DEPARTMENT OF TRANSPORTATION

Sustaining Performance of ASR-Affected Pavements: Effective Practices and Insights

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Alkali-silica reaction (ASR) remains a significant durability concern in concrete pavements, leading to internal cracking, surface deterioration, and loss of ride quality. Although preventive measures have reduced ASR in new construction, pavements built in Minnesota in the 1980s and 1990s continue to exhibit distress. This study evaluates maintenance and rehabilitation strategies using historical Ride Quality Index (RQI) and Surface Rating (SR) data, field inspections, and ultrasonic tomography imaging.

Results show that bituminous overlays provide immediate improvements in ride quality and surface condition, despite expected reflective cracking. Partial- and full-depth joint repairs, especially when combined with diamond grinding, effectively restore surface condition, although long-term performance monitoring is needed. Ultrasonic tomography is inconclusive; physical sampling would be necessary for firm conclusions.
The study highlights that while ASR cannot be reversed, its effects can be managed through timely maintenance. Integrating pavement management data with on-site evaluations and selectively applying emerging diagnostic tools like ultrasonic tomography can support more effective maintenance decisions and help extend the service life of ASR-affected pavements.

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Final Report

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Executive Summary

Alkali-silica reaction (ASR) is a long-term durability concern in concrete pavements, known to cause progressive internal cracking, surface deterioration (e.g., cracking, spalling, joint deterioration) and subsequent loss of ride quality. While the use of non-reactive aggregates and supplementary cementitious materials (SCMs) has minimized ASR in new construction, many pavements built in Minnesota in the 1980s and 1990s continue to exhibit ASR-related distress. This study evaluates the performance of maintenance and rehabilitation strategies used to manage ASR in existing concrete pavements and identifies effective practices based on historical data and field observations.

The study focused on pavement segments selected with input from MnDOT experts that had undergone interventions such as bituminous overlays or partial- and full-depth repairs. Performance was assessed using historical Ride Quality Index (RQI) and Surface Rating (SR) data, supplemented by on-site visual inspections. A site study using ultrasonic tomography imaging was also conducted on untreated pavement sections to explore the ultrasonic tomography device's potential for early detection of ASR-related subsurface damage.

Analysis of the data showed that bituminous overlays provided immediate improvements in ride quality and surface condition, particularly in segments like US 169 and MN 15. Overlays were found to show expected reflective transverse and longitudinal cracking, but overall surface condition seemed good. Partial- and full-depth joint repairs, especially when paired with diamond grinding, were effective in improving surface condition. These treatments were still in the early stages of service life, and continued monitoring will be necessary to determine their long-term performance.

Ultrasonic tomography imaging results suggested potential subsurface anomalies linked to cracking, but without physical sampling, the findings remain inconclusive. While the method showed promise as a non-destructive diagnostic tool, its practical application in pavement condition assessment will require further refinement and validation.

Ongoing monitoring of the study sites is recommended, with particular attention to diamond-ground and partially repaired sections. Selective use of ultrasonic tomography, in conjunction with coring or other evaluation techniques, could help detect internal ASR activity before surface damage becomes visible.

Although ASR cannot be reversed, this study reinforces that its effects can be managed through timely, informed maintenance. Combining pavement condition data with on-site evaluations can help extend pavement life and guide MnDOT's strategy for managing ASR-affected pavement infrastructure.

Chapter 1: Introduction

Alkali-silica reaction (ASR) is the deleterious chemical interaction of concrete alkalis in pore solution with reactive silica in aggregate. The reaction degrades the aggregate particle and produces an expansive gel known as alkali-silica gel (Figure 1). Alkali-silica gel intakes water and expands; the resulting stress is sufficient to crack concrete. A network of 3D cracking is common (Figure 1).

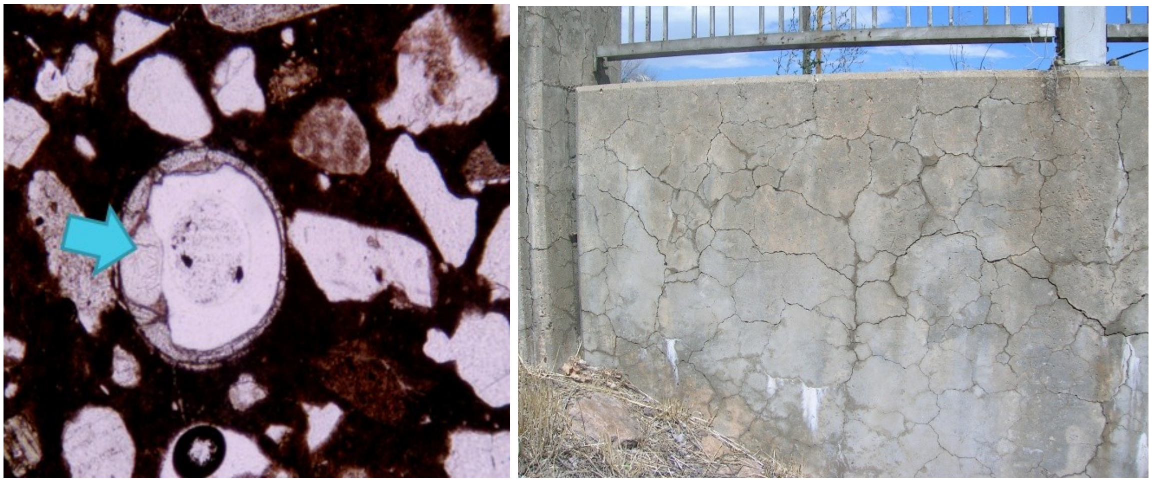

Figure 1.1: Alkali-silica gel lining an air void in mortar on the left, bridge abutment showing signs of ASR cracking on the right (*unpublished work*).

There are three essential components of ASR cracking —reactive silica, alkali, and moisture (Figure 2). The severity of cracking depends on the supply of these three components. Time, or age, can be considered as a fourth component that determines cracking. Depending on the conditions, it may take years to see cracking, and sometimes there is no visible cracking on the surface.

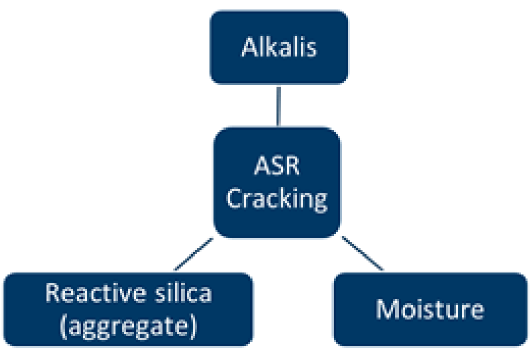

Figure 1.2 Components to develop ASR cracking.

When the use of non-reactive aggregate is not feasible (e.g., for economic reasons), it is important to determine the degree of aggregate reactivity. Therefore, testing aggregate before use in concrete is essential so that appropriate mitigation measure can be taken to control ASR. Numerous test methods have been proposed and implemented over the course of ASR research. The philosophy in ASR testing is to accelerate reaction rate by amplifying the favorable ASR conditions:

- Moisture (e.g., storing test specimens in high humidity conditions or immersing in aqueous solution)
- Alkali (e.g., using high-alkali cement and/or adding alkali to mix water)
- Combining first two by storing specimens in alkali solution
- Temperature (e.g., storing at high temperature up to 150°C)

The two widely used methods are ASTM C1260 (2023), known as the mortar bar method, and ASTM C1293 (2023), known as the concrete prism method. The former uses mortar bars cast with the aggregate in question and stores specimens in sodium-hydroxide solution at 80°C for 14 days. The aggregate is considered potentially reactive if the length change is greater than 0.10% of the length at time zero. The latter method uses concrete prisms that are stored over water at 38°C for 1 year. If the length change is greater than 0.04% of the length at time zero, the aggregate is deemed reactive. These two tests are also used to determine the efficiency of preventive measures. Supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume are very effective in controlling ASR when used in conjunction with reactive aggregate in new concrete. ASTM C1778 (2023) outlines the minimum levels of SCM to mitigate ASR based on various factors (e.g., aggregate reactivity, structure classification, alkali content of Portland cement, total alkali loading of concrete mix).

When a concrete structure is built with reactive aggregate without mitigation measures, it becomes an issue of management since the reaction is irreversible. The manifestation of ASR in the form of surface cracking, spalling, or pop-out are maintained via traditional pavement management techniques like all other pavement distresses regardless of the root cause. In pavements, typical progression of ASR is the darkening of concrete surface near the joints, then followed by map-cracking on the surface, and spalling and break-outs around joints (Weise et al., 2022). It is natural that the deterioration starts to manifest itself around the joints, which function as water reservoirs. Darkening occurs as microcracks develop; water sits in these microcracks takes longer time to evaporate, hence, these sites contrast to no-crack regions on the surface. With further progression of ASR, the 3D crack network expands and cracks widen, then concrete starts to spall from surface, particularly, at joints. At the extreme, shattered slabs and panel buckling can be observed.

1.1 ASR Management in Existing Concrete Pavements

ASR is one troublesome material related distress that can appear in 5-15 years after construction and the progression speed varies. ASR can produce severe performance problems in concrete pavements (e.g., map cracking over entire slab area, expansion-related distresses such as joint closure, spalling and/or blowups) (Smith et. al., 2022). Once pavement is built with reactive aggregate with no mitigation measure it comes down to management of the symptoms. One of the earliest guidelines to manage ASR-affected pavement is provided by Thomas et. al. (2011). The document defines the ASR symptoms as cracking, expansion causing deformation, relative movement, and displacement, localized crushing of concrete, extrusion of joint material, surface pop-outs and surface discoloration and gel exudations; and offers management strategies of structures affected by ASR. It is possible to observe one or more of these symptoms depending on the reaction conditions. The first step of any management strategy is to diagnose the problem, and this can be done by routine inspections. Highway agencies perform periodic pavement management condition surveys, albeit most of them do not specifically target ASR. Fournier et. al. (2010) summarizes the various mitigation options that have been used or proposed for use in field structures under two categories—treating the cause and treating the symptoms. Treatment of underlying causes involve actions to reduce or eliminate ASR components given in Figure 2—alkali, reactive silica, and water. Since alkali and reactive silica are built-in, perhaps water is the only component that can be dealt with. Chemical treatment such as using lithium compounds interferes with the reaction and drying of the structure using surface sealants, cladding (e.g., pavement overlay) and improved drainage aims to reduce moisture. However, methods designed to control available water has limited effectiveness since even water in vapor phase can be absorbed by ASR gel (Van Dam et. al., 2002). Treatment of symptoms include traditional pavement maintenance and preservation techniques such as crack sealing, joint resealing, partial- and full-depth repairs, stress/pressure relief by saw cutting/slot cutting to accommodate movement, and overlays. Various methods used in managing ASR-affected pavements are further reviewed below.

1.2 Joint and Crack Sealing

Sealing the joints and cracks limits the amount of water penetrating concrete. Typical performance of a joint or crack sealant material is between 3 and 10 years (Smith and Van Dam, 2019). Even at its best performing state joint and crack sealant would have very limited effect since moisture will enter concrete from other locations. Moreover, ASR gel is capable of imbibing water in gaseous state. When relative humidity is greater than 80%, the gel imbibes water vapor and subsequently swells (Stark et al., 1993).

High-Molecular Weight Methacrylate (HMWM) is used to fill cracks in concrete pavements exhibiting distress due to ASR. In addition to closing off effect, HMWM bonds or glues concrete pieces together; therefore, these materials are somewhat more suitable in wider cracks (Smith and Van Dam, 2019). Stark et al. (1993) reported the application of HMWM to an ASR-distressed section of State Route 58 near Boron, CA, and another section on I-80 near Winnemucca, NV. Krauss et al. (2006) later investigated these sections and found that the application reduced spalling and extended the pavement life by about three to five years in California pavement. On the other hand, the application in Nevada was not successful, perhaps since the ASR was in an advanced stage. Methacrylate was also tried at Seymour-Johnson Air Force Base in North Carolina to impede continued ASR expansion and found to be ineffective (TSPWG, 2019).

1.3 Improving Drainage

Similar to joint sealing and crack filling, adding a drainage system to an ASR-affected pavement aims to keep pavement dry by moving water away from the pavement. In wet climate, this is not a practical solution as rewetting is frequent and even with a good drainage system pavements remain wet due to water condensing underneath the pavement. The effectiveness of retrofitted subsurface drainage depends on the characteristics of the base materials; and the addition of the edge drains does nothing to address the deterioration that has already occurred in the pavement (Smith et al., 2022). Improving a drainage system would perhaps help to slow down the progression of ASR, however, there is no existing study solely investigating how much it would help.

