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Findings from the Pavement Preservation Group (PG) Study

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EXECUTIVE SUMMARY

State and local agencies often face the challenge of managing their pavement networks with limited resources. The natural degradation of new pavements, influenced by traffic loads and environmental factors, necessitates attention. Extending the service life of pavements without resorting to costly rehabilitation or reconstruction activities is feasible through the timely application of appropriate treatments while the pavement is still in satisfactory condition.

Although the benefits of pavement preservation are well-known, they are difficult to quantify. Several variables can affect the cost-effectiveness of the different treatments, such as pavement conditions, climate, traffic, and regional availability. Insufficient information and uncertainty regarding treatment performance under specific conditions can deter agencies from adopting a pavement preservation program.

The Pavement Preservation Group (PG) Study is a long-term research effort aimed at determining the life-extending benefits of various pavement preservation treatments. Its main purpose is to serve as a guide for agencies to select appropriate treatments that meet their site-specific needs in the most cost-effective manner possible. Under this study, numerous test sections were placed in roadways in Alabama and Minnesota between 2012 and 2019, including a wide range of treatment alternatives such as crack sealing, fog seals, chip seals, micro surfacing, thinlays, cold recycling, and various treatment combinations. Untreated sections were also used as controls in each location. Data collection was performed before treatment application, after treatment completion, and periodically once the sections were in service. Between 4 and 11 years of field performance data were collected, varying depending on location.

The approach followed for quantifying life-extending and condition-improving benefits used field performance data to develop deterioration curves for treated and untreated sections in similar initial condition and comparing them to calculate the differences. It is evident that deterioration accelerates as the pre-treatment condition worsens, reinforcing the preservation philosophy of keeping good roads good with minimal investments. To facilitate access to the study results, an online tool was developed for the visualization of performance data. Other resources, such as webinar recordings and journal and conference papers addressing specific subjects of the research, are also available to the public.

This research effort spanned more than a decade of continuous data collection and analysis, as well as outreach, and continues to generate value for the agencies and organizations involved. Future efforts will continue to monitor and analyze existing test sections and assist sponsoring states in adopting and enhancing their pavement preservation techniques.

1. INTRODUCTION

State and local agencies often face the challenge of managing their pavement networks with limited resources. The natural degradation of new pavements, influenced by traffic loads and environmental factors, necessitates attention. Extending the service life of pavements without resorting to costly rehabilitation or reconstruction activities is feasible through timely application of appropriate treatments while the pavement is still in satisfactory condition. Pavement preservation consists of "*work that is planned and performed to improve or sustain the condition of the transportation facility in a state of good repair*" *(1)*.

Implementing a pavement preservation program offers numerous advantages, including—

- Life extension of the existing pavement,
- Lower treatment costs,
- Reduced user costs,
- Improved safety for the public and the transportation workforce,
- Improved overall network health,
- Environmental benefits such as reduced air pollution and noise during construction, and
- Improved sustainability (*2*).

Although these benefits are well-known, they are difficult to quantify. Several variables can affect the cost-effectiveness of the different treatments, such as pavement condition, climate, traffic, and regional availability. Insufficient information and uncertainty regarding treatment performance under specific conditions can deter agencies from adopting a pavement preservation program.

To address this gap, the National Center for Asphalt Technology (NCAT) and the Minnesota DOT Road Research Facility (MnROAD) partnered to study the long-term performance of multiple pavement preservation treatments, aiming to determine their life-extending benefits. The results of this study can serve as a guide for agencies to select appropriate treatments that meet their site-specific needs in the most cost-effective manner possible. The most significant outcome of this research is the development of data-driven, easily accessible resources, laying the path for future program implementations.

1.1 Objectives

The main objectives for Phase II of this effort are:

- Determine the performance benefits of various pavement preservation alternatives to provide state Departments of Transportation (DOTs) with objective information to make informed pavement management decisions.
- Develop quality assurance (QA) field testing protocols to correlate construction practices with the long-term performance of pavement preservation techniques.
- Provide technology transfer guidance on how these life-extending and condition-improving benefits can be best utilized in each state.

1.2 Scope of Work

Phase II of the study involved continued monitoring and analysis of data from low- and high-volume traffic pavement preservation test sections built in Alabama and Minnesota during

Phase I, which were built between 2012 and 2016. Many of these sections did not exhibit a clear deterioration trend by the end of Phase I in 2018. Additionally, construction of cold recycling test sections in Minnesota was completed in 2019 to determine treatment performance in cold climates.

The new pooled fund was led by MnDOT, which performed data collection in the cold climate sections. NCAT served as a subcontractor, responsible for data collection in warm climate sections and conducting the majority of data analysis.

The tasks outlined in the work plan included:

1. *Collection and initial data validation of field performance data:* Gathering, processing, and analyzing data from the test sections following standard practices.
2. *Website updates:* Development and maintenance of a dedicated project website.
3. *Annual performance updates:* Delivery of project summaries on an annual basis.
4. *2020 Peer Exchange:* Supporting a national initiative for improved implementation of research findings through online meetings.
5. *Mid-project report:* Delivery of a report detailing project status halfway through the research.
6. *Sponsor meetings:* Arranging meetings with the project sponsors every six months to present findings and discuss research direction.
7. *Pooled fund implementation:* Development and deployment of products to benefit the agencies and industry funding this research.
8. *Final report:* Publication of a comprehensive report summarizing the entire research effort.

Due to the COVID-19 pandemic, some in-person meetings were adapted to fulfill research objectives.

1.3 Organization of Report

This report is structured into 13 independent chapters, including the introduction. Chapter 2 provides background information for the research study, including the development of Phases I and II. Chapters 3 through 10 provide details on the construction, performance, and key findings from each treatment group. Chapter 11 provides a performance summary of the individual test sections, while Chapter 12 discusses the process of quantifying benefits developing tools for implementing the research findings. Lastly, Chapter 13 presents final remarks and discusses expected future research efforts.

2. PAVEMENT PRESERVATION GROUP STUDY BACKGROUND

The Pavement Preservation Group (PG) Study was initiated in summer 2012 as part of NCAT's fifth Test Track research cycle. Phase I of the study was funded by seven state DOTs and FP2 (formerly the Foundation for Pavement Preservation) through Transportation Pooled Fund TPF-5(267), with the Alabama Department of Transportation (ALDOT) serving as the lead organization. The initial effort consisted of placing various preservation treatments on a low-traffic volume county road in Auburn, Alabama. Although pavement preservation treatments were applied to sections on the Test Track, the PG study sections were placed on an off-track roadway to eliminate any effects resulting from the accelerated traffic rate.

The support from FP2 was fundamental during project planning and construction, funding research as an equal partner with the DOTs and providing technical assistance and guidance during these critical stages. Their input helped develop the final treatment layout, which was approved by all sponsors. In addition, representatives were present during construction to help ensure the treatments were applied with the highest quality standards.

Based on the preliminary results of the 2012-2015 research cycle, the study was continued during NCAT's sixth Test Track research cycle with support from 15 state DOTs and FP2. The scope of work was extended to include test sections on a high-traffic volume roadway in Alabama. In addition, NCAT and MnROAD formed a partnership to provide practical and implementable results for both cold and warm U.S. climates. As a result, new test sections were constructed in 2016 on low- and high-traffic volume roadways near Pease, Minnesota to replicate several of the treatments in place in Alabama. To minimize construction variability, the same contractors and crews from the first test sections in 2012 were used to construct the new test sites in Alabama and Minnesota.

The study's success continued, gathering support for an additional research cycle in 2018. Phase II was funded under Transportation Pooled Fund TPF-5(375) and led by MnDOT. Twenty-two state DOTs, the Federal Highway Administration (FHWA), and FP2 contributed to this new effort. Phase II focused on continuing data collection and analyzing existing sections. In addition, new test sections with cold recycled technologies were constructed in 2019 on a city street in Minnesota using a set of treatments that had not been completed during the previous construction round in 2016.

2.1 Test Locations

The test sections are located on five roadways with varying traffic levels, two in Alabama and three in Minnesota. Below is a description of each test site.

Lee County Road 159 (LR-159)

Lee County Road 159 is a two-lane road providing dead-end access to a quarry and asphalt plant in Auburn, Alabama. A Lee County report from 2012 indicated its annual average daily traffic (AADT) was 563 vehicles per day *(3)*. Although the traffic volume is low, county records indicated the truck volume was 60%, due to trucks traveling to and from the quarry and asphalt plant located on the northern end of Lee Road 159, which are operated by Martin Marietta and East Alabama Paving, respectively.

One unique characteristic of Lee Road 159 is that although both lanes are subjected to the same traffic volume, loads vary significantly as trucks travel unloaded inbound (to the quarry and asphalt plant) and exit loaded in the outbound direction. This difference in equivalent single axle loads (ESALs) between the two lanes resulted in different pavement conditions at the time of treatment, as shown in Figure 1.

Figure 1. Variation in surface condition by lane in untreated pavement.

The existing pavement was 14 years old and consisted of a 5.5-inch hot mix asphalt (HMA) layer over a 6.0-inch granular base. A half-mile road segment was split into 25 sections, each measuring 100 feet in length. 23 sections received a single treatment or a combination of treatments, and 2 were left as untreated control sections. Treatment locations were primarily selected based on constructability, with similar treatment categories applied to adjacent sections. Within those constraints, treatments were selected to match the observed types and levels of distress as much as possible.

Highway 280 (US-280)

Highway 280 is a high-traffic four-lane U.S. route that runs through east-central Alabama. The test sections are located on a four-mile segment near Salem, between mileposts 128 and 132. In 2015, ALDOT reported the AADT on US-280 was 17,000 vehicles per day *(4)*. The test sections are on the outside lane of the two-lane eastbound highway, each measuring one-tenth of a mile. There are a total of 46 sections, 34 of which received a treatment or combination of treatments, and the rest were left as controls with varying levels of distress.

Within this test site, there are old test sections built for the Long-Term Pavement Performance (LTPP) program in 1992 as part of the SPS-1 experiment *(5)*. These sections have been inactive since the early 2000s and were last resurfaced in 2006. However, most of the underlying layers, which include dense-graded aggregate base, asphalt treated base, and permeable asphalt treated base, were left in place, resulting in variable pavement structures along the four-mile segment. Ground penetrating radar (GPR) testing was conducted in 2020 to verify the layer thickness in each section. The bituminous layers (asphalt mix and treated bases) ranged from 5.6 to 16.2 inches, while the aggregate base layer ranged from 4.4 to 15.8 inches.

At the time of treatment in 2015, the existing pavement surface was nine years old and showed varying levels of deterioration, with weathering and cracking as primary distresses. Cracking severity was low with signs of pumping and was mainly located along the wheel paths, as shown in Figure 2. Overall, the pavement was in better condition than LR-159.

Figure 2. Cracking in US-280 sections.

County State Aid Highway 8 (CSAH-8)

CSAH-8 is a two-lane county road near Pease, Minnesota, with an estimated AADT of 510 vehicles per day. Traffic is comprised of approximately 7% heavy vehicles, many of which are heavy implements of husbandry traveling to and from corn fields and dairy farms. The predominant distress at the time of treatment was thermal cracking (Figure 3). Each section had five to seven thermal cracks with varying levels of severity, which also affected pre-treatment ride quality.

Figure 3. Thermal cracking in CSAH-8.

The pavement was last constructed in 2005 before treatment in 2016. The existing structure consisted of 7 inches of asphalt over 6 inches of granular base. There are 21 sections in the eastbound lane and 9 in the westbound lane, all one-tenth of a mile in length. A total of 8 sections were left untreated as controls.

Highway 169 (US-169)

US-169 is a major north-south four-lane highway in central Minnesota. The test segment is located near Pease, between mileposts 185.3 and 188, and intersects with CSAH-8. The estimated AADT is approximately 16,000 vehicles per day. The northbound lane was divided into 29 test sections, leaving 8 untreated as controls. All sections were one-tenth of a mile in length.

At the time of treatment in 2016, the existing pavement surface was seven years old with signs of environmental and load-related distresses. As shown in Figure 4, there was minor loss of fines and cracking along the wheel paths as well as thermal cracking. The longitudinal joints were in fair condition. The pavement structure consisted of 6.5 inches of asphalt over a 17-inch granular base.

Figure 4. Overall pavement condition of US-169.

70th Street

70th Street is a two-lane road with an estimated AADT of 2,300 vehicles per day. The roadway is located near the MnROAD facility and is owned by the cities of Albertville (eastbound lane) and Otsego (westbound lane). The existing pavement structure consisted of 4 inches of asphalt over 6 inches of aggregate base. It was heavily distressed at the time of treatment in 2019, which made it a candidate for evaluating various cold recycling and full-depth reclamation treatments. A 1-mile stretch was divided into 16 sections, each 500-ft long. Treatments were applied on both lanes, including traditional mill and fill sections and thin overlays for comparison. Due to the shared ownership of the road, there were differences in the maintenance activities performed before treatment. The westbound lane, which services more residents, exhibited a greater amount of patching and crack sealing. The general condition of the pavement was poor, with extensive environmental and load-related cracking, as shown in Figure 5.

Figure 5. Overall pavement condition of 70th Street.

2.2 Data Collection

Data collection was performed before treatment application, after treatment completion, and periodically once the sections were in service. Between 4 and 11 years of field performance data have been collected to date, varying depending on location.

The parameters measured include:

- Cracking (percent of total section area),
- Rutting (average rut depth, mm),
- Roughness (international roughness index (IRI), in/mi),
- Macrotexture (mean profile depth (MPD), mm),
- Friction (skid number), and
- Pavement deflections (mils).

Data collection frequency varied depending on the test parameter and location. In warm climate locations with mild winters and no significant snow events, measurements were taken more frequently. Specific parameters were also collected for certain situations. For example, open-graded friction course (OGFC) thinlays in US-280 were cored annually to test for void content, permeability, and bond strength. Field permeability was also measured in these sections twice a year.

Since this research study was primarily sponsored by state DOTs, it was essential to evaluate pavement condition in a way that is consistent among agencies. Data analysis relied mainly on performance measures and condition categories outlined in the Moving Ahead for Progress in the 21st Century Act (MAP-21) criteria developed by the Federal Highway Administration *(6)*. The MAP-21 performance measures classify asphalt pavements into "good," "fair," or "poor" condition categories based on three indicators: cracking, rutting, and IRI.

Table 1 shows the condition rating for each of the performance measures.

Table 1. Condition Ratings for MAP-21 Performance Measures *(6)*

Condition Rating	**Performance Measure**		
	% of Area Cracked	**Rutting, mm**	**IRI, in/mi**
Good	< 5%	< 5	< 95
Fair	5 – 20%	5 – 10	95 – 170
Poor	> 20%	> 10	> 170

Overall pavement condition is determined based on individual condition ratings as follows:

- If all three metrics are in "good" condition, the pavement is classified as "good" condition.
- If two or more metrics are in "poor" condition, the pavement is classified as "poor" condition.
- All other combinations of metric conditions classify a pavement as "fair."

Although the analysis focused on MAP-21 criteria, other parameters were included when determined relevant for the performance assessment.

2.3 Treatments

The treatments studied in this research cover a wide range of alternatives. Specific treatments were selected during the development of each study phase with input from the sponsors and the research team. Treatments can be categorized into the following groups:

- **Crack sealing**: crack sealing and mastic as standalone treatments or in combination with chip seals and micro surfacing.
- **Fog seals**: conventional and rejuvenating fog seals.
- **Chip seals**: single, double, and triple layers, Fibermat chip seals, and scrub seals.
- **Micro surfacing**: single and double layers, micro surfacing with fibers, and high polymer-modified (HiMA) micro surfacing.
- **Dense-graded thinlays**: all virgin materials, recycled materials (rejuvenated and non-rejuvenated), containing neat, polymer-modified, and high polymer-modified binders.
- **Ultrathin bonded wearing course** (UTBWC) and **open-graded friction course** (OGFC) thinlays.
- **Treatment combinations**: chip seal/micro surfacing, chip seal/thinlay, and thinlay/micro surfacing combinations.
- **Cold recycling**: cold in-place (CIR), cold central plant (CCPR), and full-depth reclamation (FDR) with bituminous recycling agents.

The following chapters provide more detail on the construction, performance, and key findings from each treatment group. A table summarizing all treatments by location can be found in Appendix A.

3. CRACK SEALING

3.1 Construction

Crack sealing consists of applying a highly elastic material to seal roadway cracks against moisture and debris. This treatment was applied in four locations across different levels of traffic and climate, as shown in Table 2. In all sections, the material used was a hot-applied asphalt-based product as specified in ASTM D6690. Although crack sealing was performed after construction as part of routine maintenance in the cold climate locations, it was conducted by the agencies that own the roads and not specifically evaluated as part of the preservation treatments.

Table 2. Crack Sealing Test Sections by Location

Treatment	Location				
	LR-159	US-280	CSAH-8[1]	US-169[2]	70th St
Crack sealing	✓	✓	✓	✓	NA
Crack sealing + chip seal	✓	✓	✓	✓	NA
Crack sealing + micro surfacing	✓	✓	✓	✓	NA

[1] Includes application of transverse mastic.

[2] Includes application of longitudinal mastic.

NA: Not available at this location

Crack sealing was applied in two configurations: rout & seal and overband seal. For route & seal, cracks were routed, cleaned with compressed air, and heat lanced before sealing with a reservoir configuration (Figure 6). A ⅝-inch bit was used for routing in LR-159 while other locations used a ½-inch bit due to the ⅝-inch bit being too wide, especially for longitudinal cracks in the wheel paths. For overband seal, cracks were only cleaned by compressed air and heat lanced, then filled using an overband configuration (Figure 7). A V-shaped squeegee was used to minimize material buildup on the surface. In addition, the cold climate sections were treated with a hot-applied mastic product composed of highly modified polymer asphalt binder and durable, lightweight construction aggregate to rectify deteriorated areas along the longitudinal joint on US-169 and wide transverse cracks on CSAH-8. Table 3 summarizes the configurations used in each location and their respective application dates.

Table 3. Crack Sealing Application Summary

Location	Configuration	Date applied
LR-159	Rout & seal (outbound lane) Overband (inbound lane)	August 6, 2012
US-280	Overband	August 25-26, 2015
CSAH-8	Rout & seal and transverse mastic	August 1, 2016
US-169	Rout & seal and longitudinal mastic	August 1, 2016

(a) Routing

(b) Compressed air with a heat lance

(c) Crack sealing

Figure 6. Rout and seal procedure.

