now 10 years old and still in service with a PACES rating of 77. This means it may exceed the expected service life. So, an adjusted service life of 10-12 years will be used here, which is similar to that of the conventional method. Another limitation is that the cost data did not come from a specific project but was aggregated data from a different year. As micro-milling was a new process, the costs would be expected to be higher. Updated costs from a real project using both treatments will be used for the milling in this updated LCCA.

1. I-95 Project Description

The LCCA will use data from a recent micro-milling project on I-95 extending from I-16 to the Savannah River near South Carolina. The project is 13 miles long and has 3 lanes in each direction for a total of 78 lane-miles. The segment had an AADT of 84,500 vehicles in 2016 with 14% trucks. The top two layers of the new pavement are 1.5" SMA and 7/8" OGFC. Originally, this project was contracted as a micro-milling and thin overlay, but was changed to conventional milling on the 2 outside lanes and micro-milling on the inside lane due to concerns of rutting. This means there are 52 lane-miles of conventional milling and 26 lane-miles of micro-milling. The conventional milling was completed during summer 2017, and the micro-milling and OGFC overlay has yet to be completed. The contractor was contacted to obtained more details on the project.

2. Life-Cycle Cost Analysis

The rest of this chapter consists of a description of the LCCA inputs and an analysis of the results, a sensitivity study, and conclusions.

2.1 Inputs, Parameters, and Results

The service life used in this LCCA is 12 years for both the micro-milling and thin overlay, and the conventional method. A sensitivity study will be performed to assess the sensitivity to the different service lives. A discount rate of 4% is used, which is within the recommended range by FHWA and GDOT. The unit of study is a 12-foot wide lane for 1 lane-mile. The costs include the materials (SMA and OGFC) and construction costs (micro-milling and conventional milling). The costs are aggregated to include the construction, equipment, and labor. The costs for the milling were obtained from the I-95 project contractor, which improves the comparison because they are from the same project. The material costs (SMA and OGFC) were obtained from the most recent item mean summary using the weighted average cost for 12.5 mm OGFC and SMA.

Costs in addition to materials and construction were considered. The two treatments being assessed are pavement preservation treatments themselves, so there are no other maintenance costs. User costs were originally considered, as overall production of micro-milling and thin overlay can progress more quickly than conventional milling. But it was decided that they would not be included in this analysis due to the difficulty to quantify the difference.

If, for a fair comparison, it is assumed that only one travel lane is closed at a time, then the roadway could have a capacity of approximately 1,500 vehicles per hour on one direction. Looking at the hourly traffic counts for July 2016 and 2017 for the segment of roadway, the traffic capacity is only exceeded between 7-9 pm and 6-7 am just north of I-16. This is not the case south of the Savannah River (GDOT, 2017). More congestion could be expected close to I-16, but congestion would be minimal further north on the project. The maximum exceedance for the southern part of the project was 500 vehicles in an hour. However, without a method of simulating the congestion, it is difficult to determine the exact impacts.

Though micro-milling is expected to progress as quickly as conventional milling in terms of miles completed per night, it is hard to accurately evaluate the progress because the actual traffic flow and potential for congestion vary widely from project to project. Thus, the cost difference related to traffic congestion was not considered in this study. It is assumed that all the construction processes other than the milling machine are essentially the same, as what we have discussed with the contractor. The traffic control information was not included because it was not available. The costs for the materials, construction, and the net present value (NPV) and equivalent uniform annual cost (EUAC) are shown in TABLE 5.

TABLE 5: Costs of Micro-milling and Thin overlay and Conventional Method

Cost	Micro-Milling and Thin Overlay	Conventional Milling and Overlay
OGFC	$43,291	$43,291
SMA	$0	$59,178
Milling	$11,546	$13,939
NPV	$54,836	$116,408
EUAC	$5,843	$12,403

As can be seen in TABLE 5, micro-milling and thin overlay has substantial cost savings over the conventional method. This is primarily attributed to the reduction in asphaltic material being used, with $59,178 saved in SMA costs. Additionally, on this project, the micro-milling costs ($1.64/SY) were lower than conventional milling (1.98/SY). The overall result is a 53% savings when using micro-milling. This is much greater than the value found in the first study because micro-milling and thin overlay costs were over 3 times as much as conventional method in that study (Tsai, et al., 2016). Additionally, in the first study, micro-milling and thin overlay were assessed at a 10-year service life and conventional method at a 12-year service life. Because of this great discrepancy in final values, both milling costs and service interval will be tested for sensitivity in the next section.

2.2 Sensitivity Study

The micro-milling costs were increased to three times that of conventional milling, which were similar to the costs from 2007 for the first project (Tsai, et al., 2016). With this change, micro-milling and thin overlay saves 27% of the project cost compared with the conventional method. The results are shown in TABLE 6. The EUAC of micro-milling and thin overlay is still much lower than that of the conventional method. Based on the calculation, these two methods have the same cost when micro-milling costs 5.25 times more than conventional milling, which is unlikely in reality.

TABLE 6: Costs for Increased Micro-milling Price

Cost	Micro-Milling	Conventional Milling
OGFC	$43,291	$43,291
SMA	$0	$59,178
Milling	$41,818	$13,939
NPV	$85,108	$116,408
EUAC	$9,068	$12,403

The next step is to evaluate the service life impacts. The first assessment was to reduce the service life of micro-milling to 10 years, the low end of the expected service life. This impacts the EUAC and results in a 45% cost savings by using micro-milling. The results are shown in TABLE 7.

TABLE 7: Costs for 10-year Service Life Micro-milling

Cost	Micro-Milling	Conventional Milling
OGFC	$43,291	$43,291
SMA	$0	$59,178
Milling	$11,546	$13,939
NPV	$54,836	$116,408
EUAC	$6,761	$12,403

To make the EUAC of micro-milling and thin overly similar to the conventional method, the micro-milling needs a service life of 5 years. As was presented in Chapter 3, we can confidently expect micro-milling and thin overlay to last longer than 5 years when it is applied on structurally sound pavements. So, the actual EUAC of micro-milling and thin overlay is unlikely to be equal to or lower than the one of conventional method.

Because micro-milling is less expensive than conventional milling in the above scenario, the cost of micro-milling was modified as three times more expensive than conventional milling, as it was in 2007 for the first micro-milling project. In this scenario, the results showed that micro-milling must last for at least 8 years to be financially viable. This would still be a short life span for micro-milling based on the performance analysis in Chapter 3.

3. Summary

Based on the analysis, it can be concluded that the costs of micro-milling and thin overlay can vary from project to project, but it is economically preferable to the conventional method. Micro-milling could reduce the cost by 53% compared to the conventional method and resulted in a savings of $6,560 per lane-mile per year over the pavement’s lifetime, which is estimated using the milling costs for the recent I-95 project.

CHAPTER 5: SUSTAINABILITY ANALYSIS

The study performed in Chapter 3 and Chapter 4 showed that micro-milling and thin overlay is cost-effective and delivers acceptable performance that is comparable to the conventional method. The next step in assessing the sustainability of micro-milling and thin overlay is to quantify its environmental and social impacts. The project on I-95 analyzed in Chapter 4 will be used in this study. In this project, the inside lane was micro-milled and the outside lane was conventionally milled. This provides a good comparison of the two methods on the same roadway by the same contractor.

For sustainability analysis, life-cycle assessment (LCA) is used. LCA is a tool that analyzes the environmental impacts of a process, system, or an entire industry from the beginning of the process (i.e. raw materials) to the end of life (i.e. landfill/recycling). This is called a cradle-to-grave assessment. In an LCA, this is accomplished through four steps: goal definition and scoping, inventory analysis, impact assessment, and interpretation (Curran, 2006; FHWA, 2016). The first step sets the boundaries of the system being analyzed, which is based on the stated goal of the assessment. The inventory analysis catalogs all the inputs and outputs, including materials, energy, and emissions. The outputs from this step are used in the impact assessment to analyze the impacts on the environment and the population. This analysis will walk through each step, but it will not get to the level of detailed direct impacts on human health, such as increased incidences of asthma. Any reduction in pollutants or energy use in comparison to conventional milling is considered a positive impact. The following sections will discuss in detail each step; an analysis of the social sustainability is included at the end to complete the sustainability assessment.

1. Goal Definition and Scoping

The goal of this LCA is to compare and contrast the environmental impacts of two pavement preservation treatments: micro-milling and thin overlay, and conventional method. There are four general life stages of pavements: material acquisition, construction, use and maintenance, and end of life. This study will consider 3 of the 4 life stages: material acquisition, construction, and end of life. The use phase is not considered because the pavement/tire interaction is not known, nor are the differences in surface characteristics between a thin overlay and the conventional overlay. Because the surface layer is the same in both options, it is assumed that their use phases are approximately equal in terms of environmental impacts. Maintenance is not considered as these are pavement preservation treatments themselves and little to no maintenance is expected during the pavement's life. This study will also not go further than quantifying the emissions and material/energy use in the two options, as that should be sufficient to determine which is environmentally preferable. The unit of analysis will be a 12-foot wide lane for one lane-mile.

The construction process of the I-95 project is used in the analysis. This project has both micro-milling and conventional milling, and the contractor was contacted for information to aid in the environmental analysis. At the time of analysis, the conventional milling had been completed and the micro-milling had been scheduled, so the micro-milling values are based on the contractor's best estimation from past experience.

2. Inventory Analysis

Both conventional milling and micro-milling can be divided into 4 sub-systems: raw material acquisition and production, construction, use, and end of life. Each sub-system will be described in more detail in this section, including their components, inputs, and outputs. An overview is provided in FIGURE 13. Although transportation is not included as a component or sub-system, it is an important piece of the life-cycle of an asphalt pavement and is included in every sub-system and most components.