1.4 Surface Treatment

The entire pavement surface is treated with materials that are assumed to interfere with the progression of ASR and slow down the deterioration. This could be in two ways:

- Application of sealers to stop moisture penetration
- Application of lithium compounds to chemically interfere and cease ASR

Cady (1994) describes sealers in three broad categories as follows:

- Water repellents (e.g., silanes and siloxanes)
- Pore blockers (e.g., linseed oil)
- Barrier coatings (e.g., acrylics and epoxies)

Pore blockers and barrier coatings work in the same manner forming a layer that prevents water penetrating the concrete. The former has sufficiently low viscosity to allow them to penetrate the surface pores while leaving a thin layer of coating on the exterior concrete surface. The latter, on the other hand, is too viscous to penetrate the pores, thus, forms a thick coating layer on the concrete surface (Cady, 1994; Smith et. al., 2022).

Silanes, which can be either water-based or solvent-based, are reported to be the most common water repellent treatment in ASR-affected pavements (Thomas et. al., 2013a). The effectiveness of the silanes seems to be unclear as conflicting results have been reported. Nebraska Department of Roads (NDOR) carried out a study where the ability of seven sealers to prevent moisture penetration into concrete pavements as a preventative maintenance tool to mitigate concrete expansion due to ASR was investigated (Heyen et. al., 2010). Both 100% and 40% solvent-based silane products were reported to show consistently high performance. However, it is worth noting that the performance evaluation was based on chloride ion penetration; there was no evaluation on the effectiveness of ASR mitigation. Basham (2009) reported a comparative study of the effectiveness of surface treatments in Wyoming. Although the program was terminated prematurely it was reported that the siloxane might reduce the rate of ASR deterioration. However, no firm conclusions were made because of the limited samples tested. The three categories of surface treatment given above were studied comparatively on outdoor exposure blocks extracted from airfield concrete pavement that was affected by ASR (Heymsfield et. al., 2016). They investigated the effectiveness of linseed oil, elastomeric paint, and silane. Based on one-year data, the researchers reported the linseed oil and silane coatings reduced expansion marginally and longer observation was needed to validate the trend. Krauss et al. (2006) also reported silanes, and lithium oxide, made little difference stopping the progression of ASR distress in test sections included in the SHRP study in 1991 (Stark et. al., 1993).

The mitigative effect of lithium was first reported in early 1950s. McCoy and Caldwell (1951) found that 1 percent or less of specific salts would reduce expansion more than 75 percent in Pyrex glass mortar bar tests using a small percentage of opal and quartz sand as aggregate. Although the precise mechanism is unknown, Thomas et. al. (2013b) states the consensus as the siliceous aggregate preferentially reacts with lithium ions rather than potassium or sodium, and the lithium changes the nature and behavior of the ASR gel from expansive to non-expansive.

Krauss et al. (2006) summarized the continued evaluation of test sites that were treated with lithium hydroxide to stop ASR deterioration. These sites, located in Winnemucca, NV, and Newark, DE, were included in an SHRP project (Stark et. al., 1993). In the Nevada site, lithium treatment made no improvement in preventing ASR progression, and similar observation was made in the Delaware site. After four years, all test sections treated with lithium showed increased distress. Folliard et. al. (2006) summarizes topical applications of lithium nitrate on ASR-afflicted pavement sections in various states—South Dakota, Delaware, and Minnesota. The observations made 2-4 years after application showed marginal benefits. The pavements in South Dakota and Minnesota demonstrated little to no visible improvement. The pavement in Delaware presented half success as some parts performing better than the control and some parts no difference in deterioration. Nonetheless, the Delaware DOT considered the application successful as the lithium applications extended the pavement life. Wyoming DOT tested lithium nitrate on a section of air service apron at Riverton Regional Airport (Basham, 2009). After approximately five years, map cracking and relative displacements of the pavement started to occur in this concrete. The effectiveness of surface treatments (i.e., lithium nitrate, siloxane, linseed oil, silane, sodium tartarate) was evaluated on cores using damage rating index (DRI) and ultrasonic pulse velocity (UPV) measurements over two years. Lithium nitrate was ranked first indicating it slowed the ASR deterioration; however, no definitive conclusion was drawn. In 2004, a 3-mile-long pavement section was treated with lithium nitrate in Mountain Home, ID. Even after several treatments in heavily cracked pavement, the penetration of lithium solution was found to be limited to only a few millimeters, and the project was abandoned (Thomas, 2008; Thomas et. al., 2013b). Tuan et. al. (2005) also reported that there was no definitive benefit of application of the lithium material in controlling or mitigating ASR.

Smith and Van Dam (2019) reported the results of interviews with several airport authorities— Phoenix Sky Harbor International, Hartsfield-Jackson Atlanta International, Colorado Springs Municipal. These agencies all dealt with ASR-afflicted pavements for years and applied lithium nitrate topically. All three reported that the lithium makes no difference in the progression of ASR deterioration. Similarly, Department of Defense's Tri-Service Pavements Working Group (TSPWG, 2019) does not recommend lithium compounds as their use is considered an experimental technology. TSPWG(2019) also does not recommend the use of silanes and siloxanes; because these surface-sealing materials were found to be ineffective to stop or slow the progression of ASR in pavements.

1.5 Corrective Repairs of Pavement Slabs

In this category, the reaction itself is not addressed but rather the distresses and symptoms are corrected with repair such as partial-depth repair, full slab replacement (i.e., full-depth repair), and sawcut joints to relieve pressure due to ASR expansion. The objective with these repairs is not to interfere with the progression of ASR but to extend pavement life.

Partial-depth and full-depth patches are considered temporary fixes; they are applied to the areas that are severely deteriorated and become unacceptable for ride (TSPWG, 2019). Partial-depth repairs are performed around joints where ASR-induced spalling is most prevalent, and they are most effective when the distress is limited to the upper one-third to one-half of the concrete slab thickness (Smith et al, 2022). Full-depth repairs consist of removal of isolated, ASR-deteriorated areas through the entire thickness of the existing slab (Smith and Van Dam, 2019). The success of partial-depth and full-depth repairs depend on proper boundary selection. It is important to remove deep enough for partial-depth repairs that the ASR-affected section is replaced. Naturally, the reaction would continue at non-replaced portion of the pavement.

Pressure relief joints or expansion joints are 1 to 2 inches wide and are installed making full-depth saw cuts across the entire slab width and inserting a compressible filler (Smith and Van Dam, 2019). They provide temporary relief as the joint will eventually close due to further ASR expansion. The results from ASR-affected structures in military bases have been reported: at Seymour-Johnson Air Force Base in Goldsboro, NC, a 1.5-inch-wide expansion joint had closed in about two years and a 4-inch-wide joint had narrowed down to 1 inch in five to ten years. The rate of progression of ASR might create extreme cases. At Ft. Campbell Army Airfield near Hopkinsville, KY, expansion joints were closed in a matter of months. Furthermore, at Travis Air Force Base near Fairfield, CA, utility cuts in a ramp undergoing ASR were put under such pressure over the years that the concrete was crushed (TSPWG, 2019). In their ACRP synthesis, Smith and Van Dam (2019) reported that Hartsfield-Jackson Atlanta International Airport had obtained 35 to 40 years of service from their ASR-afflicted runway pavements with an aggressive patching program that includes reinforced partial-depth repairs and full-depth repairs when deterioration was excessive. Similar success in ASR-afflicted pavement management via partial-depth and full-depth repairs have been reported by the same authors in Bangor International Airport and Colorado Springs Municipal Airport. It is worth noting that both Colorado Springs and Bangor international airports reported higher success in partial-depth patching with a propriety mastic patching material because of its ability to accommodate expansion (Smith and Van Dam, 2019).

1.6 Structural Overlays

If the distress is severe, the natural next step for ASR-affected pavement is the rehabilitation with overlaying. Either hot mix asphalt (HMA) or unbonded Portland cement concrete (PCC) are options for severely deteriorated pavement. HMA overlays are more susceptible to reflection cracking and their performance is more dependent on the type and amount of pre-overlay repair work that is performed. In addition, HMA is more likely to trap moisture and tends to heat more during hot days; both could exacerbate the progression of ASR in the underlaying concrete layer. Unbonded PCC overlays have been also used to overlay ASR-affected pavement. PCC overlays are deemed to be a more effective solution since they are less sensitive to the underlying pavement conditions (Van Dam et. al., 2009; Fournier et. al., 2010).

The *TSPWG Manual* (2019) recommends HMA overlays as a stopgap to correct serious surface deterioration and increase ride, but only as a temporary measure. It further states that cracking and seating (or rubblization) of the original pavement and then overlaying it with HMA offers uncertainty since rubblization allows easier penetration of water into the concrete that would speed the ASR reaction. On the other hand, rubblization would create additional void space that could absorb ASR expansion. Buncher et al. (2008) disagrees:

> "*Given the vast amount of pavements that have been rubblized or crack/break and seated over the past 25 years, and given that ASR is not that uncommon, we believe it's fair to say that a significantly large amount of ASR-infected PCC has been rubblized or crack/break and seated.*"

Colorado's first rubblization project was done on ASR-affected pavement in 2000. After six years in service, it was reported that the HMA overlay had no distresses associated with reflective cracking from the old concrete pavement and had not demonstrated any settlement, permanent deformation (rutting), or other distress (LaForce, 2006). Bunchner et al. (2008) also reported successful HMA overlays on ASR-affected airfield pavements (i.e., runways and taxiways) in New York, Pennsylvania, and Tennessee. No performance problem was reported. Similarly, Smith and Van Dam (2019) reported an HMA overlay to rehabilitate ASR-affected runway pavement at Bangor International Airport in Bangor, ME. Good performance had been reported after 13 years of service even though the underlying concrete continued to move. Furthermore, Kwak et al. (2014) reported the performance of HMA overlay on ASR affected pavement at Gimpo International Airport in Seoul, South Korea. About 4 inches of the existing 40-inch concrete was milled and overlaid with HMA. The overlay somewhat performed less than expected: the potholes had been expected in five years, however, were seen in three years. The underperformance was attributed to the fact that the milling accelerated the ASR deterioration.

In the 1980s, Pease Air Force Base in New Hampshire used thin bonded concrete overlays on ASR-affected pavements to reduce foreign object debris (FOD). The existing pavement was milled and replaced with 3-inch-thick fully bonded PCC overlay. Underlying longitudinal cracks unrelated to ASR reflected through the overlay; however, FOD was significantly reduced. This overlay was reported to be functional in 2019 (TSPWG, 2019). In 1993 and 1994, Delaware DOT rehabilitated a 9-mile-long section of I-495 that included extensively ASR-affected CRCP using a 10-inch thick unbonded concrete overlay. The overlay was reported to perform well after more than 26 years of service (Tayabji, 2021).

Chapter 2: Pavement Sections Selected for Evaluation

Minnesota has addressed the alkali-silica reaction (ASR) problem in newer pavements by modifying concrete mixes, such as limiting total alkali content using supplementary cementitious materials (SCM). However, some pavements constructed with reactive aggregate in late 80s and 90s are still in service and show varying levels of ASR distress. MnDOT has utilized various strategies (e.g., concrete pavement rehabilitation with and without diamond grinding, chip seal, asphalt and concrete overlays) to keep these pavements in good riding condition and prolong their service life. The outcomes of these strategies have not been documented qualitatively or quantitatively; hence, the effectiveness of these strategies is unknown or anecdotal at best. Knowing which strategies work, and to what degree, is important for MnDOT to effectively allocate its resources.

The objective of this research was to assess the maintenance and rehabilitation strategies used by MnDOT for concrete pavements affected by Alkali-Silica Reaction (ASR) and to identify the most effective approaches. The study focused on selected pavement sections known to exhibit ASR-related distress. These sections had undergone a range of intervention techniques aimed at mitigating ASR damage and maintaining ride quality. The sections included in the study are as follows:

- US 169 from Blue Earth to Winnebago: 4-in. bituminous overlay (~milepost 10.000 to 20.000)
- US 169 from Winnebago to Vernon Center: 3-in. bituminous overlay (~milepost 20.000 to 34.000)
- MN 15 from New Ulm to Winthrop: 2 to 3 -in. bituminous overlay (~milepost 60.000 to 76.000)
- I-94 near St Paul: full-depth repair of the transverse joints and partial-depth repair of longitudinal joints. (~milepost 241.500 to 244.000)
- MN 55 near Mendota Heights: full-depth repair of the transverse joints and nominal amount of partial-depth repair of slabs (~milepost 199.000 to 201.000)
- MN 210 near Aitkin: partial- and full-depth repair of transverse joints, and partial-depth repair at the intersection of longitudinal joint and transverse joints including some joints left unrepaired (~milepost 143.000 to 152.000)

There are two major rehabilitation/intervention strategies utilized on the selected sections:

- Bituminous overlay
- Full and partial-depth repair, particularly transverse joints

Chapter 3: Pavement Condition Data

This chapter presents the findings from analyses conducted to evaluate the impact of maintenance and rehabilitation strategies on pavement conditions, using Ride Quality Index (RQI), Surface Rating (SR) data. The pavement performance data was provided by MnDOT.

3.1 Ride Quality Index (RQI)

RQI in Minnesota is a measure of pavement roughness or ride quality, derived from the International Roughness Index (IRI). The IRI quantifies road roughness based on the vertical movement of a standard vehicle over a section of road. A higher IRI indicates a rougher road.

