DEPARTMENT OF TRANSPORTATION

# Materials-Based Methods to Improve Rumble Strip Durability


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16. Abstract (Limit: 250 words)

Centerline rumble strips (CLRS) significantly reduce severe head-on crashes on two lane roads, although installing CLRS in asphalt pavements may accelerate deterioration of the pavement at the longitudinal construction joint. Recent research has suggested chip sealing new rumble strips as a preventive measure; however, chip sealing immediately following installation may not be practical or desirable. Other materials that have a demonstrable impact on centerline joint durability without sacrificing functionality of the rumble strip have been described. This project evaluated the effect of milling CLRS on new asphalt pavements and the efficacy of material treatment methods for improving CLRS durability while maintaining functionality on three full-scale field projects in Wisconsin. Two materials-based treatments, and the combination of the two, were evaluated with and without CLRS. The material treatments evaluated were Void Reducing Asphalt Membrane (VRAM) and Rapid Penetrating Asphalt Emulsion (RPE). Results highlight the importance of constructing a high-quality longitudinal joint to ensure durability as cracking behavior of field cores was primarily controlled by the presence of the joint. Milling CLRS can, however, influence joint performance properties. The use of VRAM or VRAM+RPE effectively reduced water permeability and delayed crack propagation and are therefore recommended to increase reliability when used in conjunction with CLRS. Functionality testing that measured exterior and interior noise and vibration revealed that these treatments did not reduce the ability of the rumble strips to warn vehicles of lane departure and may reduce the exterior noise levels experienced in neighboring areas.

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# Materials-Based Methods to Improve Rumble Strip Durability

# Final Report


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# Executive Summary

The U.S. Department of Transportation Federal Highway Administration considers the installation of centerline rumble strips (CLRS) on two-lane asphalt pavements a “Proven Safety Countermeasure.” Despite safety benefits, transportation engineers have expressed concerns regarding the installation of CLRS, including nuisance noise, accelerated pavement joint deterioration, and the effect of CLRS on maintenance activities such as snow removal. Research is needed to address these concerns so agencies can leverage the safety benefits of CLRS without compromising pavement durability.

This project evaluated the effect of milling CLRS on new asphalt pavements and the efficacy of material treatment methods for improving CLRS durability while maintaining safety on three full-scale field projects in Wisconsin. Two materials-based treatments, and the combination of the two, were evaluated with and without CLRS. The material treatments evaluated were Void Reducing Asphalt Membrane (VRAM) and Rapid Penetrating Asphalt Emulsion (RPE). Across the three projects, both standard corrugated and sinusoidal CLRS were evaluated. Functionality of the CLRS was measured to ensure the material treatments maintained adequate driver-alerting qualities. Performance testing of the field cores included permeability and cracking performance through the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and the Texas Overlay Test. Extracted binder content, aggregate gradation, and air void content were also determined for each test section.

Results from this study highlighted the foremost importance of constructing a high-quality longitudinal joint to ensure durability of the CLRS. Cracking behavior of field cores was primarily controlled by the presence of the joint and not by the milling of CLRS. Nevertheless, CLRS were shown to negatively impact joint performance parameters. Specifically, CLRS significantly increased the Texas Overlay Test Crack Progression Rate (CPR) on two of the three field projects, indicating reduced fatigue life of the joint. Application of VRAM and VRAM+RPE significantly improved CPR on sections with CLRS, mitigating the risk of accelerated deterioration. Application of the IDEAL-CT test to pavement cores taken over the joint was challenging as the presence of the joint controlled the test response. While CLRS sections did not show clear trends across projects, the presence of VRAM+RPE on sections with and without CLRS increased displacement at peak and reduced post-peak slope, resulting in a more ductile behavior of the joint, and potentially greater joint durability.

Functionality testing that measured exterior and interior noise and vibration revealed that critical interior noise and vibration intervals (difference in noise or vibration when driving on vs. off the CLRS) were maintained for VRAM, RPE, and VRAM+RPE. Exterior noise interval, which is related to nuisance noise to the public, was reduced for all treatment and project combinations except for one. VRAM, RPE, and VRAM+RPE did not reduce the ability of the rumble strips to warn vehicles of lane departure and may reduce the exterior noise levels experienced in the neighboring areas.

Results from this study highlight the importance of constructing a high-quality longitudinal joint to ensure durability as cracking behavior of field cores was primarily controlled by the presence of the joint. Milling CLRS can, however, influence joint performance properties. The use of VRAM or VRAM+RPE effectively reduced water permeability and delayed crack propagation and are therefore

recommended to increase reliability when used in conjunction with CLRS. In support of this recommendation, a one-page best practices guideline was developed to facilitate the dissemination of key findings from this work.

# Chapter 1: Introduction and Motivation for Research

The U.S. Department of Transportation Federal Highway Administration (FHWA) publishes a list of Proven Safety Countermeasures (https://highways.dot.gov/safety/proven-safety-countermeasures) consisting of design features with proven efficacy at increasing safety of local, State and National roadway infrastructure. One countermeasure recommended for implementation by the FHWA for reduction of roadway departure incidents is installation of longitudinal rumble strips on two-lane roads. Crash data presented in NCHRP Report 641 shows that milled Centerline Rumble Strips (CLRS) can provide up to a 91% reduction in injury-producing crashes on urban two-lane roads and up to 50% reduction on rural two-lane roads (Torbic et al., 2009).

Data clearly show transportation agencies are prioritizing the safety benefits of CLRS and implementing them on a growing percentage of highway projects. Survey results compiled by Kansas State University show that use of CLRS increased nearly 400% between 2005 and 2010, with as many as 38 states reporting CLRS use during that time (Rys et al., 2010). More recent Wisconsin Department of Transportation (WisDOT) bid data compiled by the research team for this project shows total miles of two-lane CLRS let between 2019 and 2022 more than doubled.

Notwithstanding proven safety benefits, the research team has identified three major concerns expressed by transportation engineers and the public regarding widespread implementation of CLRS:

- Nuisance external noise, particularly in urban areas, arising from vehicles inadvertently drifting onto the CLRS or when passing other drivers.
- Accelerated pavement deterioration on or near the CLRS as a result of damage incurred during installation and/or localized distresses resulting from the presence of the geometry feature (e.g., moisture damage due to the corrugations holding water).
- Effect of CLRS on maintenance activities such as snow and ice removal.

Therefore, there is a clear research need to address these limitations so that agencies can leverage the safety benefits of rumble strips without compromising pavement durability or disturbing surrounding communities.

# Chapter 2: Literature review

This literature review is intended to elucidate knowledge gaps requiring research to support the use of CLRS as safety tools. Specifically, this review aims to understand gaps in research on the effects of CLRS installation on pavement performance and how such effects may be offset or mitigated. Functionality of CLRS is also considered based on findings of recent NCHRP Project 17-32 research (Torbic et al., 2009).

Noise associated with CLRS can be divided into two categories: internal and external. Internal noise serves to alert the driver of a lane departure by creating a sufficient increase in noise (and vibration) over background. External noise is created as the vehicle tires traverse the rumble strip and produce an elevated noise level over background noise. Nuisance noise (i.e. "noise pollution") is concerned only with external noise. The magnitude of the so-called "On/Off" external noise increment is dependent on many variables, including pavement type and age, vehicle type, vehicle speed, and CLRS geometry, among other factors (Donavan et al., 2024). These concerns have been prevalent enough as to warrant research optimizing CLRS geometry to balance external noise with safety.

While much research on CLRS safety impacts is available, comparatively fewer studies focus on potential pavement deterioration due to CLRS installation. Most available research suggests that accelerated deterioration is a concern because CLRS are most often installed over the longitudinal construction joint, which is a vulnerable area of the pavement cross section, with typically lower density. It has been reported that when installed on pavements with sufficient structural integrity the impacts of CLRS on pavement deterioration are minimal (Torbic et al., 2009). Recent research, however, has proven the existence of micro-cracking near the pavement surface as a result of milling rumble strips; the researchers hypothesize that these micro-cracks may serve to accelerate damage near the rumble strip (Weaver et al., 2023). Another recent study suggests that installation of CLRS can impact water permeability, which may be linked to long term moisture induced distresses (DeCarlo et al., 2023). The impact of surface treatments such as chip seals on CLRS functionality as safety tools is not widely reported, but conflicting statements have been found in the literature (Donavan et al., 2017). Similarly, most of the statements surrounding maintenance activities such as snow and ice removal are either anecdotal or dismissive of a potential problem. It does not appear extensive research has been done on these topics (Watson et al., 2008).

## 2.1 Definitions and Terminology

Terminology describing rumble strips varies widely in the literature and within agency specifications. This research study investigates CLRS milled over an existing longitudinal construction joint in an asphalt pavement. Rumble strips are also often used on shoulders, edge lines, and in the lane of travel as warning devices for various purposes; although some of the findings of this study may be relevant to those applications, the focus of this study is on CLRS milled over a longitudinal construction joint. The literature also shows that hot-rolled and raised rumble strips are available in some areas, but by far the most encountered rumble strips are installed via a milling process. CLRS can be milled any time after the pavement is constructed; the focus of this study is on CLRS milled as part of the initial construction process; that is, CLRS milled within the same season as construction. Rumble strips milled into older pavements or pavements that have received a surface treatment (e.g., chip seal, micro-surfacing, etc.) may exhibit different performance (Himes et al., 2017).

CLRS geometry can be generally divided into two categories: discontinuous and continuous. Discontinuous CLRS are typically partial-cylindrical shaped (viewed in profile) corrugations that are spaced at consistent intervals. In some applications the cylindrical corrugations are paired, and the pairs are equally spaced from one another. Discontinuous rumble strips are most often square or rectangular when viewed from above (plan view). The longitudinal width of each corrugation, which can be considered the chord of a circle, varies among agencies, as does the milled depth. The transverse width of the corrugation also varies among agencies.

Continuous CLRS take the form of a sine wave and are typically called "sinusoidal" CLRS, sometimes also called "mumble strips". Sinusoidal CLRS are described primarily using three terms: wavelength, recession, and peak-to-peak height (or depth). Wavelength refers to the longitudinal measurement between two adjacent peaks or valleys in the sine wave. Recession refers to the difference in height between the pavement surface and the wave peak. Peak-to-peak height refers to the difference in height between the sine wave peak and valley; in non-recessed sinusoidal CLRS, the peak-to-peak height is the maximum depth of the rumble stip. Examples of several CLRS geometries are shown in the Figures 2.1 – 2.3 below, and discussion of agency specification follows in the next section.

For the purposes of this research, use of the term "standard" geometry implies the partial-cylindrical corrugation milled over the longitudinal joint. "Sinusoidal" is used to describe the continuous CLRS geometry milled over the longitudinal joint. It should be assumed that the longitudinal joint is located at approximately the midpoint of the CLRS transverse width for this study.

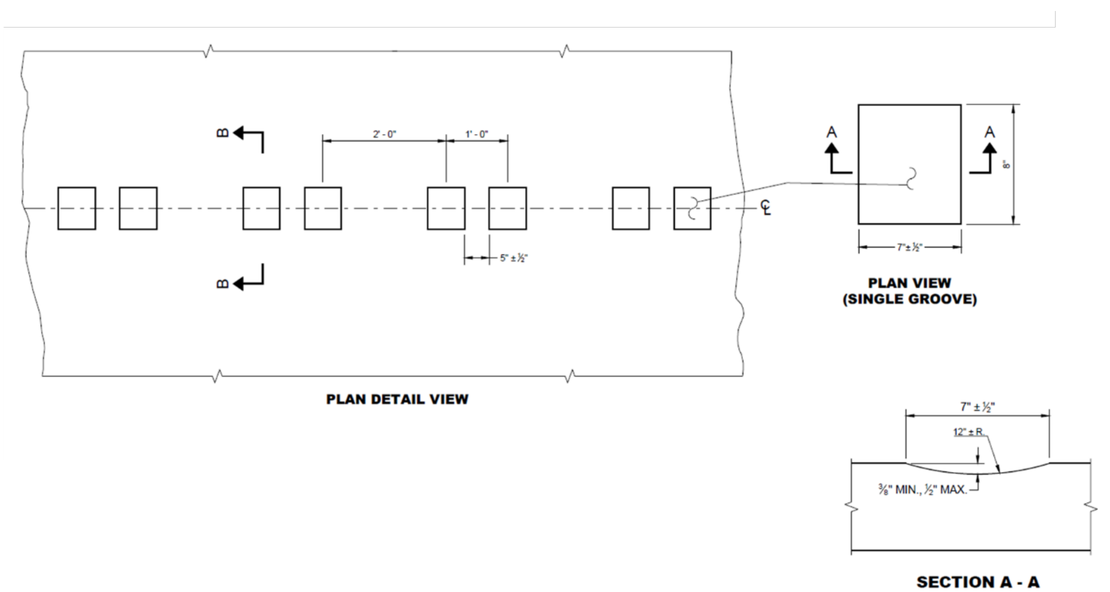



**Figure 2.1: Example of Paired Cylindrical CLRS Geometry (WisDOT).**

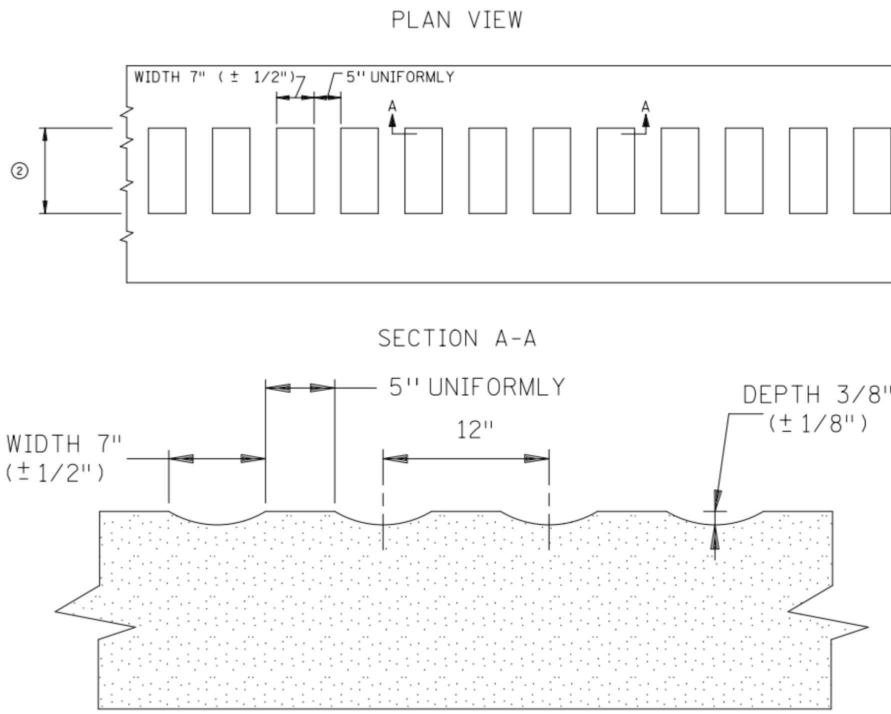
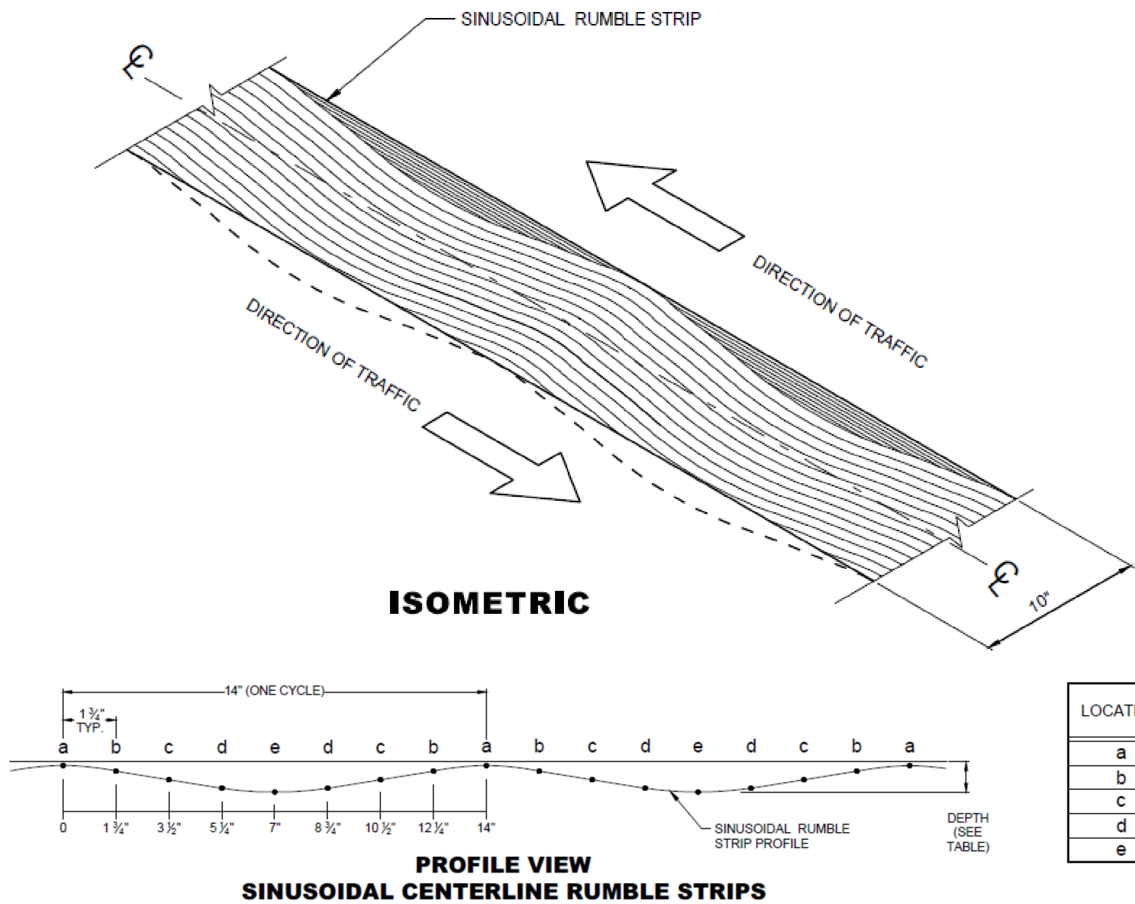



**Figure 2.2: Example of Non-Paired Cylindrical CLRS Geometry (MNDOT).**




| LOCATION | DEPTH (INCHES) |
|---|---|
| a | 1/16" |
| b | 5/32" |
| c | 9/32" |
| d | 7/16" |
| e | 1/2" |

Figure 2.3: Example of 1/16in. Recessed Sinusoidal CLRS Geometry (WisDOT).

## 2.2 NRRA Partner State Design Geometry Summary

At least two comprehensive CLRS synthesis reports have been published detailing state of practice of various highway agencies in terms of project selection, standard geometry detail, and installation guidelines for CLRS. The first was published as NCHRP Synthesis 339, Centerline Rumble Strips, in 2005, which coincided with the widespread implementation of CLRS among state agencies following FHWA guidance. As indicated in that report, use of CLRS was “clearly still in the experimental stage” (Russell & Rys, 2005). Nevertheless, the synthesis provided a foundation for other agencies to follow.

In 2017, the FHWA published report FHWA-HRT-17-026, State of the Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities, contained a summary of CLRS use guidelines and geometries current to that time for all available states. One important knowledge gap identified in that study was that State DOTs “struggle with the optimal design and location of rumble strips given the geometry and context of the roadway” (Himes et al., 2017). Unsurprisingly, standard geometry detail varies between different DOTs.

Given the increasing rate of implementation of CLRS among DOTs, and to understand how NRRA member states are utilizing CLRS, internet searches of each NRRA member DOT website were conducted for this review. As of September 2024, the NRRA pooled fund consists of 12 State DOTs active in the "Flexible Team" of research. Standard details were found for 11 of the 12 NRRA States. Three of the 12 DOTs had standard drawings for both standard and sinusoidal CLRS installations, with one state apparently having only sinusoidal as an option. Section 2.2.1 summarizes the findings of this search, with noteworthy observations identified below:

- Standard CLRS designs can be grouped into two categories: paired and single corrugations. Wisconsin is an example of paired corrugations, where two adjacent (paired) corrugations are spaced 12 in. on center with each pair spaced 24 in. on center. California is an example of single corrugation, with each individual corrugation spaced 12 in. on center. Around half of the NRRA states referenced use single corrugations.
- Although the geometry of the corrugations varied between DOTs, the maximum depth of the milling was approximately ½ in. for nearly all design details, including sinusoidal.
- The transverse width of the corrugations varied considerably, generally between 7 in. and 16 in. centered on the centerline.
- The chord length of standard geometry CLRS varies between 5-7 in. among DOTs, with 7 in. being most common among the reviewed specifications.
- Sinusoidal designs among NRRA states all utilize a 14 in. wavelength (peak to peak measurement), although the recession and mill depths are slightly variable between states.

In terms of designing the work plan for this study, it is apparent that both standard and sinusoidal design geometries should be considered to capture the NRRA member state interests. Milling depth of around ½ in. appears to be a reasonable target for this study and is representative of most member state guidelines. Since standard 6 in. pavement cores will be used to evaluate performance, rumble strip transverse width and chord length is not considered a critical factor in this study, nor is paired vs. single corrugations. Since the field projects associated with this research will be constructed in Wisconsin, the WisDOT design drawing for both standard and sinusoidal CLRS appear to be reasonable choices for the purposes of this project.