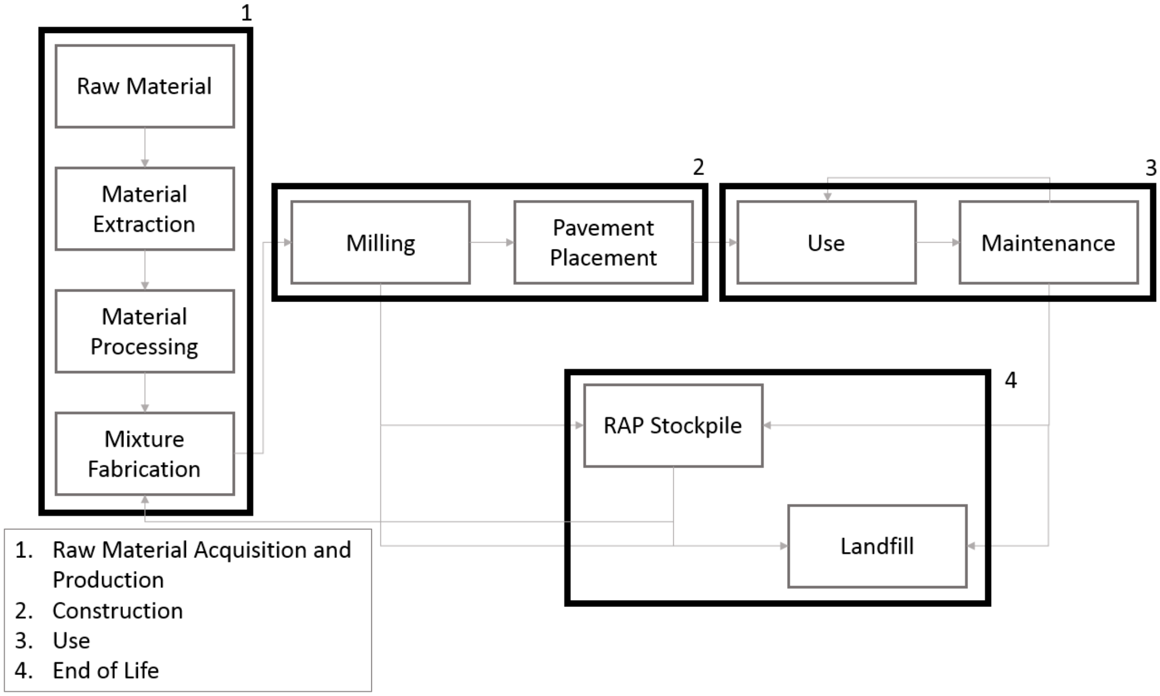


FIGURE 13: ***Sub-systems and Components of the Milling and Overlay Process***

2.1 Raw Material Acquisition and Production

This sub-system consists of 4 components: raw material, material extraction, material processing, and asphalt mixture fabrication. The starting inputs for the process are raw material and energy, which are added throughout the entire process, and the outputs are the asphalt mixture and emissions.

When making asphalt, the raw material is typically petroleum. The first step is to extract crude oil. Energy is consumed in the process of drilling, primary recovery, and/or secondary recovery (Sukin, 2017). Once extracted, the crude oil is transported to a petroleum refinery. Asphalt is one of the many products of refining petroleum. To begin the process, crude oil is transported to the refinery, which can be accomplished via pipe, tanker ship, rail, truck, or a combination of these. Each of these modes takes energy and generates emissions. Once delivered for refining, crude oil must have water, contaminants, and salts removed. Sometimes, this can be done through settling in tanks, but if the salt content remains too high, it must be desalted. Fresh water is added to separate the emulsion of water and salt from the oil, which is performed at approximately 200-300 Fahrenheit degrees (PI-1, 2017). Therefore, this step requires the addition of both water, which could be treated onsite and reused, and energy to the system.

Once desalted, the oil can be moved to distillation towers. Asphalt undergoes two phases of distillation. First, the oil is heated to approximately 700 degrees (PI-1, 2017) and sent to atmospheric distillation towers (Whiteside, 2017). The atmospheric distillation separates the lighter hydrocarbons, and the residue is sent on to vacuum distillation towers (Whiteside, 2017). The residue from this process can be taken as asphalt, or it can be cracked and turned into another material or mixed and manipulated through additives to create a different type of asphalt (PI-1, 2017). These processes also require large energy inputs. Finally, the asphalt is prepared for mixing with aggregate, typically as emulsified asphalt (Whiteside, 2017).

The asphalt only makes up a small percentage of the overall pavement. The majority is aggregate. Natural aggregate is typically produced in a quarry or mine where in situ rock is turned into aggregate. This involves blasting or digging rock from the quarry walls; then, screens and crushers are used to reduce the aggregate to the desired size (PI-2, 2017). This, too, requires energy input and results in dust emissions. As with oil used for the asphalt, rocks are a limited resource and materials use must be considered in environmental impacts as well.

The last step in producing the paving material is to mix the asphalt with the aggregate. This can be done on or off site using either a drum-mix facility or a batch mix facility. The mixture must be heated during this process to make it workable. The mixture is then transported to either the job site or storage (Whiteside, 2017).

Overall, it has been shown that the petroleum refining necessary to fabricate asphalt involves very high temperatures, up to 700 degrees Fahrenheit if no cracking occurs, throughout the process and requires large amounts of energy. The refining of petroleum is also known for its emissions. Legal codes have been in place to limit the emissions and water use from both refinery plants and asphalt processing plants (Whiteside, 2017). Reclaimed asphalt pavement (RAP) can also cut out much of this process, just needing to be re-mixed, sometimes with additives to improve the quality of the asphalt, and re-laid.

This still has the energy and emissions associated with the last component of the sub-system but can greatly reduce emissions, material use, and energy use by not returning to the raw materials step.

2.2 Construction

Much of the construction process was detailed in Chapter 2. There are two major components to the construction process: milling and pavement placement. The inputs into this sub-system are the asphaltic concrete from the raw material acquisition and production stage and energy. Outputs include a completed pavement, but also emissions, including emissions from the construction equipment and dust from the process. Emissions can also be generated by congestion from the traffic control operations if congestion occurs.

Much of the construction process is the same for micro-milling and conventional milling. The primary differences are in the number of paving passes needed and that micro-milled surfaces can be opened to traffic, allowing more construction flexibility. To keep traffic flow, conventional milling requires that the milling and the first overlay (leaving only the OGFC off) must be done in the same construction period. However, the micro-milling process can be more intensive and slower due to the higher number of teeth on the drum, potentially resulting in different amounts of fuel usage per mile milled. This was not tracked by the contractor, so the exact change is not known. Typically for this contractor, and as a representative example, micro-milling progresses at 15-20 ft./min, and conventional milling at 30-35 ft./min. Micro-milling also requires extra or slower sweeping with a broom truck to remove all the dust from the surface.

The construction timing also impacts both emissions from automobiles and construction equipment. Congestion caused by construction is heavily dependent on when construction is performed. If construction is performed at night, allowing traffic to flow during the day when vehicle flow is higher, then the increased emissions from traffic could be low to none. In the case of interstate construction work, the work is typically done at night as was done on the analyzed project. Construction timing is more flexible using micro-milling, which only needs a lane to be closed during the milling and the overlay processes; between milling and overlay, traffic can flow on the milled surface. The number of construction periods needed can impact both the congestion caused by the construction and the emissions from the equipment. Conventional milling and overlay takes longer because milling and overlay can only progress as far as can be fully completed in one construction period. Micro-milling and thin overlay, in contrast, can spend an entire construction period milling and another one overlaying. Although the micro-milling machine must progress at a speed approximately half that of conventional milling, the micro-milling project is anticipated to progress an average of 3 miles per night, whereas conventional milling progressed at an average of 1 mile per night.

Once construction is complete, no work is needed on the road until the end of its service life. It has entered the use phase. Emissions during the use phase are generally considered to be the highest of all the stages because it includes emissions from the vehicles using the road. However, without knowing details about the pavement texture and pavement/tire interaction it is not possible to determine a difference in use phase emissions between the two methods.

2.3 End of Life

When the pavement is removed at the end of life, it can go to two destinations: RAP stockpiles or landfills. RAP stockpiles is the environmentally preferable use of removed asphalt. In Georgia, the maximum amount of RAP allowed for use on a project is 30%, but the amount allowed is dependent on tests of the RAP stockpile and the required gradations (GDOT, 2014; Norouzi, 2017). Therefore, the outputs of this system could include either waste material and/or RAP that is fed into Sub-system 1 (see FIGURE 13). This phase also requires energy input and produces emissions during the transportation of the material to the stockpile or landfill.

3. Environmental Impact Assessment

With the inputs and outputs of all the sub-systems and components considered, an impact assessment can be performed. The Pavement Lifecycle Assessment Tool for Environmental and Economic Effects (PaLATE) is the tool for this analysis (Nathman, 2008). PaLATE is a tool designed for pavement construction LCA and utilizes a large database of publicly available data from sources such as the Environmental Protection Agency. It is an integrated, hybrid, and streamlined LCA tool. It is integrated because it combines environmental and economic assessments, but only the environmental part was used in this study. The combination of a process-based and matrix-based (economic input-output matrix (EIO-LCA)) life-cycle assessment method for calculations makes it a hybrid LCA. The tool is considered streamlined because it is simplified for what is needed for pavement construction LCA in Microsoft Excel spreadsheets (Nathman, 2008).

There are three types of data used in the tool. They are emissions, construction process, and human toxicity potential (HTP) (Nathman, et al., 2009). Nathman et al. discovered that the HTP module still needed improved data for accurate results, so it will not be used in this analysis (2009). Nathman et al. also determined some of the limitations of the software, which include the assumption that all on-site processes are identical and the reliance on EIO-LCA, which has its own assumptions and limitation (2009). Despite these limitations, the tool is still effective for agencies wanting to perform LCA analyses of their pavement construction and maintenance practices. Many studies have been performed using the tool, including a study on parking infrastructure (Chester, et al., 2010), pavement preservation (Chan, et al., 2011), cold in-place recycling (Cross, et al., 2011), and in situ pavement recycling (Alkins, et al., 2008), which demonstrates its usefulness to agencies. It was decided that this is the most effective tool for this analysis.