Figure 7. Crack sealing with overband configuration.

Figure 8. Crack sealing and mastic treatments in CSAH-8 test section.

In sections where crack sealing was integrated with chip seal or micro surfacing, a window of 2 to 7 days was allocated between applications to facilitate curing of the crack sealant. This expedited timeline deviates from common practice, where crack sealing is typically performed as a seasonal activity, ideally during the spring or fall, followed by surface treatments applied months later. However, due to project logistics, the work had to be completed within a short timeframe. Details on chip seal and micro surfacing application are provided in Chapters 5 and 6, respectively.

3.2 Performance and Key Findings

Crack sealing is used to prevent the intrusion of water and incompressible materials into the pavement structure and reduce cracking propagation. Whether as a standalone application or in combination with other treatments, the test sections have exhibited notable benefits in terms of cracking performance. Particularly evident during the initial years following construction, these benefits have diminished over time due to the short-term nature of crack seal treatments. By the end of Phase II, 7 of the 12 treated sections reached the “poor” condition threshold (>20% cracking). However, despite exceeding this threshold, performance was improved compared to untreated sections in similar initial conditions, which deteriorated at a faster rate.

An example of the crack seal benefits observed in the LR-159 sections, the oldest in the study, is shown in Figure 9. The images on the left correspond to unsealed sections, while the those on the right show similar test sections where crack sealing was performed. From these general overviews taken in year nine, it’s evident that crack sealing can reduce crack propagation and enhance treatment benefits. Similar trends were observed in other test locations.

Combining crack sealing with chip seals appears to be the most effective option, as both treatments can improve cracking performance. These treatments slowed the rate of cracking deterioration; all sections other than LR-159 remained under 20% cracking at the end of Phase II. Crack sealed micro surfacing sections saw a moderate improvement compared to those treated with only micro surfacing in terms of handling a higher amount of pre-treatment cracking while delivering similar performance as the other sections.

Notably, differences in performance were observed based on the sealing technique applied. When rout & seal was performed with the ⅝-inch bit followed by a surface treatment, slight compression of the sealing material occurred from traffic, resulting in reflected cracking along the sides of the routed crack (shown in Figure 10). Nonetheless, these cracks were less than ¼” in width and prevented water intrusion without compromising the integrity or functionality of the surface treatments. Switching to a smaller bit eliminated this concern, and no sealant failures were observed throughout the study.

(a) Unsealed (control) (b) Standalone crack sealing

(c) Chip seal

(d) Crack sealing + chip seal

(e) Micro surfacing

(f) Crack sealing + micro surfacing

Figure 9. Unsealed vs. sealed section comparison.

Figure 10. Cracking along routed and sealed cracks under micro surfacing.

The use of mastic in the cold climate sections contributed to sealing wide cracks and improved smoothness of the pavement surface. Sections treated with transverse mastic saw a reduction in IRI between 15 to 26 in/mi following application, along with a slower rate of deterioration compared to control sections. Although transverse cracks eventually reflected through the mastic layer, the treatment effectively mitigated their severity at low levels, providing a smoother riding surface. Figure 11 shows transverse cracks in CSAH-8 at year 2 for sealed and unsealed sections. Cracks without treatment exhibited more deterioration, affecting overall pavement condition.

To improve ride quality, transverse mastic was applied to all sections of CSAH-8 in fall 2022, including previously sealed sections. This proactive maintenance measure resulted in average IRI reduction of 21 in/mi, with the degree of improvement varying depending on the existing treatment. Rougher sections obtained the greatest benefit (as high as 60 in/mi IRI reduction), while sections already in good condition saw minimal change in roughness, as there was little room for improvement.

(a) Transverse mastic (b) Control section

Figure 11. Crack condition comparison of sections with and without transverse mastic.

4. FOG SEALS

4.1 Construction

A fog seal is a light spray application of asphalt emulsion primarily aimed at sealing existing asphalt surfaces to reduce raveling and enrich dry and weathered surfaces (*4*). Two types of fog seals were included in this study: conventional and rejuvenating. The conventional fog seal primarily serves to seal the road surface and defer surface degradation, while fog seals containing rejuvenating emulsions aim to extend pavement life by restoring the oxidized components of the asphalt binder in the pavement surface (*14*). The distribution of the fog seal test sections is shown in Table 4.

Table 4. Fog Seal Test Sections by Location

Treatment	Location				
	LR-159	US-280	CSAH-8	US-169	70th St
Conventional	NA	✓	✓	✓	NA
Rejuvenating	✓	✓	✓	✓	NA

NA: Not available at this location

All conventional fog seals consisted of a CSS-1H emulsion, and all rejuvenating fog seals consisted of a CMS-1P(QB) emulsion. Equipment calibration was performed in each location to ensure accurate application rates. The procedure involved placing pre-weighed pads on the road surface and driving the asphalt distributor over the pads while spraying the emulsion (Figure 12). The pads were then removed and re-weighed to obtain the emulsion weight by subtraction, facilitating the application rate calculation.

Figure 12. Bar rate calibration.

The pavement was swept as part of surface preparation to remove dust and loose materials. Plastic sheeting was affixed at the beginning and end of each section to protect adjacent test sections from contamination and ensure clean edges, as shown in Figure 13. The fog seals were then applied to the clean surface with a distributor truck at the diluted application rates shown in Table 5 and Table 6. Moreover, in the cold climate sections (CSAH-8 and US-169), a coal slag abrasive product known as Black Beauty sand was applied to ensure friction numbers remained above an acceptable level.

Figure 13. Fog seal application.

Table 5. Fog Seal Application Summary

Location	Application Rate (gal/sy)		Date applied
	Target	Actual	
US-280	0.09	0.12	August 26, 2015
CSAH-8	0.10	0.21*	August 1, 2016
US-169	0.10	0.14*	August 1, 2016

*Includes Black Beauty sand

Table 6. Rejuvenating Fog Seal Application Summary

Location	Application Rate (gal/sy)		Date applied
	Target	Actual	
LR-159	0.10	0.08	August 6, 2012
US-280	0.09	0.09	August 25, 2015
CSAH-8	0.10	NA	August 2, 2016
US-169	0.10	0.12*	August 2, 2016

*Includes Black Beauty sand

4.2 Performance and Key Findings

Although fog seals are typically applied to newer pavements, this study found they can also improve the cracking performance of older pavements. While these treatments have a lower durability compared to other preservation options, they were effective in maintaining a sealed pavement surface and delaying the appearance of distresses such as cracking and weathering. In fact, only three of seven test sections fell in the “poor” condition category by the conclusion of Phase II. Figure 14 shows examples of conventional fog seal sections subjected to high traffic after six years of service. In both cases, the initial cracking condition was “fair” with a cracking rate of 5-20%. The treatments helped to maintain this condition throughout the study, with cracking reaching approximately 11% in both sections. There was no significant difference in performance between the climatic regions other than the cracking types observed, which were predominantly longitudinal cracking along the wheel paths for the warm climate location and transverse cracking in the cold climate.

(a) US-280

(b) US-169

Figure 14. Condition of fog sealed sections in warm and cold climate.

A concern related to fog seal application is the potential for friction reduction after treatment. Previous studies indicate that although temporary, the decrease in skid resistance can be up to 60%. The rate of friction recovery varies depending on the type of product used *(8-13)*. This poses a safety concern, especially on busy high-speed roads.

The test sections experienced a friction reduction consistent with findings from the literature. Figure 15 shows the results from the US-280 sections, which were measured monthly after treatment application. These values are expressed as a percentage of the average friction number measured in the control sections. Immediately after fog seal application, there was a drop of approximately 30% in friction compared to untreated pavement with the same surface type. However, the values were mostly restored after approximately one year of traffic. The remaining sections also showed friction reductions of 20-30% compared to the control, except for the rejuvenating fog seal in LR-159, which was not significantly affected. However, testing was less frequent in the cold climate locations, making it challenging to determine recovery time.

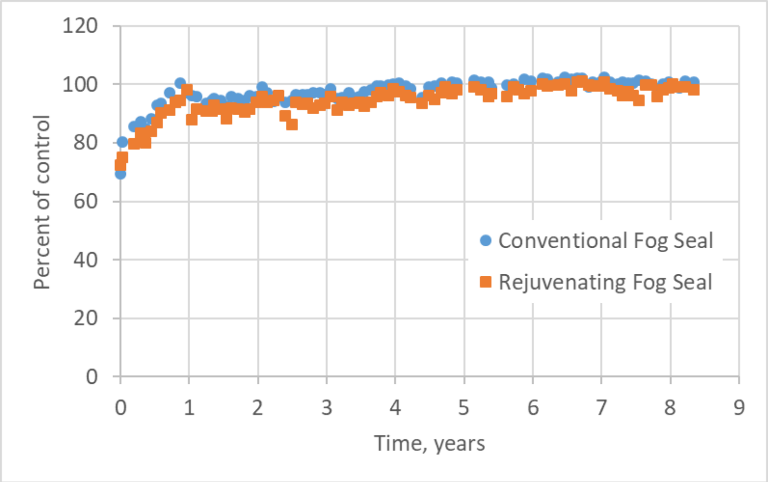


Figure 15. Friction performance in US-280 fog seal sections.

5. CHIP SEALS

5.1 Construction

Chip sealing is a process involving applying a layer of bituminous binder followed immediately by an application of aggregate. The aggregate is then rolled into the binder layer to create a durable and skid resistant surface. This process can be repeated to apply multiple layers. Various binder and aggregate types can be used to address specific distress modes or traffic situations (*14*).

Several single and multilayer sections were constructed as part of this study, including scrub seals, which are a more advanced and aggressive chip seal process. Scrub seals employ a specialized rejuvenating emulsion as the chip binder in conjunction with a mechanized scrub broom that forces the emulsion into cracks (*14*). Fibermat® chip seals, incorporating a specially formulated, polymer-modified, crack-resistant membrane, were also included. A summary of chip seal test sections is shown in Table 7.

Table 7. Chip Seal Test Sections by Location

Treatment	**Location**				
	LR-159	**US-280**	**CSAH-8**	**US-169**	**70th St**
Single layer chip seal	✓	✓	✓	✓	NA
Single layer chip seal with crack seal	✓	✓	✓	✓	NA
Double layer chip seal	✓	✓	✓	✓	NA
Triple layer chip seal	✓	✓	✓	✓	NA
Fibermat® chip seal	✓	✓	✓	✓	NA
Scrub seal	✓	NA	✓	✓	NA

NA: Not available at this location

In both the cold and warm regions, chip seal designs were performed using the McLeod Method (*15*), accommodating various aggregate sizes sourced from local materials suited to the climate. Notably, the resulting emulsion rates for the cold climate region were considered very low compared to typical rates used in Minnesota. Therefore, target rates were adjusted to align with MnDOT rates. Across all sections, granite was used as the cover aggregate, with fine, intermediate, and coarse gradations. In warm climate locations, these gradations were designated as W10, #89, and #7, respectively; in the cold climate locations, they were designated as FA 2, FA 2.5, and CA-70, respectively. The aggregate gradations are shown in

Table 8 and Table 9.

Table 8. Chip Seal Gradations of Warm Climate Sections (LR-159 and US-280)

Sieve Size	Percent Passing		
	W10 Chip seal	#89 Chip seal	#7 Chip seal
¾”	100	100	100
½”	100	100	97
⅜''	100	100	57
¼”	100	74	6
No. 4	100	43	2
No. 8	88	9	2
No. 16	35	4	2
No. 50	24	2	2
No. 100	-	1	-
No. 200	6.8	0.9	1.5

Table 9. Chip Seal Gradations of Cold Climate Sections (CSAH-8 and US-169)

Sieve Size	Percent Passing		
	FA 2 Chip seal	FA 2.5 Chip seal	CA-70 Chip seal
¾”	100	100	100
½”	100	100	99
⅜''	100	100	74
¼”	99	61	28
No. 4	83	20	11
No. 8	13	2	1
No. 16	3	1	1
No. 50	1	1	0.5
No. 100	1	0.5	0.5
No. 200	0.5	0.3	0.2

The existing surface was swept prior to construction to remove any loose material before applying the emulsion. The spray distributor and chip spreader were calibrated to ensure accurate emulsion and aggregate rates were applied. Once calibration was complete, the distributor applied the asphalt emulsion, which was immediately followed by aggregate application. The aggregate was then rolled with three passes of a pneumatic roller to embed it into the binder. After curing, the excess aggregate was removed using a broom before the road was opened to traffic. Figure 16 illustrates the procedure for chip seal application.

(a) Asphalt emulsion application

(b) Aggregate application

(c) Rolling newly placed chip seal with pneumatic roller

Figure 16. Chip seal application process.

The Fibermat® chip seal membranes were installed by specially developed equipment that uniformly incorporates the fiberglass strands in a continuous application (Figure 17). The strands are sandwiched between two layers of the modified emulsion before applying an aggregate cover. The final product is then rolled to ensure the aggregate is properly seated into the surface. Figure 18 shows the Fibermat® membrane before application of aggregate cover.

Figure 17. Fibermat® installation.

Figure 18. Fibermat® membrane.

The scrub seal application process is very similar to that of a standard chip seal. The differences between the two are the use of a rejuvenating polymer-modified emulsion and a scrub broom pulled by the distributor to force the emulsion into the cracks prior to aggregate application (Figure 19).

Figure 19. Scrub seal application.

All sections were treated during summer of their respective construction years, as shown in Table 10. Multilayer applications were completed within one to two days. Treatment details are provided in Table 11 through Table 14. Chip seals applied as part of a combination treatment are discussed in Chapter 9.

Table 10. Chip Seal Application Dates

Location	Application Date
LR-159	August 6-9, 2012, except for Fibermat® chip seal (July 17, 2012)
US-280	August 27-28, 2015
CSAH-8	August 2-5, 2016
US-169	August 2-6, 2016

Table 11. Treatment Properties in LR-159 Sections

Treatment	Aggregate Gradation	Aggregate Rate (lb/sy)		Emulsion Type	Emulsion Rate (gal/sy)	
		Target	Actual		Target	Actual
Single layer chip seal	#89	18	17	CRS-2HP	0.30	0.28
Single layer chip seal with crack seal	#89	18	17	CRS-2HP	0.30	0.28
Double layer chip seal	#89 (top) #7 (bottom)	20 21	20 22	CRS-2HP	0.42 0.29	0.38 0.30
Triple layer chip seal	W10 (top) #89 (middle) #7 (bottom)	15 16 16	15 16 21.5	CRS-2HP	0.15 0.34 0.26	0.14 0.28 0.26
Fibermat® chip seal	#89	17	19	CRS-2L	0.30	0.35
Scrub seal	#89	17	18	CMS-1P (CR)	0.30	0.25

Table 12. Treatment Properties in US-280 Sections

Treatment	Aggregate Gradation	Aggregate Rate (lb/sy)		Emulsion Type	Emulsion Rate (gal/sy)	
		Target	Actual		Target	Actual
Single layer chip seal	#89	18	16	CRS-1HP	0.29	0.31
Single layer chip seal with crack seal	#89	18	15.5	CRS-1HP	0.29	0.32
Double layer chip seal	#89 (top) #7 (bottom)	18 23	NM NM	CRS-1HP	0.44 0.29	0.44 0.32
Triple layer chip seal	W10 (top) #89 (middle) #7 (bottom)	15 18 23	19 15.5 22.5	CRS-1HP	0.20 0.34 0.26	0.23 NM NM
Fibermat® chip seal	#89	18	16	CRS-2P	0.34	0.38

NM: Not measured

Table 13. Treatment Properties in CSAH-8 Sections

Treatment	Aggregate Gradation	Aggregate Rate (lb/sy)		Emulsion Type	Emulsion Rate (gal/sy)	
		Target	Actual		Target	Actual
Single layer chip seal	FA 2.5	18	23	CRS-2P	0.32	0.33
Single layer chip seal with crack seal	FA 2.5	18	23	CRS-2P	0.32	0.33
Double layer chip seal	FA 2 (top) FA 2.5 (bottom)	16 18	15 17	CRS-2P	0.28 0.30	0.30 0.29
Triple layer chip seal	FA 2 (top) FA 2.5 (middle) CA-70 (bottom)	16 18 22	15 21 25	CRS-2P	0.28 0.40 0.30	0.30 0.41 0.30
Fibermat® chip seal	FA 2.5	18	20	CRS-2P	0.38	0.39
Scrub seal	FA 2.5	18	20.5	CMS-1P (CR)	0.30	0.30

Table 14. Treatment Properties in US-169 sections.

Treatment	Aggregate Gradation	Aggregate Rate (lb/sy)		Emulsion Type	Emulsion Rate (gal/sy)	
		Target	Actual		Target	Actual
Single layer chip seal	FA 2.5	18	20.5	CRS-2P	0.32	0.34
Single layer chip seal with crack seal	FA 2.5	18	20.5	CRS-2P	0.32	0.34
Double layer chip seal	FA 2 (top) FA 2.5 (bottom)	16 18	19.5 20.5	CRS-2P	0.27 0.32	0.28 0.34
Triple layer chip seal	FA 2 (top) FA 2.5 (middle) CA-70 (bottom)	16 18 22	19.5 17 23	CRS-2P	0.25 0.40 0.30	0.28 0.39 0.30
Fibermat® chip seal	FA 2.5	18	20.5	CRS-2P	0.38	0.40
Scrub seal	FA 2.5	18	20.5	CMS-1P (CR)	0.30	0.33

5.2 Performance and Key Findings

Chip seals were effective in delaying pavement deterioration, mainly by inhibiting crack progression. Among all the test sections, only three (located in LR-159) reached the “poor” condition category after a minimum of eight years in service. Double and triple layer chip seals exhibited notable crack resistance and remained in “good” to “fair” condition after 7 to 12 years of service. However, multilayer chip seals exhibited flushing early on, particularly in high-traffic locations. Figure 20 shows the triple layer chip seal test sections in high-traffic locations in both climates after three years of traffic. Although emulsion migrated to the surface along wheelpaths, friction test results indicated skid resistance was not compromised. In low-traffic locations, flushing was observed later in the study in isolated areas (Figure 21).