## 2.2.1 NRRA Member State Standard CLRS Drawings.

### 2.2.1.1 California DOT

Source: https://dot.ca.gov/-/media/dot-media/programs/design/documents/locked-2022-std-plans-a11y.pdf

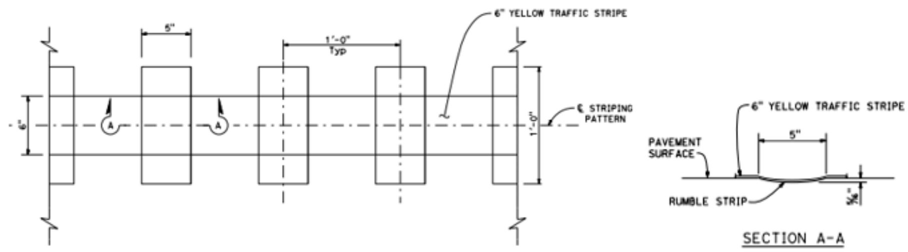
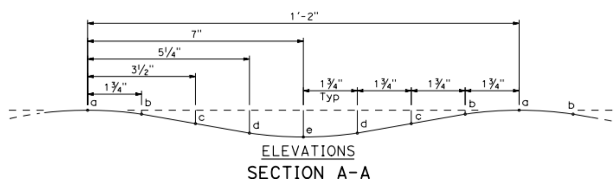



**Figure 2.4: Typical Geometry for Standard CLRS (California).**

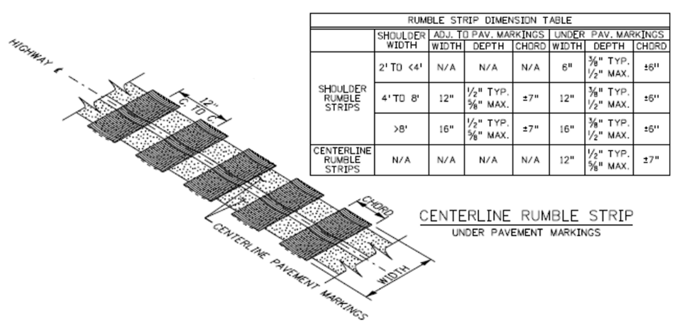



| LOCATION | SHOULDER DEPTH INCHES |
|---|---|
| a | 0 |
| b | 1/16 |
| c | 5/32 |
| d | 9/32 |
| e | 5/16 |

**Figure 2.5: Typical Geometry for Sinusoidal CLRS (California).**

### 2.2.1.2 Idaho DOT

Source: https://apps.itd.idaho.gov/apps/standarddrawings/631-1_0517s.pdf

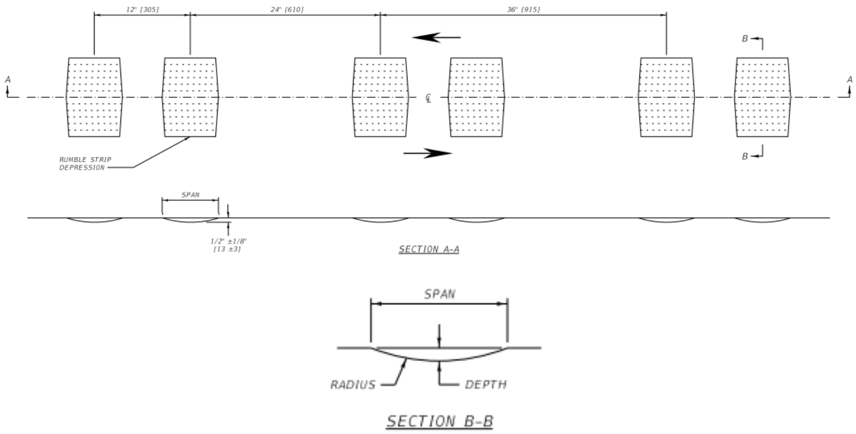



| RUMBLE STRIP DIMENSION TABLE | | | | | | | |
|---|---|---|---|---|---|---|---|
| | SHOULDER WIDTH | ADJ. TO PAV. MARKINGS | | | UNDER PAV. MARKINGS | | |
| | | WIDTH | DEPTH | CHORD | WIDTH | DEPTH | CHORD |
| SHOULDER RUMBLE STRIPS | 2' TO <4' | N/A | N/A | N/A | 6" | 3/8" TYP. 1/2" MAX. | ±6" |
| | 4' TO 8' | 12" | 1/2" TYP. 5/8" MAX. | ±7" | 12" | 3/8" TYP. 1/2" MAX. | ±6" |
| | >8' | 16" | 1/2" TYP. 5/8" MAX. | ±7" | 16" | 3/8" TYP. 1/2" MAX. | ±6" |
| CENTERLINE RUMBLE STRIPS | N/A | N/A | N/A | N/A | 12" | 1/2" TYP. 5/8" MAX. | ±7" |

**Figure 2.6: Typical Geometry for Standard CLRS (Idaho).**

### 2.2.1.3 Montana DOT

Source:
https://www.mdt.mt.gov/other/webdata/external/const/detailed_drawings/2022/Detailed_Drawings_Effective_April_2022.pdf




| | DEPTH | SPAN |
|---|---|---|
| ASPHALT | 1/2" ±1/8" | 6" TO 7" |

**Figure 2.7: Typical Geometry for Standard CLRS (Montana).**

### 2.2.1.4 North Dakota DOT

Source: https://www.dot.nd.gov/sites/www/files/documents/Standard%20Drawings/D-760-04.pdf

| Milling Depths | | |
|---|---|---|
| Location A (in) | Depth | |
| | MIL | in |
| 0 | 62.5 | 1/16 |
| 1 3/4 | 156 | 5/32 |
| 3 1/2 | 281 | 9/32 |
| 5 1/4 | 438 | 7/16 |
| 7 | 500 | 1/2 |
| 8 3/4 | 438 | 7/16 |
| 10 1/2 | 281 | 9/32 |
| 12 1/4 | 156 | 5/32 |
| 14 | 62.5 | 1/16 |

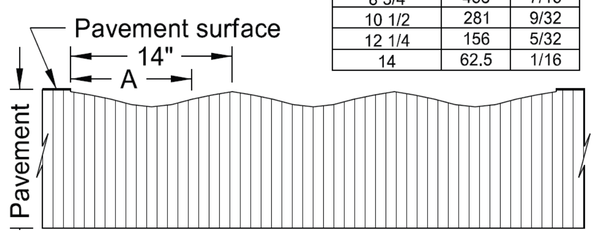



**Figure 2.8: Sinusoidal Rumble Strip Profile (North Dakota).**

### 2.2.1.5 Nebraska DOT

Source: https://dot.nebraska.gov/media/igdlwbs2/special.pdf

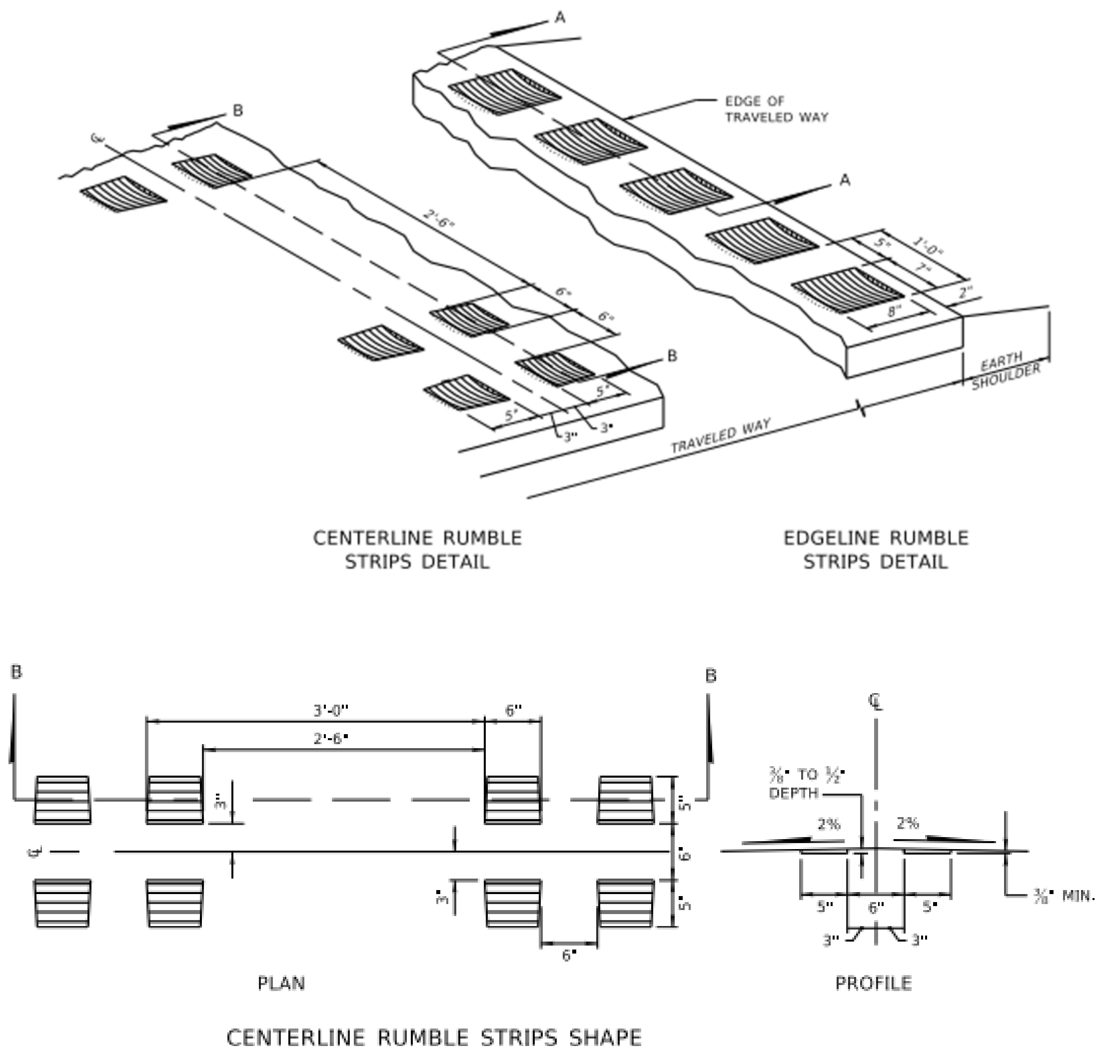



**Figure 2.9: Typical Geometry for Standard CLRS and Edgeline (Nebraska).**

### 2.2.1.6 Minnesota DOT

Source: https://www.dot.state.mn.us/trafficeng/pavement/typicaldetail/rumblestrip.pdf

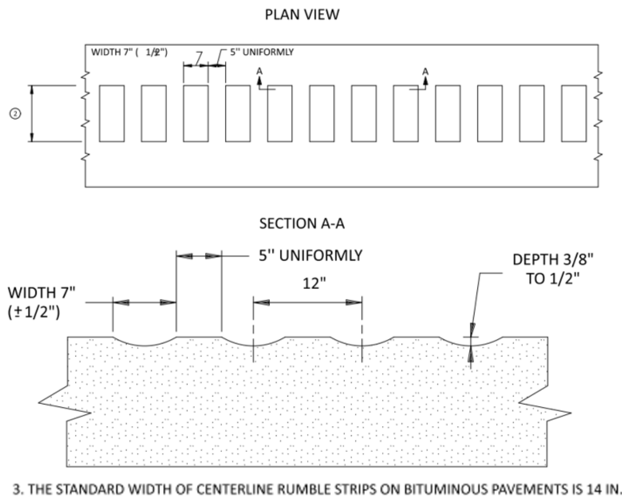



**Figure 2.10: Typical Geometry for Standard CLRS (Minnesota).**

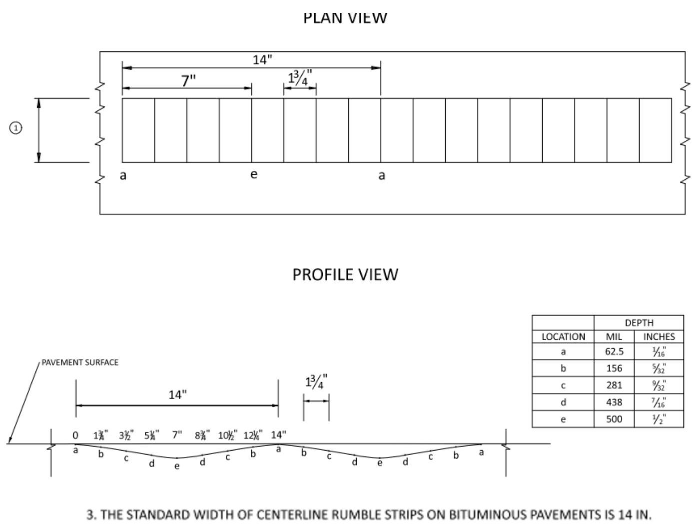



**Figure 2.11: Typical Geometry for Sinusoidal CLRS (Minnesota).**

### 2.2.1.7 Iowa DOT

Source: https://iowadot.gov/design/SRP/IndividualStandards/pv013.pdf

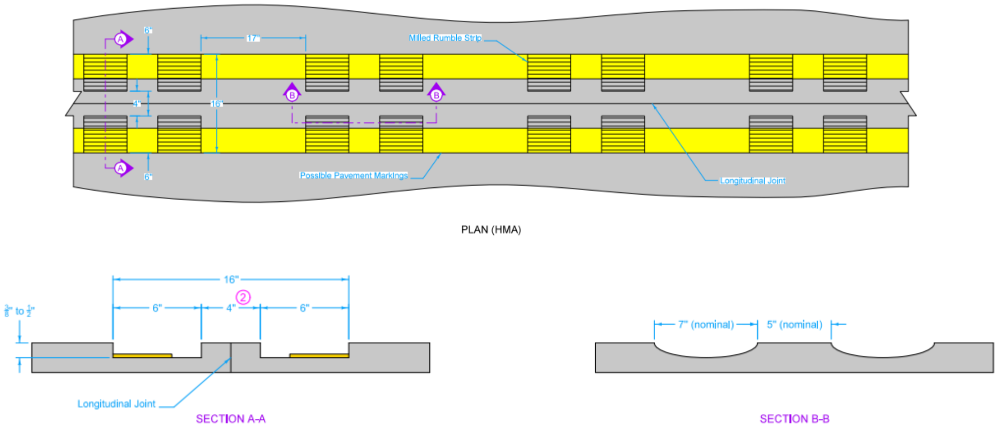



**Figure 2.12: Typical Geometry for Standard CLRS (Iowa).**

### 2.2.1.8 Missouri DOT

Source: https://www.modot.org/sites/default/files/documents/62600_1.pdf

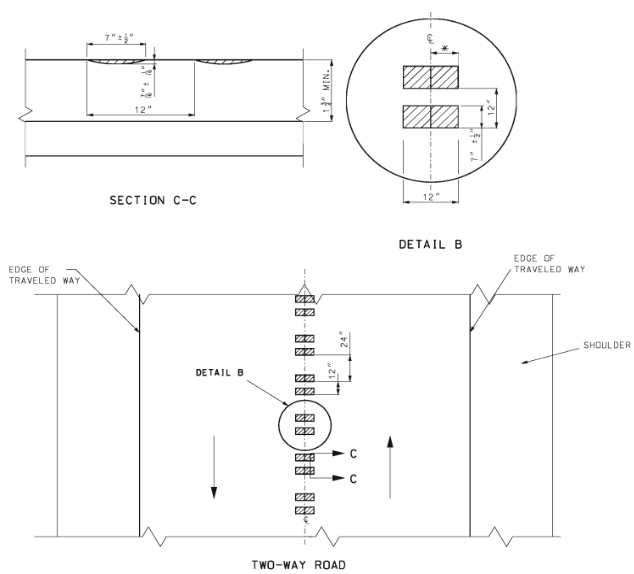



**Figure 2.13: Typical Geometry for Standard CLRS (Missouri).**

## 2.2.1.9 Illinois DOT

Source: https://apps.dot.illinois.gov/eplan/desenv/073120/009-62J32/PLANS/PL-62J32-009.pdf

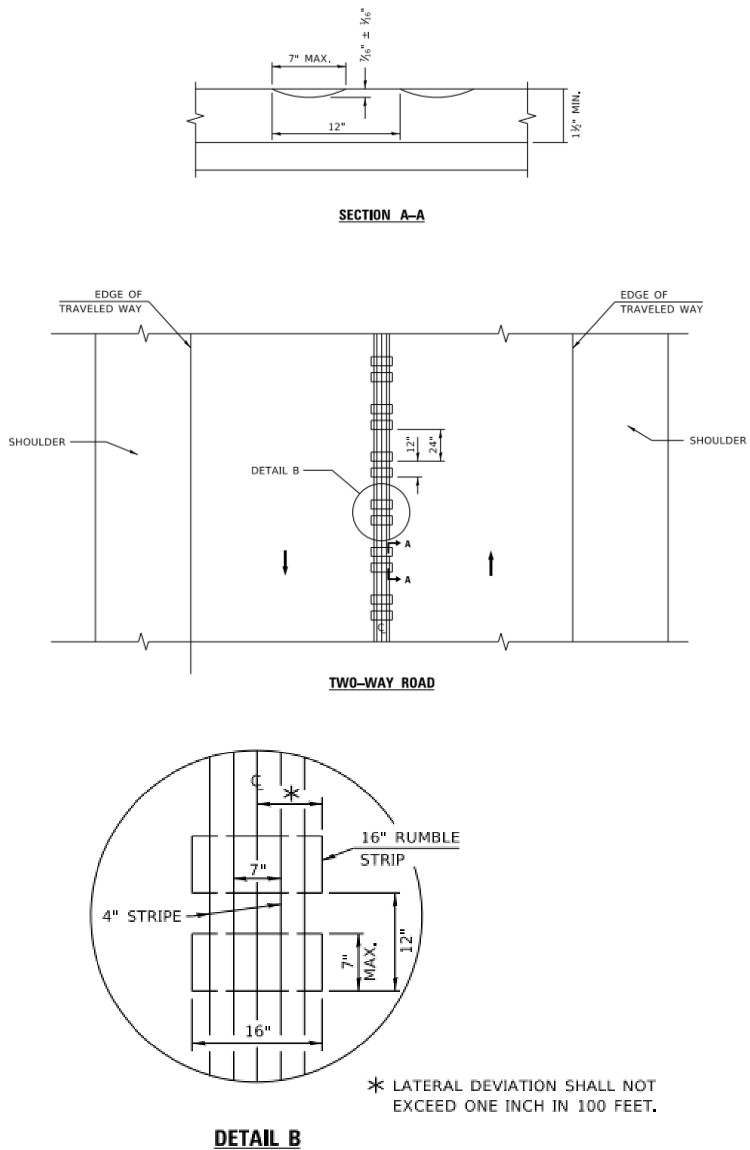



**Figure 2.14: Typical Geometry for Standard CLRS (Illinois).**

### 2.2.1.10 Wisconsin DOT

Source: https://wisconsindot.gov/rdwy/sdd/sd-13a11.pdf

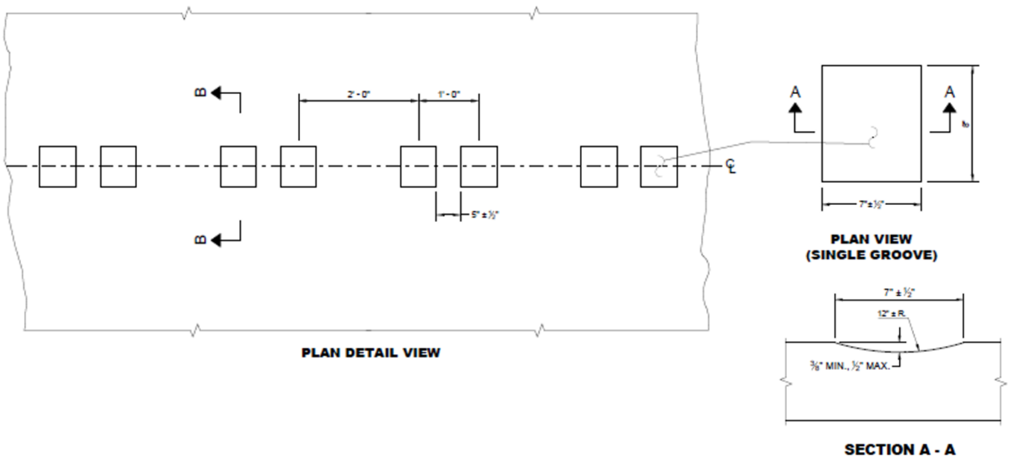
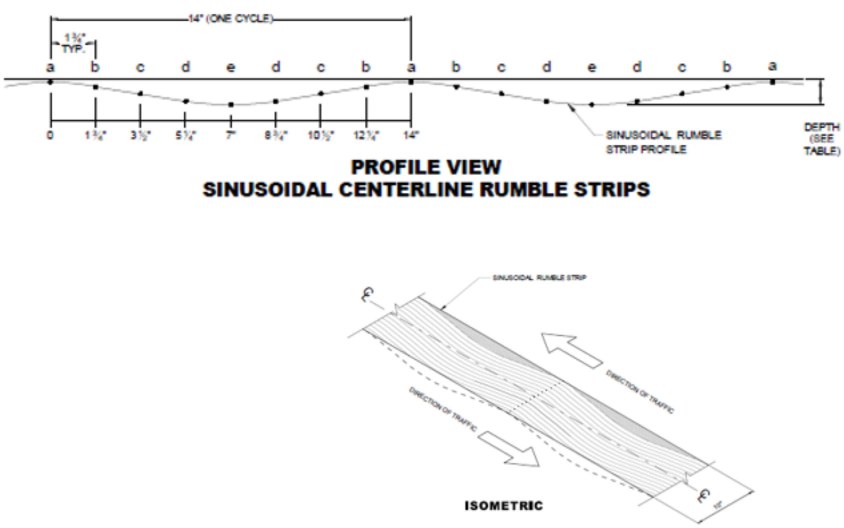



**Figure 2.15: Typical Geometry for Standard CLRS (Wisconsin).**




| LOCATION | DEPTH (INCHES) |
|---|---|
| a | 1/16" |
| b | 5/32" |
| c | 9/32" |
| d | 7/16" |
| e | 1/2" |

**Figure 2.16: Typical Geometry for Sinusoidal CLRS (Wisconsin).**

### 2.2.1.11 Michigan DOT

Source: https://mdotjboss.state.mi.us/stdplan/standardPlansIndex.htm

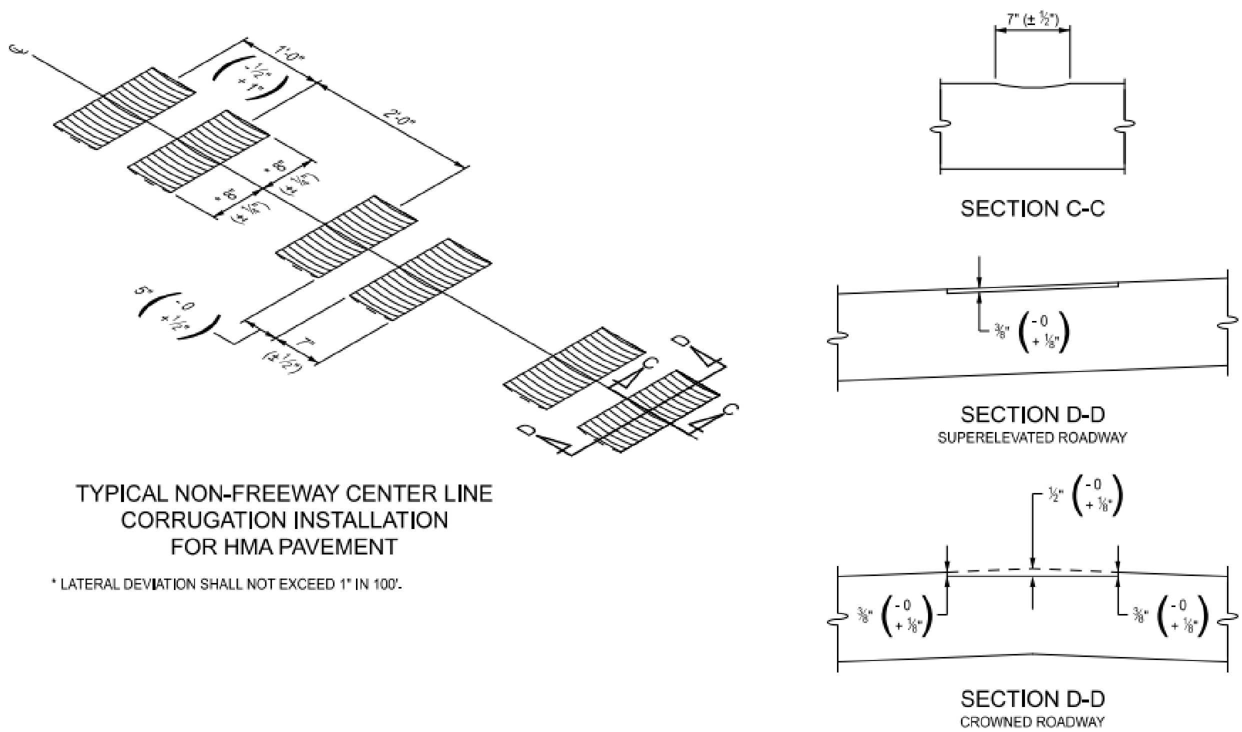



**Figure 2.17: Non-Freeway Center Line Corrugations (Michigan).**

### 2.2.1.12 Mississippi DOT

No CLRS Standard Drawing located

## 2.3 Effects of CLRS on Pavement Properties

Several studies have addressed concerns regarding the impact of milled rumble strips on pavement performance or durability (DeCarlo et al., 2023). The longitudinal paving joint in asphalt pavements, and the area surrounding the joint, is often prone to premature and accelerated deterioration. Several underlying factors have been attributed to this phenomenon, but the consensus is that comparatively low pavement density at and near the joint area results in increased air and water permeability, which in turn manifest in various pavement distresses (Bahia et al., 2021). Performance concerns arise from the fact that CLRS are being milled into an already susceptible area of the pavement. Furthermore, the milling operation may allow for increased water and air infiltration by removing the seal provided by the asphalt residue coating the aggregate and fracturing some of the aggregate. Additionally, since CLRS are recessed relative to the surrounding pavement, they provide a small reservoir for water (or ice) to be held for extended periods (Figure 2.18).

**Figure 2.18: CLRS Exhibiting Water Retention During Thaw Event in Wisconsin. Author Photo.**

Table 1 summarizes various key studies that focus on performance impacts of CLRS. Key findings as they relate to current research project are summarized below:

- Several studies that conducted agency surveys reported that some agencies are concerned with deterioration of the centerline joint being affected by the milling of CLRS. In general, these agencies are concerned with the effects of water being present at the joint and the reduced cross section after milling the CLRS (particularly relevant for thinner surface lifts or older pavements).
- Milling of CLRS is shown to produce micro-cracks at the location of the rumbles, which are speculated to cause accelerated deterioration of the rumble strips.
- Treatment options to preserve milled rumble strips include topical sealers such as chip seals and asphalt emulsion fog seals as well as Void Reducing Asphalt Membranes (VRAM). Very little work has been done to investigate the functionality (noise) impacts of these treatments.