As a spreadsheet-based tool, there are a variety of inputs needed in the model. The data for these inputs come from the contractor for the 13-mile-long project on I-95 in Georgia. The project was originally let as a micro-milling project but was changed to conventional milling on the two outside lanes and micro-milling on the inside lane. This provides the opportunity to compare micro-milling and conventional milling on the same project with the same contractor. Some data was not available because it was considered confidential or the contractor did not collect it. When there was missing data, default data from the program or the best approximation was used. For example, all the operating data for the machines used for the milling process was not available, so the closest machine already included in PaLATE was used. Additionally, it was not possible to get the mix design for the paving material, so GDOT's standard mix designs were used. These changes will not have a major impact on the results, as will be shown.

The analysis is performed on a 12-ft-wide lane for 1 mile. Micro-milling and thin overlay and conventional method have a 7/8" layer of OGFC based on GDOT specifications. The conventional method has an additional 1.5" layer of SMA according to GDOT specifications. RAP was used in the SMA, but the percentage is unknown. A RAP percentage of 5% was assumed, but a sensitivity study will be conducted to test sensitivity to this parameter. Transport distances averaged 6 miles, according to the contractor on the project. The asphalt plant uses an Astec Double Barrel, which is a type of drum-mix machine. It has reduced emissions compared to traditional drum-mix plants (Astec, 2017), so the fabric filter-controlled drum-mix in PaLATE was used to approximate this.

The outputs include energy usage, water usage, global warming potential, and air pollutants. The majority of the total in each category was caused during the material production phase. For example, during the material production phase for micro-milling, 98.2% of the total energy used in the entire process is used. For conventional milling the number is similar at 98.6% of the total energy is used during the material production. This discrepancy is shown in FIGURE 14. Even with only a 6-mile travel distance, the equipment and processes (during the construction phase) contribute only approximately ¼ of the energy use of the materials transportation, and a meager 0.4% to the total. It is clear that efforts to reduce the environmental impacts of milling operations should focus on reducing the amount of asphalt material needed, which micro-milling effectively does. FIGURE 15 and FIGURE 16 show the water usage and global warming potential, respectively, to demonstrate that materials production dominates the environmental impact in each category. Furthermore, micro-milling reduces impacts in each category assessed using PaLATE by just over 60%, as shown in TABLE 8. Micro-milling reduces material needs by 63% in this scenario, which is similar to the overall reductions in environmental impacts, and further demonstrates the benefits of reducing material use.

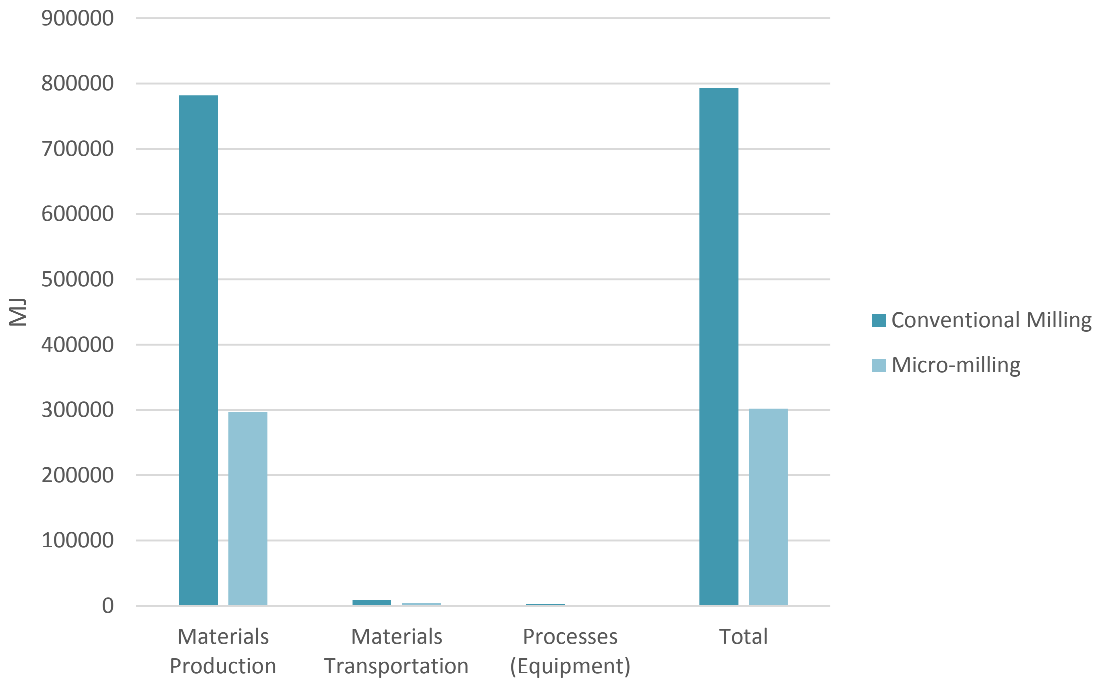


FIGURE 14: ***Energy Usage in Mega Joules (MJ) for Each Process of Conventional and Micro-milling***

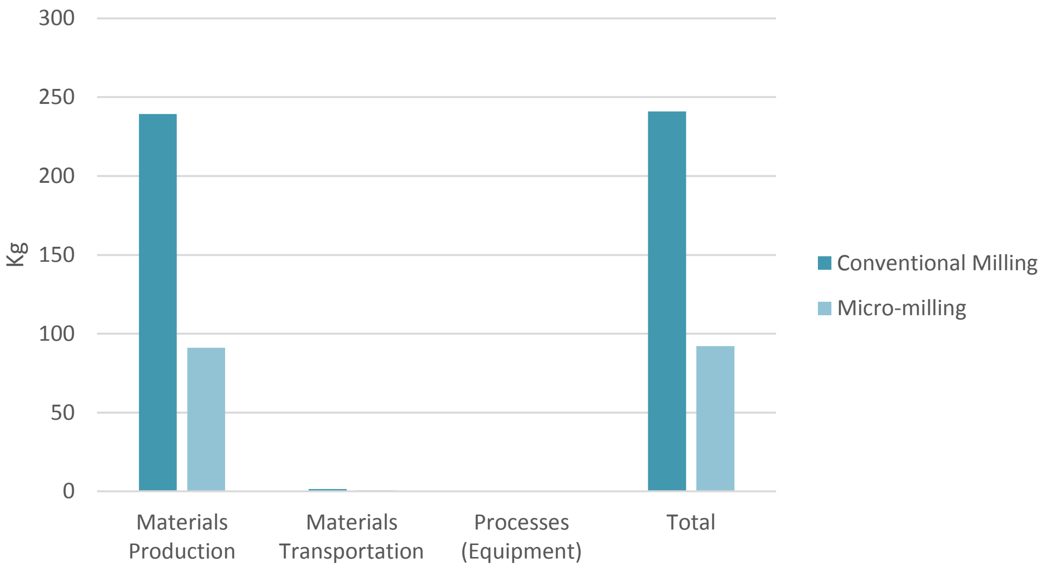


FIGURE 15: ***Water Usage in Kg for Each Process of Conventional and Micro-milling***

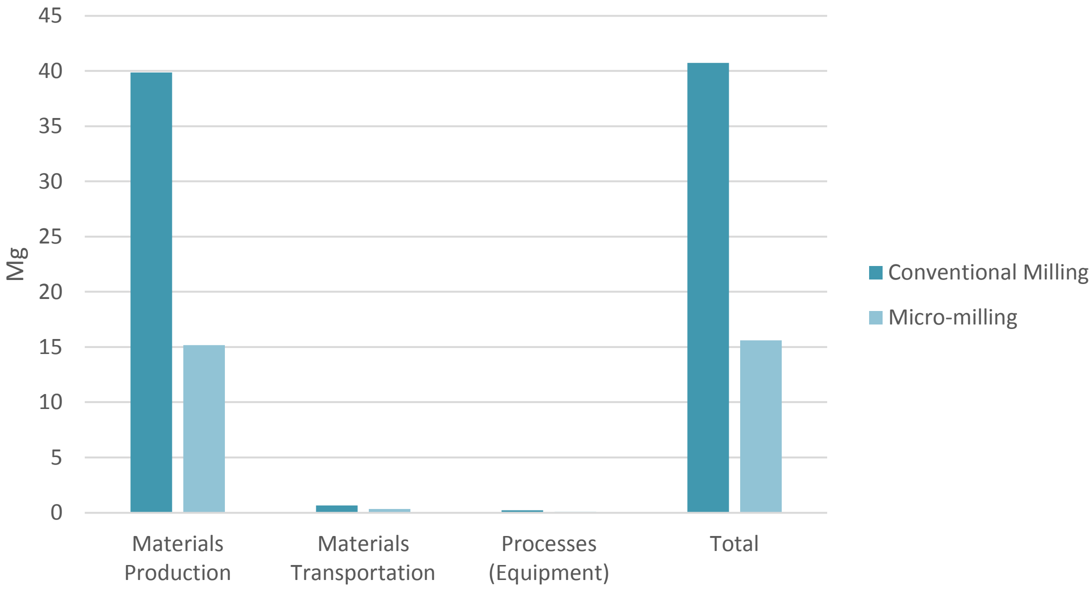


FIGURE 16: ***Global Warming Potential in Mega-grams (Mg) for Each Process of Conventional and Micro-milling***

TABLE 8: Total Impacts for Conventional and Micro-milling

Impact	Conventional Milling	Micro-Milling	% Reduction Using Micro-Milling
Energy [MJ]	793,070	301,978	61.9%
Water Consumption [kg]	241	92	61.8%
CO2 [Mg] = GWP	41	16	61.7%
NOx [kg]	259	103	60.2%
PM10 [kg]	182	71	61.1%
SO2 [kg]	8,714	3,215	63.1%
CO [kg]	143	55	61.6%

3.1 Limitations

This model, although useful, cannot perfectly model the differences between these two construction practices, nor does it break down the impacts to each component of the sub-system (i.e., there is no information available to determine which part of the materials acquisition and production phase results in the most emissions). Overall, the construction practices are very similar for both micro-milling and conventional milling, except that a micro-milled surface can be opened to traffic. This allows the contractor to mill during the entire construction period (all night in this situation), whereas the conventional milling operation must be stopped early to allow for paving. Therefore, although micro-milling requires a slower milling speed (15-20 ft./min) than conventional milling (30-35 ft./min), the daily production rate for micro-milling is 3 times that of conventional milling (*35*). The stopping and starting with conventional milling can result in more cold starts and more emissions than using one set of machines per night. It was not possible to effectively model this in the PaLATE program. This is likely not a significant impact, as the construction processes only contributed approximately 0.4% of the environmental impacts, but it is worth noting. The machines were, also, not the same as those used in this project, but, as the main goal of this thesis is to form a general comparison, this situation should not impact the overall comparison. However, to address some of these limitations and support the claim that this situation does not have a substantial impact on the results, a sensitivity analysis will be performed here.