In Minnesota, the IRI is converted to RQI to take public opinion into account. A rating panel, composed of citizens, rates road segments based on their ride experience. These ratings are given on a scale from 0 to 5, with corresponding verbal descriptions (4.1 - 5.0 Very Good; 3.1 - 4.0 Good; 2.1 - 3.0 Fair; 1.1 - 2.0 Poor; and 0.0 - 1.0 Very Poor). Panelists assess the ride quality and refine their ratings to one-tenth of a point.

The RQI calculation involves compiling ratings for multiple test sections, calculating mean and standard deviation, and adjusting if necessary. The mean or adjusted mean becomes the panel's RQI for each section. Regression analysis establishes correlations between the panel's RQI and measured IRI values for both bituminous and concrete pavements.

The RQI allows the estimation of how a panel of citizens would rate the pavement based on laser-measured IRI values. The validity of this correlation depends on the public's perception of smooth and rough roads remaining relatively stable.

RQI measurements from the year 2000 onwards for each segment in the six pavement sections—US 169-BEW (Blue Earth to Winnebago), US 169-WVC (Winnebago to Vernon Center), MN 15, I 94, MN 55, MN 210)—are plotted in Figures 3.1 to 3.6.

Figure 3.1 (US 169-BEW) strongly indicates an improvement in 2019. Figure 3.2 (US 169-WVC) does not show a significant RQI jump but visually hints an improvement in 2021. Similar analysis for MN 15 indicates a major intervention in 2013. The other three sections are inconclusive.

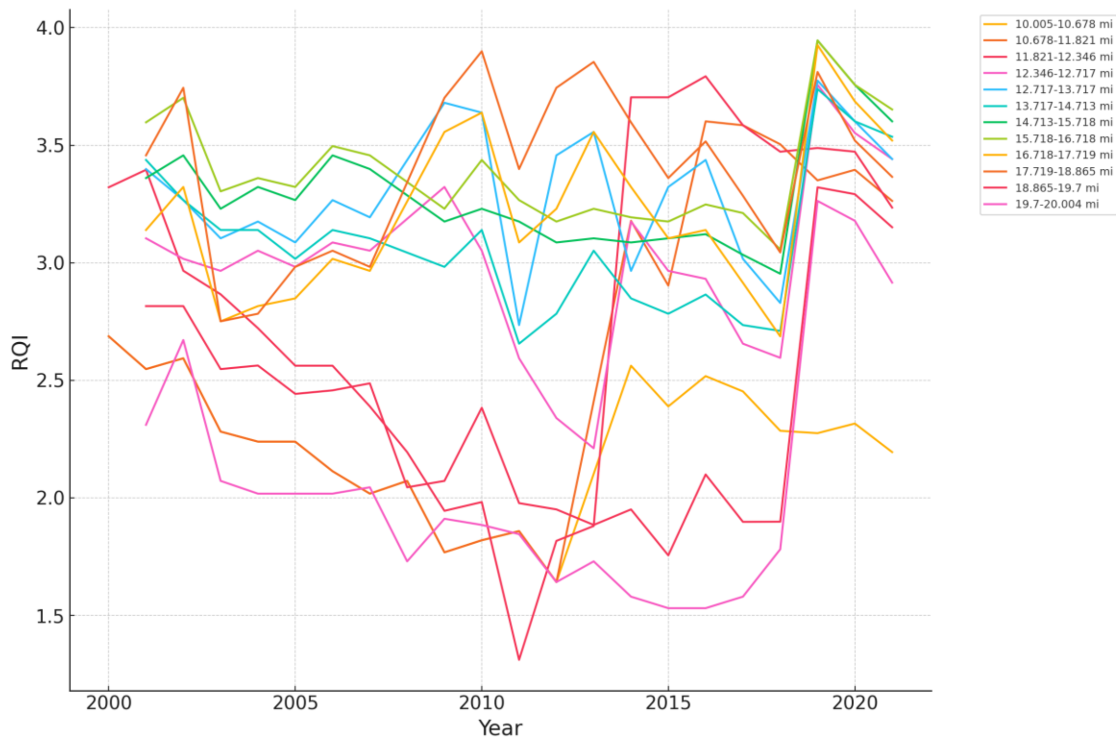

Figure 3.1 RQI measurements for each segment of US 169-BEW.

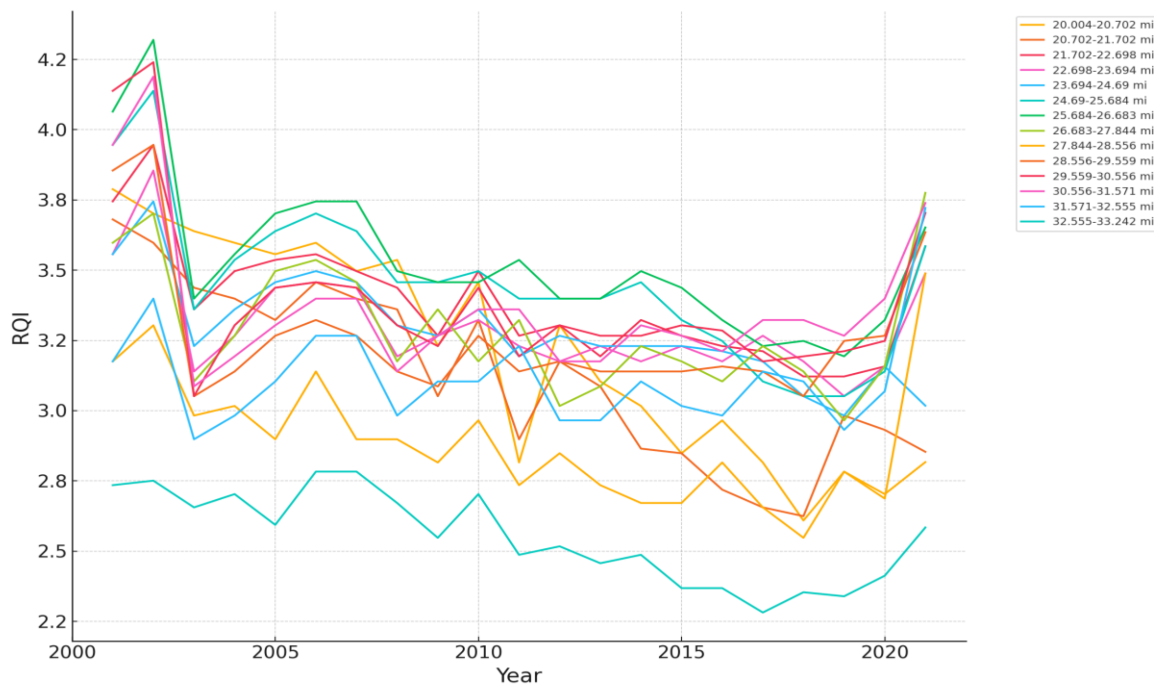

Figure 3.2 RQI measurements for each segment of US 169-WVC.

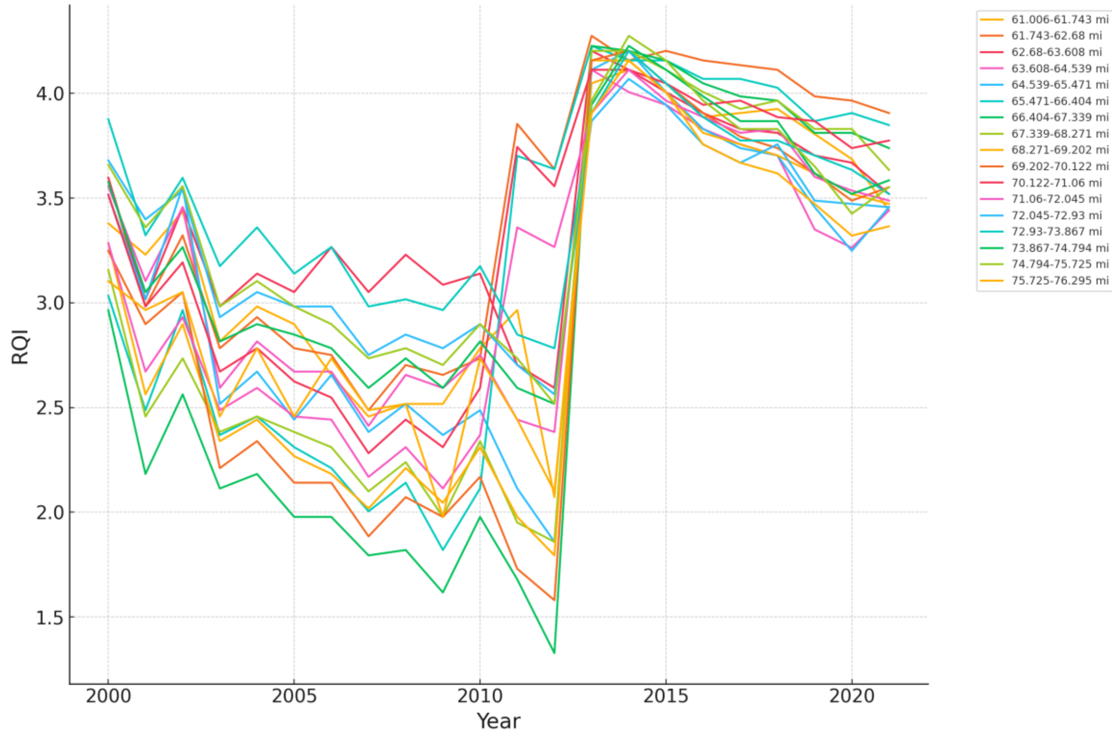

Figure 3.3 RQI measurements for each segment of MN 15.

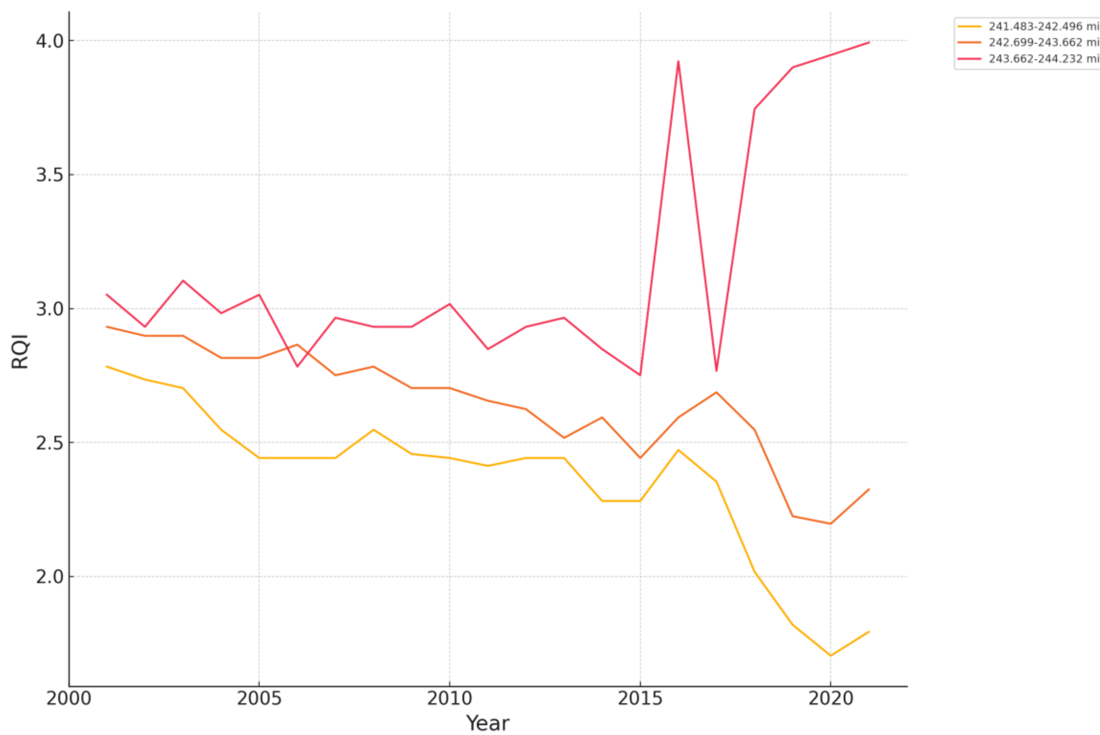

Figure 3.4 RQI measurements for each segment of I 94.