**Table 1: Key Studies Reporting on CLRS Impacts to Pavement Performance.**

| Citation (Listed chronologically) | Notes and Key Findings |
|---|---|
| (Russell & Rys, 2005) | • Several DOTs raised concerns regarding accumulation of water, snow, sand, etc. in the rumbles causing deterioration of pavement or reduced stripe visibility<br>• MnDOT concerned about effective maintenance activities on rumbles<br>• 15/24 agency respondents to survey indicated no effect on pavement deterioration because of water accumulation. Alaska and Oregon DOTs reported issues regarding premature deterioration in some scenarios. |
| (Watson et al., 2008) | • Surveyed MnDOT districts and county agencies. Nearly all respondents reported deterioration in the rumble strips, both should and centerline.<br>• A national survey received 26 State DOT responses:<br>○ 10 States responded "Yes" to "Observed Deterioration Caused by the Rumble Strips"<br>○ Two states reported using fog seals over milled rumbles<br>• Treatments to preserve the life of rumble trips include crack sealing near the rumbles, fog sealing, and proprietary surface treatments such as spray-rejuvenators. |
| (Torbic et al., 2009) | • "Very little scientific-based research has been conducted to address these concerns, but through observational reports most of the pavement performance concerns appear to be unwarranted."<br>• "Field tests refute concerns about the effects of the freeze-thaw cycle as water collects in the grooves." |
| (Rysz et al., 2010) | • Structural condition of the underlying pavement is a key consideration in using CLRS, implying milling of CLRS can compromise integrity in suspect pavements. |
| (Guin et al., 2014) | • "The majority of adverse issues regarding centerline rumble strips were in the form of anecdotal evidence."<br>• 10/28 State DOTs reported experiencing performance issues with CLRS, with five stating accelerated pavement deterioration occurring.<br>• Age of the roadway was a primary suspected cause of deterioration in most responses.<br>• Nebraska DOT altered CLRS geometry to avoid the joint, citing already suspect joint performance. |
| (Himes et al., 2017) | • "Most assessments of pavement condition are anecdotal in nature. There is little quantitative research identifying the impacts of rumble strips on pavements, particularly longitudinal joints, yet departments still often struggle to implement rumble strips in these locations."<br>• Further research is needed to understand rumble strips installed with other surface treatments, such as chip seals. |

| Citation (Listed chronologically) | Notes and Key Findings |
|---|---|
| (Weaver et al., 2023) | • Reported "superior performance of sinusoidal CLRS in comparison to rectangular CLRS" based on fatigue testing and Hamburg Wheel Tracking.<br>• "According to X-Ray CT imaging results, CLRS core samples were shown to have microcracks present… These microcracks could be propagating with the application of thermal and vehicular loads and resulting in cracking along the rumble strips… The microcracks potentially being introduced at the surface of the rumble strips during milling could be creating weak spots from which top-down fatigue cracking can propagate. Additionally, rainwater filling the microcracks might also be creating hydrostatic pressures when a truckload is applied, resulting in "single-event" cracking (crack formation with one pass of a heavy truck) along the rumble strips (which is not simulated and investigated in this study). For this reason, sealing the surface of the CLRS with chip seal or fog seal treatments right after the CLRS installation may be beneficial."<br>• Authors recommend surface sealing milled rumbles, notably with a chip seal application. But the authors concede "n. It should be noted that the improved structural performance following these recommendations may come at the cost of decreased notification for drivers. Smaller and shallower rumble strips with a longer sinusoidal wavelength and chip seal surface treatment will likely lead to less alert for drivers." |
| (DeCarlo et al., 2023) | • Controlled study evaluating effects of Void Reducing Asphalt Membrane (VRAM) on rumble strip performance using field cores and lab specimens alike.<br>• Rumble strips may increase water permeability of the pavement.<br>• "The bottom-up approach of using a VRAM to seal the centerline joint before the installation of rumble strips was effective in mitigating permeability concerns." |

Although the effects of CLRS on pavement performance have been documented by several researchers, there have been few controlled studies that focus on methods to improve CLRS performance and combat potential durability concerns. The current research project aims to address this research gap.

## 2.4 Studies Reporting on Functionality of CLRS

The primary purpose of CLRS installation is as a safety tool. As reported earlier, very little standardization exists among agencies regarding rumble strip geometry or installation guidelines (Himes et al., 2017). In fact, no widely adopted standard procedure exists to measure functionality of rumble strips. Numerous studies have reported on noise complaints resulting from CLRS installation. Noise complaints have led agencies to evaluating different geometries in attempt to limit nuisance noise while maintaining safety. NCHRP Report 1107: Effective Low-Noise Rumble Strips (2024) summarizes a recently completed study attempting to optimize CLRS geometry to balance these concerns.

NCHRP Report 1107 provides a standardized tool to evaluate functionality of rumble strips and uses that tool to recommend a CLRS geometry that minimizes external on/off interval noise. The recommended

CLRS design resulting from the research is a sinusoidal geometry with a wavelength of 15 in. and a recess no greater than 1/8 in. A peak-to-peak depth of 7/16 in.-1/2 in. is suggested. The transverse width is suggested to be 12 in. minimum (Donavan et al., 2024). This recommendation is in general agreement with the WisDOT sinusoidal design presented earlier in this report.

The same study evaluated several project locations that had a chip seal applied to the already milled sinusoidal CLRS. The researchers observed that the CLRS area was difficult to distinguish from the rest of the pavement surface: the chip seal had nearly masked the surface profile change of the CLRS. An example from that report is shown below. Two different sinusoidal CLRS geometries had been chip sealed when the researchers attempted to measure functionality.

**Figure 2.19: Example of a Sinusoidal CLRS With Chip Seal Application. From (Donavan, Janello, Rochat, & McKenna, 2024).**

Additionally, the study measured the interior and exterior on/off noise increment of the various test locations. A minimum interior on/off increment of 10 dB is suggested to adequately alert drivers to lane departure. The research team found that for the two sinusoidal CLRS that had a chip seal application, both exhibited interior noise increments below this threshold when tested at 45 mph, and one of the two fell below the threshold at 60 mph (the other barely exceeded the 10 dB threshold). The non-chip sealed CLRS, in contrast, easily exceeded the 10 dB threshold. The chip seal had evidently altered the rumble strip geometry sufficiently enough and increased baseline noise enough to reduce driver-alerting capabilities below critical levels on these two sections (Donavan et al., 2024). These results are shown in Figure 2.20.

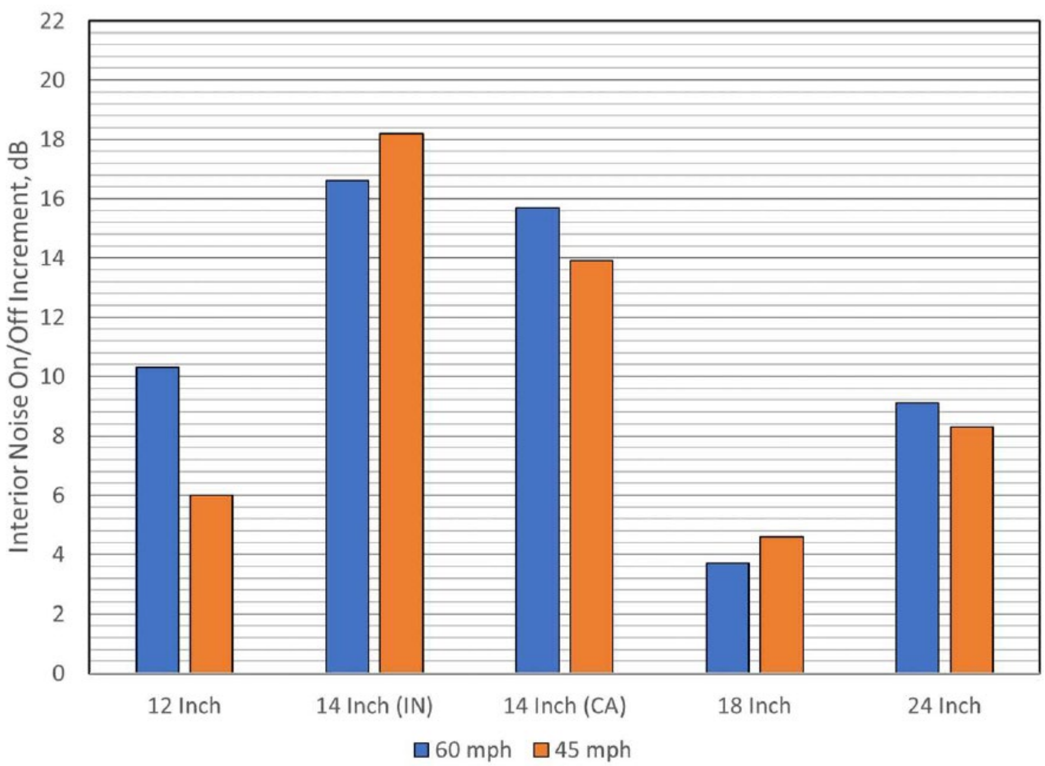



**Figure 2.20: Noise Increment of Several CLRS Geometries. The 12-inch and 18-inch Geometries Have Chip Seals Applied to Them. From (Donavan, Janello, Rochat, & McKenna, 2024).**

Key findings as they relate to this study are summarized below:

- The effectiveness of CLRS as measured by on/off noise increment is dependent on CLRS geometry and surface type (mix design). In other words, more than one geometry should be investigated during this study, and preferably the same geometry should also be evaluated in more than one location (which dictates mix design).
- Any treatment applied to a CLRS that changes the geometry of the CLRS or otherwise impacts the baseline noise of the surrounding pavement can influence the effectiveness of the CLRS as a safety tool. For this reason, material treatments that are expected to result in significant surface profile changes, such as chip seals, micro-surfacing, etc., will not be evaluated in this study.
    - It should be noted that a recent study investigating CLRS durability recommends sealing the CLRS immediately after milling with the use of an asphalt emulsion fog seal or chip seals to preserve rumble strips. The authors suggest that the "chip seal surface treatment will likely lead to less alert for drivers" and suggest further research (Weaver, Coleri, & Chitnis, 2023). The authors were likely not aware of the findings presented in NCHRP Report 1107 given the publication timelines.
- A desirable CLRS geometry and treatment plan is one that maximizes interior On/Off noise increment while minimizing exterior on/off noise increment.

# Chapter 3: Research Objectives

The use of CLRS continues to grow throughout the U.S. because of their proved effectiveness at increasing driver safety (Himes et al., 2017). Through the lens of pavement performance, the effects of installing CLRS in asphalt pavements at the location of the longitudinal construction joint are not well understood (DeCarlo et al., 2023; Weaver et al., 2023). Improvements in pavement and joint performance using materials-based strategies suggest that any damaging effects that the installation of CLRS may induce could be offset or mitigated with the same treatment strategies. Conversely, if it is found that installation of CLRS does not result in damage above baseline performance, these treatment strategies may provide extended service from the CLRS (Bahia et al., 2021). However, the effect of any preservation strategy on functionality of the rumble strip must be considered.

This project will evaluate the efficacy of material methods for improving or enhancing CLRS durability while maintaining safety through the use of full-scale field projects. The following project objectives were identified:

- Conduct a literature and agency specification review of CLRS geometry, construction methods, and durability studies,
- Determine "as-constructed" durability effects of CLRS using field cores of newly constructed asphalt pavement sections relative to control (no rumble strip) areas. At least two CLRS rumble strip geometries, including one sinusoidal geometry, should be considered. For one of the geometries, at least two different mix designs should be considered.
- Evaluate the effects of materials-based preservation treatment strategies on CLRS performance.
- Document the effects of the above-determined material strategies on rumble strip functionality as a safety tool.
- Produce "best-practice" guidelines for use of supplementary materials that mitigate the potentially detrimental effects or enhance the performance of CLRS.

# Chapter 4: Project Work Plan

The research team is unaware of a laboratory method to accurately simulate the milling of rumble strips on laboratory prepared specimens, hence full-scale field projects were considered essential for the purpose of this study. Field projects were selected within a reasonably similar geographical location to mitigate climatic impacts and evaluate the CLRS impact independently. In addition, projects captured reasonable differences in mix design materials and contractor paving methods. For an accurate evaluation, each field project contained, at a minimum, control sections without rumble strips, rumble strips with no treatment, and rumble strips with various material treatment strategies. Two rumble strip geometries were selected following WisDOT standard detail for paired cylindrical CLRS and sinusoidal CLRS. Rumble strips were milled into the projects immediately following construction.

Prior work by the research team demonstrated that materials & methods to improve longitudinal joint performance can be divided into three categories: Construction Methods, Materials During or "Pre-Construction", and Materials Following Construction (Bahia et al., 2021). Construction Methods include joint construction (butt vs. notched wedge) and rolling practice, among others. Construction Materials can be used independent of Construction Methods and are therefore the focus of this study. Based on the research objectives, eight sections were constructed on each project to evaluate material treatments on sections with and without rumble strips, as detailed in Table 2. Notably, no chip seal treatment was selected based on the findings presented in NCHRP Report 1107 (Donavan et al., 2024). VRAM and Rapid Penetrating Emulsion (RPE) were ultimately selected as the two treatment strategies based on prior work (Bahia et al., 2021; DeCarlo et al. 2023) but also based on available budget cost-share initiatives by the authors.

**Table 2: Description of Test Sections.**

| Centerline Rumble Strip Milling | Control – No Treatment | Void Reducing Asphalt Membrane (VRAM) | Rapid Penetrating Asphalt Emulsion Fog Seal (RPE) | Combination of VRAM + RPE |
|---|---|---|---|---|
| No CLRS | Section 1 | Section 2 | Section 3 | Section 4 |
| CLRS (Standard or Sinusoidal) | Section 5 | Section 6 | Section 7 | Section 8 |

Following the construction of each project, 12 road cores were taken from each test section directly over the longitudinal paving joint. The same technician team was responsible for coring on each project to help minimize variability in sampling. In the CLRS sections, cores were centered in the rumble strip corrugation to obtain a core containing the maximum milling depth. The 12 cores were taken with only slight offset (in adjacent corrugations, when applicable) to minimize the effects of paving variability on the samples and to accommodate functionality (noise) testing. In addition to the road cores, paving mixtures were sampled from the hot mix plant during production.

Road cores and plant mix samples were delivered to the Heritage Research Group laboratory for testing. The proposed testing plan for both field cores and plant mix is described in Table 3. As the table indicates, all proposed testing has been demonstrated in prior literature to be relevant to the stated objectives of this project. Since the primary distress associated with longitudinal joints is cracking (leading to longer term durability concerns), measurement of rutting resistance or high temperature stiffness is not included in this study.

**Table 3: Proposed Laboratory Testing Methods.**

| Test Method | Number of replicates | Aging Condition | Justification for Selecting Method and Expected Outcome |
|---|---|---|---|
| Bulk Specific Gravity (AASHTO T166 or T331) | Each core | • "As cored"<br>• Long-term aged | • Document air voids for performance test correction<br>• Relation to performance trends |
| Maximum Theoretical Specific gravity with Dryback method (AASHTO T209, Modified) | 2 | • "As cored"<br>• Long-term aged | • Document air voids for performance test correction<br>• Relation to performance trends |
| Ideal-CT (ASTM D8225, Modified) | 3 | • "As cored"<br>• Long-term aged | • Strength and crack propagation rate measurement<br>• Increasingly used by State DOTs as mixture performance evaluation tool<br>• Can accommodate field cores easily |
| Overlay Test (TEX-248-F, Modified) | 3 | • "As cored"<br>• Long-term aged | • Crack initiation and propagation in strain control<br>• Can accommodate field cores easily |
| Water Permeability (FM 5-565) | 3 | • "As cored"<br>• Long-term aged | • Potential correlation to long term moisture induced damage<br>• Non-destructive and can accommodate field cores. |
| Asphalt Content and Gradation (AASHTO T164, T30) | 2 | • "As cored"<br>• Long-term aged | • Verification of field production parameters<br>• Correlation to performance test outcomes |

# Chapter 5: Construction of Field Projects

## 5.1 Project Scoping and Descriptions

Field projects for this study were selected based on geography to facilitate frequent site visits by the researchers, diversity in aggregate resources, and project size/scope. To this end, participation from County Highway Agencies (CHAs) in the state of Wisconsin was requested. New paving projects within each county were targeted to standardize time in service; it is noted that milling CLRS on older pavements may introduce additional variability, falling beyond the scope of this project. Rural two-lane County Trunk Highways (CTH) were the focus of project screening since they would allow greater access to the research team, have similar posted speed limits among projects, while minimizing disruption to the respective CHA and the public. It should be noted that Wisconsin is relatively unique in the U.S. in that many Wisconsin counties conduct their own paving operations utilizing county-owned equipment and labor. Some counties, including two of the three selected for this research, also own and operate their own hot-mix asphalt production facility.

Three Wisconsin CHAs ultimately agreed to support the research effort and offer access to new paving projects during the 2023 paving season. In return for their participation, the CHAs received material and CLRS installation cost support as part of cost-share initiatives with the research team. The CHAs were instructed to plan and execute their respective projects following their internal standard practice as much as possible. The research team helped establish project site layouts for the various research sections, documented construction-related variables and sampled materials, but otherwise did not make any modifications to the projects before or during the paving process. The three projects selected for research were: CTH N in Rock County, CTH LL in Sheboygan County, and CTH F in Wood County; note Wisconsin CHAs use letter designations to name county roads. Approximate locations within the State of Wisconsin for each project are shown in Figure 5.1, with detailed layout description thereafter.

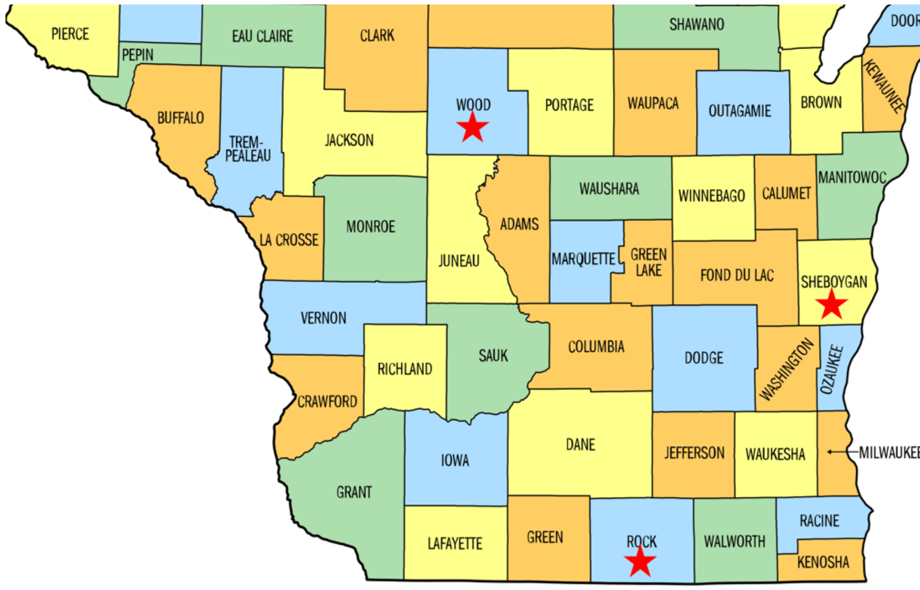



**Figure 5.1: Approximate Locations of Selected Paving Projects in Central, Southeast, And South-Central Wisconsin.**

Within each project, eight research sections were established. CLRS were milled into each project in a designated area based on material treatment locations for research purposes, project layout constraints and safety considerations. The eight research sections were described in Table 2. The length of each research section varied widely between projects, but was typically greater than one-half mile each, particularly in areas that CLRS functionality testing would be conducted.

Two of the three projects (Rock County and Sheboygan County) utilized standard Wisconsin DOT (WisDOT) CLRS geometry consisting of paired rectangular corrugations. Wood County utilized WisDOT sinusoidal geometry option. Contractors familiar with the milling of WisDOT CLRS were contracted to install the CLRS on each project. Conformance to the standard drawing details was measured by the installation contractor and research team during installation. WisDOT standard drawing details are found online on the WisDOT website. Figure 5.2 shows the as-installed CLRS for each project.

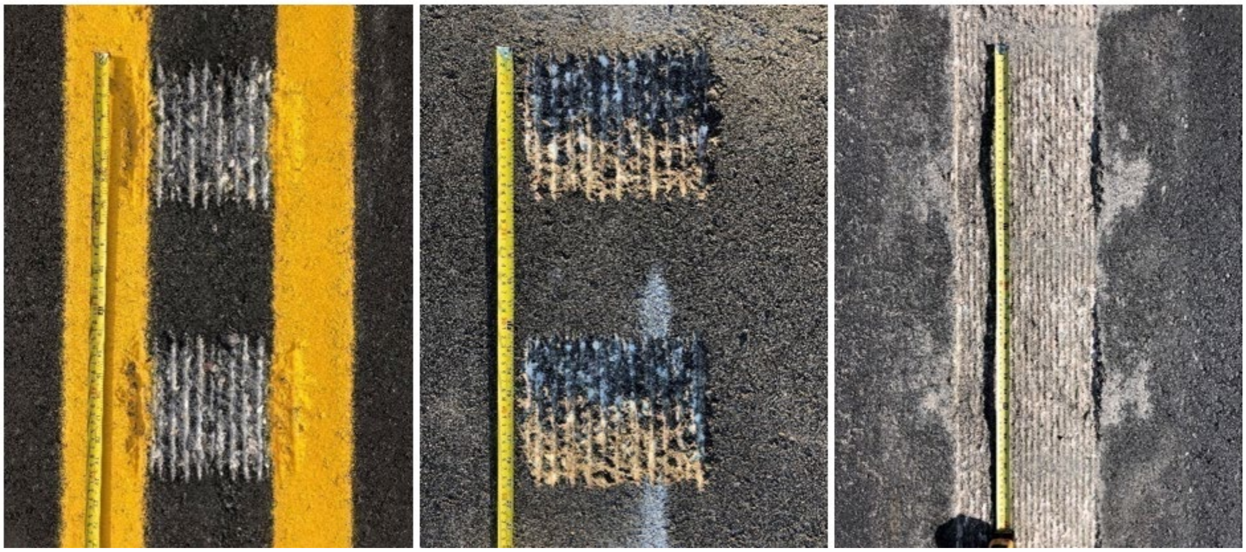


**Figure 5.2: CLRS Installed in Sheboygan County (L), Rock County (M), And Wood County (R).**

## 5.1.1 County Trunk Highway "N", Rock County, Wisconsin

The Rock County Highway Division planned reconstruction of approximately eight miles of CTH N between the Walworth County line (eastern project limit) and North Milton Road (western project limit) in 2023. Paving was conducted in three lifts (layers) over compacted aggregate base. More detailed structure and mixture properties can be found later in this report. The project section used for this study generally consisted of undivided 2-lane highway with a marked speed limit of 55 mph. CLRS were milled on approximately three miles of the project using the standard WisDOT CLRS geometry. VRAM and RPE were installed in two sections each to ensure all eight material combinations were captured. The approximate layout of CTH N is shown in Figure 5.3. Construction occurred in August through October 2023 with in-place sampling (coring) occurring on October 17th, 2023.


**Figure 5.3: Approximate Layout of CTH N, Rock County, WI. Map Image From Google Maps ([https://maps.app.goo.gl/6aoNtwK7X3zb18TE6](https://maps.app.goo.gl/6aoNtwK7X3zb18TE6)).**

## 5.1.2 County Trunk Highway "LL", Sheboygan County, Wisconsin

The Sheboygan County Transportation Department – Highway Division planned realignment and reconstruction of approximately 2.5 miles of CTH LL between State Highway 32 (northern project limit) and CTH K/Ozaukee County line. The entire project is an undivided 2-lane highway with a marked speed limit of 55 mph. Paving consisted of two lifts (layers) over compacted aggregate base. More detailed pavement structure and mixture properties can be found later in this report. CLRS were milled on approximately two miles of the project using the standard WisDOT CLRS geometry. VRAM was installed in two sections and RPE installed in one section to ensure all eight material combinations were captured. The approximate layout of CTH LL is shown in Figure 5.4; note the section layouts are superimposed over the Google Map image and is not to scale as CTH LL deviates significantly from straight north-south. Construction occurred in September and October 2023 with in-place sampling (coring) occurring on October 18th, 2023.


**Figure 5.4: Approximate Layout of CTH LL, Sheboygan County, WI. Map Image from Google Maps (https://maps.app.goo.gl/bRAP8EeJAiHuRadC8).**

### 5.1.3 County Trunk Highway "F", Wood County, Wisconsin

The Wood County Highway Department planned reconstruction of approximately 10 miles of CTH F between the intersection of CTH HH and CTH F in Eight Corners, WI (southern project limit) and Blenker, WI (northern project limit), although the research sections were located on the southern four miles of the project. The entire project is an undivided 2-lane highway with a marked speed limit of 55 mph. Paving consisted of one lift (layer) over a Cold In-Place Recycled (CIR) base. More detailed pavement structure and mixture properties can be found later in this report. CLRS were milled on approximately two miles of the project using the sinusoidal WisDOT CLRS geometry. VRAM was installed in one section and RPE installed in two sections to ensure all eight material combinations were captured. The approximate layout of CTH F is shown in Figure 5.5. Construction occurred in July and August 2023 with in-place sampling (coring) occurring on August 17, 2023.