3.2 Sensitivity Analysis

The first sensitivity analysis will consider the transportation distance. The effect of transportation distance on the overall emissions is impacted by the actual travel distance. However, the transportation distance would be unlikely to be far enough for the environmental impacts to match the impacts of material production, which is the main contributor to environmental impacts. For this micro-milling project, a travel distance of 395 miles was needed for transportation impacts to be approximately equal to the environmental impacts from material acquisition and processing. Three hundred ninety-five miles is nearly 1/5 of the distance from Georgia to California. This travel distance is unlikely to happen. For the conventional method, it requires an even longer distance, 540 miles, to make the transportation impacts equal to the environmental impacts. Thus, adding 10 miles to the travel distance may be a more useful calculation.

TABLE 9 shows the increase and percentage impact on the total for each assessed category. As can be seen, it has the greatest impact on the air emissions, especially NOx and particulate matter, which are of high concern in diesel vehicles, such as large trucks that would transport paving materials. This is an important consideration, and efforts to reduce transport distances are encouraged, but it has a minor impact on this thesis' comparison because transport is not inherent to the milling processes and depends more on the location of the stockpiles and mix sites. However, it still has some impact, as more transportation is needed to move the larger amounts of material used in conventional milling. Overall, the impact is minor and had only a small effect on the values for % reduction using micro-milling in TABLE 8 and as shown in TABLE 10**.**

TABLE 9: Sensitivity Results for Increasing Travel Distance by 10 miles

	Conventional Milling		**Micro-Milling**	
Impact	**Change**	**% Change**	**Change**	**% Change**
Energy [MJ]	14,314.49	1.77%	7491.88	2.42%
Water Consumption [kg]	2.44	1.00%	1.28	1.37%
CO2 [Mg] = GWP	1.07	2.56%	0.56	3.47%
NOx [kg]	57.01	18.06%	29.84	22.48%
PM10 [kg]	10.95	5.69%	5.76	7.52%
SO2 [kg]	3.42	0.04%	1.79	0.06%
CO [kg]	4.75	3.22%	2.49	4.35%

TABLE 10: Comparison by Increasing Transportation Distance 10 Miles

Impact	Conventional Milling	Micro-Milling	% Reduction Using Micro-Milling	Original % Reduction
Energy [MJ]	807,384.8	309,470	61.7%	61.9%
Water Consumption [kg]	243.4336	93	61.7%	61.8%
CO2 [Mg] = GWP	41.80818	16	61.3%	61.7%
NOx [kg]	315.7474	133	58.0%	60.2%
PM10 [kg]	192.5642	76	60.3%	61.1%
SO2 [kg]	8,717.86	3,217	63.1%	63.1%
CO [kg]	147.3831	57	61.2%	61.6%

The RAP percentage can also vary across projects. To consider the sensitivity of this, 30% RAP was used for the SMA and none for the OGFC. TABLE 11 shows the change in outputs for conventional milling, as this did not impact the micro-milling, which uses no SMA. This had a greater impact on the overall end results than the transportation distance, as shown in TABLE 12. This makes sense, as reducing material usage was found to be the best way to reduce environmental impacts. However, at the highest percentage of RAP allowed in Georgia, micro-milling still reduces environmental impacts by over 50% in each category compared to conventional milling.

When considering the sensitivity of the program to the equipment used, it was determined that the impacts are so minor that it could not be effectively shown using tables. Changing the paver resulted in a maximum overall energy usage change of 11 MJ for micro-milling. It is a change of 0.003%. The changes in the other categories did not appear in the results, as they were so small. This supports the claim that not having exact machines in the analysis has a negligible impact on the overall analysis.

TABLE 11: Sensitivity Results for Conventional Milling when Including 30% RAP

	Conventional Milling	
Impact	**Change**	**% Change**
Energy [MJ]	-113,927.17	-16.78%
Water Consumption [kg]	-41.56	-20.84%
CO2 [Mg] = GWP	-6.65	-19.50%
NOx [kg]	-31.15	-13.69%
PM10 [kg]	-28.42	-18.55%
SO2 [kg]	-27.66	-0.32%
CO [kg]	-23.76	-19.99%

TABLE 12: Comparison when Using 30% RAP

Impact	**Conventional Milling**	**Micro-Milling**	**% Reduction Using Micro-Milling**	**Original Reduction**
Energy [MJ]	679143.2	301977.7	55.5%	61.9%
Water Consumption [kg]	199.4322	92.072	53.8%	61.8%
CO2 [Mg] = GWP	34.09047	15.60117	54.2%	61.7%
NOx [kg]	227.5843	102.8872	54.8%	60.2%
PM10 [kg]	153.1955	70.73647	53.8%	61.1%
SO2 [kg]	8686.777	3214.99	63.0%	63.1%
CO [kg]	118.8684	54.73683	54.0%	61.6%

3.3 Interpretation

There are three major conclusions based on the results of the impact assessment. The first conclusion is that micro-milling and thin overlay is a more environmentally friendly construction practice than conventional milling. It reduces environmental impacts by approximately 62% in terms of energy use, water use, and global warming potential. Therefore, it is recommended that micro-milling and thin overlay be used whenever it is an option.

The second conclusion is that the highest environmental impacts in all three categories come from the materials acquisition and production. Efforts to reduce environmental impacts in the roadway construction industry should focus on this part of the process. One well-known method that significantly reduces the impacts from this sub-section is asphalt recycling. It is recommended that up to 30% of RAP, as recommended by GDOT and Norouzi et al., be used as much as possible (GDOT, 2014; Norouzi, 2017).

Finally, emissions are sensitive to the travel distance of materials transported to/from construction sites and RAP usage, but do not have a substantial impact on the results of the micro-milling or conventional milling comparison. However, using local materials and RAP as much as possible is highly recommended.

Although these recommendations have been generally known in the industry, it is beneficial to quantify these impacts for a better understanding of how construction impacts the environment and more specifically, to gain a stronger understanding of micro-milling and thin overlay for pavement preservation.

4. Social Impact Assessment

A sustainability analysis would not be complete without an analysis of the social sustainability of the system. Pavement construction have varying impacts on traffic safety, traffic condition, noise, etc. An understanding of the social impacts of pavement construction can benefit public relations and perceptions of the projects, which can, in turn, urge highway agencies and contractors to adopt more cost-effective and environmentally-friendly treatment methods. Due to the lack of detailed information, the following will only briefly assess the social impact of micro-milling compared with the conventional method.

4.1 Safety

Micro-milling has two safety benefits over conventional milling. For drivers, the small drop-off that allows the roadway to be open to traffic prior to the overlay increases safety. It is only possible that this be opened to traffic because the drop-off between lanes is too small to cause concern that a driver will lose control when traversing it. The second safety benefit is for the construction workers. Because micro-milling can be performed more quickly, they are exposed to interstate traffic for a shorter period of time, reducing the risk of being hit by a passing vehicle.

4.2 Traffic

Because the micro-milled surface can be opened to traffic, construction staging is more flexible, and the overall construction can be performed more quickly. Because night-time construction has little impact on traffic (and this project only had nighttime construction), and overall construction time is reduced, reduced traffic congestion is expected. This has not been quantified in this analysis for the reasons mentioned in Chapter 5, but future research could quantify this benefit.

4.3 Noise

Construction is always noisy and can have impacts on people or animals in the surrounding area. The noise difference between micro-milling and conventional milling was not discernible to the contractor and is considered negligible. However, micro-milling has the benefit of having a potentially shorter construction time, which reduces the total amount of time noise pollution from the construction occurs.

5. Summary

Overall, it was found that micro-milling produces 61.7% less greenhouse gases, uses 61.8% percent less water, and uses 61.9% less energy than conventional milling operations. The drivable surface and flexible construction schedule allow for improvements in safety, traffic flow, and noise reduction. Micro-milling and thin overlay is both environmentally and socially more sustainable than conventional milling. It is also more cost-effective, although it is important to remember that it can only be used under certain circumstances. When a road qualifies for micro-milling, it is strongly recommended that the option be used.

This treatment is favorable for transportation agencies and the public because of its performance and its economic, environmental, and social benefits. However, it may not be favorable to construction contractors because the reduction in paving material use reduces profits. There is potential to offset this by optimizing how contractors use their personnel and equipment, as micro-milling only needs the milling equipment during the milling night and the paving during the paving nights, so the unused teams can work on another project at the same time. Training is needed to promote the application of this new treatment nationally and globally. In addition, further performance analysis is needed to better understand which pre-existing conditions qualify a road for micro-milling and thin overlay. There is still room to improve the treatment and optimize performance.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

GDOT's successful projects on I-75 and I-95 have demonstrated that the performance of micro-milling and thin overlay is comparable to the conventional milling and overlay. The objectives of this research project were 1) to critically assess the long-term performance of micro-milling and thin overlay as a new and viable alternative for pavement preservation; 2) to quantitatively evaluate the economic benefit of micro-milling and thin overlay; and 3) to quantitatively evaluate the environmental sustainability benefits of micro-milling and thin overlay over the conventional method; LCAA will be used to evaluate its cost-effectiveness, and LCA will be used to evaluate its long-term environmental and social sustainability. The following summarizes the major research findings:

- The long-term performance assessment on the micro-milling and thin overlay project on I-75 showed an expected service life of 10-12 years, similar to conventional milling and overlay. The detailed crack propagation study on the project on I-95 showed that micro-milling and thin overlay is a good crack relief treatment, as evidenced by there being only 5% cracking occurring in 5 years on the I-95 project
- The economic impact study using LCCA showed that micro-milling and thin overlay saves 53% of the cost of conventional milling and overlay, which is equal to a net present value savings of more than $65,600 per lane mile. A break-even analysis shows that micro-milling and thin overlay has the same life-cycle costs as conventional milling and overlay if it lasts 5 years.