Performance varied between climatic regions due to snow plowing activities in Minnesota, as the equipment tends to dislodge the aggregate cover near the center of the lane. Once chip loss starts, it can rapidly increase due to a lack of support from the surrounding chips, leaving a slick surface of exposed binder with reduced friction *(16)*. Single layer chip seals were most affected by aggregate loss, exposing a significant portion of the surface. However, this did not translate into reduced reduction or reflect in macrotexture measurements, as most of the retained aggregate was in the wheelpath where testing is conducted.

Treatment variations such as multilayers, scrub seals, and Fibermat® helped mitigate aggregate loss from snow plowing (Figure 22). This indicates chip seals remain viable in cold climates, although the specific method used should be chosen carefully for good performance. It should be noted that Figure 22(c) shows moisture damage in the double chip seal on CSAH-8, resulting from trapped water in the underlying pavement. This caused blisters in the sealed surface, loss of binder-aggregate adhesion, and eventual material loss, including the chip seal and a portion of existing pavement. This issue stemmed directly from site conditions, not treatment performance, and has not occurred in other chip seal test sections.

Although chip seals are not intended to restore pavement roughness, long-term data collected during this study revealed a slight reduction in pavement roughness progression over time on CSAH-8 and US-169 test sections compared to control sections in similar pre-treatment condition.

(a) US-280 (b) US-169

Figure 20. Flushing in high traffic triple chip seal sections.

Figure 21. Isolated flushing in CSAH-8 at year 6.


(a) Single chip seal CSAH-8


(b) Single chip seal US-169


(c) Double chip seal CSAH-8


(d) Double chip seal US-169


(e) Triple chip seal CSAH-8


(f) Triple chip seal US-169

(g) Fibermat® chip seal CSAH-8 (h) Fibermat® chip seal US-169

(i) Scrub seal CSAH-8 (j) Scrub chip seal US-169

Figure 22. Chip seal condition in cold climate sections after 6 years.

The conditions in Figure 22 contrast the performance of the warm climate chip seal sections, where aggregate retention isn't an issue since there aren't external factors such as those mentioned above for the cold climate sections. One similarity is the improved performance when using alternatives to the single layer application, shown in Figure 23.

(a) Single chip seal LR-159

(b) Single chip seal US-280

(c) Double chip seal LR-159

(d) Double chip seal US-280

(e) Triple chip seal LR-159

(f) Triple chip seal US-280

(g) Fibermat® chip seal LR-159 (h) Fibermat® chip seal US-280

(i) Scrub seal LR-159

Figure 23. Chip seal condition in warm climate sections after 7 (US-280) and 11 (LR-159) years.

6. MICRO SURFACING

6.1 Construction

Micro surfacing is a mixture of polymer-modified asphalt emulsion, dense-graded aggregates, mineral filler, water, and other additives. The component materials are mixed and applied on a continuous basis using specialized application equipment (*14*). Micro surfacing can be placed in multi-stone thicknesses up to 1.5 inches in rut filling applications. It is intended for pavements in good structural condition with loss of friction, non-working ruts, and/or low to medium severity surface distresses such as cracking and raveling (*17*). The various micro surfacing test sections in this study are shown in Table 15. Micro surfaces applied as part of a combination treatment are discussed in Chapter 9.

Table 15. Micro Surfacing Test Sections by Location

Treatment	Location				
	LR-159	US-280	CSAH-8	US-169	70th St
Single layer micro surface	✓	✓	✓	NA	NA
Single layer micro surface with crack seal	✓	✓	✓	✓	NA
Double layer micro surface	✓	✓	✓	✓	NA
Micro surface with fibers	NA	✓	NA	✓	NA
High polymer-modified (HiMA) micro surface	NA	✓	NA	NA	NA

NA: Not available at this location

Micro surfacing mixes were designed following guidelines outlined in ISSA A143 (*18*) using local, climate-appropriate materials. Table 16 shows a treatment summary by location. One test section in US-280 (corresponding to a double layer micro surface) used a Type II gradation with limestone aggregate for comparison with the previously constructed low traffic volume sections on LR-159. All other US-280 test sections, including another double layer micro surface, used Type III sandstone mixes. Portland cement was used in all locations as mineral filler at a design rate of 1.0% by weight of the dry aggregate, which was adjusted in the field as needed to control breaking and curing.

Table 16. Micro Surfacing Treatment Summary

Location	Aggregate Gradation	Aggregate Type	Emulsion Type	Emulsion Content (%)		Application Date
				Target	Actual	
LR-159	Type II	Limestone	CSS-1HP	12.0	12.0	August 8, 2012
US-280	Type III	Sandstone	CSS-1HP	12.0	12.0 – 12.1	August 28-September 1, 2015
	Type II	Limestone			12.1	
CSAH-8	Type II	Granite	CQS-1HP	13.0	13.5 – 13.6	August 8-11, 2016
US-169	Type II	Granite	CQS-1HP	13.5	13.5	August 6, 2016

The micro surfacing machine was calibrated before construction to ensure the specified material proportions were delivered. Trial applications were conducted to ensure adequate workmanship, aesthetics, target application rates, and mixture cure time were achievable. The trial applications were performed under similar conditions as those expected during application.

Strips of plastic sheeting were placed at the stopping points to ensure a sharp, uniform edge and to protect adjacent cells from application of other treatments. The treatments were applied to the clean pavement surface with a variable width spreader box equipped with augers and a secondary strike-off at a target of 18 to 20 lbs/yd^2 and allowed to cure before returning to traffic.

Figure 24. Micro surfacing application.

As part of the Phase II research objectives, testing was conducted during construction to determine the residual asphalt binder content of the micro surfacing mixes. Samples were taken from the CSAH-8 and US-169 sections and tested for asphalt content by the ignition furnace method. This method, developed at NCAT in the 1990s, determines asphalt binder content by burning off the asphalt binder of a loose mixture sample (*19*). The remaining aggregate is then weighed, initial and final weights are compared, and the asphalt content is calculated. The procedure is commonly used for quality control and quality assurance of asphalt mixes and was selected due to its accuracy, short testing time, and wide availability, which could facilitate implementation. However, the asphalt is incorporated into the mixtures as an emulsion, which can have up to 40% water plus other chemicals and modifiers. In addition, water is also added to provide workability. Therefore, it is necessary to properly account for any water present in the micro surfacing mixtures to accurately determine the residual asphalt content.

The sample collecting procedure used a disposable aluminum pan approximately 13 by 9 by 2 inches deep, placed inside a reusable pan of similar dimensions. Material was collected directly from the machine by passing the pan assembly in front of the material flow as it came out of the chute until the pan was approximately ¾ full. Samples were then stirred with a metal spoon until an emulsion break occurred, stiffening the mix. At this point, the metal spoon was replaced with a stainless-steel drywall taping knife, which was used to evenly divide the sample into four smaller quarter samples. As the mix continued to stiffen significantly after the initial break, the sample had to be cleanly split throughout its depth before reaching the point where it could no longer be easily manipulated. Figure 25 illustrates the field sampling procedure.

(a) Pan assembly and mixing tools (b) Pan assembly handed to operator

(c) Sample obtained from machine (d) Initial mixing

(e) Sample quartering after emulsion break (f) Quartered sample ready for testing

Figure 25. Field sampling procedure.

Samples were transported to the laboratory, where they were separated to determine the baseline weights for each of the four quarters. Two opposite quarters were immediately placed in a convection oven and dried to constant mass to obtain the moisture content in the mix. The remaining two were placed in an ignition furnace and burned to constant mass following the

AASHTO T 308 procedure. The final weight was subtracted from the initial weight to calculate the mass of water and asphalt lost to the ignition process. The moisture percentage calculated for the oven-dried samples was used to correct the results by subtracting it from the percentage lost in the ignition furnace to calculate residual asphalt content.

The boxplot in Figure 26 summarizes the results. The average departure from the actual asphalt content was -0.26%. Although there was considerable data variability, most results were found to lie between -0.66% and 0.15% with 95% confidence.

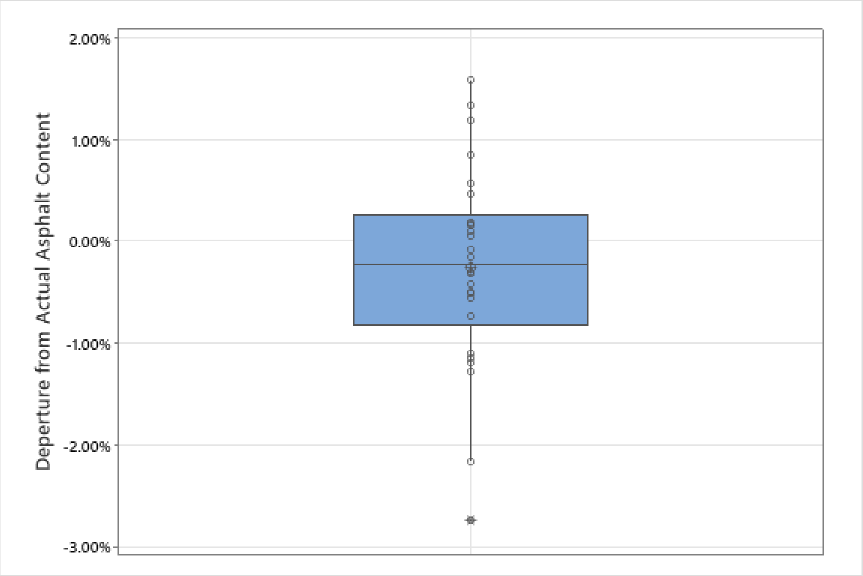


Figure 26. NCAT Preservation Group study test section results.

While this testing procedure is not recommended for agencies at this time, the results from the limited experiment show residual asphalt content can be measured with a reasonable degree of accuracy. Further refinement of the sampling and testing procedures is needed to reduce variability and allow for quality assurance implementation.

6.2 Performance and Key Findings

The micro surfacing test sections effectively restored minor rutting and roughness and provided a skid-resistant pavement surface. Although micro surfacing is not intended as a crack treatment, the test sections exhibited improved cracking performance compared to the controls. Variations from the typical single layer application, such as the use of double layer micro surfacing, enhanced performance, as shown in the side-by-side images in Figures 27 and 28. In addition, the use of fibers had a moderate improvement in cracking performance compared to a traditional micro surface, while the use of high polymer-modified emulsion yielded better results, maintaining cracking under 20% (“poor” condition threshold).

(a) Single micro surface LR-159 (b) Double micro surface LR-159

(c) Single micro surface US-280 (d) Double micro surface US-280

Figure 27. Single vs. double layer micro surfacing condition in warm climate sections after 7 (US-280) and 11 (LR-159) years.

(a) Single micro surface CSAH-8 (b) Double micro surface CSAH-8

(c) Single micro surface (with fibers) US-169 (d) Double micro surface US-169

Figure 28. Single vs. double layer micro surfacing condition in cold climate sections after 6 years.

Although micro surfacing provides a smooth, skid-resistant surface, material selection can affect friction performance. This is evident by comparing the friction numbers in the sections containing different aggregate sources (sandstone and limestone) in US-280. Figure 29 shows friction in the limestone section expressed as a percent reduction from the average of the sandstone sections. It can be seen that the limestone micro surface had approximately 40 to 55% lower friction numbers compared to the sandstone mixes. This difference is also due to the use of various gradations, shown previously in Table 16. Although friction numbers were lower when using limestone, they were still considered safe and did not pose a safety risk.

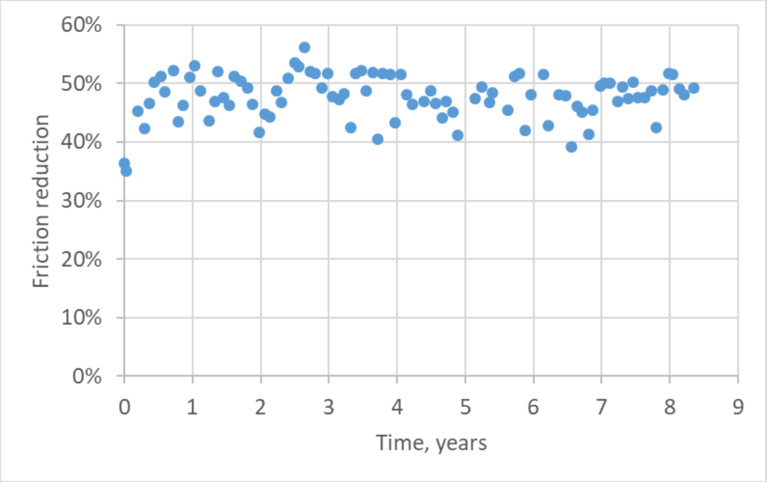


Figure 29. Friction reduction in limestone micro surface compared to sandstone micro surface.

7. DENSE-GRADED THINLAYS

7.1 Construction

A thin asphalt overlay (thinlay) is a combination of asphalt cement and aggregate placed with conventional paving equipment in depths of ¾ to 1 ½ inches over pavements with good structure but low severity surface distresses. Mixtures may be dense, gap, or open-graded and may include polymer-modified asphalt and/or reclaimed asphalt pavement *(20, 21).*

The dense-graded thinlay sections in this study used a variety of mixture designs incorporating different virgin and recycled materials. A summary of thinlay sections by location is provided in Table 17. Thinlays applied as part of a combination treatment are discussed in Chapter 9.

Table 17. Dense-Graded Thinlay Test Sections by Location

Treatment	**Location**				
	LR-159	**US-280**	**CSAH-8**	**US-169**	**70th St**
Virgin thinlay with neat binder	✓	NA	NA	NA	NA
Virgin thinlay with polymer-modified binder	✓	✓	✓	✓	NA
Virgin thinlay with high polymer-modified (HiMA) binder	✓	NA	NA	NA	NA
50% RAP thinlay	✓	NA	NA	NA	NA
5% RAS thinlay	✓	NA	NA	NA	NA
Asphalt binder replacement (ABR) thinlay	NA	✓	✓	✓	✓
Asphalt binder replacement (ABR) thinlay with rejuvenator	NA	NA	✓	✓	NA
ABR thinlay with high polymer-modified (HiMA) binder	NA	NA	NA	✓	NA

NA: Not available at this location

All mixtures had a nominal maximum aggregate size (NMAS) of 4.75 mm and were designed using local materials that met the climate requirements of each region. The design thickness of the overlays was ¾-inches. For the LR-159 sections, the surface was swept to remove dust and loose materials, and a tack coat was applied to the existing surface using a NTSS-1HM emulsion (trackless tack). The surface was milled in the remaining locations prior to treatment placement to maintain grade. This milling operation removed distresses in the pavement surface such as top-down cracking and minor rutting, further enhancing treatment performance. In addition, milling improved ride quality, especially in the cold climate sections. While transverse cracking was not completely eliminated (Figure 30), milling improved the condition around these cracks, resulting in lower IRI values after treatment.

Figure 30. Milled surface of US-169 prior to thinlay application.

The design mix gradations are shown in Table 18. ABR mixtures used in the warm climate sections contained 11% RAP and 3% RAS and used a combination of limestone screenings and coarse sand as the virgin aggregates. Meanwhile, their cold climate counterparts contained 12% RAP and 3% RAS, with sandstone screenings as the virgin aggregates.

Table 19 through Table 21 show the thinlay properties by location.

Although an asphalt binder replacement (ABR) thinlay was placed as the final surface on all 70th Street sections, the existing condition in that location was too deteriorated for these overlays to be considered preservation treatments. In this case, the intention was to use the standalone thinlays as an example of a stop-gap measure and serve as control sections to compare against more cost-effective cold recycling alternatives. The results from the 70th Street sections are discussed in Chapter 10.

Table 18. Design Gradation of All Mixtures

Sieve Size	Percent Passing				
	Warm Climate Sections			Cold Climate Sections	
	Virgin/ABR	50% RAP	5% RAS	Virgin	ABR
3/8”	100	100	100	100	100
No. 4	99	99	99	95	96
No. 8	76	78	77	76	78
No. 16	53	56	54	55	57
No. 30	36	38	37	40	41
No. 50	23	22	23	26	27
No. 100	15	15	16	16	17
No. 200	11.5	11.1	12.2	10.3	11

Table 19. LR-159 Test Section Thinlay Properties

Treatment	Binder Grade	Modifier	New Binder Content, %	Binder Replacement, %	Construction Date
Virgin thinlay (neat binder)	PG 67-22	Neat	6.1	0	August 13, 2012
Virgin thinlay (modified binder)	PG 76-22	SBS	6.1	0	August 13, 2012
Virgin thinlay (HiMA binder)	PG 88-22	SBS	6.1	0	August 13, 2012
50% RAP thinlay	PG 67-22	Neat	6.5	54	August 13, 2012
5% RAS thinlay	PG 67-22	Neat	6.2	19	August 13, 2012

Table 20. US-280 Test Section Thinlay Properties

Treatment	Binder Grade	Modifier	New Binder Content, %	Binder Replacement, %	Construction Date
Virgin thinlay (modified binder)	PG 76-22	SBS	6.1	0	August 24, 2015
ABR thinlay	PG 67-22	Neat	6.1	20	August 21, 2015

Table 21. CSAH-8 and US-169 Test Section Thinlay Properties

Treatment	Binder Grade	Modifier	New Binder Content, %	Binder Replacement, %	Construction Date
Virgin thinlay	PG 64-34	SBS	6.4	0	August 16-18, 2016
ABR thinlay	PG 64-34	SBS	5.0	21.9	August 16-20, 2016
ABR thinlay (HiMA binder)	PG 64E-34	SBS	5.0	21.9	August 20, 2016

7.2 Performance and Key Findings

Thinlays were capable of addressing multiple distresses, such as minor rutting and cracking, and improved ride quality, especially when applied after milling. In most cases, performance indicators remained in the "good" to "fair" condition categories throughout the study. Furthermore, some of the test sections were still in the overall "good" condition range at the end of Phase II.

As expected, the use of virgin materials resulted in the most crack resistant mixtures. The inclusion of recycled materials like RAP and RAS showed they can still provide durable treatments, but they must be properly evaluated during mixture design. For instance, during the construction of the first test sections in LR-159, high RAP and high RAS thinlays were included as alternatives to the virgin mixture design. These mixes were designed using a volumetric approach without additional modifications to adjust the binder grade. Although they met the design criteria, their cracking performance was reduced due to the increased stiffness of the mix (Figure 31). These sections reached the "poor" condition category after approximately seven years, which is in the lower range for the expected service life of thinlays.