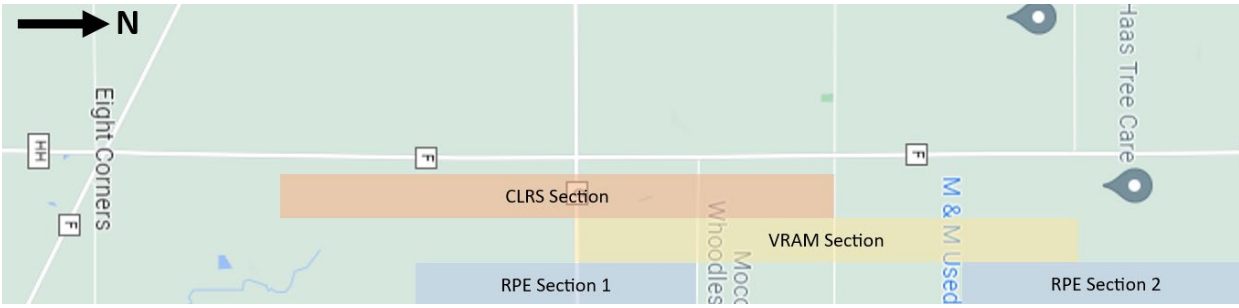



**Figure 5.5: Approximate Layout of CTH F, Wood County, WI. Map Image From Google Maps ([https://maps.app.goo.gl/i4AxmoLs3bjzwXm68](https://maps.app.goo.gl/i4AxmoLs3bjzwXm68))**

## 5.2 Construction and Sampling Sequencing

Despite differences in location, length and pavement structure, the construction sequencing for each of the three projects was similar for the surface layer. In general, sequencing followed the staging plan laid out in Figure 5.6 below, with more detailed descriptions following.

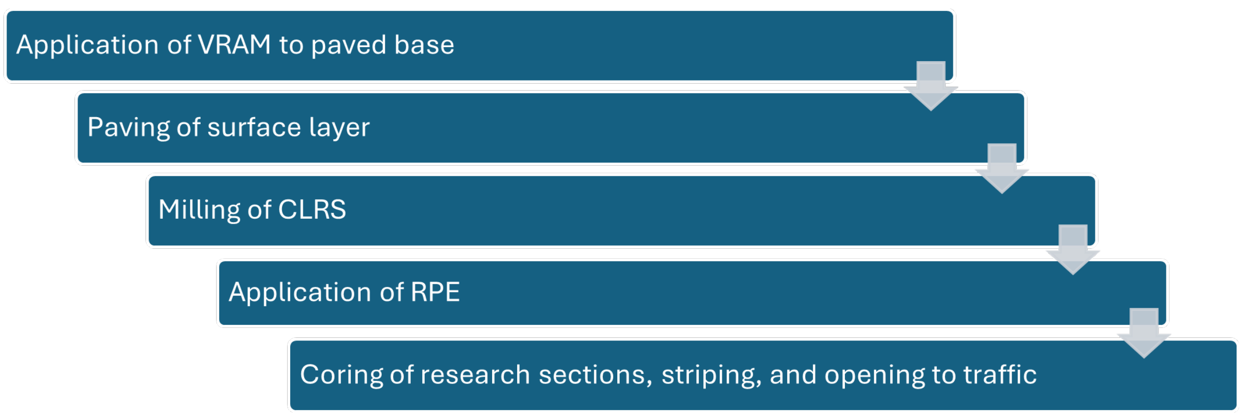



**Figure 5.6: Construction Process Sequencing.**

### 5.2.1 Application of VRAM

VRAM is applied to the existing paved lower layer centered at the location of the planned longitudinal joint. VRAM is a highly polymerized asphalt binder and is applied at approximately 320 °F using a specialized distributor. To minimize disruption to the paving process, VRAM is often applied hours or days ahead of the paving train. The cooled material is non-tracking and generally withstands incidental construction traffic without damage. For the purposes of this research, VRAM application followed MnDOT Provisional Specification 2331. A nominal 18 in. wide band of VRAM was applied for all projects with a target application rate of 0.95 lb/ft at the 18 in. width, based on mixture gradation and paving thickness. Representative photographs taken from the installation of VRAM are shown in Figure 5.7.

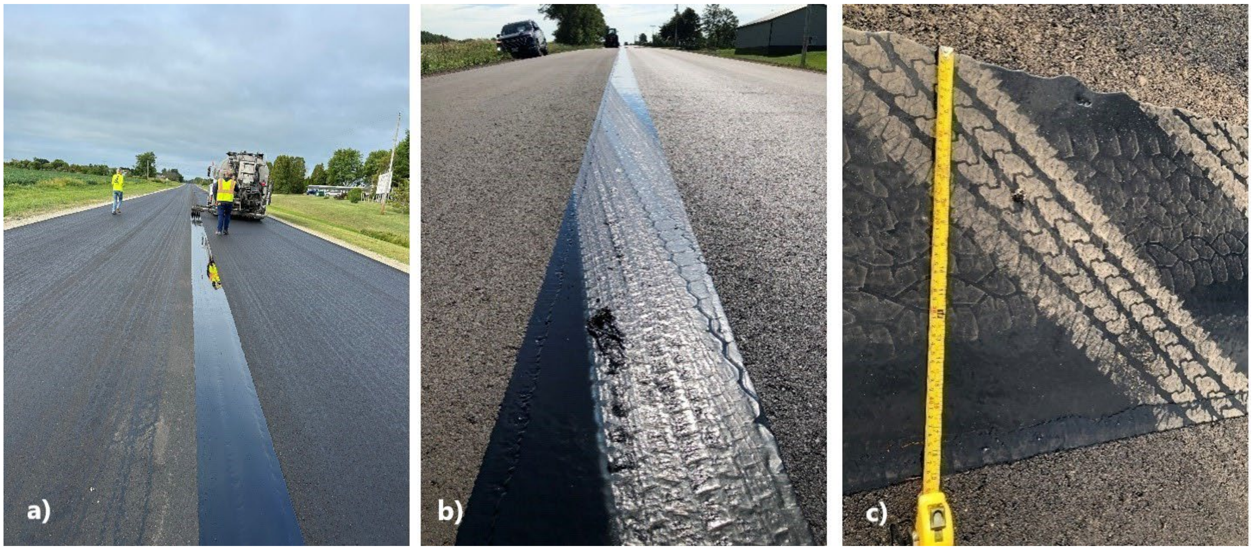



**Figure 5.7: Application of VRAM (a). VRAM Cools to a Non-Tracking Condition Allowing Construction Vehicles to Cross (b). Field Verification Includes Rate of Application and Band Width (c).**

### 5.2.2 Paving of Surface Layer & Milling of CLRS

Following application of VRAM, the surface layer of paving began within 24 hours for each project. For all three projects paving proceeded as one lane width at a time, periodically backing the paving train up to even up progress on the second paving pass. Detailed mixture properties for each county project can be found later in this report (Table 2). All three projects utilized Superpave 12.5 mm NMAS dense graded mixtures designed for WisDOT Low Traffic (“LT”) traffic volumes. Respective CHAs were instructed to follow their standard paving and quality control practices during the projects. That is, the research team did not make any modifications to CHA practice or processes. Illustrative photographs of the paving process are shown below in Figure 5.8.

When paving over VRAM sections the first paving pass covers approximately half of the width of the VRAM band (approximately 9 in. for the 18 in. nominal width band). Paving remains generally unchanged between VRAM and non-VRAM sections except that the screed end plate is raised slightly off the surface to allow the VRAM to pass underneath the screed. The second paving pass matches the construction joint by covering the other half width of VRAM. For both paving passes the rolling operation is unchanged from standard practice, although it is recommended that during the first paving pass over VRAM the first breakdown roller pass overhang the joint by approximately 6 in. on static mode.

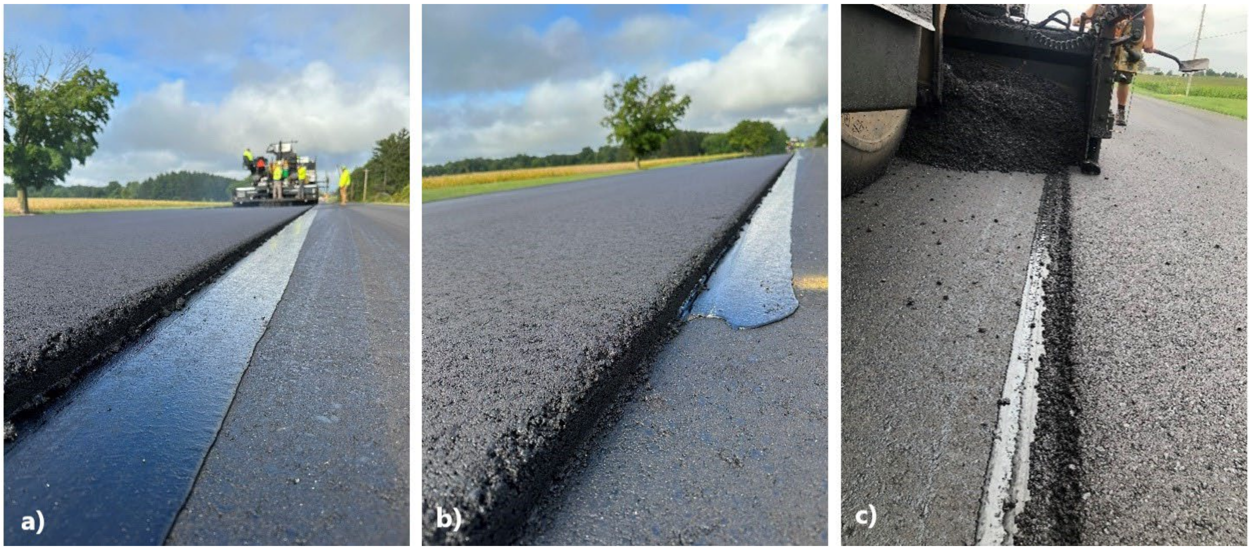



**Figure 5.8: Paving of First Pass Covers Half of the VRAM Width (a); Paving Process Does Not Change When Covering VRAM (b); Paving Second Pass Covers the Remaining VRAM to Create the Construction Joint (c).**

CLRS were milled into the cold surface following mainline paving. Both standard and sinusoidal geometries are installed using a similar milling process: the joint is cold milled centering the CLRS on the construction joint. The pavement is swept of debris and the geometry of the CLRS is checked for adherence to standard. For this research contractors familiar with the CLRS milling operation were utilized. CLRS milling operation and quality assurance typical of this project are shown in the Figure 5.9.


**Figure 5.9: Installation of CLRS Including Milling Operation (a and b), Checking Dimensions (c), and Cleaned Surface. WisDOT Sinusoidal CLRS are Shown (d).**

### 5.2.3 Application of RPE & Opening to Traffic

RPE is an oil-in-water asphalt emulsion applied using a standard asphalt distributor. The RPE used for this project was supplied at 38% residue content and applied at approximately 150-160 °F. The RPE penetrates the surface voids of the mixture and cures to a black color, similar to other asphalt emulsion fog seals. For this project the RPE was supplied and applied according to Indiana Department of Transportation (INDOT) Provisional Specification 401-R-736 with certain modifications that are explained below.

RPE can be applied in a focused band centered on the longitudinal construction joint (Figure 5.10) or applied the full lane width (Figure 5.11) of the pavement overlapping at the centerline depending on project goals. In this research project, Wood County elected to apply the RPE as a focused centerline band, while Rock and Sheboygan Counties elected full lane width application. Since the focus of this project is on longitudinal joint durability, both applications are acceptable if application rate is consistent. For the joint-focused band treatment, application is conducted in one pass, whereas for full lane width application at the joint is conducted in overlapping passes as each lane application overlaps the joint by approximately 6 in. (essentially doubling the application at the joint area). The application rate for the centerline focused RPE application is 0.10-0.12 gal/SY, while the full lane width application rate is typically 0.07-0.08 gal/SY. The rate is selected and modified for each project to balance penetration and coverage.

Following RPE application, the pavements were striped and immediately opened to traffic. The interval between application of RPE and striping varied between projects but was within approximately 72 hours in every case.


**Figure 5.10: RPE Application Over CLRS, Centerline Application Alternative (a), Freshly Applied RPE (b), and Fully Dried Ready for Striping (c).**


**Figure 5.11: RPE Application Utilizing Full Lane Width Alternative (a). Photo (b) is After Final Pass Before RPE has Fully Dried. Photo (c) is CLRS Before RPE, Photo (d) is CLRS Following RPE, Note the Macro-Texture of the Underlying Surfacing, Characteristic of a Penetrating Emulsion Treatment.**

### 5.2.4 Sampling of field cores

Each project was sampled by coring within approximately one week of RPE application to minimize disruption to the respective CHA and the public; all projects were cored by Behnke Materials Engineering. More specifically, 12 road cores were taken from each test section directly over the longitudinal paving joint, by the same technician team and using the same equipment, to help minimize variability in sampling. In the CLRS sections, cores were centered in the rumble strip corrugation to obtain a core that contained the maximum milling depth. The 12 cores were taken with only slight offset (in adjacent corrugations, when applicable) to minimize the effects of paving variability on the samples and to accommodate functionality (noise) testing, such that the core locations were not too far spaced out within each test section. Table 4 summarizes the construction and coring dates for each project. Meanwhile, Figure 5.12 (a), (b) and (c) provide examples of the coring process on sections with and without rumble strips.

**Table 4: Summary of Construction and Coring Dates for Each County Project.**

| Project Location | Construction | Coring Date |
|---|---|---|
| Rock County | August – October 2023 | October $17^{th}$, 2023 |
| Sheboygan County | September – October 2023 | October $18^{th,}$ 2023 |
| Wood County | July-August 2023 | August $17^{th}$, 2023 |

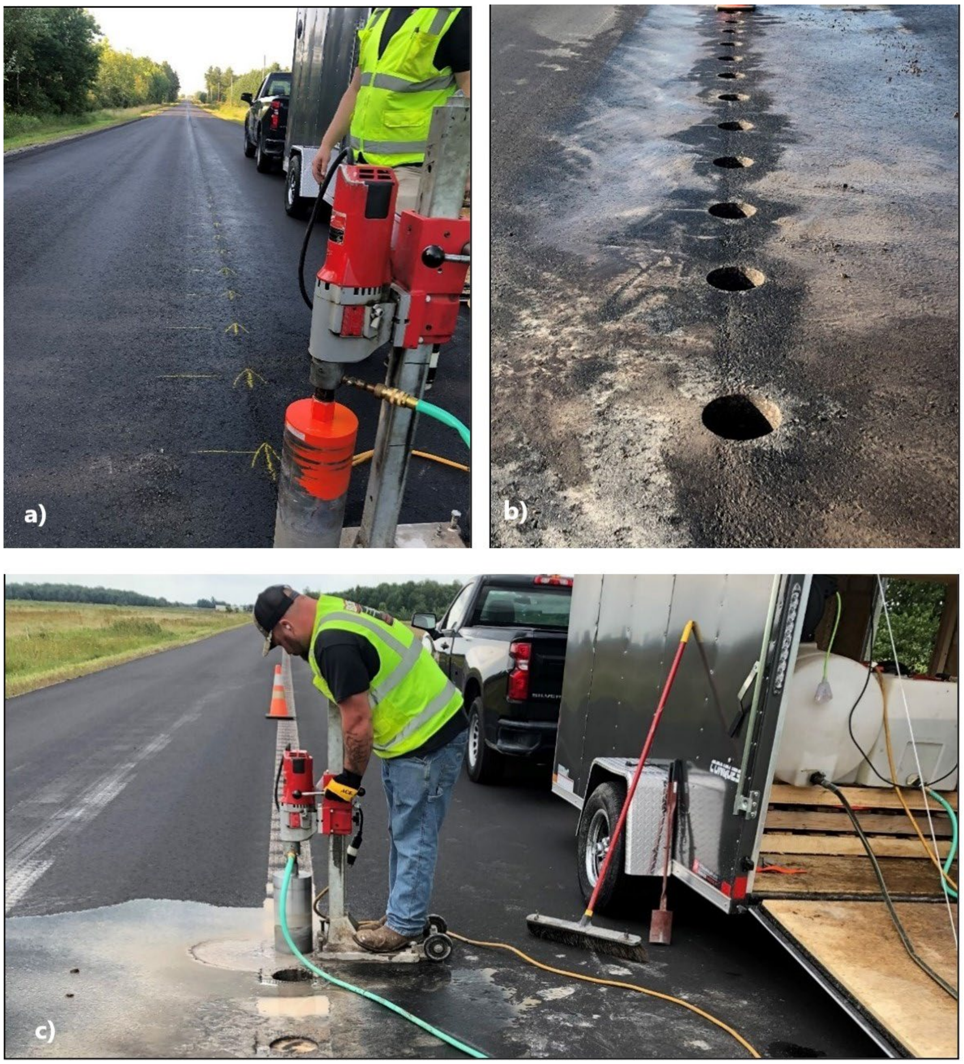



**Figure 5.12: (a) Core Locations and Direction of Paving in Section Without Rumble Strips (b) Cored Section Without Rumble Strips (c) Coring Process on Section With Rumble Strips.**

## 5.3 As-Constructed Pavement Structure and Mixture Properties

The choice to install CLRS on a roadway is dependent on several design variables such as lane departure accident history, horizontal and vertical design elements, current and future traffic volume and speed trends, location relative to urban centers, among other factors. For the purposes of this research project, it was decided not to attempt to control structure or mix design properties, but instead thoroughly document them to capture a range of in-service variables that may be encountered with CLRS in this region. Similarly, mix design selection and quality control was deferred to the respective CHAs or their mixture supplier; the research team collected and documented road cores and plant mix representative of what was constructed, independent of specifications.

Table 5 and 6 summarize the as-constructed structure and mixture properties for each respective project. Figure 5.13 shows the average mixture gradations used on the three projects plotted on a 0.45 power chart. Many similarities exist between the three projects. All three are designed as Superpave 12.5 mm NMAS dense graded mixtures utilizing PG 58-28 (unmodified) as the base binder. The Rock County mixture is a WisDOT certified asphalt mix design, which means that it satisfied all 2023 WisDOT Standard Specifications as designed and produced. The Sheboygan and Wood County designs were designed following WisDOT methodology but were not certified by the DOT as fully compliant with the 2023 WisDOT Standard Specifications. All three designs follow WisDOT Low Traffic (LT) designation, which has a design gyration number of 40. The projects differed widely in local aggregate sources, which results in varying levels of absorption, aggregate hardness/durability, and design binder contents for the mixtures. RAP was used in each mixture, but at varying contents.

The surface layer for the three projects was paved in a similar timeframe – late summer to early fall 2023. Rock and Sheboygan surface layers were placed on paved intermediate/lower layers, while Wood was paved on a compacted Cold In-Place Recycled layer, which is common practice for this CHA. The three mixture gradations were similar, following a fine graded profile which is commonplace for dense graded mixtures in Wisconsin. Lastly, the structural thickness of the upper (surface) layer for Sheboygan and Wood County was similar, whereas Rock County was about 0.5 inches lower/thinner.

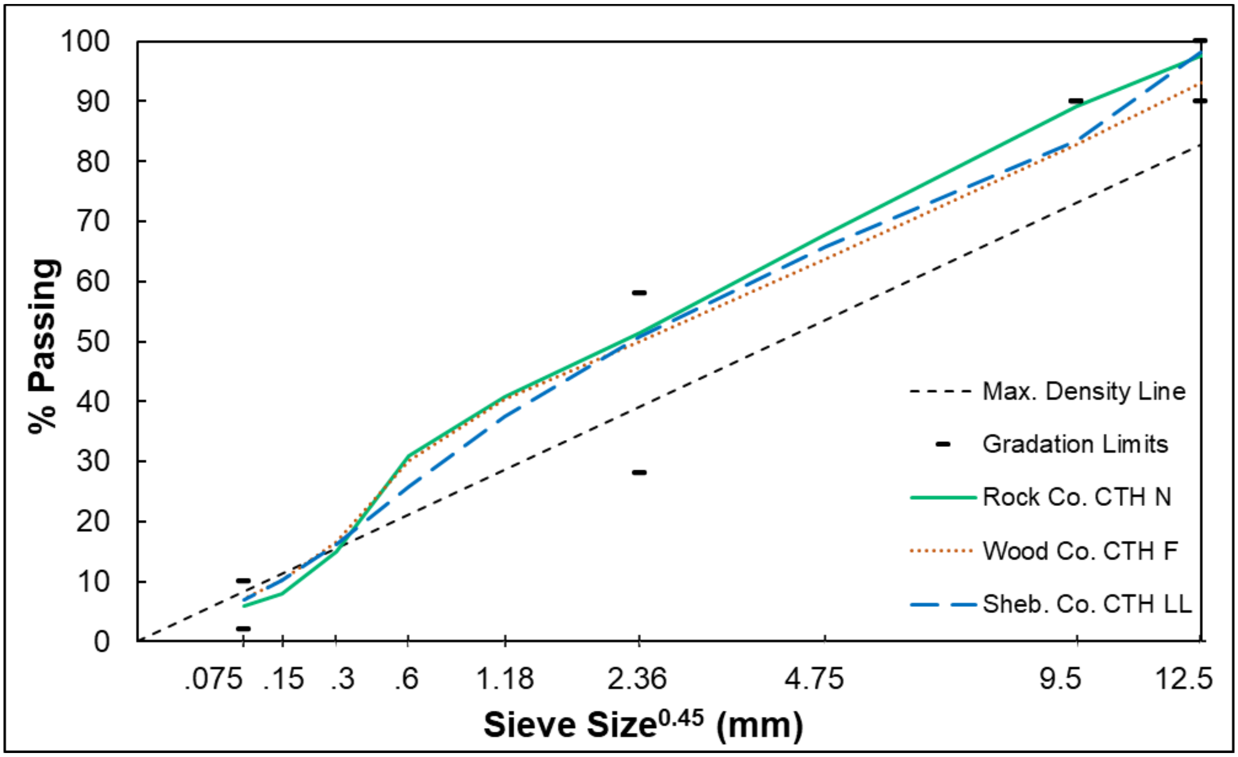



**Figure 5.13: Average Mixture Gradations Shown on 0.45 Power Chart.**

**Table 5: As-Constructed Structure and Mixture Properties.**

| County Trunk Highway (CTH) Designation: | CTH N | CTH LL | CTH F |
|---|---|---|---|
| **Location** | Rock Co. | Sheboygan Co. | Wood Co. |
| **Upper Layer Construction Date** | September/October, 2023 | September/October, 2023 | August, 2023 |
| **Average Surface Layer Measured Thickness, in (1)** | 1.46 | 2.08 | 1.96 |
| **Intermediate/Lower Layer Composition** | Compacted HMA Layer | Compacted HMA Layer | Cold In-Place Recycled Layer |
| **Surface Layer Mix Design** | Superpave 12.5 mm NMAS (WisDOT 4LT) | Superpave 12.5 mm NMAS | Superpave 12.5 mm NMAS |
| **Ndes** | 40 | 40 | 40 |
| **Asphalt Binder** | PG 58-28 (Unmodified) | PG 58-28 (Unmodified) | PG 58-28 (Unmodified) (2) |
| **RAP Use (%, by weight aggregate blend)** | 36% | 20% | 30% |
| **General Aggregate Composition** | Limestone and dolomite, natural sand and gravels, RAP | Glacial pit gravels and sands, RAP | Quarried granite, natural sand, RAP |
| **Asphalt Content, % by Mix** | 5.72 | 4.88 | 4.77 |

(1) Average measured upper layer thickness of 12 cores taken on longitudinal construction joint in non-CLRS Control section.
(2) Wood County utilizes a rejuvenator and Warm Mix Asphalt Additive on all County paving projects

**Table 6: Average Gradation of Recovered Plant Mixed Samples (AASHTO T164, T30).**

| Sieve Size | Cumulative Percent Passing | | |
|---|---|---|---|
| 3/4 in. | 100.0 | 100.0 | 100.0 |
| 1/2 in. | 97.6 | 98.2 | 93.0 |
| 3/8 in. | 89.2 | 83.5 | 82.7 |
| #4 | 67.9 | 65.8 | 63.8 |
| #8 | 51.4 | 50.8 | 49.9 |
| #16 | 40.9 | 37.6 | 40.4 |
| #30 | 30.9 | 25.9 | 30.2 |
| #50 | 15.0 | 16.1 | 16.6 |
| #100 | 8.0 | 10.3 | 10.2 |
| #200 | 6.0 | 7.0 | 7.1 |

It should be noted that Wood County commonly uses a surface mixture with around 30% RAP (by weight aggregate blend) and utilizes an asphalt rejuvenating agent to offset the aged RAP material. They also routinely use a Warm Mix Asphalt (WMA) additive to aid in compaction and moisture resistance of their mixture. It is important to note, that although this mix design has proven efficacious for their needs, it was not designed to meet all WisDOT specification parameters specifically.

## 5.4 Functionality Testing

This study included noise and vibration measurements on all field projects, to evaluate the effects of material treatments on the functionality features of rumble strips. For this study Illingworth & Rodkin, LLC was contracted to conduct field testing on each project section in June of 2024.

Measurements followed the methodology described on NCHRP Project 15-68 (Donavan, Janello, Rochat, & McKenna, 2024) with one modification. While NCHRP proposed an evaluation using four different vehicles to represent a variety of users – compact cars, mid-size sedans, mid-size SUVs and full-frame SUVs and trucks, only one vehicle type was utilized in this work as the objective was to compare material treatments (treated sections) against an untreated section (CLRS).