- The sustainability study using LCA demonstrated that micro-milling and thin overlay produces 61.7% percent fewer greenhouse gases, uses 61.8% percent less water, and uses 61.9% percent less energy than conventional milling and overlay. The qualitative evaluation of social impacts, such as the reduced construction time and increased flexibility (which improves the safety of drivers and workers) shows the advantage of using micro-milling and thin overlay.

The following are recommended for future research:

- Working with FHWA to develop a national standard. The research results clearly justify the advantages of using micro-milling and thin overlay and can be used to support the development of a national standard for this type of pavement preservation treatment.
- Extended performance assessments are recommended when more existing micro-milling and thin overlay projects are approaching the end of their service lives. This will help justify the performance of micro-milling and thin overlay involving various factors, such as the pre-construction pavement conditions, traffic, weather, etc.
- It is suggested that user costs be included in the LCCA study. However, a method of simulating traffic congestion needs to be developed to consider the impact of actual traffic on each project.
- Pre-treatment on different prior pavement conditions, especially for low-severity levels of cracking, should be further studied by choosing adequate micro-milling and thin overlay projects and/or conducting field tests. The research outcomes will be

useful for refining the current micro-milling and thin overlay specifications and practices.

- The selection of appropriate statistics (e.g., mean, 75 percentile or 95 percentile) for compliance with the 3.2 mm RVD construction quality control requirement should be further studied based on the long-term performance.
- A life-cycle cost analysis can be conducted to compare the cost-effectiveness of overlay with micro-milling and conventional milling by using test sites with similar traffic conditions and pavement designs.
- The criteria for selecting projects suitable for micro-milling and thin overlay need to be further studied, especially relaxing of constraints on prior distresses, such as low-severity level cracking. When severe, isolated rutting occurs, deep patching could be applied to pre-treat the localized pavement sections.

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APPENDIX I: EXPERIMENTAL DESIGNS FOR PERFORMANCE STUDY

In the original proposal, field experimental tests were planned to study the performance of OGFC or PEM layers directly placed on micro-milled surfaces and to evaluate the impact of different pre-treatment methods (such as no treatment, sealing with different sealing materials etc.) that are applied on minor pavement distress (such as cracks of low severity level) on the performance of the open-graded layer. During the performance of this research project, the Georgia Tech research team closely worked with GDOT's Office of Maintenance, and selected test sites on I-75, I-85, and I-95. However, due to structural issues, all these projects were changed. Especially, the ones on I-75 and I-95 were changed to conventional milling, or an interlayer was placed on a micro-milled surface after the projects had been let.

Limited by the performance time and budget, GDOT agreed to modify the project scope by removing the field performance study. The additional studies are added in this study. It includes the detailed level of long-term performance evaluation of micro-milling and thin overlay, using historical 3D pavement surface data, and the comprehensive economic and environmental sustainability study. However, the procedure used to develop the test plans on I-75 and I-95 are still useful references for future study. The following will present the tests designed for I-75 and I-95.

1. Experimental Test Design on I-75

1.1 Project Location

The originally planned micro-milling and thin overlay project on I-75 is located in Catoosa County and Whitfield County from SR 3 to the Georgia/Tennessee state line (milepost 336 to 341.50 in Whitfield County and milepost 341.50 to 354.70 in Catoosa County). The P.I. Number is M004923. FIGURE I.1 shows the project location. To select test sites on this project, the Georgia Tech research team first examined all the video-log images in office and chose 10 candidate locations based on pavement surface conditions. After that, the research team visited each potential project site, working with GDOT's Liaison Engineers to review each candidate location and mark test sections. Finally, four test sites were selected.

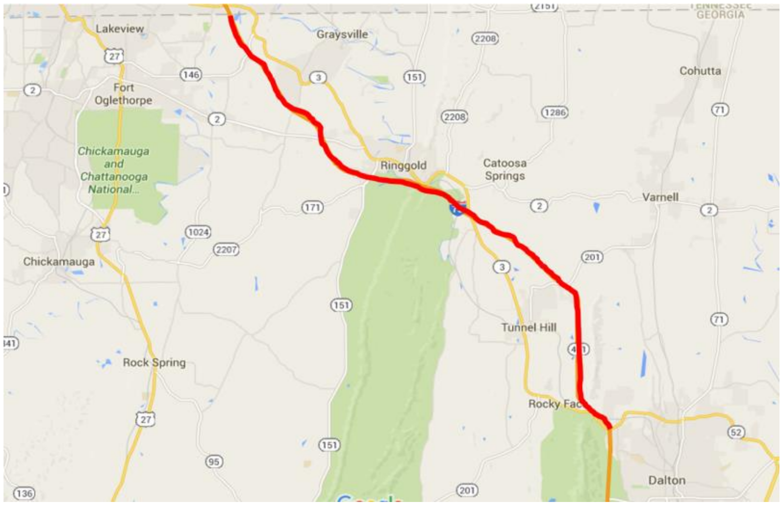

FIGURE I.1: ***Location of I-75 Test Project***

1.2 Test Sites and Construction Plan

Four test sites were selected for the I-75 project. Several test sections were laid out at each test site, including one control section without any pretreatment and some other test sections for testing different pretreatments. The following presents the test site design and construction plan:

- **Test Site #1**

This test site is located on I-75 North Lane 3 (outer lane) at milepost 346.26. FIGURE I.2 shows the pavement conditions. Raveling, load cracking, and block cracking can be found at this location. FIGURE I.3 illustrates the diagram of the test sections on Test Site #1. Three 100-ft test sections were selected.

FIGURE I.2: ***Pavement Conditions of Test Site #1***

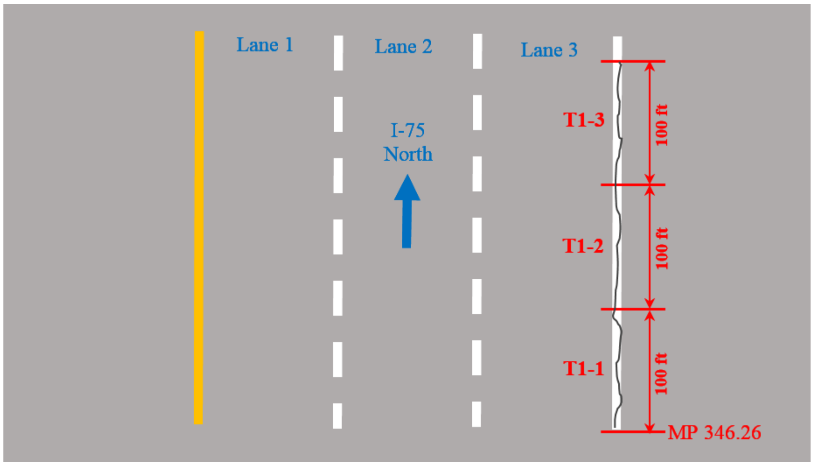

FIGURE I.3: ***Diagram of Test Site #1***

The following is the construction plan:

- T1-1: Construction joint between Lane 3 and the shoulder will be filled using Type M filling material.
- T1-2: Construction joint between Lane 3 and the shoulder will be filled using Type S sealing material.
- T1-3: Construction joint between Lane 3 and shoulder will be routed and sealed using Type S sealing material.

- **Test Site #2**

This test site is located on I-75 North, Lane 3 (outer lane), at milepost 350.223. FIGURE I.4 shows the pavement conditions. Raveling and transverse cracking are obvious. FIGURE I.5 shows a diagram of the test sections at Test Site #2. Two 100-ft test sections were selected.

FIGURE I.4: ***Pavement Conditions of Test Site #2***

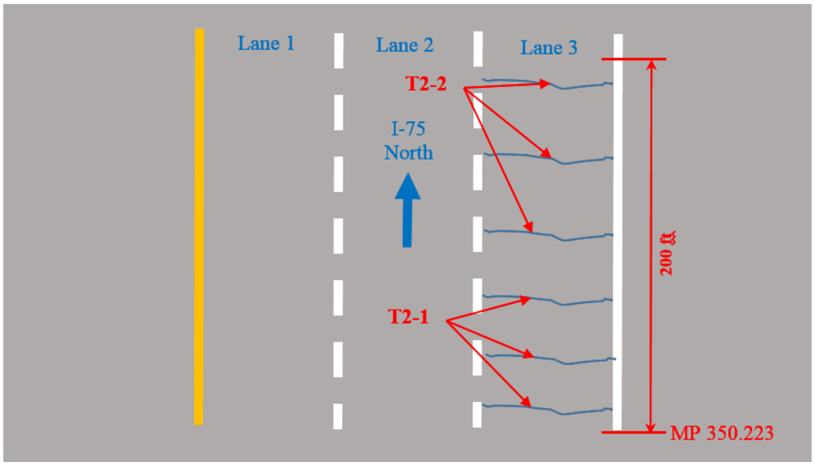

FIGURE I.5: ***Diagram of Test Site #2***

The following is the construction plan:

- T2-1: Three transverse cracks will be filled using Type M filling material.
- T2-2: Three transverse cracks will be routed and sealed using Type S sealing material.