(a) 50% RAP thinlay (b) 5% RAS thinlay

Figure 31. LR-159 high recycled content thinlay sections after 11 years.

To optimize the use of recycled materials in the remaining test locations, an ABR mixture was designed based on performance rather than volumetrics. This allowed the incorporation of RAP and RAS without compromising durability. ABR thinlays were used in the remaining test locations, leading to better performance. ABR thinlays with and without a mix rejuvenator were used in the cold climate locations, as shown in Figure 32. The use of rejuvenators has yet to result in improved cracking performance throughout the first seven years of service of these sections. More monitoring is needed to assess the potential long-term benefits of rejuvenators.

Polymer-modified binders did not provide notable benefits in terms of cracking performance during Phases I and II. However, all thinlay sections, including mixtures produced with a neat binder, showed good rutting performance. Furthermore, high polymer modification was effective in maintaining low levels of rutting, even under high-stress situations. In LR-159, the HiMA thinlay test section was placed strategically near the intersection where loaded trucks traveling from the quarry and asphalt plant brake and turn. These movements induce high stresses on the pavement, resulting in rutting and cracking. Figure 33 shows the transition from the HiMA thinlay to the untreated pavement at the intersection. Although the transition started to exhibit distress towards the end of Phase II, the surface condition was greatly improved as a result of the treatment.

(a) CSAH-8 ABR thinlay (b) CSAH-8 ABR thinlay with rejuvenator

(c) US-169 ABR thinlay (d) US-169 ABR thinlay with rejuvenator

Figure 32. ABR Thinlay sections in cold climate locations after 6 years.

Figure 33. LR-159 HiMA thinlay after 11 years.

8. UTBWC AND OGFC THINLAYS

8.1 Construction

Although commonly used, thin overlays are not constrained to dense-graded mixtures. Gap-graded and open-graded mixtures have also been used by several agencies with good performance (*20, 21*). Open-graded friction course (OGFC) mixtures have an aggregate gradation that provides an open void structure (typically between 15 to 25% air voids), resulting in a highly permeable mixture that allows water to be removed from the pavement surface by flowing through the asphalt layer. This characteristic provides added benefits compared to dense-graded mixtures, such as minimized splash and spray, increased wet weather visibility, improved friction resistance, and reduced noise levels (*14, 20-22*).

An ultra-thin bonded wearing course (UTBWC) consists of a thin, high-quality gap- or open-graded hot mix layer placed on a polymer-modified tack coat membrane by a spray paver (*23*). They can effectively address minor surface distresses such as low severity cracking, raveling, weathering, and bleeding; they can also increase surface friction and improve smoothness (*24*).

UTBWC thinlays were applied in four locations, as shown in Table 22. Five OGFC thinlay sections were placed on US-280 under warm climate and high-traffic volume conditions. Four OGFC sections were also constructed on MnROAD's low volume road, a closed 2.5-mile loop loaded by a dedicated truck with a gross vehicle weight of 80,000 lbs. This highly controlled location was selected due to the potential risk of failure of the OGFC mixtures under cold climate conditions. The design gradations for the mixtures are shown in Table 23, and the thinlay properties for the warm and cold climate test sections are presented in Table 24 and Table **25**, respectively.

Table 22. UTBWC and OGFC Thinlay Test Sections by Location

Treatment	**Location**				
	LR-159	**US-280**	**CSAH-8**	**US-169**	**70th St**
UTBWC thinlay	✓	✓	✓	✓	NA
OGFC thinlay	NA	✓	NA	NA	NA

NA: Not available at this location

Table 23. Design Gradation for All Mixtures

Sieve Size	**Percent Passing**			
	Warm Climate Sections		**Cold Climate Sections**	
	UTBWC	**OGFC**	**UTBWC**	**OGFC**
¾"	100	100	100	100
½"	97	95	100	93
⅜"	79	64	94	69
No. 4	35	15	34	13
No. 8	23	9	25	10
No. 16	18	8	18	8
No. 30	14	6	13	6
No. 50	10	5	9	4
No. 100	6	4	6	3
No. 200	4.1	3.7	4	1.7

Table 24. Thinlay Properties for LR-159 and US-280 Test Sections

Treatment	Binder Grade	Modifier	New Binder Content, %	Binder Replacement, %	Construction Date
UTBWC thinlay	PG 76-22	SBS	5.1	0	August 28, 2012 (LR-159) August 24, 2015 (US-280)
OGFC thinlay	PG 76-22	SBS	5.5	9.1	August 24-25, 2015

Table 25. Thinlay Properties for CSAH-8, US-169, and MnROAD Test Sections

Treatment	Binder Grade	Modifier	New Binder Content, %	Binder Replacement, %	Construction Date
UTBWC thinlay	PG 64-34	SBS	5.2	0	August 17, 2016 (CSAH-8) August 18, 2016 (US-169)
OGFC thinlay	PG 64-34	SBS	4.6	14.8	August 2016

The UTBWC mixes were designed with all virgin aggregates (granite from local sources) and placed at a thickness of ¾-inch. With the exception of US-280, the mixes were placed using a spray paver, a specialty paver that incorporates a heated tank for the tack material and a spray bar located immediately in front of the paver augers and screed (*25*). This allows for the mix to be delivered within seconds of the tack coat application. The heat from the hot mix causes the emulsion to break quickly and "wick" upward into the bottom portion of the hot mix lift, filling voids in the aggregate and creating an interlayer of high cohesion (*26, 27*). Figure 34 shows application using a spray paver.

Figure 34. UTBWC application with spray paver (*27*).

The five OGFC test sections on US-280 were placed at a 1-inch thickness using the same mixture, which contained 15% coarse RAP, 0.5% cellulose fiber by weight of the total mix, and 0.5% Evotherm P15 by weight of the total asphalt content (used as an anti-strip agent). Each test section used a different tack coat as shown in Table 26. Section 30 used a spray paver to apply the tack coat in a continuous operation, while the remaining sections used a conventional procedure where the tack coat was sprayed onto the roadway surface immediately prior to paving. Except for the PG 67-22 hot-applied asphalt binder, all were classified as non-tracking materials. The tack coat rates were selected based on manufacturer recommendations.

Table 26. Summary of US-280 OGFC Test Sections

Parameter	**Section Description**				
Tack coat type	CBC-1H	NTSS-1HM	PG 67-22	NT-HAP	CBC-1H
Application type	Spray paver	Conventional	Conventional	Conventional	Conventional
Undiluted tack rate, gal/sy	0.23	0.10	0.06	0.15	0.10

The OGFC sections placed on the MnROAD low volume road used the same mixture containing 15% RAP, placed at a thickness of 1-inch. Two of the thinlays were placed over Portland cement concrete (PCC) pavement, and two were placed over asphalt concrete (AC) pavement, as seen in Figure 35. In each of the existing pavement types, one section used conventional tack coat (CSS-1H) and the other used a trackless product (NTSS-1HM). All tack coats were applied using the conventional procedure.

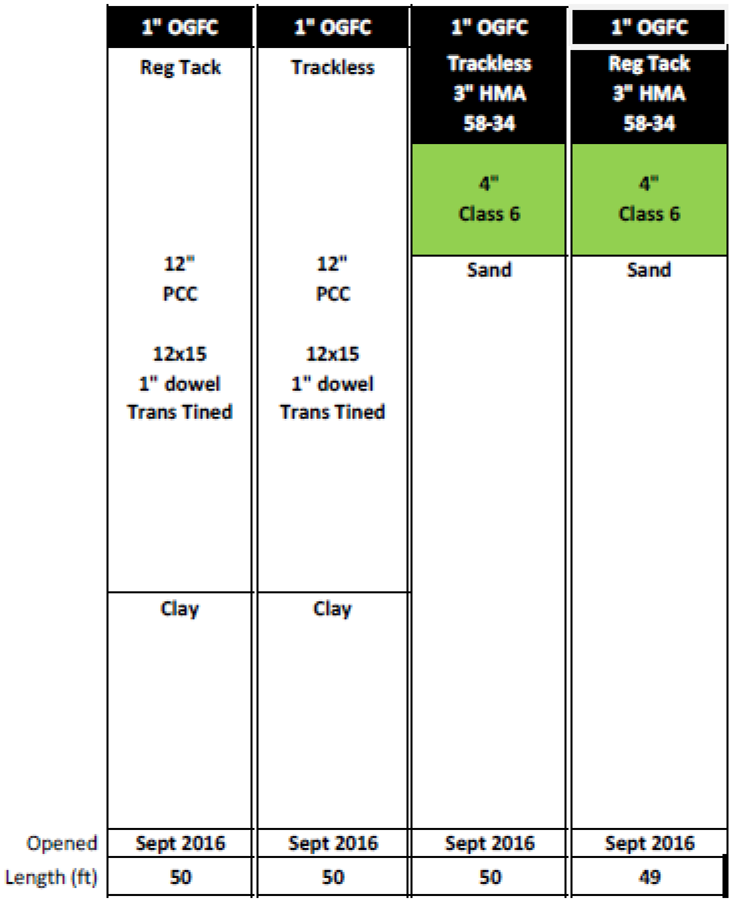


Figure 35. Schematic of MnROAD low volume road OGFC test sections (*28*).

8.2 Performance and Key Findings

UTBWC thinlays exhibited little signs of distress in most of the locations. Rutting and roughness were in the "good" condition category and cracking was "good" to "fair" by the end of Phase II.

The exception was the LR-159 section, where site-specific conditions contributed to a slippage failure in the outbound lane (Figure 36). Poor drainage and a significant rain event after approximately three years of service caused flooding and the moisture in the pavement structure, combined with the heavy truck loads, created slippage cracking near the areas with high density cracking prior to treatment application. The outbound half of the section was milled and replaced with an ABR thinlay in 2018 to avoid compromising the integrity of the adjacent section. The inbound portion remained in place for the entirety of the study. This type of issue was not repeated in any of the other locations, nor in the inbound lane of LR-159.

Figure 36. UTBWC in LR-159 five years after construction.

Although OGFC overlays have several functional advantages over conventional dense-graded mixes, that functionality can diminish throughout the treatment service life due to clogging of pores, which may be particle-related (due to dirt and pollutants) or deformation-related (due to rutting) *(29, 30)*.

In the US-280 sections, cores were taken annually and tested for air voids and permeability. Figure 37 shows that after seven years of service, the voids had decreased as a result of clogging and aggregate reorientation, which in turn resulted in a reduction in permeability. The largest reductions were in sections with the highest air void contents post construction; however, by year seven there were no significant differences in permeability among the sections.

There is little distinction among the warm climate sections in terms of the MAP-21 performance indicators. All maintained ride quality and rutting levels in the "good" condition category by the end of Phase II. Cracking varied among the sections, with only the CBC-1H section applied with the conventional method remaining under 5%. In addition, raveling was observed in some areas, mainly near the transitions of the test sections. A general overview is shown in Figure 38.

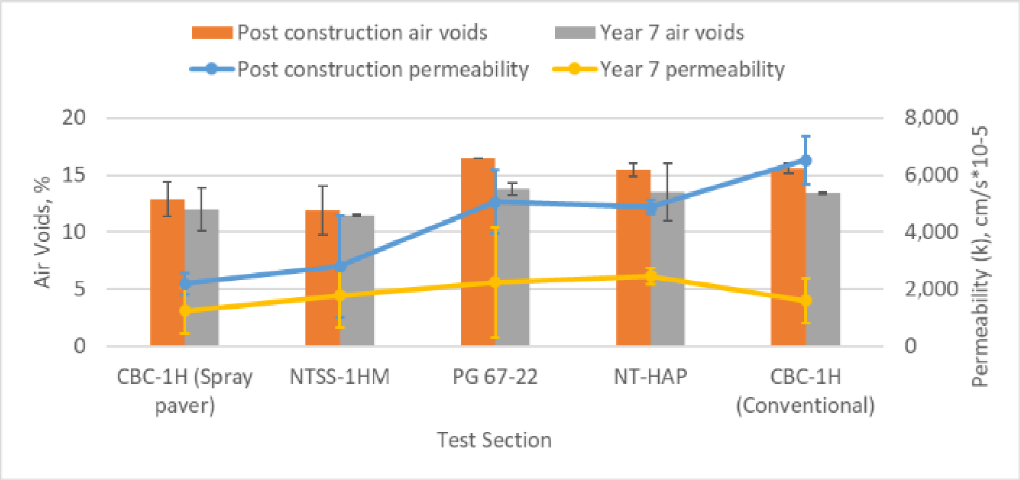


Figure 37. Air void content and permeability results for US-280 test sections.

(a) CBC-1H (Spray paver)

(b) NTSS-1HM

(c) PG 67-22

(d) NT-HAP

(e) CBC-1H (Conventional)

Figure 38. Overall condition of US-280 OGFC sections after 11 years.

In the cold climate location, the main concern was the durability of the OGFC thinlays. Compared to dense-graded mixes, OGFCs are more sensitive to temperature variations due to interconnected air voids, and therefore are more susceptible to freeze-thaw cycles. These can cause swelling stresses resulting in raveling, cracking, and delamination (31-33). The MnROAD sections exhibited reflective cracking from the underlying PCC pavement and from the transverse cracks in the asphalt pavement, but overall withstood the cold climate conditions without major issues. Some raveling developed by the end of Phase II after seven years of service. Field permeability measurements were obtained in June 2017, and follow-up measurements were taken in 2018, 2019, 2021, and 2023. Similar trends were observed with permeability declining drastically over time, reaching values ranging between $112\text{x}10^{-5}$ and $518\text{x}10^{-5}$ cm/s by 2021, similar to a dense-graded asphalt surface. Interestingly, the results from 2023 showed a significant increase in field permeability, yielding the greatest values since construction. Raveling near the testing locations may have influenced the results.

(a) OGFC over PCC (regular tack) (b) OGFC over PCC (trackless tack)

(c) OGFC over AC (regular tack) (d) OGFC over AC (trackless tack)

Figure 39. Overall condition of MnROAD low volume road OGFC sections after 6 years.

9. COMBINATION TREATMENTS

9.1 Construction

A combination treatment is a two-step process that integrates the benefits of each treatment layer, increasing their effectiveness compared to standalone treatments. In this study, various combination treatments were applied, including micro surfacing over chip seal (also referred to as a Cape seal), thinlay over chip seal, and micro surfacing over thinlay. Table 27 shows the combination treatment test sections by location.

Table 27. Combination Treatment Test Sections by Location

Treatment	Location				
	LR-159	US-280	CSAH-8	US-169	70th St
Micro surface over chip seal (cape seal)	✓	✓	✓	✓	NA
Micro surface over Fibermat® chip seal (Fibermat® cape seal)	✓	✓	✓	✓	NA
Micro surface over scrub seal (scrub cape seal)	✓	✓	✓	✓	NA
Thinlay over chip seal	NA	✓	✓	✓	NA
Thinlay over Fibermat® chip seal	✓	✓	✓	NA	NA
Thinlay over scrub seal	NA	✓	✓	NA	NA
Micro surface over thinlay	NA	✓	NA	NA	NA

NA: Not available at this location

The materials and designs used were similar to those used in the standalone applications previously discussed in Chapters 5 through 7. More information on each of the layers for the combination treatment sections is provided in Table 28 through Table 31.

Table 28. LR-159 Combination Treatment Properties

Treatment	First Layer	Construction Date	Second Layer	Construction Date
Cape seal	#89 granite chip seal	August 8, 2012	Type II limestone micro surface	August 10, 2012
Fibermat® cape seal	#89 granite Fibermat® chip seal	July 17, 2012	Type II limestone micro surface	August 10, 2012
Scrub cape seal	#89 granite scrub seal	August 6, 2012	Type II limestone micro surface	August 10, 2012
Thinlay over Fibermat® chip seal	#89 granite Fibermat® chip seal	July 17, 2012	Virgin thinlay (neat binder)	August 13, 2012

Table 29. US-280 Combination Treatment Properties

Treatment	First Layer	Construction Date	Second Layer	Construction Date
Cape seal	#89 granite chip seal	August 27, 2015	Type III sandstone micro surface	August 28, 2015
Fibermat® cape seal	#89 granite Fibermat® chip seal	August 27, 2015	Type III sandstone micro surface	August 28, 2015
Scrub cape seal	#89 granite scrub seal	August 31, 2015	Type III sandstone micro surface	September 1, 2015
Thinlay over chip seal	#89 granite chip seal	August 27, 2015	ABR thinlay	September 3, 2015
Thinlay over Fibermat® chip seal	#89 granite Fibermat® chip seal	August 27, 2015	ABR thinlay	September 3, 2015
Thinlay over scrub seal	#89 granite scrub seal	August 31, 2015	ABR thinlay	September 3, 2015
Micro surface over thinlay	ABR thinlay	August 21, 2015	Type III sandstone micro surface	August 29, 2015

Table 30. CSAH-8 Combination Treatment Properties

Treatment	First Layer	Construction Date	Second Layer	Construction Date
Cape seal	FA 2.5 granite chip seal	August 6, 2016	Type II granite micro surface	August 28, 2015
Fibermat® cape seal	FA 2.5 granite Fibermat® chip seal	August 2, 2016	Type II granite micro surface	August 28, 2015
Scrub cape seal	FA 2.5 granite scrub seal	August 3, 2016	Type II granite micro surface	September 1, 2015
Thinlay over chip seal	FA 2.5 granite chip seal	August 5, 2016	ABR thinlay	August 16, 2016
Thinlay over Fibermat® chip seal	FA 2.5 granite Fibermat® chip seal	August 3, 2016	ABR thinlay	August 16, 2016
Thinlay over scrub seal	FA 2.5 granite scrub seal	August 3, 2016	ABR thinlay	August 16, 2016

Table 31. US-169 Combination Treatment Properties

Treatment	First Layer	Construction Date	Second Layer	Construction Date
Cape seal	FA 2.5 granite chip seal	August 6, 2016	Type II granite micro surface	August 6, 2016
Fibermat® cape seal	FA 2.5 granite Fibermat® chip seal	August 2, 2016	Type II granite micro surface	August 6, 2016
Scrub cape seal	FA 2.5 granite scrub seal	August 3, 2016	Type II granite micro surface	August 6, 2016
Thinlay over chip seal	FA 2.5 granite chip seal	August 6, 2016	ABR thinlay	August 20, 2016

In each layer, the application followed the same previously described procedures, generally leaving a few days between applications. A tack coat was used in the interface between chip seals and thinlays but not for other combinations.

