

Long-Term Field Performance Evaluation of Chip Seals

by

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Chip seal, Pavement preservation, Treatment timing, Recovered asphalt binder, Long-term
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Abstract

Chip seals are widely used to preserve asphalt pavements by reducing moisture intrusion, limiting environmental exposure, and slowing surface deterioration. However, the long-term effect of application timing remains difficult to isolate because pavement condition, materials, traffic, construction, and maintenance history also influence treatment performance. This study evaluated associations between chip seal application timing, long-term field condition, and recovered binder properties at test sites maintained by agencies in Cass County, Crow Wing County, and the City of St. Cloud, Minnesota, USA. At each site, five pavement sections were chip sealed in successive years from 2015 through 2019, while one section remained untreated as a control. Field performance was evaluated using directional International Roughness Index measurements, transverse crack counts, and surface ratings. Binders recovered from upper and underlying portions of pavement cores were characterized using Fourier transform infrared spectroscopy, rotational viscosity, continuous performance grading, bending beam rheometer testing, ΔT_c , multiple stress creep recovery, linear amplitude sweep, Glover-Rowe analysis, and binder bond strength testing. Treatment effects were interpreted primarily by comparing the underlying binder from each treated section with the corresponding bottom-layer control within the same agency. Field and laboratory results were compared descriptively at the section level. Field-performance measures did not produce a uniform treatment-year sequence. Roughness and cracking varied by agency and travel direction, while St. Cloud surface ratings remained within a narrow range. The strongest evidence of an early-treatment benefit occurred at Cass County, where Section 1 exhibited more favorable bottom-layer low-temperature grade, ΔT_c , Glover-Rowe, and combined LAS

responses than the control. Crow Wing County and St. Cloud showed broader treated-versus-control differences in selected binder properties, but these differences were not consistently ordered by application year. The findings indicate that timely chip sealing can preserve the underlying asphalt binder. The magnitude and timing of this benefit were site specific, and the study did not establish a universal application year or condition threshold. Agencies should select chip seal timing using an early, condition-based preservation window supported by multiple field indicators, material characteristics, and documented maintenance history.

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Table of Contents

Abstract.....	2
Artificial Intelligence (AI) Use Disclosure Statement	4
Digital Accessibility Statement.....	5
Acknowledgments.....	6
Table of Contents.....	7
List of Tables	13
List of Figures	14
List of Abbreviations	17
Chapter 1 Introduction	20
1.1 Background	20
1.2 Objectives.....	23
1.3 Scope of Work.....	24
1.4 Thesis Organization.....	24
Chapter 2 Literature Review	26
2.1 Introduction	26
2.2 Pavement Preservation and Treatment Timing.....	28
2.2.1 Concepts and Timing of Pavement Preservation.....	28

2.2.2 Cost-Effectiveness of Preservation Treatments	31
2.2.3 Chip Seals in Pavement Preservation and Candidate Selection	33
2.3 Chip Seal Systems: Materials, Design, Construction, and Performance.....	35
2.3.1 Chip Seal Configuration and Development of Current Practice	36
2.3.2 Chip Seal Materials	37
2.3.3 Design, Construction, and Early-Age Performance	39
2.3.4 Factors Influencing Long-Term Chip Seal Performance.....	42
2.4 Pavement Performance Measurement and Long-Term Condition Evaluation	45
2.4.1 Condition Indicators for Evaluating Pavement Performance	46
2.4.2 Distress Progression: Cracking and Permanent Deformation	48
2.4.3 Interpretation Challenges for Chip Sealed Pavements.....	51
2.4.4 Longitudinal Analysis of Field Performance Data and Relevance to the Present Study	53
2.5 In-Service Asphalt Binder Aging and the Protective Role of Chip Seals	55
2.5.1 Mechanisms of In-Service Asphalt Binder Aging	56
2.5.2 Aging Gradients through Asphalt Pavement Depth	58
2.5.3 Effects of Surface Treatments on Binder Aging	60
2.5.4 Relationship between Binder Aging and Pavement Distress Development.....	62
2.6 Recovery and Characterization of Asphalt Binders from Field Cores.....	63

2.6.1 Field Core Sampling and Layer-Specific Binder Evaluation.....	65
2.6.2 Binder Extraction and Recovery from Field Cores	66
2.6.3 Chemical Characterization of Field-Aged Binders	68
2.6.4 Rheological and Damage-Related Characterization Using the Dynamic Shear Rheometer (DSR)	69
2.6.5 Low-Temperature Stiffness and Stress-Relaxation Characterization	73
2.6.6 Adhesion and Moisture Susceptibility Characterization Using the Binder Bond Strength Test.....	75
2.6.7 Integrating Chemical, Rheological, and Mechanical Aging Indicators.....	76
2.7 Long-Term Field Performance of Chip Seals and Evidence on Treatment Timing	78
2.7.1 Scope and Limitations of Long-Term Chip Seal Evidence	79
2.7.2 Treatment Timing and Performance-Measure-Dependent Effectiveness	81
2.7.3 Evidence Linking Recovered Binder Properties, Aging Gradients, and Field Performance	83
2.7.4 Implications for Local-Agency Decisions and the Present Study	86
2.8 Summary and Research Gaps	87
2.8.1 Summary of Key Findings from Previous Research	87
2.8.2 Research Gaps in Chip Seal Timing Studies	89
2.8.3 Research Gaps in Long-Term Field Binder Aging Evaluation	90

2.8.4 Research Gaps in Linking Field Performance with Recovered Binder Properties	91
2.8.5 Contribution of the Present Study	92
Chapter 3 Methodology	94
3.1 Description of Test Sites	94
3.2 Field Data Collection	100
3.3 Field Data Analysis Methods	102
3.3.1 Pavement Roughness Analysis	103
3.3.2 Surface Distress Analysis	104
3.3.3 Surface Rating Analysis	105
3.3.4 Statistical Interpretation	107
3.4 Laboratory Testing	107
3.4.1 Asphalt Binder Extraction and Recovery	108
3.4.2 Chemical Evaluation	110
3.4.3 Rheological Testing	111
3.4.4 Binder Bond Strength	124
3.4.5 Laboratory Data Screening and Validity Review	127
Chapter 4 Results and Discussion	129
4.1 Cass County (CSAH 1)	129
4.1.1 International Roughness Index	129

4.1.2 Surface Distresses	135
4.2 Crow Wing County (CSAH 3)	147
4.2.1 International Roughness Index	147
4.2.2 Surface Distresses	152
4.3 City of St. Cloud (3rd Street N).....	163
4.3.1 Surface Rating (Eastbound)	163
4.3.2 Surface Rating (Westbound).....	165
4.4 Chemical Aging of Recovered Binders (ATR-FTIR)	168
4.5 Rotational Viscosity.....	172
4.6 Superpave Performance Grade (PG).....	176
4.6.1 High-Temperature PG	176
4.6.2 Intermediate-Temperature PG	181
4.6.3 Low-Temperature PG	184
4.7 ΔT_c	194
4.8 MSCR at 58°C	198
4.9 LAS.....	205
4.10 G-R Parameter	212
4.11 Binder Bond Strength.....	218
4.12 Section-Level Comparison of Recovered Binder Properties and Field Performance	227

Chapter 5 Conclusions and Recommendations	230
5.1 Conclusions	230
5.2 Recommendations	236
5.3 Future Work	238
References	240

List of Tables

Table 1. Asphalt Layer Mix and Design Characteristics	98
Table 2. Chip Seal Layer Design Information	100
Table 3. Summary of Evaluation Types by Agency and Road Direction	102
Table 4. Summary of LMM results for Northbound IRI progression in Cass County (CSAH 1)...	134
Table 5. Summary of LMM results for Southbound IRI progression in Cass County (CSAH 1)...	134
Table 6. Cass County Field Remarks from Distress Survey (2017 - 2025).....	139
Table 7. Directional Summary of IRI and Transverse Crack Counts in 2023, CSAH-1.....	146
Table 8. Summary of LMM results for Northbound IRI progression in Crow Wing County (CSAH 3)	151
Table 9. Summary of LMM results for Southbound IRI progression in Crow Wing County (CSAH 3)	151
Table 10. Crow Wing County Field Remarks from Distress Survey (2017 - 2025).....	156
Table 11. Directional Summary of IRI and Transverse Crack Counts in 2023, CSAH-3.....	162
Table 12. High-Temperature PG (HPG) for Control and Treated Sections Year 2025	180
Table 13. Low-Temperature PG (LPG) for Control and Treated Sections Year 2025.....	190
Table 14. LAS Damage at Failure, D_f , for Control and Treated Sections in 2025.....	211
Table 15. Dry- and Wet-Conditioned Pull-Off Tensile Strength Results for All Agencies.....	225
Table 16. Section-Level Comparison of Field Performance and Selected Bottom-Layer Recovered Binder Properties	229

List of Figures

Figure 1. Location Maps of Pavement Preservation Chip Seal Study Sites by Local Agency: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud	97
Figure 2. Laboratory Testing of Extracted/Recovered Asphalt Binders	108
Figure 3. Fourier-transform infrared Spectrometer	111
Figure 4. Brookfield DV-II+ Pro Rotational Viscometer	113
Figure 5. Dynamic Shear Rheometer Setup.....	115
Figure 6. Bending Beam Rheometer Setup.....	118
Figure 7. BBS Specimen Assembly showing Pull-off Stubs bonded to a Granite Substrate	127
Figure 8. Cass County IRI Results (Pavement Age from 0 to 8 Years) Per Travel Direction: (a) Northbound, and (b) Southbound	133
Figure 9. Cass County Full Width Transverse Cracks (2017 - 2025) Per Travel Direction: (a) Northbound, and (b) Southbound	138
Figure 10. Cass County Partial Width Transverse Cracks (2017 - 2025) Per Travel Direction: (a) Northbound, and (b) Southbound	143
Figure 11. IRI and Transverse Cracking Relationship in Cass County CSAH-1	146
Figure 12. Crow Wing County IRI Results (Pavement Age from 0 to 8 Years) Per Travel Direction: (a) Northbound, and (b) Southbound	150
Figure 13. Crow Wing County Full Width Transverse Cracks (2017 - 2025) Per Travel Direction: (a) Northbound, and (b) Southbound	155
Figure 14. Crow Wing County Partial Width Transverse Cracks (2017 - 2025) Per Travel Direction: (a) Northbound, and (b) Southbound	160

Figure 15. IRI and Transverse Cracking Relationship in Crow Wing County CSAH-3	161
Figure 16. Overall Surface Distress: Surface Rating for Eastbound City of St. Cloud (2021 - 2024)	165
Figure 17. Overall Surface Distress: Surface Rating for Westbound City of St. Cloud (2021 - 2024)	167
Figure 18. C=O + S=O area for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud	171
Figure 19. Rotational Viscosity at 135°C of Recovered Binders in 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud	175
Figure 20. High-temperature continuous grades of recovered binders in 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud.	179
Figure 21. Intermediate-temperature continuous grade for recovered binders in 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud	184
Figure 22. Figure 22. Low-temperature continuous grades of recovered binders in 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud	189
Figure 23. Figure 23. BBR creep stiffness of recovered binders: (a) Cass County, tested at -18°C for the top layer and -24°C for the bottom layer; (b) Crow Wing County, tested at -18°C for both layers; and (c) City of St. Cloud, tested at -24°C for both layers.	192
Figure 24. BBR m-value of recovered binders: (a) Cass County, tested at -18°C for the top layer and -24°C for the bottom layer; (b) Crow Wing County, tested at -18°C for both layers; and (c) City of St. Cloud, tested at -24°C for both layers.	194

Figure 25. ΔT_c for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing, (c) City of St. Cloud.....	198
Figure 26. $J_{nr,3.2}$ Results @ 58°C for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud.	203
Figure 27. %R3.2 Results @ 58°C for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud.	204
Figure 28. LAS fatigue response of recovered binders in 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud. N_f represents predicted cycles to failure at 2.5%.....	209
Figure 29. LAS fatigue response of recovered binders in 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud. N_f represents predicted cycles to failure at 5.0%.....	210
Figure 30. G-R at 15°C, 0.005 rad/s for Control and Treated Sections Year 2025 for Top Layers (a) Cass County (b) Crow Wing County (c) City of St. Cloud; CS = Chip Seal, AM = Asphalt Mix	216
Figure 31. G-R at 15°C, 0.005 rad/s for Control and Treated Sections Year 2025 for Bottom Layers (a) Cass County (b) Crow Wing County (c) City of St. Cloud; CS = Chip Seal, AM = Asphalt Mix	218
Figure 32. Loss of Bond Strength Results for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud.	224

List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
AFT	Asphalt Film Thickness
ANOVA	Analysis of Variance
ASTM	ASTM International
ATR-FTIR	Attenuated Total Internal Reflection–Fourier Transform Infrared Spectroscopy
BBR	Bending Beam Rheometer
BBS	Binder Bond Strength
BP	Burst Pressure
CAM	Christensen-Anderson-Marasteanu Model
CRS-2P	Rapid-Setting, High-Viscosity, Polymer-Modified Cationic Asphalt Emulsion
CSAH	County State-Aid Highway
CSS-1h	Slow-Setting, Low-Viscosity, Hard-Penetration Cationic Asphalt Emulsion
DSR	Dynamic Shear Rheometer
DTT	Direct Tension Test
EB	Eastbound
ESAL	Equivalent Single-Axle Load
FDR	Full-Depth Reclamation
FHWA	Federal Highway Administration

FTIR	Fourier Transform Infrared Spectroscopy
G-R	Glover-Rowe Parameter
HMA	Hot-Mix Asphalt
HPG	High-Temperature Performance Grade
HSD	Honestly Significant Difference
IRI	International Roughness Index
IWD	Individual Weighted Distress
LAS	Linear Amplitude Sweep
LMM	Linear Mixed-Effects Model
LPG	Low-Temperature Performance Grade
LRRB	Local Road Research Board
LTPP	Long-Term Pavement Performance
MnDOT	Minnesota Department of Transportation
MnROAD	Minnesota Road Research Facility
MSCR	Multiple Stress Creep Recovery
NB	Northbound
NCAT	National Center for Asphalt Technology
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
PCI	Pavement Condition Index
PG	Performance Grade

POTS	Pull-Off Tensile Strength
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingles
RHEA	Rheological Evaluation and Analysis
RV	Rotational Viscosity
SB	Southbound
SPS-3	Specific Pavement Study 3
SR	Surface Rating
TCE	Trichloroethylene
TWD	Total Weighted Distress
UV	Ultraviolet
VECD	Viscoelastic Continuum Damage
WB	Westbound
WLF	Williams-Landel-Ferry

Chapter 1 Introduction

1.1 Background

Pavement preservation has become a central pillar of modern transportation asset management as agencies strive to maintain roadway networks under increasing financial, environmental, and operational pressures. Across the United States, state and local agencies are responsible for thousands of miles of asphalt pavements that must remain safe and functional despite continual exposure to traffic loading, climatic stresses, and material aging. Preservation strategies allow agencies to intervene earlier in the pavement life cycle, slowing deterioration and delaying the need for costly rehabilitation or reconstruction. This proactive approach has been widely promoted by national organizations such as the Federal Highway Administration (FHWA), which emphasizes that early intervention yields substantial life-cycle cost savings and improves long-term network performance (Galehouse et al., 2003; Peshkin et al., 2004; Waidelich, 2016)

Asphalt pavements deteriorate through a combination of mechanical and environmental mechanisms. Traffic loading induces fatigue cracking, rutting, and surface wear, while environmental exposure drives oxidative aging, thermal cracking, and moisture-related damage. Among these mechanisms, oxidative aging plays a particularly important role in long-term performance. As asphalt binder is exposed to oxygen, ultraviolet (UV) radiation, and elevated temperatures, its chemical structure changes, leading to increased stiffness, reduced ductility, and greater susceptibility to cracking. These changes occur most rapidly at the pavement surface, where oxygen diffusion and temperature fluctuations are greatest, and gradually propagate downward through the pavement layers (Airey, 2007). Over time, the accumulation

of oxidative damage reduces the pavement's ability to accommodate thermal and mechanical stresses, accelerating the onset of cracking and surface raveling.

To manage these aging processes, agencies rely on a variety of preservation treatments, among which chip seals are one of the most widely used. Chip seals consist of a thin application of asphalt binder followed by a layer of aggregate chips that are embedded into the binder to form a durable, textured surface. This treatment seals small cracks and surface voids, reduces permeability, improves skid resistance, and provides a protective barrier that slows oxidative aging by limiting oxygen and UV exposure. Because chip seals can be applied quickly and at relatively low cost, they are particularly attractive to agencies managing large networks of low- to medium- volume roads. Their ability to restore surface condition and delay deterioration makes them a key component of preservation programs across many states (Gransberg & James, 2005; Peshkin et al., 2004).

In practice, pavement condition is evaluated using a combination of distress surveys, roughness measurements, and composite indices that summarize structural and functional performance. Metrics such as the Pavement Condition Index (PCI), International Roughness Index (IRI), and other surface rating scores provide agencies with quantitative tools to track deterioration and determine when preservation treatments should be applied (International, 2020; Peshkin et al., 2004; Sayers et al., 1986). These indicators are often incorporated into pavement management systems that recommend treatment types and timing based on predefined thresholds or decision rules. While these systems offer valuable guidance, they may

not fully capture the complex interactions between binder aging, environmental exposure, and treatment effectiveness.

Previous research has examined chip seal performance using short-term field monitoring, laboratory aging protocols, and condition-based performance metrics. These studies have demonstrated that chip seals can effectively reduce cracking, improve surface texture, and extend pavement life when applied under appropriate conditions (Labi & Sinha, 2004). However, determining the optimal timing of chip seals remains challenging. Pavement aging progresses at different rates depending on climate, traffic loading, binder chemistry, and the condition of the existing pavement at the time of treatment. In colder climates, thermal cracking and freeze-thaw cycles may dominate, while in warmer regions, oxidation and surface hardening may be more critical (Peshkin et al., 2004). These regional differences complicate the development of universal treatment timing guidelines.

Laboratory aging protocols are useful for controlled comparisons and performance prediction; however, their ability to reproduce long-term field aging depends on the selected conditioning temperature, duration, and performance property being evaluated (Elwardany et al., 2016). Li et al. (2011) found significant differences between laboratory-aged binders and binders recovered from field pavement cores, as well as differences in aging with location through the asphalt layer. Studies of field cores have further shown that asphalt binder aging is nonuniform through pavement depth. Although aging is generally more pronounced near the pavement surface, oxidation and hardening may extend into underlying layers depending on oxygen availability, temperature distribution, connected air voids, and mixture characteristics (Li

et al., 2011; Woo et al., 2008; Yin et al., 2017). Understanding these gradients is essential for evaluating the long-term effectiveness of chip seals as a barrier to aging.

Despite the widespread use of chip seals, there remains a lack of comprehensive, long-term field studies that integrate chemical, rheological, mechanical and performance-based indicators to assess treatment effectiveness. Without long-term data linking treatment timing to changes in binder properties and field performance, agencies face uncertainty in determining when chip seals should be applied to achieve the greatest benefit. This uncertainty can lead to inconsistent preservation outcomes, inefficient use of maintenance budgets, and reduced pavement longevity. A more detailed understanding of how chip seal timing influences long-term performance is therefore essential for improving preservation decision-making and optimizing treatment schedules.

1.2 Objectives

The primary objective of this study is to evaluate how the timing of chip seal application is associated with long-term asphalt pavement deterioration and recovered binder chemical, rheological and mechanical properties. Using sections chip sealed in successive years after construction, the study examines whether the observed performance supports site-specific evidence of benefits from early chip seal application. Specifically, this research will:

- Analyze field performance trends for pavement treated at different times.
- Evaluate long-term oxidative aging using chemical, rheological and mechanical indicators from field-extracted binders.
- Determine how treatment timing influences aging gradients and long-term performance.

1.3 Scope of Work

To achieve the study objectives, a coordinated field and laboratory evaluation program was conducted using test sections placed by three local agencies in Minnesota at different times since 2015. The study incorporates construction documentation, long-term field performance data, and asphalt binders extracted from field cores to assess how treatment timing influences pavement aging. Field performance data were compiled and analyzed to characterize distress progression across the test sections.

Recovered asphalt binders from each section were evaluated using a set of chemical, rheological and mechanical tests selected for their ability to quantify oxidative aging and changes in performance-related properties. Laboratory and field results were compared descriptively at the section level to determine how chip seals influence aging at the surface and within underlying binder layers. The study concludes with an implementation analysis that examines the practical benefits and challenges of applying chip seals at different stages of pavement life.

1.4 Thesis Organization

This thesis is organized into five chapters:

- Chapter 1 presents the background, problem statement, objectives, scope of work, and overall structure of the study.
- Chapter 2 reviews literature on pavement preservation, chip seal performance, asphalt binder aging, laboratory and field evaluation methods, and analytical approaches for modeling long-term pavement performance.

- Chapter 3 describes the materials, field sections, data sources, and laboratory procedures used in the study.
- Chapter 4 presents the results of the field performance analysis, chemical, rheological and mechanical testing, and the relationship between aging indicators and chip seal treatment timing.
- Chapter 5 provides conclusions, implementation recommendations, and directions for future research.

Chapter 2 Literature Review

2.1 Introduction

Pavement preservation is widely recognized as a cost-effective strategy for extending pavement service life, delaying major rehabilitation, and improving the long-term use of available maintenance funds (Waidelich, 2016). Among preservation treatments, chip seals are commonly used because they provide a relatively economical means of restoring surface characteristics, reducing water infiltration, limiting oxidation, and slowing the progression of surface-related distresses (Peshkin et al., 2004; Transit New et al., 2005; Ulring et al., 2021) g et al., 2021). However, the effectiveness of chip seal is strongly influenced by the condition of the pavement at the time of application. When applied too early, the treatment may provide limited immediate benefit relative to its cost. When applied after substantial cracking, deformation, or structural deterioration has developed, the treatment may be unable to prevent continued deterioration of the underlying pavement structure (Peshkin et al., 2004).

Although chip seals have been used extensively by transportation agencies, uncertainty remains regarding the optimal application window for maximizing their long-term preservation benefit. Existing guidance often relies on pavement condition information, including observed cracking and surface distress, as well as measured indicators such as roughness (Peshkin et al., 2004). However, these indicators may not fully capture the extent of aging occurring within the asphalt pavement. In-service binder aging alters the chemical composition and rheological behavior of asphalt binders and may contribute to increased stiffness, reduced relaxation capacity, and greater susceptibility to cracking (Baumgardner, 2021; Camargo et al., 2020).

Therefore, evaluating chip seal timing solely on the basis of surface condition may overlook important changes occurring within the pavement layers.

This literature review synthesizes previous research relevant to the central question of this study: how can field condition indicators, long-term pavement performance trends, and chemical, rheological, and mechanical properties of recovered asphalt binders be integrated to identify an effective timing window for chip seal application? The review first discusses pavement preservation principles, treatment timing, and the role of chip seals within preservation programs. It then examines chip seal materials, design, construction practices, performance factors, and common failure mechanisms. Subsequent sections review field pavement performance measures, mechanisms of in-service asphalt binder aging, methods for extracting and recovering binders from field cores, and laboratory techniques used to characterize chemical and rheological aging. Finally, the review synthesizes long-term field studies of chip seal performance and identifies gaps in current knowledge related to treatment timing, aging gradients, and the relationship between recovered binder properties and field deterioration.

The purpose of this review is not only to summarize prior research but also to establish the technical basis for the present study. By evaluating how existing evidence links chip seal timing, pavement condition, binder aging, and long-term field performance, the review identifies the limitations of current timing guidance and supports the development of a more integrated framework for chip seal treatment decisions.

2.2 Pavement Preservation and Treatment Timing

2.2.1 Concepts and Timing of Pavement Preservation

Pavement preservation involves planned actions intended to maintain a transportation facility in a state of good repair before deterioration reaches a level that requires major rehabilitation or reconstruction. FHWA characterizes preservation as work that is planned and performed to improve or sustain the condition of a transportation facility, generally without adding capacity or structural value (Waidelich, 2016). In this sense, preservation is defined not only by the treatment selected, but also by the condition of the pavement when that treatment is applied.

The principle of applying the right treatment to the right pavement at the right time is widely used to describe preventive maintenance and pavement preservation practice (Galehouse et al., 2003). However, this principle does not establish a specific timing criterion for individual treatments. For chip seals, the practical issue is determining when the pavement has deteriorated enough to benefit from surface protection but has not deteriorated to the point where a surface treatment can no longer influence its long-term performance. Evaluating chip seal timing first requires distinguishing pavements that remain suitable for preservation from those that have progressed to a condition requiring rehabilitation or reconstruction.

The distinction between preservation, rehabilitation, and reconstruction provides the framework for determining whether a chip seal remains an appropriate treatment option. Preservation is intended to maintain pavement condition and slow deterioration while the pavement remains structurally adequate. In contrast, rehabilitation involves structural or

functional enhancements intended to substantially improve pavement condition, ride quality, or remaining service life. Rehabilitation efforts are often described using the four Rs: restoration, resurfacing, recycling, and reconstruction (Hall et al., 2001).

Restoration addresses existing distress and improves serviceability without substantially increasing structural capacity. Resurfacing may involve either a structural overlay, which improves capacity and serviceability, or a functional overlay, which improves ride quality and surface condition without appreciably increasing structural capacity. Recycling involves reuse of existing pavement materials during resurfacing or reconstruction, whereas reconstruction involves removal and replacement of the existing pavement structure and may include improvements to the base, subbase, subgrade, drainage system, or roadway geometry (Hall et al., 2001).

These categories should not be viewed only as increasing levels of treatment cost. They also reflect different pavement needs. A chip seal may address surface weathering, raveling, oxidation, minor cracking, and permeability; however, it cannot restore lost structural capacity or correct extensive deformation. Therefore, the decision to apply a chip seal depends on whether the pavement remains within the preservation range or has progressed to a condition requiring rehabilitation or reconstruction. In practice, agencies rely on pavement condition measures and treatment-selection thresholds to determine whether a pavement remains an appropriate preservation candidate.

Pavement condition thresholds provide the practical basis for distinguishing pavements that remain suitable for preservation from those requiring more extensive intervention.

Cracking, rutting, roughness, pavement age, traffic exposure, drainage condition, and pavement condition indices are commonly used to support these decisions (Peshkin et al., 2004). However, existing guidance and field studies do not support a single universal timing threshold that can be applied uniformly across pavement systems, traffic levels, climatic conditions, or preservation treatments.

The difficulty arises partly because treatment effectiveness can be defined in different ways. Haider and Dwaikat (2011) developed an optimum-timing approach using pretreatment pavement performance, the immediate change in pavement condition after treatment, and the expected deterioration rate after treatment. Their approach recognizes that timing should depend on the expected performance response rather than on pavement age or a single condition value alone. The model was also intended to be calibrated using local pavement-management data, reflecting differences in treatment performance among roadway systems.

Labi and Sinha (2004) reached a related conclusion through their evaluation of seal-coating effectiveness. Pavements in poorer initial condition experienced larger immediate improvements in pavement condition after treatment. In contrast, pavements in better initial condition experienced greater reductions in the subsequent deterioration rate. These findings indicate that later treatment may appear more beneficial when effectiveness is measured by immediate condition improvement, whereas earlier treatment may be more beneficial when the objective is to reduce future deterioration.

This difference does not necessarily indicate disagreement about the value of early preservation. Rather, it shows that the recommended timing depends on the performance

measure used to define treatment benefit. Studies based primarily on roughness, distress reduction, condition improvement, or service-life extension may identify different treatment points even when evaluating similar pavements. (Chen et al., 2017) similarly developed treatment-specific preventive-maintenance thresholds using LTPP data, reinforcing that threshold values depend on treatment type and the performance relationships considered.

For chip seals, pavement condition thresholds should therefore be treated as screening tools rather than universal timing rules. They provide useful information about whether a pavement may be suitable for preservation, but they do not fully explain why pavements with similar visible condition may respond differently after treatment. More importantly, identifying a feasible preservation candidate is not the same as identifying the most cost-effective time for treatment. The timing decision must also consider whether the expected performance benefit justifies the cost of applying the treatment at that stage of pavement life.

2.2.2 Cost-Effectiveness of Preservation Treatments

Life-cycle cost analysis provides a framework for evaluating whether a preservation treatment should be applied at a particular point in the pavement life cycle (Galehouse et al., 2003; Peshkin et al., 2004). Although chip seals are generally less expensive than rehabilitation or reconstruction, their value depends on the additional service life or reduction in deterioration achieved after application. A treatment applied within the feasible preservation range may still provide limited economic benefit if it is applied too early or if the expected post-treatment performance improvement is small (Peshkin et al., 2004).

Labi and Sinha (2005) evaluated life-cycle preventive-maintenance strategies for several asphalt pavement functional classes and showed that cost-effectiveness varies with pavement type, treatment level, and the cost components included in the analysis. Increasing preventive-maintenance effort did not produce unlimited economic benefit. Instead, the relationship reached a point beyond which additional investment reduced cost-effectiveness. This finding is important because it suggests that the goal is not simply to treat pavements as early as possible, but to apply preservation at a time when the expected extension in service life justifies the investment.

The timing approach proposed by Haider and Dwaikat (2011) supports this interpretation by linking optimal treatment timing to pretreatment condition, immediate treatment benefit, and the post-treatment deterioration rate. For chip seals, the relevant question is therefore whether the treatment can alter the future deterioration trajectory enough to delay rehabilitation. This question cannot be answered solely from the initial treatment cost or from the pavement condition immediately before treatment.

Life-cycle analyses are also dependent on the performance assumptions used to estimate future maintenance needs. When treatment effectiveness is estimated only from surface condition measures, uncertainty remains regarding the condition of the asphalt materials beneath the surface. This limitation is relevant to chip seal timing because differences in binder aging may influence whether a treated pavement experiences sustained performance improvement or continued deterioration after treatment. The economic value of a chip seal therefore depends on its ability to provide durable surface protection and slow deterioration

under the specific material, traffic, and environmental conditions of the pavement being treated.

2.2.3 Chip Seals in Pavement Preservation and Candidate Selection

Chip seals are nonstructural surface preservation treatments used to protect pavements that remain structurally sound. Their primary purpose is not to restore lost structural capacity, but to preserve the existing pavement surface by improving texture, reducing water infiltration, sealing minor surface cracks, limiting raveling and weathering, and slowing exposure-related deterioration (Peshkin et al., 2004; Transit New et al., 2005; Ulring et al., 2021). Because these benefits are surface-oriented, chip seals are most appropriate when the pavement has not yet developed distress that requires structural rehabilitation.

Candidate selection is therefore a critical step in chip seal use. Practical selection procedures commonly consider the type, amount, and severity of existing cracking, rutting depth, raveling, oxidation, surface texture, pavement age, traffic level, drainage condition, and evidence of structural deficiency. FHWA's chip seal checklist, for example, recommends verifying that the project is a good candidate, limiting existing rutting, evaluating existing crack severity, and avoiding chip seals on pavements with structural distress (Federal Highway, 2019). These criteria help agencies distinguish pavements that can still benefit from surface preservation from pavements that require rehabilitation or reconstruction.

The importance of candidate selection is also reflected in chip seal design guidance. Gransberg and James (2005) noted that chip seal performance is influenced by the quality of design, construction, materials, environmental conditions, and traffic conditions. Similarly,

Shuler et al. (2011) emphasized that emulsion-based chip seal performance depends on appropriate material selection, design procedures, construction control, and quality assurance. These sources indicate that chip seal success depends not only on whether a pavement is selected at the right condition level, but also on whether the selected materials and construction practices are suitable for the roadway environment.

However, candidate selection and treatment timing are related but distinct decisions. Candidate-selection criteria determine whether chip seal is a feasible treatment option, whereas timing decisions determine when the treatment is likely to provide the greatest long-term benefit. A pavement may remain suitable for chip seal over multiple years, but the expected benefit may differ depending on pavement age, distress progression, traffic exposure, and environmental aging. If the treatment is applied too early, the pavement may show limited measurable improvement. If it is applied too late, the chip seal may be unable to slow deterioration because the underlying pavement condition has already advanced beyond the preservation range.

The present study evaluates this issue using a staggered chip seal application schedule at three Minnesota test sites. At each site, five pavement sections received chip seals in successive years from 2015 through 2019, while an additional section remained untreated as a control. This configuration allows sections treated at different pavement ages to be compared under the same general roadway, traffic, and environmental conditions. The untreated control sections provide a reference for evaluating how pavement condition and binder aging progress in the absence of chip seal treatment.

Rather than evaluating a single candidate-selection threshold, this study examines whether earlier and later chip seal applications are associated with differences in long-term field performance and in the chemical, rheological, and mechanical properties of recovered asphalt binders. This approach recognizes that visible pavement condition is an important part of chip seal candidate selection but may not be sufficient to explain long-term preservation benefit. Interpreting these differences also requires understanding the chip seal system itself, including aggregate and binder properties, design application rates, construction quality, traffic loading, climate, and the condition of the existing pavement surface. These factors are reviewed in the following section.

2.3 Chip Seal Systems: Materials, Design, Construction, and Performance

Chip seal performance is controlled by a sequence of linked processes, including binder application, aggregate coverage, aggregate embedment, bond development, traffic-induced seating, and long-term exposure to climate and loading. Deficiencies at any stage can affect aggregate retention, surface texture, bleeding resistance, and bonding to the existing pavement.

Although chip seals are often treated as relatively simple surface applications, their behavior depends on the interaction of aggregate properties, binder characteristics, design assumptions, construction execution, and service conditions. Early chip seal practice relied heavily on experience-based application rates. The McLeod design method represented an important shift toward a more rational approach by relating aggregate characteristics, pavement-surface condition, traffic, and residual binder requirements to aggregate and binder application rates. Later guidance, including emulsified chip seal design procedures, expanded

this approach by incorporating material compatibility, emulsion behavior, aggregate retention, and construction quality-control considerations (Gransberg & James, 2005; McLeod, 1969; Shuler et al., 2011). The following sections examine how chip seal configuration, materials, design procedures, construction practices, early-age performance, and in-service conditions influence the development and long-term performance of the seal.

2.3.1 Chip Seal Configuration and Development of Current Practice

A conventional chip seal consists of an asphalt binder or emulsion sprayed onto an existing pavement surface, followed by cover aggregate that is immediately spread and rolled into the binder. The aggregate is intended to form a relatively uniform surface layer, while the binder provides the adhesive film required to retain the aggregate and seal the pavement surface (Gransberg & James, 2005; Shuler et al., 2011).

Chip seal practice has gradually moved beyond reliance on field experience alone toward more formalized procedures for material selection, design, construction, and quality control. NCHRP Report 680 incorporated laboratory and field methods for evaluating aggregate gradation, moisture condition, emulsion behavior, embedment, application rates, and traffic-opening conditions. These procedures provide a more systematic basis for chip seal construction, although they do not eliminate the need for project-specific engineering judgment (Shuler et al., 2011). This progression has shifted attention toward the compatibility of the aggregate, binder, and existing pavement surface. The material characteristics of the seal therefore provide the starting point for chip seal design.

2.3.2 Chip Seal Materials

Chip seal materials should be considered as a combined aggregate-binder system rather than as independent components. Aggregate properties influence coverage, texture, embedment, and retention, whereas binder properties influence wetting, adhesion, cohesion, curing, and resistance to bleeding. The compatibility between aggregate and binder is particularly important because inadequate adhesion can lead to aggregate loss even when the selected materials meet individual specification requirements (Aktaş et al., 2013; Howard et al., 2013).

The cover aggregate forms the exposed surface of the chip seal and strongly influences macrotexture, skid resistance, aggregate retention, and surface appearance. Relevant aggregate characteristics include nominal size, gradation, shape, abrasion resistance, cleanliness, absorption, and moisture condition. Relatively uniform aggregate gradation is important because it helps produce a single-stone layer with more consistent embedment. Aggregate shape also affects chip seal behavior. Cubical particles are generally preferred because they are less likely to reorient substantially under traffic, whereas flat or elongated particles can alter the effective thickness of the aggregate layer and create nonuniform embedment. Aggregate cleanliness is equally important because dust, clay coatings, and excess moisture can interfere with aggregate-binder adhesion (Gransberg & James, 2005).

Aktaş et al. (2013) evaluated clean, dusty, and precoated aggregates using an accelerated chip seal simulation device. Their results showed that precoated aggregates had better retention performance than dusty and clean aggregates, and modified binder improved

retention relative to the neat binder evaluated in the study. These findings demonstrate that aggregate condition and binder selection should be considered together when evaluating potential chip seal materials. The binder provides the adhesive layer between the aggregate and the existing pavement surface. Emulsified asphalt binders are widely used for chip seals because they can be applied at lower temperatures than hot asphalt binders. An emulsion consists of asphalt cement dispersed in water with an emulsifying agent; as the emulsion breaks and water evaporates, residual asphalt remains to bond the aggregate to the pavement surface (Shuler et al., 2011). The timing of emulsion breaking is important during construction. Aggregate spreading and rolling must occur before the emulsion has broken so that the aggregate can be properly seated in the binder. Delays during this period may reduce aggregate embedment and increase the risk of early aggregate loss (Gransberg & James, 2005; Shuler et al., 2011).

Polymer modification may improve binder cohesion, aggregate retention, and resistance to high-temperature deformation. However, modification alone does not ensure satisfactory chip seal performance. Rahman et al. (2020) found that aggregate loss varied with emulsion type and application rate, demonstrating that the binder must be evaluated within the complete chip seal system rather than by binder classification alone. Howard et al. (2013) similarly recommended evaluating aggregate-emulsion systems together rather than approving aggregate and emulsion materials independently. The selected aggregate and binder must then be proportioned and placed to achieve the intended aggregate structure, embedment, and surface texture.

2.3.3 Design, Construction, and Early-Age Performance

Chip seal design involves selecting aggregate and binder application rates that provide sufficient aggregate coverage, embedment, texture, and retention without producing excess binder at the surface. The McLeod method remains a recognized design approach because it accounts for aggregate properties, existing pavement condition, traffic, and residual binder content. The modified Kearby method similarly adjusts application rates according to pavement texture and expected traffic-induced embedment (Gransberg & James, 2005; McLeod, 1969). Design methods provide initial estimates rather than universal application rates. Aggregate size, particle shape, aggregate absorption, pavement texture, pavement absorption, residual binder content, traffic loading, and anticipated aggregate embedment may require project-specific adjustments. Research sponsored by the North Carolina Department of Transportation (NCDOT) has also shown that differences between target and actual aggregate or emulsion application rates can influence both aggregate loss and bleeding potential (Jeong et al., 2020).

Construction practices determine whether the intended design is achieved in the field. Important activities include surface preparation, binder application, aggregate spreading, rolling, curing, sweeping, and traffic management. Gürer et al. (2012) evaluated five chip seal test roads and found that construction-related variables, including aggregate adhesion, aggregate dust, ambient temperature, time between construction stages, rolling, and aggregate embedment, affected chip seal performance. Quality control should therefore include calibration of distributors and aggregate spreaders, verification of actual material application rates, aggregate coverage, weather conditions, rolling practices, and emulsion curing before unrestricted traffic is permitted. FHWA's chip seal checklist similarly emphasizes project

candidate review, existing distress repair, rutting limits, crack assessment, traffic suitability, material checks, equipment calibration, weather requirements, and application-rate verification before and during construction (Federal Highway, 2019). These procedures are important because a reasonable design can still perform poorly when material placement is nonuniform or field conditions differ substantially from the assumed design conditions (Jeong et al., 2020; Shuler et al., 2011).

The success of design and construction becomes evident first through early-age chip seal behavior, particularly aggregate retention, texture development, and surface bonding. Early-age performance is governed by the ability of the aggregate-binder system to develop adequate adhesion, cohesion, embedment, and mechanical interlock before substantial traffic loading occurs. Raveling and bleeding are among the most commonly reported chip seal distress modes, and both can originate shortly after construction when the binder has not adequately retained aggregate or when aggregate becomes excessively embedded (Gransberg & James, 2005; Pierce & Kebede, 2015). Aggregate embedment must be sufficient to retain aggregate particles while preserving enough exposed aggregate to provide surface texture. Chip seal design methods commonly target aggregate embedment between approximately 50 and 70 percent of aggregate height. Insufficient embedment leaves aggregate vulnerable to traffic-induced displacement, whereas excessive embedment reduces macrotexture and increases the potential for binder to cover the aggregate surface (Gransberg & James, 2005).

Kumbargeri et al. (2019) evaluated the effects of aggregate and binder application rates on percent embedment, aggregate orientation, and aggregate loss. Their results showed that

aggregate orientation and embedment were influenced by the relative application rates of binder and aggregate, confirming that aggregate retention is related to the internal structure of the seal rather than binder quantity alone. Aggregate loss may result from inadequate adhesion, insufficient binder, incomplete curing, dirty or wet aggregate, delayed rolling, premature traffic exposure, or unsuitable aggregate-binder combinations. These mechanisms should be distinguished from later deterioration associated with aging of the chip seal or underlying pavement because they often reflect early construction or material compatibility problems.

The opposite early-age problem can also occur when the chip seal contains too much effective binder or when aggregate becomes over embedded. In this case, the binder may rise to the surface and reduce the exposed aggregate texture. Bleeding occurs when excess binder migrates to the chip seal surface, creating dark areas where aggregate becomes partially covered. Flushing refers to the accompanying reduction in macrotexture as binder fills or covers the voids around aggregate particles. Both conditions can reduce surface friction and alter the intended surface characteristics of the chip seal (Gransberg & James, 2005). Bleeding can result from excessive binder application, soft residual binder, elevated pavement temperature, and continued aggregate embedment under traffic. However, reducing the binder application rate without considering aggregate retention can create the opposite problem of aggregate loss. The appropriate design objective is therefore to balance binder availability for adhesion against the need to maintain aggregate exposure and surface texture (Kumbarger et al., 2019; Shuler et al., 2011). When this balance is not achieved, or when moisture and surface preparation problems

interfere with bonding, early-age failures may also occur at the aggregate-binder or chip seal-pavement interface in the form of debonding.

Debonding can occur in two ways. First, aggregate-binder debonding occurs when aggregate particles separate from the binder film, leading to chip loss. Second, chip seal-pavement debonding occurs when the chip seal layer loses adhesion to the existing pavement surface. These failures may result from poor surface preparation, moisture at the interface, insufficient curing, incompatible aggregate-binder combinations, or inadequate binder coverage. You et al. (2019) showed that asphalt emulsion–aggregate combinations and repeated freeze–thaw cycles significantly influenced aggregate adhesion and the bond strength at the chip seal–pavement interface. These findings indicate that chip seal performance depends not only on material application rates and aggregate embedment but also on the integrity of the bonds among the aggregate, asphalt emulsion, and underlying pavement.

Early-age failures such as aggregate loss, bleeding, flushing, and debonding often reflect problems in material compatibility, construction timing, surface preparation, or initial traffic control. However, chip seals that perform adequately during the early service period may still experience different long-term outcomes depending on climate, traffic loading, existing pavement condition, and the condition of the asphalt material beneath the surface. These long-term factors are discussed in the following section.

2.3.4 Factors Influencing Long-Term Chip Seal Performance

Long-term chip seal performance depends on more than successful early aggregate retention. Even when a chip seal is properly designed and constructed, its ability to maintain

surface protection over time is influenced by the environment in which it is placed, the traffic it carries, and the condition of the pavement surface to which it is bonded. These factors interact throughout the service life of the treatment, which means that similar chip seals may perform differently under different climatic, traffic, and pavement-substrate conditions (Gransberg & James, 2005; Pierce & Kebede, 2015).

Climate is one of the first external factors affecting both construction quality and long-term performance. During construction, temperature influences binder viscosity, emulsion breaking, curing, aggregate seating, and the potential for bleeding. Moisture, humidity, wind, and precipitation can affect curing and adhesion during placement. After construction, repeated environmental exposure can continue to affect the chip seal system, particularly in cold regions where freeze-thaw cycles may weaken aggregate-binder adhesion and chip seal-pavement interface bond strength (Gransberg & James, 2005; You et al., 2019). Gürer et al. (2012) also found that ambient temperature and rolling conditions influenced aggregate embedment and macrotexture development on field test roads, indicating that construction-season conditions can affect later chip seal behavior rather than only short-term workability.

In addition to environmental exposure, traffic loading strongly influences how the chip seal develops after placement. Traffic initially helps seat aggregate into the binder, but continued loading can also accelerate embedment, bleeding, aggregate displacement, and texture loss. These effects are not determined by traffic volume alone. Heavy trucks, vehicle speed, channelized wheel paths, braking, acceleration, grades, and turning movements can produce localized stresses that differ from those experienced under uninterrupted straight-

through traffic (Pierce & Kebede, 2015). For this reason, chip seal design guidance often adjusts binder application rates according to traffic level, since continued traffic-induced embedment affects the amount of binder needed to retain aggregate while maintaining adequate surface texture (Gransberg & James, 2005).

Performance is also affected by the condition of the existing pavement surface. A porous, oxidized, or highly textured surface may absorb more binder than a smooth or flushed surface, reducing the amount of effective binder available to hold aggregate. Surface hardness and texture can also influence the extent to which aggregate embeds into the existing pavement after placement. Therefore, the same binder and aggregate application rates may not produce the same embedment, texture, or retention on pavements with different surface conditions (Gransberg & James, 2005; Shuler et al., 2011).

Beyond the visible surface, the condition of the existing asphalt layer beneath the chip seal can also influence long-term treatment response. Howard et al. (2013) showed this by evaluating different emulsion, aggregate, and pavement-surface combinations while also measuring changes in existing pavement properties. Their inclusion of recovered binder viscosity, mixture creep response, and BBR mixture-beam behavior indicates that chip seal performance is not controlled only by the newly placed seal, but also by the material condition of the pavement receiving the treatment. This is important for timing studies because pavements with similar visible surface condition may have different levels of binder aging and stiffness beneath the surface, which may affect how they respond after chip sealing. Current chip seal design and candidate-selection guidance accounts for observable surface factors such

as texture, absorption, aggregate properties, application rates, traffic, and weather conditions. However, these procedures provide less direct information about the chemical, rheological, and mechanical condition of the aged asphalt binder within the existing pavement layers. As a result, two pavements may appear similar at the surface but differ in stiffness, relaxation capacity, and susceptibility to future cracking. These differences may help explain why chip seals placed at different pavement ages can produce different long-term performance outcomes.

The factors discussed help explain why chip seals may perform differently after placement, even when similar materials and design procedures are used. Their effects are eventually reflected in observable pavement condition, including changes in surface texture, cracking, roughness, rutting, and visual distress. Therefore, evaluating chip seal timing and long-term effectiveness requires field performance measures that can capture both functional pavement condition and surface-related deterioration.

2.4 Pavement Performance Measurement and Long-Term Condition Evaluation

Field performance measurement provides the observable basis for evaluating whether chip seal treatment has delayed deterioration, maintained pavement serviceability, or extended the time before more substantial intervention is required. Because chip seals are surface preservation treatments, their benefits may be reflected in several ways. These benefits are not always captured by one measure alone. Roughness describes functional ride quality, cracking reflects fracture-related deterioration, rutting indicates permanent deformation, macrotexture describes surface texture characteristics, and condition indices summarize observed distress into broader pavement-condition ratings.

For this reason, long-term chip seal performance cannot be evaluated adequately using a single field measure because chip seals may affect different aspects of pavement condition at different rates. Roughness, cracking, rutting, macrotexture, and composite condition indices each describe a different part of the pavement response. Therefore, evaluating chip seal effectiveness requires considering both functional condition and distress progression over time rather than relying on one isolated condition value.

2.4.1 Condition Indicators for Evaluating Pavement Performance

Pavement condition indicators are used to describe how pavement performance changes with age, traffic loading, environmental exposure, treatment application, and maintenance history. In pavement preservation studies, these indicators are important because preservation treatments are intended to slow deterioration and maintain serviceability rather than necessarily restore the pavement to a like-new condition. However, no single indicator fully represents pavement performance. Roughness, cracking, rutting, macrotexture, and composite condition indices each describe a different aspect of pavement response.

IRI is commonly used to describe pavement functional condition and ride quality. It is calculated from longitudinal pavement profile data using a standardized vehicle-response model (Sayers et al., 1986). In long-term performance studies, a stable or slowly increasing IRI may indicate that the pavement continues to provide acceptable ride quality, while a rapid increase may suggest the development of profile irregularities caused by cracking, deformation, settlement, patching, or localized deterioration. However, IRI does not directly measure

structural capacity, cracking severity, or asphalt binder aging. Pavements with similar IRI values may still differ in distress condition, surface texture, and susceptibility to future deterioration.

Visual distress surveys provide a more direct record of observable pavement deterioration. Standardized distress-identification procedures are useful because they define how distresses such as cracking, rutting, potholes, patching, and surface defects should be identified and measured (Miller & Bellinger, 2014). This distinction is important because different distress types reflect different deterioration mechanisms. For example, transverse cracking, longitudinal cracking, fatigue cracking, raveling, and rutting should not be interpreted as equivalent forms of damage.

Composite pavement condition indices, such as PCI, other agency-specific condition ratings, summarize observed distress into a single numerical value. ASTM D6433 provides a standardized method for determining PCI based on visual distress surveys (International, 2020). These indices are useful for network-level decision-making because they provide a general indication of pavement condition. However, because they combine multiple distress types into one score, they may mask the specific distress mechanisms controlling pavement deterioration. For this reason, PCI, and similar indices should be interpreted together with individual distress quantities and measured roughness.

For chip sealed pavements, macrotexture is also an important performance indicator because the treatment is designed to provide a textured wearing surface. A chip seal may maintain functional surface texture even when changes in IRI are small. Conversely, loss of macrotexture through aggregate loss, flushing, or excessive embedment can reduce the

functional value of the seal even if the pavement remains relatively smooth. Previous National Center for Asphalt Technology (NCAT)/Minnesota Road Research Facility (MnROAD) chip seal studies evaluated macrotexture together with cracking, rutting, and roughness, showing that chip seal performance is better interpreted using multiple field indicators rather than ride quality alone (Vargas-Nordbeck, 2018; Vargas-Nordbeck et al., 2019).

2.4.2 Distress Progression: Cracking and Permanent Deformation

While roughness and condition indices describe functional and overall pavement condition, distress progression provides more direct information about the mechanisms controlling pavement deterioration. Cracking, patching, potholes, rutting, and surface defects are commonly separated in pavement distress surveys because they represent different forms of pavement response and should not be interpreted as equivalent indicators of performance (Miller & Bellinger, 2014).

Cracking is one of the most important distress indicators in chip seal performance evaluation because it reflects both the condition of the existing pavement and the extent to which deterioration continues after treatment. However, cracking after chip seal application should not automatically be interpreted as failure of the treatment. Some cracks may reflect pre-existing deterioration, thermal movement, reflection from underlying layers, traffic-related fatigue, or aging of the asphalt materials beneath the surface. The relevant question is not only whether cracks are present after chip sealing, but whether the treatment changes the rate, extent, or severity of cracking compared with untreated pavement or pavement treated at a different time. Field studies from the NCAT/MnROAD Pavement Preservation Group Study have

used cracking as a major indicator in chip seal performance evaluation, while roughness and rutting often show smaller or less direct treatment responses (Vargas-Nordbeck, 2018; Vargas-Nordbeck et al., 2019).