- **Test Site #3**

This test site is located on I-75 South, Lane 3 (outer lane), at milepost 352.143. FIGURE I.6 shows the pavement conditions. Raveling, load cracking, block cracking, and the deterioration of construction joints can be found at this location. FIGURE I.7 shows the diagram of the test sections at Test Site #3. Five 100-ft test sections were selected.

FIGURE I.6: ***Pavement Conditions of Test Site #3***

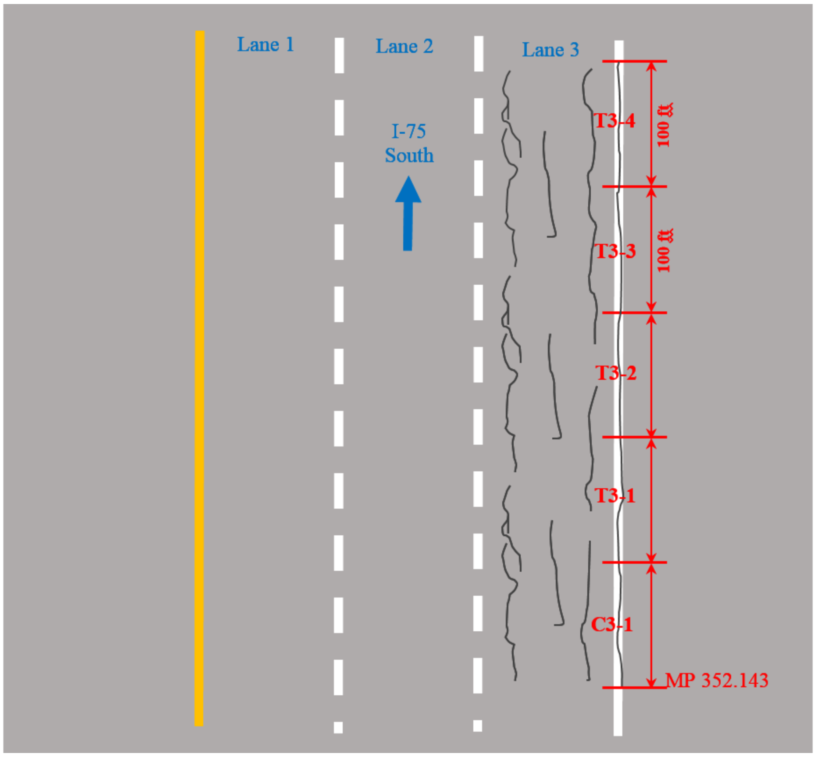

FIGURE I.7: ***Diagram of Test Site #3***

The following is the construction plan:

- C3-1: This 100-ft section will be used as the control section; there will be no treatment on cracks and construction joints.
- T3-1: Construction joint between Lane 3 and the shoulder and cracks (load cracks and block cracks) in this 100-ft section will be filled using Type M filling material.
- T3-2: Construction joint between Lane 3 and the shoulder and cracks (load cracks and block cracks) in this 100-ft section will be filled using Mastic filling material.
- T3-3: Construction joint between Lane 3 and shoulder and cracks (load cracks and block cracks) in this 100-ft section will be filled using Type S sealing material.

    - T3-4: Construction joint between Lane 3 and the shoulder and cracks (load cracks and block cracks) in this 100-ft section will be Routed and Sealed using Type S sealing material

- **Test Site #4**

This test site is located on I-75 South, Lane 3 (outer lane), MP 347.00. FIGURE I.8 shows the pavement conditions. Raveling, load cracking, block cracking, and the deterioration of construction joints can be found at this location. FIGURE I.9 shows the diagram of the test sections on Test Site #4. Five 100-ft test sections were selected.

FIGURE I.8: ***Pavement Conditions of Test Site #4***

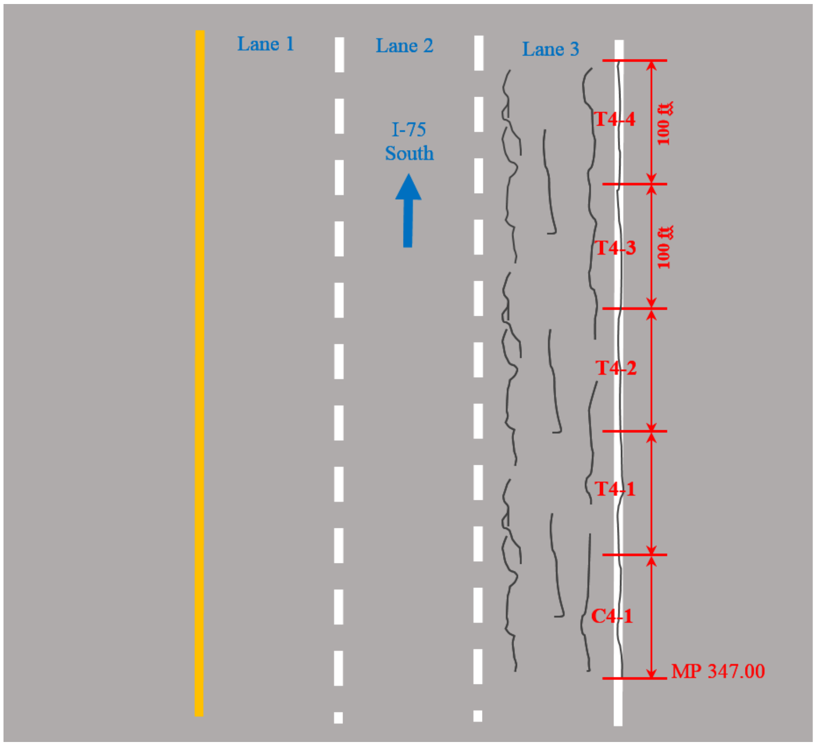

FIGURE I.9: ***Diagram of Test Site #4***

The following is the construction plan:

- C4-1: This 100-ft section will be used as the control section; there will be no treatment on cracks and construction joints.
- T4-1: Construction joint between Lane 3 and the shoulder and cracks (load cracks and block cracks) in this 100-ft section will be filled using Type M filling material.
- T4-2: Construction joint between Lane 3 and the shoulder and cracks (load cracks and block cracks) in this 100-ft section will be filled using Mastic filling material.
- T4-3: Construction joint between Lane 3 and the shoulder and cracks (load cracks and block cracks) in this 100-ft section will be filled using Type S sealing material.

- T4-4: Construction joint between Lane 3 and the shoulder and cracks (load cracks and block cracks) in this 100-ft section will be routed and sealed using Type S sealing material.

2. Experimental Test Design on I-95

2.1 Project Location

The originally planned micro-milling and thin overlay project on I-95 is from north of I-16 to the Savannah River in Effingham County (milepost 99 to 112). The P.I. Number is M005539. FIGURE I.10 shows the project location. To select test sites on this project, the Georgia Tech research team first examined all the video-log images in office and chose 11 candidate locations based on pavement surface conditions. After that, the research team visited the project site and worked with GDOT's Liaison Engineers to review each candidate's location and marked test sections. Finally, seven test sites were selected on this project.

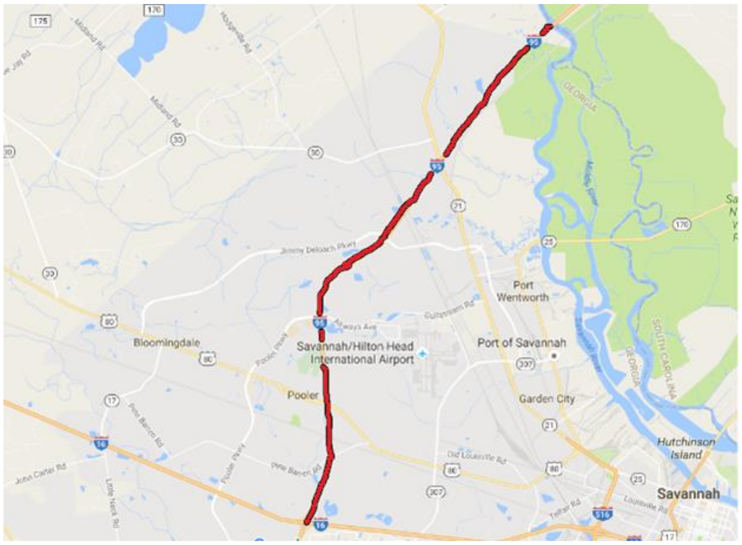

FIGURE I.10: ***Location of I-95 Test Project***

2.2 Test Sites and Construction Plan

Seven test sites were selected. Four of them are on I-95N and three on I-95S. The numbering of all the test sites is not continuous because some pre-selected sites were discarded after field investigation. FIGURE I.11 shows the locations of all the test sites. Each test site starts with a 100-ft control section, followed by several 100-ft test sections. For example, the control section for Site #2 is C2. The following test sections are T2-1, T2-2, T2-3, T2-4, and T2-5. The following presents the test site design and construction plan:

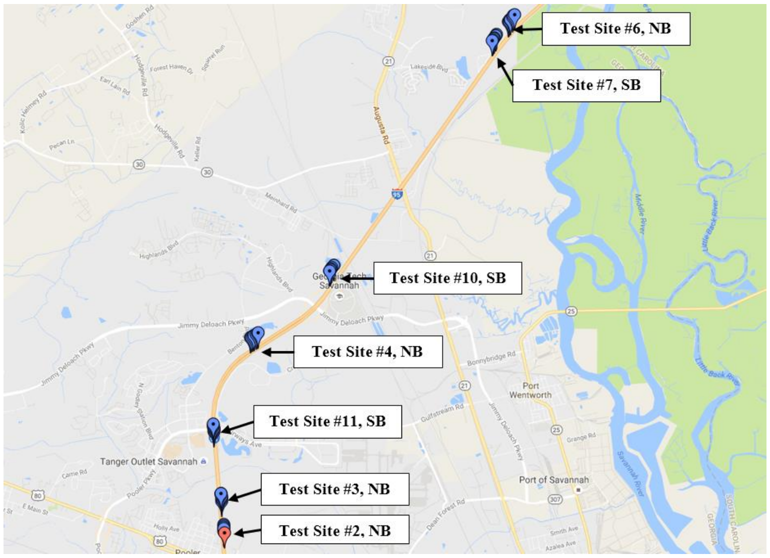

FIGURE I.11: ***Test Site Location Map***

- **Test Site #2**

This test site is located on I-95 North, Lane 3 (outer lane), at milepost 101.747. FIGURE I.12 shows the pavement conditions. Non-wheel-path longitudinal cracks can be found at this location. FIGURE I.13 shows the diagram of the test sections at Test Site #2. Six 100-ft test sections were selected.