9.2 Performance and Key Findings

Combination treatments have proven to be very effective options, especially for pavements subjected to low traffic volumes, as shown in the example in Figure 40. The performance indicators mostly remained in the “good” and “fair” condition categories. Only cracking in certain high-traffic sections exceeded 20% by the end of Phase II, some of which were already in the “fair” condition range prior to treatment application.

Figure 40. Scrub cape seal on LR-159 after 11 years of service.

Combination treatments significantly reduced roughness progression in the cold climate locations by lowering the severity of transverse cracking. As Figure 41 shows, although transverse cracking is reflected through the treatment combination (far side), the pavement around the crack is in better condition compared to the untreated section (near side), where spalling and additional cracking is visible.

The micro surface over thinlay combination used in US-280 was selected to address friction concerns due to the fineness and low macrotexture of the thinlay mix. To improve the skid resistance of the pavement, a micro surface was added as the final wearing surface. Figure 42 shows friction number results of the micro surfacing over thinlay section and the average of the thinlay combination sections as a percentage of the control sections. The micro surfacing over thinlay section consistently had friction numbers around 20% higher than the untreated sections. Conversely, the combination treatment sections where the thinlays were the wearing surface initially had friction numbers comparable to the control sections but decreased in time until reaching a reduction of approximately 30%. Although friction levels are considered safe in all of these sections, if a particular project considers the fine thinlay mix a safety risk, adding a micro surfacing layer can improve skid resistance while preserving the existing pavement.

Figure 41. Severity of transverse cracking in treated and untreated sections.

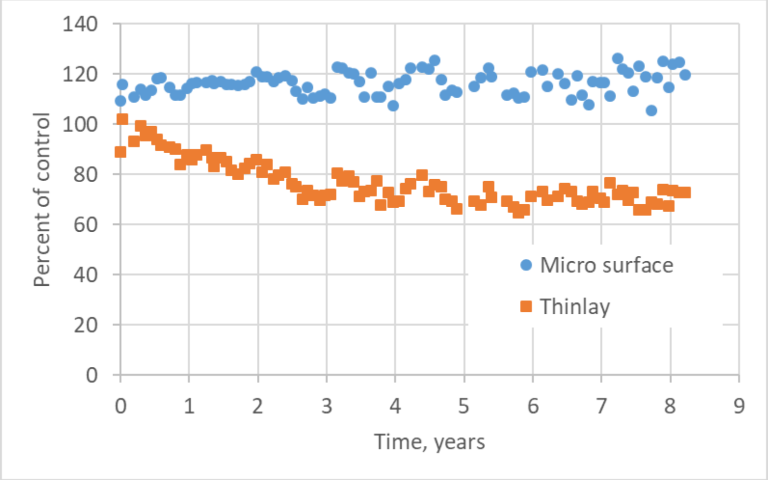


Figure 42. Friction performance in US-280 sections compared to untreated.

10. COLD RECYCLING

10.1 Construction

Cold recycling is a series of asphalt pavement rehabilitation methods that reuse existing or stockpiled materials (often in the form of RAP) without the application of heat. The process can be done in situ using a specialized train of equipment (cold in-place recycling) or at a central location using a mobile plant (cold central plant recycling). Full-depth reclamation is another technique in which the total thickness of the asphalt layer and a predetermined portion of underlying unbound materials are reclaimed (*34*). Although it is not considered a cold recycling technology, it is included in the cold recycling treatment group for the purpose of this report. Table 32 shows the locations of the cold recycling test sections.

Table 32. Cold Recycling Test Sections by Location

Treatment	Location				
	LR-159	US-280	CSAH-8	US-169	70th St
Cold central plant recycling (CCPR)	✓	✓	NA	NA	✓
Cold in-place recycling (CIR)	NA	✓	NA	NA	✓
Full depth reclamation (FDR)	NA	NA	NA	NA	✓

NA: Not available at this location

The test sections were designed and constructed using bituminous recycling agents (foamed asphalt or emulsified asphalt) following Asphalt Recycling & Reclaiming Association (ARRA) guidelines (*35-37*). Table 33 through Table 35 provide more details on the treatment properties.

Table 33. LR-159 Cold Recycling Treatment Properties

Treatment	Recycling Agent	Content, %	Optimum Moisture Content, %	Cement Content, %	Construction Date
CCPR	Foamed asphalt	2.0	NA	1.0	August 8, 2012

NA: Not available at this location

Table 34. US-280 Cold Recycling Treatment Properties

Treatment	Recycling Agent	Content, %	Optimum Moisture Content, %	Cement Content, %	Construction Date
CCPR	Foamed asphalt	2.5	7.2	1.5	September 9, 2015
CCPR	Engineered emulsion	3.0	7.0	1.5	September 9, 2015
CIR	Foamed asphalt	1.8	4.9	1.5	September 11, 2015
CIR	Engineered emulsion	3.2	4.4	1.5	September 10, 2015

Table 35. 70th Street Cold Recycling Treatment Properties

Treatment	Recycling Agent	Content, %	Optimum Moisture Content, %	Cement Content, %	Construction Date
CCPR	Foamed asphalt	2.3	4.5	1.0	August 21, 2019
CCPR	Engineered emulsion	3.5	2.5	0.0	August 21-22, 2019
CIR	Foamed asphalt	2.6	4.5	1.0	August 21, 2019
CIR	Engineered emulsion	3.0	2.0	0.0	August 22, 2019
FDR	Foamed asphalt	2.5	6.0	1.0	August 21, 2019
FDR	Engineered emulsion	3.5	6.0	1.0	August 22, 2019

The pavement structure varied among the sections, as shown in Figure 43 and Figure 44. For LR-159, all bituminous material was removed and replaced with the foamed CCPR mix and then surfaced with a ¾-inch virgin thinlay. In US-280 sections, the existing structure varied, as shown in Figure 43. In all cases, the thickness of the cold recycled layer was 4 inches, but the thickness of the remaining asphalt concrete layer ranged from 3.4 to 12.5 inches. It should also be noted that the CIR sections did not have a base layer. Due to the increased traffic level on US-280, the thinlay used for the wearing surface was increased to a thickness of 1-inch and consisted of an ABR mix.

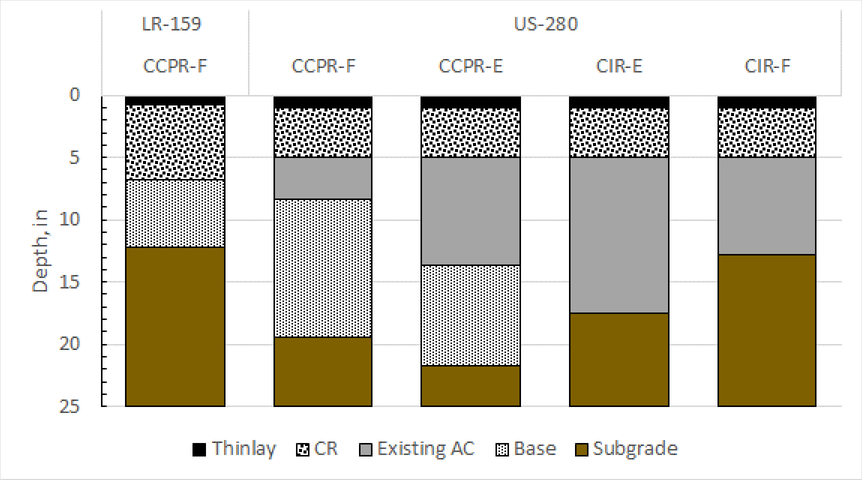


Figure 43. Pavement cross-sections in warm climate locations.

The existing pavement in the 70th Street location consisted of a 4-inch layer of asphalt concrete over 6 inches of granular base on top of a clay subgrade. The CIR and CCPR layers were 3 inches deep, leaving 1 inch of the existing pavement in place. The FDR sections were constructed at 7 inches deep, replacing all of the existing asphalt material and leaving 3 inches of the aggregate base in place. Additionally, mill and inlay rehabilitation options were used in two sections to represent a more traditional approach; one was 2 inches deep, and the other was 3 inches deep. All sections were surfaced with a 1-inch ABR thinlay, including seven sections where the thinlay was placed directly on the existing, heavily distressed pavement. These were designated as “control” sections and are representative of the stopgap measures agencies often apply to maintain pavements serviceable over short-term periods. Figure 45 shows a schematic of the test section layout for 70th Street. Due to time and logistic constraints, the focus of the project was on the eastbound lane. However, some rehabilitation options were also placed on the westbound lane.

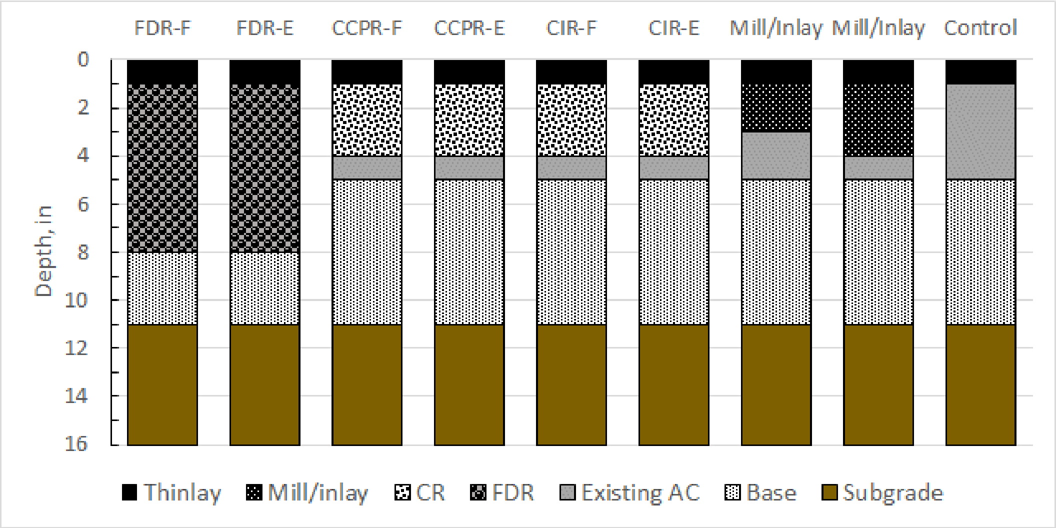
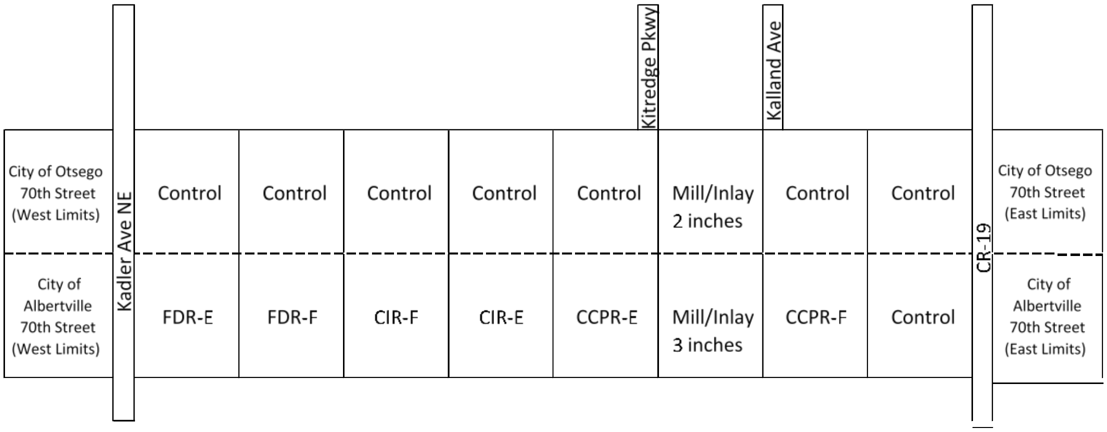


Figure 44. 70th Street pavement cross-sections.



City of Otsego 70th Street (West Limits)	Control	Control	Control	Control	Control	Mill/Inlay 2 inches	Control	Control	City of Otsego 70th Street (East Limits)
City of Albertville 70th Street (West Limits)	FDR-E	FDR-F	CIR-F	CIR-E	CCPR-E	Mill/Inlay 3 inches	CCPR-F	Control	City of Albertville 70th Street (East Limits)

Figure 45. 70th Street test section layout (wearing surface is a 1-inch ABR thinlay).

During construction, a Wirtgen KM220 mobile mixing plant was used to produce the CCPR mixes at a nearby off-site location (NCAT Test Track for the warm climate sections, MnROAD facility for the cold climate sections). The mix was then transported to the sites and placed using conventional paving equipment. Recycling of the CIR sections was carried out using a Wirtgen 3800CR recycling machine, which can recycle a full lane in one pass and stabilize it with a bituminous agent (Figure 46). For the FDR sections, a Wirtgen WR 250i reclaimer was mobilized to the 70th Street site, but due to mechanical issues and time constraints, the equipment could not be used. Instead, the existing pavement was milled and processed using the CIR equipment. The material was placed in a windrow before being spread with a motor grader and compacted with sheepsfoot and steel drum vibratory rollers.

The NCAT mobile lab was onsite, and quality control was performed by sampling the different recycled mixes to test for total water content, added asphalt content, and aggregate gradation. Compacted samples were cured and tested for indirect tensile strength or stability, depending on the recycling agent used.

Figure 46. 70th Street CIR equipment train.

Figure 47. Reclaimed material in FDR section.

10.2 Performance and Key Findings

Cold recycled sections have provided a durable rehabilitation alternative. Even with a thin asphalt wearing surface, the test sections were able to withstand significant traffic with “good” to “fair” performance. In general, the recycled mixes exhibited increased rutting and roughness progression compared to the control sections but were in “good” to “fair” condition categories by the end of Phase II. Cracking was also in the “good” to “fair” range, with the warm climate sections exhibiting cracking mainly in the wheel paths while the cold climate sections contained mostly transverse cracking.

Figure 48 shows the overall condition of the US-280 test sections. The foamed CCPR section has the most cracking, which is made more visible due to the pumping of fines. It should be noted that this section had the thinnest asphalt layer prior to construction, and therefore, replacing part of it with the CCPR mix resulted in a nearly 1:1 ratio of cold recycling to asphalt concrete. This resulted in a pavement structure with a lower composite modulus compared to the other test sections.

(a) CCPR – foamed asphalt (b) CCPR – emulsion

(c) CIR – foamed asphalt (d) CIR – emulsion

Figure 48. Overall condition of US-280 cold recycled sections after 7 years.

Figure 49 shows the overall condition of the recycled sections on 70th Street. In this case, the FDR sections exhibited the highest percentage of cracking. Crack sealing was performed by the cities as part of routine maintenance beginning in 2020.

(a) CCPR – foamed asphalt (b) CCPR – emulsion

(c) CIR – foamed asphalt (d) CIR – emulsion

(e) FDR – foamed asphalt (f) FDR – emulsion

Figure 49. Overall condition of 70th Street cold recycled sections after 4 years.

A phenomenon observed in 70th Street is the formation of secondary cracks around the main transverse cracks (Figure 50). This could be related to frost heave action and vertical movement of the pavement on both sides of the primary crack. This type of deterioration is more severe in the FDR and control sections.

Figure 50. Transverse cracking in 70th Street test section.

Although the existing pavement was in poor condition and was not a proper candidate for a thinlay, the control sections still benefited from treatment application, providing a surface with an improved level of service. Notably, IRI values, which were in the 274 to 429 in/mi range prior to treatment, were drastically reduced to 90 in/mi or less and have not been in the "poor" condition category during the study. However, cracking performance was expectedly poor, with all sections above 20% by the end of Phase II. Figure 51 shows an example of the condition of the control sections. These results emphasize the importance of proper project selection. Thinlays are effective treatments when applied to pavements in good to fair condition; although they can temporarily improve the condition of a poor roadway, their service life and expected benefits are greatly diminished by following this practice.

The traditional mill and inlay treatments resulted in the best performance, but field results suggest cold recycling techniques can also be sustainable alternatives for rehabilitating asphalt pavements. The added environmental and potential life cycle cost benefits could incentivize this option.

Figure 51. Overall condition of 70th Street control section (thinlay only) after 4 years.

11. PERFORMANCE SUMMARY

This chapter summarizes the performance of the test sections according to the MAP-21 indicators (cracking, rutting, and IRI). The following tables show the results by location and condition indicator at three key points in time: pre-treatment, post-construction, and at the end of Phase II, keeping in mind that test section age varies by location. Cells are color-coded to represent the condition category (green = good, yellow = fair, red = poor).

It is important to point out two of the control sections in US-169 (sections 169015 and 169016) were resurfaced in 2020 due to advanced pavement deterioration. Cracking was over 30%, and the sections exhibited additional distresses such as raveling, potholes, and shoving, which compromised ride quality. The sections had been in the study for four years, accounting for 11 years since construction. The untreated pavement could not provide an acceptable level of service and was outperformed by every treated section. Figure 52 shows the pavement condition in one of these control sections just before resurfacing. Construction was performed by MnDOT’s District 3 and is not considered part of the research. The summary tables show sections 169015 and 169016 as “out of study”. Only the data collected while the sections were active were analyzed and used to develop the performance curves discussed in Chapter 12.

Figure 52. US-169 control section condition before resurfacing.

11.1 Cracking

Cracking is one of the indicators with the fastest progression over time, especially for the cold climate sections. Logically, the older sections tend to exhibit higher amounts of cracking; however, performance is also affected by pre-treatment cracking condition. In general, lighter treatments reached the “poor” condition earlier, while more robust applications such as multilayers, thinlays, and treatment combinations maintained lower cracking percentages. In many cases, they remained in the “good” or “fair” condition categories by the end of Phase II as shown in Table 36 through

Table 40.