The interpretation of cracking also depends on crack type. Transverse cracking is particularly important in cold-climate pavement systems because it may be associated with thermal contraction, age-related embrittlement, and reflection of cracks from lower pavement layers. Binder aging can reduce relaxation capacity and increase susceptibility to non-load-related cracking and age-related embrittlement distress (Baumgardner, 2021). For chip seal evaluation, transverse cracking should therefore be interpreted as a pavement-system response rather than as a direct measure of chip seal failure. A chip seal may slow surface exposure, but transverse cracks may continue to develop if cracking mechanisms are already active within the underlying asphalt layers.

Longitudinal and fatigue cracking require separate interpretation because they can reflect different deterioration mechanisms. Longitudinal cracking may occur in wheel paths, along construction joints, or near pavement edges, whereas fatigue cracking is commonly associated with repeated traffic loading and inadequate structural support (Miller & Bellinger, 2014). Combining all cracking into one total-cracking value may obscure the mechanism controlling deterioration. Where data allow, crack type, location, extent, and severity should therefore be retained so that treatment effects can be interpreted in relation to likely distress mechanisms rather than only total crack quantity.

Permanent deformation provides a different type of information from cracking. Rutting represents permanent deformation in the asphalt layer, base, or subgrade and may indicate mixture instability, heavy traffic loading, high-temperature deformation, weak support, or moisture-related weakening. Because chip seals add little structural thickness, rutting is not usually a primary distress that chip seals are expected to correct. Instead, rutting is useful in chip seal studies because it helps indicate whether the pavement was structurally suitable for preservation at the time of treatment. Continued rut growth after chip sealing may suggest that the pavement had progressed beyond the range where a surface preservation treatment alone could provide meaningful long-term benefit. Recent chip-seal field studies have evaluated rutting together with cracking, roughness, and overall pavement condition. Mousa et al. (2020) incorporated rutting into the pavement-condition assessment used to evaluate treatment performance and timing, while Umutoniwase et al. (2023) directly analyzed cracking, rutting, and IRI, and found that chip sealing significantly reduced crack-growth rates but did not significantly affect rutting or roughness growth rates. These findings reinforce that chip seals should not be expected to correct existing permanent deformation and that rutting should be considered when determining whether a pavement remains an appropriate candidate for surface preservation.

Together, cracking and rutting help distinguish pavements that remain suitable for surface preservation from pavements that are deteriorating beyond the preservation range. A pavement may remain smooth while cracking increases, or it may show limited surface change while deformation continues in the wheel paths. Long-term chip seal evaluation therefore

requires distress progression to be interpreted alongside roughness, condition indices, macrotexture, and treatment history.

2.4.3 Interpretation Challenges for Chip Sealed Pavements

Field condition data from chip sealed pavements require careful interpretation because chip seals intentionally change the surface texture and appearance of the pavement. The same treatment that improves surface protection and friction can also influence profile measurements, distress visibility, and the way surface defects are recorded. As a result, indicators developed primarily for dense-graded asphalt pavements may not always describe chip sealed surfaces with the same sensitivity.

One important challenge is the effect of chip seal macrotexture on roughness measurement. IRI is calculated from longitudinal profile data, but the measured profile can be influenced by profiler sensor type, laser footprint, filtering, wheel-path location, and surface texture. NCHRP Report 434 documented that coarse chip seals can affect roughness measurements and reported that some sensor systems measured higher IRI values on chip sealed surfaces because of the interaction between the sensor footprint and the coarse texture (Karamihas et al., 1999). FHWA smoothness guidance similarly notes that small-footprint point lasers may capture texture-related features on textured surfaces rather than a profile representative of the tire footprint (Smith & Ram, 2016). This does not mean that IRI data from chip sealed pavements are invalid. Rather, IRI trends should be interpreted with knowledge of the profiler type, surface texture, and consistency of measurement methods across years.

A second challenge is that chip seal distress mechanisms are not always the same as those emphasized in conventional asphalt pavement surveys. Chip seals may exhibit aggregate loss, bleeding, flushing, texture loss, streaking, or localized debonding, while many pavement management systems emphasize cracking, rutting, roughness, potholes, and patching. Pierce and Kebede (2015) emphasized the need for chip seal performance measures because treatment-specific indicators are needed to estimate service life and support resurfacing decisions. This supports the use of both conventional pavement indicators and chip seal-specific observations when evaluating long-term performance.

Maintenance activities can also complicate the interpretation of longitudinal field data. Crack sealing, patching, localized repairs, and additional surface treatments can change the visible condition of a pavement without reversing the underlying binder aging or structural deterioration. For example, crack sealing may reduce the amount of visible cracking recorded during a survey, but this does not necessarily mean that the underlying cracking mechanism has stopped. Vargas-Nordcbeck and Jalali (2020) showed that the benefit of crack sealing depends on pretreatment condition and time after application. Therefore, maintenance history should be considered when interpreting cracking trends, because apparent stabilization in visible cracking may reflect maintenance intervention rather than a true change in pavement deterioration.

Long-term preservation studies should therefore treat maintenance history as part of the analytical record. The Pavement Preservation Group Study documented preservation sections placed in Alabama and Minnesota, untreated controls, periodic data collection, and treatment comparisons under different pavement, traffic, and climatic conditions (Vargas-

Nordbeck et al., 2024). This type of longitudinal record is useful because it allows changes in condition to be interpreted with respect to treatment application, time since treatment, climate, traffic, and maintenance history rather than by annual condition values alone.

If a pavement appears to perform well based only on IRI, continued cracking or material aging may be overlooked. Conversely, an increase in IRI after chip seal placement may partly reflect surface texture or measurement sensitivity rather than structural deterioration. A more reliable interpretation requires combining roughness, distress progression, macrotexture, condition indices, maintenance history, and knowledge of the chip sealed surface.

2.4.4 Longitudinal Analysis of Field Performance Data and Relevance to the Present Study

Longitudinal field data are most useful when interpreted as performance trajectories rather than isolated yearly observations. The premise is not only whether one section has higher or lower roughness, cracking, rutting, macrotexture, or condition index at a single survey date, but whether its rate of change differs from comparable sections over time. This approach is consistent with pavement preservation evaluation because preservation treatments are intended to slow deterioration and extend service life rather than necessarily produce large immediate improvements in every condition measure.

Several chip seal studies have used this type of long-term performance framework. Mamlouk and Dosa (2014) used LTPP data to evaluate chip seal effectiveness as a preventive maintenance treatment. Mousa et al. (2020) evaluated short- and long-term chip seal performance and timing in hot and humid climates using field condition data from Louisiana. NCAT/MnROAD studies have also used longitudinal treated and untreated sections to estimate

chip seal benefit, evaluate treatment life, and compare performance under different climatic regions (Vargas-Nordbeck, 2018; Vargas-Nordbeck et al., 2024; Vargas-Nordbeck & Jalali, 2020; Vargas-Nordbeck et al., 2019). These studies support evaluating chip seal performance through changes in deterioration rate, treatment service life, and relative benefit compared with untreated control sections.

For staggered chip seal applications, longitudinal analysis is especially useful. Sections treated in different years can be compared according to pavement age at treatment, time since treatment, and subsequent changes in field condition. Untreated control sections provide a reference for evaluating how pavement condition might have progressed without chip seal application. This structure allows treatment timing to be evaluated not only by post-treatment condition, but also by differences in deterioration trajectory relative to untreated pavement exposed to similar roadway and environmental conditions.

However, field condition measures alone cannot fully describe the internal condition of pavement materials. Roughness, cracking, rutting, macrotexture, and condition indices describe the response visible at or near the pavement surface, whereas binder oxidation, rheological stiffening, and reduced relaxation capacity develop within the pavement layers. Two sections may therefore show similar field condition while having different levels of binder aging and different susceptibility to future cracking.

The present study addresses this limitation by combining longitudinal field-performance trends with laboratory characterization of binders recovered from field cores. Field measurements provide evidence of functional condition and distress progression, while

recovered binder testing provides information about chemical, rheological, and mechanical aging within the pavement layers. Integrating these two sources of information provides a more complete basis for evaluating chip seal timing than surface condition indicators alone.

2.5 In-Service Asphalt Binder Aging and the Protective Role of Chip Seals

In-service asphalt binder aging is a progressive process that changes both the chemical composition and rheological behavior of the binder after construction. As asphalt binder ages, it generally becomes stiffer, less ductile, and less able to relax thermally induced stresses. These changes are important for pavement preservation because they influence the pavement's susceptibility to cracking, raveling, and other age-related forms of deterioration (Baumgardner, 2021; Lu & Isacsson, 2002; Petersen, 2009).

Binder aging is not controlled by time alone. Pavements of similar age may experience different aging rates because of differences in binder source, mixture design, air void structure, pavement density, traffic loading, temperature history, moisture exposure, and solar radiation. Aging is also not uniform through the pavement depth. The near-surface portion of the asphalt layer is typically exposed to more oxygen, ultraviolet radiation, moisture, and temperature fluctuation than material located deeper in the pavement structure. Therefore, the binder recovered from the surface layer may exhibit substantially different properties from binder recovered from lower layers.

This issue is central to chip seal timing. A chip seal may reduce future exposure of the existing pavement surface to oxygen, water, and sunlight, but it cannot reverse oxidation, embrittlement, or cracking susceptibility that has already developed within the asphalt mixture.

For this reason, the preservation benefit of a chip seal may depend not only on visible surface condition, but also on the aging state of the asphalt binder at the time of treatment.

2.5.1 Mechanisms of In-Service Asphalt Binder Aging

Asphalt binder aging in service is governed by several related mechanisms, including oxidation, volatilization, thermal exposure, ultraviolet radiation, and moisture-related environmental effects. These mechanisms are often discussed separately, but they occur together in the field. Temperature affects oxidation rate, pavement density affects oxygen movement, moisture can weaken adhesive bonds and create additional pathways for deterioration, and UV radiation accelerates aging near the exposed surface.

Oxidative aging is generally considered the dominant long-term aging mechanism in asphalt pavements. During oxidation, oxygen reacts with susceptible binder components and forms more polar chemical groups, commonly reflected by increases in carbonyl and sulfoxide functional groups. These chemical changes alter the balance of binder fractions and are commonly associated with increased stiffness, reduced phase angle, lower ductility, and reduced relaxation capacity (Camargo et al., 2020; Lu & Isacsson, 2002; Petersen, 2009). From a performance standpoint, this means that an aged binder may resist deformation at high temperature but become less capable of relaxing stress at low temperature, increasing the potential for cracking.

Oxidation is also affected by oxygen transport within the compacted asphalt mixture. Oxygen must reach the binder through surface openings, connected air voids, cracks, or other pathways before oxidation can occur. Wen and Wang (2018) showed that oxygen diffusion

coefficients in compacted asphalt mixtures vary with mixture volumetric characteristics and can affect aging susceptibility. This means that field aging depends not only on binder chemistry, but also on mixture structure and the ability of oxygen to move through the pavement.

Volatilization and thermal aging are more influential during production, mixing, placement, and early pavement life, when asphalt binder is exposed to elevated temperatures. Loss of lighter binder components and short-term oxidation during mixing can increase viscosity and contribute to initial hardening. After construction, long-term field aging is controlled more strongly by oxidation, but thermal exposure remains important because pavement temperature affects reaction rate, oxygen diffusion, and the development of thermal stresses (Airey, 2007; Camargo et al., 2020). Therefore, chronological pavement age should not be treated as a direct measure of aging severity. Two pavements constructed in the same year may age differently if they experience different thermal histories, surface densities, or environmental exposure.

Also, UV radiation contributes primarily to aging near the pavement surface. Unlike oxygen and heat, which may influence material deeper in the pavement through diffusion and temperature gradients, UV exposure is concentrated at the exposed surface. Laboratory studies comparing thermal-oxidative and photo-oxidative aging have shown that UV exposure can produce chemical and rheological changes that differ from thermal aging alone (Abouelsaad & White, 2022). This is relevant to chip seals because the treatment covers the existing asphalt surface with a binder-aggregate layer, reducing direct solar exposure to the original surface. However, the extent of UV protection depends on aggregate coverage, binder durability, aggregate retention, and whether cracks or gaps later expose the old pavement surface.

Additionally, moisture does not age asphalt binder in the same direct chemical manner as oxygen, but it can accelerate pavement deterioration by weakening aggregate-binder adhesion, contributing to stripping, and interacting with freeze-thaw cycles. Moisture can also enter through cracks, open-textured areas, construction joints, or poorly sealed surfaces and can promote damage beneath the treatment layer. For chip sealed pavements, this distinction is important. A chip seal may reduce surface water infiltration, but it cannot eliminate moisture-related damage caused by poor drainage, subsurface water, or active cracks beneath the surface. Moisture protection should therefore be interpreted as a reduction in exposure, not as complete elimination of moisture-related deterioration mechanisms.

Together, these mechanisms show that binder aging is controlled by both environment and mixture structure. Oxidation, heat, UV radiation, and moisture act through the pavement surface, but their effects are shaped by density, permeability, air void connectivity, cracking, and pavement temperature. This explains why aging often varies with pavement depth.

2.5.2 Aging Gradients through Asphalt Pavement Depth

Field aging is commonly more severe near the pavement surface because the upper layer is directly exposed to oxygen, sunlight, moisture, and larger temperature fluctuations. However, the depth of aging is not limited to the surface alone. Oxygen can move through connected air voids and cracks, allowing oxidation to occur below the uppermost portion of the pavement. The aging condition of the surface binder may not fully represent the aging condition of the underlying asphalt layers.

Woo et al. (2008) evaluated recovered binders from field cores taken from long-term pavement sections in Texas and reported that binder aging could occur several inches below the pavement surface. Their work also showed that accessible air voids were related to oxidation and hardening rate. This finding is important because it demonstrates that field aging can extend beyond the surface layer when the mixture structure allows oxygen movement.

The concept of aging gradients is also supported by oxygen diffusion research. Wen and Wang (2018) showed that oxygen diffusion in compacted asphalt mixtures depends on mixture volumetric characteristics and that oxygen availability inside the pavement has implications for long-term durability. In practical terms, two pavements exposed to similar climate and traffic conditions may develop different aging gradients if their air-void structure, density, or permeability differs.

Aging gradients are particularly important when evaluating chip seal timing because chip seals act at the surface. If most aging is still concentrated near the surface and the pavement remains relatively intact, a chip seal may reduce further environmental exposure and slow additional hardening. If oxidation and cracking susceptibility have already extended deeper into the pavement, the same surface treatment may provide less long-term benefit because the underlying mixture has already lost part of its relaxation capacity. Therefore, depth-specific binder recovery and testing provide information that surface condition surveys alone cannot capture.

2.5.3 Effects of Surface Treatments on Binder Aging

Surface treatments are intended to protect the existing pavement by reducing exposure to oxygen, water, sunlight, and traffic-induced surface wear. For chip seals, this protection is provided by the combined binder-aggregate layer applied over the existing asphalt surface. The aggregate provides cover and texture, while the binder seals the surface and helps reduce infiltration. This protective role is widely recognized in chip seal guidance, which describes chip seals as treatments used to reduce water intrusion, protect against oxidation, and slow surface deterioration on pavements that remain structurally adequate (Transit New et al., 2005; Ulring et al., 2021).

The aging benefit of a chip seal is based mainly on reducing future exposure, not restoring binder that has already aged. A continuous chip seal may reduce oxygen access to the original pavement surface, but oxygen can still enter through cracks, joints, edges, and connected voids within the asphalt mixture. Recent work by Chen and Wang (2024) supports this general concept by evaluating preventive maintenance treatments using oxygen diffusion behavior and showing that different surface treatments can provide different levels of oxygen-retarding performance. Therefore, the protective role of a chip seal should be understood as slowing or reducing aging progression, not stopping it completely.

Chip seals may also reduce moisture and UV exposure. The binder-aggregate layer helps shield the existing asphalt surface from direct rainfall and sunlight, while the aggregate cover reduces direct UV exposure to the original pavement surface. This is important because UV aging is concentrated near the exposed surface and moisture can weaken bonds and increase deterioration through cracks or permeable areas. However, the durability of this protection

depends on construction quality, aggregate retention, crack development, traffic loading, and environmental exposure. If the seal loses aggregate, flushes, cracks, or debonds, the protective barrier becomes less effective over time.

Field and laboratory evidence on the anti-aging role of surface treatments is promising but still limited. Velasquez et al. (2009) evaluated surface-treated Minnesota pavement sections using mixture and binder mechanical testing and reported that the chip sealed section showed favorable low-temperature-related properties, including lower mixture and binder stiffness and higher binder *m*-value compared with other sections. However, the authors cautioned that the findings were based on a limited number of samples. That caution matters beyond this single study: the sections evaluated were drawn from one climate region and a narrow range of traffic and mixture types, so the direction of the effect may not generalize to other regions or binder sources without independent replication.

Treatment timing affects the magnitude of this protective benefit. A chip seal applied while the near-surface mixture is still relatively flexible may reduce future exposure before severe oxidation and embrittlement develop. A chip seal applied after substantial aging, cracking, or stiffness increase may still reduce water infiltration and protect the surface, but it cannot fully recover lost binder relaxation capacity or reverse oxidation. Therefore, the same treatment may produce different long-term outcomes depending on the aging state of the pavement when it is applied.

2.5.4 Relationship between Binder Aging and Pavement Distress Development

Binder aging affects pavement performance because it changes how the asphalt mixture responds to temperature, traffic loading, and environmental exposure. As binders oxidize and harden, the mixture may become stiffer and less able to dissipate energy or relax stress. These changes can increase susceptibility to transverse cracking, block cracking, raveling, and other age-related distresses, although field performance also depends on mixture structure, pavement thickness, traffic loading, foundation support, drainage, and climate (Baumgardner, 2021; Lu & Isacsson, 2002; Petersen, 2009).

The connection between binder aging and cracking is especially important in cold-climate pavement systems. Reduced relaxation capacity can allow thermal stresses to build more rapidly as pavement temperature decreases. Baumgardner (2021) explains that the ΔT_c parameter provides insight into asphalt binder relaxation properties and age-related embrittlement distresses. Therefore, binder aging should not be evaluated only as an increase in stiffness; it should also be evaluated in terms of the binder's ability to relax stress and resist cracking.

A direct one-to-one relationship between any single binder-aging index and field cracking should not be expected. Pavements with similar oxidation levels may perform differently because of differences in mixture design, air-void structure, traffic exposure, pavement thickness, and drainage. Likewise, cracking may be caused by thermal movement, reflection from underlying layers, fatigue loading, construction joints, or structural deficiency, even when binder aging is not the only controlling factor. Binder aging measures should

therefore be interpreted as explanatory material indicators rather than as complete substitutes for field performance data.

The value of combining field performance and recovered binder testing is that the two sources of information describe different parts of the pavement response. Field measurements show how the pavement performs at the surface through roughness, cracking, rutting, texture, and visual condition. Recovered binder tests show how the asphalt material has changed chemically and rheologically within the pavement layers. When these data are interpreted together, they can help distinguish pavements that appear similar at the surface but differ in stiffness, oxidation level, relaxation capacity, and susceptibility to future cracking.

This combined approach is necessary for evaluating the protective role of chip seals. If a chip seal slows field deterioration and the recovered binder shows lower aging severity relative to an untreated control, the treatment may be providing both functional and material-level preservation benefit. If field condition appears stable but recovered binders show substantial aging, the pavement may be more vulnerable to future cracking than the surface condition alone suggests. For this reason, evaluating chip seal timing requires both long-term field performance data and laboratory characterization of binders recovered from different pavement depths.

2.6 Recovery and Characterization of Asphalt Binders from Field Cores

Recovered-binder testing provides a direct means of evaluating asphalt-binder condition after actual pavement service. However, the measured properties may be influenced by the extraction solvent, recovery procedure, residual solvent, and heating applied during laboratory

processing (Mikhailenko et al., 2019). Field-recovered binders may also exhibit nonuniform aging through the pavement depth because of differences in oxygen availability, temperature exposure, air-void connectivity, and mixture characteristics (Woo et al., 2008; Yin et al., 2017). This makes recovered binder characterization especially important for chip seal timing research because the treatment effect is not limited to surface appearance. A chip seal may reduce future environmental exposure at the surface, but its preservation value depends partly on the aging condition of the binder when the treatment was applied (Li et al., 2011).

Recovered binder results must be interpreted within the limitations of extraction and recovery. These procedures are necessary for separating binder from mixture, but they may influence measured properties through solvent effects, residual solvent, recovery temperature, heating duration, loss of volatile fractions, or binder modification (Mikhailenko et al., 2019). Asphalt binder oxidation also changes rheological behavior over time by increasing stiffness and reducing stress-relaxation capacity, which means recovered binder testing must distinguish between in-service aging, original material characteristics, and laboratory recovery effects (Federal Highway, 2015; Petersen & Glaser, 2011). Therefore, the strongest use of recovered binder data in this study is comparative: treated sections, untreated controls, upper layers, and lower layers are evaluated within a consistent recovery and testing framework.

In this study, recovered binder characterization is used to determine whether sections chip sealed at different pavement ages exhibit measurable differences in oxidation, stiffness, relaxation capacity, cracking-related response, and asphalt-aggregate bond condition. The objective is not simply to report binder test values, but to determine whether those values

collectively indicate delayed aging, reduced embrittlement, or improved preservation of the underlying asphalt binder.

2.6.1 Field Core Sampling and Layer-Specific Binder Evaluation

Field cores provide a physical link between pavement performance and the material state of the asphalt layers beneath the surface. Their value in preservation research is not limited to confirming that aging has occurred. More importantly, cores allow the researcher to determine where aging has occurred. This depth-specific distinction is critical because surface condition alone may not represent the aging state of the entire asphalt layer (Woo et al., 2008; Yin et al., 2017).

Field aging is commonly nonuniform with depth. The pavement surface is exposed to greater oxygen availability, ultraviolet radiation, temperature cycling, moisture, and air exchange than deeper material. As oxidation progresses, binder stiffness increases and stress relaxation slows, which can increase the likelihood of thermally induced and age-related cracking (Federal Highway, 2015; Petersen, 2009). Woo et al. (2008) showed that binders can age several inches below the pavement surface and that lower accessible air voids are associated with lower oxidation and hardening rates. This finding is important because it demonstrates that field aging is not purely a surface phenomenon. Yin et al. (2017) similarly demonstrated that field aging varies with pavement depth and affects both binder and mixture properties.

The mechanism behind this depth gradient is related to oxygen diffusion, air-void connectivity, temperature, and binder chemistry. Prapaitrakul et al. (2011) Prapaitrakul et al.

(2009) modeled asphalt binder oxidation as a transport-controlled process, showing that oxygen availability and diffusion affect the rate and depth of binder aging. This helps explain why two pavements with similar surface condition may have different recovered binder properties through depth. A pavement with greater connected air voids or more open surface texture may allow oxidation to progress more deeply than a denser pavement with less accessible pore structure.

Layer-specific sampling is therefore directly relevant to chip seal timing. A chip seal applied early may limit continued exposure of the near-surface binder before severe oxidation develops. A chip seal applied after substantial near-surface aging has already occurred may reduce future exposure, but it cannot reverse embrittlement that has already developed. Thus, comparing upper and lower recovered binders helps distinguish between sections where chip sealing may have slowed surface aging and sections where aging had already progressed before treatment.

2.6.2 Binder Extraction and Recovery from Field Cores

Extraction and recovery are required before recovered binders can be chemically or rheologically characterized. However, these steps should be treated as part of the measurement system rather than as neutral sample preparation. The selected solvent, extraction approach, recovery temperature, recovery duration, and residual-solvent removal process can affect the stiffness, viscosity, volatility, and chemical composition of the recovered binder (Mikhailenko et al., 2019).

Mikhailenko et al. (2019) reviewed the main factors that influence recovered binder properties, including extraction method, recovery method, solvent type, residual solvent, and additional aging during recovery. Their review emphasized that no extraction and recovery method is completely free from artifacts. This concern is particularly important for field-aged binders because they may already be oxidized, stiffened, and sensitive to additional heat exposure. Residual solvent can soften recovered binder, while excessive heating or volatile loss can increase apparent stiffness.

Polymer-modified binders, reclaimed asphalt pavement (RAP)-containing mixtures, and severely aged binders may also respond differently to extraction and recovery than unmodified virgin binders. RAP is especially relevant because the recovered binder from a mixture containing recycled material may represent a blend of virgin binder, aged RAP binder, and binder aged during field service. The FHWA ΔT_c technical brief notes that pre-aged materials such as RAP and recycled asphalt shingles (RAS) can shift binder relaxation properties toward more negative ΔT_c values, similar to extended aging of virgin binder (Baumgardner, 2021). Therefore, recovered binder properties should be interpreted as measured indicators of field condition under a defined laboratory procedure, not as exact reconstructions of the binder in the pavement before coring.

For this study, extraction and recovery uncertainty does not eliminate the value of recovered binder testing, but it requires integrated interpretation. If treated and control sections are processed using the same procedures, systematic differences in oxidation, rheology, low-temperature relaxation, or bond strength can still provide meaningful evidence of

relative aging condition. This is why chemical, rheological, low-temperature, and adhesion-related indicators are considered together rather than relying on one recovered binder property alone.

2.6.3 Chemical Characterization of Field-Aged Binders

Chemical characterization helps determine whether rheological changes are associated with oxidation rather than only binder source, polymer modification, RAP content, or recovery effects. Asphalt oxidation produces more polar functional groups and contributes to age hardening, molecular association, increased stiffness, and reduced relaxation capacity (Federal Highway, 2015; Petersen & Glaser, 2011). Petersen and Glaser (2011) identified oxidation products as central contributors to binder age hardening, while FHWA's chemo-mechanical aging framework links oxidation chemistry to changes in binder rheology and pavement stress development.

Fourier Transform Infrared Spectroscopy (FTIR)-based carbonyl and sulfoxide indices are useful because they provide chemical evidence of oxidation exposure. Carbonyl growth is commonly associated with oxygen uptake and long-term oxidative aging, while sulfoxide formation may reflect sulfur oxidation and can be prominent during earlier stages of aging depending on binder chemistry (Federal Highway, 2015; Petersen & Glaser, 2011). Nie et al. (2020) demonstrated that FTIR-based carbonyl and sulfoxide indices can be used to characterize aging behavior in both unmodified and modified asphalt binders, while Islam et al. (2024) reported that carbonyl index values from field-extracted binders were strongly related to

pavement service age. These studies support the use of FTIR as a chemical complement to rheological testing.

However, carbonyl and sulfoxide indices are affected by binder source, crude chemistry, modification, recycled binder contribution, and index calculation method (Nie et al., 2020; Petersen & Glaser, 2011). Their value in this study is not as universal thresholds, but as section- and layer-level indicators of relative oxidation within the same testing program. This is particularly important when comparing sections with different material histories, such as mixtures containing RAP or polymer-modified binders.

For chip seal timing, chemical characterization helps evaluate whether the treatment reduced environmental aging at the pavement surface. Lower carbonyl or sulfoxide indices in treated upper-layer binders relative to the control would support the interpretation that chip sealing helped limit oxidation after application. Similar chemical indices across treated and control sections may indicate that aging had already progressed before treatment, that the chip seal effect was limited, or that material variability, including RAP contribution, influenced the recovered binder response.

2.6.4 Rheological and Damage-Related Characterization Using the Dynamic Shear Rheometer (DSR)

Rheological characterization translates chemical aging into mechanical implications. Oxidation generally increases binder stiffness, reduces viscous flow, lowers phase angle, and decreases stress-relaxation capacity (Federal Highway, 2015; Petersen & Glaser, 2011). These changes can improve high-temperature deformation resistance while simultaneously increasing

susceptibility to cracking at intermediate and low temperatures. Therefore, rheological results must be interpreted as performance tradeoffs rather than as uniformly beneficial or harmful changes.

Multiple Stress Creep Recovery (MSCR) and Linear Amplitude Sweep (LAS) are reviewed here because they are standard components of the recovered binder characterization framework used throughout the literature, alongside rotational viscosity (RV), DSR-based grading and rheological indicators, Bending Beam Rheometer (BBR) and ΔT_c , FTIR, and Binder Bond Strength (BBS) (Anderson et al., 2011; Baumgardner, 2021; D'Angelo et al., 2007; Hintz et al., 2011). Not every recovered binder study reports all of these tests together, but each contributes to interpreting deformation response, fatigue-related damage, and long-term binder performance.

RV provides an initial indication of bulk flow resistance and aging-related stiffening. For recovered binders, higher viscosity may reflect oxidative hardening, aged recycled binder contribution, polymer effects, or loss of lighter fractions (Mikhailenko et al., 2019; Petersen & Glaser, 2011). However, viscosity alone does not determine cracking susceptibility because a binder may resist flow at high temperature while still having poor relaxation capacity at lower temperatures. Its main value in this study is as a supporting stiffness-related indicator.

DSR-derived complex modulus and phase angle provide a broader interpretation of viscoelastic balance. Aging commonly increases G^* and reduces phase angle, indicating a stiffer and less viscous response (Federal Highway, 2015; Petersen & Glaser, 2011). In chip seal timing research, this distinction matters because a higher recovered high-temperature grade may

suggest improved rutting resistance, but it may also indicate age hardening and reduced cracking resistance. Thus, high-temperature stiffness should not be interpreted as evidence of preservation benefit unless it is considered alongside intermediate- and low-temperature indicators.

MSCR results describe deformation resistance and recovery behavior under repeated creep and recovery loading. D'Angelo et al. (2007) developed MSCR to improve high-temperature binder characterization, particularly for modified binders whose stress-dependent response may not be captured by conventional Superpave rutting parameters. MSCR nonrecoverable creep compliance is commonly interpreted as an indicator of permanent deformation resistance, while percent recovery is used to evaluate elastic response and stress dependence (Asphalt, 2019; D'Angelo et al., 2007). For field aged binders, however, lower nonrecoverable creep compliance may reflect oxidative hardening rather than improved material health. Therefore, MSCR is useful for identifying deformation-related behavior, but it does not by itself indicate whether chip sealing preserved the binder.

Intermediate-temperature DSR indicators provide a closer connection to cracking-related response. Aging-induced increases in stiffness and reductions in phase angle indicate reduced relaxation capacity, which can increase vulnerability to fatigue, block, and transverse cracking (Anderson et al., 2011; Federal Highway, 2015; Rowe, 2014). Traditional parameters such as $G^* \sin \delta$ provide useful information but may not fully capture damage resistance, especially for polymer-modified binders or field-aged binders with complex material histories.

Furthermore, the Glover-Rowe (G-R) parameter is useful because it combines stiffness and phase angle into a cracking-related index. Higher G-R values generally indicate a binder that is both stiff and less capable of relaxation, which is consistent with embrittlement and age-related cracking risk (Anderson et al., 2011; Rowe, 2014). Recent work has continued to evaluate Glover-Rowe as a sensitive indicator of aging-related cracking behavior, especially when interpreted with other rheological and chemical indicators (Guan et al., 2023; Rahman et al., 2023). Its role in this study is not to predict pavement cracking by itself, but to help connect recovered binder rheology with observed cracking trends when interpreted together with BBR, ΔT_c , FTIR, and field distress data.

Additionally, LAS provides a damage accumulation perspective by evaluating binder fatigue resistance under increasing strain demand. Hintz et al. (2011) described LAS as a binder-level fatigue assessment approach developed to move beyond simple stiffness-based interpretation and consider progressive damage using viscoelastic continuum damage concepts. Later reviews of binder fatigue testing have continued to identify LAS as a useful accelerated fatigue characterization method, while also noting that fatigue life estimates depend on test temperature, failure definition, aging condition, and analysis procedure (Nouali et al., 2024). Because pavement fatigue performance also depends on mixture structure, layer thickness, support conditions, traffic, temperature, and existing distress, LAS results are best treated as relative binder-level indicators rather than direct predictions of pavement fatigue life.

For chip seal timing, DSR-based characterization helps determine whether treated sections retained a more favorable rheological balance than untreated control sections. A

favorable preservation response would not simply mean lower stiffness or higher stiffness.

Rather, it would mean limited oxidative stiffening, adequate deformation resistance, and better retained relaxation capacity at intermediate temperatures.

2.6.5 Low-Temperature Stiffness and Stress-Relaxation Characterization

Low-temperature characterization is essential in cold-climate chip seal studies because transverse cracking and thermally induced distress are strongly influenced by binder stiffness and stress-relaxation capacity. A binder may appear acceptable based on high-temperature properties but still be vulnerable to cracking if it cannot relax thermal stresses during cooling (Anderson et al., 2011; Baumgardner, 2021; Federal Highway, 2015). This is particularly important for cold region field sections, where seasonal temperature drops can expose differences in binder embrittlement that may not be evident from high-temperature grading alone.

BBR stiffness and m-value should be interpreted together. Stiffness reflects resistance to deformation under low-temperature loading, while m-value reflects the rate of stress relaxation. Aging tends to increase stiffness and reduce relaxation capacity (Baumgardner, 2021; Federal Highway, 2015). A binder with high stiffness and low m-value is more likely to accumulate thermal stress because it cannot dissipate stress quickly enough as pavement temperature decreases.

ΔT_c strengthens the low-temperature interpretation because it compares the critical temperature controlled by stiffness with the critical temperature controlled by relaxation. More negative ΔT_c values indicate that the binder is increasingly controlled by its relaxation capacity

rather than stiffness alone. Baumgardner (2021) described ΔT_c as a binder parameter that provides insight into relaxation properties associated with non-load-related cracking and age-related embrittlement. The Asphalt (2019) similarly describes ΔT_c as a durability-related parameter that is sensitive to aging and relaxation behavior. Therefore, ΔT_c is useful for identifying embrittlement that may not be apparent from high-temperature grade, viscosity, or stiffness alone.

ΔT_c is also important for interpreting binders containing recycled materials (Baumgardner, 2021). This matters in field-core research because recovered binder relaxation properties may reflect both the original mixture design and the aging that occurred during pavement service. Therefore, when ΔT_c differs among sections, the interpretation should consider treatment timing, depth, binder source, recycled binder contribution, and field exposure history together.

For chip seal timing, a less negative ΔT_c in treated upper-layer binders relative to the control would suggest that chip sealing helped preserve low-temperature relaxation capacity. A highly negative ΔT_c in a later-treated section may indicate that substantial embrittlement had already developed before treatment. These results should be interpreted with transverse cracking data because field cracking is also affected by mixture stiffness, aggregate structure, pavement thickness, thermal contraction, traffic, and pre-existing cracks.

2.6.6 Adhesion and Moisture Susceptibility Characterization Using the Binder Bond Strength Test

Adhesion and moisture susceptibility represent a different performance dimension from chemical oxidation or rheological stiffening. A binder may have acceptable stiffness and relaxation properties but still perform poorly if the asphalt-aggregate bond deteriorates under moisture exposure. Moisture damage can develop through loss of adhesion at the binder-aggregate interface, loss of cohesion within the asphalt mastic, or combined adhesive-cohesive failure mechanisms (Bhasin et al., 2006; Caro et al., 2008; Omar et al., 2020). This distinction is important for chip seal research because preservation treatments are expected to reduce moisture infiltration, seal small surface openings, and protect the underlying asphalt layer from environmental exposure.

Caro et al. (2008) reviewed moisture damage mechanisms and emphasized that void structure, moisture transport, aggregate mineralogy, binder chemistry, and traffic loading all influence moisture susceptibility. Bhasin et al. (2006) showed that loss of physical adhesion between asphalt binder and aggregate is an important mechanism that accelerates moisture damage in asphalt mixtures. These findings show why moisture susceptibility cannot be fully explained by binder stiffness alone. A binder may become stiffer with age but still lose bond durability if moisture weakens the binder-aggregate interface.

Moraes et al. (2011) showed that asphalt-aggregate bond strength depends on binder modification, aggregate type, and moisture exposure time, and that BBS testing can distinguish differences in bond strength and moisture susceptibility. Their work also showed that polymer modification can improve adhesion between asphalt and aggregate as well as cohesion within

the binder. This makes BBS particularly useful in recovered binder research because it evaluates an interfacial property that cannot be captured by FTIR, DSR, or BBR alone.

For field-aged binders, aging can have competing effects on bond strength. Moderate stiffening may increase cohesive strength because the binder film becomes more resistant to pull-off failure. However, severe oxidation can reduce flexibility, increase brittleness, and weaken the binder's ability to maintain a durable bond under moisture conditioning (Caro et al., 2008; Moraes et al., 2011; Omar et al., 2020). Which effect dominates depends on the aging level, binder chemistry, aggregate mineralogy, modification, moisture exposure, and existing damage condition.

For chip seal timing, BBS results help determine whether treated sections retained better interfacial durability than untreated control sections. If chip sealing reduces moisture infiltration and environmental exposure, treated sections may show lower moisture-conditioned bond strength loss than the control. Conversely, poor BBS performance in a treated section may indicate that moisture-related deterioration had already occurred before treatment or that surface sealing did not fully preserve the asphalt-aggregate interface.

2.6.7 Integrating Chemical, Rheological, and Mechanical Aging Indicators

No single binder test can fully characterize field aging. FTIR identifies oxidation products, viscosity and DSR describe stiffness and viscoelastic response, MSCR evaluates deformation and recovery behavior, Glover-Rowe and LAS provide cracking-related rheological indicators, BBR and ΔT_c evaluate low-temperature stiffness and relaxation, and BBS evaluates adhesion and moisture susceptibility (Anderson et al., 2011; Baumgardner, 2021; Mikhailenko et al., 2019;

Moraes et al., 2011; Petersen & Glaser, 2011; Rowe, 2014). Each test captures a different part of the aging and performance pathway.

The most useful interpretation is a cause-effect framework. Chemical indices indicate whether oxidation has occurred. Rheological measures show how that oxidation has changed binder stiffness, elasticity, relaxation, and recovery. Low-temperature properties indicate whether the binder can resist thermal cracking. Adhesion testing indicates whether the binder-aggregate bond remains durable under moisture exposure. Field performance data, including cracking, IRI, and other indicators, then provide the pavement-level context needed to determine whether the measured binder condition is reflected in actual section performance.

These indicators may not always move in the same direction. A recovered binder may show increased high-temperature grade and improved MSCR deformation resistance while also showing higher Glover-Rowe values, more negative ΔT_c , and poorer cracking resistance (Anderson et al., 2011; Baumgardner, 2021; D'Angelo et al., 2007). Similarly, a binder may show moderate chemical oxidation but limited change in recovery behavior because polymer modification affects elastic response. These apparent contradictions are not errors. They reflect the fact that aging can improve one performance dimension while degrading another.

For chip seal timing, the integrated testing framework allows treatment effectiveness to be evaluated more completely than surface distress measurements alone. Early chip seal application would be expected to reduce surface oxidation, limit top-layer stiffening, preserve intermediate- and low-temperature relaxation, and maintain better asphalt-aggregate bond condition. Later application may still reduce future exposure, but it may not reverse oxidation,

embrittlement, or moisture-related bond degradation that occurred before treatment (Buss et al., 2018; Federal Highway, 2015; Li et al., 2011).

Therefore, the objective of recovered binder characterization in this study is not to identify one universal aging threshold. Instead, the objective is to determine whether sections chip sealed at different pavement ages exhibit systematic differences in binder oxidation, stiffening, relaxation capacity, cracking-related response, and adhesion durability. This integrated interpretation provides a stronger basis for evaluating the optimal timing of chip seal application and for linking field performance trends to the underlying material condition of the asphalt binder.

2.7 Long-Term Field Performance of Chip Seals and Evidence on Treatment Timing

Long-term field performance studies generally show that chip seal effectiveness is conditional rather than universal. Treatment response depends on pretreatment pavement condition, climate, traffic loading, pavement structure, construction quality, and the performance measure used to define benefit. A chip seal may reduce the rate of cracking or protect the near-surface asphalt from moisture and oxidation, but it should not be expected to correct roughness, rutting, or distress caused by structural deficiencies in the underlying pavement layers.

This distinction is important for treatment timing research. The preservation benefit of a chip seal is not determined only by the calendar year in which the treatment is applied, but by whether the pavement still retains enough structural and material integrity for a surface treatment to meaningfully alter its future deterioration rate. Therefore, the strongest long-term

evidence supports a conditional interpretation: chip seals are most effective when applied before surface cracking, binder aging, and moisture-related deterioration have progressed beyond the functional role of a thin surface seal.

2.7.1 Scope and Limitations of Long-Term Chip Seal Evidence

Long-term field studies provide the most relevant evidence for chip seal timing because they capture traffic loading, environmental exposure, construction variability, and in-service aging that cannot be fully reproduced in laboratory testing. The Long-Term Pavement Performance Specific Pavement Study 3, commonly referred to as LTPP SPS-3, remains one of the most important national datasets for pavement preservation because it included untreated control sections and four preventive maintenance treatments: crack sealing, slurry seals, chip seals, and thin hot-mix asphalt overlays. Morian et al. (1998) used five years of SPS-3 monitoring data to evaluate treatment performance, timing of application, and cost-effectiveness across sites in the United States and Canada. Because this evaluation relied on only five years of monitoring, it captures early-stage treatment performance but may not reflect the longer-term durability trends that typically emerge over a full pavement service life.

However, SPS-3 results should be interpreted within the limits of the experiment. The SPS-3 design was intended to compare preservation treatments across a wide range of climatic, traffic, subgrade, pavement-condition, and structural conditions. It was not designed to isolate the chemical aging state of the existing asphalt binder before treatment or to evaluate depth-dependent binder aging after chip seal placement. As a result, SPS-3 is valuable for identifying

broad preservation trends, but it cannot establish a single universal chip seal timing threshold that applies to all pavement structures, binder systems, climates, and traffic levels.

Later SPS-3 analyses reinforce this limitation. FHWA's long-term SPS-3 summary showed that treatment effectiveness varied by distress type, climate, traffic level, and pretreatment condition. Thin overlays and chip seals were generally more effective than slurry seals and crack seals for fatigue cracking, while thin overlays showed the clearest benefit for roughness and rutting progression. These findings are useful for agency-level treatment selection, but they also show that chip seal performance cannot be reduced to one performance measure or one timing rule.

State-level and local field studies provide more detailed information on local materials, construction practices, and agency decision-making, but they are usually less generalizable than SPS-3 because they are tied to specific climates, traffic levels, pavement structures, and treatment specifications. Therefore, the literature is strongest when national and local studies are interpreted together. National datasets identify broad performance patterns, while focused field projects help explain the material and pavement mechanisms behind those patterns.

A related limitation is the statistical interpretation of small-sample field and binder studies. Field core programs often involve limited numbers of sections, cores, directions, and recovered binder replicates because coring, extraction, recovery, and binder testing are labor-intensive and material-limited. Under these conditions, ANOVA, Tukey HSD, regression, and correlation results are useful for screening differences and identifying consistent patterns, but the absence of statistical significance at the 95% confidence level should not automatically be

interpreted as evidence of no practical effect. The broader statistical literature cautions against using $p < 0.05$ as a rigid decision boundary, especially when sample size, field variability, and measurement uncertainty limit power (Amrhein et al., 2019; Wasserstein & Lazar, 2016).

Pavement-material studies also commonly pair statistical testing with engineering interpretation, graphical trends, effect direction, and physical plausibility, particularly when evaluating aging, fracture, and recovered binder properties from field cores. This supports interpreting small-sample field results as evidence of trends and relative material response rather than as definitive proof of treatment superiority.

2.7.2 Treatment Timing and Performance-Measure-Dependent Effectiveness

The most consistent finding across long-term chip seal studies is that pretreatment pavement condition strongly influences treatment effectiveness. Morian et al. (1998) evaluated SPS-3 performance using a Pavement Rating Score that incorporated fatigue cracking, longitudinal cracking, transverse cracking, patching, bleeding, and rutting. This approach is important because it recognizes that chip seal effectiveness cannot be represented adequately by a single distress measure. A pavement may remain smooth while cracking progresses, or it may show limited rutting while oxidation and transverse cracking increase.

Gong et al. (2016) reached a similar conclusion using SPS-3 data and multiple performance indicators. Their analysis found that thin overlays and chip seals were effective in retarding fatigue cracking, while thin overlays were the only treatment consistently associated with slower long-term increases in roughness, rutting, longitudinal cracking, and transverse cracking. They also reported that pavements in poorer pretreatment surface condition

deteriorated faster in terms of roughness and longitudinal cracking. These findings do not mean that chip seals are ineffective. Rather, they show that chip seals are more effective for deterioration mechanisms that can be influenced by surface sealing than for mechanisms controlled by structural capacity, deformation, or preexisting roughness.

This measure-dependent response is consistent with the physical function of chip seals. Thin overlays add material thickness and can improve ride quality immediately, whereas chip seals are thin surface treatments intended primarily to seal the pavement, reduce moisture infiltration, improve surface texture, and slow surface-related deterioration. Therefore, a chip seal may reduce crack progression or protect the existing surface without producing a substantial improvement in IRI. Evaluating chip seals only with roughness may underestimate their preservation value, while evaluating them only through visual surface condition may overlook continued aging or cracking beneath the seal.

More recent SPS-3 analysis by Jia et al. (2020) further supports this conditional interpretation. Their study evaluated preventive maintenance treatments using roughness, rutting, transverse cracking, longitudinal cracking, and alligator cracking. They concluded that long-term effectiveness varied by treatment type and performance measure, and that each treatment may have a critical range of original pavement condition beyond which its long-term effectiveness declines. This finding directly supports the use of multiple field performance indicators in chip seal timing studies rather than relying on IRI, cracking, or surface rating alone.

Focused field studies support the same conclusion at the project level. In the NCAT pavement preservation experiment on Lee County Road 159 in Alabama, chip seal sections were

monitored using cracking, roughness, rutting, and macrotexture. Vargas-Nordbeck (2018) reported that treatment performance depended strongly on initial pavement condition, particularly the percentage of area cracked, and that pavements treated while still in good condition tended to remain in that condition longer. This result reinforces the preservation principle that chip seals should be applied while deterioration is still primarily surface-related and before cracking becomes too extensive.

Taken together, the evidence indicates that treatment timing should not be framed as identifying the latest possible year a chip seal can be applied. Instead, timing should be framed around whether the pavement condition, distress mechanism, and material state remain compatible with the function of a surface seal. A chip seal may be beneficial when the pavement is structurally sound and early deterioration is driven by oxidation, permeability, raveling, or low-to-moderate cracking. Its effectiveness becomes more limited when deterioration is governed by deep cracking, rutting, roughness, or insufficient structural capacity.

2.7.3 Evidence Linking Recovered Binder Properties, Aging Gradients, and Field Performance

Compared with the literature on field condition trends, fewer long-term studies directly connect recovered binder properties to chip seal timing and field performance. This is a major limitation because roughness, rutting, surface rating, and visual cracking do not directly describe the chemical and rheological condition of the existing asphalt binder. Two pavements may show similar visible distress but differ substantially in oxidation level, stiffness, relaxation capacity, low-temperature cracking susceptibility, and depth-dependent aging.

Islam et al. (2016) provide one of the clearest examples of linking chip seal field performance to recovered binder properties. Their study evaluated laboratory-aged and field-aged chip seal binders and related rheological properties to long-term raveling performance. They reported strong relationships between recovered binder response and field raveling, including a strong relationship between shear stress at failure of field-aged binders and long-term raveling performance. This work is important because it demonstrates that chip seal performance can be connected to measurable binder properties rather than only to visual distress surveys.

However, the Islam et al. (2016) study focused primarily on the chip seal binder and aggregate-retention behavior. It does not fully address how the aging condition of the underlying asphalt pavement affects the timing of chip seal placement or the long-term cracking response of the existing pavement layers. This distinction is central to the present study because chip seal performance involves both the newly placed aggregate-binder layer and the aging response of the pavement beneath it.

Minnesota and MnROAD-related research provides more direct evidence for connecting treatment timing with asphalt aging and layer-specific material response. Marasteanu et al. (2008) investigated the optimum time for surface treatment application using binder and mixture tests, including DSR, BBR, DTT, FTIR, and mixture fracture testing. Their work emphasized that surface treatment timing should be related to the aging and deterioration processes occurring in the pavement surface layer, not only to visible surface condition. The study also used ANOVA, correlation matrices, and Tukey HSD tests to identify binder and

mixture properties associated with deterioration, while acknowledging that the analysis did not identify a single clear trigger for optimum treatment timing.

The MnROAD-related findings are relevant because they show that the surface layer and underlying layer may age differently. Marasteanu et al. (2008) reported that asphalt binder and mixture properties varied with construction year, depth, wheel path location, and treatment timing. In mixture testing, lower layers generally showed higher relaxation rates than upper layers, which supports the concept of an aging gradient through pavement depth. This provides a mechanistic basis for evaluating chip seal timing using layer-specific recovered binder properties rather than treating the core as one uniform material.

Howard et al. (2013) also support examining the existing pavement rather than evaluating the new chip seal layer alone. Their Mississippi chip seal study evaluated chip and scrub seals using seven emulsions, three aggregates, and four asphalt pavement types. The study assessed both aggregate retention and near-surface pavement response using recovered binder viscosity, repeated creep of mixture bars, and BBR mixture-beam testing. This approach is valuable because it separates two related but distinct questions: whether the chip seal system retains aggregate and whether the treatment affects the near-surface properties of the existing asphalt pavement.

Together, these studies suggest that long-term chip seal performance should be interpreted through both field distress response and recovered binder characterization. Field performance data show whether a treatment changed the observed deterioration trajectory. Binder and mixture testing help explain why that trajectory occurred. The present study builds

on this combined framework by comparing staggered chip seal application years, untreated control sections, long-term field performance measures, and layer-specific recovered binder properties from the upper and underlying asphalt layers.

2.7.4 Implications for Local-Agency Decisions and the Present Study

For local agencies, chip seal decisions must remain practical and condition-based, since network-level data are typically limited to roughness, cracking, rutting, surface distress, traffic, drainage, pavement age, and maintenance history — rather than the chemical or rheological binder properties evaluated in this study. The literature does not support replacing these measures with recovered binder testing for routine project selection. Binder extraction, recovery, chemical testing, and rheological characterization are too time-consuming and resource-intensive for routine network-level screening.

However, the literature does show that conventional condition data do not fully explain why pavements with similar visible distress may respond differently after chip seal placement. Pretreatment roughness and cracking are useful indicators of current condition, but they do not directly measure oxidation, stiffening, loss of relaxation capacity, low-temperature cracking susceptibility, or depth-dependent binder aging. Laboratory characterization of recovered binder is most valuable as a research tool for explaining treatment response and improving future timing guidance.

The present study addresses this gap through a staggered-treatment field design. At each site, chip seals were applied to five sections in successive years, while a sixth section remained untreated as a control. This design makes it possible to compare long-term field

performance among pavements treated at different stages of pavement life and to relate those trends to chemical, rheological, and damage-related properties of binders recovered from the upper and underlying asphalt layers.

The literature therefore supports three conclusions. First, chip seal effectiveness depends strongly on pretreatment pavement condition, but no universal timing threshold applies across all projects. Second, chip seal benefits are performance-measure dependent; cracking and surface protection may respond differently from roughness or rutting. Third, long-term field studies rarely combine staggered treatment timing, untreated controls, multiple field performance measures, and layer-specific recovered binder characterization. This combination forms the principal contribution of the present study.