Functionality of rumble strips comprises outside noise and inside noise and vibration. From a safety standpoint, higher inside noise and vibration would be desirable to effectively alert drivers of lane departures. However, outside noise should be minimized, to provide the least disruption possible to surrounding communities. Outside noise was recorded through "pass-by" measurements, where a microphone was placed 25 feet away from the centerline of the roadway, on the opposite lane of travel. This would measure the pavement-tire noise as CLRS were driven over. In addition, interior noise was measured using a microphone placed in front of the passenger headrest, 29 inches above the seat, and vibration was measured through an accelerometer installed on the passenger seat track.

The full testing report for this initiative is available on the NRRA project website for this study *(Wisconsin Rumble Strip Noise and Vibration Functionality)*. The average on/off internal noise interval (increment) was determined to be well above the recommended 10 dB interval for alerting drivers of lane departure for all treatment combinations on each project. Internal vibration increments were all 5 dB or more above the minimum recommended increment of 10 dB. Interestingly, pass-by noise increments for the various treatments were lower than the "Control" sections in all but section on one project, suggesting the material treatments may reduce the exterior nuisance noise levels when drivers contact the rumble strips.

# Chapter 6: Laboratory Evaluation of Road Cores and Mixture Samples

## 6.1 Materials

Materials evaluation for this project was conducted on field cores, retrieved from projects in Rock, Sheboygan and Wood Co. in the state of Wisconsin, as described in Chapter 5: . Twelve cores were sampled from each of the eight test sections, making it a total of 96 field cores per project for subsequent laboratory evaluation, as shown in Table 7.

In addition to field cores, loose asphalt mixture from each project was sampled from the hot mix plant on multiple production dates. The mix was kept in tight sealed containers for further evaluation by the research team, namely to verify volumetric properties, as well as to establish a baseline cracking resistance of each mix using lab compacted samples (not containing a joint). Details regarding the mix design of each field project were presented in Section 5.3 .

**Table 7: Core Details for Each Field Project.**

| Project ID | Rock Co. | Wood Co. | Sheboygan Co. |
|---|---|---|---|
| Control | 12 cores | 12 cores | 12 cores |
| Control + VRAM | 12 cores | 12 cores | 12 cores |
| Control + RPE | 12 cores | 12 cores | 12 cores |
| Control + VRAM + RPE | 12 cores | 12 cores | 12 cores |
| CLRS | 12 cores | 12 cores | 12 cores |
| CLRS + VRAM | 12 cores | 12 cores | 12 cores |
| CLRS + RPE | 12 cores | 12 cores | 12 cores |
| CLRS + VRAM + RPE | 12 cores | 12 cores | 12 cores |
| Total | **96 cores** | **96 cores** | **96 cores** |

## 6.2 Methodology

Upon sampling all field cores and loose plant mix during production, materials were delivered to Heritage Research Group for laboratory evaluation. An inventory of field cores was performed first to ensure the integrity of all samples. All cores were then trimmed directly below the surface lift line, preserving the VRAM layer in those cores that contained it. Next, cores were randomly divided into different group sets in preparation for the various performance tests included in the project study plan, as summarized in Table 8 and detailed in Chapter 4: .

**Table 8: Originally Proposed Testing Plan.**

| Test Method | Justification or Expected Outcome |
|---|---|
| Bulk Density (AASHTO T166, Dryback method) | • Correlation to nuclear density, when applicable<br>• Document voids for performance test correction |
| IDEAL-CT (ASTM D8225) | • Strength and crack propagation rate measurement<br>• Widespread use in HMA leading to more comparative data & understanding of measurement |
| Overlay Test (TEX-248-F, modified) | • Crack initiation and propagation rate measurement<br>• Can use centerline field cores to manufacture specimens |
| Permeability (FM 5-565) | • Resistance to water intrusion and flow |
| Total Asphalt Content and Gradation (AASHTO T164, T30) | • Correlation to performance test outcomes |

*Note: Original work plan includes duplicating the testing after AASHTO R30 Long Term Aging*

In addition to testing field cores "as constructed", subject to short term aging at the plant, the study plan included long-term aging of field cores per AASHTO R30 to simulate the evaluation of performance properties of the longitudinal joint after years in service. The standard aging protocol for field cores consists of 5 days at 85 ℃ in a force draft oven.

To this end, six field cores per test section (per project) were proposed to undergo this aging protocol and later tested for cracking resistance and permeability. However, after one day of oven aging on a single specimen, the team observed loss of integrity of the field core and flow of VRAM binder, meaning some of the treatment was lost, as shown in Figure 6.1 (a) and (b). This behavior upon aging prevents an accurate performance evaluation, leading to potentially confounding results. Thus, the research team with input from the TAP, decided to remove long term oven aging from the test plan and use those field cores to confirm observed trends in test results by running additional replicates and thus build a more robust dataset for analysis.

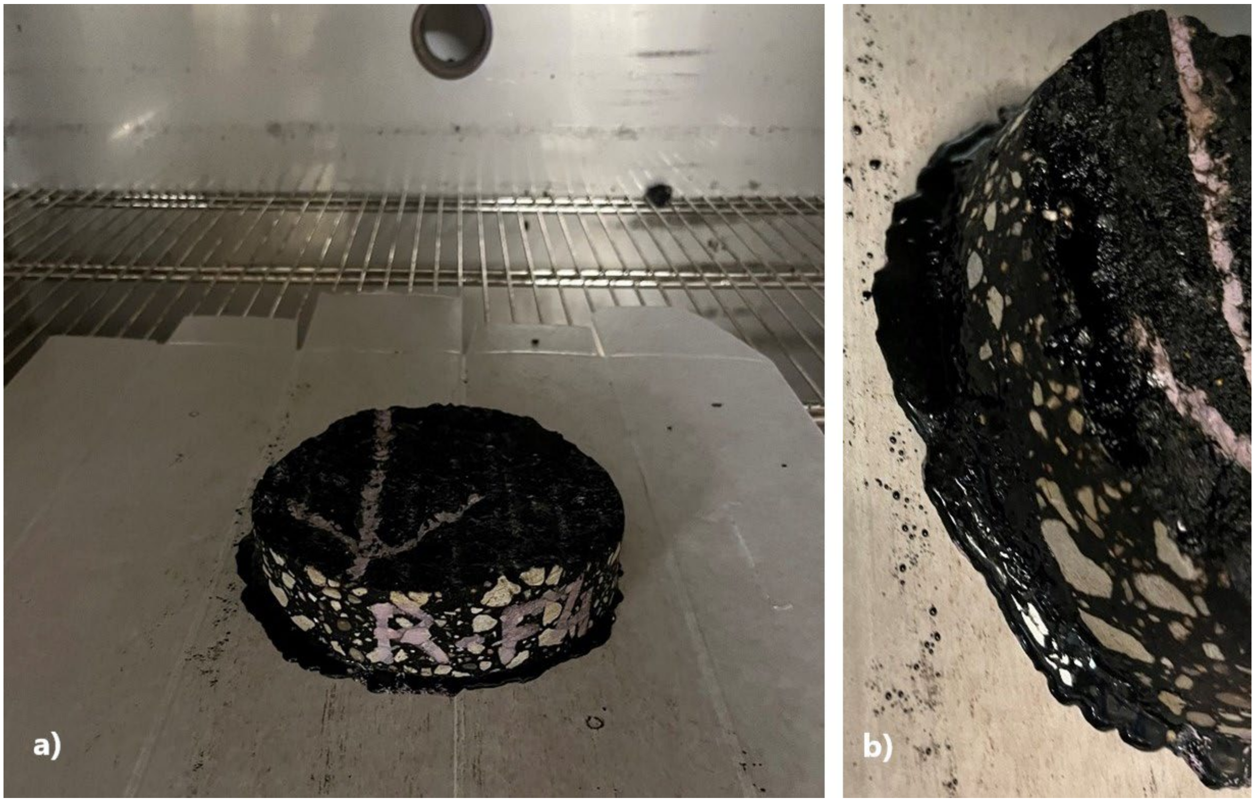



**Figure 6.1: (a) VRAM + RPE Field Core After ~1 Day of Oven Aging At 85 °C and (b) Detail of VRAM Binder Flowing from Specimen.**

The subsequent sections will therefore refer to the evaluation of field cores "as cored" (i.e., without additional laboratory aging) following the full proposed test plan: bulk specific gravity and air voids, asphalt content and gradation, permeability, Ideal-CT and Texas Overlay Test.  Figure 6.2 provides an illustration of the flow of all field cores through the lab for volumetric and performance testing.

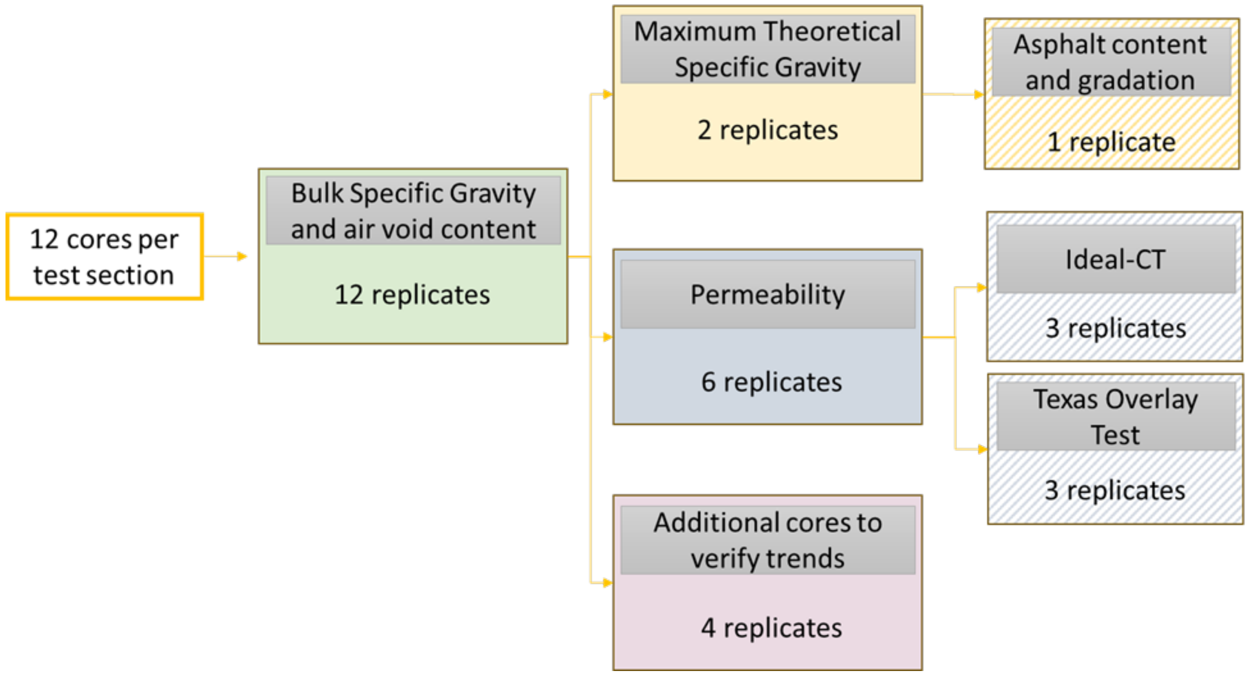



**Figure 6.2: Flowchart of Number of Replicates Per Testing Method for a Given Treatment Section.**

The following subsections provide greater detail on the methodology followed for each test, number of replicates and anticipated outcomes.

### 6.2.1 Specific Gravity, Asphalt Content, and Gradation

Air void content of field cores was determined with two main objectives: first, to understand the effect of material treatments on air void content of the joint and consequently, its potential impacts on performance properties with and without CLRS. To answer this question, bulk specific gravity of all field cores (after trimming) was determined following AASHTO T 166 method. Meanwhile, theoretical maximum specific gravity ($G_{mm}$) of each mix was determined through the Dryback Method on two field cores broken down in the laboratory to capture any additional binder content from material treatments such as VRAM or RPE that may impact the $G_{mm}$ value. One $G_{mm}$ sample from each treatment section was then sent for extraction to determine asphalt content following AASHTO T 164. Extracted aggregate was tested for particle size distribution following AASHTO T 30.

### 6.2.2 Permeability

For each test section, six out of twelve field cores were tested for permeability. Additionally, loose plant mix was compacted in the lab to determine a baseline permeability value for the surface mix without consideration to construction practices (i.e. no joint), no rumble strips, and no material treatments.

The permeability test uses 150mm (6-in) specimens, and for the field cores, each was cut at the interface of the existing pavement surface to ensure the VRAM system was preserved with the new HMA overlay where applicable. The falling head permeameter (Figure 6.3) as developed by Florida DOT was used to determine the permeability constant as shown in Equation 1 for each sample. At least three replicates were run per field core, following the FDOT standardized method FM 5-565. The average permeability constant was reported for each treatment section and for the plant produced lab compacted samples.

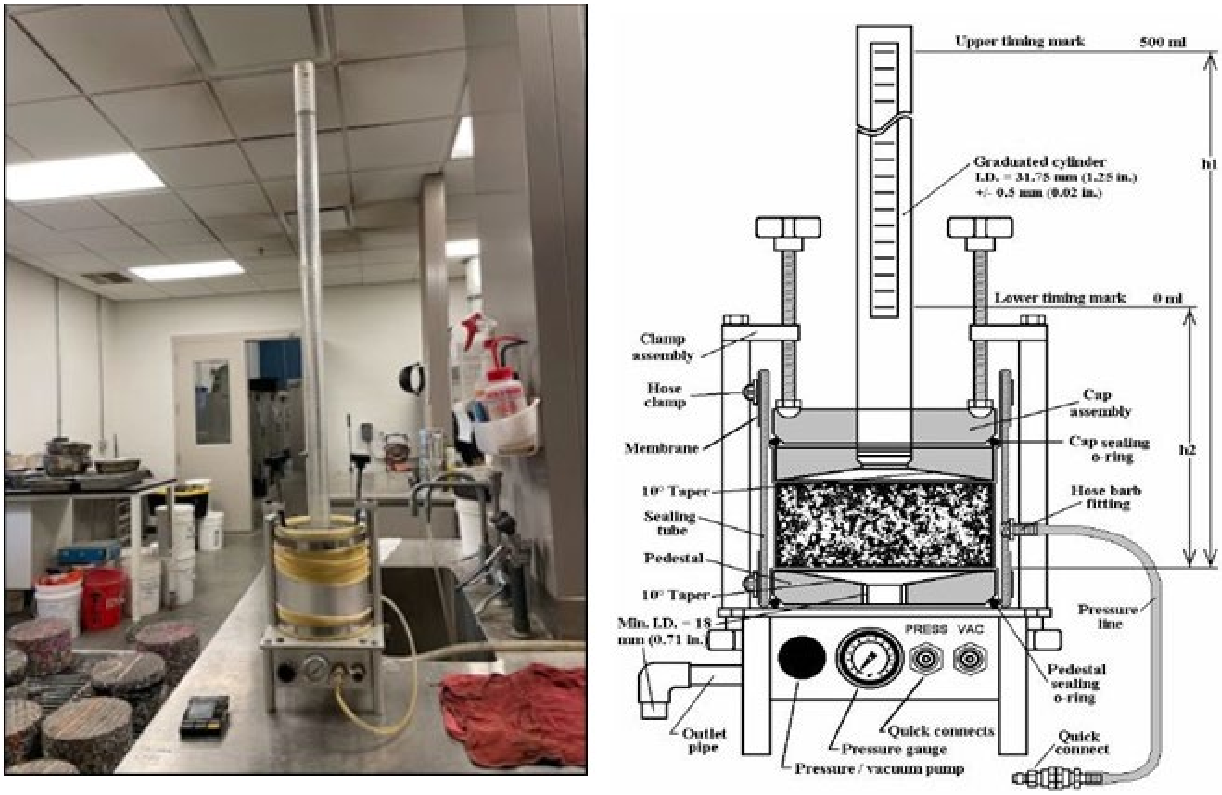



**Figure 6.3: Permeability Lab Test Set Up and Schematic Representation.**

$$k = \left[\left(\frac{aL}{At}\right) * \ln\left(\frac{h_1}{h_2}\right)\right] * t_c$$

**Equation 1**

Where:

$k$ = coefficient of permeability

$a$ = cross-sectional area of standpipe

$L$ = thickness of test specimen

$A$ = cross-sectional area of test specimen

t = time elapsed between h1 and h2

$h_1$ = initial head

$h_2$ = final head

$t_c$ = temperature correction factor

### 6.2.3 Texas Overlay Test

The Texas Overlay Test (OT) following Tex-248-F method is designed to evaluate the susceptibility of bituminous mixtures to reflective cracking. In the current study, this method was applied to assess the performance of asphalt mixtures under repeated loading, simulating the fatiguing action at joints undergoing expansion and contraction.

Three field cores from each treatment section were dedicated to OT testing. Additionally, plant produced laboratory compacted samples were prepared to evaluate the cracking resistance of the surface mixture. All samples were 150mm in diameter, 76mm wide, and thickness of each sample varied due to the presence of rumble strips and the constructed surface layer thickness.

Testing was conducted at a constant temperature of 25°C in the Asphalt Mixture Performance Tester (AMPT) as shown in Figure 6.4. The test applies a cyclic triangular waveform with a maximum displacement of 0.635 mm. Each cycle takes 10 seconds, with the sliding block reaching maximum displacement in 5 seconds and returning to its initial position in the next 5 seconds. The overlay tester records load, displacement, and temperature every 0.1 seconds. The data is used to calculate the Critical Fracture Energy (CFE) and Crack Propagation Rate (CPR) parameters.

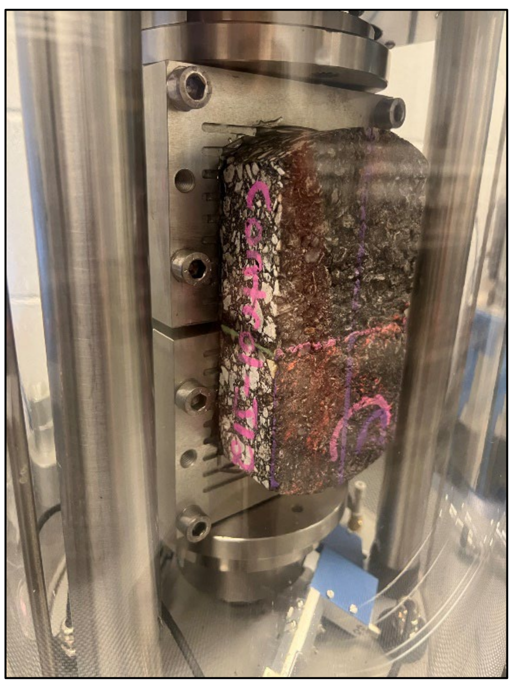
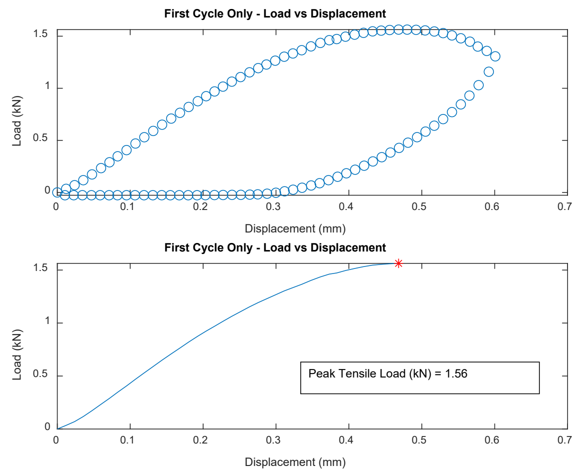


**Figure 6.4: Overlay Test Set Up in Asphalt Mixture Pavement Analyzer With Samples Oriented Such That the Pavement Surface or Ruble Strips Are on Top Side (Not Glued).**

CFE measures the energy required to initiate a crack at the bottom of the specimen during the first loading cycle. It characterizes the specimen's resistance to cracking at the onset of the test. Equation 2 is used to calculated CFE from Figure 6.5.  A higher CFE value is considered desirable.




**Equation 2**

$$CFE = \frac{W_C}{b * h}$$

Where;

CFE = critical fracture energy J/m$^2$

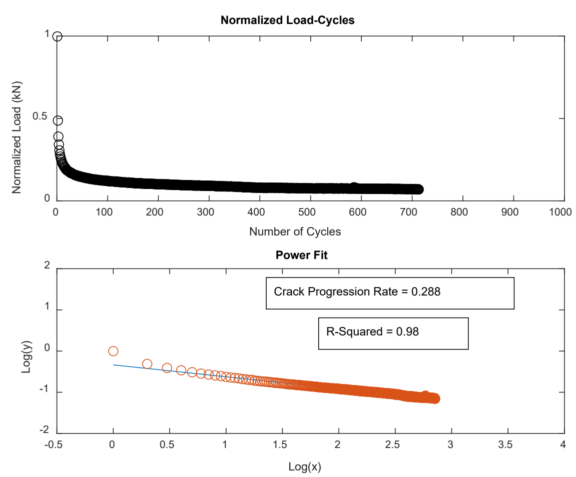
$W_c$ = fracture area (J)

b = specimen width (m)

h = specimen height (m)

**Figure 6.5: Example Plot of First Cycle During Overlay Test Showing Load Versus Displacement Curve.**

Meanwhile, CPR quantifies the reduction in load necessary to propagate the crack under cyclic loading conditions. It reflects the flexibility and fatigue properties of the specimen as the crack grows. CPR is determined by the rate at which the load decreases over the number of cycles. Mathematically CPR is expressed as shown in Equation 3, where beta is a parameter derived from the load reduction data as shown in Figure 6.6. A lower CPR value indicates better resistance to crack propagation, meaning the material is more flexible and has better fatigue properties.




**Equation 3**

Power Equation representing normalized load reduction curve

$$y = ax^b$$

Where;

y = normalized load (kN)

x = number of cycles

a = coefficient equals to unity

b = crack progression rate

**Figure 6.6: Example Plot Showing Normalized Peak Load Versus Number of Cycles And Power Fit Curve Used To Determine Crack Propagation Rate (CPR).**

### 6.2.4 Indirect Tensile Cracking Test (IDEAL-CT)

The Indirect Tensile Asphalt Cracking Test (IDEAL-CT) is used to determine the cracking susceptibility of the asphalt mixture in accordance with ASTM D8225-19. The IDEAL-CT test requires 150mm diameter field cores or lab compacted specimens. The test is designed for 62mm specimen height but may be used for other heights, such as, 38.1 – 50.8mm. The test is run in an indirect tensile fixture at a temperature of 25°C and 50mm per minute loading rate.

Similar to permeability testing, plant produced, lab compacted specimens were fabricated to assess the cracking resistance properties of the surface asphalt mixture without considering the presence of the joint or treatments to the joint as a baseline. Additionally, three field cores from each treatment section with and without rumble strips were randomly selected for IDEAL-CT testing. As explained before, each core was cut at the interface of the surface and intermediate lifts, taking care to preserve the VRAM with the surface mix for testing. Figure 6.7 shows an example of the IDEAL CT test set up. Upon conclusion of the test, load-displacement curves were analyzed in depth along with the calculation of the CT-Index as shown in Equation 4.


**Figure 6.7: IDEAL-CT Setup for Testing of Field Cores.**

$$CT\ Index = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^{-6}$$

Equation 4

Where:
$CT\ Index$ = cracking tolerance index
$G_f$ = failure energy (Joules/m$^2$)
$l_{75}$ = displacement at 75% the peak load after the peak (mm)
$|m_{75}|$ = absolute value of the post peak slope $m_{75}$ (N/mm)
$D$ = specimen diameter (mm)
$t$ = specimen thickness (mm)

# Chapter 7: Results and Discussion

## 7.1 Specific gravity and air voids

Air void content of field cores was determined with two main objectives: first, to understand the effect of material treatments on air void content of the joint and consequently, its potential impacts on performance properties, with and without CLRS.

Maximum specific gravity ($G_{mm}$) for each test section was determined through the Dryback Method and results are shown in Figure 7.1. Specific gravity varied for each project as each followed a distinct mix design, where the Job Mix Formula (JMF) values of $G_{mm}$ were 2.487, 2.468 and 2.583 for Rock Co., Wood Co. and Sheboygan Co., respectively. Nevertheless, all three projects showed a reduction in $G_{mm}$ for sections containing VRAM relative to the untreated sections, likely due to the increased binder content. On the other hand, RPE, applied at lower rates and only containing 38% residual asphalt, resulted in comparable specific gravity to the untreated sections, both with and without rumble strips.