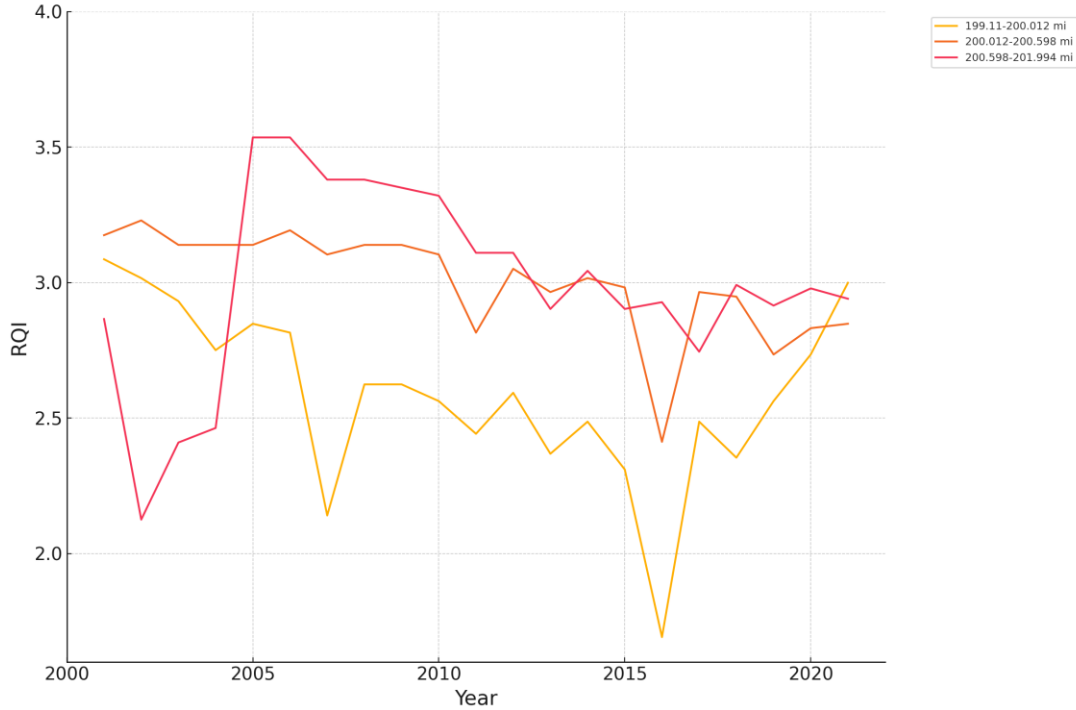

Figure 3.5 RQI measurements for each segment of MN 55.

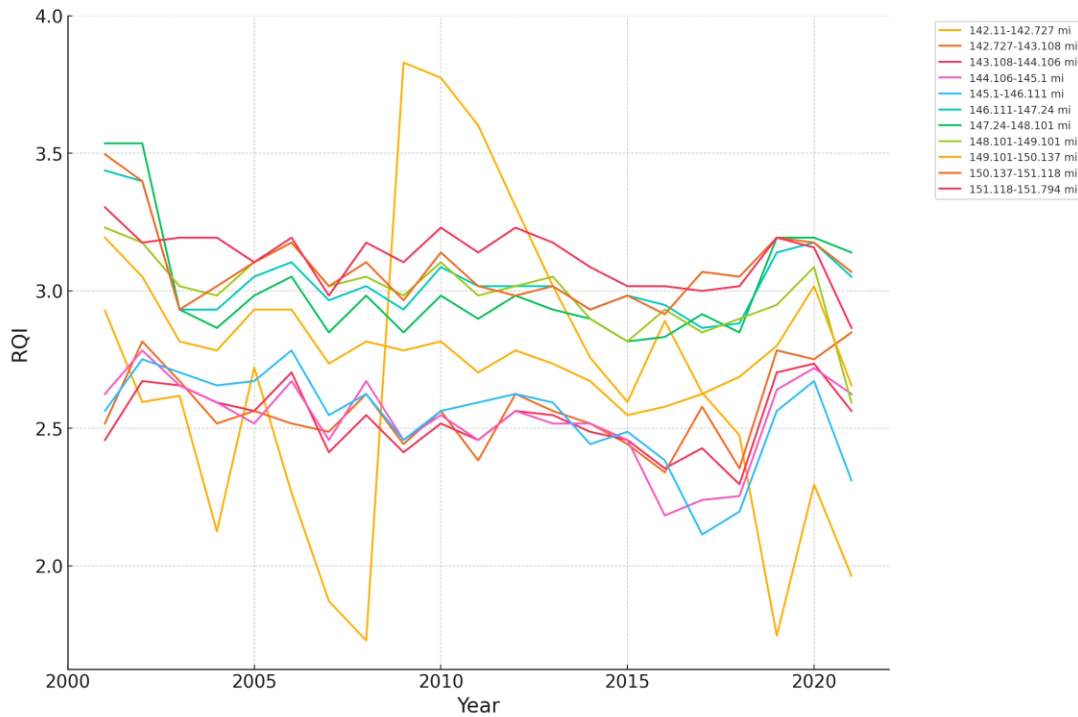

Figure 3.6 RQI measurements for each segment of MN 210.

Figure 3.7 provides a limited analysis: The line average represents the mean RQI for all pavement segments in each year. The line represents the central tendency or the typical condition of the pavements (i.e., RQI) for that year. The shaded band represents plus/minus one standard deviation to the mean for that year. The visual data shows the intervention in 2018-19. Similar analyses are given in Figure 3.8 and 3.9 for US 169-WVC and MN 15, respectively. The US 169-WVC plot shows an intervention in 2020-21 and MN 15 one shows a significant RQI improvement in 2013 collection.

Figure 3.7 Average RQI across all segments in US 169-BEW section.

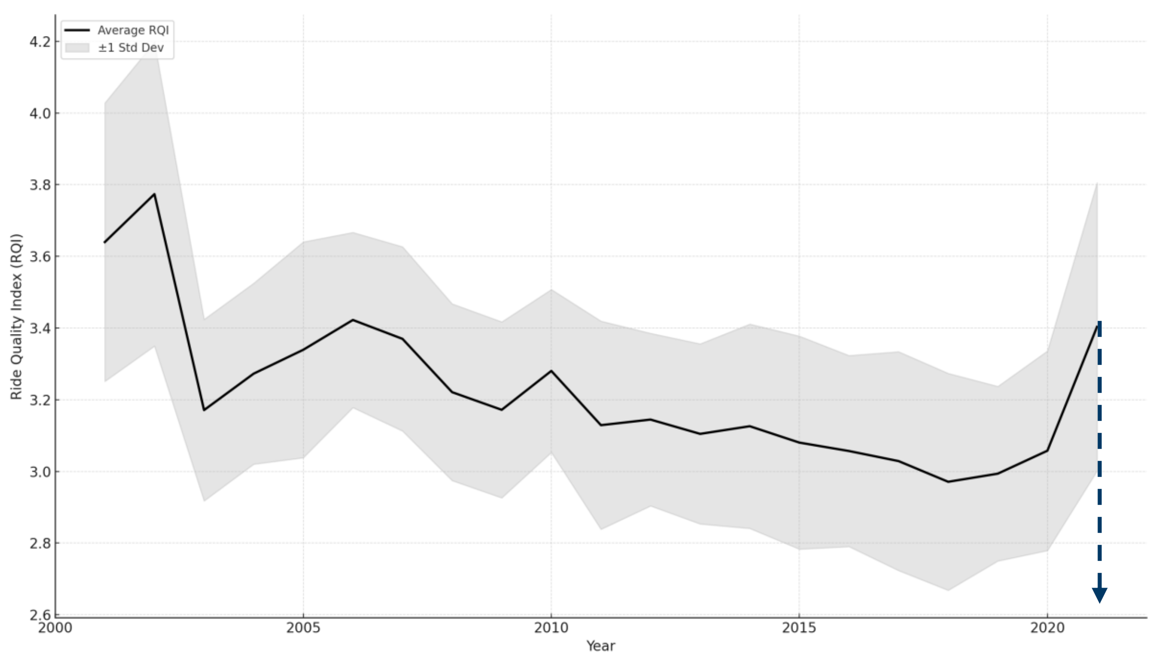

Figure 3.8 Average RQI across all segments in US 169-WVC section.

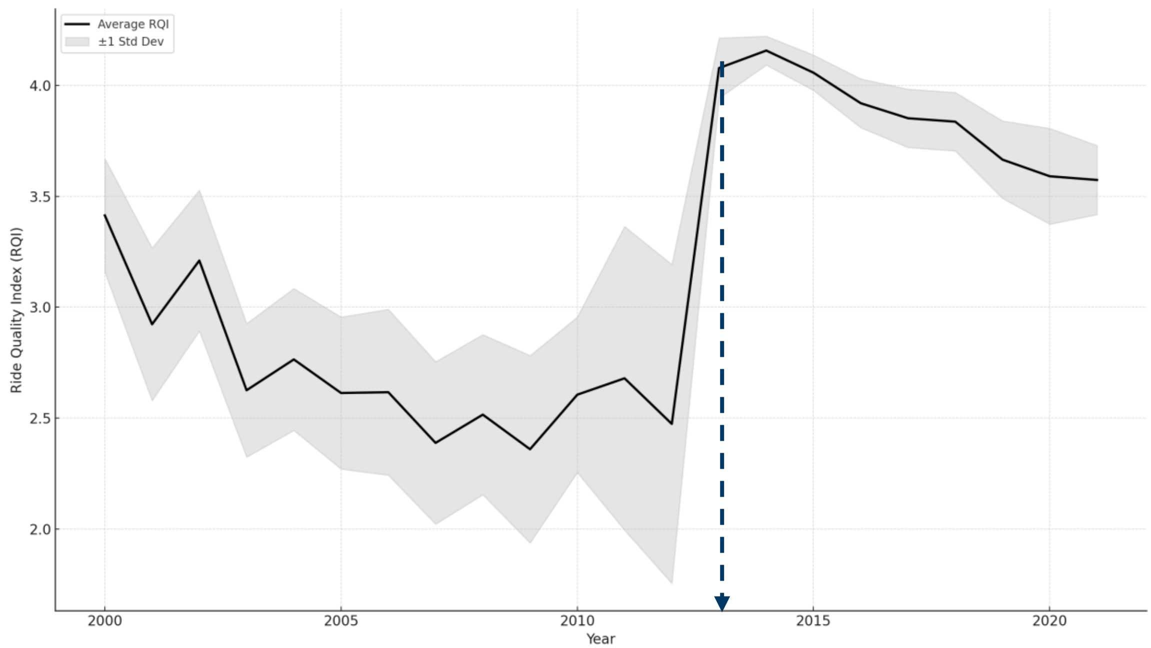

Figure 3.9 Average RQI across all segments in US MN 15 section.

3.2 Surface Rating (SR)

MnDOT quantifies pavement distress using Surface Rating (SR), which measures visible pavement distresses such as cracks, patches, and ruts. Table 3.1 provides the distress types used in SR calculation. A 500-foot segment at the beginning of each mile and section is assessed, representing a 10% sample. For undivided roadways, only the outside lane in the direction of increasing mile markers (typically northbound or eastbound) is evaluated. On divided highways, the outside lanes in both directions are rated. Within each 500-foot sample, the proportion of each distress type is calculated and then multiplied by a corresponding weighting factor to produce a weighted percentage. Distresses with greater severity levels or those indicative of significant structural issues—such as alligator cracking or broken panels—are assigned higher weighting factors. SR is an index on a scale of 4.0 (MnDOT, 2018).

Table 3-1. Pavement Distress Types Used in Surface Rating (SR) Calculation (adopted from MnDOT, 2018).

Bituminous Surfaced Pavement	Transverse Cracking Longitudinal Cracking Longitudinal Joint Distress Multiple Cracking Alligator Cracking Rutting Raveling & Weathering Patching
Jointed Concrete Pavement	Transverse Joint Spalling Longitudinal Joint Spalling Faulted Joints Cracked Panels Broken Panels Faulted Panels Overlaid Panels Patched Panels D-cracked Panels
Continuously Reinforced Concrete Pavement	Patch Deterioration Localized Stress D-Cracking Transverse Cracking

The analysis using SR is limited to US 169-BEW and US 169-WVC sections due to data availability. SRs from the year 2000 onwards are plotted in Figures 3.10 and 3.11. The segment average for US 169-BEW and US 169-WVC in Figures 3.12 and 3.13, respectively. The line represents the typical SR for that particular section by averaging the segments within the section. The shaded band represents plus/minus one standard deviation to the mean. The data is fairly in agreement with the RQI results as they peak in 2019 and 2021 for US 169-BEW and US 169-WVC, respectively. It is worth noting that both SR plots show a spike or two valleys before the peak which is assumed to be the major intervention.