2.8 Summary and Research Gaps

2.8.1 Summary of Key Findings from Previous Research

This literature review examined pavement preservation philosophy, chip seal systems and performance, pavement condition evaluation, in-service asphalt binder aging, laboratory characterization of recovered binders, longitudinal performance analysis, and long-term evidence on chip seal effectiveness. Collectively, the literature shows that chip seals are most effective when applied as preservation treatments to pavements that remain structurally adequate and exhibit primarily surface-related deterioration. Their performance depends on a combination of factors, including pretreatment pavement condition, traffic loading, climate, aggregate and binder properties, design application rates, construction quality, pavement structure, and environmental exposure.

Previous research also shows that chip seal timing cannot be determined reliably from a single condition measure. Roughness, cracking, rutting, PCI and visual distress surveys describe different aspects of pavement behavior and may not change at the same rate after treatment. A section may continue to provide acceptable ride quality while cracking progresses, or it may show visible surface deterioration without a substantial increase in roughness. Therefore, chip seal effectiveness should be interpreted using multiple performance indicators and evaluated as a longitudinal trend rather than through isolated pre- and post-treatment observations.

The literature further demonstrates that asphalt binder aging is an important contributor to long-term pavement deterioration. Oxidation, temperature exposure, ultraviolet radiation, moisture-related damage, and mixture permeability can alter binder chemistry and rheological response over time. These aging effects are generally more severe near the pavement surface but may extend into underlying asphalt layers depending on mixture air-void structure, pavement permeability, and environmental exposure. Chip seals may reduce future exposure of the pavement surface to oxygen, moisture, and solar radiation; however, they cannot reverse oxidation, stiffening, or embrittlement that has already developed within the asphalt mixture before treatment.

Recovered binder testing provides a direct means of evaluating these material changes. FTIR indices can identify oxidation-related chemical changes, while viscosity, DSR-based parameters, MSCR, LAS, Glover-Rowe, BBR, and ΔT_c provide complementary information on stiffening, deformation resistance, fatigue-related behavior, cracking susceptibility, and low-temperature relaxation capacity. No individual laboratory test fully represents field aging or

pavement performance. A combined chemical and rheological framework is therefore more informative than reliance on a single aging indicator.

Long-term chip seal studies also show that treatment effectiveness is performance-measure dependent. Some studies report improved cracking performance, reduced deterioration rates, or extended service life, while others show limited or inconsistent effects on roughness or other functional indicators. This variability does not necessarily indicate that chip seals are ineffective. Rather, it demonstrates that the preservation benefit depends on when the treatment is placed, what condition measure is used to evaluate response, and whether the analysis captures long-term deterioration behavior.

2.8.2 Research Gaps in Chip Seal Timing Studies

Most chip seal timing studies have relied on pavement condition measures, treatment cost, and post-treatment field performance to define the optimal preservation window. These studies provide valuable agency-level guidance, but the reported timing relationships vary across pavement systems. Differences in climate, traffic, pavement structure, aggregate and binder materials, pretreatment condition, construction practices, and performance measures make it difficult to transfer a timing threshold developed for one agency or roadway type directly to another.

In addition, studies may reach different conclusions depending on how treatment effectiveness is defined. A chip seal applied later in pavement life may appear beneficial when evaluated by immediate surface improvement or short-term serviceability, whereas an earlier treatment may be more favorable when effectiveness is evaluated through reduced long-term

deterioration rate. This distinction indicates that chip seal timing should not be defined only as the latest pavement condition at which treatment remains feasible. It should also consider whether the treatment is applied early enough to influence future deterioration.

A key limitation of conventional timing criteria is that they rarely account directly for the aging condition of the existing asphalt binder. Surface distress and functional condition provide evidence of pavement response, but they do not identify the extent of oxidation, stiffening, or reduced stress-relaxation capacity within the asphalt layers. As a result, two pavements with similar surface condition may differ substantially in material aging state and may not respond similarly to chip seal treatment.

Another gap is the limited integration of treatment timing, untreated control performance, and material aging measurements within the same long-term field study. Without untreated control sections, it is difficult to distinguish treatment-related changes from deterioration that would have occurred naturally over time. Without recovered binder characterization, it is difficult to determine whether observed field performance differences are associated with differences in binder aging.

2.8.3 Research Gaps in Long-Term Field Binder Aging Evaluation

Field aging research has established that binder properties can vary substantially with pavement depth. However, many studies have focused on untreated pavements, laboratory-aged materials, limited core depths, or relatively short field exposure periods. As a result, there is limited evidence describing how chip seals influence aging gradients between the surface layer and underlying asphalt layers over extended service periods.

The available evidence suggests that surface treatments may reduce future environmental exposure and slow aging near the pavement surface. However, the magnitude and duration of this effect remain uncertain because relatively few studies have compared treated and untreated sections using binders recovered from multiple pavement depths. Existing studies also differ in binder type, pavement structure, climate, treatment configuration, sampling depth, extraction method, and recovery procedure, limiting direct comparison across projects.

Another limitation is that extraction and recovery procedures may affect measured binder properties. This does not prevent meaningful comparison among recovered binders when samples are processed consistently, but it does require caution when interpreting absolute values or applying universal aging thresholds. Recovered binder results are most useful when interpreted comparatively within a controlled field design and in combination with field performance data.

2.8.4 Research Gaps in Linking Field Performance with Recovered Binder Properties

Long-term chip seal studies commonly report roughness, cracking, rutting, aggregate retention, or service-life extension. Recovered binder studies commonly report chemical indices and rheological properties. These two bodies of literature have often developed separately, leaving a gap between pavement-level performance evaluation and material-level aging characterization.

As a result, few studies have directly evaluated whether differences in field performance among chip sealed sections can be explained, at least in part, by differences in binder aging within the surface and underlying asphalt layers. The relationship is not expected to be one-to-one because pavement distress is also affected by traffic, climate, pavement structure, drainage, mixture properties, construction quality, and maintenance history. Nevertheless, integrating field performance with recovered binder characterization may help explain why pavements with similar visible condition respond differently after chip seal placement.

A further gap is the limited use of untreated control sections in studies that also evaluate recovered binder properties. Control sections are necessary for distinguishing changes associated with chip seal treatment from aging and deterioration that would have occurred without treatment. They are especially important in long-term studies because both treated and untreated sections continue to age under traffic and environmental exposure.

There is also a need for studies that connect binder aging indicators to performance trends rather than to single-year condition observations. Because chip seal benefits may appear as a reduced rate of deterioration rather than an immediate improvement in all performance measures, longitudinal analysis is needed to evaluate whether material differences correspond to long-term field response.

2.8.5 Contribution of the Present Study

The present study addresses these gaps through a long-term field evaluation of chip seal sections treated at different stages of pavement life. At each of three test sites, five sections received chip seals in successive years from 2015 through 2019, while an additional section

remained untreated as a control. This staggered-treatment design provides an opportunity to compare sections treated at different pavement ages while evaluating untreated deterioration under similar site-specific traffic, climate, and pavement structure conditions.

The study combines longitudinal field performance data with chemical, rheological, and mechanical characterization of binders recovered from the surface and underlying asphalt layers. Field measures, including roughness, cracking, rutting, and surface condition where available, are evaluated together with recovered binder indicators such as FTIR oxidation indices and rheological properties. This combined framework allows chip seal effectiveness to be interpreted not only in terms of observed pavement condition, but also in terms of depth-dependent binder aging.

Rather than proposing a universal chip seal timing threshold, the study evaluates whether binder aging indicators can supplement conventional field condition measures when interpreting chip seal timing effectiveness. This approach recognizes that optimal timing is likely site-specific and dependent on both pavement condition and material aging state. The results are intended to provide a more complete basis for understanding how treatment timing, long-term field performance, and depth-dependent binder aging are related in chip sealed pavements.

Chapter 3 Methodology

This chapter details the methodology used in this study to evaluate whether the timing of chip seal applications influences the long-term pavement aging and performance. A three-phased methodology was employed to address this: review of construction documentation, field data collection and analysis, and asphalt binder characterization.

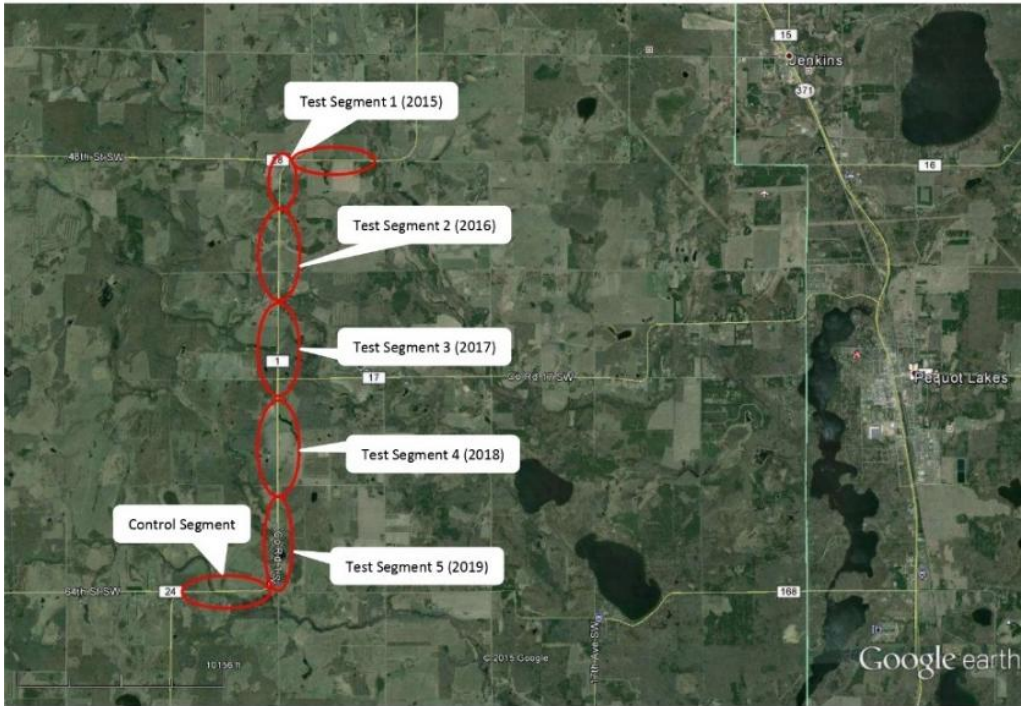
The first phase describes the three participating test sites namely, Cass County, Crow Wing County, and the City of St. Cloud, including their roadway characteristics, construction history, and chip seal timing. The second phase presents the field data collected over a 10-year period encompassing roughness and surface distress along with the analytical methods used to identify the performance trends across test sites. The final phase details the extraction and laboratory characterization of recovered asphalt binders, using rheological, chemical, and mechanical analyses to quantify the degree of binder aging and relate those findings to observed field performance.

3.1 Description of Test Sites

Three test sites were selected to represent a range of roadway environments, traffic levels, and pavement structures typical of local agency networks in Minnesota, as shown in Figure 1. One site was located in Cass County, one in Crow Wing County, and one in the City of St. Cloud. All pavements were newly constructed as part of full reconstruction projects. Construction was completed in 2015 for Cass County and in 2014 for both Crow Wing County and the City of St. Cloud.

Each site was subsequently divided into six test sections. Five sections received chip seal treatments in successive years between 2015 and 2019, while one section remained untreated to serve as a control. As shown in Figure 1, the control and treated sections were not always immediately adjacent, particularly at the county sites. Consequently, localized differences in traffic operations associated with intersections, access points, or surrounding land use cannot be completely ruled out. However, all sections were located on the same roadway within each agency and were selected to represent comparable roadway characteristics, allowing treatment timing to be evaluated under long-term field conditions.

Chip seal treatments were applied between 2015 and 2019 in accordance with MnDOT seal coat guidelines and local agency practices. Tables 1 and 2 summarize the asphalt mixture characteristics and chip seal design information for the three study sites. Within each site, comparable chip seal materials, target application rates, and construction practices were used across the successive treatment years, allowing treatment timing to be evaluated while minimizing differences in the chip seal system itself. Across the three sites, however, the roadways differed in traffic level, pavement structure, binder grade, RAP content, and asphalt mixture characteristics. In addition, fog seals were applied to all treated sections in Cass County and Crow Wing County, whereas only the 2018 and 2019 treated sections received fog seals in the City of St. Cloud. These site-specific differences provide important context for interpreting long-term field performance and recovered binder aging across the three study sites.



(a)



(b)



(c)

Figure 1. Location Maps of Pavement Preservation Chip Seal Study Sites by Local Agency: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud

Table 1. Asphalt Layer Mix and Design Characteristics

Parameter	Cass County	Crow Wing County	City of St. Cloud
Route name	CSAH 1	CSAH 3	3 rd Street N
2-Way ADT, vpd (2014)	882	1,630	10,600
Projected ADT, vpd (2034)	1,323	1,740	15,800
Design ESALs (20-Year)	< 1 million	< 1 million	1-3 million
Length of Each Test Section, ft.	5,280	5,280	300
Existing Granular Base Thickness, in.	4.0 in. Class 5 granular base beneath 4.0 in. FDR stabilized with T15.	8.0 in. Class 5 granular base with 2.0 in. stabilized layer used to address sandy subgrade conditions.	8.0 in.

*Wearing course mixture

CSAH = County state aid highway; FDR = full-depth reclamation; PG = performance grade; AC = asphalt concrete; RAP = reclaimed asphalt pavement; ADT = average daily traffic; vpd = vehicles per day; ESALs = equivalent single axle loads; NMAAS = nominal maximum aggregate size; AFT = asphalt film thickness.

Table 1. Asphalt Layer Mix and Design Characteristics (*continued*)

Parameter	Cass County	Crow Wing County	City of St. Cloud
Nominal Maximum Aggregate Size	2.0 inches of 9.5 mm NMAS mix for both wearing and non-wearing courses	2.0 inches of 9.5 mm NMAS wearing course and 2.0 inches of 12.5 mm NMAS non-wearing course	Two 1.5-inch lifts of 9.5 mm NMAS wearing course and 2.0 inches of 12.5 mm NMAS non-wearing course
Binder Grade AASHTO M332	PG 58H-34	PG 58S-28	PG 58H-34
Total AC %	4.8	4.8	5.44 5.33*
RAP %	20	38	0
Air voids (%)	3.0	4.0	4.3 2.7*
Adj. AFT, μm (min. 8.5)	9.0	8.9	8.3 8.8*

*Wearing course mixture

CSAH = County state aid highway; FDR = full-depth reclamation; PG = performance grade; AC = asphalt concrete; RAP = reclaimed asphalt pavement; ADT = average daily traffic; vpd = vehicles per day; ESALs = equivalent single axle loads; NMAS = nominal maximum aggregate size; AFT = asphalt film thickness.

Table 2. Chip Seal Layer Design Information

Parameter	Cass County	Crow Wing County	City of St. Cloud
Route name	CSAH 1	CSAH 3	3 rd Street N
Emulsion Type	CRS-2P	CRS-2P	CRS-2P
(Application Rate, gal/sq yd)	(0.32)	(0.32)	(0.24 – 0.30)
Aggregate Size, mm	4.75	4.75	4.75 – 9.5
(Application Rate, lb/sq yd)	(17)	(17)	(16 – 20)
Fog Seal Applied	Yes	Yes	2018, 2019 only
Fog Seal Type	CSS-1h	CSS-1h	CSS-1h
(Application Rate, gal/sq yd)	(0.12)	(0.12)	(0.14)

CSAH = County state aid highway; CRS-2P = rapid-setting, high-viscosity, polymer-modified

cationic asphalt emulsion; CSS-1h = slow-setting, low-viscosity, cationic asphalt emulsion made with hard base asphalt.

3.2 Field Data Collection

The type and level of detail of pavement distress data varied across the three participating agencies. As a result, the field data collection component of this study incorporated multiple performance indicators, each selected to align with the data routinely collected at each site. Three primary evaluation approaches were used to characterize pavement condition across the test sections in Cass County, Crow Wing County, and the City of St. Cloud.

First, pavement roughness was evaluated using annual IRI measurements for the two county sites. These data were collected using MnDOT's pavement monitoring program using the Department's certified automated inertial profiler fleet. The inertial profilers satisfy the requirements of AASHTO M 328 for inertial profiling systems, and longitudinal pavement profiles are measured in accordance with ASTM E950 to compute IRI. Annual measurements were available for both travel directions from 2015 through 2023, providing a continuous record of functional pavement performance for longitudinal analysis.

Second, transverse cracking was assessed in Cass County and Crow Wing County using manual windshield surveys conducted by agency personnel. These surveys documented both full-width and partial-width transverse cracks, providing insight into structural surface distress development over time. Field remarks recorded during the surveys were also reviewed to supplement the numerical crack counts with qualitative observations such as chip loss, cupping, plow abrasion, and localized surface defects. Crack data were available from 2017 through 2025, allowing comparison of treated and untreated sections across multiple years of service.

Third, for the City of St. Cloud, detailed distress surveys were used to compute a surface rating based on the procedures outlined in the MnDOT Pavement Distress Identification Manual (MnDOT, 2011). The St. Cloud dataset included quantities of multiple distress types and severity levels, which were converted into a standardized surface rating. Surface rating data were available for 2021, 2023, and 2024, providing a multi-year snapshot of urban pavement condition. A summary of the specific evaluation types used at each agency, along with the corresponding road directions and data collection periods, is provided in Table 3. This table

highlights the differences in available datasets and supports the selection of appropriate analysis methods for each site.

Table 3. Summary of Evaluation Types by Agency and Road Direction

Agency	Road Direction	IRI Analysis Period	Transverse Crack Counts	Surface Rating Period
Cass County	Northbound- Southbound	2015-2023	2017-2025	Not evaluated
Crow Wing County	Northbound- Southbound	2015-2023	2017-2025	Not evaluated
City of St. Cloud	Eastbound- Westbound	Not evaluated	Not evaluated	2021–2024

3.3 Field Data Analysis Methods

The field data analysis component of this study evaluated long-term pavement performance to determine whether the timing of chip seal application influenced functional deterioration. Because the three participating agencies collected different types of distress data, the analysis incorporated multiple performance indicators and applied statistical methods appropriate to each dataset. The primary analyses included longitudinal modeling of condition trends, transverse cracking evaluation, and section-level distress comparisons.

Pavement performance data were collected repeatedly from the same test sections over multiple years, resulting in longitudinal observations that are correlated within each

section rather than statistically independent. Conventional regression methods assume that observations are independent and therefore do not adequately account for the correlation introduced by repeated measurements on the same pavement section, which can lead to biased standard errors and invalid statistical inference (Pinheiro & Bates, 2000). In addition, the study design was inherently unbalanced because chip seal treatments were applied in different years (2015-2019), resulting in unequal numbers of pre-treatment and post-treatment observations among sections. The available pavement performance records also differed in the number of pavement/survey years across the three study sites. Linear mixed-effects models (LMM) provide an appropriate analytical framework for this type of longitudinal pavement performance data because they account for within-section correlation while accommodating unbalanced datasets and unequal numbers of repeated observations (Gueorguieva & Krystal, 2004; Pinheiro & Bates, 2000). Accordingly, separate LMMs were developed for the IRI and surface-rating datasets to evaluate changes in pavement condition over time. The model specification for each performance measure is described in the following sections.

3.3.1 Pavement Roughness Analysis

Annual IRI measurements collected between 2015 and 2023 for the Cass County and Crow Wing County test sections were used to evaluate pavement roughness progression following chip seal application. The objective of the model was to distinguish natural pavement aging from the immediate and long-term effects of chip seal treatment.

The IRI model included three fixed effects. Pavement age was included to quantify changes in roughness associated with natural pavement aging. A post-treatment indicator was

included to estimate the immediate change in IRI following chip seal application. Time since chip seal application was included to determine whether the annual rate of IRI progression changed after treatment. Section was included as a random intercept to account for repeated observations collected from the same pavement section. The model is expressed as Equation 1.

$$IRI_{jt} = \beta_0 + \beta_1 Age_{jt} + \beta_2 Post_{jt} + \beta_3 TimeAfter_{jt} + u_j + \varepsilon_{jt} \quad \text{Equation 1}$$

where:

- IRI_{jt} : IRI value for section j at time t
- β_0 : Model intercept
- β_1 : Fixed effect of pavement age (years since original construction)
- β_2 : Post-treatment indicator, where 1 represents an observation after chip seal application and 0 represents a pretreatment or untreated observation
- β_3 : Number of years since chip seal application; equal to 0 before treatment and for the untreated control
- u_j : Random intercept for section j
- ε_{jt} : Residual error term

3.3.2 Surface Distress Analysis

Surface distress data were analyzed to characterize deterioration patterns across the test sections in Cass County, Crow Wing County, and the City of St. Cloud. Because the participating agencies collected different distress data, the analysis was tailored to the available

measurements at each site. For the county sites, transverse cracking served as the primary distress indicator. Full-width and partial-width transverse cracks were quantified for each section, and the resulting crack counts were used to compare distress development among treatment years. The results were summarized using bar charts to facilitate comparison among sections.

For the City of St. Cloud, pavement condition surveys included multiple distress types and severity levels rather than transverse crack counts alone. These distress data were converted to a standardized surface rating using the procedures described in the Minnesota Department of Transportation Pavement Distress Identification Manual (MnDOT, 2011). Surface rating values were subsequently used to compare pavement condition among sections and survey years.

3.3.3 Surface Rating Analysis

Surface rating (SR) was used to evaluate changes in overall pavement surface condition for the City of St. Cloud. Unlike the county sites, where transverse crack counts were analyzed directly, the City of St. Cloud pavement condition surveys included multiple distress types and severity levels. These distress data were converted to a standardized surface rating using the procedures described in the Minnesota Department of Transportation Pavement Distress Identification Manual (MnDOT, 2011).

The surface rating calculation consisted of four steps. First, the recorded distress quantities were converted to percentage values based on the applicable measurement unit (section length, crack count, or affected area). Second, each distress percentage was multiplied

by the corresponding weighting factor specified in the MnDOT manual to calculate the Individual Weighted Distress (IWD), as shown in Equation 2.

$$IWD = \text{Percent Distress} \times \text{Weighting Factor} \quad \text{Equation 2}$$

Third, the Individual Weighted Distress values were summed to obtain the Total Weighted Distress (TWD), representing the combined contribution of all recorded pavement distresses. Finally, the TWD was converted to a surface rating using the MnDOT surface rating equation (Equation 3).

$$SR = e^{(1.386 - 0.045 * TWD)} \quad \text{Equation 3}$$

SR values ranged from 0.0 to 4.0 in increments of 0.1, where 0.0 represents the poorest pavement condition and 4.0 represents the best pavement condition. The calculated SR were analyzed using a linear mixed-effects model to evaluate changes in pavement condition over time. Survey year, treatment status (treated versus untreated), and treatment year were included as fixed effects to evaluate temporal changes in surface condition, the overall effect of chip seal treatment, and the influence of treatment timing, respectively. A section-specific random intercept was included to account for repeated observations collected from the same pavement section. The model is presented in Equation 4.

$$SR_{jt} = \beta_0 + \beta_1 \text{SurveyYear}_{jt} + \beta_2 \text{Treated}_j + \beta_3 \text{Treatment Year}_j + u_j + \varepsilon_{jt} \quad \text{Equation 4}$$

where:

SR_{jt} : Surface rating for section j at survey year t ;

β_0 : Model intercept

β_1 : Fixed effect for survey year

β_2 : Fixed effect of treatment status (treated versus untreated)

β_3 : Fixed effect of chip seal treatment year

u_j : Random intercept for section j

ε_{jt} : Residual error term

3.3.4 Statistical Interpretation

For both the IRI and surface rating models, statistical significance was assessed using p-values computed with Satterthwaite's approximation. Model slopes were used to quantify the rate of change in pavement condition over time. This longitudinal modeling framework provided a rigorous basis for evaluating performance trends and supported visual observations and field remarks with formal statistical evidence.

3.4 Laboratory Testing

The laboratory testing program was designed to characterize the chemical, rheological and mechanical properties of asphalt binders extracted and recovered from field cores collected in the summer of 2025. The recovered binders represent asphalt binders that had undergone different periods of in-service aging following chip seal application. At the time of coring in 2025, the treated sections had experienced approximately six to ten years of field aging, depending on the year of chip seal application. Because the objective of the laboratory phase was to evaluate the binders in their field-aged condition, no additional laboratory aging (such as Rolling Thin-Film Oven or Pressure Aging Vessel conditioning) was applied. This

approach preserved the condition of the recovered binders at the time of coring and allowed their properties to be evaluated after long-term field exposure under actual service conditions.

The testing program in Figure 2 consisted of three major components: (1) extraction and recovery of binder from two depth intervals within each core, (2) chemical characterization using ATR-FTIR spectroscopy, and (3) rheological characterization using rotational viscosity, Superpave DSR and BBR testing, MSCR testing, and the Glover-Rowe parameter. Binder Bond Strength (BBS) testing was also performed to evaluate the adhesive and cohesive properties of the aged binders. Figure 2 provides an overview of the laboratory workflow.

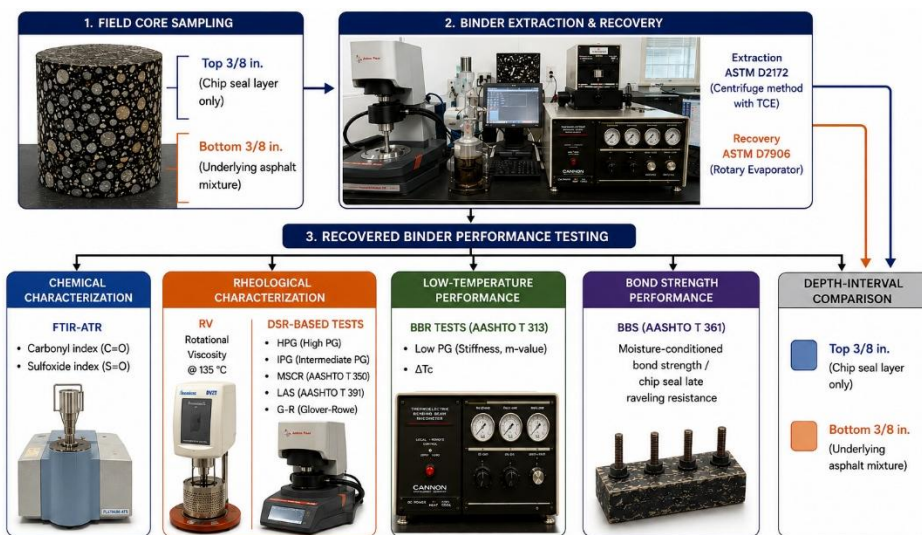


Figure 2. Laboratory Testing of Extracted/Recovered Asphalt Binders

3.4.1 Asphalt Binder Extraction and Recovery

Binder extraction was performed using the centrifuge method specified in ASTM D2172 (2024), with trichloroethylene (TCE) used as the extraction solvent. The recovered solutions were subsequently processed using a rotary evaporator in accordance with ASTM D5404 (2021)

to remove solvent under controlled temperature and pressure conditions. This procedure ensured that the recovered binder was representative of the in-place material and free of residual solvent that could influence test results.

To evaluate depth-dependent aging and the influence of chip seal treatment, binder samples were recovered from two portions of each field core. The upper 3/8 inch represented the surface interval. For treated sections, this interval included chip seal emulsion residue and the uppermost portion of the asphalt mixture. For the control section, the upper interval represented the exposed original pavement mixture without a chip seal. The subsequent 3/8 inch represented the underlying pavement binder in both treated and control sections.

This depth-segmented approach allowed aging near the pavement surface to be compared with aging occurring deeper within the asphalt layer. The treated upper interval was interpreted as a combined chip seal and near-surface HMA binder system, whereas the control upper interval represented the unprotected original pavement surface. The treated bottom interval represented the underlying pavement binder beneath the chip seal, while the control bottom interval represented the underlying binder beneath an unsealed pavement surface. Comparisons between the upper layers of the treated and untreated sections were used to evaluate the influence of chip sealing on near-surface binder aging, while comparisons between the upper and lower intervals within the treated sections were used to assess aging gradients through the pavement depth. Because the treated and control sections experienced the same general roadway climate and environmental exposure, these comparisons provide a consistent basis for evaluating relative differences in aging through pavement depth.

3.4.2 Chemical Evaluation

Chemical aging was evaluated using attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy, as shown in Figure 3. ATR-FTIR identifies chemical functional groups by measuring the absorption of infrared radiation at characteristic wavenumbers. In asphalt binders, oxidative aging is associated with the formation of oxygen-containing functional groups, particularly carbonyl and sulfoxide groups, which generally increase as aging progresses (Coates, 2000; Petersen, 2009).

Spectra were collected from 4000 to 650 cm^{-1} at a resolution of 4 cm^{-1} , with each spectrum averaged over 64 scans to improve signal quality. The carbonyl area was calculated by integrating the spectrum from 1661 to 1754 cm^{-1} , using the absorbance at 1754 cm^{-1} as the baseline. The sulfoxide area was calculated by integrating the spectrum from 995 to 1047 cm^{-1} , using the absorbance at 1047 cm^{-1} as the baseline. Only positive areas relative to the respective baselines were included in the calculations.

The resulting baseline-corrected carbonyl and sulfoxide areas were used as indicators of oxidative aging. Higher values were interpreted as indicating greater accumulation of oxidation-related functional groups. The two areas were summed to obtain a combined $\text{C=O} + \text{S=O}$ oxidation measure, which was used to compare recovered binders from treated and untreated sections within each agency.

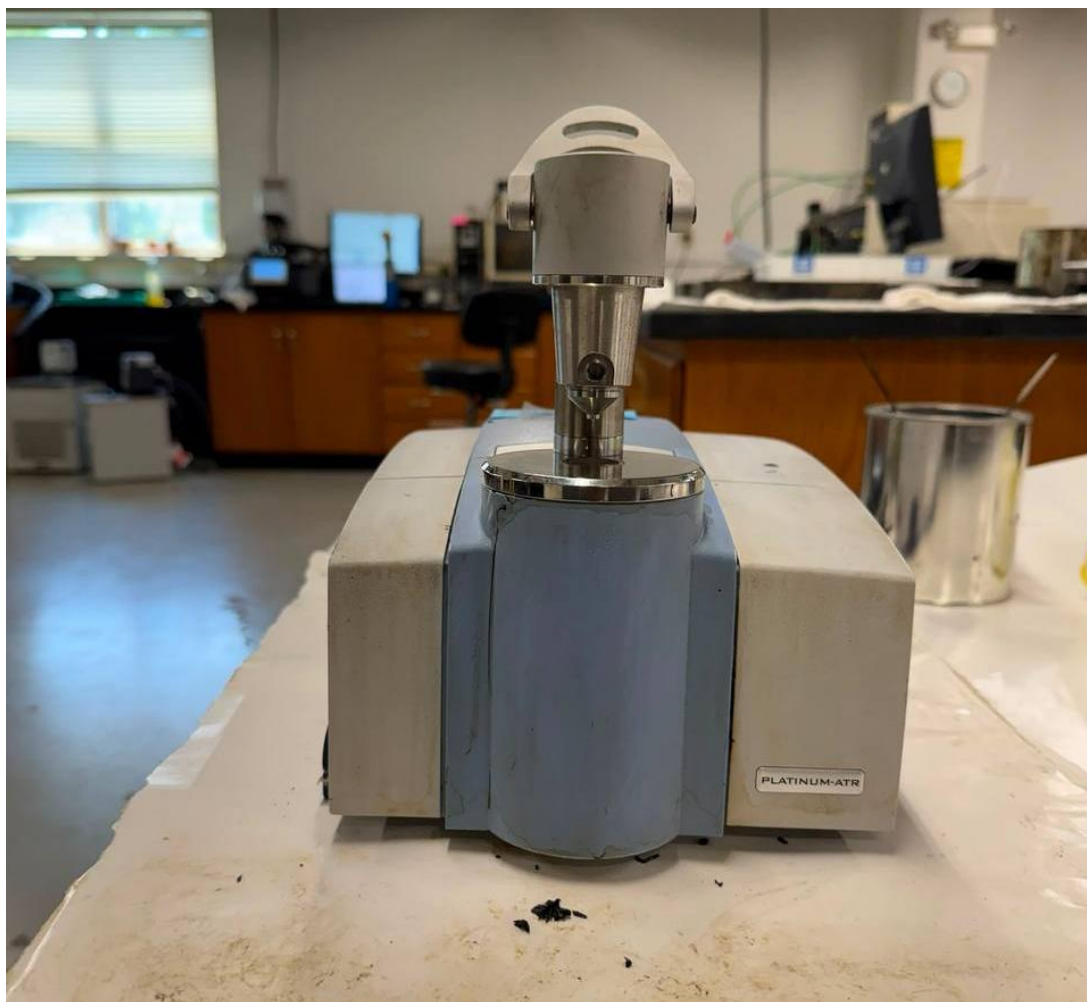


Figure 3. Fourier-transform infrared Spectrometer

3.4.3 Rheological Testing

Rheological testing was conducted to assess the mechanical behavior of the recovered binders across a range of temperatures relevant to rutting, fatigue, and thermal cracking performance.

3.4.3.1 Rotational Viscosity

RV test was conducted primarily to evaluate long-term stiffening of the recovered asphalt binders. Because binder viscosity generally increases with oxidative aging, the RV

results provided an indirect measure of the extent of aging among the pavement sections and recovered layers. The test also offered supporting information on workability-related properties, including pumpability, mixability, and ease of placement and compaction, and can be used to develop temperature-viscosity relationships for estimating mixing and compaction temperatures.

Testing was performed in accordance with AASHTO T 316 (2022). Prior to testing, the environmental chamber, sample chamber, Spindle No. 21, and the binder samples were preheated to the test temperature of 135 °C as shown in Figure 4. Each recovered binder was heated only until it reached a pourable state to avoid additional thermal aging. The binder was then transferred into the preheated sample chamber and allowed to equilibrate thermally. Once the binder reached the target temperature, the viscometer was operated at a constant rotational speed of 20 rpm. The torque required to maintain this speed was recorded continuously over a three-minute interval. Three viscosity readings, expressed in Pascal-seconds (Pa.s), were obtained and averaged to produce the reported RV value for each sample.

Higher viscosity values indicate increased resistance to flow and are typically associated with more advanced oxidative hardening. By comparing RV values across treated and untreated sections and between surface and subsurface binder layers, the test provided insight into how chip seal timing influenced long-term binder stiffening.

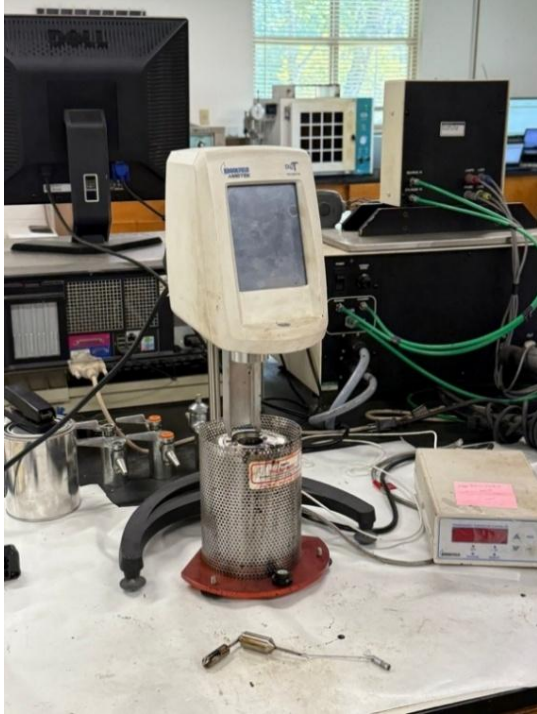


Figure 4. Brookfield DV-II+ Pro Rotational Viscometer

3.4.3.2 Superpave Performance Grade (PG) and ΔT_c Parameter

- **High- and Intermediate-Temperature PG:**

The DSR test was conducted to characterize the viscoelastic behavior of the recovered asphalt binders at intermediate and high service temperatures. The test evaluates the complex shear modulus $|G^*|$ and phase angle δ , which together describe the balance between elastic and viscous responses in the binder. These properties are directly related to rutting resistance at high temperatures and fatigue susceptibility at intermediate temperatures. All testing followed the procedures outlined in AASHTO T 315 (M 320).

High-temperature testing was performed using a 25-mm plate with a 1-mm gap, while intermediate-temperature testing used an 8-mm plate with a 2-mm gap. For high-temperature characterization, the DSR was operated at a loading frequency of 10 rad/s (1.59 Hz), which

corresponds to the standard frequency used for Superpave Performance Grade (PG) evaluation. A target strain of 12 percent was applied, and the binder was conditioned for the first 10 loading cycles to ensure thermal and mechanical stabilization. Data from the subsequent 10 cycles were used to compute $|G^*|$, δ , and the rutting parameter $|G^*|/\sin \delta$. Higher values of this parameter indicate increased stiffness and improved resistance to permanent deformation.

Intermediate-temperature testing followed the same general procedure but was conducted at lower temperatures appropriate for fatigue evaluation. The resulting $|G^*|$ and δ values provided insight into the binder's ability to dissipate strain energy and resist cracking under repeated loading. By comparing DSR results across treated and untreated sections and between surface and subsurface binder layers, the test provided a detailed assessment of how chip seal timing influenced long-term rheological aging and performance. Figure 5 presents the DSR setup for an experiment.



Figure 5. Dynamic Shear Rheometer Setup

- **Low-Temperature PG and ΔT_c :**

Low-temperature rheological properties of the recovered asphalt binders were evaluated using the BBR in accordance with AASHTO T 313 (2022). The BBR test characterizes the binder's ability to resist thermal cracking by measuring its creep stiffness $S(t)$ and relaxation capability (m-value) at low service temperatures. These parameters are used to determine the continuous low-temperature grade and to compute the ΔT_c parameter, which provides additional insight into the binder's capacity to relieve thermally induced stresses.

Each binder sample was heated only until sufficiently fluid to pour and then cast into rectangular molds. After pouring, the specimens were allowed to cool at room temperature for 45 to 60 minutes. The exposed surface was trimmed flush with a heated spatula to ensure uniform geometry. The specimens were then placed in a freezer at -12°C for 5 to 10 minutes to

facilitate demolding without deformation. Prior to testing, the demolded beams were conditioned in a temperature-controlled liquid bath at the specified test temperature from -36 to 0°C within $\pm 0.1^\circ\text{C}$ for 60 ± 5 minutes. The BBR apparatus (Figure 6) applies a constant load at the midspan of a simply supported beam for 240 seconds while monitoring midspan deflection. A computerized data acquisition system records load, deflection, and time, which are used to compute bending stress, bending strain, and creep stiffness. Creep stiffness at 60 seconds, $S(60)$, was calculated using Equation 5:

$$S(t) = \frac{PL^3}{4bh^3\Delta(t)} \quad \text{Equation 5}$$

where:

- $S(t)$: creep stiffness at time t , MPa
- P : constant applied load, N
- L : span length between supports, mm
- b : beam width, mm
- h : beam thickness, mm
- $\Delta(t)$: midspan deflection at time t , mm

The m -value, which represents the slope of the logarithm of creep stiffness versus the logarithm of loading time, was also determined. Higher m -values indicate greater stress-relaxation capability and improved resistance to thermal cracking. The ΔT_c parameter was calculated as the difference between $T_{c,S}$, the critical low temperature at which the creep

stiffness criterion of 300 MPa is met, and $T_{c,m}$, the critical low temperature at which the m -value criterion of 0.300 is met, as shown in Equation 6:

$$\Delta T_c = T_{c,S} - T_{c,m} \quad \text{Equation 6}$$

Less negative ΔT_c values generally indicate greater low-temperature relaxation capacity and have been associated with lower susceptibility to aging-related, non-load-induced cracking. However, interpretation of ΔT_c should be interpreted cautiously for severely aged and polymer-modified binders because it reflects linear-viscoelastic rheological behavior rather than directly measuring cracking failure resistance (Elwardany et al., 2020). By comparing stiffness, m -value, and ΔT_c across treated and untreated sections and between surface and subsurface binder layers, the BBR test provided a detailed assessment of how chip seal timing influenced long-term low-temperature aging behavior.



Figure 6. Bending Beam Rheometer Setup

- **MSCR**

The MSCR test was conducted to evaluate the high-temperature deformation resistance and elastic recovery characteristics of the recovered asphalt binders. The MSCR procedure provides two key parameters: the non-recoverable creep compliance J_{nr} and the percent recovery R . Together, these parameters quantify the binder's ability to resist permanent deformation and recover elastically under repeated loading. Compared to traditional DSR-based rutting parameters, MSCR results offer a more direct assessment of rutting performance, particularly for modified binders where elastic response plays a significant role. All testing followed the procedures outlined in AASHTO T 350 (M 332).

Each binder sample was heated only until pourable and then loaded between 25-mm parallel plates with a 1-mm gap, as specified in the standard. Testing was conducted at the binder's high pavement design temperature to ensure that the results reflected in-service rutting conditions. The MSCR test applies a controlled shear stress to the binder specimen in a repeated creep-and-recovery loading pattern. Each cycle consists of a one-second creep phase, during which the binder is subjected to a constant shear stress, followed by a nine-second recovery phase. This sequence is repeated for twenty cycles at a low stress level of 0.1 kPa and for an additional ten cycles at a higher stress level of 3.2 kPa. The two stress levels allow evaluation of both linear viscoelastic behavior and stress sensitivity. The non-recoverable creep compliance J_{nr} is calculated from the residual strain remaining at the end of each recovery period in Equation 7:

$$J_{nr} = \frac{\varepsilon_{nr}}{\sigma} \quad \text{Equation 7}$$

where ε_{nr} is the non-recoverable strain and σ is the applied shear stress. Lower J_{nr} values indicate improved resistance to permanent deformation. Percent recovery R is calculated using Equation 8:

$$R = \frac{\varepsilon_r}{\varepsilon_r + \varepsilon_{nr}} \times 100 \quad \text{Equation 8}$$

where ε_r is the recoverable strain. Higher recovery values indicate a stronger elastic response and improved ability to rebound after loading.

Stress sensitivity was further evaluated using the $J_{nr,diff}$ parameter, which expresses the percent difference in J_{nr} between the two stress levels. Elevated J_{nr} values indicate that the binder exhibits pronounced non-linear behavior under increasing stress, which may signal susceptibility to rutting under heavy traffic loads. By comparing MSCR results across treated and untreated sections and between surface and subsurface binder layers, the test provided a detailed assessment of how chip seal timing influenced the elastic character, stress sensitivity, and high-temperature deformation resistance of the recovered binders.

- **LAS**

The fatigue resistance of the recovered asphalt binders was evaluated using the LAS test in accordance with AASHTO T 391-20 (2024). The LAS procedure provides a mechanistic assessment of intermediate-temperature fatigue behavior by combining viscoelastic characterization with continuum damage mechanics. All testing was performed using a Dynamic Shear Rheometer (DSR) equipped with 8-mm parallel plates and a 2-mm testing gap. Specimen preparation, trimming, and temperature conditioning followed the requirements of AASHTO T 315 to ensure consistent geometry and thermal equilibrium. A test temperature of 20°C was used for all recovered binders. The temperature was selected after considering the initial linear-viscoelastic modulus of the binders at 10 Hz so that the specimens could undergo measurable fatigue damage during the amplitude sweep (Safaei et al., 2016). Using a common temperature also provided a consistent basis for comparing the valid LAS responses among the sites and treatment sections.

The LAS protocol consists of two sequential loading stages designed to characterize both the undamaged viscoelastic response and the damage evolution behavior of the binder. The first stage is a frequency sweep conducted at a constant strain amplitude of 0.1 percent over a frequency range of 0.2 to 30 Hz. During this stage, the complex shear modulus $|G^*|$ and phase angle δ are recorded. The storage modulus G' , which represents the recoverable elastic component of the binder response, is calculated as:

$$G' = |G^*| \cos(\delta) \quad \text{Equation 9}$$

A log-log regression of G' versus frequency is then used to determine the damage sensitivity parameter α , which characterizes how the binder stiffness changes with loading frequency and provides input for the subsequent damage analysis. Immediately following the frequency sweep, the second stage of the LAS test is performed. This stage consists of an amplitude sweep conducted in strain-controlled mode at a constant loading frequency of 10 Hz. The applied strain amplitude increases continuously from 0.1 percent to 30 percent during the amplitude-sweep sequence. Throughout the sweep, the DSR records peak shear stress, peak shear strain, phase angle, and complex modulus at each loading cycle. These data are used to quantify the progressive reduction in modulus as the binder accumulates damage.

Binder damage accumulation $D(t)$ is calculated using the continuum damage mechanics framework specified in AASHTO T 391-20. The relationship between $|G^*| \sin(\delta)$ and the damage variable is fit to a power-law model to determine the fatigue parameters A_{35} and B . These parameters describe the binder's resistance to damage initiation and the rate at which

damage progresses under increasing strain. The predicted fatigue life N_f is then calculated using Equation 10:

$$N_f = A_{35}(\gamma_{\max})^{-B} \quad \text{Equation 10}$$

where $\gamma_{\max}$ is the maximum applied shear strain amplitude. Predicted fatigue life was calculated at applied strain levels of 2.5 and 5.0 percent. The initial complex shear modulus and the damage at failure, D_f , were also evaluated to provide context for the calculated fatigue lives.

Because the LAS test is conducted under strain-controlled loading, N_f is influenced by the initial stiffness of the binder. A comparatively soft binder may produce a high calculated fatigue life because it experiences lower stress at the same applied strain. Therefore, N_f was interpreted together with the initial complex modulus and D_f , rather than being used alone to rank fatigue performance. The LAS results were used as supporting indicators of fatigue-related binder response, subject to the availability and validity of the recovered binder specimens. Only tests that produced a valid damage response were included in the reported results. Specimens that could not complete the procedure because of insufficient recovered binder, excessive brittleness, premature fracture, or edge failure were reported as not available and were excluded from treatment comparisons.

- **Master Curve and Glover-Rowe Parameter**

Frequency sweep testing was performed using a DSR to characterize the viscoelastic behavior of the recovered asphalt binders over a broad range of loading frequencies and

temperatures. The resulting rheological measurements were used to construct master curves and determine the G-R parameter, which provide complementary indicators of binder aging and cracking susceptibility. All testing was conducted in accordance with AASHTO T 315.

Frequency sweep measurements were obtained at multiple isothermal temperatures covering the expected service temperature range of the asphalt binders. At each temperature, loading frequency was varied incrementally and the corresponding complex shear modulus, $|G^*|$, and phase angle, δ , were recorded. These measurements characterize the stiffness and viscoelastic response of the binder under different loading conditions.

To combine the individual isothermal datasets into a continuous representation, the principle of time-temperature superposition was applied. Frequency sweep segments were horizontally shifted along the reduced frequency axis to construct master curves referenced to a selected temperature. Shift factors were determined using the Williams-Landel-Ferry (WLF) equation, and their temperature dependence was evaluated to ensure valid superposition behavior. Master curves were fitted using the Christensen-Anderson-Marasteanu (CAM) model implemented in the Rheological Evaluation and Analysis (RHEA) software. The CAM model provides a continuous representation of the binder viscoelastic response over a wide range of reduced frequencies and temperatures. Model parameters were obtained through nonlinear regression to minimize deviations between the fitted curves and the experimental $|G^*|$ data.

The G-R parameter was evaluated at a reference condition of 15 °C and 0.005 rad/s using the discrete master curve values generated in RHEA. These conditions represent low-

temperature, slow-loading behavior associated with the initiation of age-related cracking. The G-R parameter was calculated as:

$$G-R = \frac{|G^*|\cos^2(\delta)}{\sin(\delta)} \quad \text{Equation 11}$$

Higher G-R values indicate increased stiffness and reduced phase angle, both characteristic of an aged, embrittled binder with diminished ability to relax stresses. Published threshold values suggest that binders with G-R values above approximately 180 kPa are at elevated risk of block cracking, while values exceeding 600 kPa are strongly associated with advanced cracking distress in the field. By comparing master curve shapes and G-R parameter magnitudes across treated and untreated sections and between surface and subsurface binder layers, the frequency sweep analysis provided a detailed and physically meaningful assessment of how chip seal timing influenced oxidative hardening and long-term cracking susceptibility in the recovered binders.

3.4.4 Binder Bond Strength

The dry- and moisture-conditioned bond-strength response of the recovered asphalt binders was evaluated using the BBS test in accordance with AASHTO T 361-22. The BBS test was included because oxidative aging can alter the adhesive and cohesive properties of asphalt binders, potentially affecting their strength and moisture susceptibility. The BBS procedure quantifies the tensile force required to detach a pull-off stub bonded to an aggregate substrate with asphalt binder. This measurement provides insight into binder-aggregate compatibility, cohesive strength within the binder film, and the susceptibility of the binder-aggregate

interface to moisture-induced damage, depending on the observed failure mode. The test was therefore used as a supporting measure of the dry and moisture-conditioned strength of the recovered binders rather than as a direct measure of field chip retention or pavement durability (Figure 7).

Granite aggregate substrates were prepared following the conditioning requirements of the standard. Each substrate was cleaned in an ultrasonic bath containing distilled water maintained at $60\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ for 60 minutes to remove dust, fines, and contaminants that could interfere with binder adhesion. After cleaning, both the substrates and the pull-off stubs were placed in a forced-draft oven at $150\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ for 30 minutes, followed by an additional hour at the same temperature to ensure complete drying and thermal stabilization.

Recovered binder was applied to each 20-mm pull-off stub at a mass of $0.4\text{ g} \pm 0.05\text{ g}$, producing a uniform thin film between the stub and the aggregate surface. Two conditioning protocols were used to evaluate the dry and moisture-conditioned pull-off response. For dry-conditioned specimens, the bonded assemblies were stored under standard laboratory conditions for 24 hours prior to testing. For wet-conditioned specimens, the assemblies were allowed to cool for one hour after binder application and were then submerged in a water bath maintained at $40\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$ for 48 hours. After removal from the bath, the specimens were surface-dried for one hour before testing to ensure consistent moisture exposure.

Bond strength testing was performed using a Type IV pneumatic adhesion tester. The device applies increasing tensile force to the pull-off stub until failure occurs. The maximum air

pressure at failure, referred to as the burst pressure (BP), was converted to pull-off tensile strength (POTS) using the following relationship:

$$POTS = \frac{(BP \cdot A_G) - C}{A_{PS}} \quad \text{Equation 12}$$

where:

- POTS: pull-off tensile strength (kPa)
- BP: burst pressure at failure (kPa)
- A_G : contact area of the gasket with the reaction plate (mm²)
- C: piston constant provided by the manufacturer
- A_{PS} : area of the pull-off stub (mm²)

Failure modes were classified as adhesive, cohesive, or mixed. Specimens exhibiting failure at the stub-binder interface were excluded from analysis because such failures indicate improper specimen preparation rather than the intended binder-substrate or cohesive response. Four replicate pull-off tests were performed for each combination of section, recovered layer, and conditioning state, and the average POTS value and standard deviation were reported. Statistical differences among the control and treated sections were evaluated using analysis of variance at a significance level of $\alpha=0.05$. When the ANOVA indicated a statistically significant section effect, Tukey's honestly significant difference test was used for pairwise comparisons among sections. To quantify the effect of moisture on adhesive performance, the Loss of Bond Strength (%) was calculated as:

$$\text{Loss of Bond Strength (\%)} = \frac{\text{POTS}_{\text{dry}} - \text{POTS}_{\text{wet}}}{\text{POTS}_{\text{dry}}} \times 100 \quad \text{Equation 13}$$

Higher POTS values indicate stronger adhesive or cohesive bonding, while bond strength ratios (wet/dry) approaching unity reflect reduced moisture susceptibility. Together, these metrics provide a comprehensive assessment of the long-term adhesive performance of binders recovered from chip sealed and untreated pavement sections.