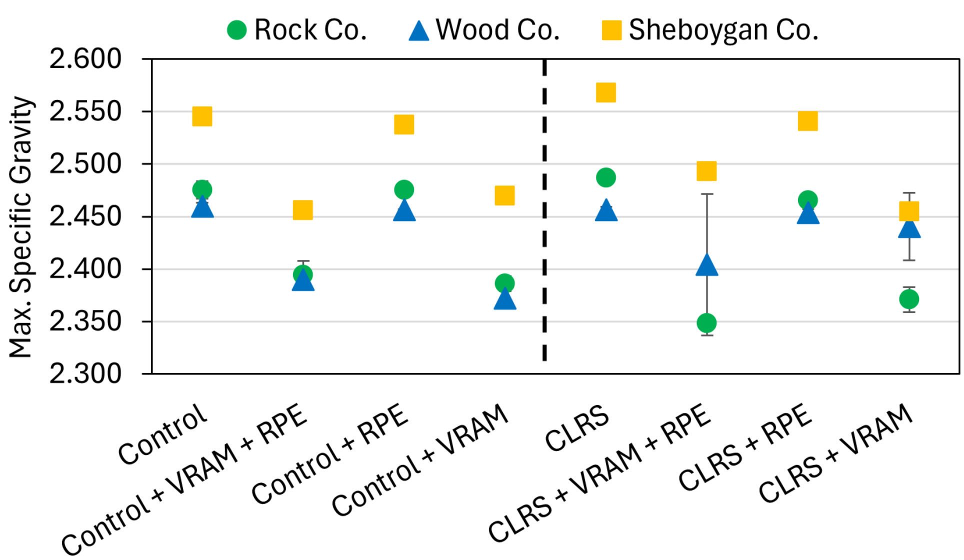



**Figure 7.1: Maximum Theoretical Specific Gravity of Field Cores for Each Test Section and Project.**

The bulk specific gravity ($G_{mb}$) of trimmed cores measured following AASHTO T 166 was used with the above values of $G_{mm}$ to calculate air void content, as shown in Figure 7.2. A target air void content of 7% is commonly used for performance testing of asphalt mixtures; this target is indicated on Figure 7.2 for reference. Different trends were observed across the three field projects, both due to milling of CLRS and application of material treatments. Sheboygan Co. showed the largest change in air void content on CLRS sections, with a 2% increase relative to the control sections (from 12.8% to 15.1%).

On the other hand, air void content increased only slightly for Rock Co. and remained virtually unchanged after the addition of rumble strips at Wood Co. Two potential reasons why a greater increase in air void content was observed in Sheboygan Co. after the installation of rumble strips may be (1) a higher starting air void content at the longitudinal joint, or (2) the type of rumble strip geometry utilized. Starting with higher air voids after construction might favor a greater degradation of the joint in addition to milling of rumble strips, resulting in even more interconnected voids. This could potentially lead to a more accelerated deterioration of the joint due to greater moisture ingress and faster oxidation rate of the mix. In terms of geometry, both Rock and Sheboygan counties followed the standard geometry for CLRS per WisDOT, while Wood followed a sinusoidal milling pattern, which could indicate that the latter might be more beneficial for joint durability. However, the effects of CLRS geometry fall beyond the scope of this research project as they were regarded as equal.

The application of material treatments showed effectiveness at reducing air void content, meaning they can contribute to mitigating damage at the joint, both with and without rumble strips. It is well understood that lower voids are indicative of higher field density, which contributes to greater pavement durability. The most distinct improvement was found at Sheboygan Co., with VRAM causing the greatest reduction in air voids relative to the untreated sections (5.4% for the Control and 4.8% for CLRS). Similar trends were observed for the VRAM-containing sections in Rock Co., with reductions of around 2% relative to the control – while Wood Co. remained mostly unchanged. It should be noted, however, that the trimming of field cores along the lift line occasionally stripped off some of the binder film, potentially impacting air void content of VRAM cores.

Overall, the milling of CLRS increased the air void content along the longitudinal joint, particularly for the Sheboygan County project and, to a lesser extent, Rock Co. Although the increase in air void content might lead to accelerated damage along the joint, both RPE and VRAM proved effective at reducing air void content, even without the presence of rumble strips.

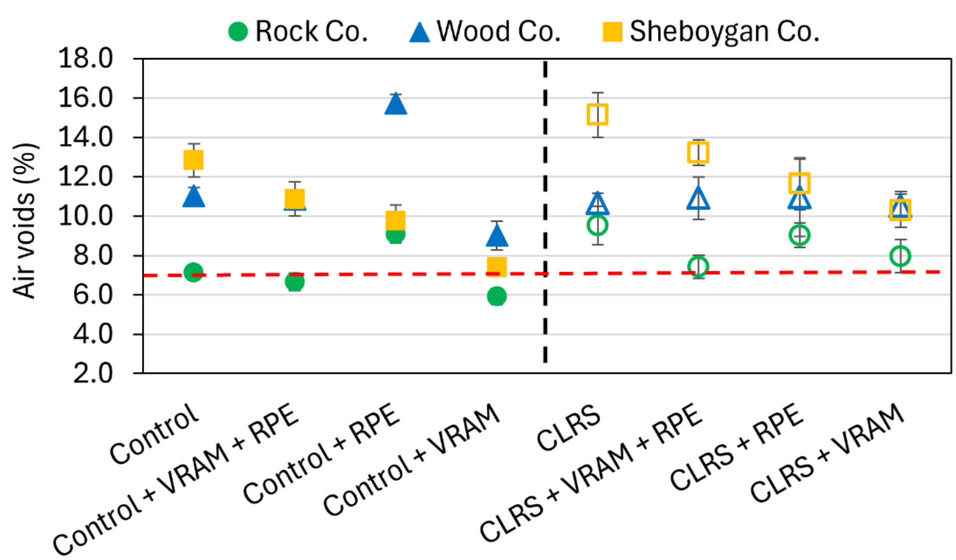



**Figure 7.2: Average Air Void Content of Field Cores for Each Test Section and Project.**

It is also worth noting that the air void content of cores across sections and projects differs greatly from the target air void content for laboratory performance testing, which may challenge performance data interpretation and comparison. For laboratory compacted specimens, the target air void content is $7.0 \pm 0.5\%$ for Ideal CT, the Texas Overlay and permeability tests, but most test sections showed higher values, with some even greater than 15%. This is inherent to testing of field cores and is considered in the interpretation of results.

## 7.2 Asphalt content and gradation

Field cores from each test section were subjected to binder extraction, and the extracted aggregate was tested for particle size distribution. Extracted asphalt content and gradations for Rock Co. are presented in Figure 7.3 and Figure 7.4, respectively.

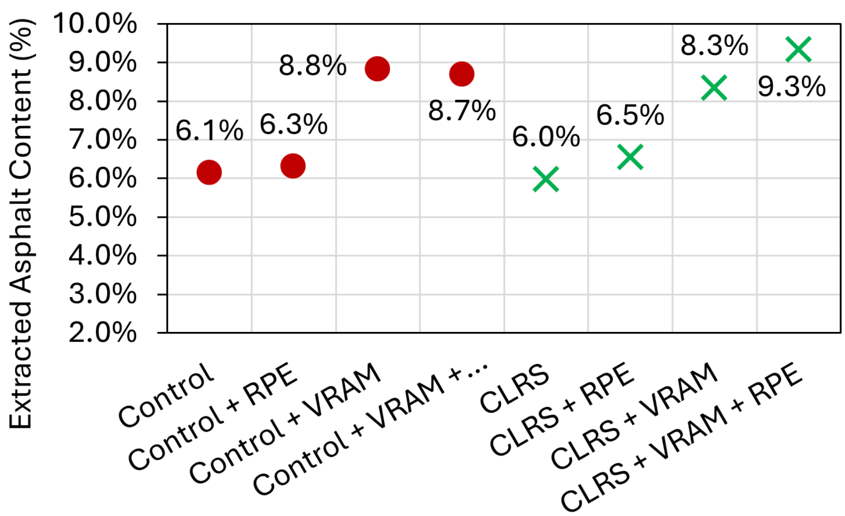



**Figure 7.3: Extracted Asphalt Content for Rock Co. Test Sections.**

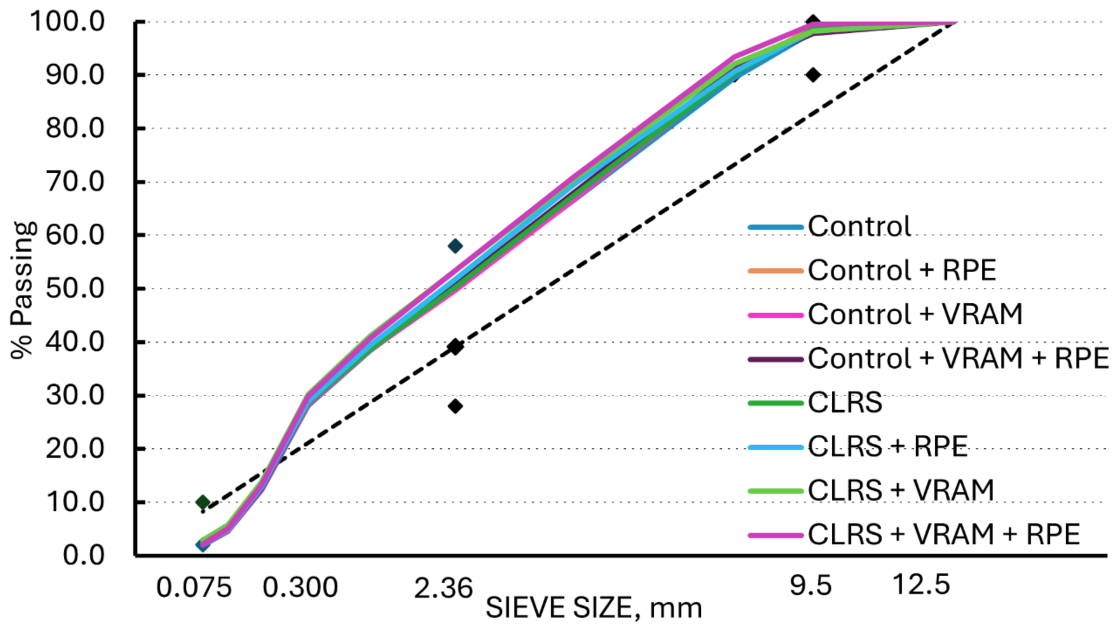



**Figure 7.4: Extracted Aggregate Gradations from Rock Co. Test Sections.**

The binder contents for the multiple test sections were aligned with the expected effects of each material treatment, for sections with and without rumble strips. The untreated sections showed consistent binder contents of approximately 6%, which increased with the application of treatments along the longitudinal joint. RPE caused an increase of a few tenths, consistent with an emulsion with low residual asphalt content. On the other hand, the presence of VRAM below the joint was accompanied by an increase in asphalt content of approximately 3%, for sections with and without rumble strips. Not only did this material treatment increase the binder content along the joint, but it is also worth noting this binder is highly polymerized, two variables which might bring benefits for performance properties and will be discussed in the coming sections.

As far as extracted aggregate gradations, results for Rock Co. showed consistency across sections, as given by the overlapping curves. Thus, it is concluded that sampling was conducted with considerable precision, resulting in field cores that were highly representative of each test section as well as the overall field project. With high uniformity in gradation and consistent binder contents across sections, results of performance evaluation better reflect differences in material treatments.

Similarly, extracted binder content and gradations for Wood County test sections are presented in Figure 7.5 and Figure 7.6, respectively. As with Rock Co. binder content along the joint increased on the VRAM treated sections, with a 2% increase for the control sections, as opposed to a 1% for the CLRS section. However, as VRAM is applied prior to paving, this difference is not attributed to the milling of CLRS themselves, but potentially to the trimming along the lift line of the core that stripped off some of the VRAM binder film.

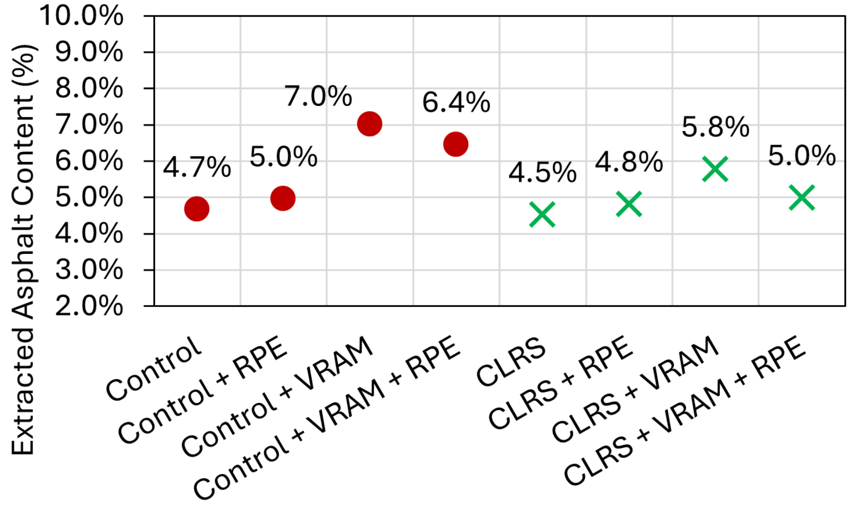



**Figure 7.5: Extracted Asphalt Content for Wood Co. Test Sections.**

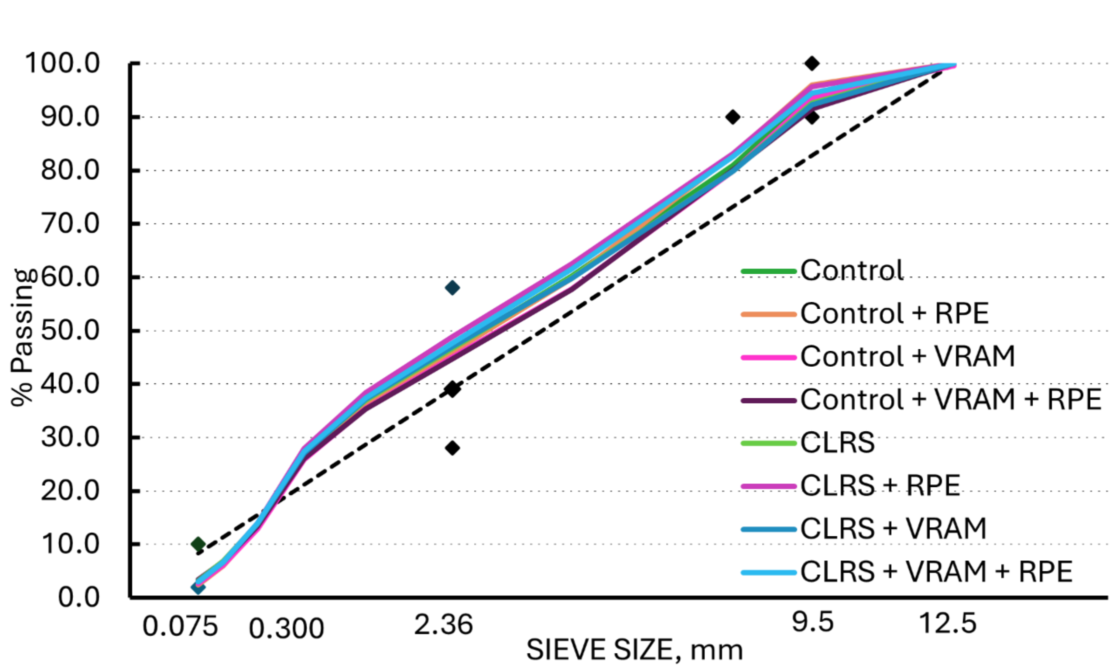



**Figure 7.6: Extracted Aggregate Gradations from Wood Co. Test Sections.**

The extracted gradations in Figure 7.6 show a similar consistency to that found for Rock Co, with overlapping gradation curves across every test section. Although some spread is observed, especially on the mid-sized sieves, measured differences are between 1 and 2%, all within the expected testing variability. Once again this highlights the consistency in sampling, which led to highly representative field cores.

Results for extracted binder content and gradations for Sheboygan Co. are presented in Figure 7.7 and Figure 7.8, and exhibit similar results to the previous two projects.

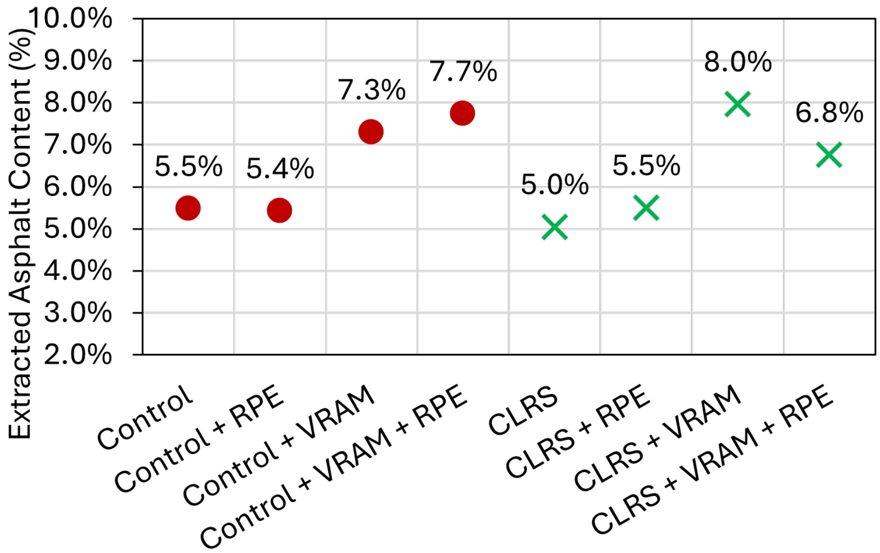



**Figure 7.7: Extracted Aggregate Gradations for Sheboygan Co. Test Sections.**

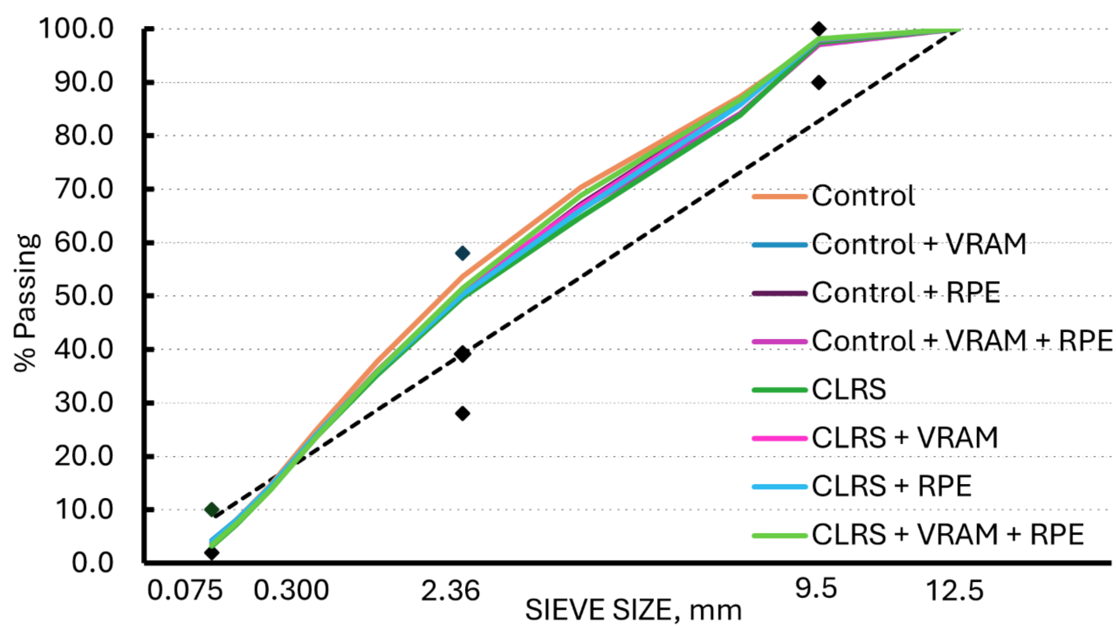



**Figure 7.8: Extracted Aggregate Gradations for Sheboygan Co. Test Sections.**

The control as well as CLRS sections exhibited an increase in binder content of around 2% with the presence of VRAM relative to the untreated sections. It is noted that in every case the untreated binder content was project specific and depended on the HMA mix design that was selected for each county. Similarly, the extracted aggregate gradation was project specific, and low variability was observed across the eight evaluated test sections.

Overall, extracted asphalt content and gradation showed similar trends across the three field projects in this work. First, an increase in asphalt content of 2 to 3% was found for sections containing VRAM or a combination of VRAM and RPE. In addition, extracted aggregate gradations showed considerably low dispersion across test sections within each of the three projects. More specifically, no differences beyond testing variability were observed between the control sections and those containing CLRS. From a durability standpoint this is a major factor to keep in mind, as the milling of CLRS did not cause significant aggregate degradation or major changes in gradation along the joint.

## 7.3 Permeability

Permeability evaluation was conducted on field cores trimmed along the asphalt interface, meaning sample height matched the overlay lift thickness and included the underlying VRAM, whenever present. One objective of this research was to determine whether the milling of CLRS would lead to more permeable mixes along the joint. To this end, permeability results for Rock Co., Wood Co. and Sheboygan Co. are presented in Figure 7.9 (a), (b) and (c).

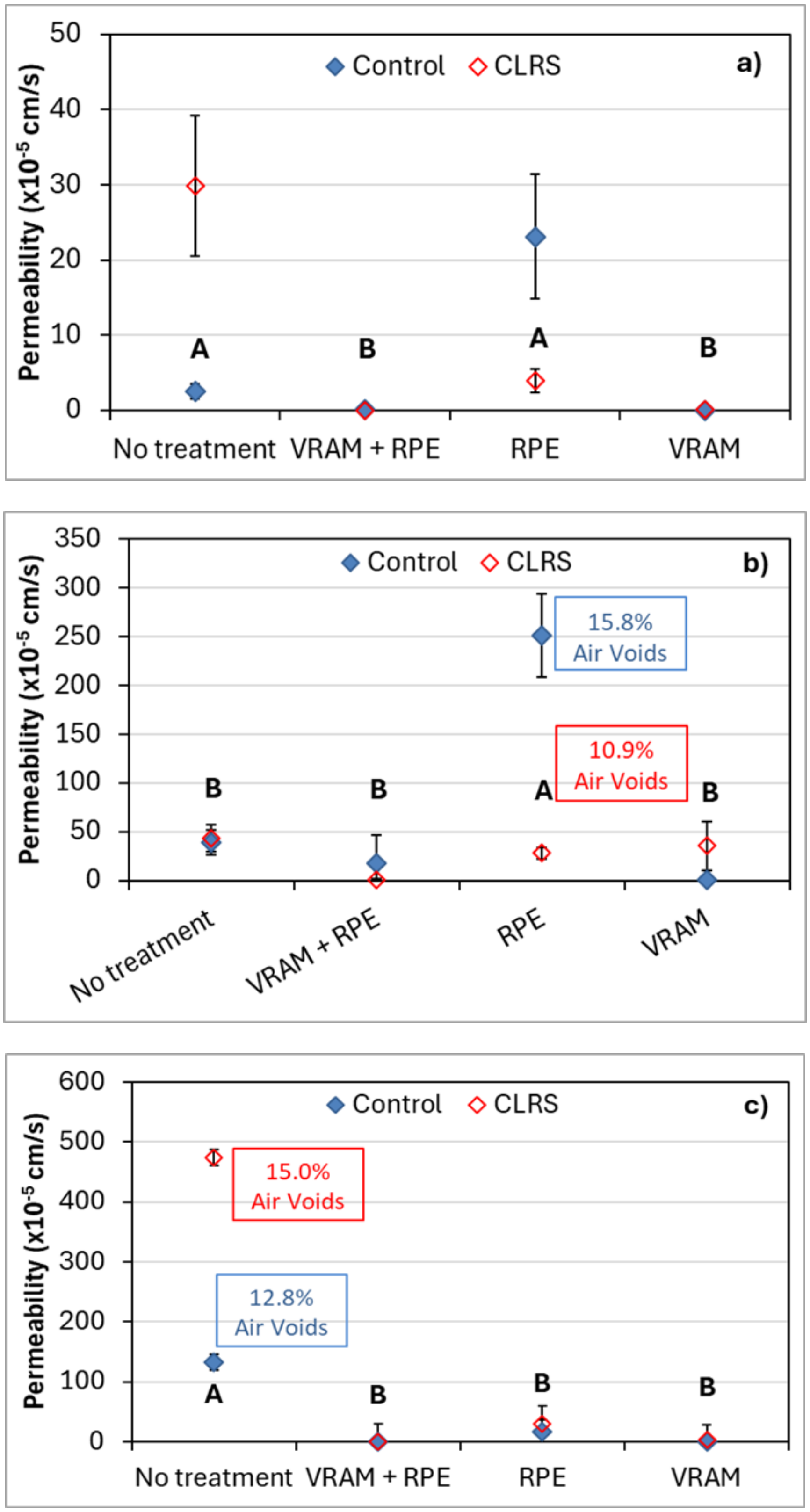



**Figure 7.9: Permeability Results for Control and CLRS Sections on (a) Rock Co., (b) Wood Co., and (c) Sheboygan Co.**

Results for the three counties showed that for the majority of test sections, the milling of CLRS did not increase permeability at the joint. Statistical analysis for a confidence level of 95% was performed, with results sharing the same letter indicating no significant difference in permeability between the control (solid filled markers) and CLRS (unfilled markers) test sections.