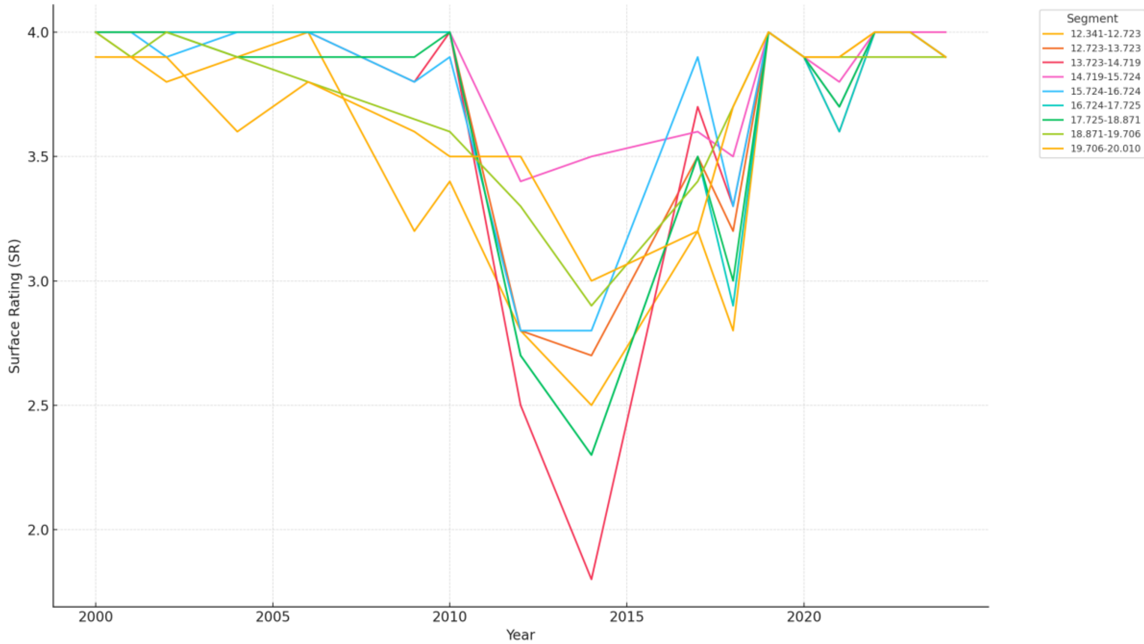

Figure 3.10 SR measurements for each segment of US 169-BEW.

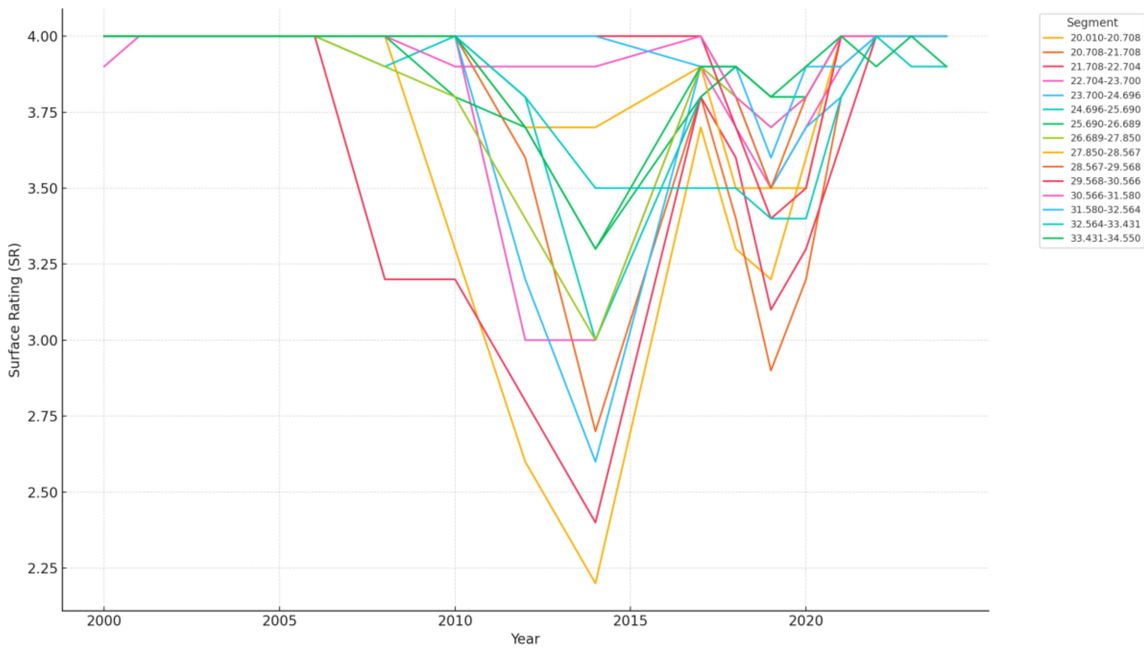

Figure 3.11 SR measurements for each segment of US 169-WVC.

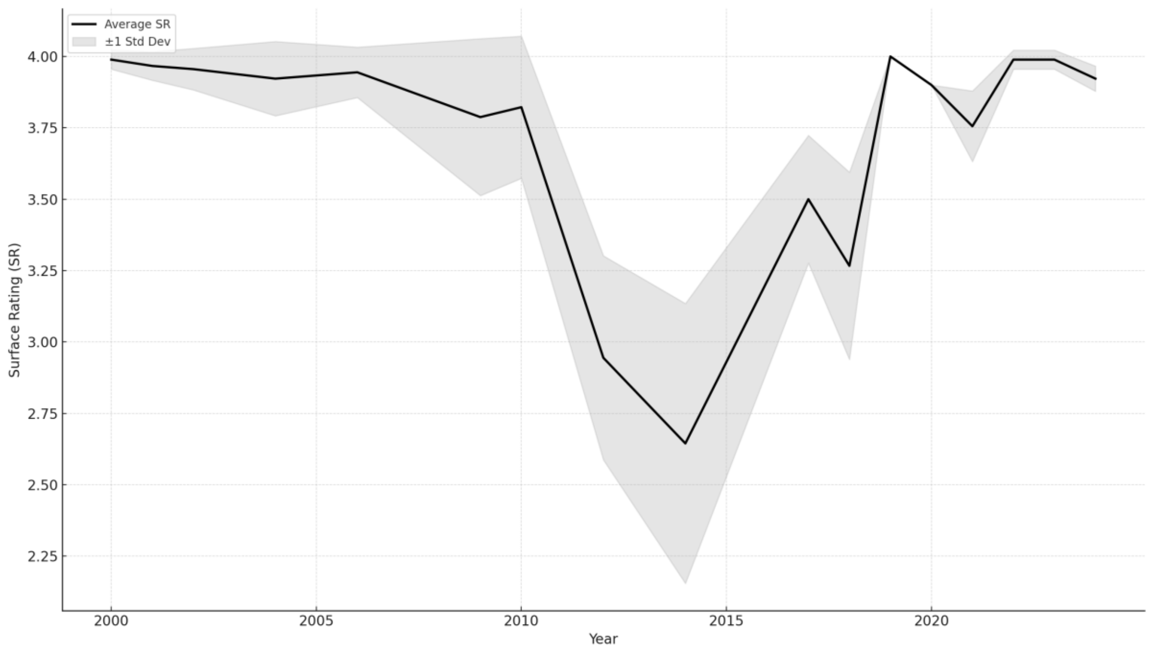

Figure 3.12 Average SR across all segments in US 169-BEW section.

Figure 3.13 Average SR across all segments in US 169-WVC section.

3.3 Pavement Images from PMS

Some of these observations from RQI analysis are confirmed with Pathweb images collected via the MnDOT Pavement Management System (PMS), which include collection in years 2019, 2020, 2021, and 2022. US 169-BEW: seems overlaid in or just before 2019 and another surface treatment in 2022. Moreover, US 169-WVC images show original concrete pavement overlaid in 2021 (Figure 3.14).

Figure 3.14 Asphalt overlay of US 169-WVC.

ASR manifests itself as map cracking on the surface and initially it is in the form of fine cracking. The process requires moisture; therefore, it is often concentrated around the joints, possibly co-existing with freeze-thaw cracking. The Pathweb image resolution is not sufficient to identify fine cracking (Figure 3.15). MnDOT collects D-cracking (Figure 3.16) and localized distress and incorporates it to its SR. Therefore, SR might be a better ASR indicator, hence, can be used to determine effective strategies.

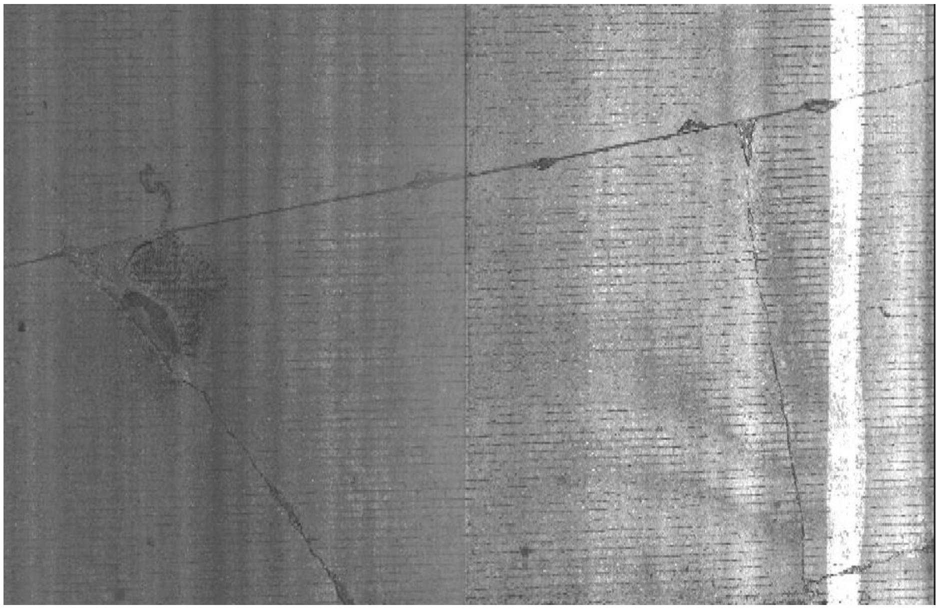

Figure 3.15 Pathweb image from US 169-WVC (Mile post 20.505).

Figure 3.16 D-cracking (MnDOT, 2011).

Chapter 4: Site Visits for Pavement Surface Evaluation

This chapter presents findings from project site visits conducted to assess the performance of various maintenance strategies. The following pavement sections were examined to qualitatively evaluate their surface conditions:

- US 169 from Blue Earth to Winnebago
- US 169 from Winnebago to Vernon Center
- MN 15 from New Ulm to Winthrop
- MN 55 near Mendota Heights/MSP
- MN 210 near Aitkin

As reported in the previous task reports, US 169 and MN15 sections have been overlaid with asphalt; MN55 and MN210 sections have been patched (i.e., partial-depth or full-depth repair), mostly at transverse joints. The I-94 (near St. Paul) section was not included in site visits due to practical challenges (i.e., difficult to access due to heavy traffic).

4.1 US 169 from Blue Earth to Winnebago

This site includes about a 9-mile stretch on US 169 starting from Blue Earth, MN to Winnebago, MN as shown in Figure 4.1. The Construction Project Log in MnDOT's Roadway Data (2025) shows the original 7.5-in concrete pavement constructed in 1991. The log data does not show an entry after 1994, however, it is known that a bitumionus overlay was constructed around 2019.

The reflective cracking on the transverse joints of the underlying concrete pavement are prominent (Figure 4.2). These reflective cracks often extend to the shoulder edge. Some low severity cracking on wheelpath started to develop (Figure 4.2). There is also cracking on the centerline (Figure 4.3) some probably reflecting from the longitudinal concrete pavement joint underneath and some due to separation of the seams between the bituminous lanes. Furthermore, longitudinal reflective cracking on the shoulder along the edges of the original pavement is present (Figure 4.4). Randomly oriented transverse cracking also exists in small number of locations (Figure 4.5). In one of these locations, Figure 4.6, the cracking is in advanced stage. This might be associated with a problem related to the underlying concrete. Overall, this section is in good shape.

Figure 4.1 US 169 from Blue Earth to Winnebago (created using Google Maps).

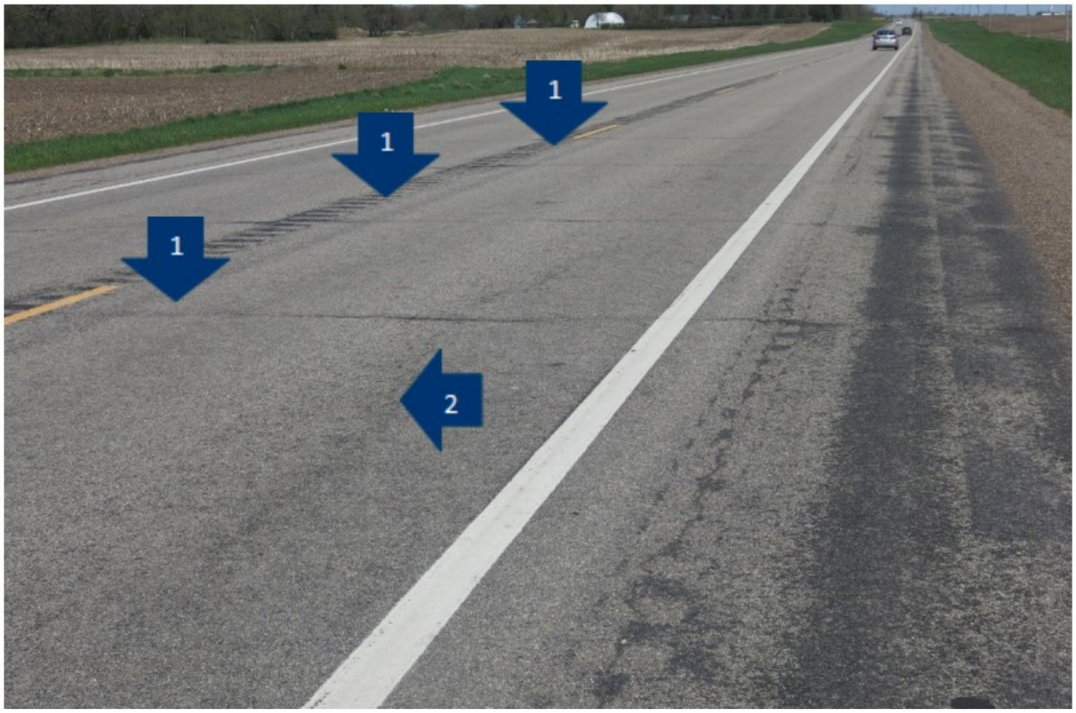

Figure 4.2 Reflective cracking (1) and wheelpath cracking (2).