Figure 7. BBS Specimen Assembly showing Pull-off Stubs bonded to a Granite Substrate

3.4.5 Laboratory Data Screening and Validity Review

The LAS and BBS replicate datasets were reviewed before section-level results were calculated. Potential extreme values were evaluated using Dixon's *Q*-test at the 95% confidence level. Critical values of 0.970 and 0.829 were used for three- and four-replicate datasets,

respectively. A value was excluded only when the calculated Q exceeded the applicable critical value, and no more than one value was removed from a replicate set.

LAS results were also reviewed using the initial linear viscoelastic complex shear modulus criterion described in Section 3.4.3. Binder-layer combinations that did not produce valid LAS results were reported as N.A. and excluded from interpretation. The retained LAS and BBS replicates were used to calculate the reported means, standard deviations, and derived parameters.

This chapter described the materials and methods used to evaluate the long-term performance of chip seal treatments applied at different stages of pavement service life. The study methodology included field performance evaluation using roughness, cracking, and surface condition data; laboratory characterization of recovered asphalt binders through rheological, chemical, and adhesive testing; and statistical analyses to quantify treatment effects and compare performance among agencies, sections, and pavement layers. Together, these methods provide the framework for assessing how chip seal application timing influences pavement performance, binder aging, and aging gradients within the asphalt layer. The results obtained from these field observations, laboratory measurements, and statistical analyses are presented and discussed in Chapter 4.

Chapter 4 Results and Discussion

This chapter presents the field and laboratory results for the three participating agencies. The discussion examines long-term pavement performance through three complementary analytical components: (1) field performance trends, including roughness and surface distress progression; (2) laboratory binder characterization, which evaluates the aging behavior and chemical, rheological and mechanical properties of recovered binders; and (3) correlation analyses that assess the relationships between field performance measures (IRI, surface rating, and transverse cracking) and recovered binder properties. Together, these components provide a comprehensive evaluation of chip seal timing, material behavior, and the mechanisms that help explain the observed performance trends. Results are organized by agency and performance metric, beginning with Cass County.

4.1 Cass County (CSAH 1)

4.1.1 International Roughness Index

IRI progression for the northbound and southbound directions of CSAH 1 is shown in Figures 8(a) and 8(b). In the northbound direction, Figure 8(a) shows that the untreated control section experienced a gradual and consistent increase in IRI, remaining below 75 inches per mile throughout the monitoring period. This relatively stable trend indicates moderate surface deterioration in the absence of treatment and serves as a baseline for evaluating the treated sections.

The treated sections displayed substantial variability in post-treatment roughness progression. Section 1, which received a chip seal approximately one month after the final HMA lift in 2015, exhibited a steep increase in IRI over time. Although this section received the earliest

treatment, roughness increased steadily throughout the monitoring period. Sections 2 and 3 followed similar patterns, with IRI values exceeding 100 in./mi. by 2023, indicating accelerated roughness growth after treatment.

Sections 4 and 5 performed somewhat better, showing more moderate increases in IRI. However, even these sections deteriorated faster than the untreated control. Overall, the northbound results suggest that chip sealing was not associated with reduced roughness progression. The segmented linear mixed-effects model results are summarized in Table 4. Pavement age was significantly associated with increasing IRI ($\beta_1 = 1.70$ in./mi./year, $p < 0.001$), indicating that roughness increased as the pavement aged. The immediate post-treatment level change was not statistically significant ($\beta_2 = 1.57$ in./mi., $p = 0.212$). However, the post-treatment slope increased significantly ($\beta_3 = 3.79$ in./mi./year, $p < 0.001$), indicating that the rate of IRI progression became steeper following treatment.

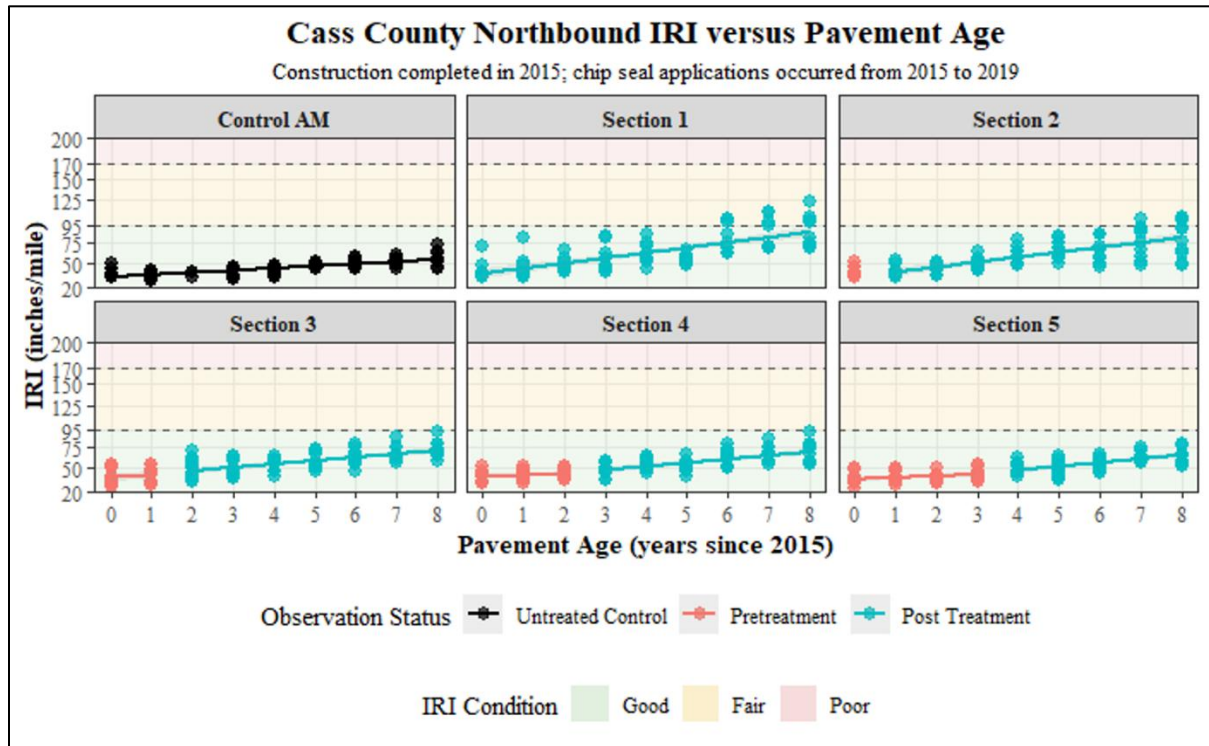
Figure 8(b) presents the IRI progression for the southbound direction. The untreated control section experienced a steady and pronounced increase in roughness, exceeding 100 in./mi. by 2023. This reflects substantial surface degradation in the absence of treatment. In contrast, all treated sections in the southbound direction exhibited lower and more stable IRI values throughout the analysis period. Sections 1 through 5 consistently outperformed the control, with Sections 1 and 2 showing the lowest roughness levels. For Sections 2 through 5, a modest pre-treatment increase in IRI is visible, followed by a gradual post-treatment progression. Section 1, which lacked a pre-treatment phase, maintained stable roughness levels across the entire monitoring period.

These results suggest that chip sealing may have been associated with smoother long-term performance in the southbound direction. Earlier treatment, as seen in Sections 1 and 2, appears to correspond with slightly better outcomes, although the differences among treated sections are modest. The segmented linear mixed-effects model results are summarized in Table 5. Pavement age remained a significant predictor of IRI ($\beta_1 = 6.14$ in./mi./year, $p < 0.001$). No statistically significant immediate change in IRI was observed following treatment ($\beta_2 = -0.36$ in./mi., $p = 0.841$). However, the post-treatment slope decreased significantly ($\beta_3 = -3.32$ in./mi./year, $p < 0.001$), indicating that roughness continued to increase after treatment but at a significantly slower rate than before treatment.

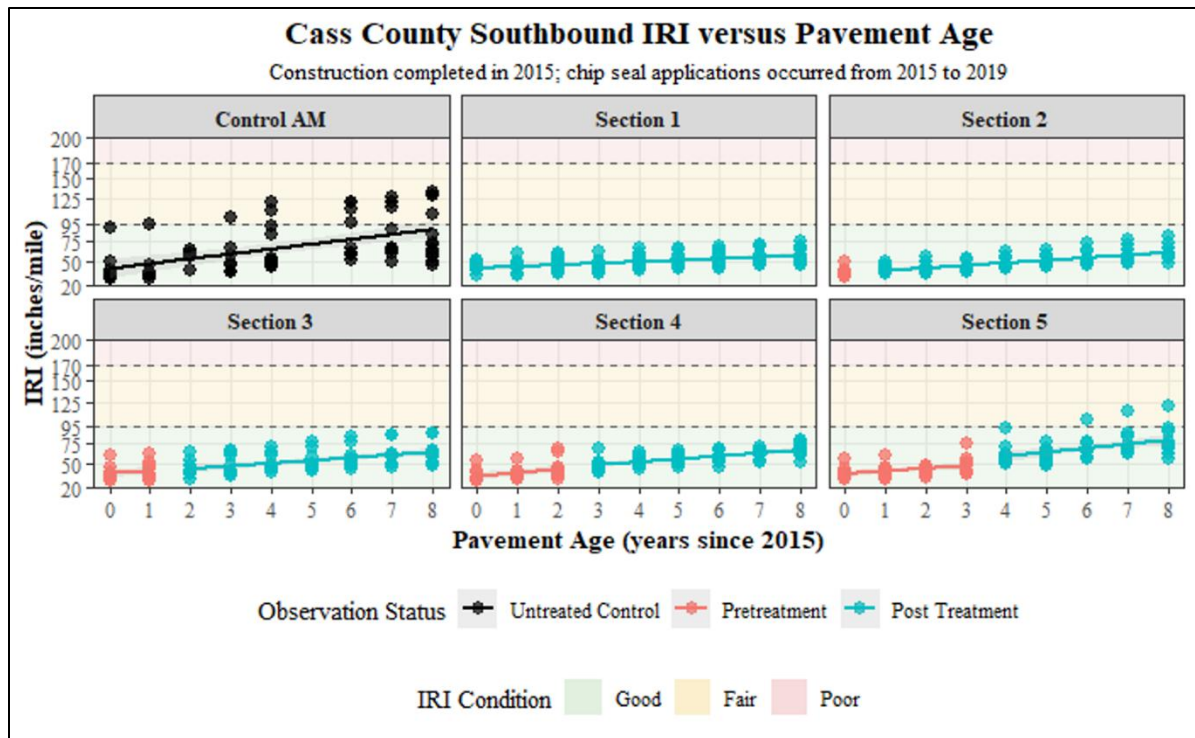
The contrasting results between the northbound and southbound directions require careful interpretation. One plausible explanation is the influence of chip seal surface macrotexture on inertial profiler measurements. Chip seal surfaces exhibit coarse macrotexture because the embedded aggregate layer and residual binder create a rough, textured surface profile. This texture can influence IRI measurements, particularly during the early years after treatment while aggregate embedment is still occurring (Karamihas et al., 1999). Consequently, elevated IRI values may reflect changes in surface texture in addition to pavement deterioration, potentially obscuring the functional effects of chip seal treatment.

The LMM nevertheless demonstrated contrasting post-treatment roughness trends between the northbound and southbound directions. Because the observed directional differences cannot be attributed to treatment timing alone based on the available data, the

results are interpreted separately for each travel direction rather than as a single site-wide treatment response.



(a)



(b)

Figure 8. Cass County IRI Results (Pavement Age from 0 to 8 Years) Per Travel Direction: (a) Northbound, and (b) Southbound

Table 4. Summary of LMM results for Northbound IRI progression in Cass County (CSAH 1)

Model term	Estimate	p-value	Interpretation
Pavement age	+1.70 in./mi./year	<0.001	IRI increased significantly as the pavement aged.
Post-treatment level change	+1.57 in./mi.	0.212	No significant immediate change after treatment.
Change in slope after treatment	+3.79 in./mi./year	<0.001	IRI increased more rapidly after treatment.
Post-treatment slope	+5.50 in./mi./year	<0.001	Overall post-treatment deterioration rate.

Table 5. Summary of LMM results for Southbound IRI progression in Cass County (CSAH 1)

Model term	Estimate	p-value	Interpretation
Pavement age	+6.14/year	<0.001	IRI increased significantly with pavement age.
Post-treatment level change	-0.36	0.841	No significant immediate change after treatment.
Change in slope after treatment	-3.32/year	<0.001	IRI progression became significantly slower after treatment.
Post-treatment slope	+2.82/year	<0.001	Roughness continued increasing, but at a slower rate.

4.1.2 Surface Distresses

Full-Width Transverse Cracking

Figure 9 presents the progression of full-width transverse cracking from 2017 to 2025 in the northbound and southbound directions of Cass County CSAH 1. At the beginning of the monitoring period in 2017, all sections exhibited relatively low full-width transverse cracking, with counts below 40. However, variability among the sections was already evident. Section 5, which had not yet been chip sealed, recorded 12 cracks in both directions, whereas the untreated control section recorded 34. Because both sections were untreated at the time of the survey, this difference cannot be attributed to chip seal application and instead reflects inherent spatial or section-specific variability within the test location. Therefore, subsequent performance should be interpreted relative to each section's initial cracking condition rather than solely through comparisons of absolute crack counts. By 2020, cracking had accelerated across nearly all sections. In the northbound direction, Section 4 reached 102 cracks, followed by Section 1 with 91 and Section 3 with 83. The control section increased more gradually to 60. The southbound direction showed similar patterns. Section 4 again had the highest cracking at 104, and Sections 1 and 3 also experienced substantial increases. The control section rose to 60. These results indicate that several treated sections deteriorated more rapidly than the untreated control during the early years of service.

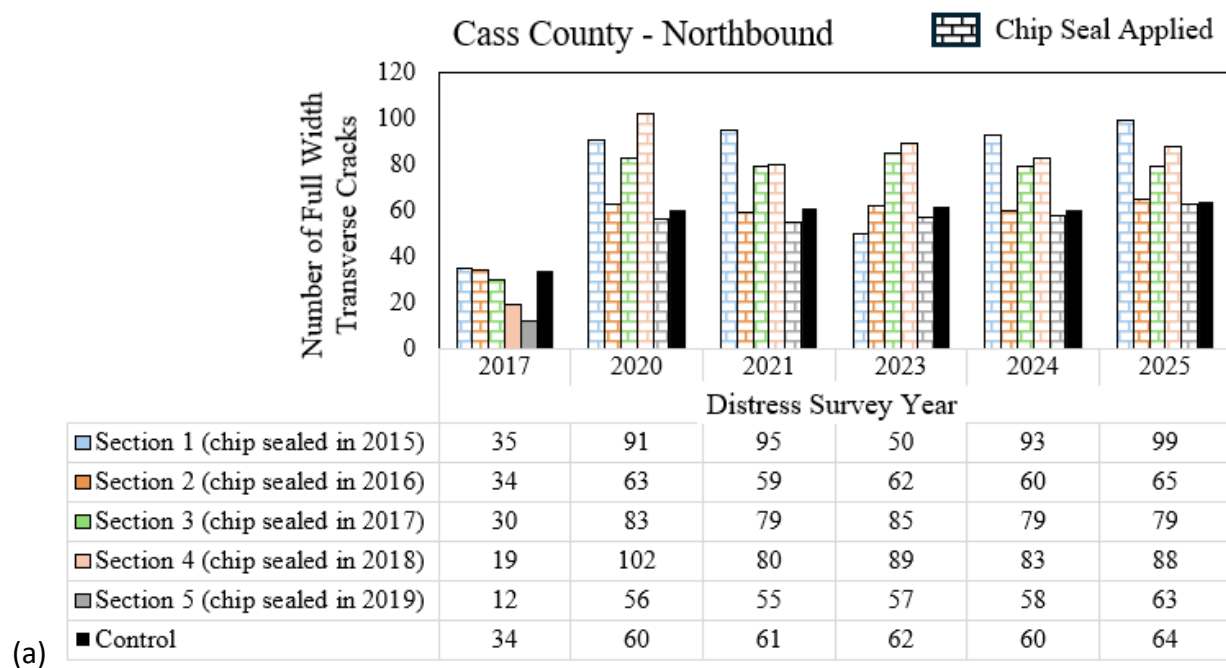
Cracking progression became more variable after 2021. Sections 2 and 5 remained relatively stable or even declined slightly, while other sections remained elevated. Section 5 continued to show the lowest deterioration, suggesting that it had better resistance to early

cracking. This performance is consistent with its later treatment year, which may have allowed the pavement to mature before the chip seal was applied. Routine crack sealing was introduced in 2023, but its influence on the observed trends is uncertain. In Section 1, crack counts dropped from 95 to 50 in both directions. By 2025, the values returned to 99. Field observations suggest that the temporary reduction may reflect misidentified features such as sealed cracks or plow marks rather than actual improvement. Because windshield surveys were conducted independently each year, some fluctuations may be attributed to observational variability rather than true changes in pavement condition.

Section 5 remained the best performing treated section by the end of the monitoring period, with 63 cracks northbound and 62 southbound. The control sections showed relatively stable performance, increasing slightly to 64 and 67 cracks, respectively, northbound and southbound. Field remarks summarized in Table 6 support the numerical trends. Treated sections exhibited widespread cupping of transverse cracks, chip loss, and plow abrasion. Section 3 developed potholes and scraping, while Section 5 showed wear at fog lines and joints. Although the control section had lower crack counts than the worst performing treated sections, it exhibited fatigue and block cracking, which are indicative of more serious structural concerns.

Overall, the results suggest that chip sealing and subsequent crack sealing were associated with partial benefits, but long-term performance depended more strongly on treatment timing, inherent pavement durability, and surface wear conditions. Sections 2, treated in 2016, and Section 5, treated in 2019, consistently outperformed Sections 1, 3, and 4

by 2025. Traffic loading appeared to play a limited role in transverse cracking because crack counts remained relatively consistent between the northbound and southbound lanes. This contrasts with IRI trends, which showed greater directional differences and suggests that roughness was more sensitive to loading than cracking. Periodic crack sealing between 2023 and 2025 may have contributed to slower deterioration in sections that were already showing signs of distress.



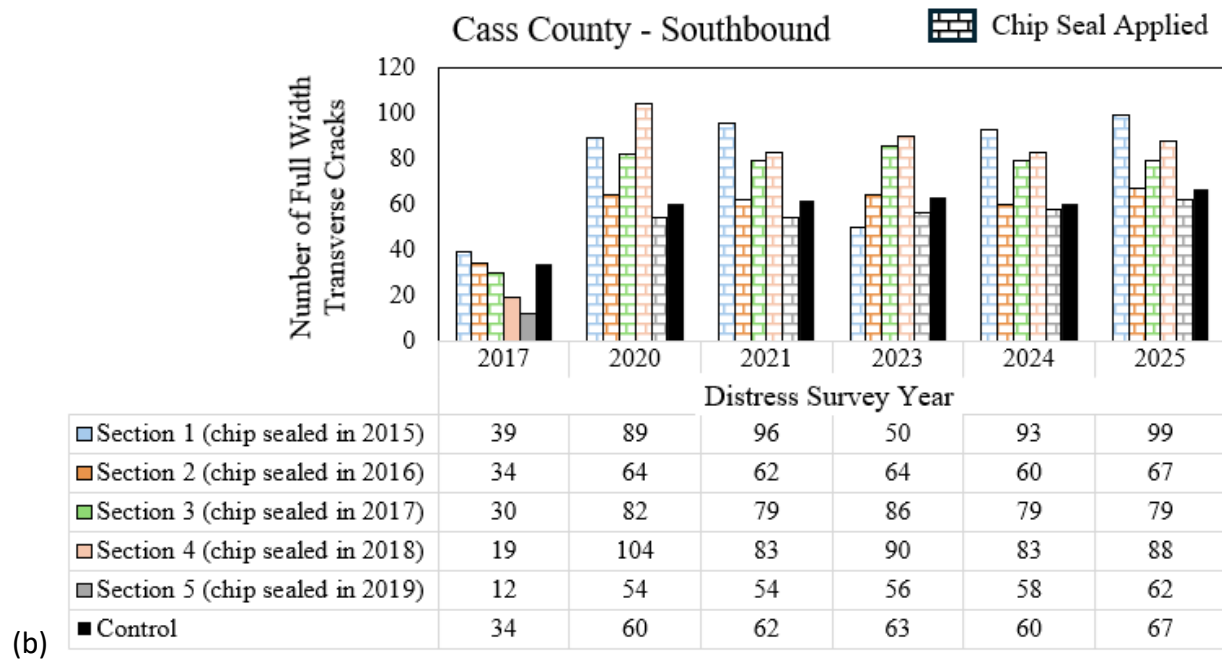


Figure 9. Cass County Full Width Transverse Cracks (2017 - 2025) Per Travel Direction: (a) Northbound, and (b) Southbound

Table 6. Cass County Field Remarks from Distress Survey (2017 - 2025)

Section ID	Year	Field Remarks
Control	2017	Good condition. No seal coat. Cracks not sealed.
	2020	No seal coat. Cracks not sealed.
	2021	No seal coat. Cracks not sealed.
	2023	No seal coat. Sealed cracks. Block cracked.
	2024	No seal coat. Crack sealed. Block cracked. Fatigue cracked.
	2025	No sealcoat. Crack sealed. Block cracked. Fatigue cracked.
Section 1	2017	Good condition. Seal coated. Cracks not sealed.
	2020	Seal coated. Cracks not sealed.
	2021	Seal coated. Cracks not sealed.
	2023	Seal coated. Cracks routed and sealed.
	2024	Section cracks sealed.
	2025	Section cracks sealed. Transverse cracks cupped. Block cracked.
Section 2	2017	Good condition. Seal coated. Cracks not sealed.
	2020	Seal coated. Cracks not sealed.
	2021	Seal coated. Cracks not sealed.
	2023	Seal coated. Cracks routed and sealed.
	2024	Section cracks sealed. Areas losing seal coat rock.
	2025	Section cracks sealed. Transverse cracks cupped. 3 potholes in NB lane from plowing.

Table 6. Cass County Field Remarks from Distress Survey (2017 - 2025) (*continued*)

Section ID	Year	Field Remarks
Section 3	2017	Good condition. Seal coated. Cracks not sealed.
	2020	Seal coated. Cracks not sealed.
	2021	Seal coated. Cracks not sealed.
	2023	Seal coated. Cracks routed and sealed.
	2024	Section cracks sealed.
	2025	Section cracks sealed. Transverse cracks cupped. 50 ft of scrapes/potholes in NB. Block cracked.
Section 4	2017	Good condition. Seal coated. Cracks not sealed.
	2020	Seal coated. Cracks not sealed.
	2021	Seal coated. Cracks not sealed.
	2023	Seal coated. Cracks routed and sealed.
	2024	Section cracks sealed. Areas losing seal coat rock. Some chip loss over prior center skip stripes.
	2025	Section cracks sealed. Transverse cracks cupped.

Table 6. Cass County Field Remarks from Distress Survey (2017 - 2025) (*continued*)

Section ID	Year	Field Remarks
Section 5	2017	Good condition. Seal coated. Cracks not sealed.
	2020	Seal coated. Cracks not sealed.
	2021	Seal coated. Cracks not sealed.
	2023	Seal coated. Cracks routed and sealed.
	2024	Section cracks sealed. Plow wear on aggregate. Loss over prior center stripes.
	2025	Section cracks sealed. Transverse cracks cupped. Heavy scrapping at fog lines, center joint, and side of transverse cracks.

Partial Width Transverse Cracking

Figure 10 presents the progression of partial-width transverse cracking in the northbound and southbound directions of Cass County CSAH 1. These data provide insight into the early stages of crack formation and the extent to which partial-width cracks either stabilize or evolve into more severe full-width cracking over time. At the beginning of the monitoring period, partial-width cracks were present in several sections but remained relatively limited in number. This pattern is consistent with the early development of thermally induced surface cracking, which often initiates at the pavement edge or within the wheel path before propagating across the full lane width. The presence of partial-width cracks in 2017 suggests that the pavement was beginning to experience surface-level distress even though overall cracking levels were still low.

As the monitoring period progressed, full-width cracking became more prevalent across several sections, while partial-width cracking became less prominent. This pattern suggests that some partial-width cracks may have extended across the lane under continued thermal cycling and traffic loading. By 2025, full-width cracking was the dominant transverse-cracking form observed in the test sections. Although individual cracks were not tracked from one survey to the next, the overall trend is consistent with continued crack propagation over time. The partial-width cracking results also showed that section performance did not follow a simple treatment-year sequence.

Overall, the partial-width cracking results show that cracking continued after chip seal application and that the section ordering did not follow a simple treatment-year sequence. The data should therefore be interpreted as descriptive evidence of crack development rather than proof that chip sealing either caused or prevented the transition from partial-width to full-width cracking.

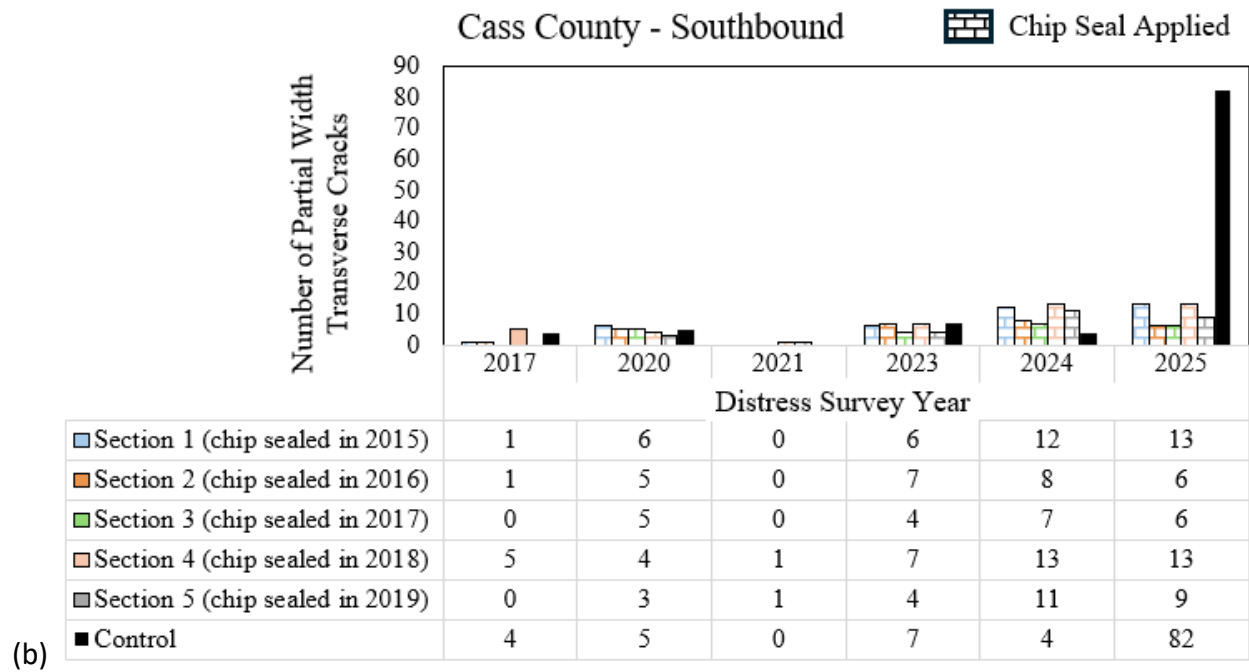
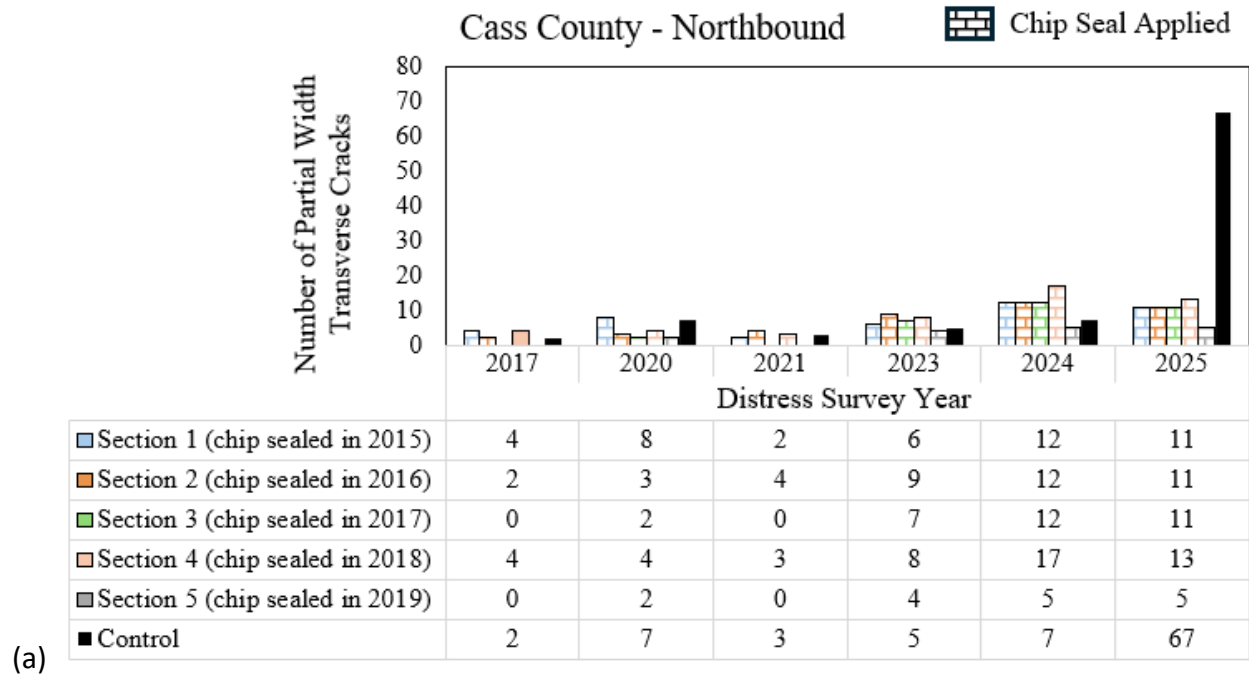


Figure 10. Cass County Partial Width Transverse Cracks (2017 - 2025) Per Travel Direction: (a) Northbound, and (b) Southbound

The relationship between ride quality and surface distress was examined using regression analysis and Pearson correlation of 2023 IRI values and full-width transverse crack counts. This analysis was intended to determine whether roughness could serve as a reliable indicator of cracking severity or whether the two metrics reflected distinct aspects of pavement performance.

In the northbound direction, the correlation between IRI and cracking was weak and negative ($r = -0.26$, $p = 0.615$; slope = -0.37). The southbound direction showed an even weaker negative correlation ($r = -0.09$, $p = 0.870$; slope = -0.14). Neither relationship was statistically significant, indicating that IRI and transverse cracking were largely independent of one another. As shown in Figure 11 and Table 7, high IRI values did not consistently correspond to high crack counts, and low IRI values did not reliably indicate low cracking.

Several examples illustrate this disconnect. Section 5, which was chip sealed in 2019, and the untreated control section both exhibited relatively high IRI values (77.6 and 82.8 inches per mile) but comparatively low crack counts (56 and 63). This combination suggests that these sections maintained comparatively limited observed cracking despite reduced ride quality. One likely explanation is the use of a polymer-modified asphalt binder (PG 58H-34), which may have enhanced cracking resistance even as surface texture or wear contributed to higher IRI. Conversely, Section 4, chip sealed in 2018, had a moderate IRI value of 67.3 but the highest crack count at 90. This indicates that the section experienced significant structural distress without a corresponding increase in roughness. Such behavior is consistent with pavements

where cracking initiates and propagates without immediately affecting ride quality, particularly when cracks remain narrow or are distributed uniformly across the lane.

These findings suggest that transverse cracking did not strongly explain the variation in IRI among the test sections. Sections with greater cracking did not consistently exhibit higher IRI values, indicating that the effect of cracking on measured roughness was influenced by site- and direction-specific conditions. Pavement structure, binder grade, construction variability, environmental exposure, and treatment timing all likely contributed to the observed patterns. The weak correlations also reinforce the importance of using multiple performance indicators when evaluating chip seal effectiveness. Roughness and cracking capture different dimensions of pavement condition, and neither metric alone provides a complete picture of long-term performance.

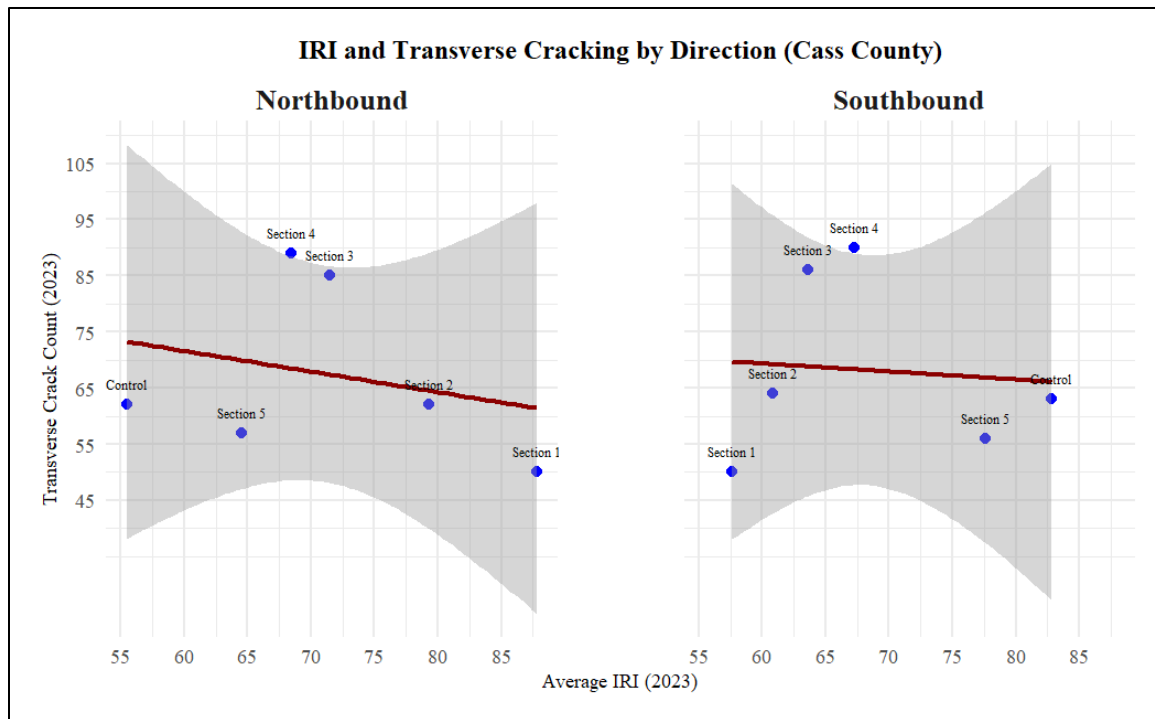


Figure 11. IRI and Transverse Cracking Relationship in Cass County CSAH-1

Table 7. Directional Summary of IRI and Transverse Crack Counts in 2023, CSAH-1

Section	Northbound			Southbound		
	Average IRI	Full-width Transverse Crack Count	Partial-width Transverse Crack Count	Average IRI	Full-width Transverse Crack Count	Partial-width Transverse Crack Count
Control	55.5	62	5	82.8	63	7
Section 1	87.8	50	6	57.7	50	6
Section 2	79.3	62	9	60.8	64	7
Section 3	71.5	85	7	63.6	86	4
Section 4	68.4	89	8	67.3	90	7
Section 5	64.6	57	4	77.6	56	4

4.2 Crow Wing County (CSAH 3)

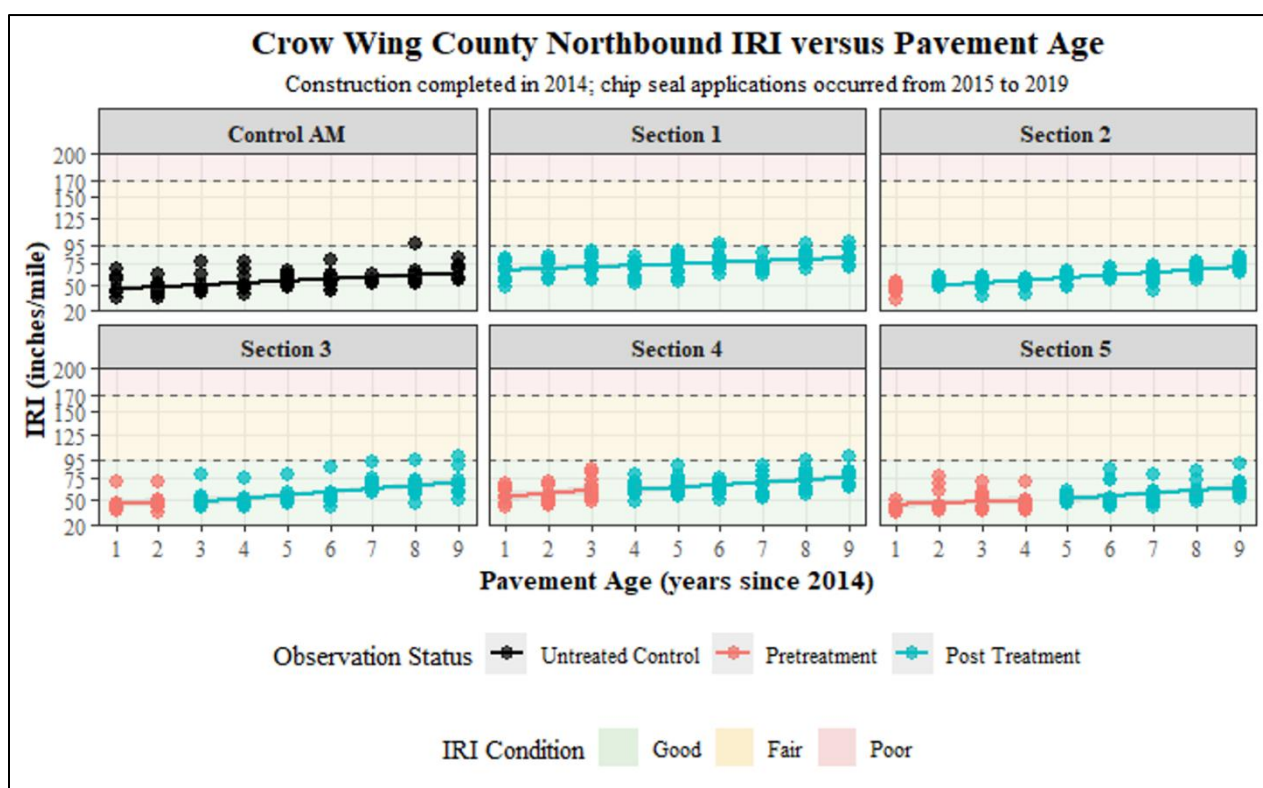
4.2.1 International Roughness Index

The progression of IRI in the northbound and southbound directions of Crow Wing County CSAH 3 is presented in Figures 12(a) and 12(b). In both directions, roughness generally increased with pavement age. However, the section trajectories overlapped substantially and did not follow a consistent sequence based on chip seal application year. Earlier-treated sections did not consistently maintain lower IRI than either the control or the sections treated later.

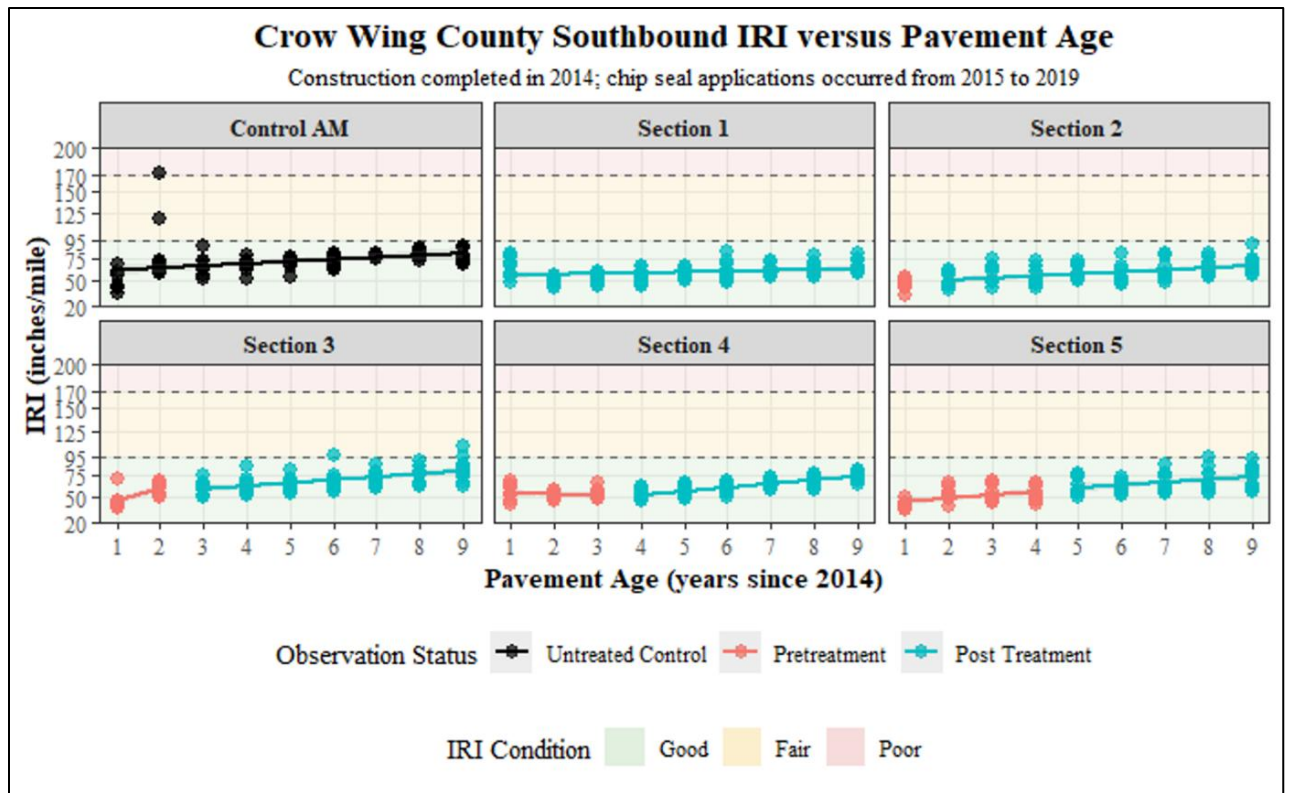
In the northbound direction, Section 1 generally exhibited higher IRI values during the later years of monitoring, while Sections 2 through 5 showed varying degrees of increase and substantial overlap with the untreated control. The control followed a comparatively moderate fitted trajectory, but its later-year observations were not consistently lower than those of every treated section. The visual results therefore indicate section-level variability rather than a clear early-to-late treatment pattern. The segmented linear mixed-effects model in Table 8 showed that pavement age was a significant predictor of northbound IRI, with an estimated increase of 2.08 in./mi./year ($p < 0.001$). The estimated immediate post-treatment level change was 1.02 in./mi. and was not statistically significant ($p = 0.510$). The estimated change in slope after treatment was an increase of 0.61 in./mi./year, but this change was also not statistically significant ($p = 0.176$). The estimated post-treatment slope was 2.69 in./mi./year ($p < 0.001$), indicating that roughness continued to increase after treatment. However, the significance of the post-treatment slope indicates continued pavement aging and should not be interpreted as evidence of a statistically significant treatment effect.

In the southbound direction, IRI also increased across the monitoring period, but the relative section rankings varied with pavement age. The control included several unusually high observations during the early monitoring years, while its later observations overlapped those of the treated sections. Section 4 generally remained among the smoother sections, whereas Section 5 increasingly overlapped the other sections at later pavement ages. Overall, the visual results did not show a consistent roughness advantage for either the earlier- or later-treated sections. In Table 9, the southbound segmented model estimated an age-related IRI increase of 2.69 in./mi./year ($p < 0.001$). The immediate post-treatment level change was estimated as 2.50 in./mi. and was not statistically significant ($p = 0.125$). The estimated change in slope after treatment was -0.47 in./mi./year, indicating a small numerical reduction in the rate of IRI progression, but the change was not statistically significant ($p = 0.320$). The estimated post-treatment slope remained positive at 2.22 in./mi./year ($p < 0.001$). Thus, southbound roughness continued to increase after treatment, and the model did not provide statistical evidence that chip sealing changed the deterioration rate.

Overall, pavement age was the consistent predictor of IRI progression in both Crow Wing County directions. Neither the immediate post-treatment level change nor the change in slope after treatment was statistically significant. Consequently, the results do not demonstrate that chip sealing either increased or reduced IRI progression during the monitoring period. They also do not identify a consistent roughness advantage associated with earlier application. Surface macrotexture, localized pavement condition, construction variability, and measurement conditions may have contributed to the observed section-level differences, but their individual effects were not quantified in the present analysis.



(a)



(b)

Figure 12. Crow Wing County IRI Results (Pavement Age from 0 to 8 Years) Per Travel

Direction: (a) Northbound, and (b) Southbound

Table 8. Summary of LMM results for Northbound IRI progression in Crow Wing County (CSAH 3)

Model term	Estimate	p-value	Interpretation
Pavement age	+2.08 in./mi./year	<0.001	IRI increased significantly as the pavement aged.
Post-treatment level change	+1.02 in./mi.	0.510	No significant immediate change after treatment.
Change in slope after treatment	+0.61 in./mi./year	0.176	IRI increased more rapidly after treatment.
Post-treatment slope	+2.69 in./mi./year	<0.001	Overall post-treatment deterioration rate.

Table 9. Summary of LMM results for Southbound IRI progression in Crow Wing County (CSAH 3)

Model term	Estimate	p-value	Interpretation
Pavement age	+2.69 in./mi./year	<0.001	IRI increased significantly as the pavement aged.
Post-treatment level change	+2.50 in./mi.	0.125	No significant immediate change after treatment.
Change in slope after treatment	-0.47 in./mi./year	0.320	IRI increased more rapidly after treatment.
Post-treatment slope	+2.22 in./mi./year	<0.001	Overall post-treatment deterioration rate.

4.2.2 Surface Distresses

Full-Width Transverse Cracking

Figure 13(a) and Figure 13(b) illustrate the progression of full-width transverse cracking from 2017 through 2025 in both directions of Crow Wing County CSAH 3. At the start of the monitoring period, cracking levels were relatively low across all sections, with counts below 60. The control section began at 25 cracks in both directions, which aligns with field remarks in Table 6 describing a clean, sealed, and well-preserved surface. These early conditions indicate that the pavement structure was still performing adequately and that differences among sections had not yet emerged.

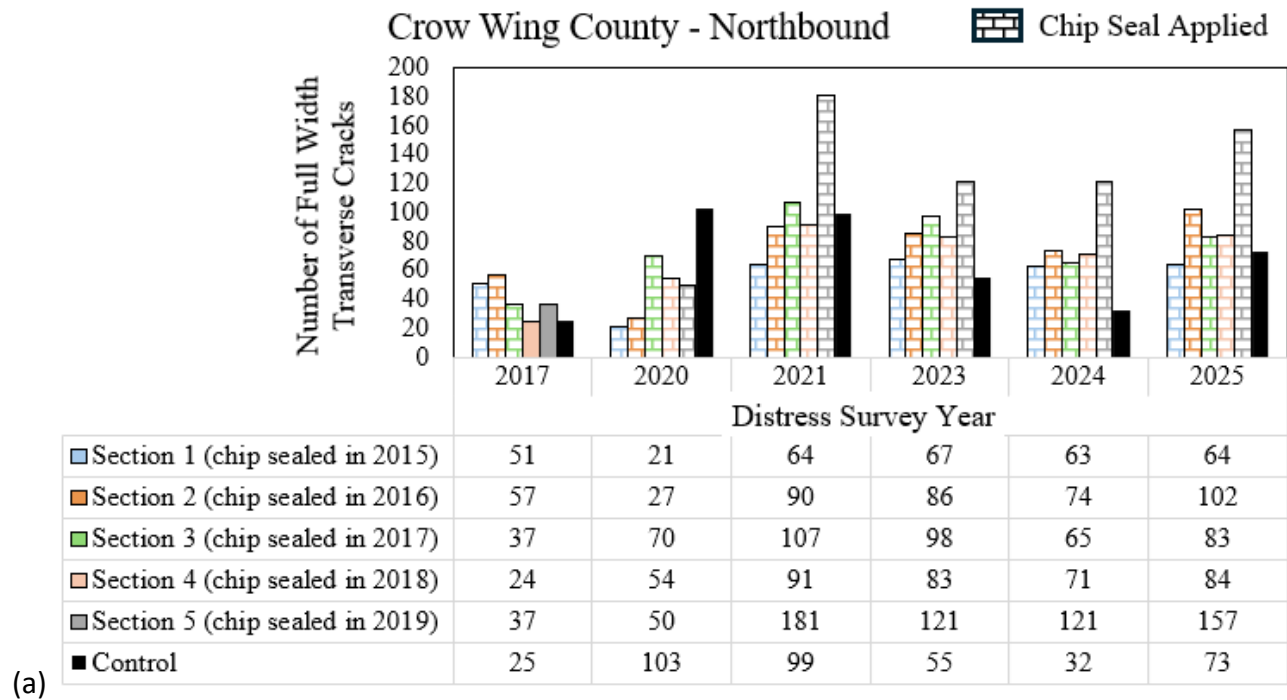
In the northbound direction, deterioration accelerated rapidly in several treated sections. Section 5 exhibited the most severe progression, increasing from 37 cracks in 2017 to 157 by 2025. Sections 2 and 3 also showed substantial deterioration, ending at 102 and 83 cracks, respectively. Section 4 reached 84 cracks, and field observations noted persistent block cracking and more than 30 pothole patches, indicating substantial observed surface distress and localized maintenance needs. Section 1, which was chip sealed in 2015, performed best among the treated sections and ended with 64 cracks. The untreated control section increased more gradually and closed at 73 cracks, which suggests that the absence of treatment did not necessarily lead to the worst outcomes. Field remarks support these numerical trends. Maintenance engineers documented ongoing crack sealing, chip retention issues, and isolated surface damage across several treated sections. These observations confirm that deterioration was widespread and not limited to a single treatment year or construction condition.

In the southbound direction, Section 5 again performed the worst, ending with 146 cracks. Sections 2 and 3 also experienced significant deterioration, closing at 106 and 93 cracks. Section 4 followed with 85 cracks, while Section 1 remained one of the most stable sections at 63. The control section increased steadily to 66 cracks. Field remarks indicated consistent maintenance activity, snowplow-related edge damage, and generally good chip retention across most sections as shown in Table 10.