FIGURE I.12: ***Pavement Conditions of Test Site #2***

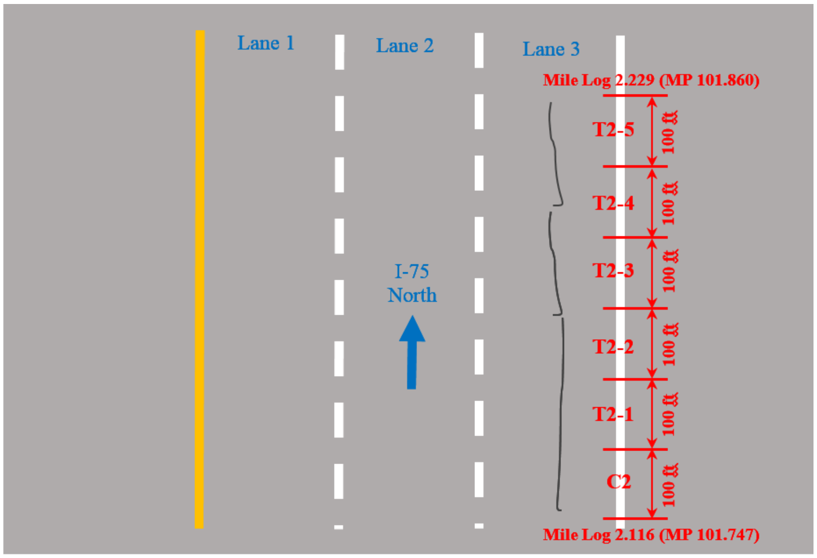

FIGURE I.13: ***Diagram of Test Site #2***

The following is the construction plan:

- C2: This 100-ft section will be used as the control section; there will be no treatment on cracks.
- T2-1: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type M filling material.

  - T2-2: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type M filling material.
  - T2-3: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type S sealing material.
  - T2-4: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type S sealing material.
  - T2-5: Cracks (block cracks; longitudinal) in this 100-ft section will be routed and sealed using Type S sealing material.

- **Test Site #3**

This test site is located on I-95 North, Lane 3 (outer lane), at milepost 102.252. FIGURE I.14 shows the pavement conditions. Load cracking can be found at this location. FIGURE I.15 shows the diagram of the test sections at Test Site #3. Six 100-ft test sections were selected.

FIGURE I.14: ***Pavement Conditions of Test Site #3***

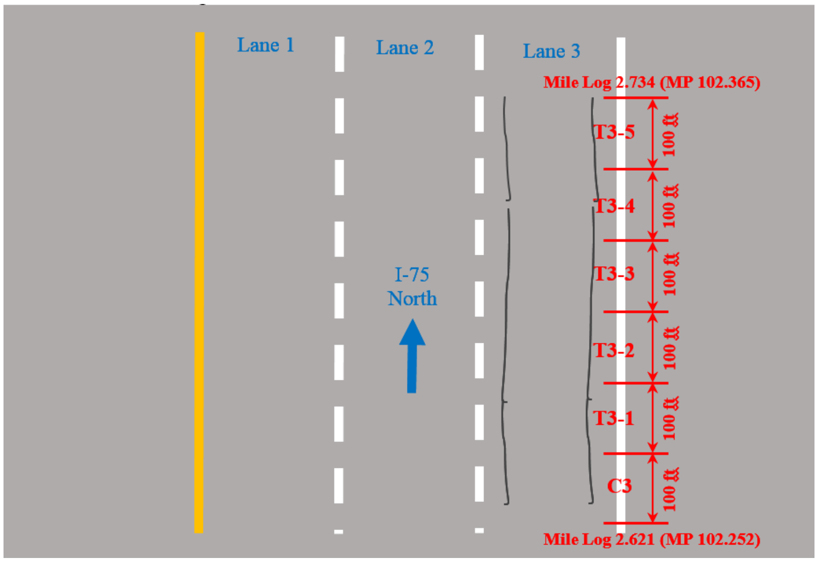

FIGURE I.15: ***Diagram of Test Site #3***

The following is the construction plan:

- C3: This 100-ft section will be used as control section; there will be no treatment on cracks.
- T3-1: Cracks (load cracks) in this 100-ft section will be filled using Type M filling material.
- T3-2: Cracks (load cracks) in this 100-ft section will be filled using Type M filling material.
- T3-3: Cracks (load cracks) in this 100-ft section will be filled using Type S sealing material.
- T3-4: Cracks (load cracks) in this 100-ft section will be filled using Type S sealing material.
- T3-5: Cracks (load cracks) in this 100-ft section will be routed and sealed using Type S sealing material.

- **Test Site #4**

This test site is located on I-95 North, Lane 3 (outer lane), at milepost 104.771. FIGURE I.16 shows the pavement conditions. Severe raveling and load cracking can be found at this location. FIGURE I.17 shows the diagram of the test sections at Test Site #4. Eight 100-ft test sections were selected.

FIGURE I.16: ***Pavement Conditions of Test Site #4***

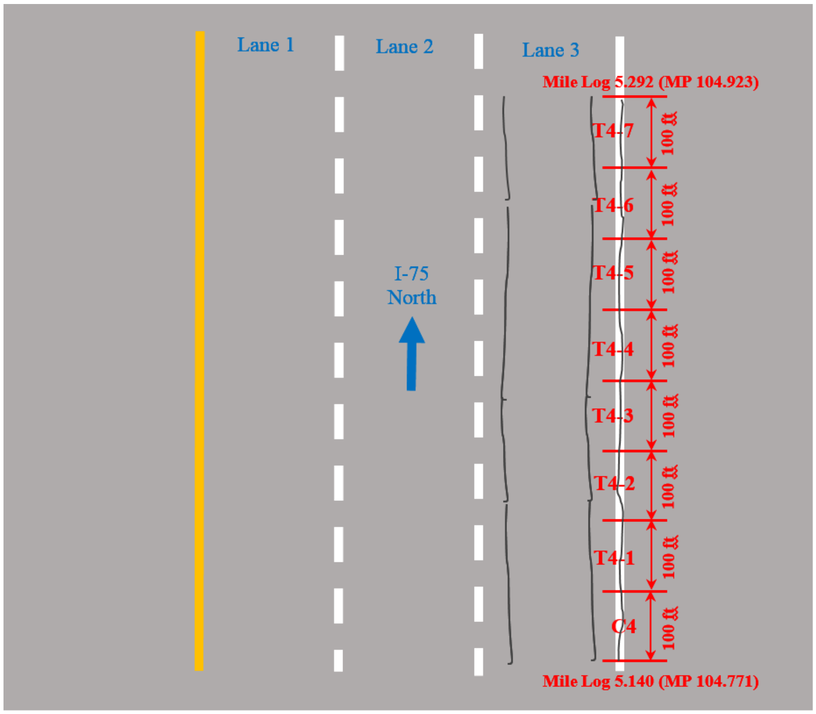

FIGURE I.17: ***Diagram of Test Site #4***

The following is the construction plan:

- C4: This 100-ft section will be used as control section; there will be no treatment on cracks.
- T4-1: Construction joint between Lane 3 and the shoulder and cracks (load cracks) in this 100-ft section will be filled using Type M filling material.
- T4-2: Construction joint between Lane 3 and the shoulder and cracks (load cracks) in this 100-ft section will be filled using Type M filling material.
- T4-3: Construction joint between Lane 3 and the shoulder and cracks (load cracks) in this 100-ft section will be filled using Type S sealing material.
- T4-4: Construction joint between Lane 3 and the shoulder and cracks (load cracks) in this 100-ft section will be filled using Type S sealing material.

- T4-5: Construction joint between Lane 3 and the shoulder, and cracks (load cracks) in this 100-ft section will be filled using Mastic filling material.
- T4-6: Construction joint between Lane 3 and the shoulder, and cracks (load cracks) in this 100-ft section will be filled using Mastic filling material.
- T4-7: Construction joint between Lane 3 and the shoulder and cracks (load cracks) in this 100-ft section will be routed and sealed using Type S sealing material.

- **Test Site #6**

This test site is located on I-95 North, Lane 3 (outer lane), at milepost 110.722. FIGURE I.18 shows the pavement conditions. Non-wheel-path longitudinal cracking can be found at this location. FIGURE I.19 shows the diagram of the test sections at Test Site #6. Seven 100-ft test sections were selected.

FIGURE I.18: ***Pavement Conditions of Test Site #6***

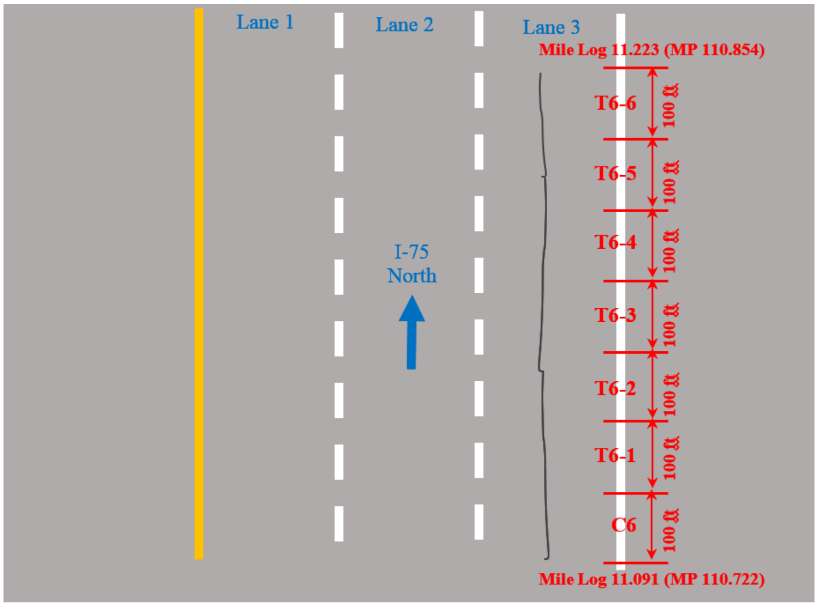

FIGURE I.19: ***Diagram of Test Site #6***

The following is the construction plan:

- C6: This 100-ft section will be used as control section; there will be no treatment on cracks.
- T6-1: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type M filling material.
- T6-2: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type M filling material.
- T6-3: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type S sealing material.
- T6-4: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type S sealing material.
- T6-5: Cracks (block cracks; longitudinal) in this 100-ft section will be routed and sealed using Type S sealing material.