Figure 4.3 Reflective cracking on the centerline.

Figure 4.4 Longitudinal cracking on shoulder along the original pavement edge.

Figure 4.5 Randomly oriented transverse cracking.

Figure 4.6 Advanced cracking at transverse joint of the original concrete layer.

4.2 US 169 from Winnebago to Vernon Center

This site covers about a 14-mile stretch on US 169 starting from Winnebago, MN to Vernon Center, MN as shown in Figure 4.7. The Construction Project Log in MnDOT's Roadway Data indicates 8-in concrete pavement constructed in 1992. Similar to the previous site the log data do not show construction, however it is known that a bituminous layer was constructed over the concrete pavement in 2021.

This stretch of US 169 was overlaid a few years after the previous project site. Similar observations are valid. The asphalt mix for this site seem different, somewhat rough (Figure 4.8). Reflective transverse cracking (Figures 4.9 and 10) is prominent and at locations seemed wider than the previous project site. In general, these transverse cracks do not extend to the shoulder, however, arrested by the longitudinal cracking on shoulder along the original pavement edge (Figure 4.11). No centerline cracking is observed in this section. After three years of service the surface is in good condition.

Figure 4.7 US 169 from Winnebago to Vernon Center (created using Google Maps).

Figure 4.8 Asphalt pavement surface.

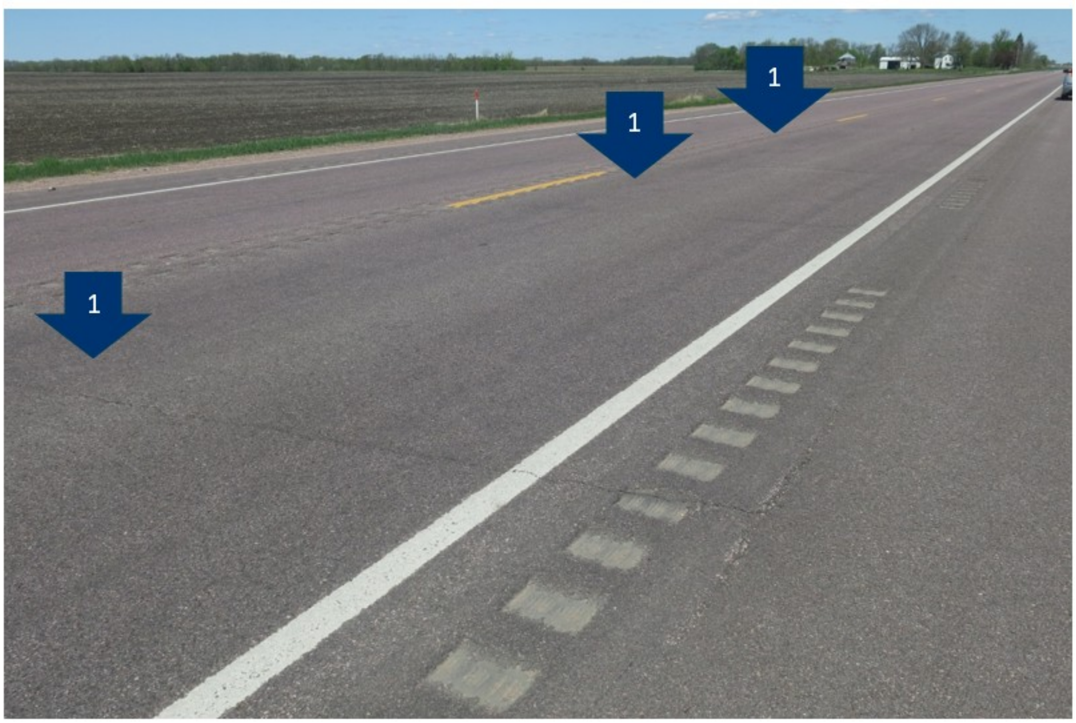

Figure 4.9 Reflective cracking over transverse joints of the underlying concrete pavement.

Figure 4.10 Transverse reflective cracking.

Figure 4.11 Longitudinal cracking along the original pavement edge.

4.3 MN 15 from New Ulm to Winthrop

This site covers about 15 miles along MN 15, starting at MN 14 junction near New Ulm, MN and ending before MN 19 near Winthrop, MN as shown in Figure 4.12. The Construction Project Log in MnDOT's Roadway Data shows the original 7.5-in concrete pavement that was constructed in 1985 and 1986. A bituminous overlay construction in 2012 is logged in the database. This well aligns well with the finding in the previous task delivery where a significant RQI improvement is seen in 2013.

In this site, the observations are similar to the previous two sites, however, the cracking are in an advanced stage comparatively. The overlay is older than the previous two sites. Transverse reflecting cracks extend to the shoulder (Figure 4.13). The longitudinal cracking is prominent (Figure 4.14): the cracks are severe, and material loss is seen frequently (Figure 4.15). There are also a few sites that show advanced deterioration other than cracking (Figure 4.16). Crack sealing has been observed on this site (Figure 14.17)

Figure 4.12 MN 15 from New Ulm to Winthrop (created using Google Maps).

Figure 4.13 Reflective transverse cracking.

Figure 4.14 Longitudinal cracking on the centerline.

Figure 4.15 Material loss in cracks.

Figure 4.16 Deteriorated pavement surface.

Figure 4.17 Sealed longitudinal cracks.

4.4 MN 210 from Deerwood to Aitkin

This project site covers approximately 9-mile stretch on MN 210 starting near Deerwood, MN and ending near Aitkin, MN as shown in Figure 4.18. In the Construction Project Log in MnDOT's Roadway Data the original 8-in concrete pavement was built in 1991. This site underwent partial- and full-depth repairs of transverse joints and slabs (Figure 4.19), with the work completed within the past two years. Diamond grinding was done (Figure 4.20) after the repair work, and the joints are sealed. Transverse tining on the original pavement surface can be observed at some locations (Figure 4.20). The site visit in this project was to evaluate the initial condition and monitor how the condition progresses over the years. Spalling and cracking were observed at transverse (Figure 4.21) and longitudinal joints (Figure 4.22), with severity levels ranging from low to high. Sporadic deterioration, potentially related to ASR cracking, was also observed (Figure 4.23).

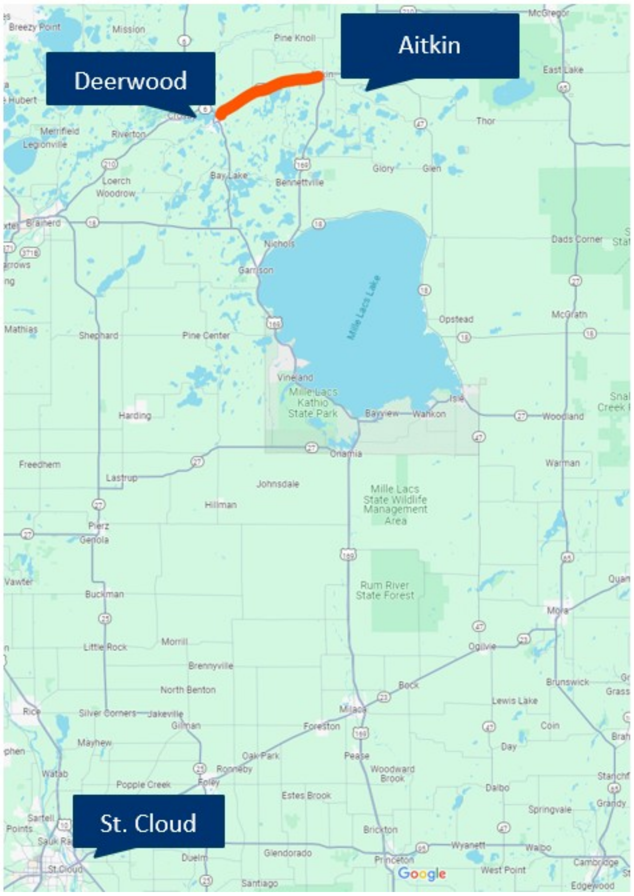

Figure 4.18 MN 210 from Deerwood to Aitkin (created using Google Maps).

Figure 4.19 Partial- and full-depth repair.

Figure 4.20 Diamond grinding.

Figure 4.21 Spalling at transverse joint.

Figure 4.22 Spalling at longitudinal joint.

Figure 4.23 Cracking in the vicinity of joints.

4.5 MN 55 near Mendota Heights/MSP

This project is about 3-mile stretch of MN 55 near Mendota Heights, MN. The section is shown in Figure 4.24. Due to safety concerns (i.e., heavy traffic flowing) the evaluation of this site was limited. The pavement was recently undergone for full-depth replacement at the transverse joints, then the surface was diamond ground (Figures 4.25 and 4.26).

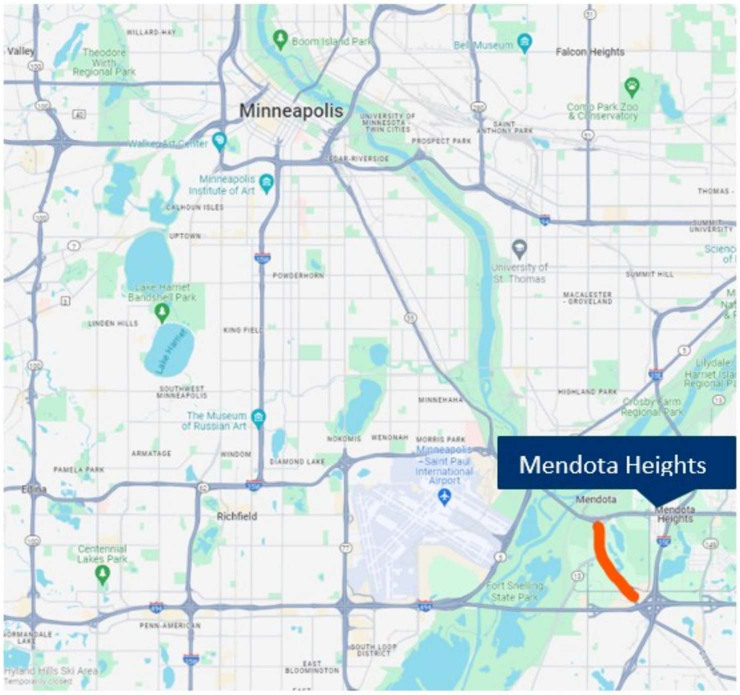

Figure 4.24 MN 55 near Mendota Heights/MSP (created using Google Maps).

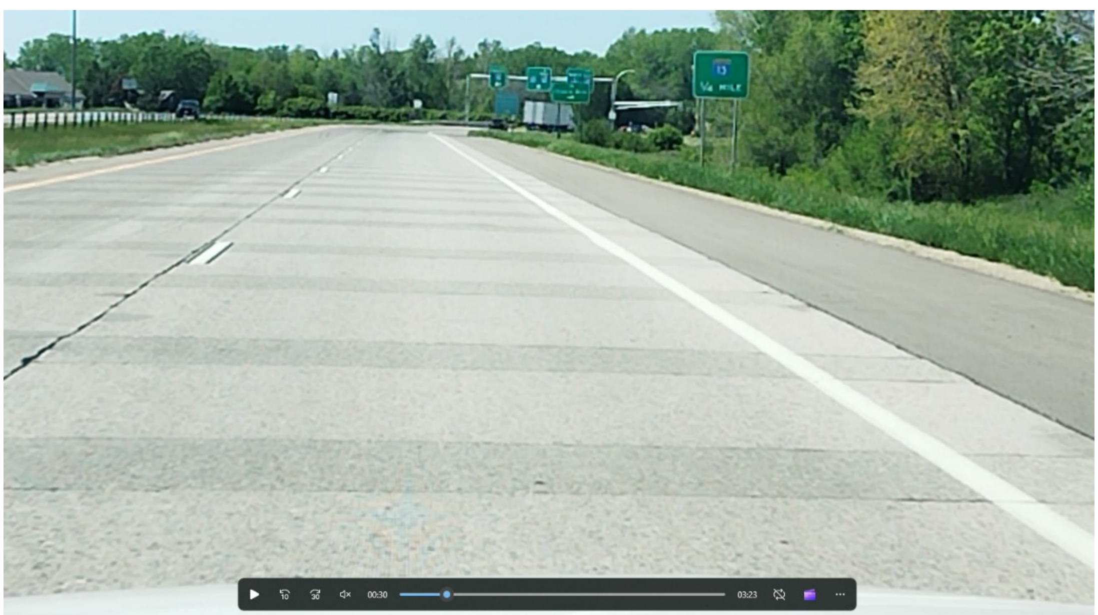

Figure 4.25 Full-depth repair of concrete pavement

Figure 4.26 Diamond ground pavement surface.