Figure 7.9 (b) for Wood Co. shows a statistical difference in permeability between the Control and CLRS for the RPE treated section alone. While it is hypothesized that the milling of rumble strips would lead to higher permeability values, the opposite was true for the RPE treated sections. Therefore, the significantly higher permeability may be attributed to the higher air void content of the RPE control section (15.8%) relative to the RPE section with rumble strips (10.9%).

Similarly, Figure 7.9 (c) for Sheboygan Co. shows a statistically significant difference in permeability for the CLRS untreated section as opposed to the control. In this case, the CLRS section field core had 15% air voids, while the control had 12.8% air voids, which may explain the difference in permeability. As shown in Section 7.1 , the milling of CLRS did not cause a systematic increase in air voids across test sections. Thus, these differences in permeability potentially resulted from variability in air void content when testing field cores from the longitudinal joint.

While Figure 7.9 (a), (b) and (c) showed that milling CLRS did not significantly increase permeability, the magnitude of permeability measurements is also worth highlighting. If the high air void sections are disregarded, the permeability of all three projects fell below 100 x $10^{-5}$ cm/s, on sections with and without rumble strips. A number of studies have determined 100 x $10^{-5}$ cm/s as the critical field permeability value for 12.5mm NMAS mixtures, below which pavements may be considered impermeable (Cooley Jr., Brown, & Maghsoodloo, 2003; Hainin, Cooley JR, & Prowell, 2003; Mallick, Cooley Jr, Teto, Bradbury, & Peabody, 2003). Thus, results showed that all field projects were impermeable, even after milling of rumble strips.

Although rumble strips did not harm permeability, this study showed the longitudinal joint had high air void contents (Figure 7.2), which would make it highly susceptible to moisture ingress and asphalt oxidation. Thus, the application of material treatments might be helpful at mitigating that risk, regardless of the presence of rumble strips. Therefore, the effect of material treatments on permeability was studied for each field project, with and without rumble strips. Results for Rock Co. detailed in Figure 7.10 (a), (b) and (c).

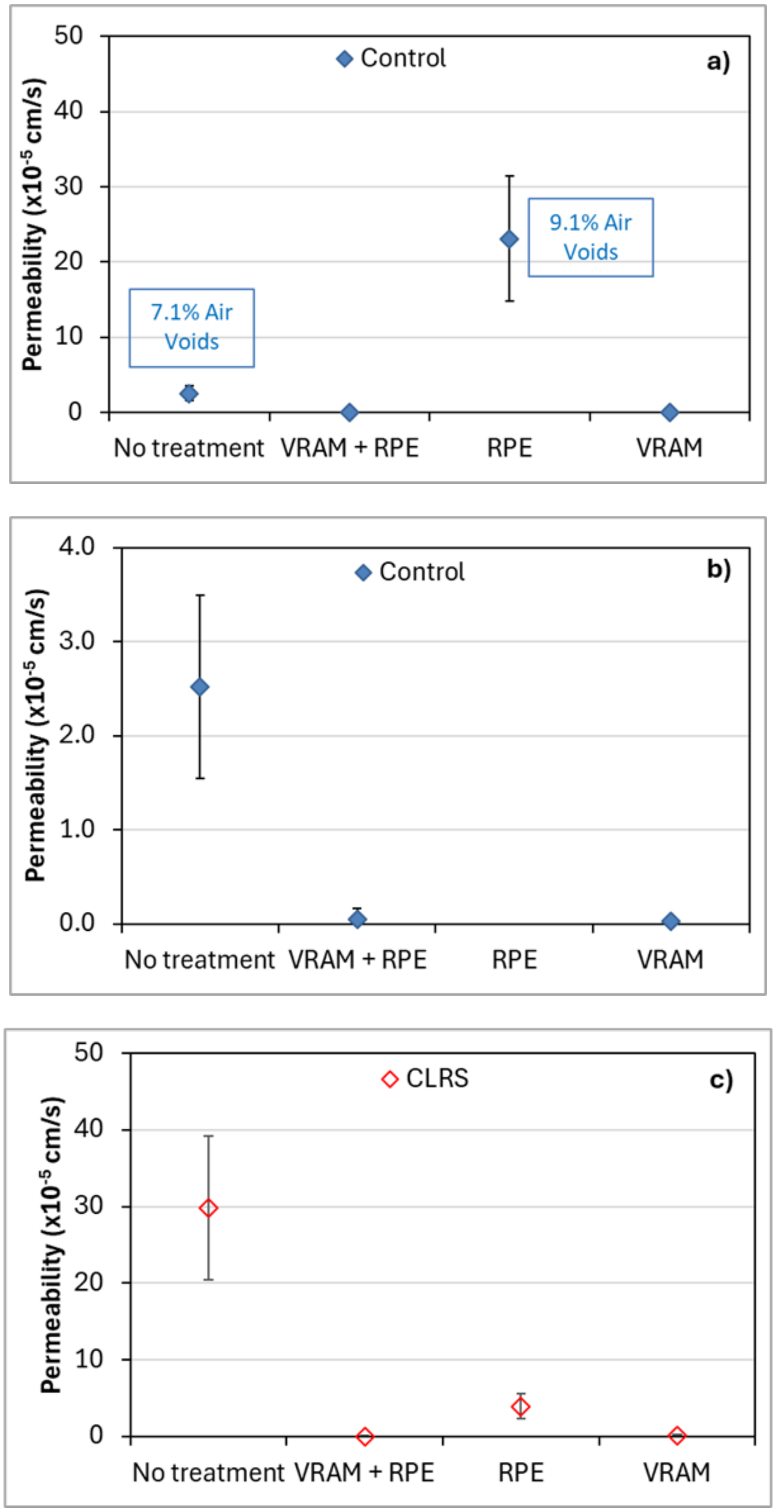



**Figure 7.10: Permeability Results for Rock Co. (a) Without Rumble Strips (b) Without Rumble Strips After Removing RPE Outlier and (c) With Rumble Strips.**

When analyzing permeability results for the Control sections of Rock Co. (Figure 7.10 (a)) the value for the RPE section appeared significantly higher than any other material treatment, and even higher than the untreated section. However, air void content for said section was 2% higher than any other, potentially leading to the increased permeability. For this reason, it was considered an outlier and removed from the dataset, as shown in Figure 7.10 (b). When looking at Figure 7.10 (b) and (c), a similar trend can be observed, which indicates that the application of material treatments reduced permeability relative to the untreated counterpart. Although the Rock Co. mixture may essentially be considered impermeable, with every value lower than $30 \times 10^{-5} cm/s$, both VRAM and RPE contributed to an even lower permeability at the joint.

A similar analysis was performed for Wood Co., as shown in Figure 7.11 (a), (b) and (c). The RPE test section presented results that differed considerably to the remaining control sections (Figure 7.11 (a)), possibly due to higher air void content (15.8 % against 11.1% for the untreated) and was thus considered an outlier. Consequently, both the control and the CLRS test sections followed a similar trend to Rock Co., where the addition of material treatments reduced permeability along the joint, regardless of the presence of rumble strips.

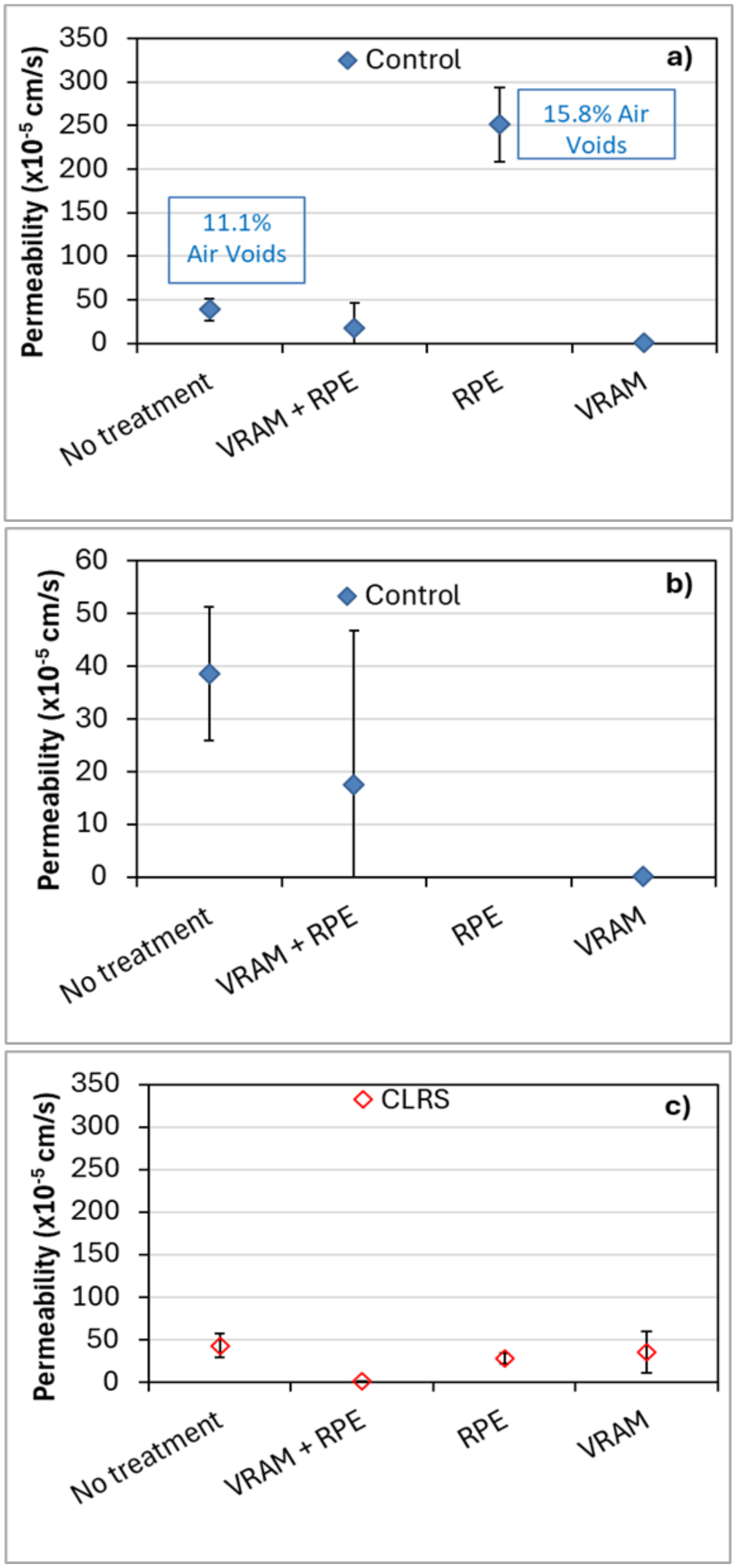



**Figure 7.11: Permeability Results for Wood Co. (a) Without Rumble Strips (b) Without Rumble Strips After Removing RPE Outlier and (c) With Rumble Strips.**

Finally, permeability results for Sheboygan Co. are presented in Figure 7.12 (a) and (b). A clear trend is observed for sections with and without rumble strips, where the application of material treatments consistently decreased permeability. As with Rock and Wood projects, permeability values for most test sections are low enough to be considered impermeable, possibly due to being a fine-graded dense asphalt mixture. However, the milling of rumble strips led to a considerable increase in permeability from $132 \times 10^{-5} cm/s$ to $474 \times 10^{-5} cm/s$. To this end, the application of material treatments resulted in permeability results close to zero, making the joint essentially impermeable, even after the milling of rumble strips.

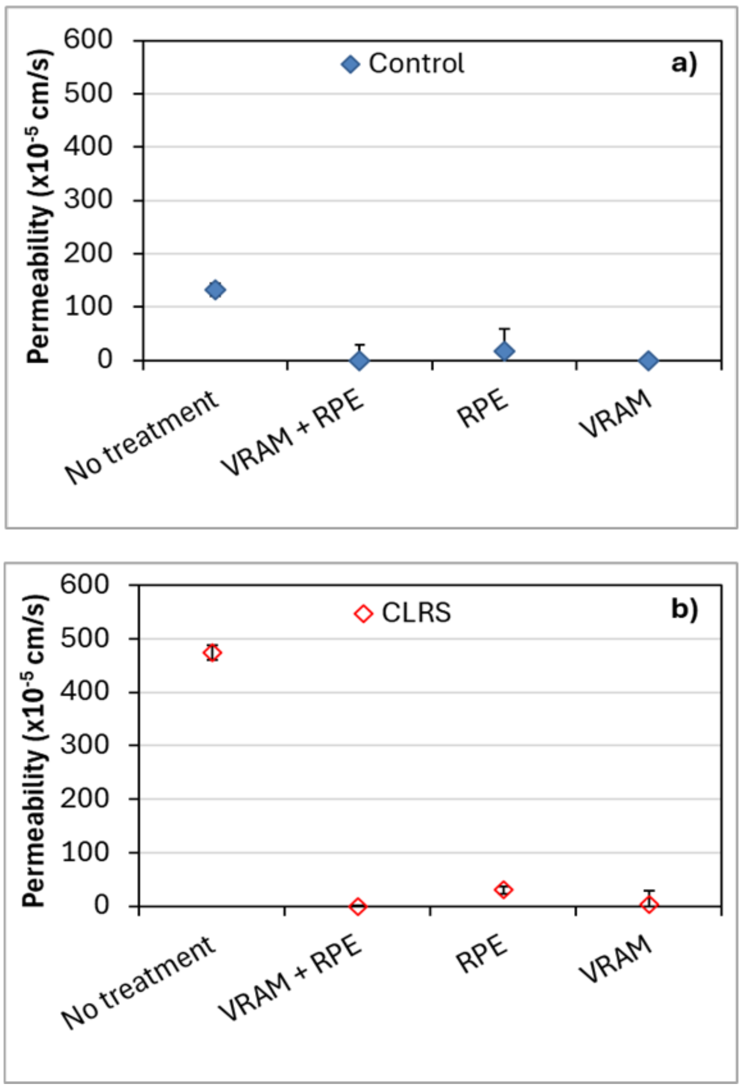



**Figure 7.12: Permeability Results for Sheboygan Co. (a) Without Rumble Strips and (b) With Rumble Strips.**

## 7.4 Texas Overlay Test

Durability of the joint was further evaluated using the Texas Overlay Test. Critical Fracture Energy (CFE) was determined to understand the effects of rumble strips and material treatments on crack initiation, while the Normalized Crack Progression Rate (CPR) was indicative of crack progression.

The effect of rumble strips on crack initiation and propagation was determined across the three field projects. CFE results are presented in Figure 7.13, and results for statistical analysis are shown in Table 9 below. Critical fracture energy appeared to decrease after milling of rumble strips for Rock Co., an increase was observed for Wood Co, and a slight reduction was observed at Sheboygan Co. However, statistical analysis showed that the overall effect of rumble strips on CFE was not significant, as given by the means in the same statistical grouping in Table 9. A reduction in CFE would be indicative of earlier onset of cracking at the joint; therefore, the milling of rumble strips did not harm the integrity of the joint and similar crack initiation would be expected.

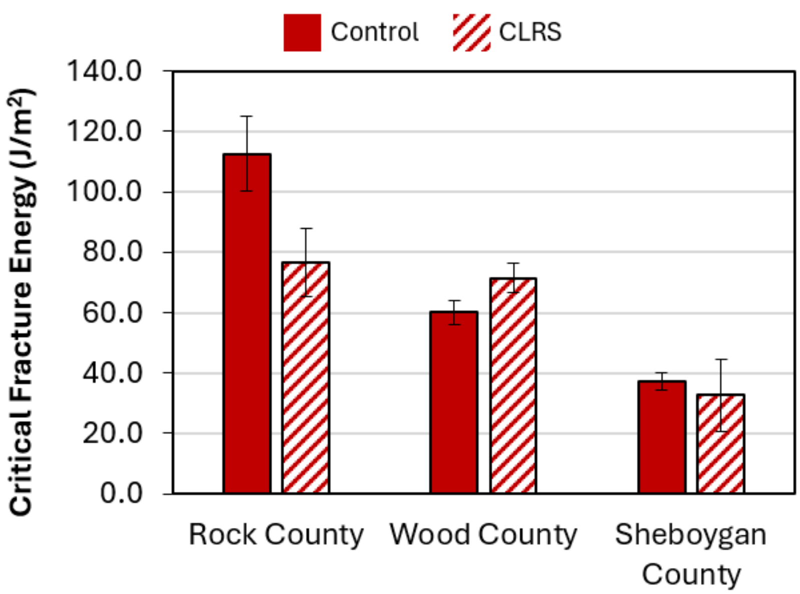



**Figure 7.13: Effect of Rumble Strips on Critical Fracture Energy for All Field Projects.**

**Table 9: Statistical Analysis on Critical Fracture Energy - With and Without Rumble Strips.**

| **Critical Fracture Energy (J/m$^2$)** | | | |
|---|---|---|---|
| Treatment | Mean | Standard deviation | Statistical grouping |
| CLRS | 60.3 | 22.6 | A |
| Control | 70.0 | 34.1 | A |

Meanwhile, CPR results across projects are shown in Figure 7.14, and the corresponding statistical analysis in Table 10 below. In this case, the presence of rumble strips significantly increased CPR relative to the control, with Wood and Sheboygan projects showing a greater increase than Rock Co. Consequently, the presence of rumble strips resulted in a faster crack propagation along the joint, which is considered detrimental to performance. Recalling from Task-1 literature review, research conducted by Weaver et al. showed that milling rumble strips can produce micro cracking at the surface, which could explain the higher CPR as a result of higher stress concentrations on the joint (Weaver, Coleri, & Chitnis, 2023).

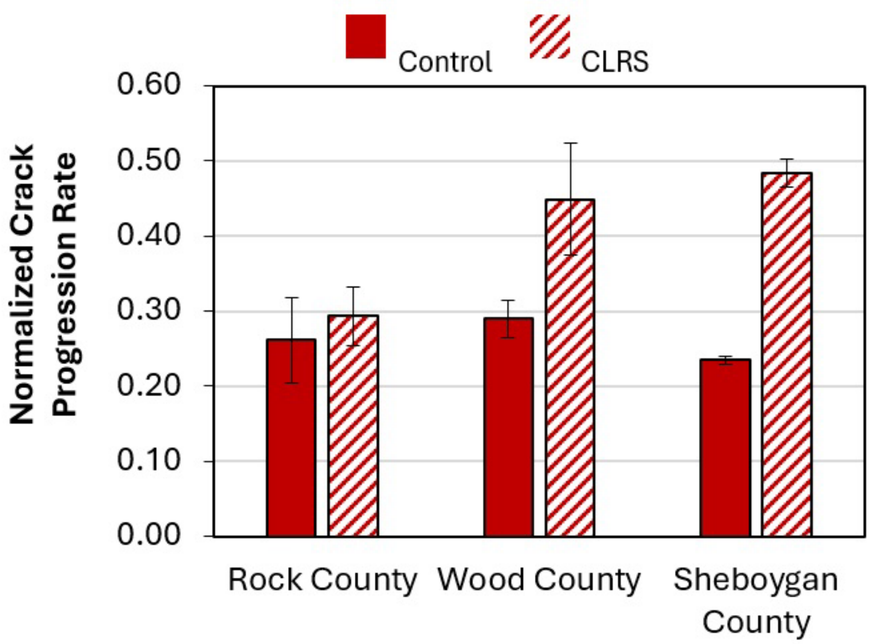



**Figure 7.14: Effect of Rumble Strips on Crack Progression Rate for All Field Projects.**

**Table 10: Statistical Analysis on Normalized Crack Progression Rate - With and Without Rumble Strips.**

| Normalized Crack Progression Rate | | | |
|---|---|---|---|
| **Treatment** | **Mean** | **Standard deviation** | **Statistical grouping** |
| CLRS | 0.4088 | 0.0976 | A |
| Control | 0.2623 | 0.0392 | B |

The above results showed that, when analyzing all field projects, the addition of rumble strips had a negligible effect on crack initiation (i.e. no statistical difference in CFE), but accelerated crack propagation (i.e. increased CPR). Thus, the research team evaluated how each material treatment impacted CFE and CPR, to mitigate the detrimental impacts of rumble strips on cracking performance.

CFE results for Rock Co. are shown in Figure 7.15, with the different material treatments shown side by side. In addition, statistical analysis was performed with a significance level of 95% as summarized in

Table 11 presented below. Means that shared the same letter designation belonged to the same statistical grouping and thus showed no statistical significance. It should be noted that the comparison was performed between treated and untreated sections for the Control, separate from CLRS.

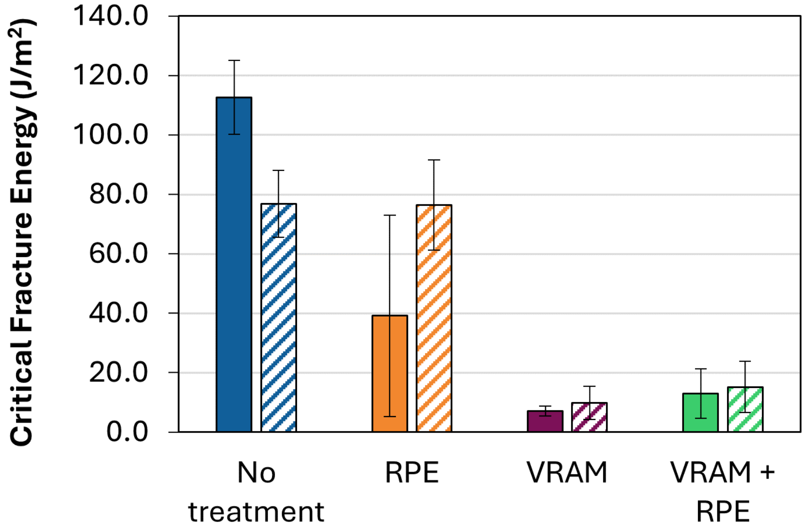



**Figure 7.15: Critical Fracture Energy for Rock Co. - With and Without Rumble Strips.**

**Table 11: Statistical Analysis for Critical Fracture Energy - Rock Co.**

| | Control | | | CLRS | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean ($J/m^2$)** | **Standard Deviation** | **Grouping** | **Mean ($J/m^2$)** | **Standard Deviation** | **Grouping** |
| **No treatment** | **112.6** | **12.4** | **A** | **76.8** | **11.3** | **C** |
| RPE | 39.1 | 33.9 | B | 76.4 | 15.2 | C |
| VRAM | 7.1 | 1.6 | B | 9.8 | 5.6 | D |
| VRAM + RPE | 12.9 | 8.3 | B | 15.2 | 8.6 | D |

The overall trends show that, for both the control and the rumble strips sections, the application of VRAM significantly reduced CFE. As this parameter relates to crack initiation, a lower value would indicate the joint can withstand lower stress levels prior to cracking and would thus be undesirable. However, VRAM consists of a highly modified asphalt binder, and therefore requires higher strains to engage the polymer network and accurately capture binder failure. The first cycle of the overlay test causes a displacement of 0.6mm and it is hypothesized that this did not cause the high strain levels required to measure CFE. On the other hand, RPE did not cause significant changes to CFE relative to the untreated sections, and thus did not contribute to delay crack initiation at the joint.

A similar analysis was performed for crack progression rate, with results and statistical analysis presented in Figure 7.16 and Table 12, respectively.