  - T6-6: Cracks (block cracks; longitudinal) in this 100-ft section will be routed and sealed using Type S sealing material.

- **Test Site #7**

This test site is located on I-95, South Lane 3 (outer lane), at milepost 110.460. FIGURE I.20 shows the pavement conditions. Non-wheel-path longitudinal cracking can be found at this location. FIGURE I.21 shows the diagram of the test sections at Test Site #7. Six 100-ft test sections were selected.

FIGURE I.20: ***Pavement Conditions of Test Site #7***

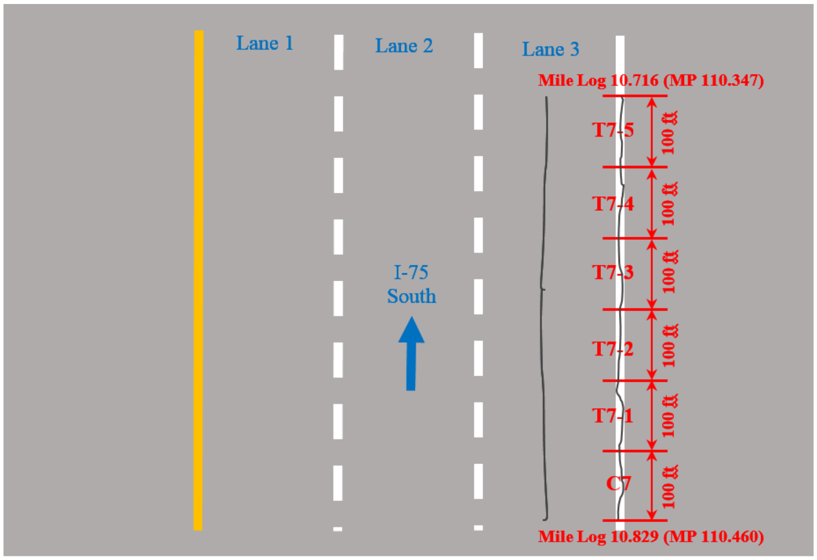

FIGURE I.21: ***Diagram of Test Site #7***

The following is the construction plan:

- C7: This 100-ft section will be used as control section; there will be no treatment on cracks.
- T7-1: Construction joint between Lane 3 and the shoulder and cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type M filling material.
- T7-2: Construction joint between Lane 3 and shoulder and cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type M filling material.
- T7-3: Construction joint between Lane 3 and the shoulder, and cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type S sealing material.

  - T7-4: Construction joint between Lane 3 and the shoulder will be filled using Mastic filling material; and cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type S sealing material.
  - T7-5: Construction joint between Lane 3 and the shoulder and cracks (block cracks; longitudinal) in this 100-ft section will be routed and sealed using Type S sealing material.

- **Test Site #10**

This test site is located on I-95 South, Lane 3 (outer lane), at milepost 106.387. FIGURE I.22 shows the pavement conditions. Load cracking can be found at this location. FIGURE I.23 shows the diagram of the test sections at Test Site #10. Six 100-ft test sections were selected.

FIGURE I.22: ***Pavement Conditions of Test Site #10***

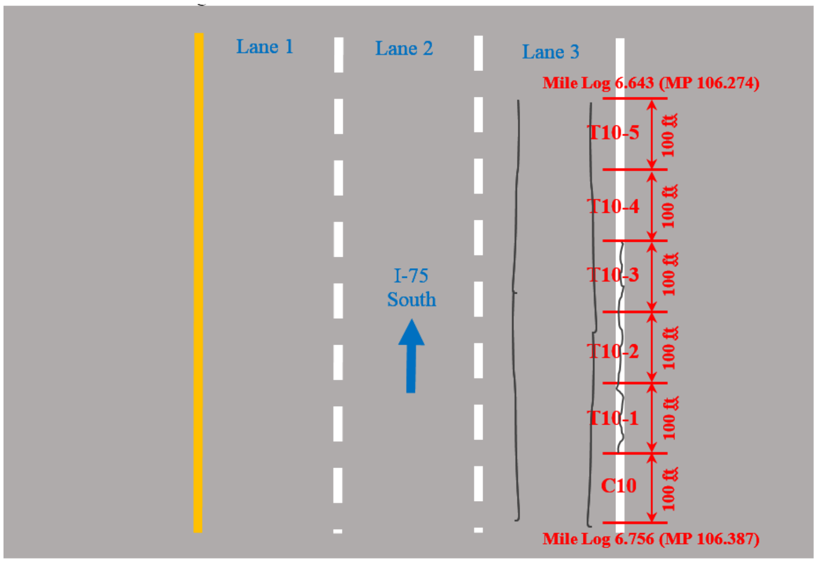

FIGURE I.23: ***Diagram of Test Site #10***

The following is the construction plan:

- C10: This 100-ft section will be used as control section; there will be no treatment on cracks.
- T10-1: Construction joint between Lane 3 and the shoulder and cracks (load cracks) in this 100-ft section will be filled using Type M filling material.
- T10-2: Construction joint between Lane 3 and the shoulder will be filled using Type S sealing material; and cracks (load cracks) in this 100-ft section will be filled using Type M filling material.
- T10-3: Construction joint between Lane 3 and the shoulder will be filled using Mastic filling material; cracks (load cracks) in this 100-ft section will be filled using Type S sealing material.
- T10-4: Cracks (load cracks) in this 100-ft section will be filled using Type S sealing material.

- T10-5: Cracks (load cracks) in this 100-ft section will be routed and sealed using Type S sealing material.

- **Test Site #11**

This test site is located on I-95 South, Lane 3 (outer lane), at milepost 106.387. FIGURE I.24 shows the pavement conditions. Non-wheel-path longitudinal cracking can be found at this location. FIGURE I.25 shows the diagram of the test sections at Test Site #11. Six 100-ft test sections were selected.

FIGURE I.24: ***Pavement Conditions of Test Site #11***

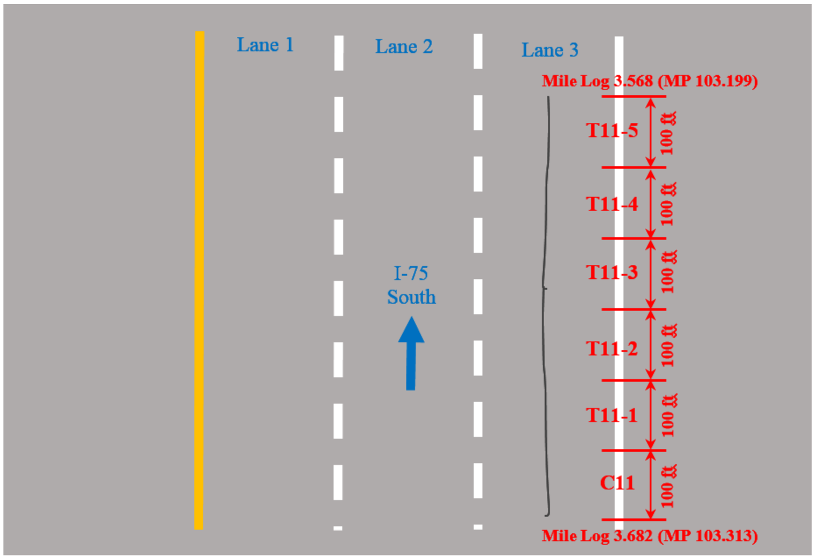

FIGURE I.25: ***Diagram of Test Site #11***

The following is the construction plan:

- C11: This 100-ft section will be used as the control section; there will be no treatment on cracks.
- T11-1: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type M filling material.
- T11-2: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type M filling material.
- T11-3: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type S sealing material.
- T11-4: Cracks (block cracks; longitudinal) in this 100-ft section will be filled using Type S sealing material.

  T11-5: Cracks (block cracks; longitudinal) in this 100-ft section will be routed and sealed using Type S sealing material.

3. Summary

This Appendix presents the field test designs that were applied to two originally-planned micro-milling and thin overlay projects on I-75 and I-95, which were completed in 2015 and 2016, respectively. These two designs were included in GDOT's project letting packages and were successfully contracted. However, after the projects started, the pavement evaluation results, performed by GDOT's Office of Materials and Testing (OMAT), showed that the pavement structural conditions were not good enough (excessive rutting issues) for micro-milling and thin overlay. Thus, the original construction plan had to be changed. Consequently, these two field test plans were canceled. One lesson we have learned is that the communication between different offices is very critical. After the cancellation of the I-95 project, we had contacted OM and found another potential micro-milling and thin overlay project. However, after we communicated with OMAT, it was found that the pavement evaluation showed excessive rutting issues, too. Thus, we had to disregard this potential project. Due to the limited project performance duration and resources, GDOT agreed to cancel the tasks for field tests. Nevertheless, the procedure for developing the test plans presented in this chapter are valuable for future reference when a suitable project is available. The additional studies are added in this study. It includes the detailed level of long-term performance evaluation of micro-milling and thin overlay, using historical 3D pavement surface data, and the comprehensive economic and environmental sustainability study.