Crack sealing, conducted between 2021 and 2025, may have helped delay more severe deterioration but did not consistently improve outcomes. Sections treated earlier did not always perform better, suggesting that sealing alone was insufficient to counteract the underlying mechanisms driving crack propagation. The observed performance issues may be partially attributed to material properties. The unmodified PG 58S-28 binder used in the mix design provides adequate performance under standard temperature conditions but offers limited resistance to thermal and fatigue cracking compared to modified binders such as the PG 58H-34 polymer-modified asphalt used in Cass County. In addition, the mixture contained 38 percent RAP, which likely increased stiffness and reduced the pavement's ability to accommodate tensile strains. This reduced flexibility, combined with Minnesota's freeze-thaw cycles and repetitive loading, may have contributed to premature crack initiation and propagation in the treated sections.

Overall, cracking increased in all sections, including the control. While some chip sealed sections, such as Section 1, performed reasonably well, others, such as Section 5, deteriorated significantly despite routine maintenance. These results indicate that cracking performance was

influenced by a combination of treatment timing, environmental stressors, and material properties rather than chip sealing alone. The findings reinforce the need to consider binder grade, RAP content, and climatic exposure when evaluating the long-term effectiveness of surface treatments.



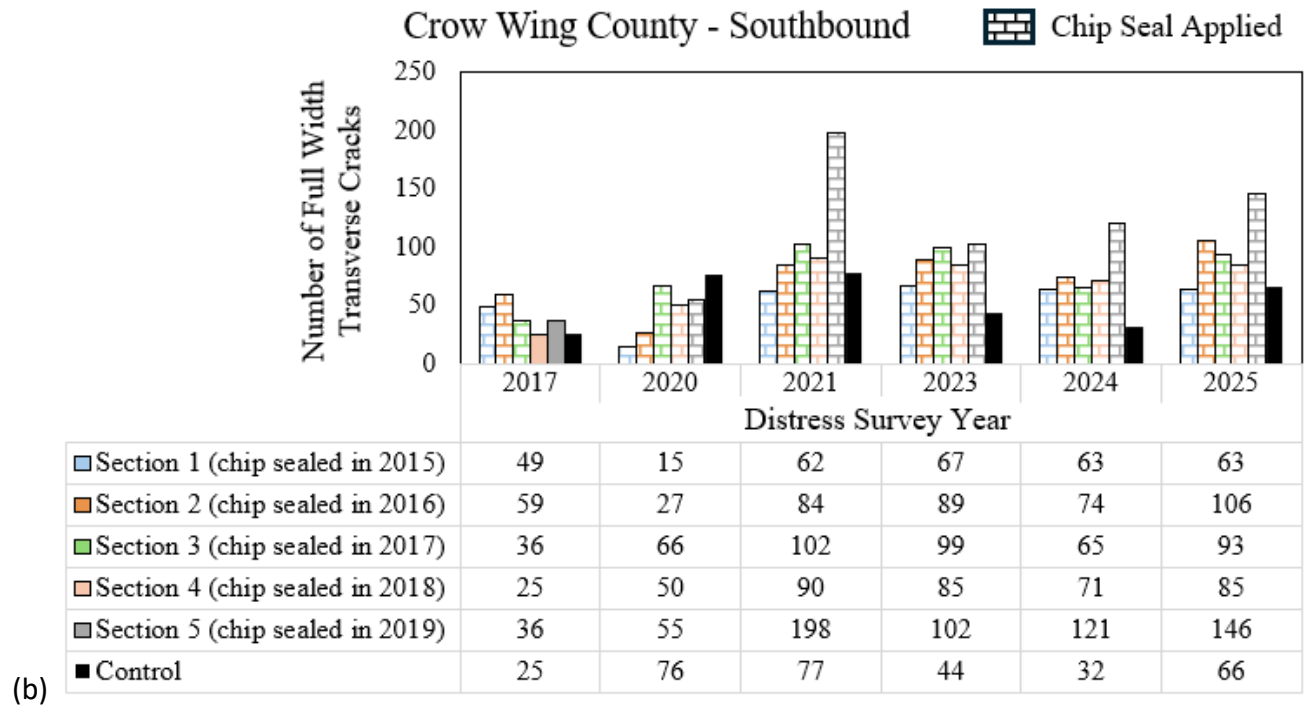


Figure 13. Crow Wing County Full Width Transverse Cracks (2017 - 2025) Per Travel Direction:

(a) Northbound, and (b) Southbound

Table 10. Crow Wing County Field Remarks from Distress Survey (2017 - 2025)

Section ID	Year	Field Remarks
Control	2017	No seal coat. Clean and sealed. Good condition.
	2020	No seal coat. Clean and sealed.
	2021	No seal coat. Crack sealed.
	2023	No seal coat. Crack sealed.
	2024	No seal coat. Crack sealed. Block cracked.
	2025	No seal coat. Crack sealed. Block cracked.
Section 1	2017	Clean and seal over the chip seal surface.
	2020	Chip seal surface above clean and seal cracks.
	2021	Clean and seal over the chip seal surface. Cracked through chip.
	2023	Chip in good condition. Sealed cracks.
	2024	Crack sealed. Chip surface is in good condition. A 2024 roundabout project used this section just south of the Vet Office for stockpile.
	2025	Crack sealed. Longitudinal cracks. Potholes in sealcoat. Chip surface is in good condition. The South end of section is new from 2024 roundabout project.

Table 10. Crow Wing County Field Remarks from Distress Survey (2017 - 2025) (continued)

Section ID	Year	Field Remarks
Section 2	2017	Clean and seal over the chip seal surface.
	2020	Chip seal surface above clean and seal cracks.
	2021	Crack seal over chip seal.
	2023	Sealed cracks. Pothole/delamination.
	2024	Crack sealed. Block cracked. Good chip retention. Few potholes/popoff.
	2025	Crack sealed. Potholes in seal coat. Block cracked. Good chip retention.
Section 3	2017	Chip seal surface above clean and seal cracks.
	2020	Chip seal surface above clean and seal cracks.
	2021	Crack seal over chip seal.
	2023	Chip okay, some CL wear. Potholes.
	2024	Crack sealed. Block cracked. Good chip retention. Few potholes/popoff.
	2025	Crack sealed. Block cracked. Good chip retention. Potholes in seal coat.

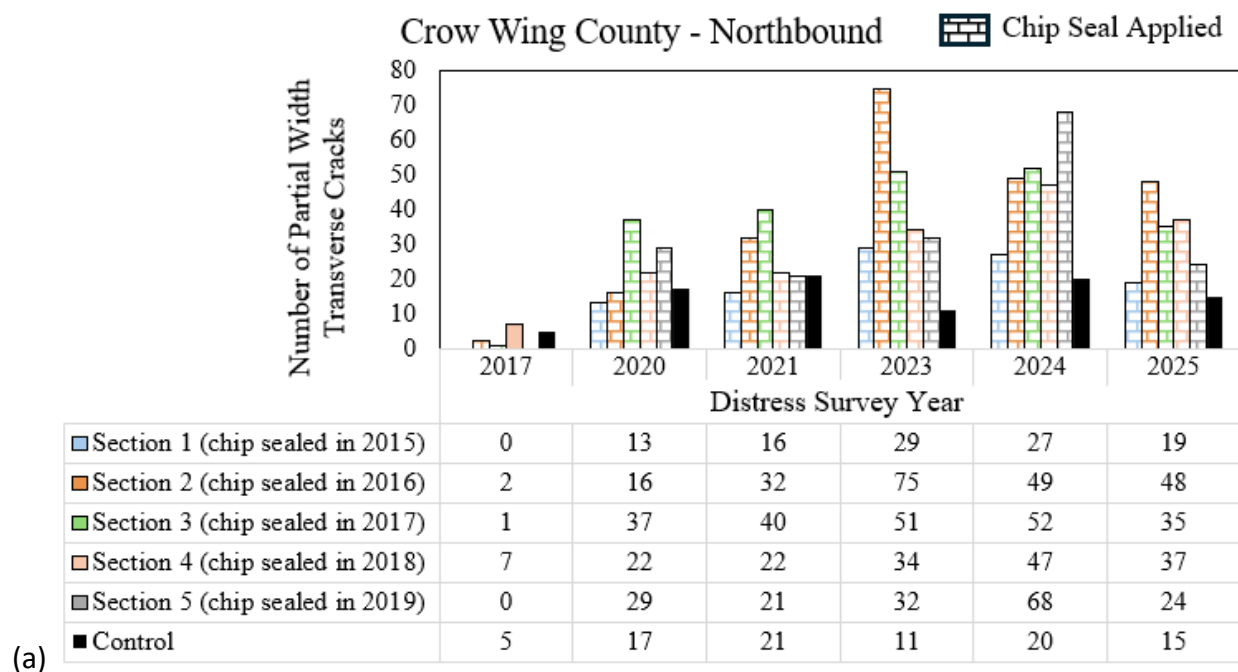
Table 10. Crow Wing County Field Remarks from Distress Survey (2017 - 2025) (continued)

Section ID	Year	Field Remarks
Section 4	2017	Clean and sealed. Good condition.
	2020	Chip seal surface above clean and seal cracks.
	2021	Crack seal over chip seal.
	2023	Mostly crack sealed. Chip good condition, minor chip wear at fog line. Block cracked. Potholes.
	2024	Crack sealed. Block cracked. Good chip retention.
	2025	Crack sealed. Potholes in seal coat (37 patches). Block cracked. Good chip retention. Section has some snowplow damage at fog line where road curves.
Section 5	2017	Clean and sealed. Good condition.
	2020	Chip seal surface above clean and seal cracks.
	2021	Crack seal over chip seal.
	2023	Sealed cracks. Block cracked.
	2024	Section crack sealed. Block cracked. Areas of wear and chip popout/potholes.
	2025	Crack sealed. Noted chip loss at center of each lane. Block cracked.

Partial-Width Transverse Cracking

Figure 14(a) and Figure 14(b) show the progression of partial width transverse cracking in the northbound and southbound directions of Crow Wing County CSAH 3. Partial-width cracks were present at the beginning of monitoring and became less prominent relative to full-width cracks over time. This pattern is consistent with progression of some cracks across the lane, but individual cracks were not tracked between surveys; maintenance, visibility, and classification changes may also have affected the recorded counts.

Directional differences were minimal, indicating that environmental factors dominated the development of this distress type. These results reinforce the conclusion drawn from Cass County that chip sealing did not prevent the initiation of early cracking or consistently slow the transition to full-width cracks. Early identification and timely maintenance remain important, as partial width cracks tend to evolve into more severe forms of distress.



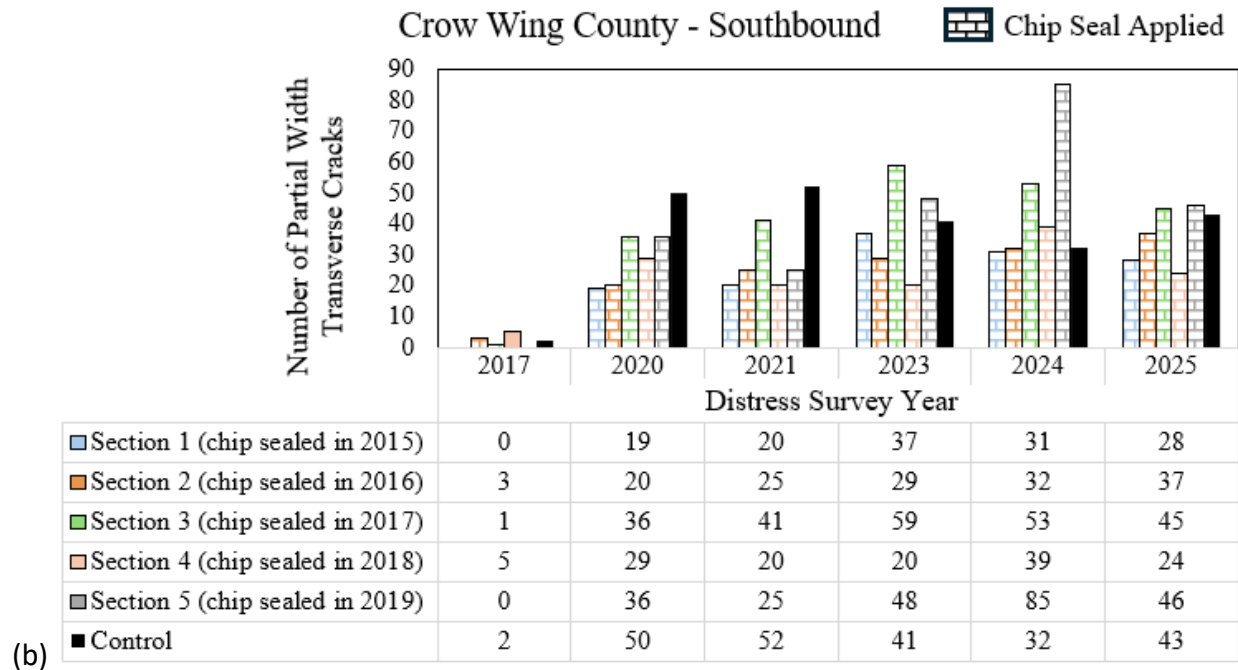


Figure 14. Crow Wing County Partial Width Transverse Cracks (2017 - 2025) Per Travel

Direction: (a) Northbound, and (b) Southbound

The relationship between ride quality and transverse cracking in Crow Wing County was evaluated using Pearson correlation and simple linear regression, as summarized in Figure 15 and Table 7. As in Cass County, the associations between 2023 IRI and full width transverse cracking were weak and not statistically significant. The northbound direction showed a weak negative correlation ($r = -0.27$, $p = 0.605$), and the southbound direction exhibited an even weaker negative relationship ($r = -0.08$, $p = 0.879$). These results indicate that roughness and cracking were largely independent.

The weak correlations suggest that factors other than IRI governed cracking performance. Construction quality, mixture composition, binder grade, RAP content, environmental exposure, and traffic loading patterns likely played more substantial roles. In

particular, the use of an unmodified PG 58S-28 binder and relatively high RAP content may have increased stiffness and reduced flexibility, making the pavement more susceptible to thermal and fatigue cracking regardless of surface roughness. Overall, the Crow Wing County results align with the broader conclusion from Cass County: IRI alone is not a reliable indicator of transverse cracking performance. The two measures capture different aspects of pavement condition, reinforcing the need to evaluate multiple performance indicators when assessing chip seal effectiveness.

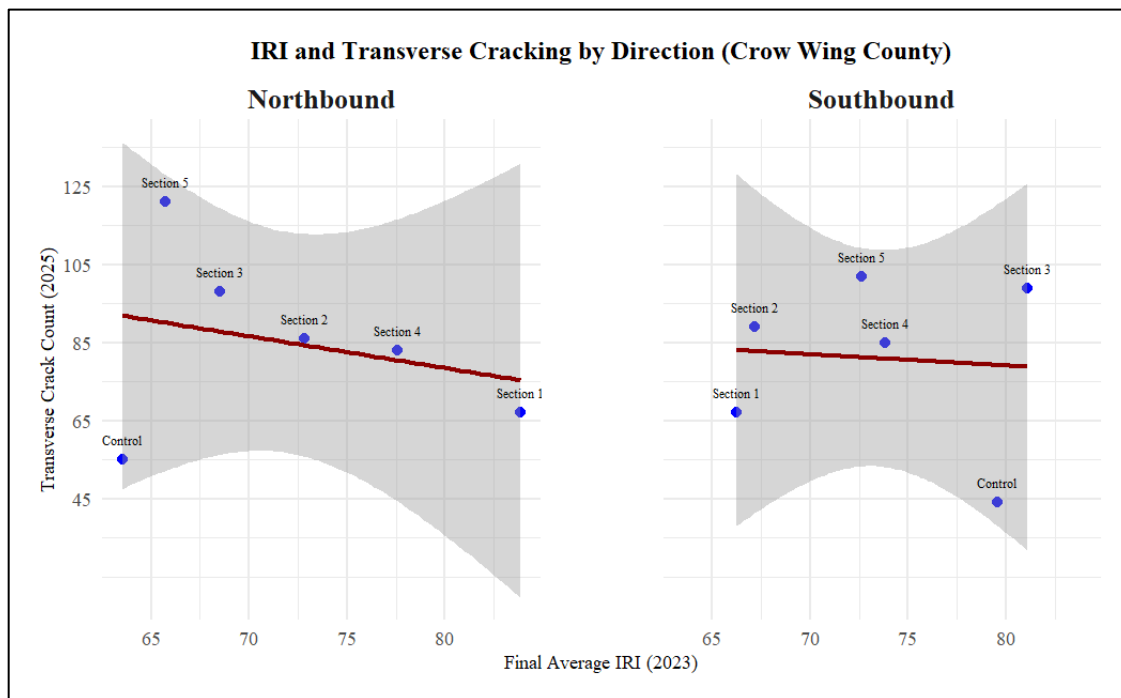


Figure 15. IRI and Transverse Cracking Relationship in Crow Wing County CSAH-3

Table 11. Directional Summary of IRI and Transverse Crack Counts in 2023, CSAH-3

Section	Northbound			Southbound		
	<i>Average IRI</i>	<i>Full-width Transverse Crack Count</i>	<i>Partial-width Transverse Crack Count</i>	<i>Average IRI</i>	<i>Full-width Transverse Crack Count</i>	<i>Partial-width Transverse Crack Count</i>
Control	63.5	55	11	79.6	44	41
Section 1	83.9	67	29	66.3	67	37
Section 2	72.8	86	75	67.2	89	29
Section 3	68.5	98	51	81.1	99	59
Section 4	77.6	83	34	73.8	85	20
Section 5	65.7	121	32	72.6	102	48

A comparison of the performance trends in Cass County (Table 7) and Crow Wing County (Table 11) suggests that differences in long-term pavement behavior were influenced more by the underlying mix designs than by chip sealing timing alone. Cass County used a PG 58H-34 polymer-modified asphalt binder with 20 percent RAP, a combination that provides enhanced elasticity and improved resistance to thermal and fatigue cracking. This mixture design likely contributed to the relatively favorable cracking performance observed in Cass County, where several chip sealed sections exhibited comparable or lower transverse crack counts than the untreated control. The IRI trends in Cass County were also relatively stable, indicating that the pavement structure retained its functional integrity despite surface wear.

In contrast, Crow Wing County used an unmodified PG 58S 28 binder with 38 percent RAP. This mixture is inherently stiffer and less capable of accommodating tensile strains,

particularly under cold-climate conditions. While some Crow Wing sections maintained or improved IRI relative to the control, several chip sealed sections exhibited substantially higher transverse crack counts. The combination of an unmodified binder and a high RAP percentage likely increased mixture brittleness, making the pavement more susceptible to thermal contraction and fatigue cracking. These effects were evident in both directions of CSAH 3, where cracking progressed rapidly despite routine maintenance and chip sealing.

Taken together, these findings indicate that binder modification and RAP content played a significant role in long-term pavement preservation effectiveness. Chip sealing alone did not overcome the limitations imposed by a stiffer, less flexible mixture. Pavements constructed with polymer-modified binders and moderate RAP levels demonstrated better resistance to cracking, while those built with unmodified binders and high RAP contents showed accelerated distress. This comparison underscores the importance of considering mixture design characteristics when evaluating the expected benefits of surface treatments and when developing preservation strategies for cold-climate pavements.

4.3 City of St. Cloud (3rd Street N)

4.3.1 Surface Rating (Eastbound)

The surface rating metric provides an aggregate assessment of pavement condition by incorporating multiple distress types, including transverse cracking, longitudinal cracking, block cracking, and patching. Figure 16 presents the surface ratings for all five chip sealed sections and the untreated control over the three-year observation period. Overall, the Eastbound direction demonstrated strong performance, with most sections maintaining a rating of 4.0 throughout the study period.

A slight decline was observed in Section 3, which decreased from 4.0 to 3.9 in 2024. Section 4 and the control section also recorded ratings of 3.9 in both 2023 and 2024, indicating only minimal surface changes. These small variations suggest that the pavement structure remained in good condition and that distress development was limited across all sections. The linear mixed-effects model supports this interpretation. Although the model detected a statistically significant decline in surface rating over time, the magnitude of change was small. The survey year variable produced a negative slope of -0.0069 with a p-value of 0.034, indicating a gradual but measurable reduction in surface condition from 2021 to 2024. This trend aligns with expected aging processes, particularly given the projected increase in traffic volumes from 10,600 vehicles per day in 2014 to an estimated 15,800 by 2034. The anticipated cumulative loading of 1 to 3 million ESALs would reasonably contribute to incremental surface wear.

The chip seal treatment variable produced a positive slope of 0.0252 with a p-value of 0.465, indicating no statistically significant difference in surface condition between treated and untreated sections. The absence of a measurable treatment effect can be attributed to the high quality of the original pavement materials. The mixture used a PG 58H-34 polymer-modified binder and contained no reclaimed asphalt pavement. These characteristics likely enhanced the pavement's resistance to cracking and oxidative aging. The relatively high binder content would have increased film thickness, further improving durability and reducing susceptibility to environmental hardening. As a result, the Eastbound sections of 3rd Street N demonstrated strong inherent performance, which likely reduced the observable impact of chip seal

treatments during the evaluation period. The pavement’s robust material properties and favorable structural condition overshadowed any preservation benefits that chip sealing might otherwise have provided.

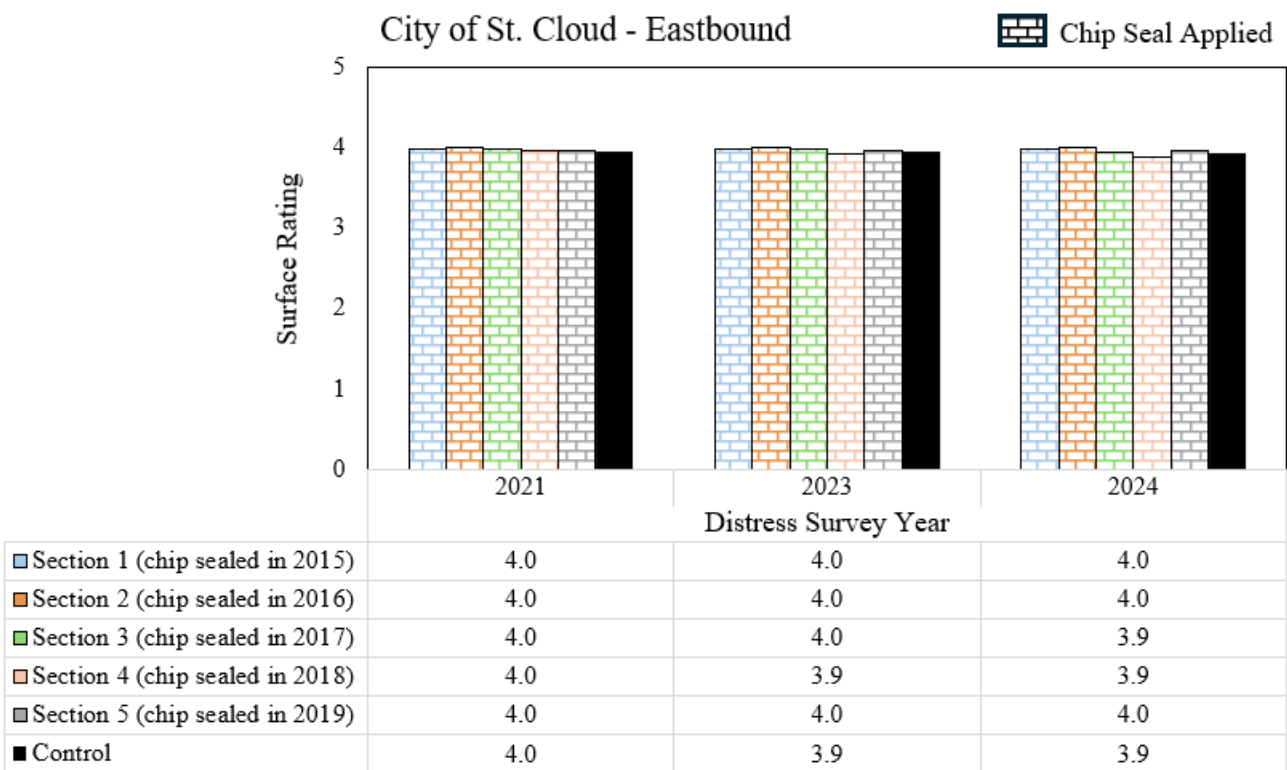


Figure 16. Overall Surface Distress: Surface Rating for Eastbound City of St. Cloud (2021 - 2024)

4.3.2 Surface Rating (Westbound)

The same performance evaluation was conducted for the westbound direction of 3rd Street N in the City of St. Cloud. As shown in Figure 17, surface ratings exhibited a slight decline over the inspection years of 2021, 2023, and 2024. Section 5 experienced the most noticeable reduction, ending with a rating of 3.7 in 2024. Sections 1 through 4 remained between 3.8 and 3.9, indicating only minor surface changes. Section 1 demonstrated the most consistent

performance across all years, suggesting greater durability or reduced exposure to cumulative stressors such as traffic loading, environmental aging, or winter maintenance activities.

Although Section 5 exhibited the largest decrease in surface rating, the magnitude of the decline was small. Overall deterioration was minimal, and all sections remained in good surface condition throughout the monitoring period. The linear mixed model for the westbound direction revealed a statistically significant decline in surface condition over time. The survey year variable returned a negative slope of -0.0321 with a p-value of 0.008, indicating a steady reduction in surface rating from 2021 to 2024. Although this trend was statistically significant, its practical effect was limited because the ratings remained within a narrow range and did not indicate substantial deterioration.

The chip seal treatment variable produced a positive slope of 0.1212 with a p-value of 0.106. Although not statistically significant at the 0.05 level, the positive slope suggests a possible benefit from treatment. This marginal trend may indicate that chip seals helped slow deterioration, although the extent of improvement remains uncertain given the limited variation in surface ratings. Despite these differences, surface ratings across most sections remained high. The relatively small gap between treated and untreated segments highlights the influence of the original pavement materials. The westbound sections were constructed with a PG 58H-34 polymer-modified binder, contained no reclaimed asphalt pavement, and featured a relatively high binder content. These characteristics likely contributed to increased flexibility, improved rutting resistance, and enhanced durability against oxidative aging. As a result, the inherent robustness of the initial mix design appears to have played a dominant role in

long-term performance, with chip sealing providing only marginal additional benefit during the evaluation period.

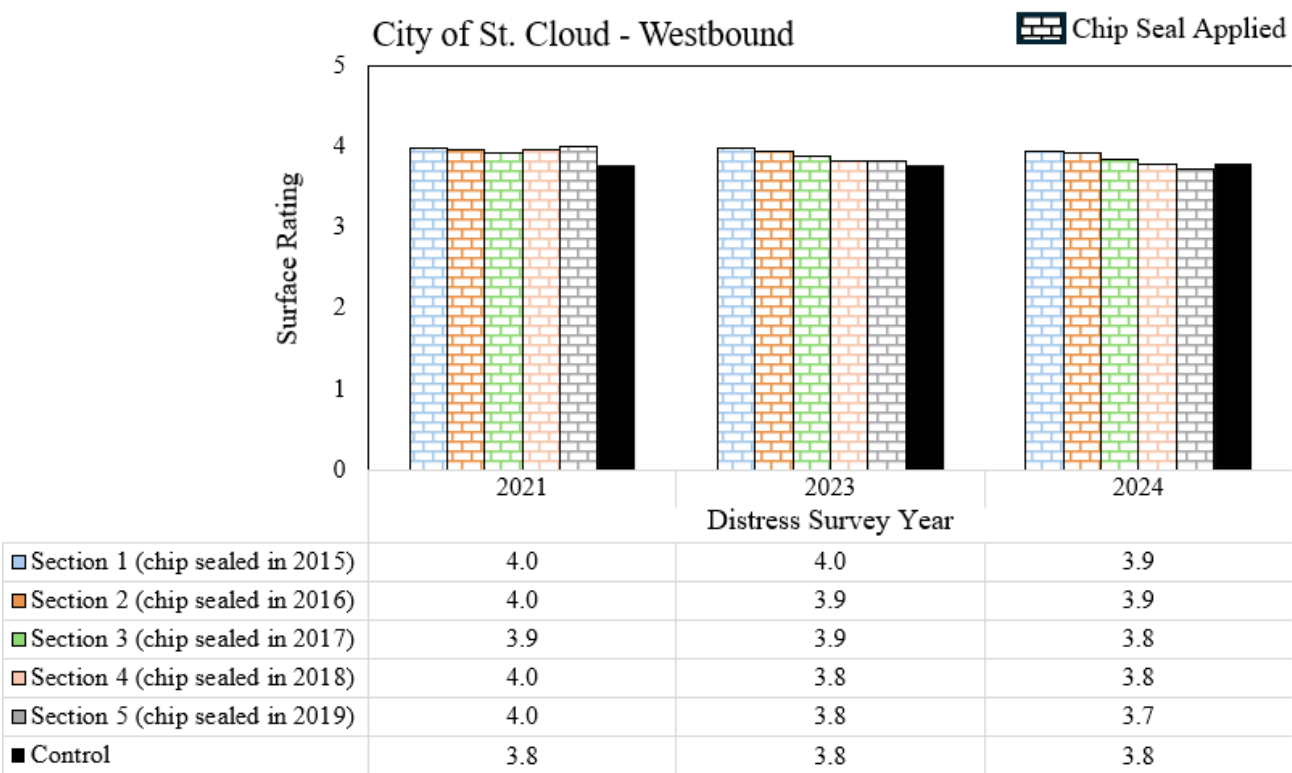


Figure 17. Overall Surface Distress: Surface Rating for Westbound City of St. Cloud (2021 - 2024)

The laboratory binder characterization phase evaluated the aging behavior and the chemical, rheological, and mechanical properties of the recovered binders. In this section, each characterization test is used to compare performance across the three participating agencies, allowing differences in binder aging and property evolution to be assessed systematically under each testing protocol.

4.4 Chemical Aging of Recovered Binders (ATR-FTIR)

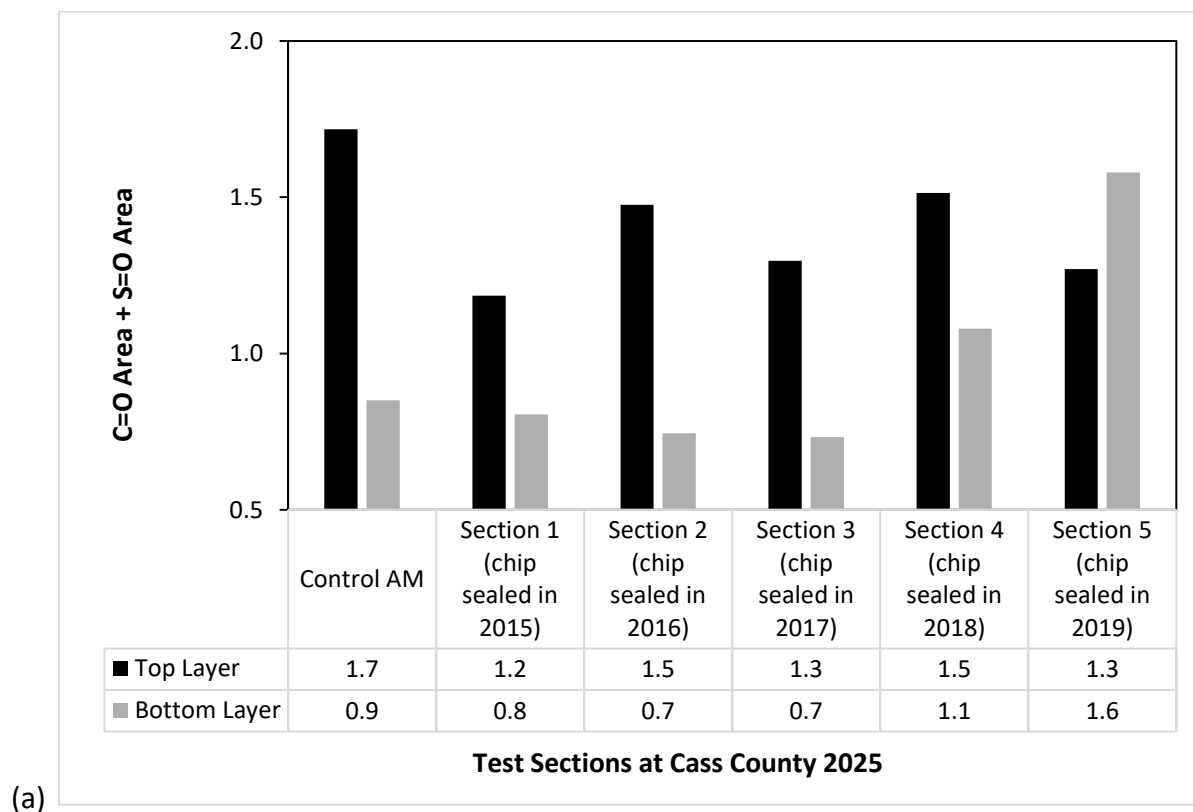
The combined oxidation index, calculated as the sum of the carbonyl and sulfoxide absorption areas, was used as a comparative indicator of asphalt-binder oxidation. Prolonged exposure to oxygen promotes the formation of carbonyl- and sulfoxide-containing compounds, which are associated with increased molecular polarity, intermolecular association, and binder hardening (Petersen & Glaser, 2011). Higher combined oxidation index values therefore generally indicate a greater degree of oxidative aging. Because the recovered top layer from each treated section contained chip seal residue in addition to near-surface HMA binder, whereas the control top layer contained only HMA binder, direct comparisons between treated and untreated sections were based primarily on the bottom-layer binders within each site.

At Cass County [Figure 18(a)], the bottom-layer combined oxidation index was 0.9 for the untreated control. Sections 1, 2, and 3 produced lower values of 0.8, 0.7, and 0.7, respectively, indicating less oxidation in the underlying binders than in the binder beneath the untreated pavement. In contrast, Sections 4 and 5 produced combined oxidation index values of 1.1 and 1.6, respectively. The lower values observed in Sections 1 through 3 are consistent with chip sealing during the earlier and intermediate portions of the pavement service period reducing oxidation within the underlying HMA layer. However, the higher values measured in Sections 4 and 5 indicate that this preservation response was not maintained across all treatment years. The Cass County results therefore show a timing-related preservation signal, although the response was neither uniform nor strictly monotonic with chip seal application year.

At Crow Wing County [Figure 18(b)], the untreated control produced a bottom-layer combined oxidation index of 1.7, while all treated sections produced lower values ranging from 0.7 to 1.5. Section 3 had the lowest bottom-layer oxidation index at the site, indicating that its underlying HMA binder remained substantially less oxidized than the binder beneath the untreated control. The remaining treated sections also had lower values than the control, providing additional evidence of reduced oxidation beneath the chip sealed surfaces. Although the results did not follow the exact chronological sequence of treatment application, they demonstrate a clear treated-versus-control preservation response at depth. The magnitude and sequence of these differences may also have been influenced by the mixture's 38% RAP content and unmodified PG 58S-28 binder. The recovered material included aged RAP binder with an oxidation history that preceded construction of the test sections, which may have contributed to the variability among treatment years.

At the City of St. Cloud [Figure 18(c)], the bottom-layer combined oxidation indices showed comparatively small differences among the untreated control and treated sections. The results did not establish a clear chronological relationship between chip seal application year and oxidation level, nor did they show the same degree of treated-versus-control separation observed at Crow Wing County or in Sections 1 through 3 at Cass County. The relatively narrow range among sections indicates that the FTIR response at this site was less sensitive to treatment timing. The polymer-modified, RAP-free mixture may have contributed to the limited variation, although the individual effects of material composition, environmental exposure, and treatment timing cannot be separated using the available data.

Overall, the FTIR results provide chemical evidence that chip sealing was associated with lower oxidation beneath the pavement surface at Cass and Crow Wing Counties. At Cass County, the preservation response was concentrated in Sections 1 through 3, whereas the later-treated Sections 4 and 5 did not exhibit the same benefit. At Crow Wing County, every treated section had a lower bottom-layer combined oxidation index than the untreated control, with Section 3 showing the strongest separation. The City of St. Cloud exhibited only minor differences among sections and did not show a distinct treatment-timing pattern. These findings demonstrate that recovered binder chemistry was capable of identifying preservation-related differences associated with chip sealing, although the strength and chronological consistency of the response depended on the site.



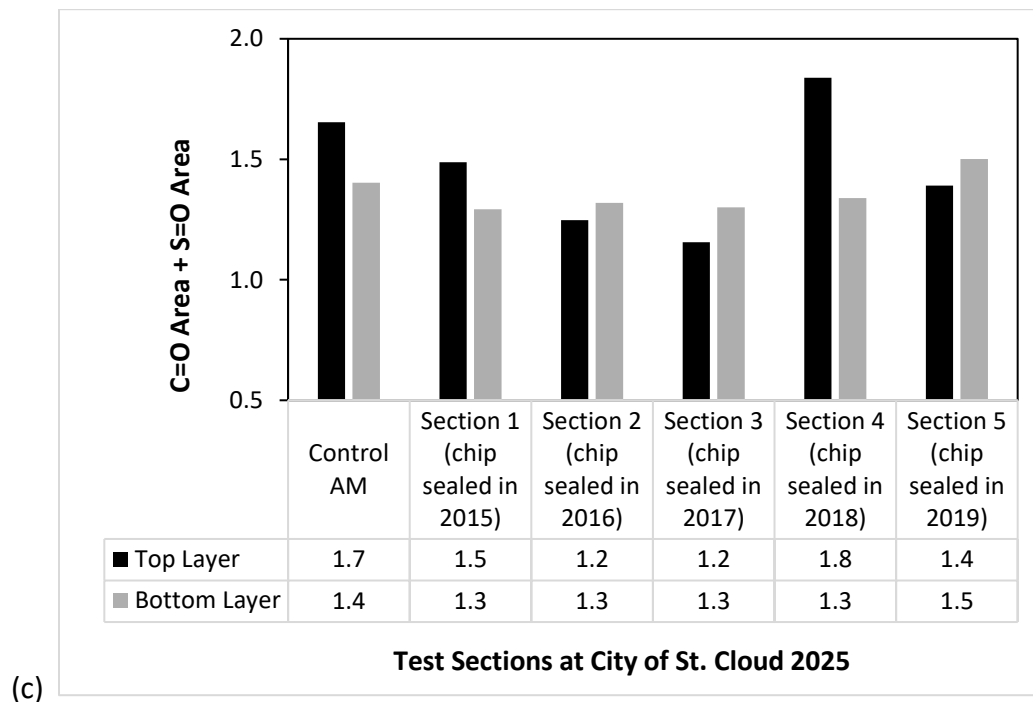
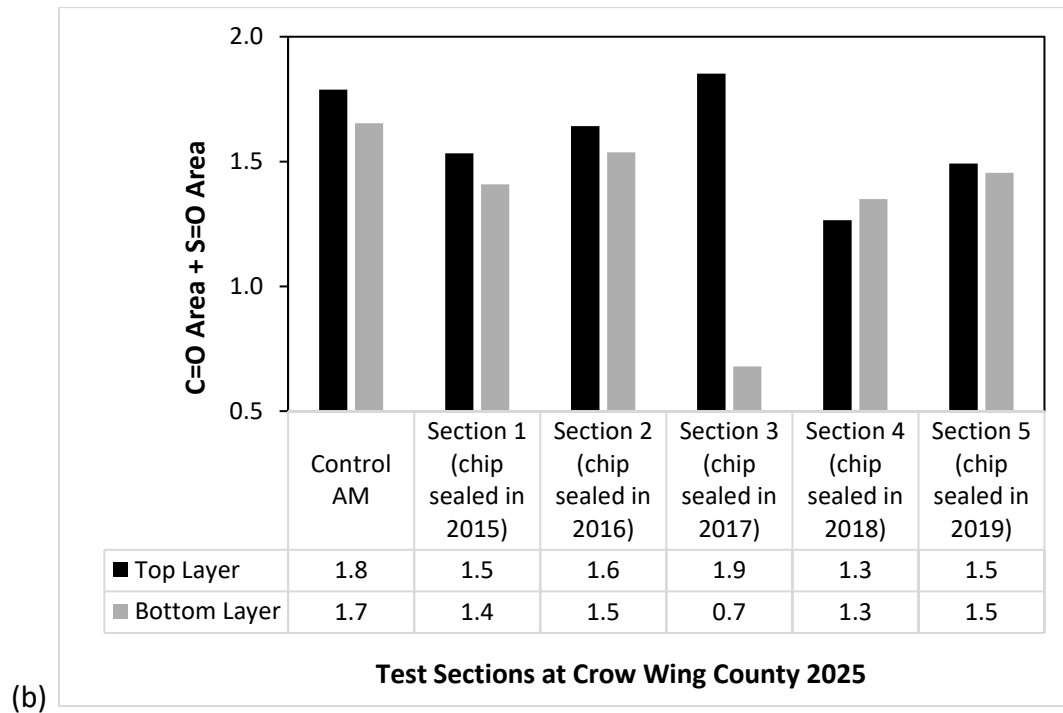


Figure 18. C=O + S=O area for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud

4.5 Rotational Viscosity

Rotational viscosity at 135°C was used to characterize the consistency of the recovered binders at elevated temperature. Higher viscosity generally indicates a stiffer or more hardened binder, although the measured value may also be influenced by binder modification, RAP content, and the composition of the recovered material.

At Cass County [Figure 19(a)], the bottom-layer viscosity of the untreated control was approximately 1.1 Pa.s. Section 1 produced a lower value of approximately 0.7 Pa.s, indicating that the underlying binder in the earliest-treated section remained less viscous than the control. Section 3 also produced a substantially lower bottom-layer viscosity of approximately 0.5 Pa.s. Section 2 was similar to the control at approximately 1.2 Pa.s, while Sections 4 and 5 produced higher values of approximately 1.7 and 1.4 Pa.s, respectively. The Cass County results therefore identify favorable bottom-layer responses in Sections 1 and 3, but they do not establish a monotonic treatment-year pattern. Section 1 supports an early-treatment preservation response, while the similarly low value in Section 3 shows that the response was not limited to the earliest application year.

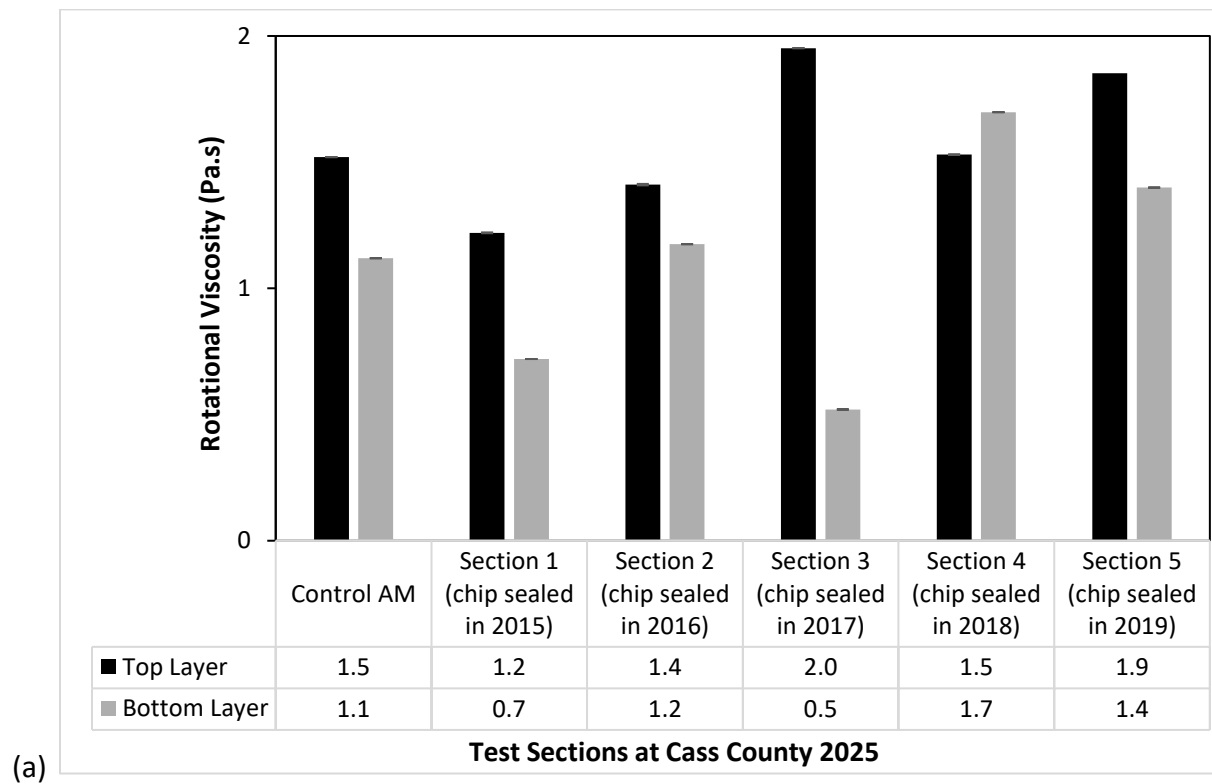
At Crow Wing County [Figure 19(b)], the bottom-layer viscosities were closely grouped. The untreated control produced a value of approximately 0.8 Pa.s, while the treated sections ranged from approximately 0.7 to 0.8 Pa.s. Sections 1, 3, and 5 were slightly below the control, whereas Sections 2 and 4 were approximately equal to it. The narrow range indicates that rotational viscosity provided little separation among the Crow Wing County sections. The

results do not identify a chronological treatment-year response, although several treated sections were slightly less viscous than the untreated control.

At the City of St. Cloud [Figure 19(c)], the bottom-layer control had a viscosity of approximately 1.2 Pa.s. All treated sections produced lower values, ranging from approximately 0.8 to 1.0 Pa.s. Section 3 had the lowest bottom-layer viscosity, while Sections 1, 2, 4, and 5 also remained below the control. These results indicate that the underlying binders beneath the treated sections were generally less viscous than the binder beneath the untreated pavement. However, the section rankings did not follow the sequence of treatment application, and the earliest-treated section did not produce the lowest value. The St. Cloud results therefore support a general treated-versus-control difference rather than a specific early-treatment effect.

Overall, the bottom-layer rotational-viscosity results showed site-specific preservation responses. Cass County exhibited lower viscosity in Sections 1 and 3 but higher values in Sections 4 and 5. Crow Wing County showed little variation among the control and treated sections. St. Cloud showed a broader treated-versus-control difference, with all treated bottom-layer binders less viscous than the control. Rotational viscosity therefore identified differences in recovered binder consistency at depth, but it did not establish a universal or strictly chronological relationship between chip seal application year and binder hardening. The rotational-viscosity findings should be interpreted together with the continuous-grade, ΔT_c , Glover-Rowe, and LAS results. Because viscosity is a bulk consistency measurement, it provides

useful supporting information about binder hardening but does not independently identify the oxidation mechanism or predict cracking performance.



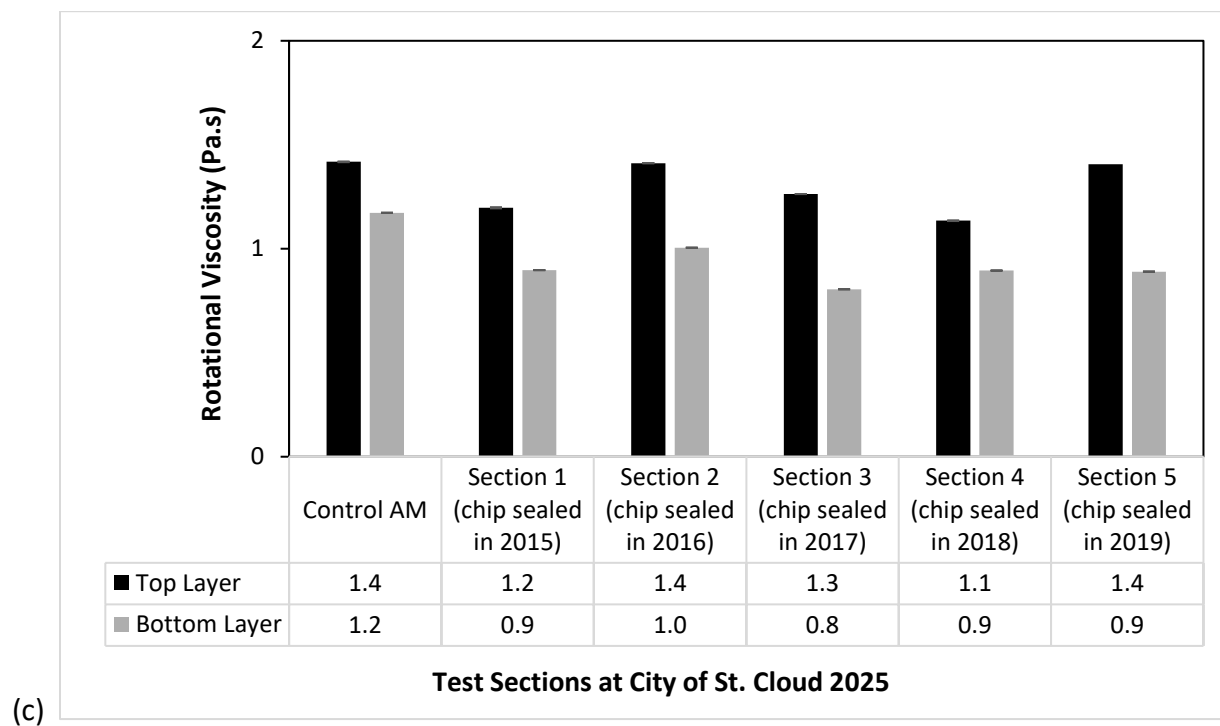
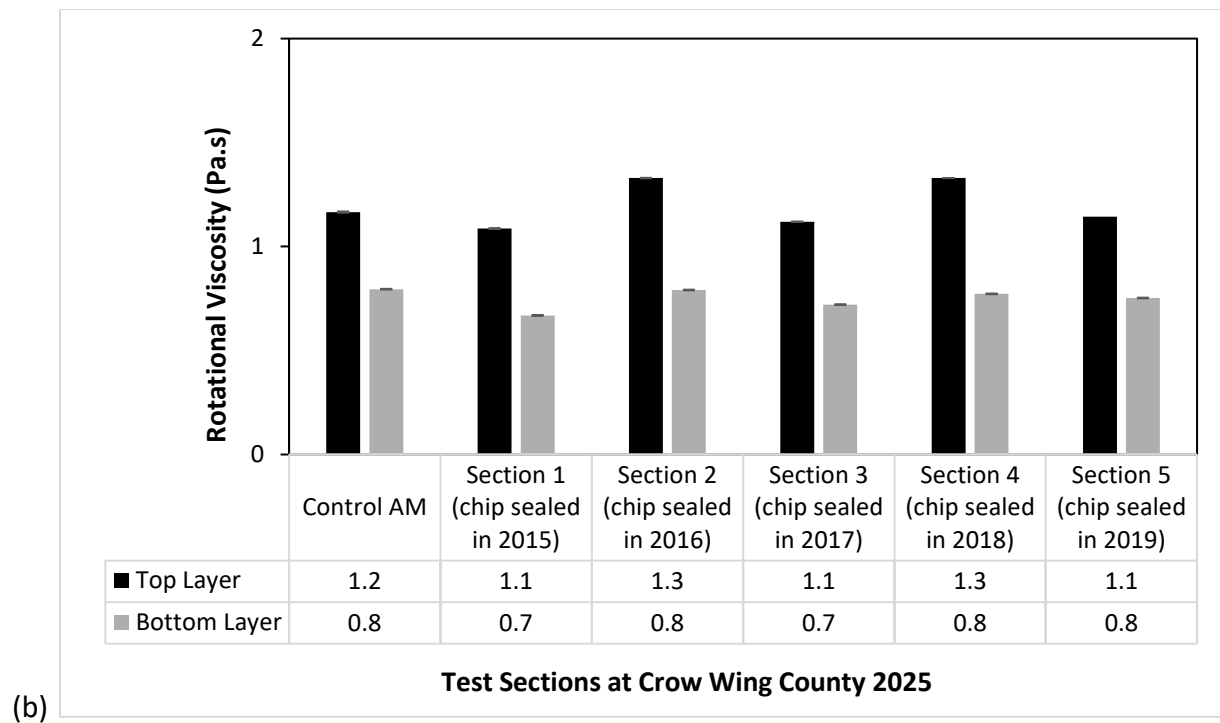


Figure 19. Rotational Viscosity at 135°C of Recovered Binders in 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud

4.6 Superpave Performance Grade (PG)

4.6.1 High-Temperature PG

The high-temperature continuous grade represents the critical temperature at which the recovered binder satisfies the Superpave high-temperature criterion. Higher continuous-grade values indicate a stiffer binder and greater resistance to high-temperature deformation. For recovered binders, however, a higher value may also reflect greater hardening during field service.