Table 36. LR-159 Cracking Performance (Age = 11 Years)

Section No.	Description	Cracking, % Area		
		Pre-treat.	Post const.	End of Phase II
L1	Rejuvenating fog seal	5.4	0.0	54.0
L2	Fibermat® chip seal	2.6	0.0	34.0
L3	Control	4.1	4.1	43.1
L4	Control	16.1	16.1	72.1
L5	Crack sealing	25.4	0.0	65.3
L6	Single layer chip seal	0.9	0.0	35.5
L7	Single layer chip seal with crack sealing	17.4	0.0	35.3
L8	Triple layer chip seal	6.7	0.0	8.8
L9	Double layer chip seal	2.6	0.0	15.0
L10	Cape seal	5.1	0.0	9.2
L11	Single layer micro surfacing	5.5	0.0	55.3
L12	Single layer micro surfacing with crack sealing	18.1	0.0	68.1
L13	Double layer micro surface	14.2	0.0	14.4
L14	Fibermat® cape seal	7.0	0.0	8.4
L15	Scrub cape seal	8.0	0.0	8.8
L16	Scrub seal	4.8	0.0	15.2
L17	Fibermat® chip seal	12.9	0.0	22.6
L18	Thinlay over Fibermat® chip seal	8.6	0.0	7.6
L19	Virgin thinlay (neat binder)	16.5	0.0	11.4
L20	Thinlay on foamed CCPR	10.7	0.0	10.0
L21	Virgin thinlay (modified binder)	4.0	0.0	15.8
L22*	UTBWC thinlay	2.9	0.0	35.5
L23	50% RAP thinlay	5.3	0.0	50.6
L24	5% RAS thinlay	3.3	0.0	55.0
L25	HiMA thinlay	5.0	0.0	16.6

*Inbound lane only. Outbound lane was milled and inlaid with ABR thinlay in 2018.

Table 37. US-280 Cracking Performance (Age = 8 Years)

Section No.*	Description	Cracking, % Area		
		Pre-treat.	Post const.	End of Phase II
U6	Virgin thinlay	3.8	0.0	1.5
U7	Double layer micro surface (limestone)	1.6	0.0	7.2
U8	Crack sealing	12.2	0.0	3.3
U9	Micro surface with fibers	1.4	0.0	22.1
U10	HiMA micro surface	6.3	0.0	11.7
U11	Rejuvenating fog seal	0.8	0.0	13.2
U12	Conventional fog seal	2.4	0.0	10.7
U13	Control	1.1	1.1	11.0
U14	Single layer chip seal with crack sealing	10.5	0.0	8.9
U15	Scrub cape seal	4.5	0.0	8.2
U16	Single layer chip seal	3.6	0.0	15.2
U17	Control	3.8	3.8	18.1
U18	Single layer micro surface	16.1	0.0	27.0
U19	Control	5.4	5.4	18.9
U20	Control	7.9	7.9	22.6
U21	Scrub cape seal	13.0	0.0	26.1
U22	Single layer micro surface with crack sealing	9.4	0.0	34.4
U23	Cape seal	1.2	0.0	19.3
U24	Fibermat® cape seal	0.6	0.0	29.4
U25	Fibermat® chip seal	2.2	0.0	4.4
U26	Triple layer chip seal	0.4	0.0	5.6
U27	Double layer chip seal	3.6	0.0	1.4
U28	Double layer micro surface (sandstone)	7.4	0.0	1.5
U29	Control	1.6	1.6	0.5
U30	Mill & OGFC thinlay (CBC-1H spray paver)	1.2	0.0	25.6
U31	Mill & OGFC thinlay (NTSS-1HM)	5.7	0.0	19.8
U32	Mill & OGFC thinlay (PG 67-22)	1.2	0.0	9.4
U33	Mill & OGFC thinlay (NT-HAP)	9.3	0.0	7.3
U34	Mill & OGFC thinlay (CBC-1H conventional)	4.4	0.0	2.7
U35	Mill & ABR thinlay over scrub seal	14.6	0.0	20.7
U36	Mill & ABR thinlay over Fibermat® chip seal	14.2	0.0	24.7
U37	Mill & ABR thinlay over chip seal	2.6	0.0	25.0
U38	Mill & micro surface over ABR thinlay	1.9	0.0	19.4
U39	Mill & ABR thinlay	7.4	0.0	16.4
U40	ABR thinlay over foamed CCPR	2.5	0.0	8.7
U41	ABR thinlay over emulsion CCPR	4.0	0.0	2.8
U42	Untreated – traffic loop	1.7	0.0	5.9
U43	ABR thinlay over emulsion CIR	2.5	0.0	2.4
U44	ABR thinlay over foamed CIR	2.8	0.0	5.8
U45	Mill & UTBWC thinlay	3.7	0.0	0.4
U46	Control	2.9	2.9	4.3

* Sections U1 – U5 are “Unassigned” and may be available for future treatments.

Table 38. CSAH-8 Cracking Performance (Age = 7 Years)

Section No.	Description	Cracking, % Area		
		Pre-treat.	Post const.	End of Phase II
8001	Crack sealing / transverse mastic	2.5	0.0	9.4
8002	Chip seal with crack sealing / transverse mastic	1.9	0.0	4.8
8003	Single layer chip seal	7.4	0.0	7.6
8004	Cape seal (micro on chip seal)	4.5	0.0	10.0
8005	Double layer chip seal	2.8	0.0	1.6
8006	Triple layer chip seal	1.7	0.0	1.5
8007	Fibermat® chip seal	3.6	0.0	2.9
8008	Fibermat® cape seal	3.5	0.0	2.8
8009	Scrub cape seal	2.5	0.0	6.0
8010	Scrub seal	4.0	0.0	10.0
8011	Micro surface with crack sealing / transverse mastic	5.6	0.0	30.0
8012	Single layer micro surface	3.6	0.0	17.3
8013	Double layer micro surface	3.8	0.0	10.4
8014	Conventional fog seal	3.9	3.9	17.4
8015	Rejuvenating fog seal	7.6	8.0	27.5
8016	Mill & ABR thinlay over Fibermat® chip seal	4.2	0.0	8.9
8017	Mill & ABR thinlay over scrub seal	5.2	0.0	7.9
8018	Mill & ABR thinlay over chip seal	3.8	0.0	8.1
8019	Control	4.0	5.8	17.4
8020	Control	5.0	6.1	11.9
8021	Control	4.5	6.1	13.1
8022	Control	2.9	3.0	13.2
8023	Mill & virgin thinlay	4.3	0.0	3.7
8024	Mill & ABR thinlay	2.0	0.0	2.3
8025	Control	2.3	3.4	10.7
8026	Control	1.2	1.5	10.0
8027	Control	2.7	3.4	9.4
8028	Mill & UTBWC thinlay	1.7	0.0	5.9
8029	Mill & ABR thinlay with rejuvenator	1.4	0.0	11.1
8030	Control	3.0	4.3	13.7

Table 39. US-169 Cracking Performance (Age = 7 Years)

Section No.	Description	Cracking, % Area		
		Pre-treat.	Post const.	End of Phase II
169000	Control	30.2	30.2	35.3
169001	Crack sealing / longitudinal mastic	3.6	0.0	41.0
169002	Chip seal with crack sealing / longitudinal mastic	2.9	0.0	4.7
169003	Single layer chip seal	3.2	0.0	6.6
169004	Double layer chip seal	3.2	0.0	5.6
169005	Triple layer chip seal	3.1	0.0	3.5
169006	Cape seal	4.7	0.0	20.4
169007	Micro surface with crack sealing / longitudinal mastic	3.2	0.0	40.1
169008	Micro surface with fibers	2.6	0.0	20.8
169009	Double layer micro surface	2.1	0.0	27.7
169010	Fibermat® chip seal	2.8	0.0	3.5
169011	Fibermat® cape seal	2.8	0.0	5.5
169012	Scrub cape seal	2.9	0.0	5.7
169013	Scrub seal	2.8	0.0	3.9
169014	Control	17.0	17.0	32.2
169015*	Control	15.1	15.1	NA
169016*	Control	13.1	13.1	NA
169017	Rejuvenating fog seal	4.6	12.5	36.0
169018	Control	10.6	10.6	13.8
169019	Conventional fog seal	3.5	9.9	10.6
169020	Control	7.9	7.9	4.4
169021	Control	5.7	5.7	5.5
169022	Mill & ABR thinlay with rejuvenator	4.1	0.0	18.2
169023	Mill & virgin thinlay	2.6	0.0	3.2
169024	Mill & UTBWC thinlay	3.1	0.0	3.6
169025	Mill & HiMA thinlay	5.4	0.0	25.4
169026	Mill & ABR thinlay	2.6	0.0	13.2
169027	Mill & ABR thinlay over chip seal	3.9	0.0	15.0
169028	Control	10.9	10.9	13.4

*Sections were resurfaced in September of 2020 due to the deteriorated condition of the pavement and were out of study by the end of Phase II

Table 40. 70th Street Cracking Performance (Age = 4 Years)

Section No.	Description	Cracking, % Area		
		Pre-treat.	Post const.	End of Phase II
7001	ABR thinlay over FDR emulsion	100	0.0	7.9
7002	ABR thinlay over FDR foam	100	0.0	9.4
7003	ABR thinlay over CIR foam	100	0.0	5.3
7004	ABR thinlay over CIR emulsion	100	0.0	2.4
7005	ABR thinlay over CCPR emulsion	100	0.0	3.3
7006	ABR thinlay over 3" mill & inlay	100	0.0	4.2
7007	ABR thinlay over CCPR foam	100	0.0	5.1
7008	ABR thinlay	100	0.0	23.5
7011	ABR thinlay	100	0.0	36.6
7012	ABR thinlay	100	0.0	30.8
7013	ABR thinlay	100	0.0	29.5
7014	ABR thinlay	100	0.0	34.8
7015	ABR thinlay	100	0.0	28.0
7016	ABR thinlay over 2" mill & inlay	100	0.0	4.0
7017	ABR thinlay over CCPR foam	100	0.0	2.0
7018	ABR thinlay	100	0.0	21.7

11.2 Rutting

Rutting levels were “good” to “fair” before treatment application and have shown little increase over time. As a result, none of the sections reached the “poor” rutting condition category. Some changes observed in

Table 41 through

Table 44 may be attributed to testing variability.

Table 41. LR-159 Rutting Performance (Age = 11 Years)

Section No.	Description	Average Rut Depth, mm		
		Pre-treat.	Post const.	End of Phase II
L1	Rejuvenating fog seal	5.0	3.5	4.6
L2	Fibermat® chip seal	4.8	3.3	4.8
L3	Control	4.7	3.4	4.9
L4	Control	4.9	3.5	5.2
L5	Crack sealing	4.3	6.2	3.8
L6	Single layer chip seal	4.1	4.7	3.3
L7	Single layer chip seal with crack sealing	4.8	5.6	4.1
L8	Triple layer chip seal	6.5	6.0	4.4
L9	Double layer chip seal	5.4	5.5	4.3
L10	Cape seal	5.3	5.3	5.5
L11	Single layer micro surfacing	5.9	6.3	6.1
L12	Single layer micro surfacing with crack sealing	6.3	7.7	6.3
L13	Double layer micro surface	6.9	7.4	7.7
L14	Fibermat® cape seal	6.0	5.9	7.5
L15	Scrub cape seal	5.1	5.1	6.1
L16	Scrub seal	5.4	4.8	5.3
L17	Fibermat® chip seal	5.2	4.7	5.2
L18	Thinlay over Fibermat® chip seal	4.3	2.0	2.9
L19	Virgin thinlay (PG 67-22)	4.8	1.4	3.2
L20	Thinlay on foamed CCPR	5.0	1.8	4.4
L21	Virgin thinlay (PG 76-22)	4.3	1.9	4.5
L22*	UTBWC thinlay	5.2	2.2	3.4
L23	50% RAP thinlay	5.0	1.4	2.4
L24	5% RAS thinlay	6.1	1.3	2.8
L25	HiMA thinlay	6.2	1.6	2.9

*Inbound lane only. Outbound lane was milled and inlaid with ABR thinlay in 2018.

Table 42. US-280 Rutting Performance (Age = 8 Years)

Section No.*	Description	Average Rut Depth, mm		
		Pre-treat.	Post const.	End of Phase II
U6	Virgin thinlay	7.2	0.8	3.4
U7	Double layer micro surface (limestone)	6.2	3.4	6.1
U8	Crack sealing	5.8	6.3	6.6
U9	Micro surface with fibers	6.2	4.7	5.3
U10	HiMA micro surface	4.0	3.9	4.0
U11	Rejuvenating fog seal	3.6	3.9	4.4
U12	Conventional fog seal	4.1	3.6	4.3
U13	Control	5.4	5.5	6.0
U14	Single layer chip seal with crack sealing	4.9	5.4	5.9
U15	Scrub cape seal	3.7	4.9	4.2
U16	Single layer chip seal	3.5	3.8	4.2
U17	Control	3.0	2.8	4.5
U18	Single layer micro surface	4.5	3.2	4.3
U19	Control	4.9	4.9	5.3
U20	Control	4.1	3.9	5.2
U21	Scrub cape seal	3.6	4.1	5.2
U22	Single layer micro surface with crack sealing	3.7	3.3	4.1
U23	Cape seal	3.3	4.1	4.4
U24	Fibermat® cape seal	3.7	3.0	3.7
U25	Fibermat® chip seal	4.4	3.4	3.3
U26	Triple layer chip seal	4.1	3.9	3.1
U27	Double layer chip seal	3.3	2.9	2.3
U28	Double layer micro surface (sandstone)	3.4	2.5	2.7
U29	Control	2.6	2.1	3.5
U30	Mill & OGFC thinlay (CBC-1H spray paver)	3.7	1.9	2.8
U31	Mill & OGFC thinlay (NTSS-1HM)	3.8	1.9	2.5
U32	Mill & OGFC thinlay (PG 67-22)	3.4	2.0	2.6
U33	Mill & OGFC thinlay (NT-HAP)	2.6	2.1	2.5
U34	Mill & OGFC thinlay (CBC-1H conventional)	3.2	1.9	2.4
U35	Mill & ABR thinlay over scrub seal	1.7	1.1	2.3
U36	Mill & ABR thinlay over Fibermat® chip seal	2.4	1.3	3.2
U37	Mill & ABR thinlay over chip seal	3.3	1.4	2.5
U38	Mill & micro surface over ABR thinlay	3.1	1.5	1.7
U39	Mill & ABR thinlay	2.9	0.9	2.4
U40	ABR thinlay over foamed CCPR	3.3	1.1	5.7
U41	ABR thinlay over emulsion CCPR	2.7	1.1	4.2
U42	Untreated – traffic Loop	3.5	3.6	4.2
U43	ABR thinlay over emulsion CIR	2.7	1.1	5.1
U44	ABR thinlay over foamed CIR	3.3	1.3	5.1
U45	Mill & UTBWC thinlay	3.0	1.5	3.5
U46	Control	3.7	11.2	4.9

* Sections U1 – U5 are "Unassigned" and may be available for future treatments.

Table 43. CSAH-8 Rutting Performance (Age = 7 Years)

Section No.	Description	Average Rut Depth, mm		
		Pre-treat.	Post const.	End of Phase II
8001	Crack sealing / transverse mastic	3.1	1.8	2.5
8002	Chip seal with crack sealing / transverse mastic	3.3	1.4	1.9
8003	Single layer chip seal	3.2	1.5	2.3
8004	Cape seal (micro on chip seal)	3.2	1.7	1.4
8005	Double layer chip seal	3.0	1.7	2.2
8006	Triple layer chip seal	2.9	1.3	1.3
8007	Fibermat® chip seal	3.1	1.5	1.7
8008	Fibermat® cape seal	1.7	1.4	0.9
8009	Scrub cape seal	2.3	1.7	1.4
8010	Scrub seal	2.8	1.9	2.0
8011	Micro surface with crack sealing / transverse mastic	2.8	3.0	2.8
8012	Single layer micro surface	3.4	2.3	2.6
8013	Double layer micro surface	3.7	2.8	2.6
8014	Conventional fog seal	2.8	1.9	3.7
8015	Rejuvenating fog seal	4.1	3.0	6.3
8016	Mill & ABR thinlay over Fibermat® chip seal	3.4	0.5	2.4
8017	Mill & ABR thinlay over scrub seal	3.6	0.8	2.2
8018	Mill & ABR thinlay over chip seal	2.8	0.6	2.1
8019	Control	3.4	1.6	3.2
8020	Control	2.7	1.2	2.3
8021	Control	3.5	2.2	3.3
8022	Control	2.3	1.8	2.7
8023	Mill & virgin thinlay	1.9	0.6	1.9
8024	Mill & ABR thinlay	2.2	0.6	1.9
8025	Control	1.4	0.6	1.6
8026	Control	2.1	1.2	2.2
8027	Control	2.3	1.6	2.7
8028	Mill & UTBWC thinlay	2.7	1.2	2.4
8029	Mill & ABR thinlay with rejuvenator	2.2	0.5	1.7
8030	Control	1.9	1.5	2.3

Table 44. US-169 Rutting Performance (Age = 7 Years)

Section No.	Description	Average Rut Depth, mm		
		Pre-treat.	Post const.	End of Phase II
169000	Control	3.6	2.1	3.3
169001	Crack sealing / longitudinal mastic	3.6	3.0	3.7
169002	Chip seal with crack sealing / longitudinal mastic	3.5	2.6	2.9
169003	Single layer chip seal	3.1	2.5	2.8
169004	Double layer chip seal	1.9	1.4	1.9
169005	Triple layer chip seal	2.4	1.6	2.1
169006	Cape seal	3.6	2.3	2.2
169007	Micro surface with crack sealing / longitudinal mastic	2.9	3.2	2.7
169008	Micro surface with fibers	3.0	2.1	1.9
169009	Double layer micro surface	2.3	2.9	2.3
169010	Fibermat® chip seal	2.5	2.7	2.8
169011	Fibermat® cape seal	2.2	2.0	1.8
169012	Scrub cape seal	2.2	1.5	1.4
169013	Scrub seal	2.1	1.6	1.3
169014	Control	3.2	3.5	3.6
169015*	Control	3.4	4.3	NA
169016*	Control	3.4	3.5	NA
169017	Rejuvenating fog seal	2.9	2.8	2.4
169018	Control	3.9	2.6	3.4
169019	Conventional fog seal	4.6	3.3	4.2
169020	Control	5.2	4.3	4.9
169021	Control	4.8	3.3	3.5
169022	Mill & ABR thinlay with rejuvenator	3.9	1.3	2.7
169023	Mill & virgin thinlay	4.2	1.0	2.4
169024	Mill & UTBWC thinlay	4.2	2.4	3.0
169025	Mill & HiMA thinlay	3.7	1.9	3.7
169026	Mill & ABR thinlay	4.0	2.0	4.2
169027	Mill & ABR thinlay over chip seal	4.7	1.1	4.3
169028	Control	3.9	2.6	3.9

*Sections were resurfaced in September of 2020 due to the deteriorated condition of the pavement and were out of study by the end of Phase II

Table 45. 70th Street Rutting Performance (Age = 4 Years)

Section No.	Description	Average Rut Depth, mm		
		Pre-treat.	Post const.	End of Phase II
7001	ABR thinlay over FDR emulsion	10.5	1.6	2.1
7002	ABR thinlay over FDR foam	8.2	0.7	1.3
7003	ABR thinlay over CIR foam	10.6	1.2	3.0
7004	ABR thinlay over CIR emulsion	9.6	2.1	5.1
7005	ABR thinlay over CCPR emulsion	9.0	2.3	5.8
7006	ABR thinlay over 3" mill & inlay	10.3	1.2	3.7
7007	ABR thinlay over CCPR foam	10.1	1.1	2.2
7008	ABR thinlay	10.1	2.2	5.0
7011	ABR thinlay	7.9	1.7	5.1
7012	ABR thinlay	7.0	2.0	4.5
7013	ABR thinlay	4.7	1.4	3.4
7014	ABR thinlay	6.4	1.7	4.3
7015	ABR thinlay	5.2	1.9	4.4
7016	ABR thinlay over 2" mill & inlay	5.2	1.8	3.0
7017	ABR thinlay over CCPR foam	6.8	2.3	2.5
7018	ABR thinlay	6.8	2.3	5.2

11.3 Roughness

Roughness performance is mainly predominant in the cold climate sections, where the severity of transverse (thermal) cracking significantly affects ride quality. Similar to the cracking trends observed, roughness progression depends on the IRI of the sections at the time of treatment.