Chapter 5: Field Investigation of Unrehabilitated ASR-Affected Pavement

This chapter reports the findings from ultrasonic tomography tests conducted on pavement surfaces along US 169, north of Vernon Center, MN (Figure 5.1). The pavement sections investigated have not undergone treatment. Three specific locations were selected for analysis, as indicated in Figure 5.1. The first two segments exhibited significant surface distress around the joints, extending to the mid-slab, while the third site showed some joint distress but no visible mid-slab cracking. Representative images are provided in Figures 5.2–5.

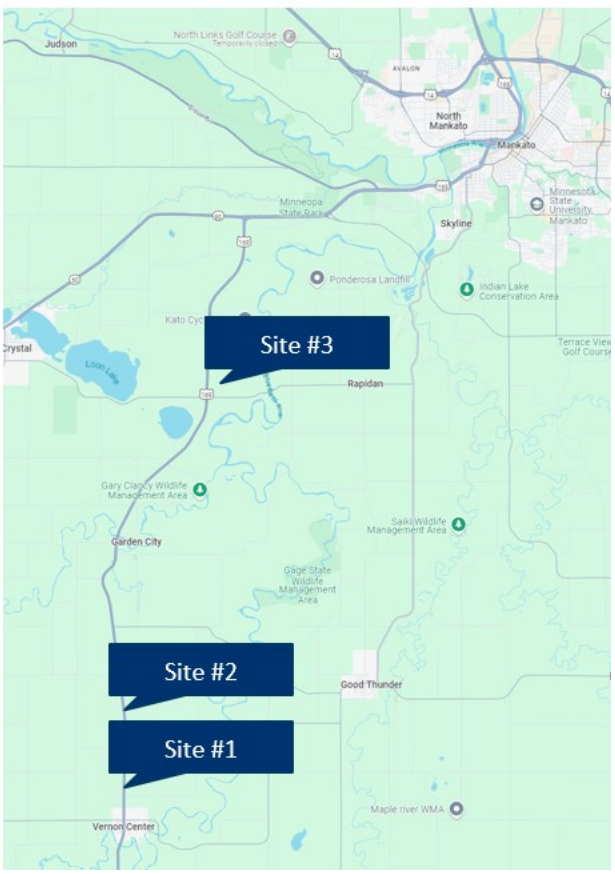

Figure 5.1 Field test sites on US 169 (created using Google Maps).

Figure 5.2 Surface distress (Site #1).

Figure 5.3 Surface distress (Site #2).

Figure 5.4 Surface distress (Site #2).

Figure 5.5 Surface distress (Site #3).

5.1 Findings from Ultrasonic Tomography Testing

Ultrasonic tomography technique, also known as Ultrasonic Shear-Wave Tomography or Ultra Sonic Pulse Echo, is a non-destructive testing method used to evaluate subsurface concrete condition. Ultrasonic tomography can be used for the following applications (Popovics et al., 2017; Tran and Roesler, 2020; FHWA, 2024):

- Concrete thickness estimation
- Reinforcement depth location
- Detection of delamination or de-bonding
- Joint diagnostics (e.g., detection of concrete deterioration, dowel position, spalling, etc. at PCC joints)
- Flaw detection (e.g., defect, honeycombing, poor consolidation detection, mud balls)
- Joint activation

In this study, the ultrasonic tomography was utilized to assess the subsurface condition of concrete. An ACS A1040 model testing device was used. Alkali-silica reaction (ASR) is anticipated to manifest as a 3D cracking network within the concrete. Testing was conducted at sites with visible surface cracking (Figure 5.6) and at locations with no visible surface cracking (Figure 5.7). The working hypothesis is that ASR associated cracking may be present beneath the surface even if there are no visible signs at the surface. Measurement points were selected approximately one foot away from the joints and at mid-slab locations (Figure 5.8). Field observations indicate that cracking at the joints is severe. This is expected, as joints retain moisture longer than mid-slab sections, increasing moisture-related distress such ass freeze-thaw crackin and ASR related deterioration.

Figure 5.6 Pavement subsurface condition evaluation using ultrasonic tomography.

Figure 5.7 Pavement subsurface condition evaluation using ultrasonic tomography.

Figure 5.8 Pavement subsurface condition evaluation using ultrasonic tomography.

In ultrasonic tomography images, color variations indicate changes in the signal as it passes through different layers. In addition to pavement base, the defects such as high-density cracking or delamination would typically appear as a zone as illustrated in Figure 5.9 (Hoegh et al., 2011).

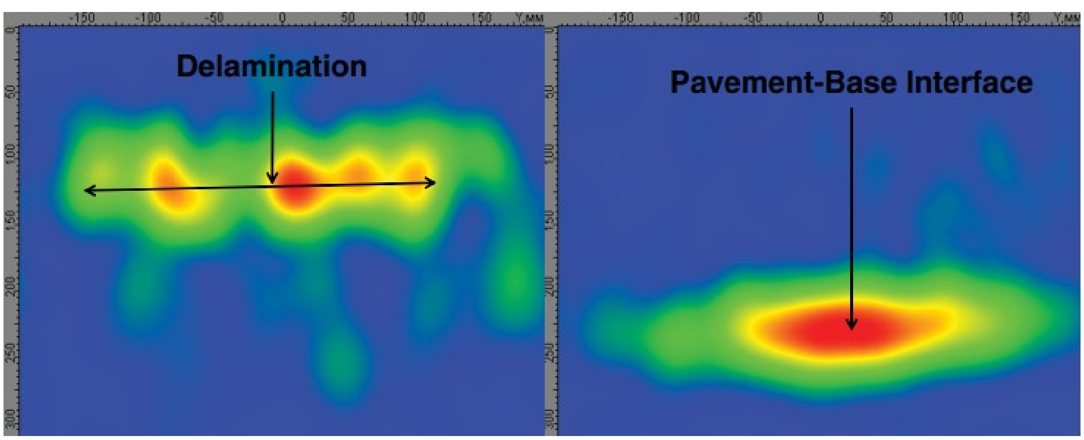

Figure 5.9 Ultrasonic tomography image from that shows delamination at mid-height (Hoegh et. al., 2011).

Representative ultrasonic tomography images from sites are presented in Figures 5.10-12. In these images, the green zone at between 200-250 mm represents the pavement-base interface, indicating the transition from the dense pavement medium. The lighter-colored regions between the surface and the base indicate areas where signals travel through a medium of different density, suggesting potential cracking. Some slabs, particularly from Site #2, produced these images with higher intensity (Figure 5.13). Nonetheless, it is difficult to draw a firm conclusion. Further evaluation, such as physical sampling of the pavement cross-section, is needed to verify the connection between ultrasonic tomography imaging and ASR-associated cracking. Notably, no discernible differences were observed between joint locations and mid-slab areas.

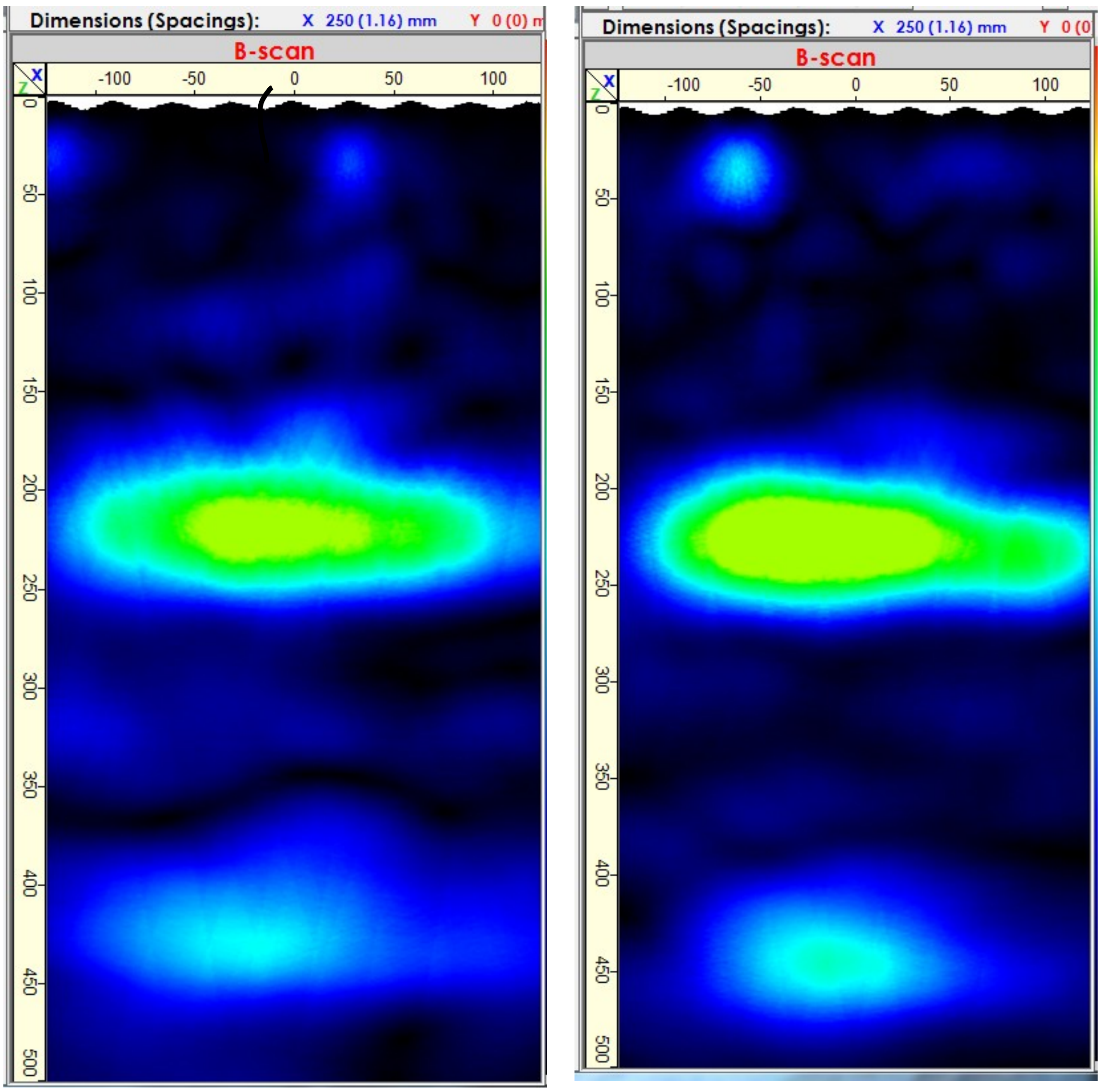

Figure 5.10 Site #1 images taken close to joint (left) and at mid slab (right).