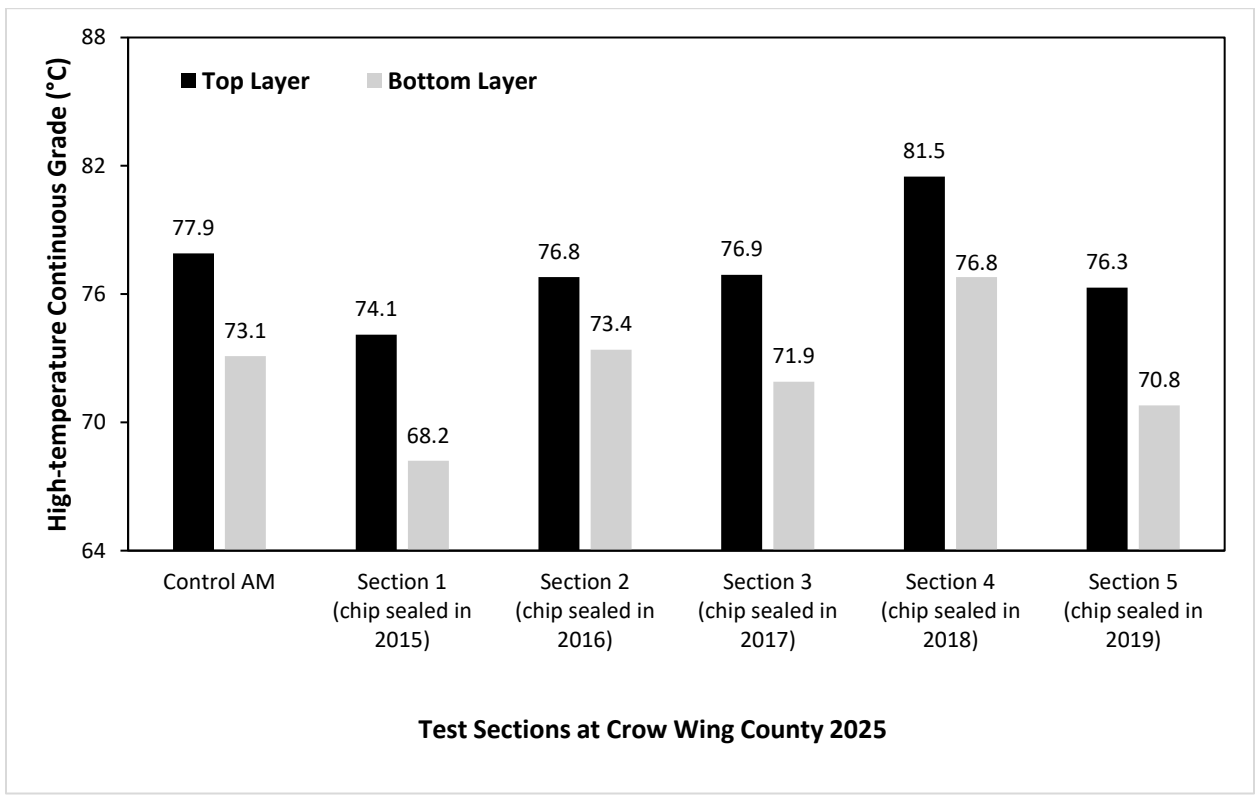
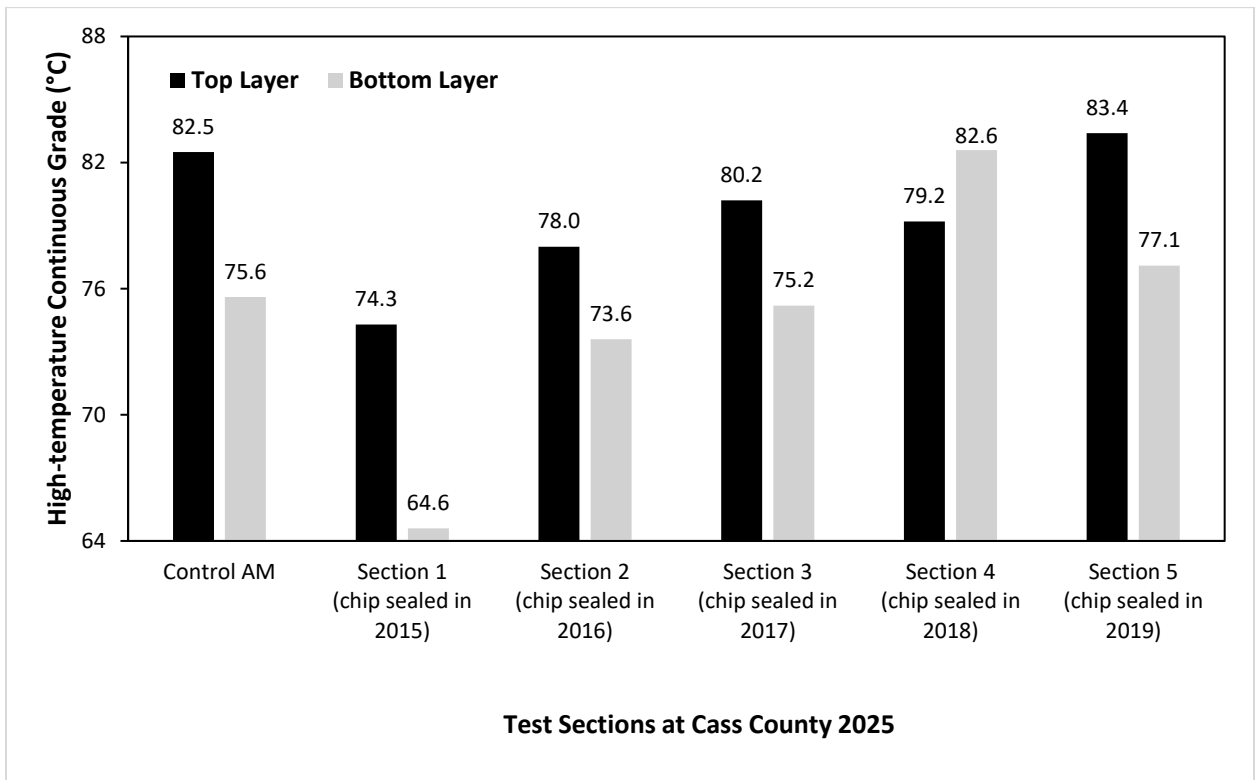
At Cass County [Figure 20(a)], the bottom-layer continuous grade of the untreated control was 75.6°C. Section 1 produced a substantially lower value of 64.6°C, indicating that the underlying binder in the earliest-treated section remained considerably less stiff than the binder beneath the untreated control. Section 2 also remained below the control at 73.6°C, while Section 3 was similar to the control at 75.2°C. Sections 4 and 5 produced higher values of 82.6°C and 77.1°C, respectively. These results provide the clearest high-temperature preservation signal for Section 1, with a smaller benefit in Section 2. However, the section values did not follow a continuous chronological sequence because Sections 4 and 5 were stiffer than the control.

At Crow Wing County [Figure 20(b)], the bottom-layer continuous grade was 73.1°C for the control. Sections 1, 3, and 5 produced lower values of 68.2°C, 71.9°C, and 70.8°C, respectively. Section 2 was nearly equal to the control at 73.4°C, while Section 4 produced the highest bottom-layer value at 76.8°C. Section 1 showed the largest treated-versus-control reduction and therefore the most favorable high-temperature response at depth. Nevertheless,

the alternating section rankings indicate that the response did not consistently follow chip seal application year.

At the City of St. Cloud [Figure 20(c)], the control bottom layer had a continuous grade of 71.9°C. Section 1 produced a nearly identical value of 72.0°C, while Sections 2 through 5 produced lower values of 70.5°C, 66.9°C, 68.0°C, and 68.6°C, respectively. The lower grades in Sections 2 through 5 indicate that their underlying binders were less stiff than the binder beneath the untreated control. However, Section 1 did not exhibit the lowest value, and the section rankings did not correspond to the chronological order of treatment application. The St. Cloud results therefore indicate a general treated-versus-control difference for several sections but do not identify an early-treatment advantage or a specific optimum application year.

Overall, the bottom-layer high-temperature continuous grades revealed site-specific preservation responses. Cass County showed a pronounced benefit in Section 1 and a smaller benefit in Section 2. Crow Wing County showed lower grades in several treated sections, with the greatest separation occurring in Section 1. At St. Cloud, Sections 2 through 5 were less stiff than the control, but the response did not favor the earliest treatment. Thus, high-temperature continuous grade identified differences between treated and untreated sections at depth, but it did not establish a universal or monotonic relationship between treatment year and recovered binder stiffness. These results should be considered together with the low-temperature, relaxation, and fatigue-related indicators because a lower high-temperature grade may indicate reduced age hardening but also represents lower high-temperature stiffness. Table 12 provides the summary of the results for high-temperature performance grade.



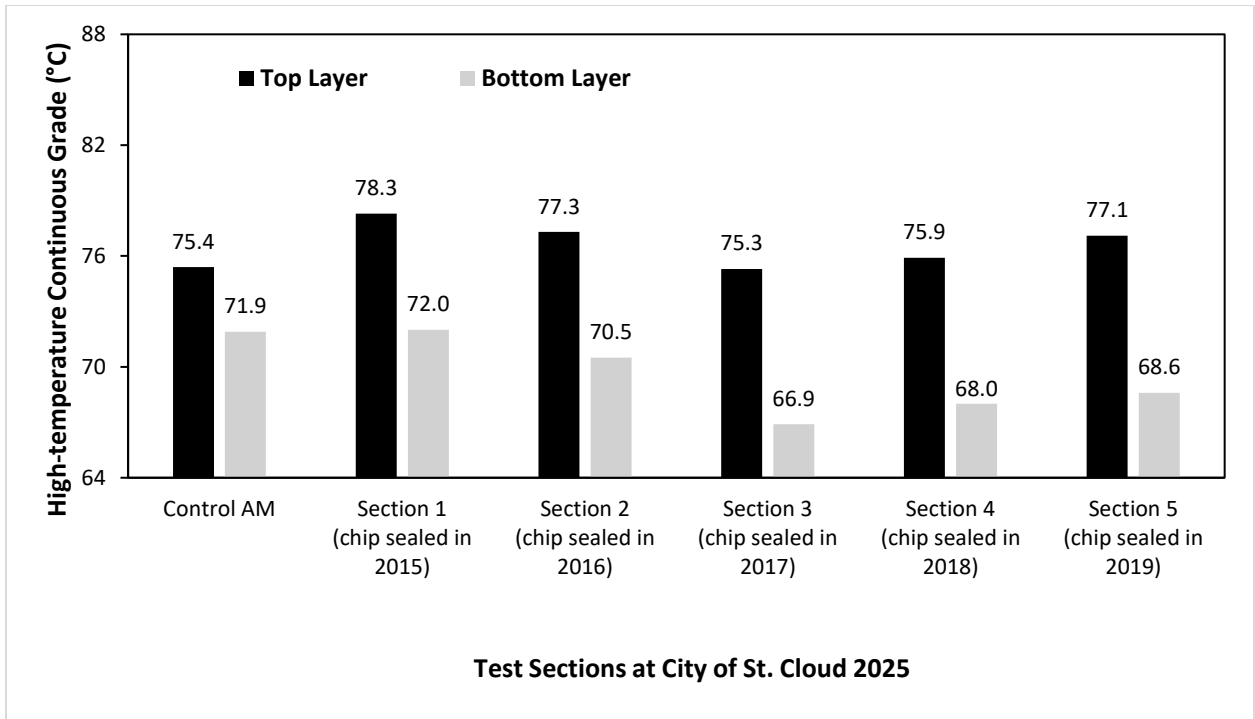


Figure 20. High-temperature continuous grades of recovered binders in 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud.

Table 12. High-Temperature PG (HPG) for Control and Treated Sections Year 2025

Agency	Section	Top-Layer HPG	Bottom-Layer HPG
Cass County	Control AM	82	70
	Section 1	70	64
	Section 2	76	70
	Section 3	76	70
	Section 4	82	82
	Section 5	82	76
Crow Wing County	Control AM	76	70
	Section 1	70	64
	Section 2	76	70
	Section 3	76	70
	Section 4	76	76
	Section 5	76	70
City of St. Cloud	Control AM	70	70
	Section 1	76	70
	Section 2	76	70
	Section 3	70	64
	Section 4	70	64
	Section 5	76	64

4.6.2 Intermediate-Temperature PG

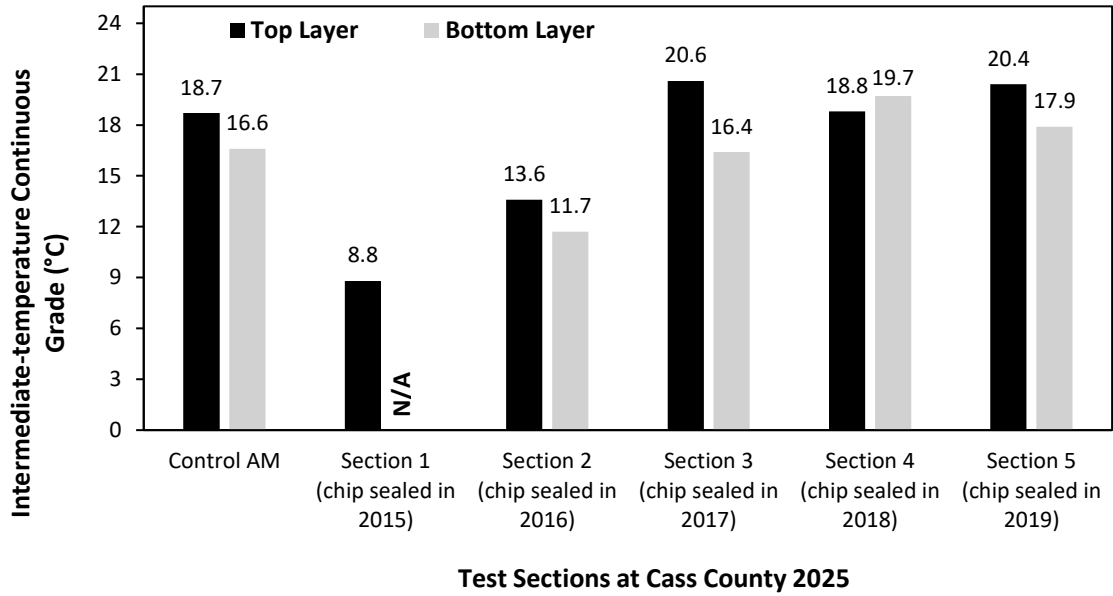
The intermediate-temperature continuous grade was used to characterize the stiffness of the recovered binders under fatigue-related loading conditions. Lower continuous-grade values indicate that the binder satisfies the intermediate-temperature criterion at a lower temperature and generally reflect a less age-hardened, more fatigue-tolerant response.

At Cass County [Figure 21(a)], the untreated control had a bottom-layer intermediate-temperature continuous grade of 16.6°C. Section 2 produced a lower value of 11.7°C, indicating a more favorable intermediate-temperature response than the control. Section 3 was nearly identical to the control at 16.4°C, while Sections 4 and 5 produced higher values of 19.7°C and 17.9°C, respectively. A valid bottom-layer value was not available for Section 1 and was therefore not used in the treatment comparison. The Cass County results suggest a preservation response in Section 2, but the later-treated sections did not retain the same advantage.

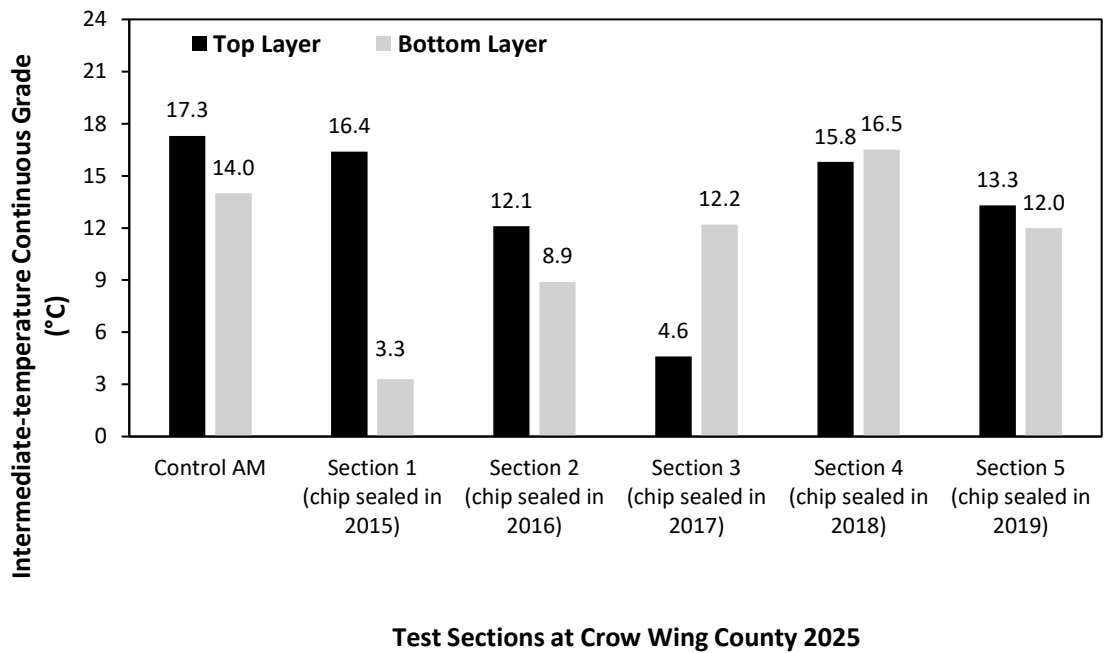
At Crow Wing County [Figure 21(b)], the bottom-layer control value was 14.0°C. Sections 1, 2, 3, and 5 produced lower values of 3.3°C, 8.9°C, 12.2°C, and 12.0°C, respectively. Section 1 showed the largest separation from the control and therefore the most favorable intermediate-temperature response at this site. Section 4 was the only treated section with a higher bottom-layer grade than the control, at 16.5°C. Although most treated sections were more favorable than the untreated control, the values did not follow a strictly chronological sequence because Section 5 also remained below the control.

At the City of St. Cloud [Figure 21(c)], the bottom-layer control value was 3.8°C. Sections 1 and 2 produced lower values of 0.6°C and 2.7°C, respectively, whereas Sections 3, 4, and 5 produced higher values of approximately 5.0°C to 5.1°C. The distinction between the earlier- and later-treated sections was clearer at this site than at Crow Wing County. Sections 1 and 2 exhibited more favorable intermediate-temperature grades than the control, while the sections treated from 2017 through 2019 did not.

Overall, the bottom-layer intermediate-temperature grades provide evidence of a treatment-timing response, although its consistency varied among agencies. The most favorable values were associated with the earlier-treated sections at Crow Wing County and St. Cloud, while Cass County showed a favorable response in Section 2 but lacked a valid Section 1 bottom-layer result. The later-treated sections generally showed smaller benefits or values above the control, particularly at Cass County and St. Cloud. These results indicate that earlier chip seal application was associated with better retention of intermediate-temperature binder properties at some sites, but the section rankings were also influenced by site-specific binder and mixture characteristics. Absolute grade values should therefore not be compared across agencies as direct measures of treatment effectiveness.



(a)



(b)

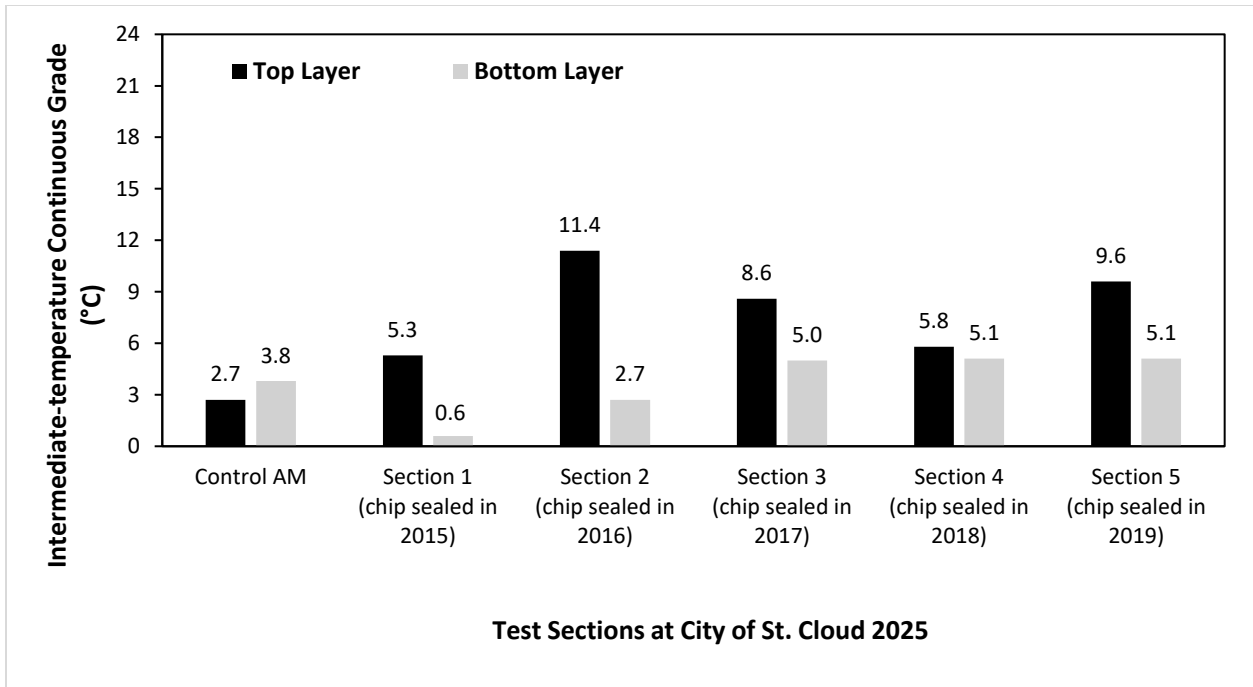


Figure 21. Intermediate-temperature continuous grade for recovered binders in 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud

4.6.3 Low-Temperature PG

The low-temperature continuous grade represents the critical temperature at which the recovered binder satisfies the governing BBR stiffness or m-value criterion. More negative continuous-grade values indicate that the binder can satisfy the low-temperature requirements at a colder temperature and therefore reflect a more favorable low-temperature response.

At Cass County [Figure 22(a)], the untreated control had a bottom-layer low-temperature continuous grade of -29.0°C . Section 1 produced the most favorable value at -34.6°C , approximately 5.6°C colder than the control. Section 2 was also more favorable than the control at -31.2°C , while Section 3 was similar at -29.7°C . Sections 4 and 5 produced values

of -27.4°C and -28.7°C, respectively, and therefore did not show the same low-temperature benefit. The results indicate that the strongest preservation response occurred in the earliest-treated section, with a smaller benefit in Section 2. However, the section values did not form a strictly monotonic treatment-year sequence.

The BBR stiffness and m-value results support the favorable response observed for Cass County Section 1. Within the bottom layer, Section 1 had significantly lower stiffness and a significantly higher m-value than the control, indicating both reduced age-related hardening and greater relaxation capacity. Section 2 also had a more favorable continuous grade than the control, but the combined stiffness and m-value response was not as pronounced as that of Section 1. Sections 4 and 5 were similar to or less favorable than the control, reinforcing the distinction between the earlier-treated sections and those treated later. Because the Cass County top- and bottom-layer BBR measurements were conducted at different temperatures, the supporting stiffness and m-value comparisons are limited to treated-versus-control comparisons within the same layer.

At Crow Wing County [Figure 22(b)], the bottom-layer control had a continuous grade of -27.5°C. Every treated section produced a more negative value, ranging from -28.0°C in Section 2 to -29.8°C in Section 1. Sections 1, 3, and 5 produced the most favorable values at -29.8°C, -29.7°C, and -29.4°C, respectively. The treated-versus-control separation therefore indicates that the underlying binders beneath the chip sealed sections generally retained better low-temperature properties than the untreated control. The response did not, however, follow a

chronological treatment-year sequence because several later-treated sections performed similarly to Section 1.

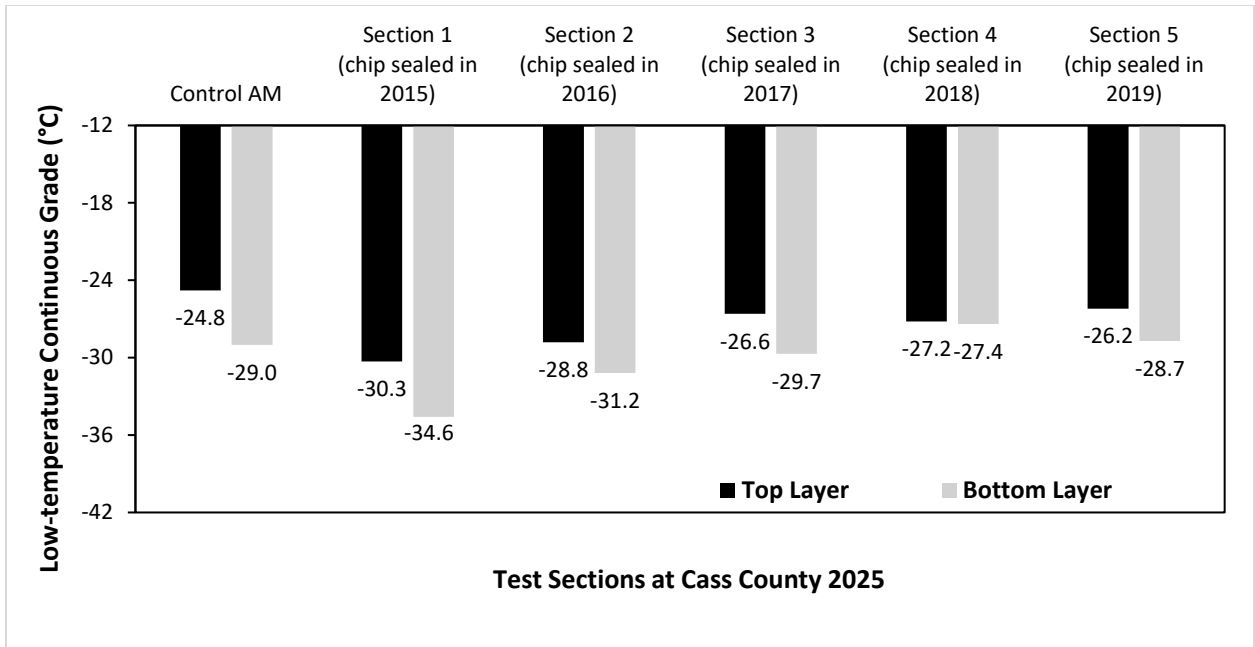
The Crow Wing County BBR results provide additional context for this pattern. All treated bottom-layer binders had significantly lower stiffness than the control. Sections 1, 3, and 5 also had significantly higher bottom-layer m-values, while Sections 2 and 4 did not show the same statistically confirmed relaxation benefit. Thus, the lower continuous grades in the treated sections resulted from different combinations of stiffness and relaxation response. The results support a broad treated-versus-control benefit at this site but do not isolate that benefit to the earliest treatment year.

At the City of St. Cloud [Figure 22(c)], the untreated control had a bottom-layer continuous grade of -31.9°C . All treated sections produced slightly more negative values, ranging from -33.0°C to -33.7°C . Sections 1 and 2 produced the most favorable values at -33.7°C and -33.6°C , while Sections 3 through 5 ranged from -33.0°C to -33.2°C . The treated sections therefore exhibited a consistent but relatively small low-temperature advantage over the control. Although Sections 1 and 2 were the most favorable, the narrow range among all treated sections does not establish a strong chronological treatment-year progression.

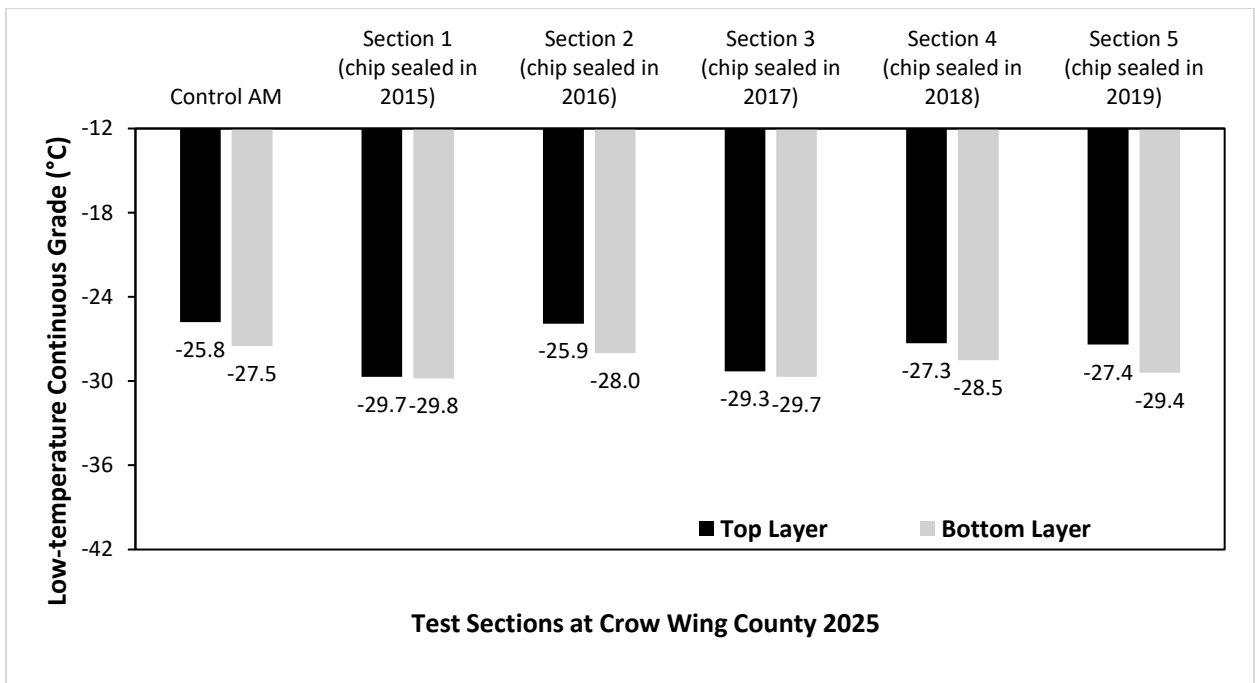
The St. Cloud BBR results were consistent with the continuous-grade response. Every treated section had a significantly higher bottom-layer m-value than the control, and most also had lower bottom-layer stiffness. This indicates that the treated sections generally retained greater low-temperature relaxation capacity than the untreated section. The relatively narrow range of continuous grades among the treated sections suggests that the polymer-modified

binder system may have limited the degree to which treatment-year differences could be distinguished.

Overall, the bottom-layer low-temperature continuous grades provide the strongest evidence of a preservation-related binder response. Cass County showed a pronounced advantage in Section 1 and a smaller benefit in Section 2, supporting an early-treatment effect at that site. Crow Wing County and St. Cloud showed broader treated-versus-control benefits that extended across several or all treatment years. These results demonstrate that chip sealing was associated with more favorable low-temperature binder properties, but the form of the response differed by agency. Only Cass County exhibited a clearly concentrated early-treatment benefit, whereas the other sites showed a more general treatment effect without a consistent chronological ranking. Table 13 provides the summary of the results for low-temperature performance grade.



(a)



(b)

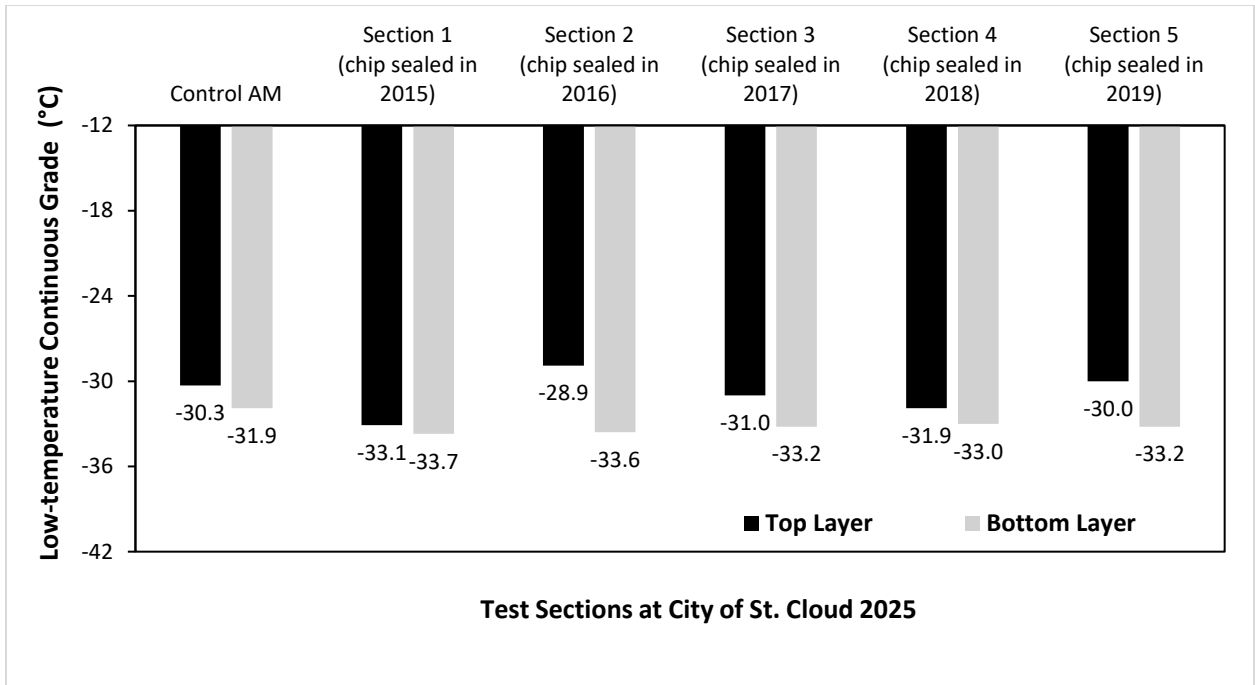
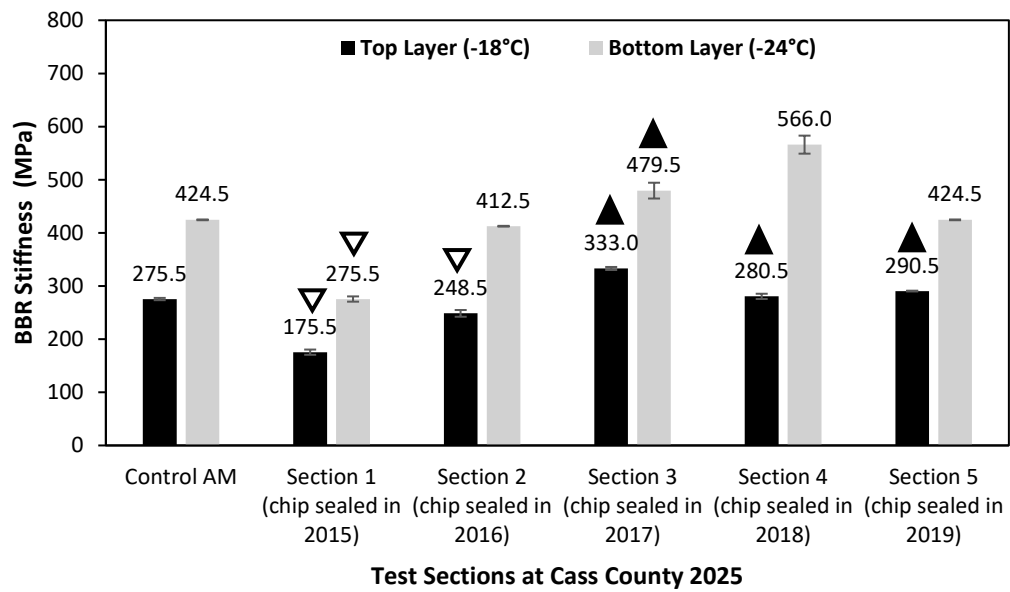


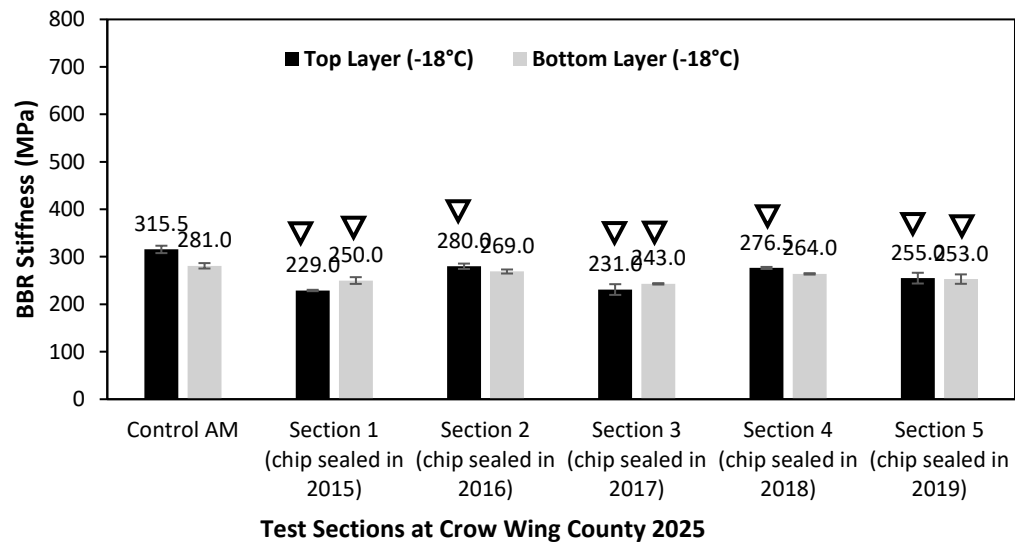
Figure 22. Figure 22. Low-temperature continuous grades of recovered binders in 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud

Table 13. Low-Temperature PG (LPG) for Control and Treated Sections Year 2025

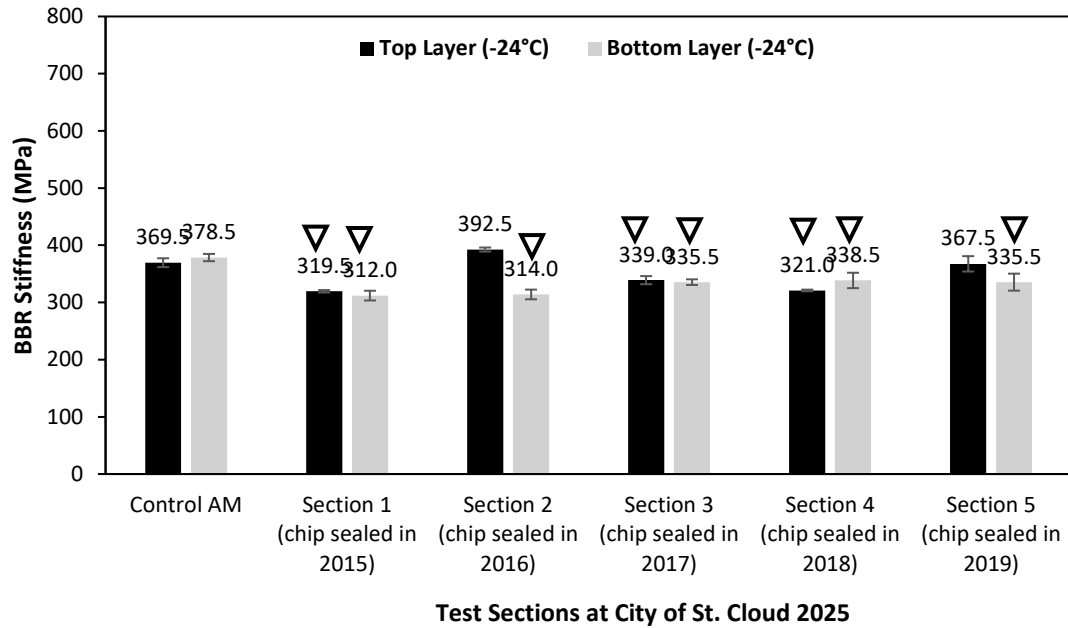
Agency	Section	Top-Layer LPG	Bottom-Layer LPG
Cass County	Control AM	-22	-28
	Section 1	-28	-34
	Section 2	-28	-28
	Section 3	-22	-28
	Section 4	-22	-22
	Section 5	-22	-28
Crow Wing County	Control AM	-22	-22
	Section 1	-28	-28
	Section 2	-22	-28
	Section 3	-28	-28
	Section 4	-22	-28
	Section 5	-22	-28
City of St. Cloud	Control AM	-28	-28
	Section 1	-28	-28
	Section 2	-28	-28
	Section 3	-28	-28
	Section 4	-28	-28
	Section 5	-28	-28



(a)



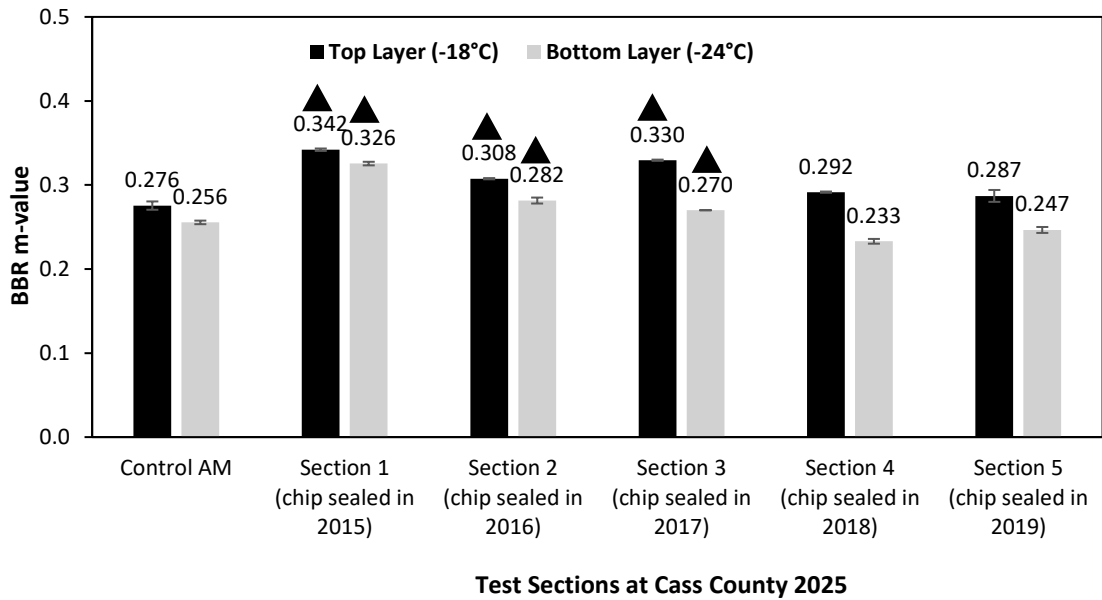
(b)



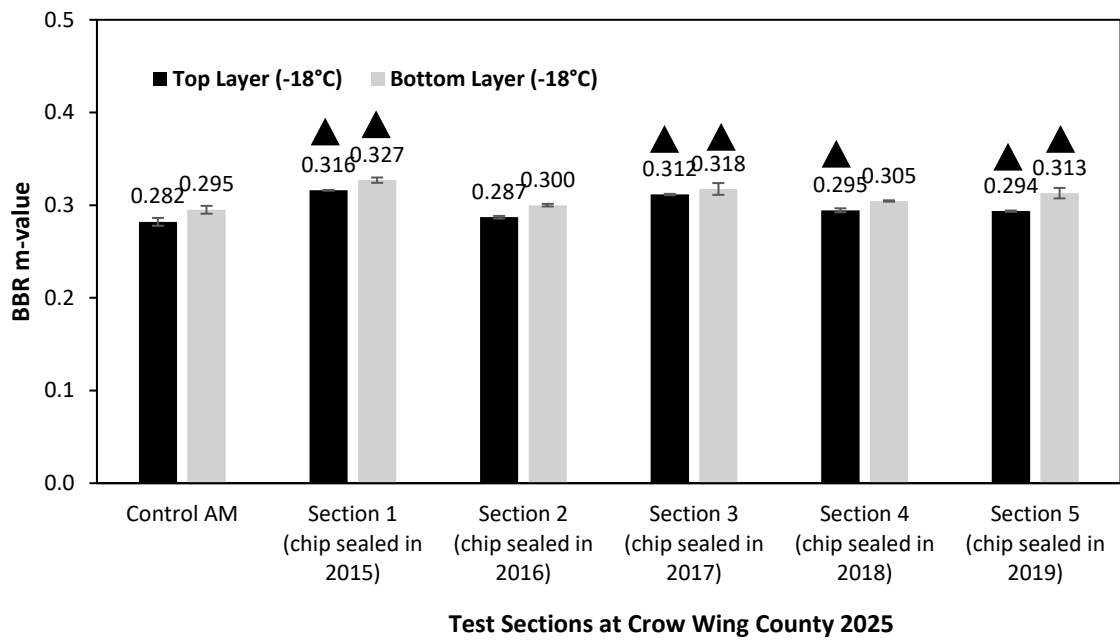
(c)

(▲ = Statistically higher than the control; ▼ = Statistically lower than the control)

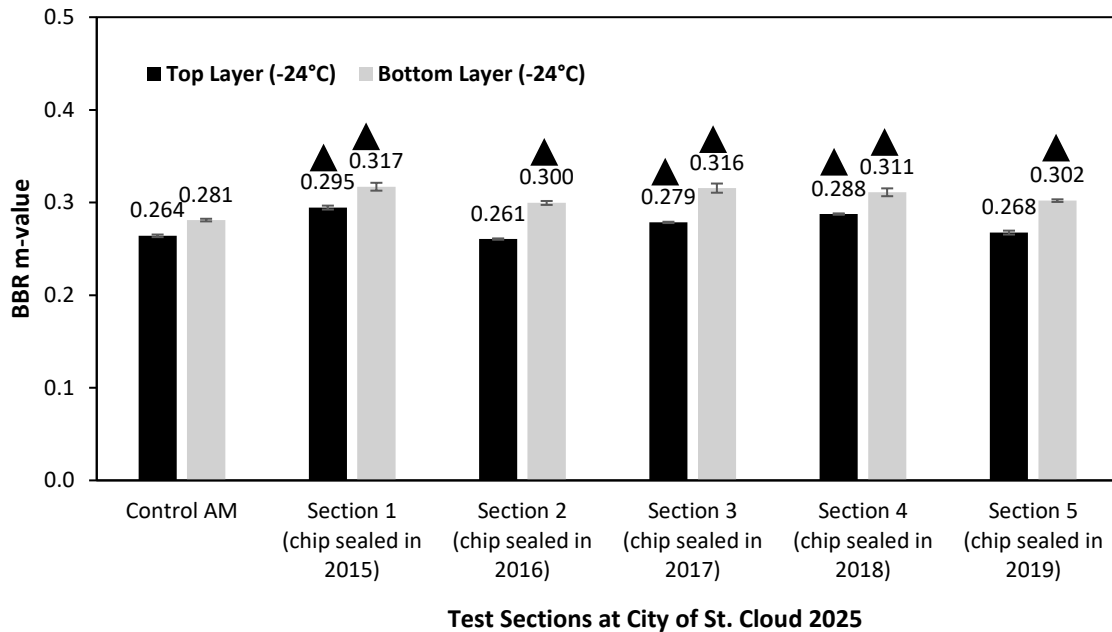
Figure 23. Figure 23. BBR creep stiffness of recovered binders: (a) Cass County, tested at -18°C for the top layer and -24°C for the bottom layer; (b) Crow Wing County, tested at -18°C for both layers; and (c) City of St. Cloud, tested at -24°C for both layers.



(a)



(b)



(c)

(▲ = Statistically higher than the control; ▽ = Statistically lower than the control)

Figure 24. BBR m-value of recovered binders: (a) Cass County, tested at -18°C for the top layer and -24°C for the bottom layer; (b) Crow Wing County, tested at -18°C for both layers; and (c) City of St. Cloud, tested at -24°C for both layers.

4.7 ΔT_c

ΔT_c represents the difference between the critical temperatures determined from the BBR stiffness and m-value criteria. More negative values indicate a greater loss of relaxation capacity relative to stiffness and are generally associated with increased susceptibility to non-load-related cracking. Because each section-layer combination was represented by one independently recovered field sample, small differences in ΔT_c were not interpreted as meaningful treatment effects. The primary comparisons were made between each treated bottom-layer binder and the bottom-layer control within the same agency.

At Cass County [Figure 25(a)], the untreated bottom-layer control had a ΔT_c of -1.9°C . Section 1 produced a substantially more favorable value of $+1.6^\circ\text{C}$, representing a difference of 3.5°C relative to the control. Sections 2 and 3 also produced more favorable values of $+0.6^\circ\text{C}$ and $+1.3^\circ\text{C}$, respectively. Section 4, at -0.9°C , was only modestly more favorable than the control, while Section 5 produced a value of $+0.7^\circ\text{C}$.

The bottom-layer Cass County results therefore show that Sections 1 through 3 retained greater relaxation capacity than the untreated control, with the strongest separation occurring in Section 1. Although the results do not form a strictly monotonic treatment-year sequence, the comparatively large control-to-Section 1 contrast supports an early-treatment preservation response. The Section 1 result is also consistent with its favorable low-temperature continuous grade and LAS response.