It should be noted in LR-159, additional factors influenced the roughness results. The sections in this location are shorter (100 feet), which causes any discontinuity to have a greater impact on overall roughness. Additionally, unlike the other locations where milling was performed to maintain grade, the thinlay sections toward the southern end of LR-159 were placed after brooming and tacking the existing pavement, creating a difference in elevation where the test sections transition from surface treatments to thinlays. This affects vehicle dynamics during testing, generally yielding higher IRI measurements near these sections.

Table 46. LR-159 Roughness Performance (Age = 11 Years)

Section No.	Description	IRI, in/mi		
		Pre-treat.	Post const.	End of Phase II
L1	Rejuvenating fog seal	68	82	128
L2	Fibermat® chip seal	68	72	92
L3	Control	71	68	72
L4	Control	71	74	89
L5	Crack sealing	77	86	88
L6	Single layer chip seal	55	69	72
L7	Single layer chip seal with crack sealing	61	82	87
L8	Triple layer chip seal	64	97	99
L9	Double layer chip seal	74	91	88
L10	Cape seal	60	82	81
L11	Single layer micro surfacing	112	80	89
L12	Single layer micro surfacing with crack sealing	79	75	80
L13	Double layer micro surface	78	89	101
L14	Fibermat® cape seal	85	79	94
L15	Scrub cape seal	61	66	63
L16	Scrub seal	71	75	78
L17	Fibermat® chip seal	77	100	108
L18	Thinlay over Fibermat® chip seal	82	125	116
L19	Virgin thinlay (PG 67-22)	76	64	77
L20	Thinlay on foamed CCPR	67	120	144
L21	Virgin Thinlay (PG 76-22)	83	89	113
L22*	UTBWC thinlay	52	114	141
L23	50% RAP thinlay	62	100	123
L24	5% RAS thinlay	96	100	116
L25	HiMA thinlay	174	162	208

*Inbound lane only. Outbound lane was milled and inlaid with ABR thinlay in 2018.

Table 47. US-280 Roughness Performance (Age = 8 Years)

Section No.*	Description	IRI, in/mi		
		Pre-treat.	Post const.	End of Phase II
U6	Virgin thinlay	49	54	74
U7	Double layer micro surface (limestone)	63	70	78
U8	Crack sealing	49	53	63
U9	Micro surface with fibers	53	54	53
U10	HiMA micro surface	45	53	56
U11	Rejuvenating fog seal	47	45	74
U12	Conventional fog seal	45	45	54
U13	Control	63	52	54
U14	Single layer chip seal with crack sealing	54	55	62
U15	Scrub cape seal	46	67	64
U16	Single layer chip seal	50	50	57
U17	Control	48	51	55
U18	Single layer micro surface	62	61	64
U19	Control	61	59	78
U20	Control	46	54	89
U21	Scrub cape seal	52	65	94
U22	Single layer micro surface with crack sealing	50	60	73
U23	Cape seal	42	45	63
U24	Fibermat® cape seal	46	56	52
U25	Fibermat® chip seal	45	55	61
U26	Triple layer chip seal	38	57	50
U27	Double layer chip seal	38	54	52
U28	Double layer micro surface (sandstone)	40	51	43
U29	Control	39	45	58
U30	Mill & OGFC thinlay (CBC-1H spray paver)	35	52	54
U31	Mill & OGFC thinlay (NTSS-1HM)	35	40	66
U32	Mill & OGFC thinlay (PG 67-22)	44	41	50
U33	Mill & OGFC thinlay (NT-HAP)	38	48	40
U34	Mill & OGFC thinlay (CBC-1H conventional)	42	63	81
U35	Mill & ABR thinlay over scrub seal	41	51	78
U36	Mill & ABR thinlay over Fibermat® chip seal	44	42	96
U37	Mill & ABR thinlay over chip seal	48	62	88
U38	Mill & micro surface over ABR thinlay	44	54	72
U39	Mill & ABR thinlay	46	46	79
U40	ABR thinlay over foamed CCPR	45	63	121
U41	ABR thinlay over emulsion CCPR	42	54	76
U42	Untreated – traffic loop	45	55	62
U43	ABR thinlay over emulsion CIR	37	78	93
U44	ABR thinlay over foamed CIR	39	65	129
U45	Mill & UTBWC thinlay	45	45	72
U46	Control	31	36	43

* Sections U1 – U5 are "Unassigned" and may be available for future treatments.

Table 48. CSAH-8 Roughness Performance (Age = 7 Years)

Section No.	Description	IRI, in/mi		
		Pre-treat.	Post const.	End of Phase II
8001	Crack sealing / transverse mastic	107	81	120
8002	Chip seal with crack sealing / transverse mastic	122	101	134
8003	Single layer chip seal	104	106	118
8004	Cape seal (micro on chip seal)	100	92	117
8005	Double layer chip seal	93	94	107
8006	Triple layer chip seal	95	96	95
8007	Fibermat® chip seal	101	107	111
8008	Fibermat® cape seal	87	102	103
8009	Scrub cape seal	80	90	108
8010	Scrub seal	97	97	103
8011	Micro surface with crack sealing / transverse mastic	111	96	110
8012	Single layer micro surface	115	88	111
8013	Double layer micro surface	128	99	112
8014	Conventional fog seal	121	116	133
8015	Rejuvenating fog seal	166	160	199
8016	Mill & ABR thinlay over Fibermat® chip seal	148	80	125
8017	Mill & ABR thinlay over scrub seal	101	56	91
8018	Mill & ABR thinlay over chip seal	106	83	104
8019	Control	108	95	110
8020	Control	90	80	91
8021	Control	114	111	126
8022	Control	100	98	96
8023	Mill & virgin thinlay	89	37	63
8024	Mill & ABR thinlay	89	32	48
8025	Control	124	116	115
8026	Control	88	84	83
8027	Control	106	96	97
8028	Mill & UTBWC thinlay	144	60	76
8029	Mill & ABR thinlay with rejuvenator	122	51	74
8030	Control	83	84	94

Table 49. US-169 Roughness Performance (Age = 7 Years)

Section No.	Description	IRI, in/mi		
		Pre-treat.	Post const.	End of Phase II
169000	Control	88	86	115
169001	Crack sealing / longitudinal mastic	76	73	117
169002	Chip seal with crack sealing / longitudinal mastic	75	67	95
169003	Single layer chip seal	68	67	96
169004	Double layer chip seal	81	78	112
169005	Triple layer chip seal	78	81	105
169006	Cape seal	77	70	98
169007	Micro surface with crack sealing / longitudinal mastic	68	57	99
169008	Micro surface with fibers	72	54	83
169009	Double layer micro surface	76	69	87
169010	Fibermat® chip seal	76	80	95
169011	Fibermat® cape seal	75	67	83
169012	Scrub cape seal	76	64	82
169013	Scrub seal	72	70	87
169014	Control	74	73	102
169015*	Control	90	85	NA
169016*	Control	74	68	NA
169017	Rejuvenating fog seal	74	66	103
169018	Control	82	79	101
169019	Conventional fog seal	65	64	79
169020	Control	70	66	84
169021	Control	84	80	112
169022	Mill & ABR thinlay with rejuvenator	80	40	49
169023	Mill & virgin thinlay	67	28	43
169024	Mill & UTBWC thinlay	65	31	44
169025	Mill & HiMA thinlay	64	62	74
169026	Mill & ABR thinlay	61	61	62
169027	Mill & ABR thinlay over chip seal	65	59	71
169028	Control	72	79	95

*Sections were resurfaced in September of 2020 due to the deteriorated condition of the pavement and were out of study by the end of Phase II

Table 50. 70th Street Roughness Performance (Age = 4 Years)

Section No.	Description	IRI, in/mi		
		Pre-treat.	Post const.	End of Phase II
7001	ABR thinlay over FDR emulsion	317	76	90
7002	ABR thinlay over FDR foam	385	67	127
7003	ABR thinlay over CIR foam	377	68	91
7004	ABR thinlay over CIR emulsion	396	69	78
7005	ABR thinlay over CCPR emulsion	376	74	82
7006	ABR thinlay over 3" mill & inlay	418	49	55
7007	ABR thinlay over CCPR foam	429	61	75
7008	ABR thinlay	429	89	122
7011	ABR thinlay	319	82	128
7012	ABR thinlay	307	76	105
7013	ABR thinlay	274	65	77
7014	ABR thinlay	335	78	95
7015	ABR thinlay	298	72	98
7016	ABR thinlay over 2" mill & inlay	294	42	55
7017	ABR thinlay over CCPR foam	384	64	69
7018	ABR thinlay	384	90	108

11.4 Overall Performance

At the end of Phase II, most of the sections remained in "good" to "fair" condition according to the MAP-21 performance criteria. Figure 53 shows the condition distribution of the total number of sections at the end of the study. Cracking is the main form of deterioration, with most sections in "fair" to "poor" condition. Roughness is also a relevant performance indicator, particularly in the cold climate sections. Rutting levels were low before treatment and remained in "good" to "fair" condition throughout the study.

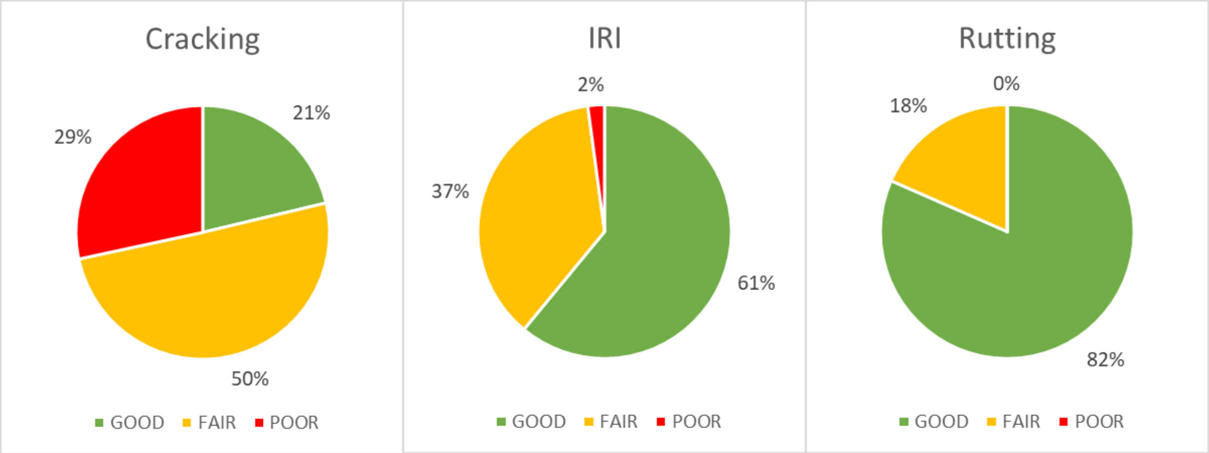


Figure 53. Percentage of sections in each condition category by performance measure.

When looking at the MAP-21 overall condition assessment, most sections ended Phase II in "fair" condition, as shown in Figure 54. However, due to the broad criteria used for the overall condition assessment, there are significant differences in performance among sections classified as "fair". The control sections, which account for approximately 22% of the total, exhibited faster deterioration rates compared to the treated sections in similar pre-treatment condition. The following chapter discusses how this information is used to determine the benefits of the various pavement preservation treatments.

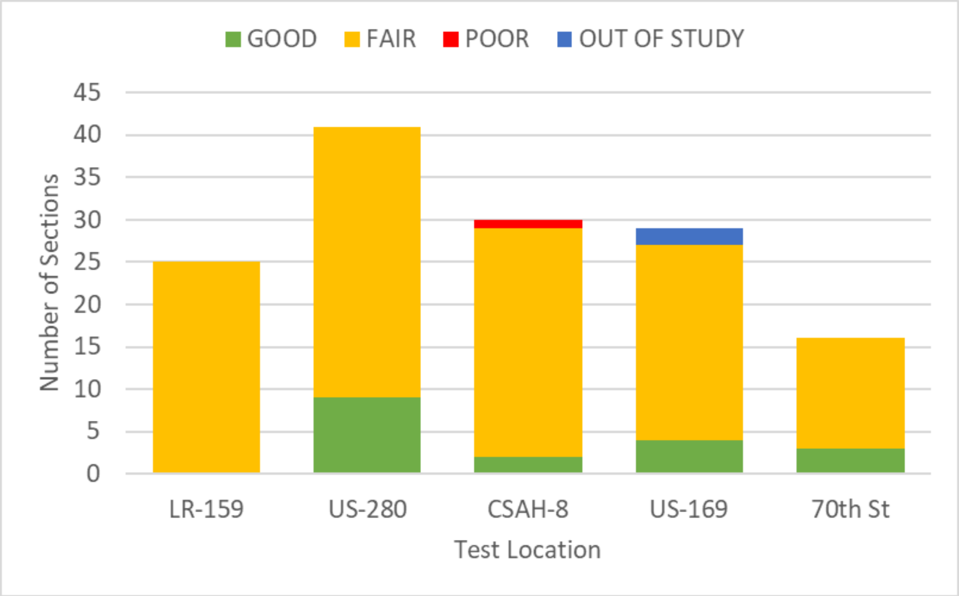


Figure 54. Overall pavement condition of the test sections by the end of Phase II.

12. QUANTIFICATION OF BENEFITS

The approach followed for quantifying life-extending and condition-improving benefits uses field performance data to develop deterioration curves for treated and untreated sections in similar initial condition and comparing them to calculate the differences. After analyzing the trends from Phases I and II, cracking and roughness are considered the predominant performance indicators.

12.1 Cracking

To account for the effect of the existing pavement condition, test sections were divided into smaller subsections of varying sizes depending on treatment location. Prior to treatment application, cracking was measured in every test section, and each subsection was classified as "good", "fair", or "poor" according to the MAP-21 criteria, generating a set of performance curves based on pre-treatment condition. For LR-159, where conditions varied significantly (mainly due to the difference in loading between the two lanes), this approach resulted in three performance curves for almost every treatment. The test sections were more uniform in the other locations, and only one or two curves could be generated.

In general, the deterioration curves obtained from the subsection process show that deterioration accelerates as the pre-treatment condition worsens, as illustrated in the example in Figure 55, reinforcing the preservation philosophy of keeping good roads good with minimal investments.

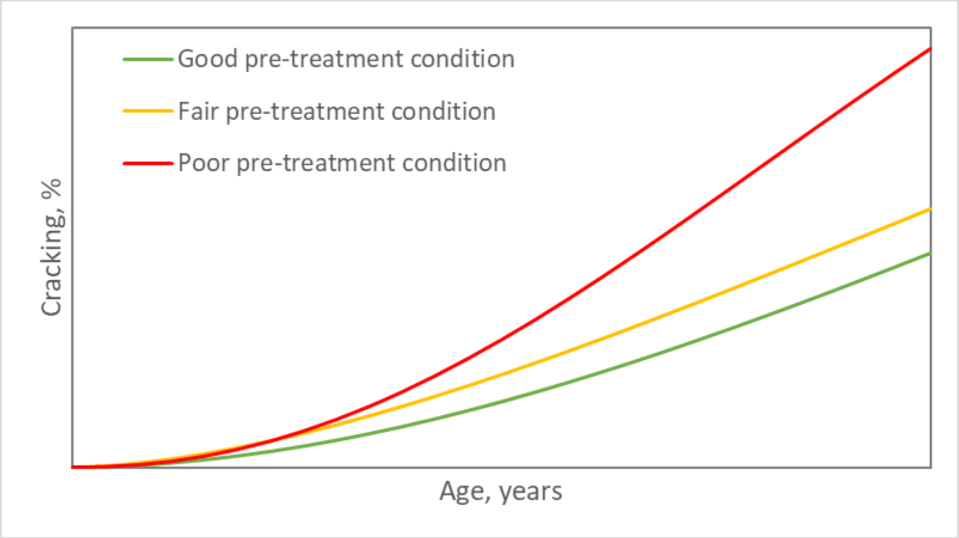


Figure 55. Example of deterioration curves based on pre-treatment condition.