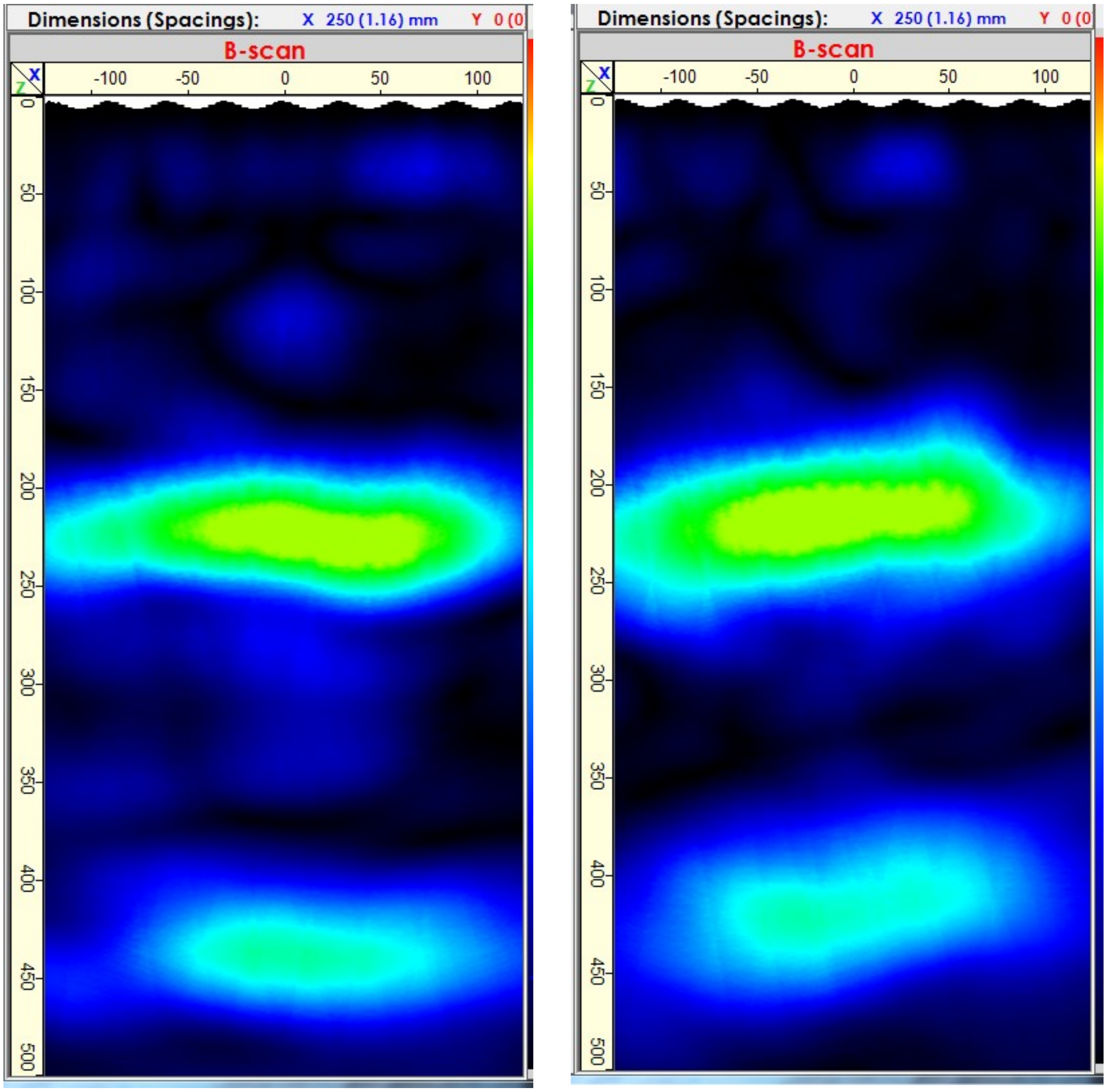

Figure 5.11 Site #2 images taken close to joint (left) and at mid slab (right).

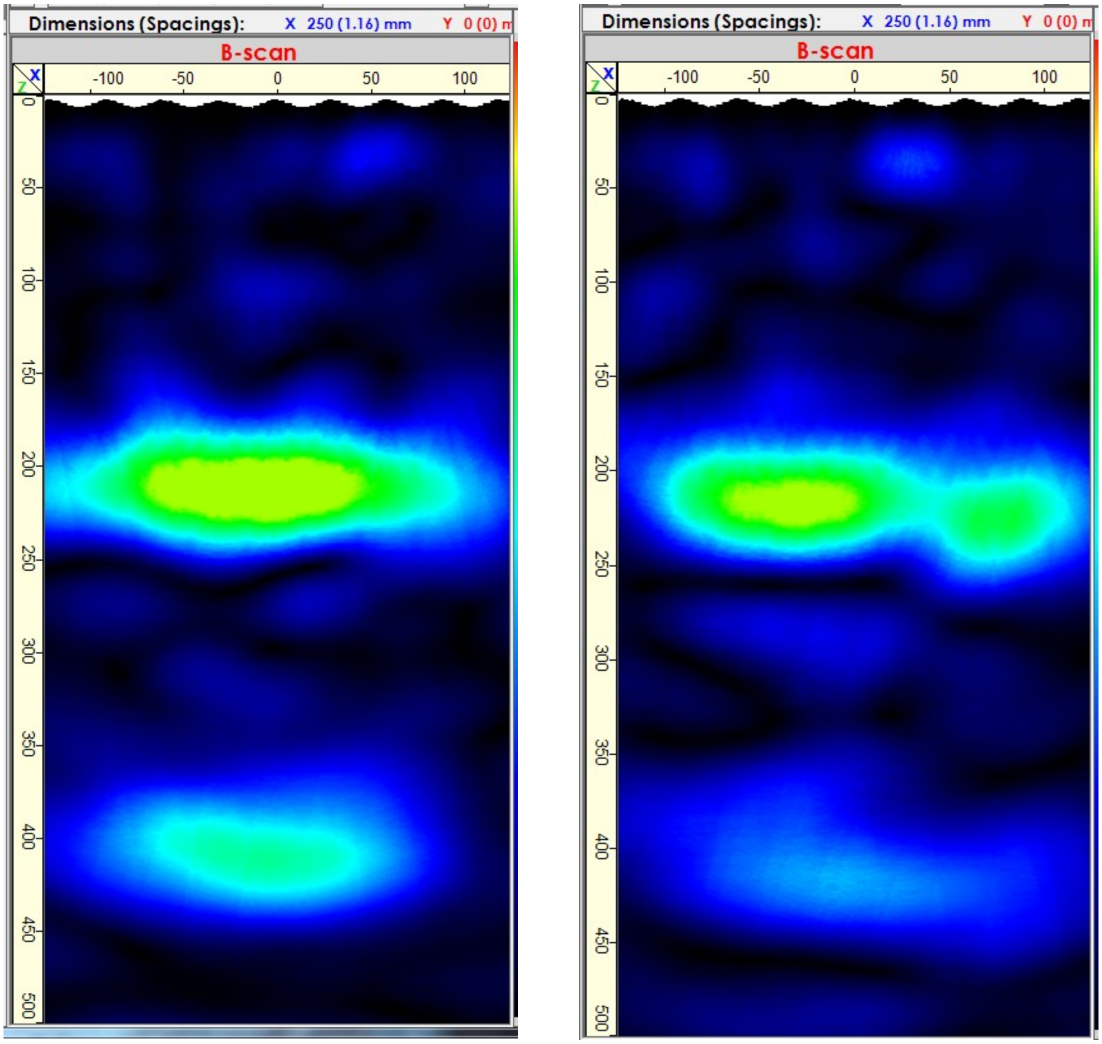

Figure 5.12 Site #3 images taken close to joint (left) and at mid slab (right).

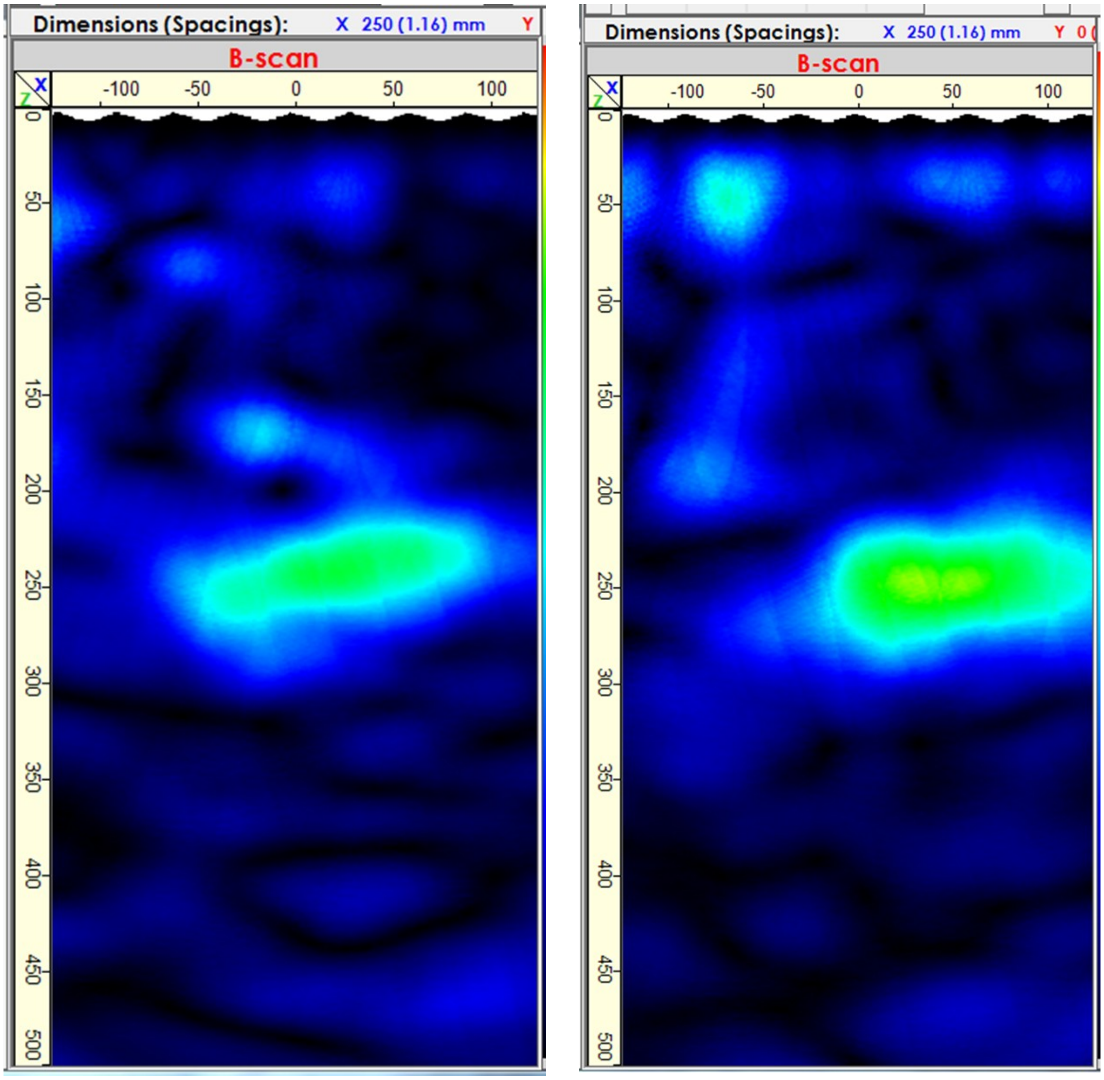

Figure 5.13 Site #2 images pointing to potential cracking.

Chapter 6: Conclusion

This study evaluated the effectiveness of various maintenance and rehabilitation strategies employed by MnDOT to manage alkali-silica reaction (ASR) in concrete pavements. The approach combined literature synthesis, historical performance data (RQI and SR), and field evaluations of selected pavement sections. The pavement sections were chosen in consultation with MnDOT experts and, although they do not represent the entire network of ASR-affected pavements in the state, they are assumed to be reasonably representative in terms of maintenance history. These segments covered two key intervention types—bituminous overlays and partial/full-depth repairs historically employed by MnDOT.

In addition to these evaluations, a focused site study using ultrasonic tomography was conducted to explore the potential of detecting ASR-related distress at early stages. The goal was to assess whether ultrasonic tomography could reveal subsurface cracking before visible signs emerged at the surface. Although the ultrasonic tomography scans identified areas with potential differences in material density, which may suggest cracking, the results were inconclusive. Further physical sampling is needed to validate ultrasonic tomography's ability to detect early-stage ASR in pavement applications.

Quantitative analysis of RQI and SR data demonstrated that bituminous overlays often yield an immediate improvement in surface condition and ride quality. This was particularly evident in the US 169-BEW and MN 15 segments, where post-intervention data showed distinct upward trends in RQI values. However, overlays also exhibited limitations over time, such as reflective cracking and susceptibility to continued ASR activity beneath the surface.

Site visits indicated that bituminous overlays have generally performed well, offering improved ride quality, although reflective cracking—particularly at transverse and longitudinal joints—along with some localized distress, was observed. Partial- and full-depth repairs at joints, especially when combined with diamond grinding, appeared effective in addressing localized damage and enhancing surface smoothness. Notably, the full- and partial-depth repairs recently applied to ASR-affected pavements are currently in good condition and demonstrate encouraging short-term results. However, since these interventions are still in the early stages of their service life, continued monitoring will be necessary to assess their long-term performance and durability.

Chapter 7: Recommendations

To improve the management of ASR-affected concrete pavements and guide future efforts, the following recommendations are offered:

- Monitor current sites long-term: Establish a long-term monitoring program for the study sections. Regular RQI, SR, and visual assessments will help track performance and guide future maintenance decisions.
- Focus on diamond-ground and partial repairs: Give special attention to sites with partial-depth repairs and diamond grinding, as these treatments expose reactive aggregate. Continued observation is needed to determine if ASR-related distress is triggered or accelerated.
- Use ultrasonic tomography and other non-destructive tools for early detection: Investigate an array of diagnostic tools to monitor ASR, particularly near joints. While results in this study were inconclusive, combining these tools with core sampling or other techniques could improve early detection and diagnosis.

Overall, ASR cannot be reversed, but its effects can be managed to extend service life. Pairing pavement condition data with expert evaluation and selective use of diagnostic tools may strengthen ASR management strategies.

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