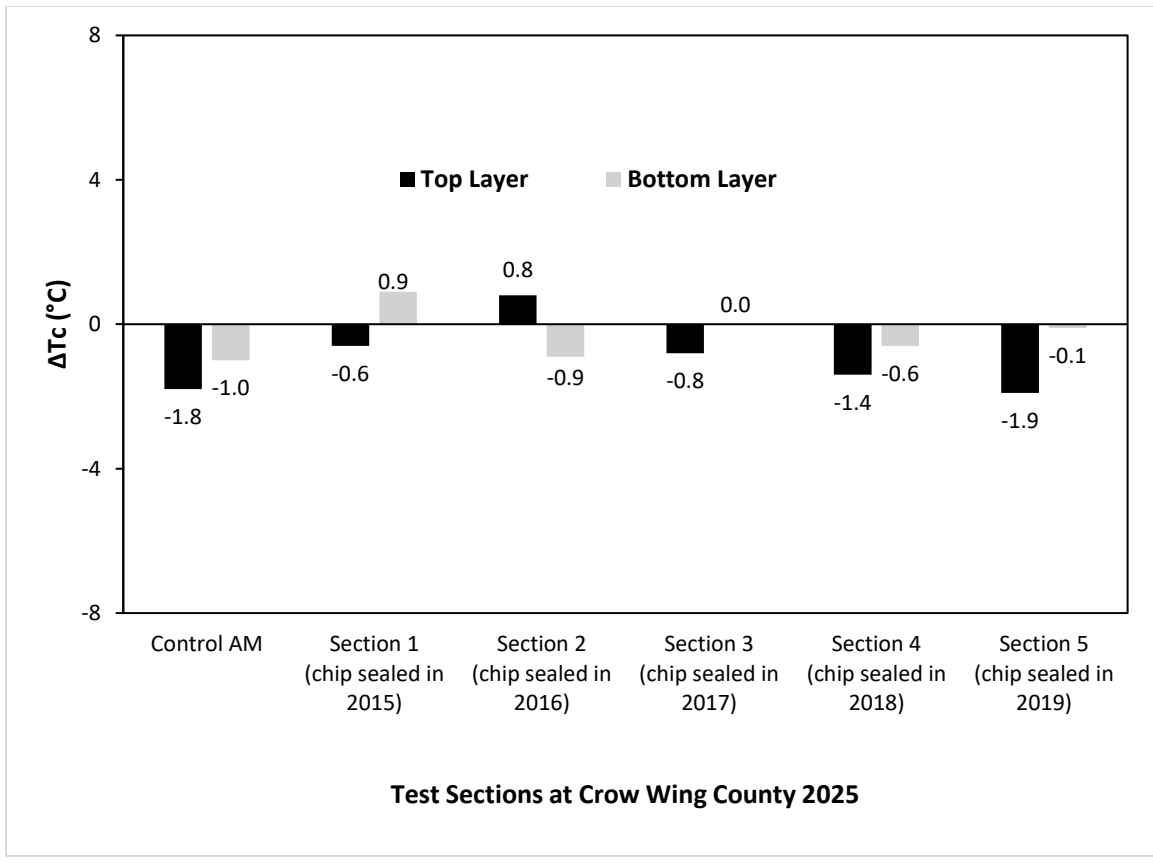
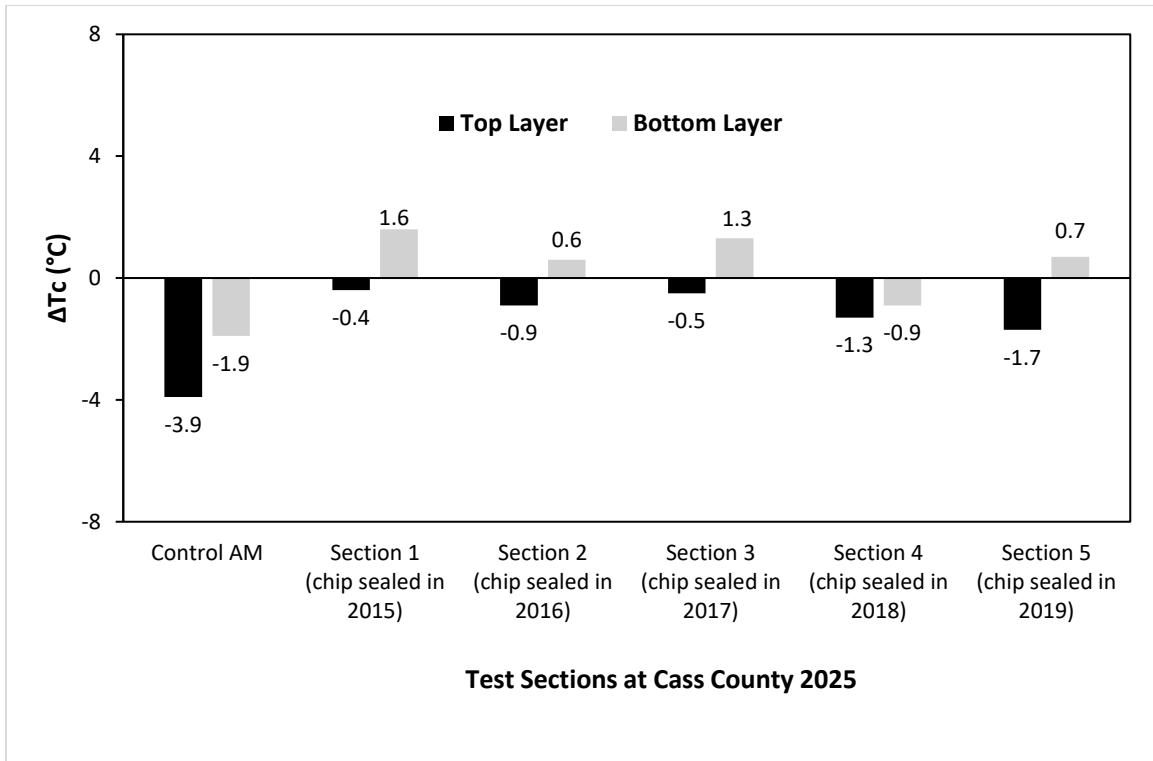
The top-layer Cass County results provide supporting same-depth evidence. The control top layer had a ΔT_c of -3.9°C , compared with -0.4°C for Section 1. However, because the upper recovered material in the treated sections included chip seal residue while the control upper layer consisted only of HMA binder, the bottom-layer comparison provides the more defensible basis for evaluating treatment effects.

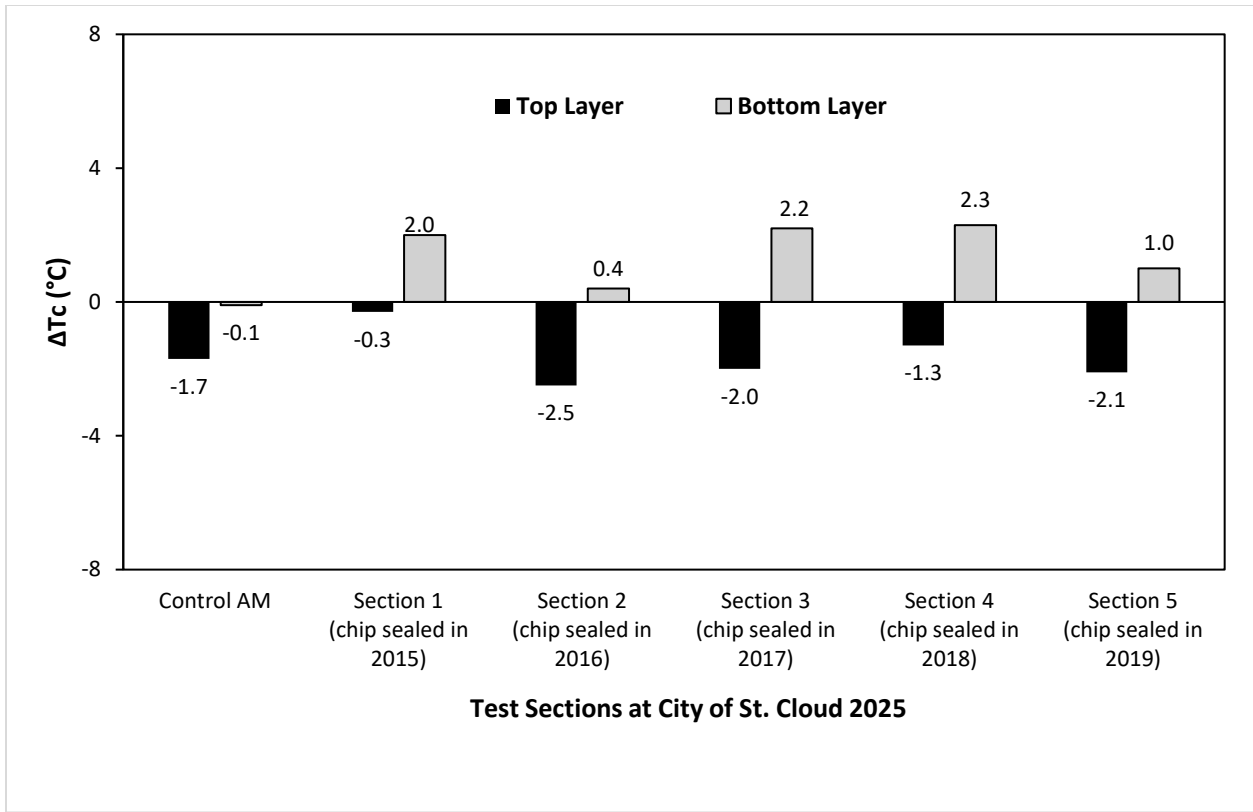
At Crow Wing County [Figure 25(b)], the bottom-layer control had a ΔT_c of -1.0°C . The treated sections ranged from -0.9°C to $+0.9^\circ\text{C}$. Section 1 produced the largest separation from the control at $+0.9^\circ\text{C}$, while Sections 2 through 5 differed from the control by approximately 0.1°C to 1.0°C . Given the lack of independent field replication and the precision of the BBR-

derived parameter, these relatively small contrasts were not interpreted as evidence of a treatment-year effect. The Crow Wing County results therefore do not establish a defensible chronological relationship from ΔT_c alone.

At the City of St. Cloud [Figure 25(c)], the bottom-layer control produced a ΔT_c of -0.1°C . The treated sections ranged from $+0.4^\circ\text{C}$ to $+2.3^\circ\text{C}$. Although all treated bottom-layer values were more positive than the control, several differences were small, and the section rankings did not follow treatment year. In addition, the polymer-modified binder may have contributed to the positive ΔT_c values through its elastic response. The St. Cloud results were therefore interpreted comparatively within the agency and were not used as an absolute measure of superior performance or as evidence of a clear timing sequence.

Overall, the bottom-layer ΔT_c results provide the strongest treatment-related evidence at Cass County. Section 1 showed a 3.5°C improvement relative to the bottom-layer control, while Sections 2 and 3 also remained more favorable. The smaller differences at Crow Wing County and most of the St. Cloud comparisons were not interpreted because they were near the practical precision of the BBR-derived parameter and did not follow treatment year. Thus, ΔT_c supports an early-treatment preservation response at Cass County but does not establish a consistent treatment-timing relationship across all three agencies.





(c) Figure 25. ΔT_c for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing, (c) City of St. Cloud.

4.8 MSCR at 58°C

The MSCR test characterizes the high-temperature creep and recovery response of asphalt binder through the nonrecoverable creep compliance, $J_{nr,3.2}$, and percent recovery, $\%R_{3.2}$, measured at 3.2 kPa. Lower $J_{nr,3.2}$ indicates less permanent strain and therefore greater resistance to rutting. However, for binders recovered after approximately six to ten years of field service, a low $J_{nr,3.2}$ may also indicate greater age-related stiffening. Consequently, the lowest $J_{nr,3.2}$ should not automatically be interpreted as the most favorable preservation response. A higher value relative to the control may indicate that the treated-section binder

retained greater compliance, provided that the resulting traffic classification remains acceptable.

The $J_{nr,3.2}$ and $\%R_{3.2}$ parameters are obtained from the same creep-recovery cycles and are therefore related rather than independent measures. Percent recovery is also influenced by the creep compliance of the binder, regardless of polymer presence or content (Rodezno et al., 2021; Bahia et al., 2018). The two parameters were therefore interpreted together, with the primary treatment comparison based on the bottom-layer treated sections relative to the bottom-layer control within each agency.

At Cass County [Figures 26(a) and 27(a)], the bottom-layer control had a $J_{nr,3.2}$ of 0.17 kPa^{-1} and a recovery of 39.4%. Section 1 produced a higher $J_{nr,3.2}$ of 0.43 kPa^{-1} and a lower recovery of 34.5%. This combination indicates that the underlying binder in Section 1 remained more compliant and less stiffened than the binder beneath the untreated control. Sections 2 and 3 each produced a $J_{nr,3.2}$ of 0.06 kPa^{-1} , with recoveries of 61.2% and 62.5%, respectively. Section 4 produced the lowest $J_{nr,3.2}$, 0.02 kPa^{-1} , together with the highest recovery, 74.1%, while Section 5 produced a $J_{nr,3.2}$ of 0.09 kPa^{-1} and a recovery of 54.4%. These four sections were less compliant and showed greater elastic recovery than the control, indicating a more highly stiffened recovered binder response. The Cass County comparison therefore supports Section 1 as the least-stiffened bottom-layer binder, rather than Section 4 as the “best” result. The relatively compliant Section 1 response is consistent with its favorable low-temperature continuous grade, ΔT_c , and LAS results. Section 4 retained the greatest resistance to nonrecoverable deformation, but its very low $J_{nr,3.2}$ and high recovery indicate a substantially

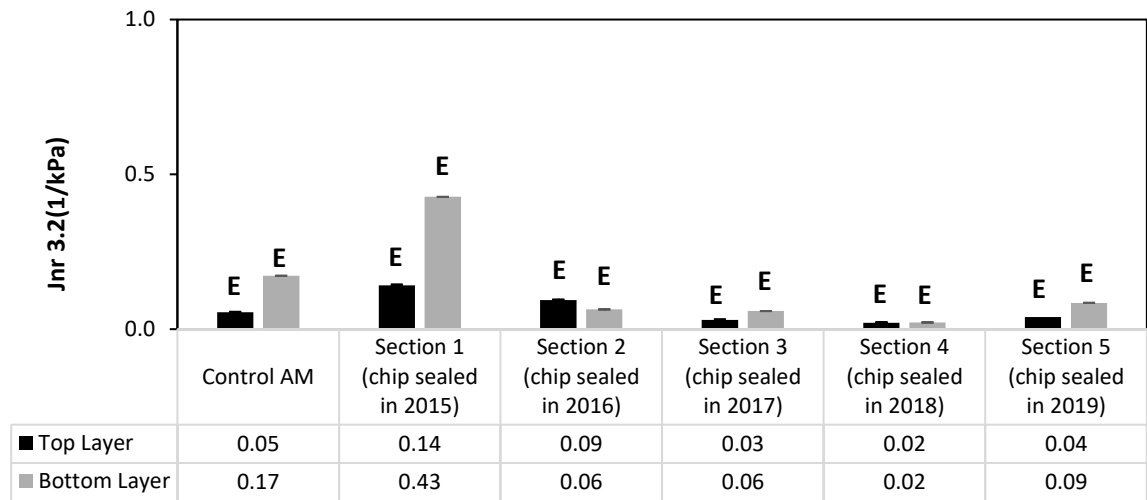
stiffer aged-binder condition. There is therefore no reversal between the MSCR and relaxation-related tests and no need to invoke polymer phase separation to reconcile them. All Cass County binders remained within the Extreme traffic classification, so the differences affected the aging interpretation but did not change the traffic-grade classification.

At Crow Wing County [Figures 26(b) and 27(b)], the bottom-layer control had a $J_{nr,3.2}$ of 0.33 kPa^{-1} and a recovery of 14.88%. Sections 1, 3, and 5 produced higher $J_{nr,3.2}$ values of 0.70, 0.45, and 0.49 kPa^{-1} , respectively, together with lower recoveries of 7.52%, 11.47%, and 10.61%. Relative to the control, these sections retained greater compliance and exhibited less elastic recovery, indicating less stiffened bottom-layer binders. In contrast, Section 2 produced a lower $J_{nr,3.2}$ of 0.24 kPa^{-1} and a higher recovery of 20.46%, while Section 4 produced the lowest value at the site, 0.17 kPa^{-1} and the highest recovery, 28.20%. Sections 2 and 4 therefore exhibited a stiffer recovered binder response than the control. The Crow Wing County results do not form a monotonic treatment-year sequence. Section 1 was the most compliant relative to the control, but Sections 3 and 5 also remained more compliant, whereas Sections 2 and 4 were stiffer. The MSCR response therefore provides some evidence that the earliest-treated section retained a less hardened binder condition, but the same response was not restricted to the earliest treatment year. The Very Heavy classifications observed for some of the more compliant bottom-layer binders represent lower rutting resistance than the Extreme classification, but they should not be interpreted as evidence of greater aging.

At the City of St. Cloud [Figures 26(c) and 27(c)], the bottom-layer control had a $J_{nr,3.2}$ of 0.24 kPa^{-1} and a recovery of 38.9%. Section 1 was slightly more compliant than the control,

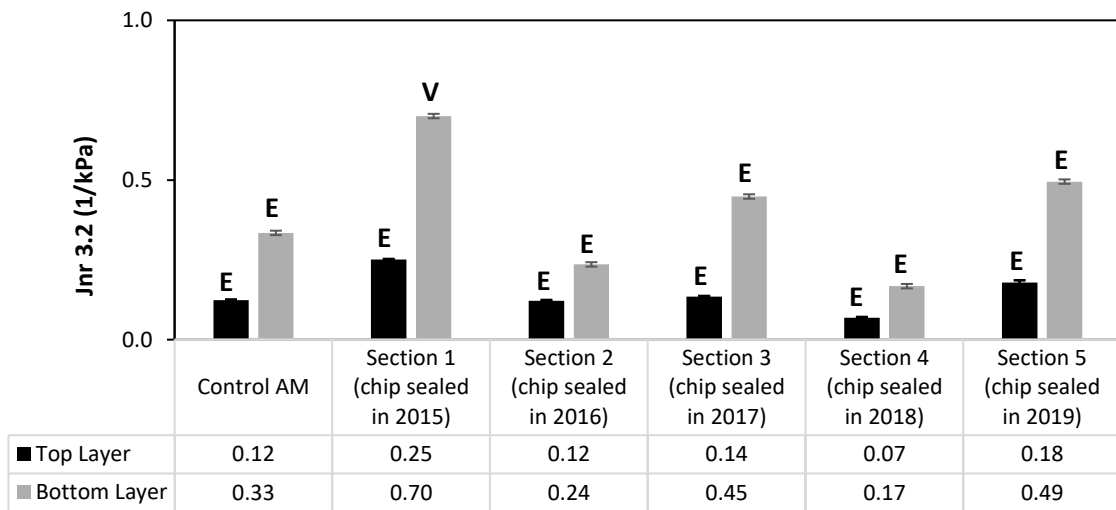
with a $J_{nr,3.2}$ of 0.32 kPa^{-1} , while its recovery of 38.6% was nearly identical to the control. Section 2 produced a lower $J_{nr,3.2}$ of 0.16 kPa^{-1} and a higher recovery of 50.2%, indicating a stiffer response than the control. Sections 3, 4, and 5 produced substantially higher $J_{nr,3.2}$ values of 0.79, 0.49, and 0.52 kPa^{-1} respectively, and lower recoveries of 22.3%, 27.9%, and 26.6%. These sections were therefore more compliant and less elastic than the control at depth. The St. Cloud results also lack a chronological treatment-year pattern. Section 2 was stiffer than the control, while Sections 1 and 3 through 5 retained equal or greater compliance. Thus, the MSCR response indicates differences in bottom-layer field hardening among the treated sections, but it does not identify the earliest treatment as consistently least aged at this site.

Overall, the bottom-layer MSCR results show that the relationship between chip seal application year and recovered binder stiffness was site specific. Cass County provided the clearest agreement with the other aging indicators because Section 1 was substantially more compliant than the control and the later-treated sections. Crow Wing County also showed a compliant Section 1 response, although Sections 3 and 5 behaved similarly. At St. Cloud, several treated sections were more compliant than the control, but the response did not follow treatment year. The $J_{nr,3.2}$ -based traffic classifications remain useful for documenting current resistance to permanent deformation. However, the section with the lowest $J_{nr,3.2}$ should not be labeled the best-preserved binder because low compliance may reflect age hardening. For the chip seal timing assessment, the relevant interpretation is whether the treated bottom-layer binder remained more or less compliant than the corresponding untreated control, considered together with $\%R_{3.2}$ low-temperature grade, ΔT_c , and LAS response.



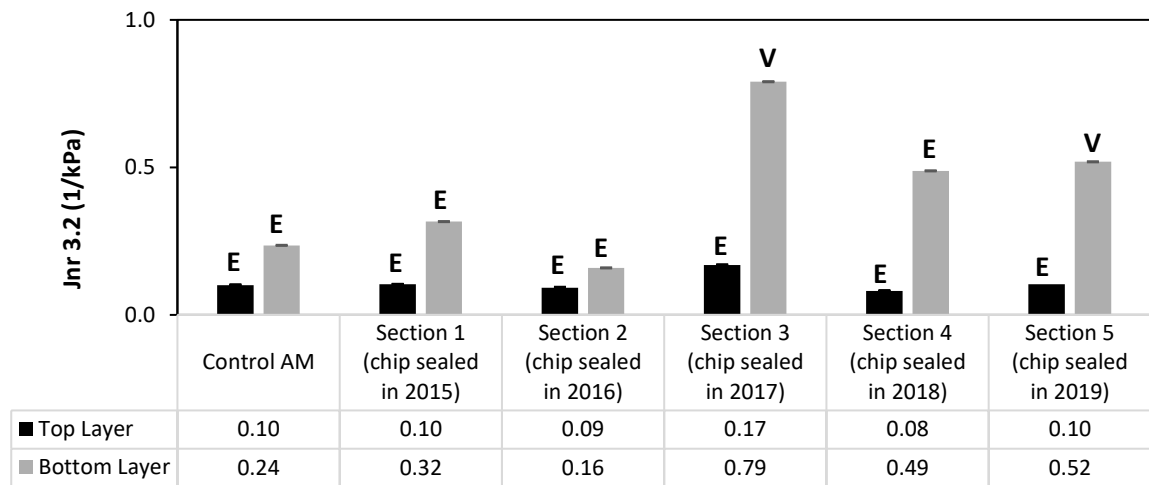
Test Sections at Cass County 2025

(a)



Test Sections at Crow Wing County 2025

(b)

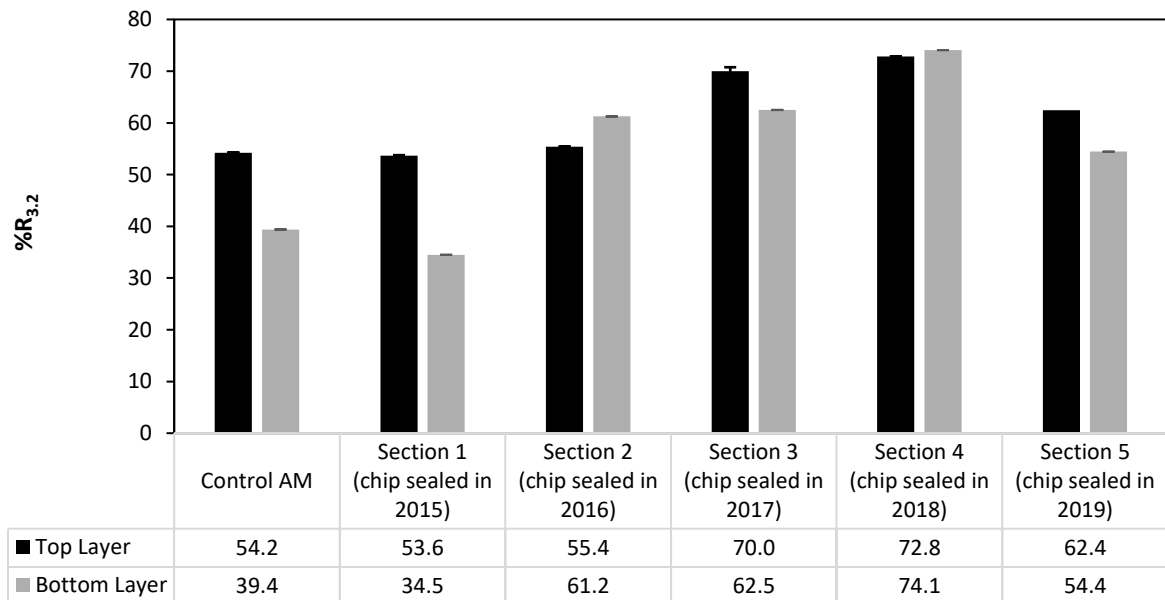


Test Sections at City of St. Cloud 2025

(c)

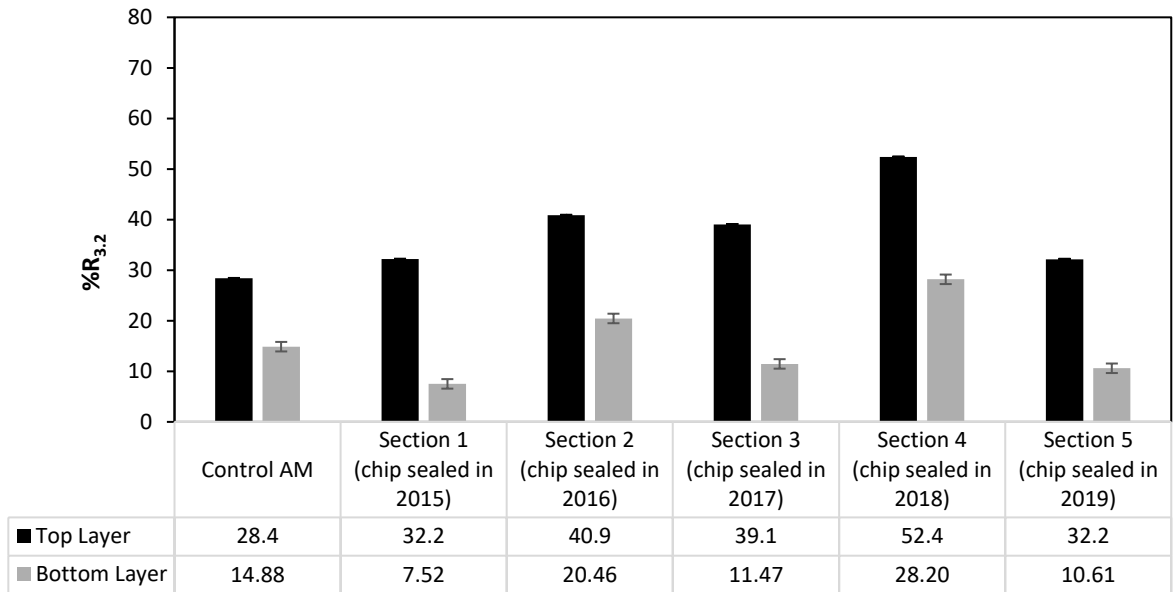
Figure 26. $J_{nr,3.2}$ Results @ 58°C for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud.

E (Extreme) traffic loading (>30 million ESALs and <20 km/h); V (Very Heavy) traffic loading (>30 million ESALs or <20 km/h)



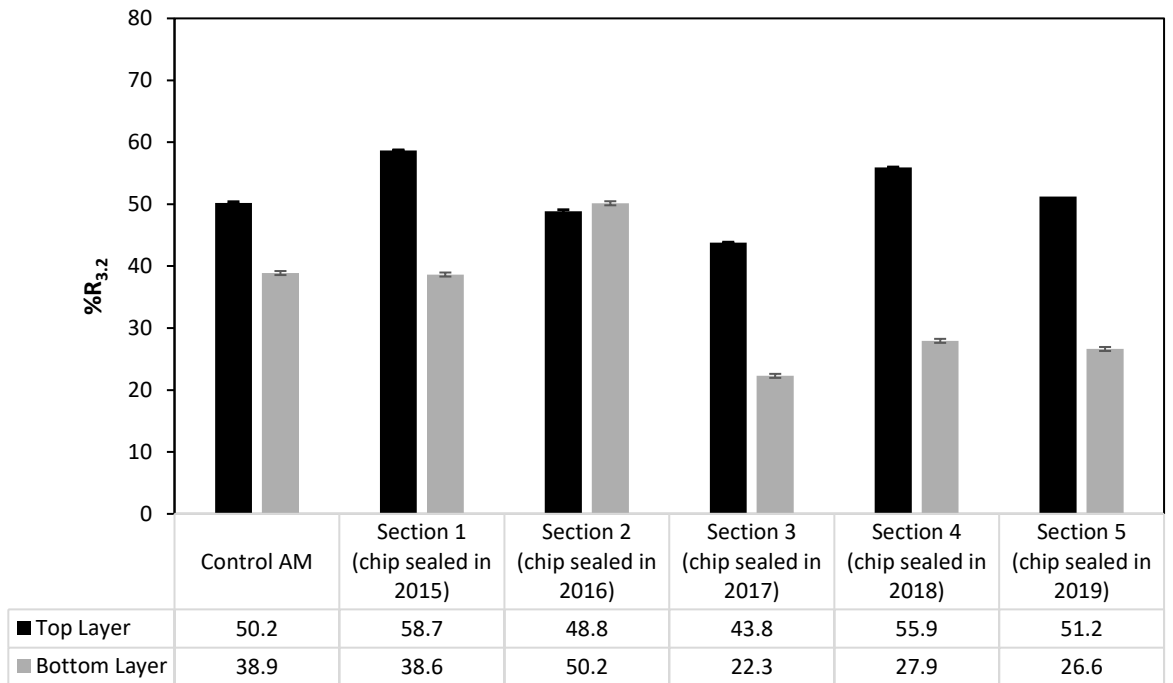
Test Sections at Cass County 2025

(a)



(b)

Test Sections at Crow Wing County 2025



(c)

Test Sections at City of St. Cloud 2025

Figure 27. %R3.2 Results @ 58°C for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing County, (c) City of St. Cloud.

4.9 LAS

The LAS test provides a fatigue-related measure of the recovered binder response under increasing strain. Because the test is strain controlled, the predicted fatigue life, N_f , is influenced by the initial stiffness of the binder. A lower initial $|G^*|$ can contribute to a higher calculated N_f because the binder develops lower stress at the same applied strain. Therefore, the LAS results were interpreted using N_f , initial $|G^*|$, and damage at failure, D_f (Table 14), together. The discussion emphasizes bottom-layer comparisons with the untreated control because the bottom interval represents the underlying asphalt mixture within each agency.

At Cass County, Section 1 exhibited the clearest favorable response relative to the untreated control. At 2.5% strain, the bottom-layer N_f increased from 13,288 cycles in the control to 32,540 cycles in Section 1. At 5.0% strain, the corresponding values were 1,081 and 3,430 cycles. Section 1 also had a lower initial $|G^*|$ of 7.9 MPa, compared with 14.4 MPa for the control, and a higher D_f of 70.6, compared with 39.4 for the control. These combined results indicate that the Section 1 bottom-layer binder was less stiff and tolerated more accumulated damage before failure than the untreated control. The remaining Cass County treated sections did not show the same response. Sections 2 through 5 had bottom-layer fatigue lives below the control at both strain levels. Their initial $|G^*|$ values were also higher, ranging from 19.3 to 23.6 MPa, while their D_f values ranged from 22.4 to 29.4, all below the control value of 39.4. Thus, the Cass County results do not show a gradual treatment-year progression. Instead, they identify a distinct advantage for the earliest-treated section, followed by substantially less favorable responses in the sections treated later.

This Section 1 response is consistent with the favorable low-temperature grade and ΔT_c results observed at Cass County. The agreement suggests that the binder beneath the earliest-treated section retained a more favorable balance of stiffness, relaxation capacity, and fatigue damage tolerance than the binder beneath the untreated control. However, the LAS result should be treated as supporting evidence rather than as an independent confirmation because N_f , initial modulus, and D_f are related outputs obtained from the same recovered binder response.

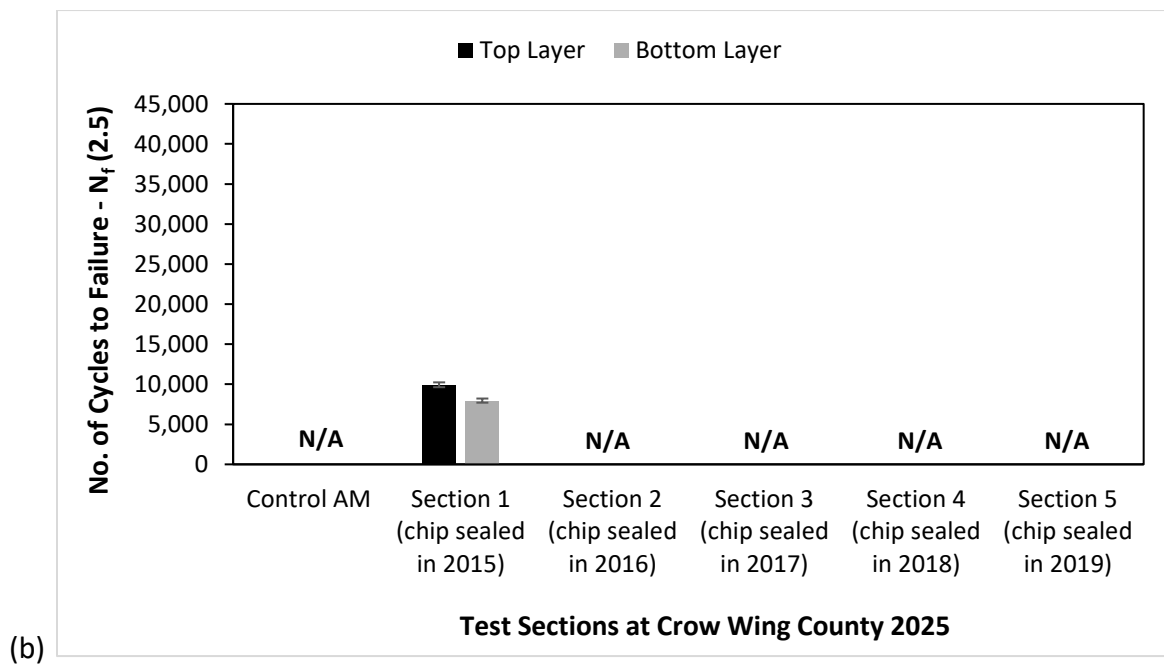
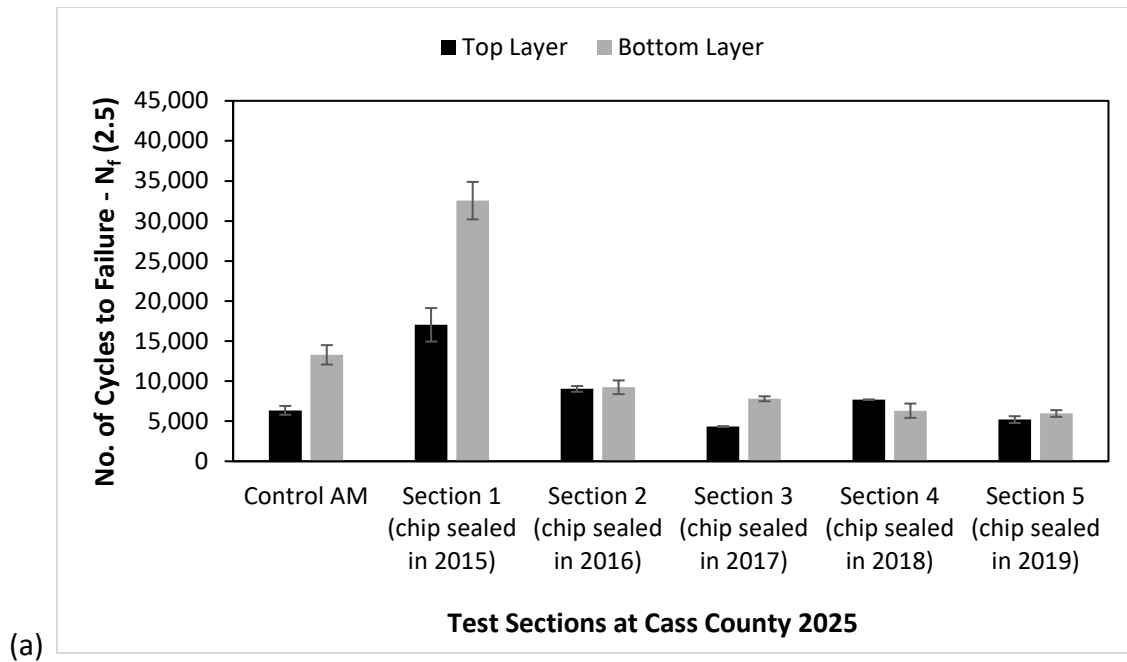
At the City of St. Cloud, the valid bottom-layer results showed a broader treated-versus-control preservation signal. The control had an N_f of 21,085 cycles at 2.5% strain and 1,882 cycles at 5.0% strain. All valid treated sections produced fatigue lives equal to or greater than the control. At 2.5% strain, the treated values ranged from 21,359 cycles in Section 5 to 36,826 cycles in Section 2. At 5.0% strain, they ranged from 2,299 cycles in Section 5 to 3,434 cycles in Section 1. The supporting parameters followed the same general pattern. The control bottom layer had an initial $|G^*|$ of 11.0 MPa and a D_f of 51.9. The valid treated sections had lower initial moduli, ranging from 7.6 to 9.2 MPa, and higher D_f values, ranging from 60.8 to 70.9. Therefore, the higher fatigue lives of the treated sections were associated not only with lower initial stiffness but also with greater calculated damage tolerance. This combined response suggests that the underlying binders beneath the treated St. Cloud sections retained more favorable fatigue-related properties than the binder beneath the untreated control.

The St. Cloud results did not, however, produce a monotonic treatment-year ranking. Section 2 had the highest N_f at 2.5% strain, while Section 1 had the highest N_f at 5.0% strain and

the highest D_f . Sections 4 and 5 also remained favorable relative to the control. Thus, the results support a general treated-versus-control difference at depth but do not identify one optimum application year. The polymer-modified, RAP-free mixture may also have contributed to the relatively high damage tolerance observed throughout the site.

Overall, the bottom-layer LAS results provide site-specific supporting evidence of binder preservation. Cass County showed a pronounced benefit only in Section 1, indicating that the earliest chip seal application was associated with a substantially more favorable fatigue-related binder condition than the untreated control and the later-treated sections. St. Cloud showed a broader treated-versus-control benefit, although without a clear chronological treatment-year sequence. Crow Wing County could not be evaluated for a treatment effect because only Section 1 produced valid LAS results.

These findings support Objective 3 by showing that chip seal application was associated with differences in the retained fatigue-related properties of the underlying binder. The clearest LAS response occurred in Cass County Section 1, while the valid St. Cloud results showed a broader treated-versus-control difference without a treatment-year sequence. However, the incomplete Crow Wing County dataset and the absence of a monotonic response at St. Cloud prevent the LAS results from establishing a universal relationship between application year and fatigue performance.



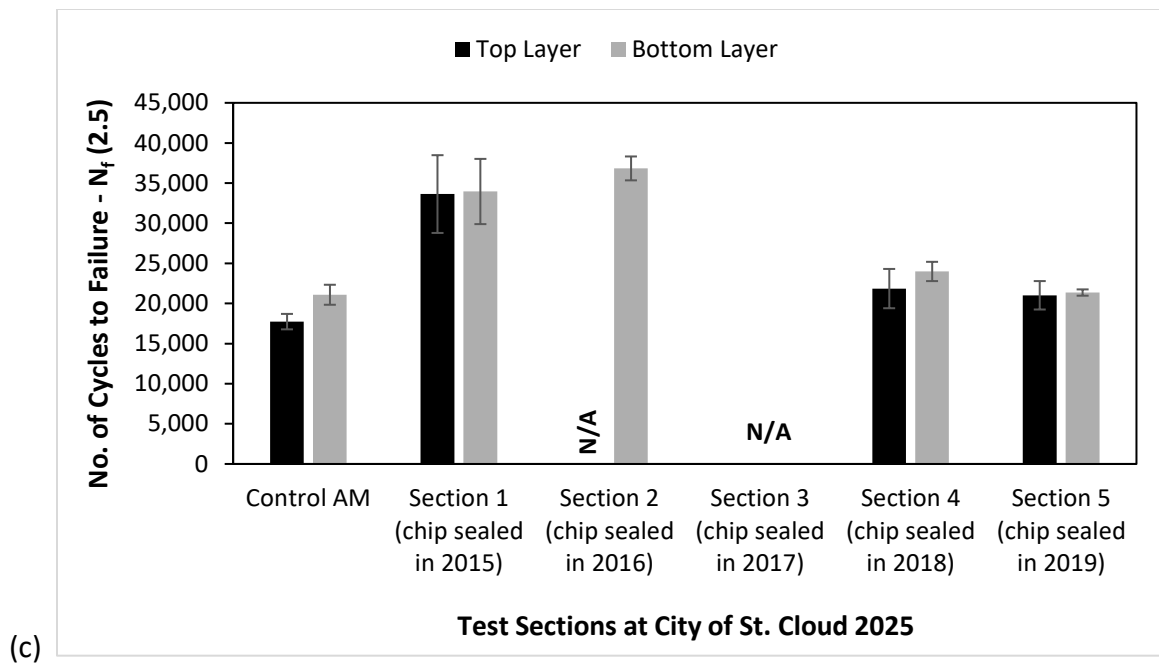
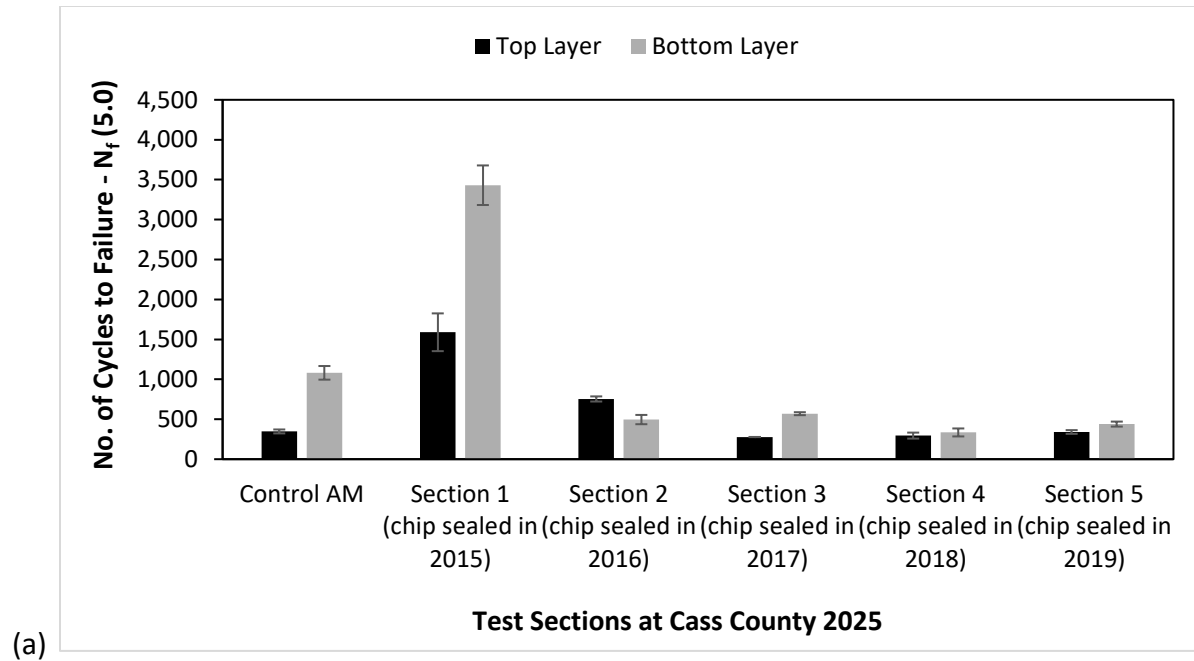


Figure 28. LAS fatigue response of recovered binders in 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud. N_f represents predicted cycles to failure at 2.5%



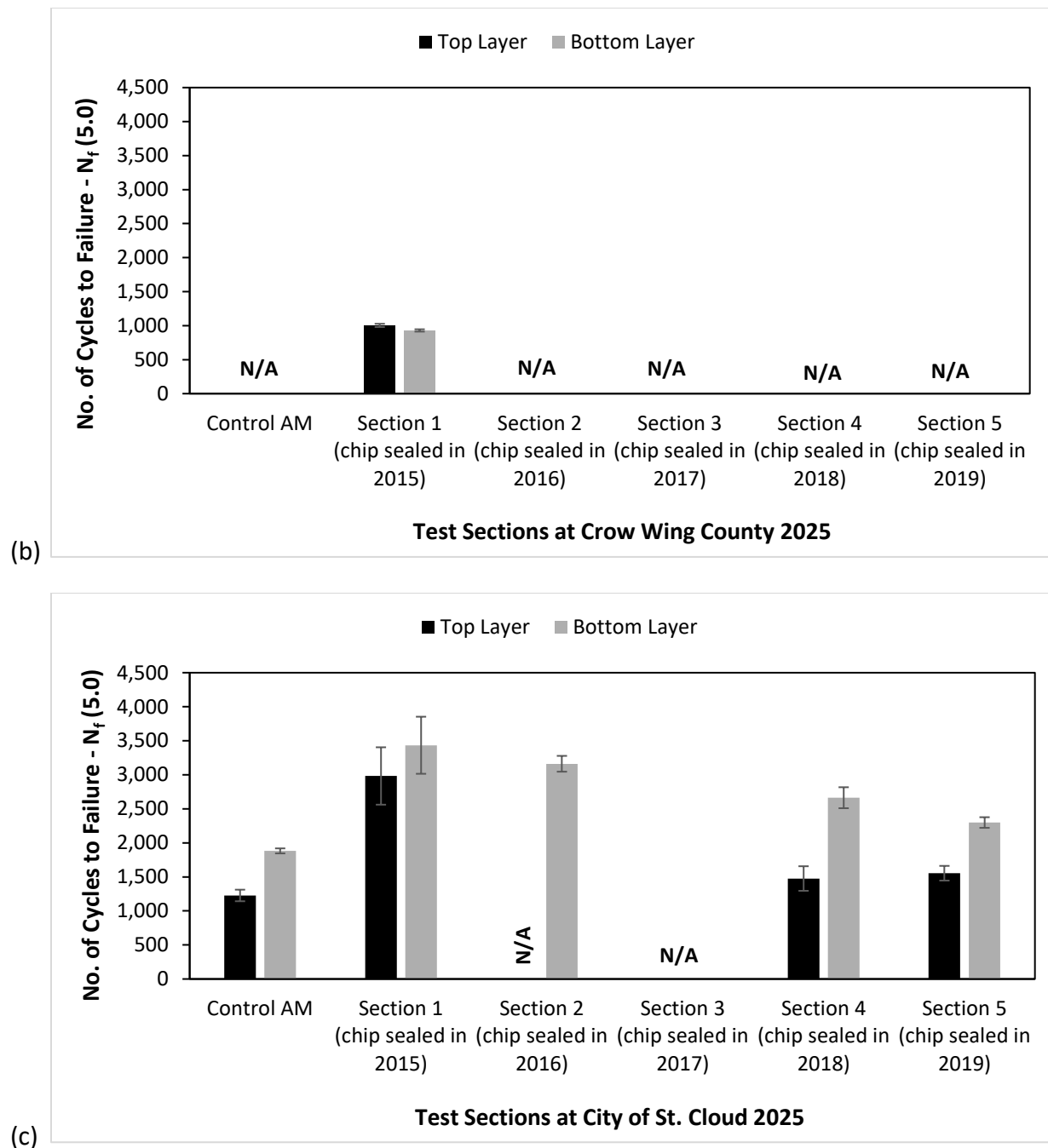


Figure 29. LAS fatigue response of recovered binders in 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud. N_f represents predicted cycles to failure at 5.0%

Table 14. LAS Damage at Failure, D_f , for Control and Treated Sections in 2025

Section	Chip Seal Year	Top Layer	Bottom Layer
<i>Cass County</i>			
Control AM	Untreated	22.7	39.4
Section 1	2015	48.1	70.6
Section 2	2016	33.4	25.8
Section 3	2017	21.4	29.4
Section 4	2018	20.5	22.4
Section 5	2019	23.3	26.3
<i>Crow Wing County</i>			
Control AM	Untreated	–	–
Section 1	2015	40.6	42.8
Section 2	2016	–	–
Section 3	2017	–	–
Section 4	2018	–	–
Section 5	2019	–	–
<i>City of St. Cloud</i>			
Control AM	Untreated	39.6	51.9
Section 1	2015	62.0	70.9
Section 2	2016	–	63.8
Section 3	2017	–	–
Section 4	2018	42.3	66.3
Section 5	2019	44.2	60.8

4.10 G-R Parameter

The G-R parameter combines complex shear modulus and phase angle to characterize binder embrittlement associated with cracking susceptibility. None of the recovered binders approached the commonly cited 180 to 600 kPa damage range. Therefore, the G–R parameter was used to compare relative binder condition among sections rather than to classify the binders as being within a cracking-damage zone. The top- and bottom-layer values are presented in Figure 30 and Figure 31, respectively.

At Cass County, the top-layer control had a G-R value of 16.7 kPa. Sections 1 and 2 produced values of 8.7 and 14.8 kPa, respectively, while Sections 3, 4, and 5 produced higher values of 28.2, 22.8, and 35.9 kPa. The top-layer results therefore varied considerably among sections and did not follow the chronological order of chip seal application. The bottom-layer control had a G-R value of 5.0 kPa. Sections 1 and 2 produced lower values of 1.7 and 3.4 kPa, respectively, indicating less embrittled underlying binders than the untreated control. Section 3 was equal to the control at 5.0 kPa, while Sections 4 and 5 produced higher values of 24.5 and 16.8 kPa. Section 1 therefore exhibited the most favorable bottom-layer G-R response at the site. This result was consistent with its favorable low-temperature continuous grade, ΔT_c , and valid LAS response. However, these indicators describe related aspects of binder stiffness, phase response, relaxation, and damage tolerance and should not be treated as statistically independent confirmation.