Cracking trends over time can be described using a sigmoidal model that results in an s-shaped curve using an equation of the form:

$$Cracking = \left(1 - e^{\left(-at^{b}\right)}\right) \times 100 \tag{1}$$

Where *t* is the time since treatment application in years, and *a* and *b* are regression coefficients.

The life-extending benefit in years is quantified by estimating the time needed for both curves to reach the "poor" condition threshold (20%) and obtaining the difference, as seen in Figure 56. In addition, the condition-improving benefit is calculated by obtaining the difference in cracking between the two curves at any time. Alternatively, an average benefit can be calculated for a given time period.

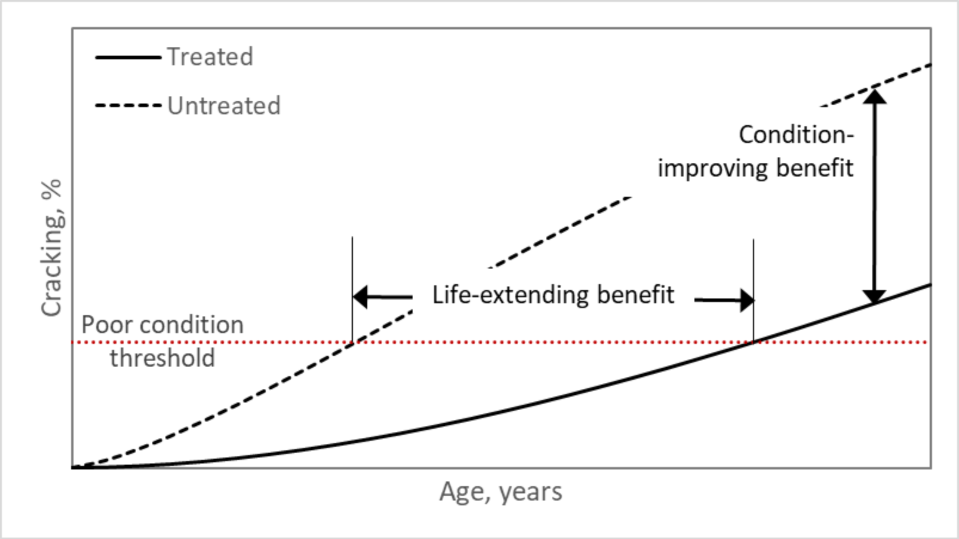


Figure 56. Schematic of benefit calculation based on cracking performance.

12.2 Roughness

The benefits in terms of roughness are calculated using the same approach as for cracking. The subsections were not used to generate datasets based on pre-treatment condition for this indicator, since roughness was fairly uniform throughout the sections. The existing pavement condition was still accounted for in the development of the deterioration curves by following an exponential trend of the form:

$$IRI_t = IRI_0 e^{\beta t} \tag{2}$$

Where IRI_t is the estimated IRI at time t, IRI_0 is the IRI at time $t = 0$, t is the time in years, and β is a regression parameter representing the deterioration rate of the IRI curve.

The treated and untreated performance curves are compared similarly to determine the life-extending and condition-improving benefits. In addition, the performance jump (PJ) shown in Figure 57 is defined as the difference between IRI measured before the treatment application (IRI_{pre}) and IRI measured after construction (IRI_{post}). This is used to assess the treatment's immediate effect on ride quality.

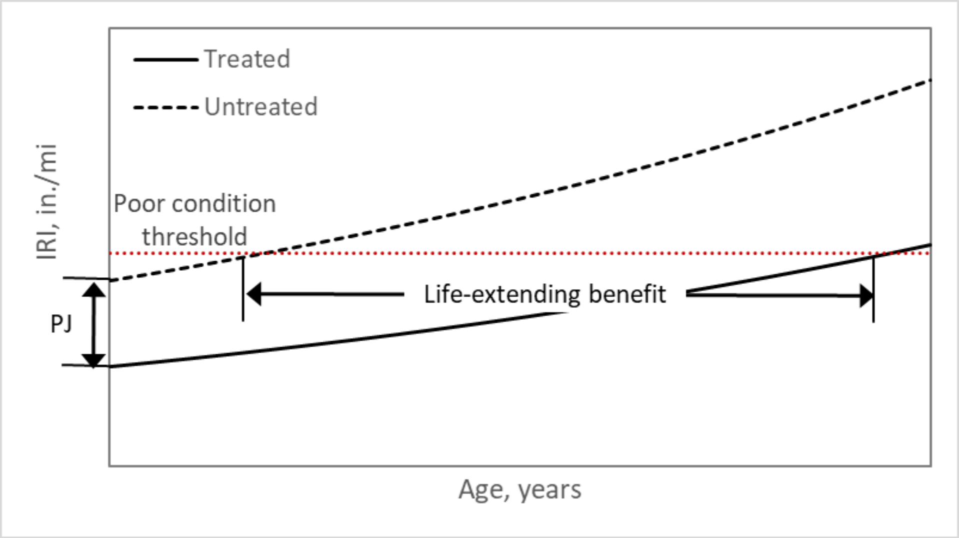


Figure 57. Schematic of benefit calculation based on roughness performance.

12.3 Tools for Implementation

As discussed in Chapter 11, most sections have not reached the “poor” condition thresholds for these indicators. In some cases, it is possible to extrapolate beyond the study period to estimate the service life of the treatments (i.e., time to “poor” condition). Still, for most, extrapolation leads to unreliable results. If the deterioration rate is slow, the model resembles a horizontal line that does not reach the threshold within a reasonable time. Distresses could develop earlier and accelerate pavement deterioration, and therefore, far extrapolation is not recommended.

From the results obtained throughout Phases I and II, it is possible to observe the condition-improving benefits of the treatments and use that information, along with an agency-specific cost analysis, as a basis for treatment selection. To facilitate access to the study results, an online tool was developed for the visualization of performance data. The interface allows the user to navigate through several menus to select the location, treatment type, and pre-treatment condition of interest and displays the current condition of the section (including a recent photograph) and available deterioration curves. Figure 58 shows an example of the interface layout. This tool is available at aub.ie/PG-tool and continues to be developed to update content and improve the user experience. A user manual is also available on the website.

Figure 58. Online tool screenshot.

In addition, NCAT and MnROAD conducted a series of webinars between July 2022 and October 2023 to discuss the study results in depth. This emerged as an alternative to Task 4 (2020 Peer Exchange), which could not be conducted due to the COVID-19 pandemic. Each 2-hour webinar focused on a different treatment category (divided as in this report), covering construction, performance, key findings, and open discussion. The webinar recordings are available at aub.ie/PG-webinars. Numerous journal and conference papers addressing specific subjects of the research were also published during this study. A complete list of publications is available at aub.ie/PG-publications.

13. FINAL REMARKS

The Pavement Preservation Group Study is a unique research project that allowed for the collection and analysis of long-term field data under highly controlled procedures. The partnership between NCAT and MnROAD took the original Phase I effort to a new level by expanding the scope of work and gathering support from nearly half of the State DOTs in the United States. Industry involvement was critical to the project's success, giving various stakeholders a voice and helping all work toward a common goal.

With the conclusion of Phase II, it is clear pavement preservation can significantly extend pavement life. However, the benefits depend on variables such as climate, traffic, and existing pavement condition. This research used a consistent method to account for these variables and provide agencies with a quantification of benefits based on consistent field performance data rather than anecdotal information.

It is important to note that engineering judgment is necessary to put these research findings into practice. As discussed throughout this report, the preservation treatment categories are different in nature and not necessarily applicable in all situations. Relevant parameters should considered during treatment selection.

This research effort spanned more than a decade of continuous data collection and analysis, as well as outreach, and continues to generate value for the agencies and organizations involved. Future efforts will continue to monitor and analyze existing test sections and assist sponsoring states in adopting and enhancing their pavement preservation techniques.

Transportation Pooled Fund TPF-5(522) *National Partnership to Improve the Quality of Pavement Preservation Treatment Construction & Data Collection Practices* will add a third phase to the PG Study with a strong focus on implementation. Phase III is scheduled from 2024 to 2028 under MnDOT's leadership with technical expertise from NCAT, the National Center for Pavement Preservation (NCPP), and FP2, Inc. to assist sponsoring agencies in the selection, design, construction, and monitoring of pavement preservation projects that will also improve the products developed during Phases I and II.

REFERENCES

1. Waidelich, W. *Guidance on Highway Preservation and Maintenance Memorandum*. Federal Highway Administration, February 25, 2016. https://www.fhwa.dot.gov/preservation/memos/160225.pdf
2. Hicks, R. G., and M. Stroup-Gardiner. *Economic Benefits of Pavement Preservation Applied to Flexible Pavements*. CP2C 20-7-1006, CP2 Center, 2008.
3. Lee County Highway System Index. May 29, 2012. http://www.leeco.us/business/highway/docs/FY_11_12_Highway_System_Index_for_Website.pdf. Accessed 3/14/2017.
4. Alabama Traffic Data. https://aldotgis.dot.state.al.us/atd/default.aspx. Accessed Jul.12, 2019.
5. Chatti, K., N. Buch, S. W. Haider, A. S. Pulipaka, R. W. Lyles, D. Gilliland, and P. Desaraju. *LTPP Data Analysis: Influence of Design and Construction Features on the Response and Performance of New Flexible and Rigid Pavements*. Final report, NCHRP Project 20-50, 2005.
6. National Performance Management Measures; Assessing Pavement Condition for the National Highway Performance Program and Bridge Condition for the National Highway Performance Program. *Federal Register*, 82(11), Federal Highway Administration, 2017.
7. Recommended Performance Guidelines, 3rd ed. Asphalt Emulsion Manufacturers Association (AEMA), Annapolis, Md., 2004.
8. Shoenberger, J. E. *Rejuvenators, Rejuvenator/Sealers, and Seal Coats for Airfield Pavements*. U. S. Army Engineer Research and Development Center, Vicksburg, Miss., 2003. https://apps.dtic.mil/sti/pdfs/ADA412361.pdf.
9. Steven, B., C. L. Monismith, and B. W. Tsai. *Friction Testing of Pavement Preservation Treatments: Friction Measurements on Fog Seal Trials Using Six Rejuvenators, State Route KER58*. Technical Memorandum UCPRC-TM-2008-06, University of California Pavement Research Center, Davis and Berkeley, 2009.
10. Li, S., S. Noureldin, Y. Jiang, and Y. Sun. *Evaluation of Pavement Surface Friction Treatments.* No. FHWA/IN/JTRP-2012/04, Purdue University, Joint Transportation Research Program, 2011.
11. Islam, R. M., S. Arafat, and N. M. Wasiuddin. Quantification of Reduction in Hydraulic Conductivity and Skid Resistance Caused by Fog Seal in Low-Volume Roads. *Transportation Research Record: Journal of the Transportation Research Board*, 2657(1), 2017, pp. 99-108.
12. Kebede, A. A. *Asphalt Pavement Preservation using Rejuvenating Fog Seals.* PhD dissertation. Purdue University, 2016.
13. Taghavi, M., S. Hesami, E. Hesami, and S. Mohammadirad. Laboratory Study to Evaluate the In-Situ Use of Rejuvenator Seal Material to Restore In-Service Asphalt Pavement. *Journal of Materials in Civil Engineering*, 34(10), 2022.
14. MTAG Volume I Flexible Pavement Preservation, 2nd ed. Caltrans Division of Maintenance, 2010.
15. McLeod, N. W. A General Method of Design for Seal Coats and Surface Treatments. *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 38, 1969, pp. 537-628.
16. Chipsealing in New Zealand. Transit New Zealand, 2005.

17. Preservation Toolbox. For Pavement Preservation (FP^2) Inc. http://www.fp2.org/preservation-toolbox/. Accessed Nov. 7, 2016.
18. Recommended Performance Guideline for Micro Surfacing. ISSA A143, International Slurry Surfacing Association, Annapolis, Md., 2010.
19. Brown, E. R., and S. Mager. *Asphalt Content by Ignition Round Robin Study*. NCAT Report 95-3, National Center for Asphalt Technology at Auburn University, 1995.
20. Newcomb, D. E. *Thin Asphalt Overlays for Pavement Preservation*. Information Series 135, National Asphalt Pavement Association, 2009.
21. Watson, D. E., and M. Heitzman. *NCHRP Synthesis 464: Thin Asphalt Concrete Overlays*, Transportation Research Board, Washington, D.C., 2014.
22. Watson, D. E., A. K. Moore, K. Williams, and L. A. Cooley. Refinement of New-Generation Open-Graded Friction Course Mix Design. *Transportation Research Record: Journal of the Transportation Research Board*, 1832(1), 2003, pp. 78–85.
23. Corley-Lay, J. B., and J. N. Mastin. Ultrathin Bonded Wearing Course as Pavement Preservation Treatment for Jointed Concrete Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, 2007, pp. 11-17.
24. Bureau of Local Roads and Streets Manual. Illinois Department of Transportation, Springfield, Ill., 2018.
25. Wilson, B., S. Banihashemrad, and M. Sakhaeifar. *Comparative Analysis of Tack Coats, Spray Paver Membranes, and Underseals: Technical Report*. Report No. FHWA/TX-18/0-6908-R1, Texas A&M Transportation Institute, 2018.
26. Cooper, S. B., and L. N. Mohammad. *NovaChip™ Surface Treatment Six Year Evaluation*. Technical Assistance Report No. 407-04-0034, Louisiana Transportation Research Center, 2004.
27. Kuennen, T. Asphalt Emulsion Bond Coats Optimize UTBO, Thinlay Performance*. Pavement Preservation Journal*, Fall 2017.
28. MnROAD Test Sections - Low Volume Road. Minnesota Department of Transportation. https://www.dot.state.mn.us/mnroad/test-cells/lowvolume.html. Accessed Apr. 17, 2024.
29. Alvarez, A. E., A. E. Martin, C. K. Estakhri, J. W. Button, C. J. Glover, and S. H. Jung. *Synthesis of Current Practice on the Design, Construction, and Maintenance of Porous Friction Courses.* Texas Transportation Institute, 2006.
30. Chen, J., H. Li, X. Huang, and J. Wu. Permeability Loss of Open-Graded Friction Course Mixtures due to Deformation-Related and Particle-Related Clogging: Understanding from a Laboratory Investigation. *Journal of Materials in Civil Engineering*, *27*(11), 2015.
31. Chen, J., J. Li, H. Wang, W. Huang, W. Sun, and T. Xu. Preparation and Effectiveness of Composite Phase Change Material for Performance Improvement of Open Graded Friction Course. *Journal of Cleaner Production*, 214, 2019, pp. 259-269.
32. Yang, Z. Freezing-and-Thawing Durability of Pervious Concrete Under Simulated Field Conditions. *Materials Journal*, *108*(2), 2011, pp. 187-195.
33. Kandhal, P. S., and R. B. Mallick. *Open Graded Friction Course: State of the Practice*. Transportation Research Circular E-C005, Transportation Research Board, National Research Council, Washington, D.C., 1998.

34. Bowers, B. F., B. K. Diefenderfer, S. A. Cross., A. Vargas, and F. Gu. *Construction Guidelines for Cold Central Plant Recycling and Cold In-Place Recycling.* NCHRP Project 14-43, 2023.
35. Recommended Mix Design Guidelines for Cold Recycling Using Emulsified Asphalt Recycling Agent. Asphalt Recycling & Reclaiming Association, Glen Ellyn, Il., 2023.
36. Recommended Mix Design Guidelines for Full Depth Reclamation (FDR) Using Emulsified Asphalt Stabilizing Agent. Asphalt Recycling & Reclaiming Association, Glen Ellyn, Il., 2023.
37. Recommended Mix Design Guidelines for Cold Recycling Using Foamed (Expanded) Asphalt Recycling Agent. Asphalt Recycling & Reclaiming Association, Glen Ellyn, Il., 2023.

APPENDIX A

Table A-1. Summary of Treatments by Location

Treatment	Location				
	LR-159	US-280	CSAH-8	US-169	70th St
Crack sealing	✓	✓	✓	✓	NA
Crack sealing + chip seal	✓	✓	✓	✓	NA
Crack sealing + micro surfacing	✓	✓	✓	✓	NA
Conventional fog seal	NA	✓	✓	✓	NA
Rejuvenating fog seal	✓	✓	✓	✓	NA
Single layer chip seal	✓	✓	✓	✓	NA
Double layer chip seal	✓	✓	✓	✓	NA
Triple layer chip seal	✓	✓	✓	✓	NA
Fibermat® chip seal	✓	✓	✓	✓	NA
Scrub seal	✓	NA	✓	✓	NA
Single layer micro surface	✓	✓	✓	NA	NA
Double layer micro surface	✓	✓	✓	✓	NA
Micro surface with fibers	NA	✓	NA	✓	NA
High polymer-modified (HiMA) micro surface	NA	✓	NA	NA	NA
Virgin thinlay with neat binder	✓	NA	NA	NA	NA
Virgin thinlay with polymer-modified binder	✓	✓	✓	✓	NA
Virgin thinlay with high polymer-modified (HiMA) binder	✓	NA	NA	NA	NA
50% RAP thinlay	✓	NA	NA	NA	NA
5% RAS thinlay	✓	NA	NA	NA	NA
Asphalt binder replacement (ABR) thinlay	NA	✓	✓	✓	✓
Asphalt binder replacement (ABR) thinlay with rejuvenator	NA	NA	✓	✓	NA
ABR thinlay with high polymer-modified (HiMA) binder	NA	NA	NA	✓	NA
UTBWC thinlay	✓	✓	✓	✓	NA
OGFC thinlay	NA	✓	NA	NA	NA
Micro surface over chip seal (cape seal)	✓	✓	✓	✓	NA
Micro surface over Fibermat® chip seal (Fibermat® cape seal)	✓	✓	✓	✓	NA
Micro surface over scrub seal (scrub cape seal)	✓	✓	✓	✓	NA
Thinlay over chip seal	NA	✓	✓	✓	NA
Thinlay over Fibermat® chip seal	✓	✓	✓	NA	NA
Thinlay over scrub seal	NA	✓	✓	NA	NA
Micro surface over thinlay	NA	✓	NA	NA	NA
Cold central plant recycling (CCPR)	✓	✓	NA	NA	✓
Cold in-place recycling (CIR)	NA	✓	NA	NA	✓
Full depth reclamation (FDR)	NA	NA	NA	NA	✓

NA: Not available at this location