At Crow Wing County, the top-layer control had a G-R value of 13.6 kPa. Sections 1, 2, 3, 4, and 5 produced values of 4.6, 10.2, 6.6, 21.7, and 6.5 kPa, respectively. Most treated sections

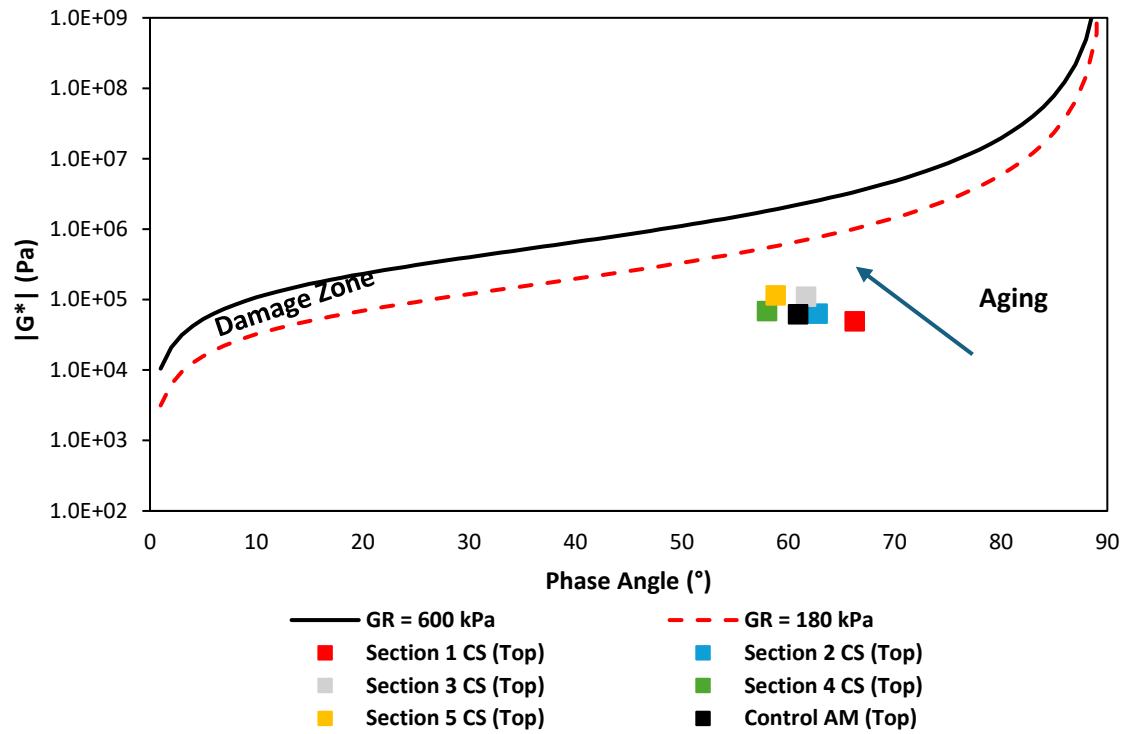
had lower top-layer values than the control, except Section 4, which produced the highest value at the site. As at Cass County, the top-layer rankings did not follow treatment chronology. For the bottom layer, the control had a G-R value of 4.5 kPa. Sections 1, 3, and 4 produced lower values of 0.8, 1.7, and 3.9 kPa, respectively. Section 5 was similar to the control at 4.6 kPa, while Section 2 produced the highest bottom-layer value at 7.5 kPa. Section 1 exhibited the lowest bottom-layer G-R value, but the section rankings did not follow the chronological order of chip seal application. The results therefore indicate section-level differences in recovered binder embrittlement but do not establish a continuous treatment-year progression.

At the City of St. Cloud, the top-layer control produced a G-R value of 11.2 kPa. Sections 1 through 5 produced values of 2.6, 10.4, 5.2, 5.7, and 8.5 kPa, respectively. All treated sections had lower top-layer values than the control, although the section rankings did not show a consistent early-to-late treatment pattern. For the bottom layer, the control produced a G-R value of 2.9 kPa. All treated sections had lower values, ranging from 1.2 to 1.7 kPa. Section 5 produced the lowest value at 1.2 kPa, followed by Section 2 at 1.3 kPa, Section 1 at 1.4 kPa, Section 3 at 1.6 kPa, and Section 4 at 1.7 kPa. The treated sections therefore exhibited less embrittled bottom-layer binders than the untreated control, although the narrow range among the treated values did not identify an early-treatment advantage or a specific optimum application year. Because St. Cloud used a polymer-modified, RAP-free mixture, its absolute G-R values should not be directly compared with those from the county sites as evidence of treatment effectiveness.

Overall, the top-layer G-R results showed substantial section-level variability and no consistent chronological relationship with chip seal application year. Their interpretation is also limited by the difference in material composition between the treated and control top-layer samples. The bottom-layer results showed a pronounced favorable response for Cass County Section 1, a mixed response at Crow Wing County, and a broader treated-versus-control difference at the City of St. Cloud. The results did not establish a universal or monotonic relationship between treatment year and binder embrittlement. Instead, they provided additional, mechanistically related support for the site-specific patterns identified through the other recovered binder measurements.

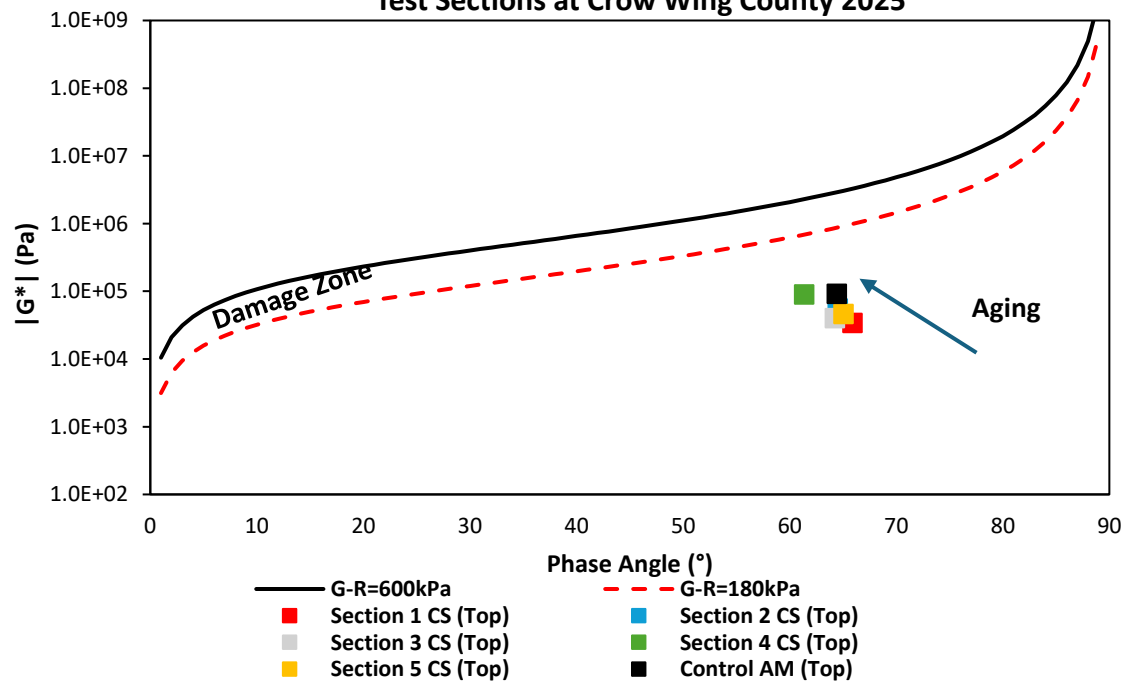
The agreement among the G-R parameter, ΔT_c , low-temperature continuous grade, and valid LAS results strengthens the qualitative interpretation of binder condition where the indicators point in the same direction. However, these measurements were obtained from the same recovered materials and depend on overlapping rheological properties. Their agreement should therefore be described as convergence among complementary indicators. The combined results suggest that chip seal application was associated with more favorable retained binder properties in selected sections, with the clearest early-treatment response occurring at Cass County.

Test Sections at Cass County 2025

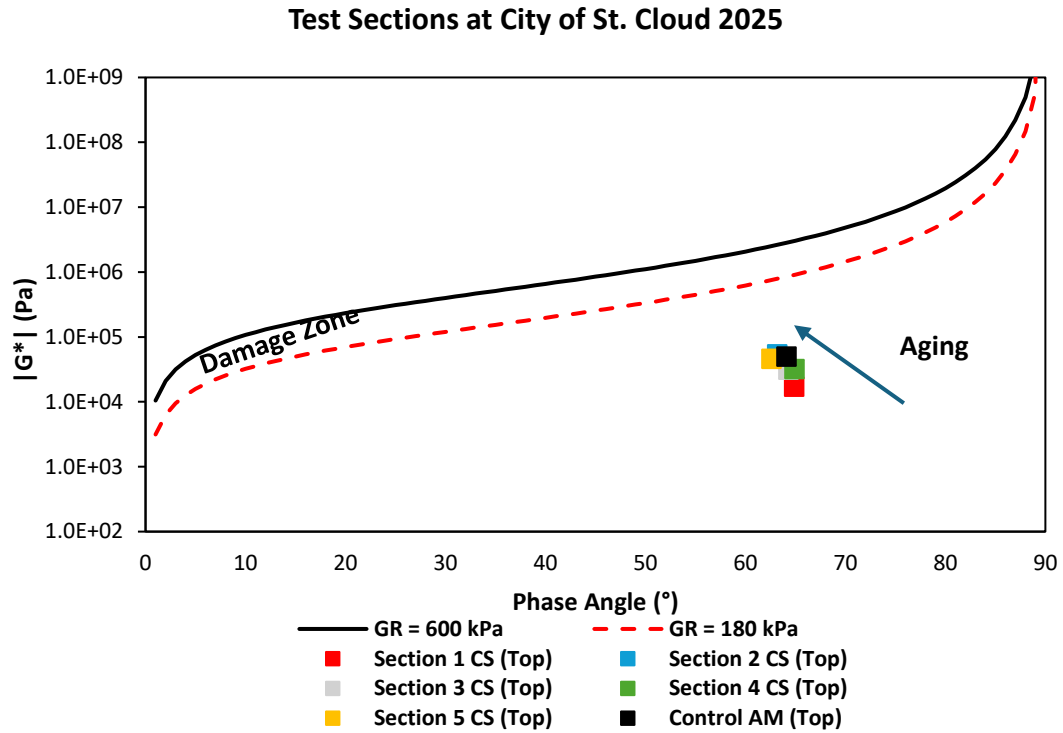


(a)

Test Sections at Crow Wing County 2025



(b)

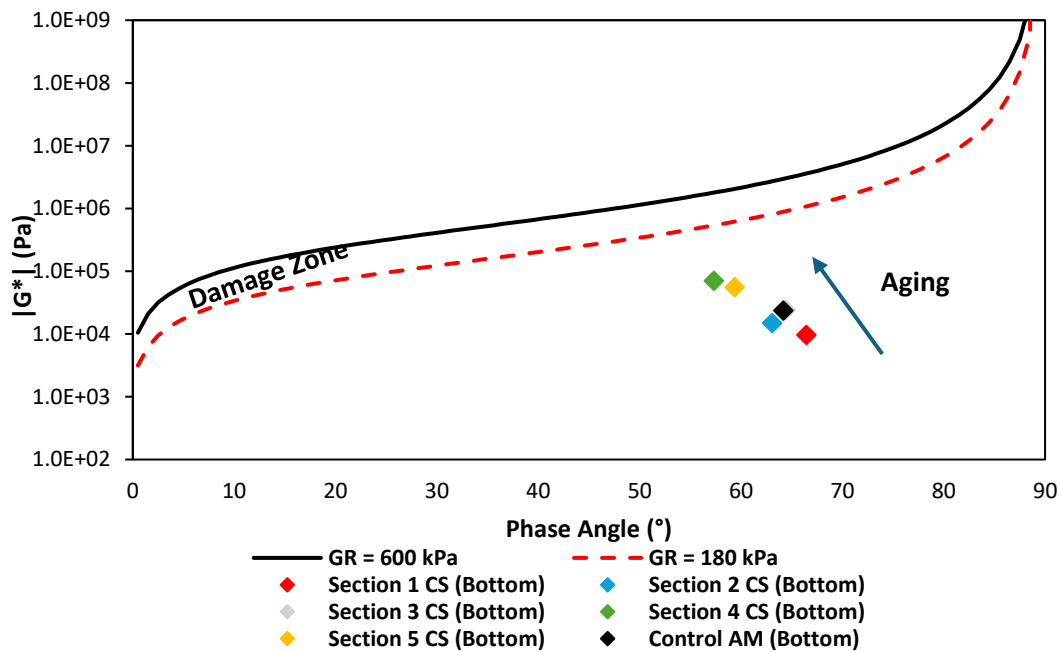


(c)

Figure 30. G-R at 15°C, 0.005 rad/s for Control and Treated Sections Year 2025 for Top Layers

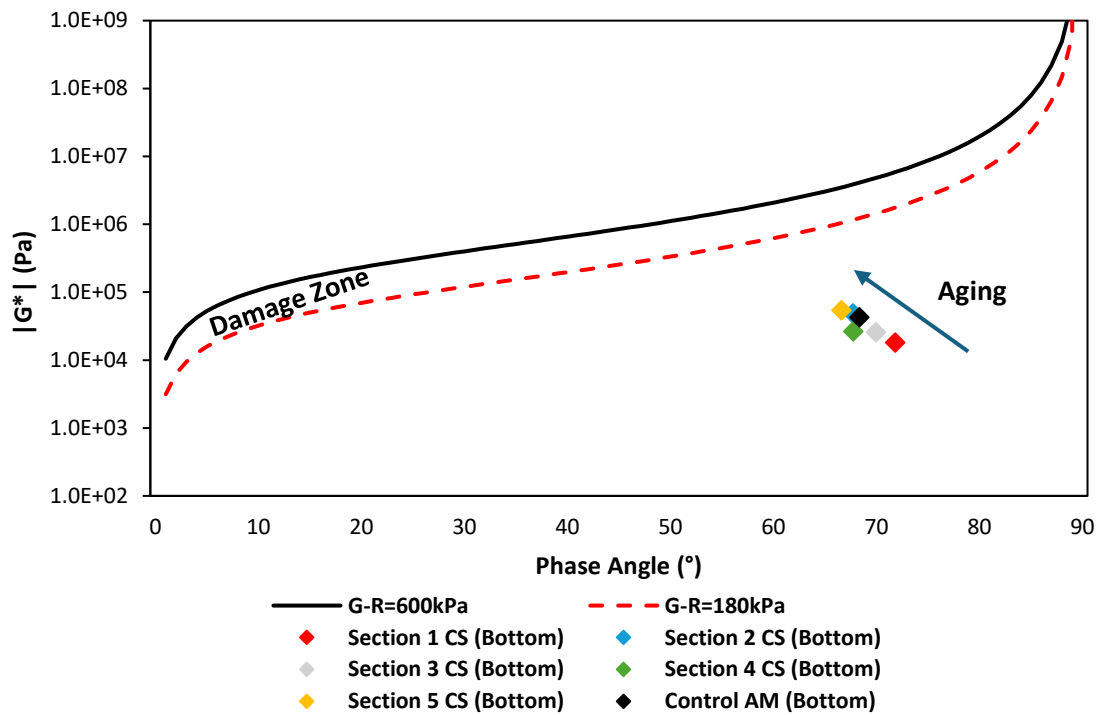
(a) Cass County (b) Crow Wing County (c) City of St. Cloud; CS = Chip Seal, AM = Asphalt Mix

Test Sections at Cass County 2025

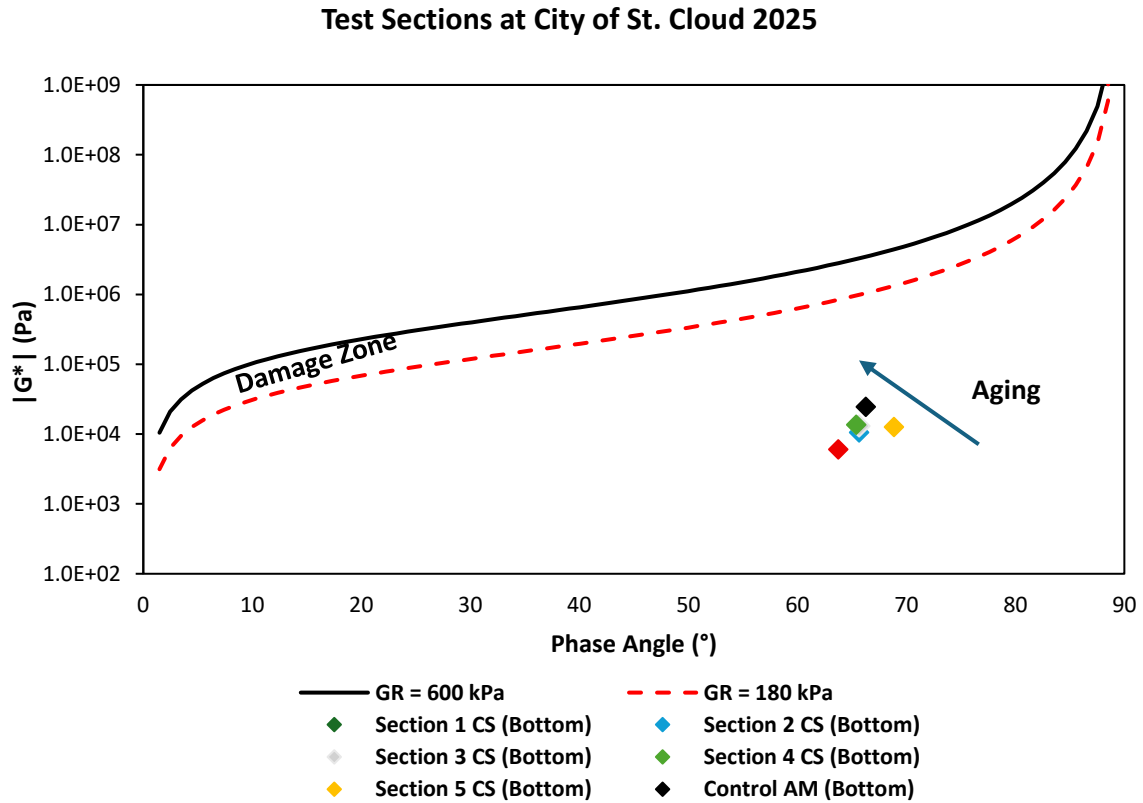


(a)

Test Sections at Crow Wing County 2025



(b)



(c)

Figure 31. G-R at 15°C, 0.005 rad/s for Control and Treated Sections Year 2025 for Bottom Layers (a) Cass County (b) Crow Wing County (c) City of St. Cloud; CS = Chip Seal, AM = Asphalt Mix

4.11 Binder Bond Strength

The BBS test was used to evaluate changes in pull-off tensile strength following 48 hours of moisture conditioning. All specimens exhibited cohesive failure within the binder film rather than adhesive failure at the binder–aggregate interface. Therefore, the results primarily characterize the cohesive strength of the recovered binder and its ability to retain that strength after moisture exposure. They should not be interpreted as direct measurements of binder–aggregate adhesion or field chip retention. The dry- and wet-conditioned POTS means and standard deviations for each agency, section, and recovered layer are summarized in Table 15.

As shown in Table 15, the dry-conditioned top-layer POTS values at Cass County ranged from 2.8 to 4.1 MPa. Section 5 produced the highest top-layer strength, followed by the control, whereas Section 1 produced the lowest value. Bottom-layer dry strengths were less variable, ranging from 2.4 to 3.7 MPa, with the control producing the highest value and Section 1 the lowest. Following moisture conditioning, the control retained the highest top-layer strength at 3.8 MPa, while Sections 1 and 3 decreased to 1.8 and 1.7 MPa, respectively. The wet-conditioned bottom-layer values ranged from 1.9 to 3.0 MPa, with Section 3 producing the highest retained strength and Section 1 the lowest.

At Crow Wing County, the valid dry- and wet-conditioned POTS results presented in Table 15 showed a narrower range than the Cass County results. Section 3 produced the highest dry strength in both layers. After moisture conditioning, the top-layer values were more closely grouped, ranging from 2.7 to 3.0 MPa, whereas the bottom-layer values ranged from 1.8 to 2.8 MPa. Section 5 produced the lowest wet-conditioned bottom-layer strength. Results were not available for Section 4, and the available control data were insufficient for a complete treated-versus-control comparison at this site.

The City of St. Cloud POTS results presented in Table 15 were generally lower than those measured at Cass County. Dry-conditioned top-layer strengths ranged from 2.3 to 3.4 MPa, with Sections 2 and 4 producing the highest values. Bottom-layer dry strengths ranged from 2.1 to 2.6 MPa among the valid results. After moisture conditioning, Section 4 retained the highest strength in both layers, with values of 3.2 MPa in the top layer and 2.3 MPa in the bottom layer. Section 1 produced the lowest wet-conditioned top-layer value at 1.8 MPa, while Section 2

produced the lowest bottom-layer value at 1.6 MPa. Control results were not available at this site, and the Section 5 bottom-layer result was also unavailable.

The percentage losses presented in Figure 32 were calculated from the dry- and wet-conditioned POTS means reported in Table 15. In several section-layer combinations, the wet-conditioned mean equaled or exceeded the corresponding dry-conditioned mean, resulting in a zero or negative calculated loss. Because these values did not represent a measurable reduction in pull-off strength after conditioning, they were reported as not applicable and were excluded from the percent-loss comparison. Interpretation therefore considered the valid percentage losses together with the original dry and wet POTS values and the observed cohesive failure mode.

At Cass County, the moisture-conditioned response varied considerably by section and layer. Section 3 exhibited the largest top-layer loss at 46.2%, while its bottom layer showed only a small reduction. Section 1 also experienced a substantial top-layer loss of 36.0%. In contrast, Sections 2 and 4 retained most of their top-layer strength after conditioning. The corrected bottom-layer losses for Sections 2 and 5 were 11.8% and 26.1%, respectively. These results show that the moisture-conditioned response did not follow the same section ranking observed for ΔT_c , LAS, or the continuous low-temperature grades. In particular, the favorable relaxation-related response of Section 1 did not correspond to high moisture-conditioned strength retention.

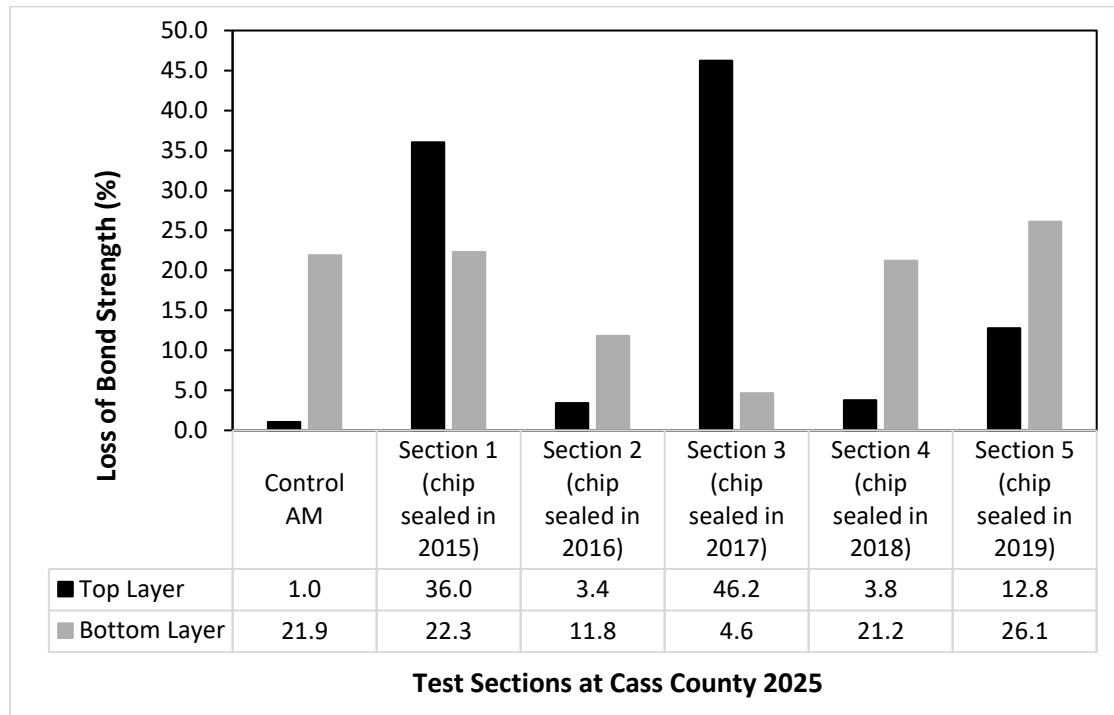
At Crow Wing County, the valid treated-section losses were generally moderate, although Section 3 showed losses of approximately 25% in both layers. Sections 1 and 2

retained a larger proportion of their dry bond strength, with losses ranging from 5.1% to 11.0%. Section 4 had an invalid top-layer result but showed a 25.1% loss in the bottom layer, while Section 5 exhibited a greater reduction in the bottom layer than in the top layer. Because the control top-layer result was invalid, the differences primarily describe variability among the treated sections and layers but cannot establish whether chip sealing improved moisture resistance relative to the untreated pavement.

At St. Cloud, the valid losses also varied among sections. Section 1 showed the largest top-layer reduction, while Section 4 retained most of its dry-conditioned strength in both layers. The corrected bottom-layer loss for Section 3 was 22.9%. Section 5 showed little change in its top-layer strength, although its bottom-layer response was unavailable. Without valid control results, the St. Cloud data cannot support a treated-versus-untreated comparison.

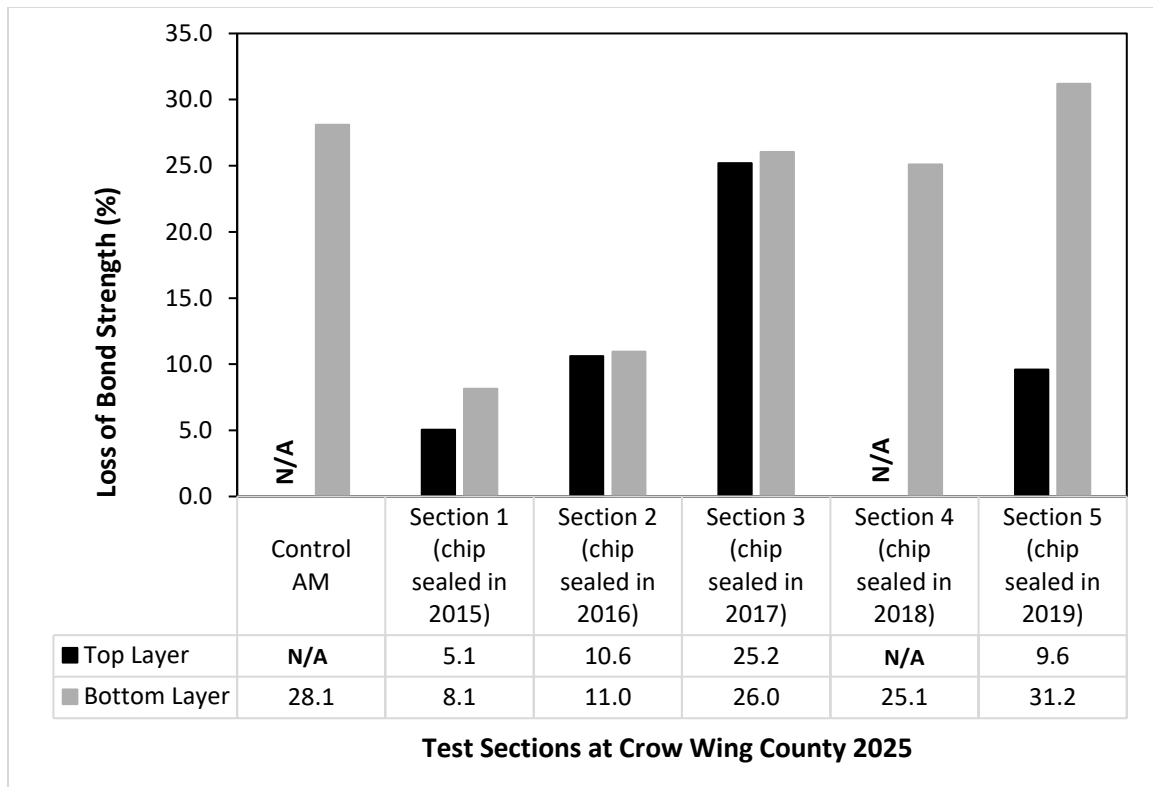
Overall, the BBS results showed a treatment-age-related pattern in the top-layer response, although the pattern was not uniform across every agency, section, and layer. At Cass County, dry top-layer POTS generally increased from 2.8 MPa in Section 1, chip sealed in 2015, to 4.1 MPa in Section 5, chip sealed in 2019, consistent with greater stiffening of the longer-aged recovered binder. The wet-conditioning results showed a complementary exposure-time response: all top-layer strength losses greater than 25% occurred in sections chip sealed from 2015 through 2017, whereas the valid losses for sections chip sealed in 2018 and 2019 were 12.8% or less. This pattern indicates that the longer-exposed seal-binder systems generally retained less cohesive strength after moisture conditioning. Because all specimens failed cohesively, the results characterize moisture-conditioned cohesive strength retention rather

than binder-aggregate adhesion. The BBS response therefore represents a distinct moisture-related aspect of recovered binder performance and should be interpreted separately from relaxation capacity, fatigue tolerance, and oxidative aging.



(a)

(b)



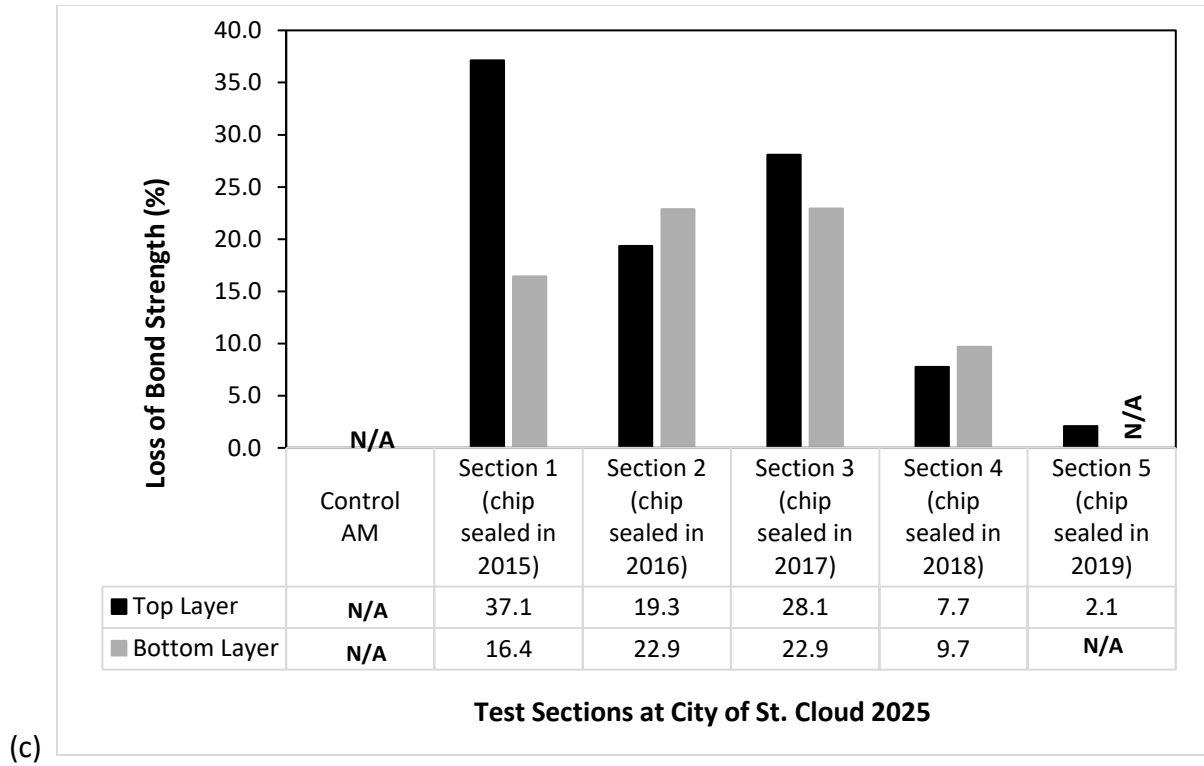


Figure 32. Loss of Bond Strength Results for Control and Treated Sections Year 2025: (a) Cass County, (b) Crow Wing County, and (c) City of St. Cloud.

Table 15. Dry- and Wet-Conditioned Pull-Off Tensile Strength Results for All Agencies

Agency	Section	Condition	Top-Layer Mean (MPa)	Top-Layer SD	Bottom-Layer Mean (MPa)	Bottom-Layer SD
Cass County	Control	Dry	3.9	0.70	3.7	0.19
	AM	Wet	3.8	0.67	2.9	0.52
	Section 1	Dry	2.8	0.04	2.4	0.09
	(2015)	Wet	1.8	0.37	1.9	0.39
	Section 2	Dry	3.3	0.25	3.3	0.64
	(2016)	Wet	3.2	0.12	2.9	0.02
	Section 3	Dry	3.2	0.16	3.1	0.30
	(2017)	Wet	1.7	0.14	3.0	0.51
	Section 4	Dry	3.5	0.12	3.1	0.15
	(2018)	Wet	3.4	0.26	2.4	0.34
	Section 5	Dry	4.1	0.20	3.3	0.13
	(2019)	Wet	3.6	0.23	2.4	0.05

**Table 15. Dry- and Wet-Conditioned Pull-Off Tensile Strength Results for All Agencies
(continued)**

Agency	Section	Condition	Top-Layer Mean (MPa)	Top- Layer SD	Bottom-Layer Mean (MPa)	Bottom- Layer SD
Crow Wing County	Control	Dry	-	-	3.3	0.07
	AM	Wet	-	-	2.4	0.39
	Section 1	Dry	2.8	0.04	2.4	0.23
	(2015)	Wet	2.7	0.28	2.2	0.18
	Section 2	Dry	3.0	0.13	3.2	0.08
	(2016)	Wet	2.7	0.40	2.8	0.67
	Section 3	Dry	4.0	0.32	3.6	1.64
	(2017)	Wet	3.0	0.45	2.7	0.33
	Section 4	Dry	-	-	2.6	0.36
	(2018)	Wet	-	-	1.95	0.08
	Section 5	Dry	3.1	0.76	2.6	0.66
	(2019)	Wet	2.8	0.51	1.8	0.43

**Table 15. Dry- and Wet-Conditioned Pull-Off Tensile Strength Results for All Agencies
(continued)**

Agency	Section	Condition	Top-Layer Mean (MPa)	Top-Layer SD	Bottom-Layer Mean (MPa)	Bottom-Layer SD
City of St. Cloud	Control	Dry	-	-	-	-
	AM	Wet	-	-	-	-
	Section 1	Dry	2.8	0.24	2.4	0.11
	(2015)	Wet	1.8	0.18	2.0	0.21
	Section 2	Dry	3.4	0.11	2.1	0.00
	(2016)	Wet	2.7	0.33	1.6	0.07
	Section 3	Dry	2.9	0.64	2.4	0.24
	(2017)	Wet	2.1	0.33	1.9	0.02
	Section 4	Dry	3.4	0.03	2.6	0.34
	(2018)	Wet	3.2	0.72	2.3	0.23
	Section 5	Dry	2.3	0.34	N.A.	N.A.
	(2019)	Wet	2.3	0.29	N.A.	N.A.

4.12 Section-Level Comparison of Recovered Binder Properties and Field Performance

This section compares field performance with selected bottom-layer recovered binder properties at the section level. Within each agency, the treated sections were evaluated relative to the untreated control. For Cass and Crow Wing Counties, field performance was represented by the most recent full-width transverse crack counts, reported separately by

travel direction. For the City of St. Cloud, eastbound and westbound surface ratings were retained separately. These descriptive comparisons were used to determine whether the field and laboratory indicators exhibited similar section-level patterns.

Table 16. Section-Level Comparison of Field Performance and Selected Bottom-Layer Recovered Binder Properties

Agency	Section	Chip Seal year	Latest Directional Field Values	ΔT_c (°C)	G-R (kPa)	C=O + S=O	LAS N_f , 2.5%	Descriptive comparison with control
Cass County	Control AM	—	NB: 64; SB: 67	-1.9	5.0	0.9	13,288	—
	Section 1	2015	NB: 99; SB: 99	1.6	1.7	0.8	32,540	The binder indicators were more favorable than the control, particularly ΔT_c and the combined LAS response. However, the 2025 crack counts were substantially higher than the control in both directions.
	Section 2	2016	NB: 65; SB: 67	0.6	3.4	0.7	9,735	Crack counts were nearly identical to the control. The bottom-layer ΔT_c , G-R, and oxidation index were more favorable, although the LAS response was below the control.
	Section 3	2017	NB: 79; SB: 79	1.3	5.0	0.7	7,803	Crack counts exceeded the control in both directions despite favorable ΔT_c and oxidation results. The lower LAS response was consistent with a less favorable fatigue-related binder condition than the control.
	Section 4	2018	NB: 88; SB: 88	-0.9	24.5	1.1	6,313	Crack counts exceeded the control in both directions. The high G-R value and low LAS response also indicated a less favorable binder condition, although J_{nr} was not interpreted as a cracking indicator.
	Section 5	2019	NB: 63; SB: 62	0.7	16.8	1.6	5,967	Crack counts were slightly below the control, although G-R, oxidation, and LAS results were less favorable. The field and binder indicators therefore did not show the same section-level pattern.
Crow Wing County	Control AM	—	NB: 73; SB: 66	-1.0	4.5	1.7	—	—
	Section 1	2015	NB: 64; SB: 63	0.9	0.8	1.4	7,957	Section 1 had fewer cracks than the control in both directions and more favorable ΔT_c , G-R, and oxidation values. LAS was valid only for this treated section and therefore could not be used for a treatment trend.
	Section 2	2016	NB: 102; SB: 106	-0.9	7.5	1.5	—	Crack counts were substantially higher than the control in both directions. The G-R value was also higher, while ΔT_c was similar to the control.
	Section 3	2017	NB: 83; SB: 93	0.0	1.7	0.7	—	Crack counts exceeded the control even though the bottom-layer G-R and oxidation values were lower. The field and binder indicators did not show consistent agreement.
	Section 4	2018	NB: 84; SB: 85	-0.6	3.9	1.3	—	Crack counts were higher than the control in both directions. The binder indicators were generally close to or slightly more favorable than the control.
	Section 5	2019	NB: 157; SB: 146	-0.1	4.6	1.5	—	Section 5 had the highest crack count in both directions. Its ΔT_c , G-R, and oxidation values did not differ sufficiently from the control to explain the magnitude of the field distress.
City of St. Cloud	Control AM	—	EB SR: 3.9; WB SR: 3.8	-0.1	2.9	1.4	21,085	—
	Section 1	2015	EB SR: 4.0; WB SR: 3.9	2.0	1.4	1.3	33,950	Surface ratings were slightly higher than the control in both directions. The bottom-layer binder indicators were also generally more favorable.
	Section 2	2016	EB SR: 4.0; WB SR: 3.9	0.4	1.3	1.3	36,826	Surface ratings were slightly higher than the control. The section had the highest valid LAS fatigue life, although the small surface-rating range limits interpretation.
	Section 3	2017	EB SR: 3.9; WB SR: 3.8	2.2	1.6	1.3	—	Surface ratings were similar to the control despite ΔT_c and G-R values. A LAS comparison was not available.
	Section 4	2018	EB SR: 3.9; WB SR: 3.8	2.3	1.7	1.3	23,987	Surface ratings were similar to the control. The binder indicators were generally favorable, but the narrow field-performance range prevented meaningful differentiation.
	Section 5	2019	EB SR: 4.0; WB SR: 3.7	1.0	1.2	1.5	21,359	The eastbound rating remained high, while the westbound rating was lower than the control. Binder indicators were mixed and did not show a comparable directional field pattern.

Chapter 5 Conclusions and Recommendations

This chapter presents the conclusions drawn from the long-term field-performance and recovered binder evaluations. The findings are interpreted collectively to determine whether chip seal application timing influenced pavement roughness, cracking, surface condition, and the retained properties of the underlying asphalt binder. Because the three study sites differed in pavement structure, traffic, binder type, mixture composition, maintenance history, and environmental exposure, the conclusions emphasize consistent within-site patterns rather than direct comparisons of absolute values among agencies.

5.1 Conclusions

The findings demonstrate that chip seal application timing was reflected more clearly in the long-term condition of the recovered binder than in the conventional field-performance measurements. Field roughness, transverse cracking, and surface rating did not produce a uniform treatment-year sequence across the three agencies. In contrast, several bottom-layer chemical and rheological indicators distinguished treated sections from their respective controls and identified site-specific preservation responses.

The strongest evidence of a timing-related benefit occurred at Cass County, where the earliest-treated section exhibited the most favorable overall bottom-layer binder response. Sections treated within approximately the first two years after construction generally produced more favorable results than several later-treated sections. Crow Wing County also showed some favorable results for the earliest-treated section, particularly in transverse cracking and selected binder properties, although the incomplete LAS dataset limited the strength of this

conclusion. The City of St. Cloud showed broader differences between treated sections and the untreated control but did not exhibit a consistent sequence based on treatment year. Taken together, these findings suggest that the first two years after construction may represent a practical early-application window for pavements similar to those evaluated. This period should not be treated as a fixed universal requirement because pavement condition and site characteristics remain essential to the timing decision.

The field-performance hypothesis was only partially supported. At Cass and Crow Wing Counties, full-width transverse crack counts varied among treatment sections and between travel directions. The section rankings were not consistently ordered according to chip seal application year. Cass County Section 1, for example, had favorable recovered binder properties but higher 2025 crack counts than the control in both directions. At Crow Wing County, Section 1 had fewer 2025 cracks than the control in both directions, while Sections 2 through 5 generally had higher counts. At the City of St. Cloud, surface ratings remained within a narrow range, which limited the ability to distinguish treatment-year effects. These results indicate that field condition was influenced by treatment timing together with traffic direction, construction variability, maintenance activities, localized distress, and the original pavement and mixture characteristics.

The strongest evidence of an early-treatment effect occurred at Cass County. The bottom-layer binder recovered from Section 1 exhibited a substantially more favorable low-temperature continuous grade, ΔT_c , Glover-Rowe parameter, and combined LAS response than the bottom-layer control. Its relatively high $J_{nr,3.2}$ also indicated that the binder remained more

compliant and less age hardened than the control and the later-treated sections. The FTIR oxidation index was slightly lower than the control, providing additional chemical evidence of preservation beneath the treated surface. Together, these results indicate that the earliest chip seal application at Cass County was associated with improved long-term retention of binder relaxation capacity and damage tolerance.

The Cass County response did not extend uniformly across all treatment years. Sections 2 and 3 retained favorable values for some bottom-layer indicators, but Sections 4 and 5 generally showed greater stiffness, embrittlement, or oxidation. The results therefore support an early-treatment preservation response at this site but do not establish a continuous year-by-year relationship between application timing and binder condition.

At Crow Wing County, all treated sections had lower bottom-layer FTIR oxidation indices than the control, and several sections had more favorable low-temperature, intermediate-temperature, Glover-Rowe, and MSCR responses. However, the section rankings varied among indicators and did not follow the order of chip seal application. LAS could not be used to evaluate treatment timing because valid results were available only for Section 1. The Crow Wing County findings therefore support preservation-related differences between treated and untreated sections but do not identify a particular optimum treatment year.

At the City of St. Cloud, several bottom-layer indicators favored the treated sections relative to the control. All valid treated sections had more favorable low-temperature continuous grades, lower Glover-Rowe values, and generally favorable LAS responses when N_f , initial $|G^*|$, and D_f were interpreted together. However, these responses were distributed

among multiple treatment years rather than concentrated in Section 1. The narrow surface-rating range and the polymer-modified material system further limited the ability to identify a distinct timing sequence. The results therefore indicate a general treated-versus-control binder response at this site rather than a specific early-treatment effect. The FTIR results showed that the protective influence of chip sealing was most appropriately evaluated using the underlying bottom-layer binder. At Cass County, Sections 1 through 3 had lower bottom-layer oxidation indices than the control. At Crow Wing County, every treated section had a lower value than the control. St. Cloud showed only minor separation among sections. These findings demonstrate that recovered binder chemistry could identify preservation-related differences beneath some treated surfaces, although the magnitude of the response depended on the agency and material system.

The low-temperature continuous grade, BBR, and ΔT_c results provided the clearest rheological evidence of binder preservation. The Cass County Section 1 bottom-layer ΔT_c differed from the control by approximately 3.5°C, a contrast large enough to support interpretation. Most Crow Wing County and St. Cloud differences were approximately 1°C and were not interpreted as meaningful timing effects. Positive ΔT_c values at the polymer-modified sites were treated as within-agency comparative results rather than as an absolute scale for ranking agencies.

The Glover-Rowe, ΔT_c , continuous-grade, FTIR, and LAS results provided complementary information about recovered binder condition. Their agreement strengthened the qualitative interpretation where the indicators followed the same section-level pattern. However, they

were derived from the same recovered materials and depend on overlapping chemical and rheological properties. Their agreement therefore represents convergence among related indicators rather than statistically independent confirmation.

LAS provided supporting rather than definitive evidence. At Cass County, Section 1 showed the clearest favorable response when predicted fatigue life, initial modulus, and damage at failure were considered together. The valid St. Cloud results generally favored the treated bottom-layer binders relative to the control, but the rankings did not follow application year. Crow Wing County could not support a treatment comparison because only Section 1 produced valid results. LAS therefore supported selected within-agency conclusions but did not independently establish a general treatment-timing relationship.

The MSCR results showed that rutting resistance and binder aging must be interpreted separately. A low $J_{nr,3.2}$ indicated strong resistance to nonrecoverable deformation but could also indicate substantial age-related stiffening. Cass County Section 1 had a higher bottom-layer $J_{nr,3.2}$ than the control, which was consistent with its less hardened condition in the low-temperature and relaxation-related tests. The lowest $J_{nr,3.2}$ values were therefore not interpreted as the best-preserved binders. MSCR remained useful for documenting current traffic-grade classification but did not establish a consistent treatment-year pattern.

Binder Bond Strength identified a treatment-age-related moisture response that was distinct from the rheological findings. At Cass County, dry top-layer POTS generally increased from the 2015-treated section to the 2019-treated section. Across the evaluated sites, top-layer

wet-conditioning losses greater than 25% occurred only in sections chip sealed from 2015 through 2017, while the valid 2018 and 2019 losses were 12.8% or less. This pattern indicates that the longer-exposed seal-binder systems generally retained less cohesive strength after moisture conditioning. Because all specimens failed cohesively, the BBS results characterize moisture-conditioned cohesive strength retention and should not be interpreted as direct evidence of binder–aggregate adhesion or field aggregate retention.

The section-level comparison between laboratory and field measurements did not identify a single binder property capable of predicting field performance. Some sections showed agreement between favorable binder properties and lower distress, while others did not. The lack of uniform alignment reflects differences in distress mechanism, travel direction, maintenance history, traffic, material composition, and construction conditions. Recovered binder characterization should therefore be used to explain material condition and aging mechanisms rather than as a stand-alone predictor of field performance.

Overall, the study supports the following principal conclusion:

Timely chip seal application can preserve selected chemical and rheological properties of the underlying asphalt binder, but the magnitude and timing of that benefit depend on the pavement, mixture, binder system, and site conditions. The strongest evidence of an early-treatment benefit occurred at Cass County. The Crow Wing County and St. Cloud results showed more general treated-versus-control differences without a consistent treatment-year sequence.

The study does not establish a universal application year or condition threshold. Each treatment year was represented by one roadway section, and the three agencies differed in pavement structure, materials, traffic, maintenance history, and environmental exposure. The conclusions are therefore site specific and should not be interpreted as proof that every pavement should be chip sealed during the same service year.

5.2 Recommendations

Agencies should consider chip sealing while the pavement remains structurally adequate and before cracking, surface loss, or roughness has progressed to a level that limits the effectiveness of a surface treatment. For pavements similar to those evaluated in this study, application during approximately the first two years after construction appears to be the most favorable practical window. This timing should not be applied as a fixed calendar requirement because the appropriate treatment point depends on the condition and characteristics of the individual pavement.

Treatment decisions should account for the combined influence of pavement age, existing distress, traffic loading, climate, pavement structure, mixture composition, binder type, drainage, construction quality, and previous maintenance. These factors can affect both the observed field performance and the condition of the recovered binder. Consequently, a treatment timing that performs well at one site may not produce the same response at another site, even when the pavements are exposed to similar environmental conditions.

No single field measurement should be used as the sole trigger for chip seal application. Roughness, cracking, rutting, surface condition, and maintenance history describe different

aspects of pavement deterioration and may not change at the same rate. A pavement may retain acceptable ride quality while the surface binder continues to age, or it may exhibit visible cracking without a substantial increase in IRI. Agencies should therefore evaluate the overall condition of the pavement and confirm that the observed distress remains primarily surface related before selecting chip sealing as the appropriate treatment.

Pavements exhibiting advanced fatigue cracking, severe rutting, widespread moisture damage, base failure, extensive patching, or other indications of structural deterioration should be considered for rehabilitation rather than routine chip sealing. Directional differences in traffic, drainage, wheel-path condition, snowplow exposure, and construction variability should also be considered where they are relevant because averaging measurements across directions may conceal meaningful performance differences.

Construction and maintenance records should be retained as part of the treatment history. Crack sealing, fog sealing, patching, surface repairs, and other interventions can affect subsequent field measurements and recovered binder properties. Without this information, differences among sections may be incorrectly attributed to chip seal timing alone.

Recovered binder testing may be used as a supplementary project-level diagnostic when agencies need to investigate treatment performance, compare preservation practices, or calibrate local treatment windows. However, laboratory results should be interpreted together with field condition, pavement structure, material composition, and maintenance history. They should not replace routine pavement-condition assessment or be used as stand-alone predictors of field performance.

The results support the development of locally calibrated treatment windows rather than a single universal application year. Agencies should use their own pavement-management records and long-term performance data to determine how traffic, climate, materials, and maintenance practices influence chip seal effectiveness within their networks. The approximately two-year early-application window identified in this study should therefore be treated as a site-specific guide that requires confirmation under local conditions.

5.3 Future Work

Future studies should replicate each treatment timing across several roadway sections rather than representing each year with one section. Replication across multiple agencies and material systems would allow treatment timing to be distinguished more effectively from section-specific construction, traffic, and environmental effects.

Pretreatment and post-treatment measurements should be collected consistently. These should include IRI, rut depth, crack type, crack count, crack width, severity, surface condition, structural response, drainage condition, and maintenance history. Cracks should be georeferenced or tracked using repeatable image-based surveys so that crack initiation and growth can be distinguished from crack sealing and other maintenance activities.

Original binder, mixture binder, chip seal emulsion residue, and recovered binder continuous grades should be measured whenever possible. Measured original continuous grades would provide a defensible baseline for evaluating field-age hardening and would avoid transformations based only on nominal PG classifications.

Additional work should quantify the proportions of chip seal residue and HMA binder in the recovered upper interval. Testing the residue and original HMA binder separately would improve interpretation of FTIR, rheological, and moisture-conditioning results from the treated surface material.

LAS validation should be expanded using additional independent field samples. Future field comparisons should use verified fatigue-cracking measurements rather than total transverse cracking or general surface rating. MSCR and high-temperature continuous-grade results should be evaluated against section-level rutting data.

Future BBS investigations should include additional independent recovered binder samples, controlled film thickness, consistent substrates, and detailed documentation of cohesive and adhesive failure. The relationship between laboratory cohesive-strength loss and observed field surface loss should be evaluated before BBS is used as an agency-level treatment-timing criterion.

Finally, future studies should include pavement structure, layer thickness, density, air-void distribution, Falling Weight Deflectometer response, traffic loading, pavement temperature, moisture exposure, and drainage. These measurements would help explain why sections with similar recovered binder properties sometimes exhibited different field-performance responses.

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