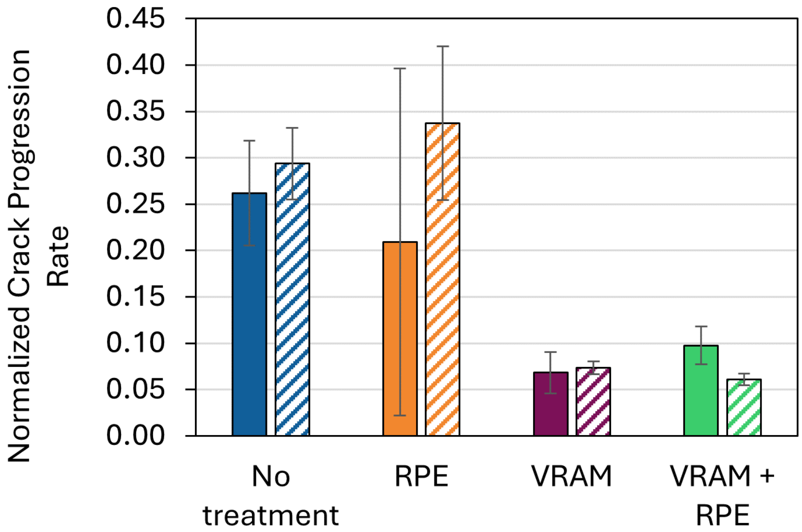



**Figure 7.16: Crack Progression Rate for Rock Co. - With and Without Rumble Strips.**

**Table 12: Statistical Analysis for Crack Progression Rate - Rock Co.**

| | Control | | | CLRS | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean** | **Standard Deviation** | **Grouping** | **Mean** | **Standard Deviation** | **Grouping** |
| **No treatment** | **0.262** | **0.057** | **A** | **0.294** | **0.039** | **C** |
| RPE | 0.209 | 0.187 | A | 0.337 | 0.083 | C |
| VRAM | 0.068 | 0.022 | A | 0.073 | 0.007 | D |
| VRAM + RPE | 0.097 | 0.021 | A | 0.061 | 0.006 | D |

The presence of VRAM effectively reduced crack progression rate on the CLRS sections, whereas no statistical significance was observed for the Control (i.e. shared statistical group "A"). It may be argued that these results on the Control sections might be driven by the high standard deviation shown by the RPE value, leading to confounding effects in the statistical analysis. Overall, the application of VRAM (or VRAM followed by RPE) contributed towards a slower crack propagation rate, which would potentially lead to a greater durability at the joint. Additionally, low stress levels would likely be expected along the longitudinal joint because it is not subjected to traffic loading, which makes crack propagation rate a more suitable indicator for joint durability than critical fracture energy.

CFE and CPR were also studied for Wood Co. test sections. The effect of each material treatment on CFE – with and without rumble strips – is presented in Figure 7.17, and the corresponding statistical analysis in Table 13 below. In this case, RPE reduced CFE for the control sections, but had no significant effect on the CLRS sections. Similar to Rock Co. every section containing VRAM (or VRAM + RPE) saw a significant reduction in CFE, which further supports the hypothesis that the lower CFE is a result of the Overlay Test configuration for the evaluation of polymer modified binders.

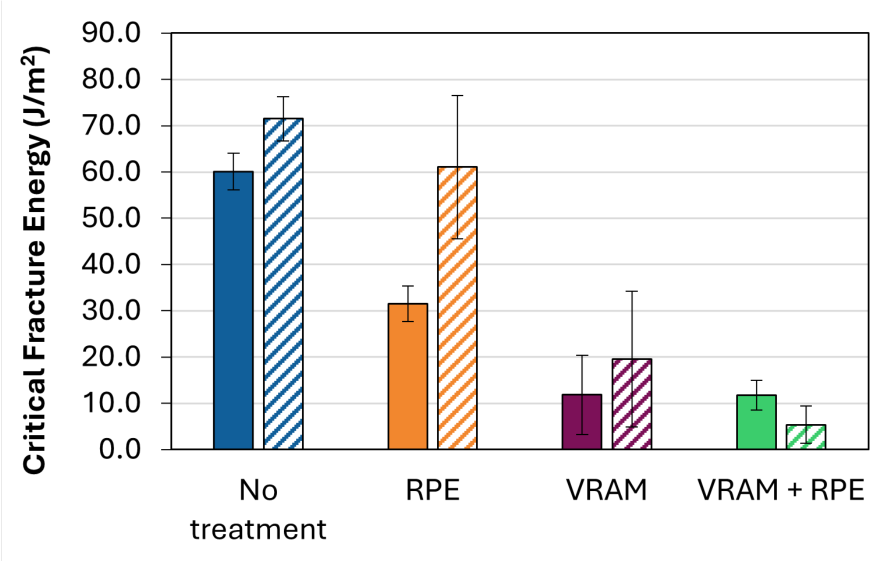



**Figure 7.17: Critical Fracture Energy for Wood Co. - With and Without Rumble Strips.**

**Table 13: Statistical Analysis for Critical Fracture Energy - Wood Co.**

| | Control | | | CLRS | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean ($J/m^2$)** | **Standard Deviation** | **Grouping** | **Mean ($J/m^2$)** | **Standard Deviation** | **Grouping** |
| **No treatment** | **60.1** | **4.0** | **A** | **71.5** | **4.8** | **D** |
| RPE | 31.5 | 3.8 | B | 61.0 | 15.5 | D |
| VRAM | 11.8 | 8.5 | C | 19.6 | 14.6 | E |
| VRAM + RPE | 11.8 | 3.2 | C | 5.4 | 4.0 | E |

Results and statistical analysis for CPR on Wood Co. sections are shown in Figure 7.18 and Table 14, respectively. The application of VRAM led to a significant reduction of crack progression rate, both for control and rumble strips sections but with a clearer trend observed for the latter. Results agree with Rock Co. and appear to indicate VRAM is effective at delaying the propagation of cracks along the longitudinal joint.

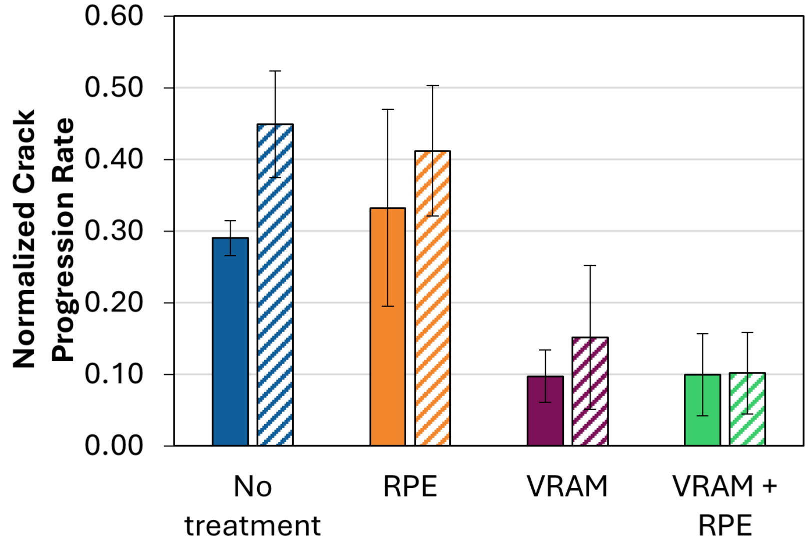



**Figure 7.18: Crack Progression Rate for Wood Co. - With and Without Rumble Strips.**

**Table 14: Statistical Analysis for Crack Progression Rate - Wood Co.**

| | Control | | | CLRS | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean** | **Standard Deviation** | **Grouping** | **Mean** | **Standard Deviation** | **Grouping** |
| **No treatment** | **0.290** | **0.025** | **A/B** | **0.449** | **0.074** | **C** |
| RPE | 0.332 | 0.138 | A | 0.412 | 0.091 | C |
| VRAM | 0.097 | 0.037 | B | 0.152 | 0.101 | D |
| VRAM + RPE | 0.099 | 0.057 | A/B | 0.102 | 0.057 | D |

Finally, CFE results and statistical analysis for Sheboygan Co. are presented in Figure 7.19 and Table 15 below. A similar trend was observed for this field project that aligns with the findings from Rock and Wood Co: the application of RPE kept CFE mostly unchanged, while the presence of VRAM (or a combination of the two) reduced fracture energy, even without rumble strips. The consistency of results across field projects which differ in mix design, base layers and even geometry of rumble strips indicates that this can be attributed to the material treatment itself. Although VRAM reduced CFE, which appears to be detrimental to cracking resistance of the joint, this does not align with the expected performance properties of a polymer modified binder. In this regard, the team argued this might be due to a lower strain level in the test configuration that did not capture the true failure of VRAM. Further work beyond the scope of this project would be needed to confirm this claim.

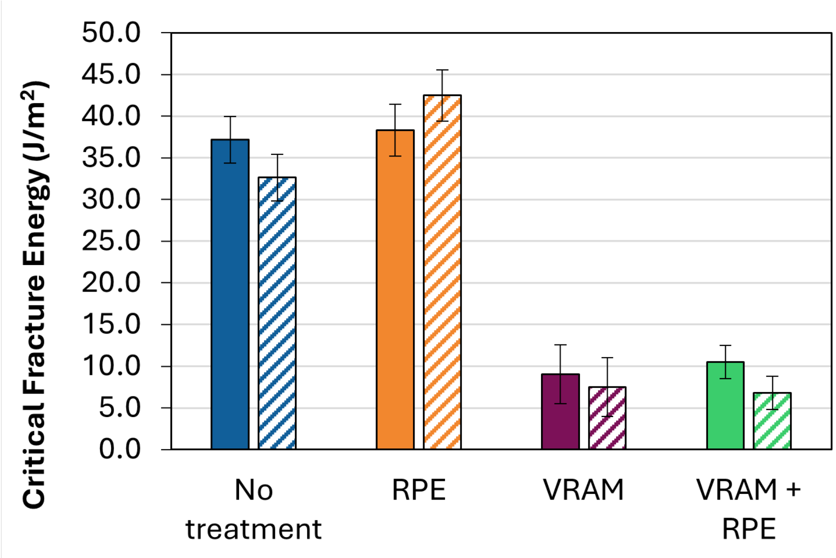



**Figure 7.19: Critical Fracture Energy for Sheboygan Co. - With and Without Rumble Strips.**

**Table 15: Statistical Analysis for Critical Fracture Energy - Sheboygan Co.**

| | Control | | | CLRS | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean ($J/m^2$)** | **Standard Deviation** | **Grouping** | **Mean ($J/m^2$)** | **Standard Deviation** | **Grouping** |
| **No treatment** | **37.2** | **2.8** | **A** | **32.6** | **12.0** | **C** |
| RPE | 38.3 | 3.1 | A | 42.5 | 2.8 | C |
| VRAM | 9.0 | 3.5 | B | 7.5 | 3.2 | D |
| VRAM + RPE | 10.5 | 2.0 | B | 6.8 | 0.9 | D |

Results for crack progression rate for Sheboygan Co. are shown in Figure 7.20, with the corresponding statistical analysis in Table 16 below. Results for Sheboygan Co. also followed the observed trends for Rock Co. and Wood Co., where RPE had no effect on crack propagation, while VRAM resulted in a significant reduction in CPR. Therefore, the application of VRAM enhanced durability of the joint across every field project, not only after the milling of rumble strips but on the control sections as well.

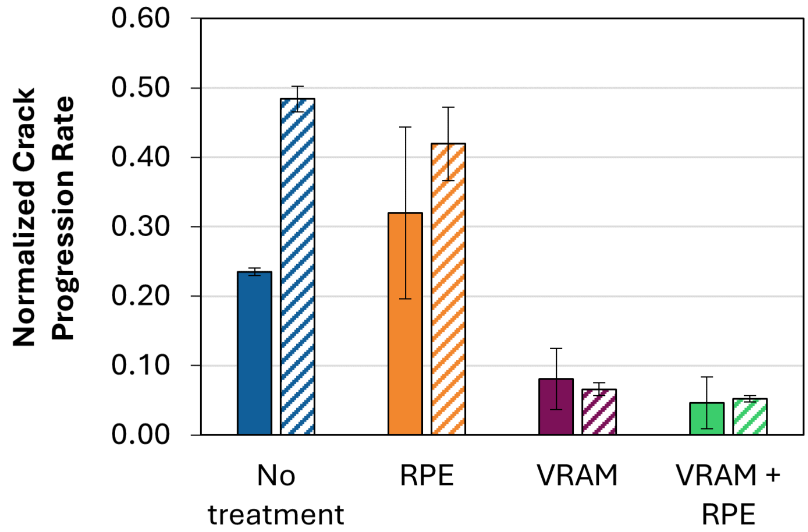



**Figure 7.20: Crack Progression Rate for Sheboygan Co. - With and Without Rumble Strips.**

**Table 16: Statistical Analysis for Crack Progression Rate - Sheboygan Co.**

| | Control | | | CLRS | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean** | **Standard Deviation** | **Grouping** | **Mean** | **Standard Deviation** | **Grouping** |
| **No treatment** | **0.235** | **0.005** | **A** | **0.484** | **0.018** | **C** |
| RPE | 0.320 | 0.124 | A | 0.419 | 0.053 | C |
| VRAM | 0.081 | 0.044 | B | 0.066 | 0.009 | D |
| VRAM + RPE | 0.046 | 0.037 | B | 0.052 | 0.005 | D |

## 7.5 IDEAL-CT

Durability of the joint was further evaluated through the IDEAL-CT test, which addresses cracking resistance of mixtures at intermediate temperatures. The output of the test is the CT Index (see Section 1.1.1 ), where a higher value is indicative of better cracking resistance. CT Index results for Rock Co., Wood Co., and Sheboygan Co. are presented in Figure 7.21, Figure 7.22 and Figure 7.23, respectively.

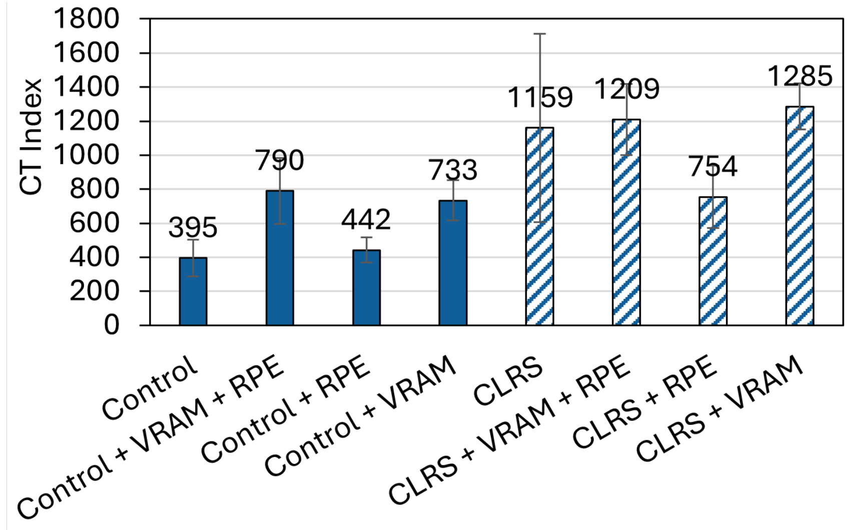



**Figure 7.21: Average CT Index for Rock Co. Test Sections.**

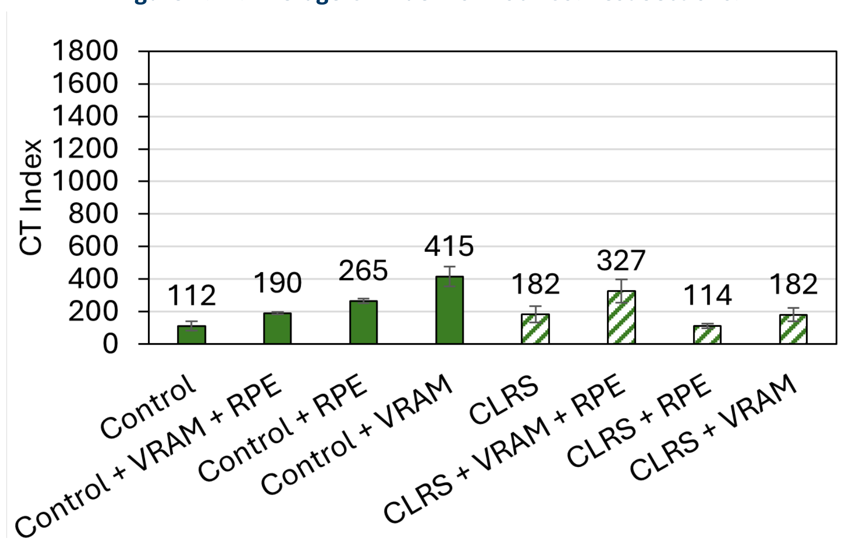



**Figure 7.22: Average CT Index for Wood Co. Test Sections.**

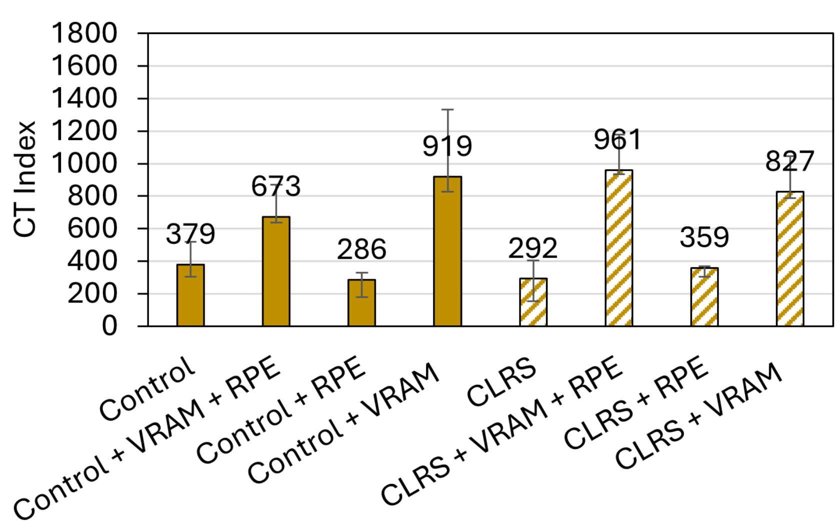



**Figure 7.23: Average CT Index for Sheboygan Co. Test Sections.**

One immediate observation made by the research team is the magnitude of CT Index values for the three field projects, particularly for Rock County. Commonly cited acceptance thresholds for CT Index range from about 30 to 150, whereas values observed during this project reach nearly 1300 units(See Appendix B for additional details). Thus, CT Index values that can go from double to as much as ten-fold the traditionally accepted thresholds might be providing confounding information, especially when evaluating the longitudinal joint, which is known to be a weaker plane within the asphalt mat.

Consequently, the research team decided to study cracking resistance at the joint through the analysis of load-displacement curves obtained through Ideal CT Testing. More specifically, the team analyzed (a) peak load, to target crack initiation, (b) displacement at peak, to understand strain tolerance and (c) post-peak slope to evaluate the ductile behavior of the material as cracking progressed. Figure 7.24 shows a set of overlapping results for Rock Co.: a lab compacted specimen fabricated with plant mix (grey continuous line), an untreated field core from a control section (blue continuous line) and an untreated field core with rumble strips (blue dashed line).

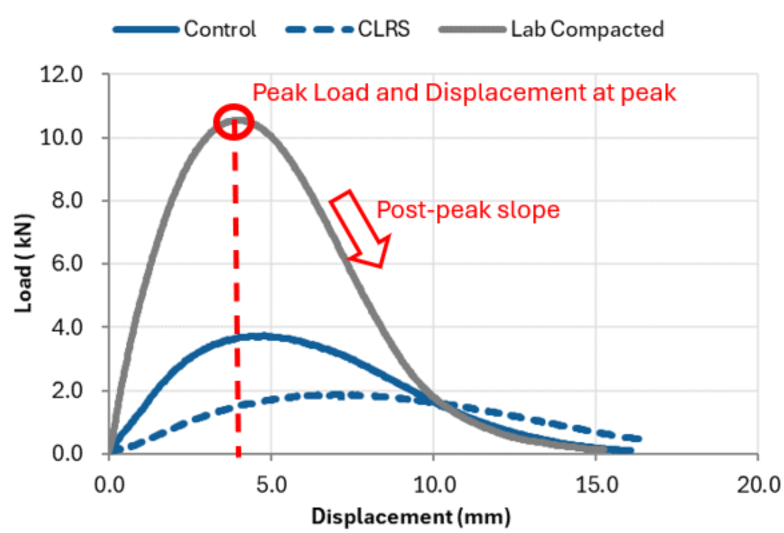



**Figure 7.24: Example Load Displacement Curve for Lab Compacted Specimens and Field Cores.**

The overlapping load displacement curves in the figure above showed the differences in fracture behavior between lab compacted specimens and field cores. First, a considerable reduction in peak load was observed for field cores (with and without rumble strips) suggesting a lower cracking resistance, as samples withstood much lower loading before the onset of cracking. However, displacement at peak shifted slightly right on field cores, especially for the case of rumble strips, which would indicate a higher strain tolerance than for lab compacted specimens. Finally, post peak slopes of field cores showed a considerably flatter slope, suggesting more ductile behavior at the joint, potentially indicating slower crack propagation. The observed differences in load displacement curves indicate that the selected parameters might better explain fracture behavior than the CT Index when testing field cores taken over the longitudinal joint.

The team attempted to explain the causes for the observed differences in load displacement curves. Sample thickness and air void content were identified as the two variables with the greatest potential impact on the load displacement curve shape. Sample thickness was the lift thickness on site, which rarely matched the 62mm height used for laboratory-compacted specimens. However, the CT Index definition (See Section 1.1.1 ) incorporates a correction factor that normalizes the results to a thickness of 62 mm. Air void content was scattered and deviated from the target of 7% traditionally adopted for performance testing (See Section 7.1 ). As the calculation of CT Index does not include an air void correction factor, additional testing was done on lab compacted specimens at varying air void contents, fabricated from plant mix sampled on production days for each project.

Load displacement curves at multiple air void contents are presented in Figure 7.25 for Rock Co. To eliminate any potential variability introduced by material treatments, only the untreated sections were studied, both with and without rumble strips. Testing was done on three replicates per section, therefore a representative curve was selected, as opposed to plotting an "average curve". A lab compacted specimen at 6.2% air voids was compared against a "Control" field core with a similar air void content: 6.9%. Similarly, the representative "CLRS" field core had an air void content of 10.8% and was therefore compared against a lab compacted specimen at 11.1% air voids.

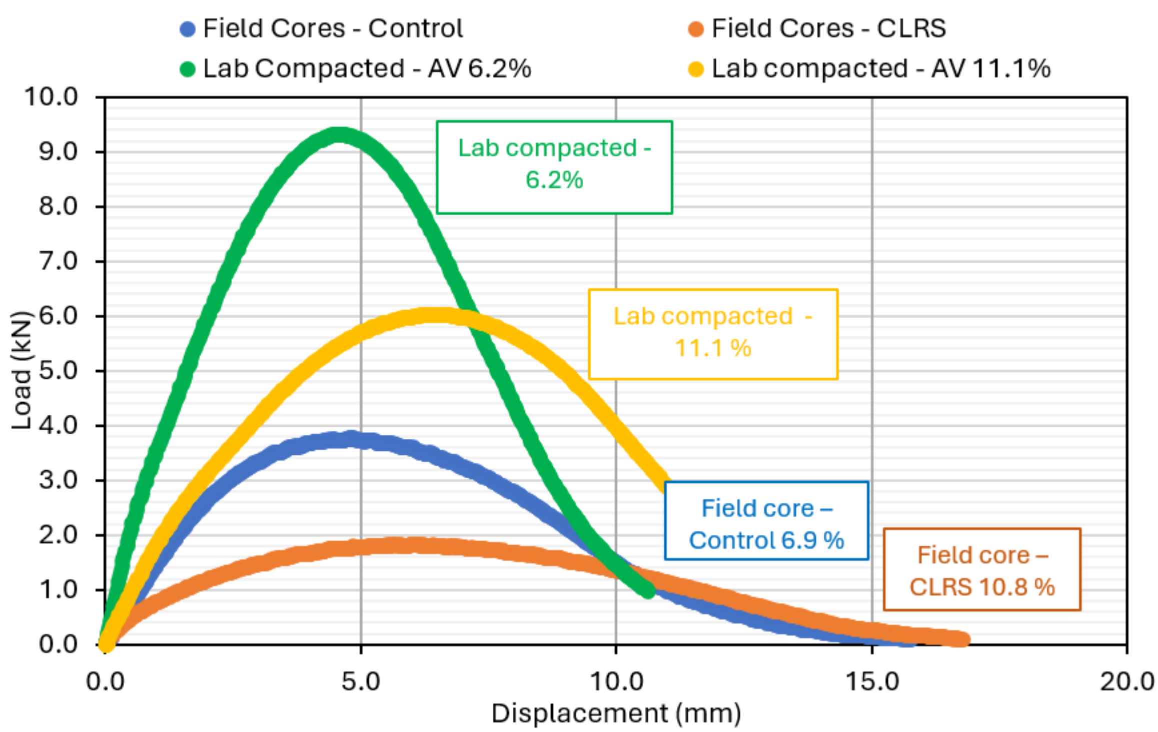



**Figure 7.25: Load Displacement Curves for Lab Specimens and Field Cores at Multiple Air Void Contents - Rock Co.**

Load displacement curves in Figure 7.25 show that, even at comparable air void contents, the fracture behavior of field cores differed from that of lab compacted specimens. Like Figure 7.24, higher peak loads and steeper post peak slopes were found for lab compacted specimens, suggesting a delayed crack initiation but a more brittle post peak behavior, i.e. faster crack propagation. Field cores, on the other hand, were characterized by low peak loads and flatter slopes. Overall, results for Rock Co. showed that field cores had a distinct fracture behavior that was not related exclusively to air void content nor the presence of rumble strips.

The remaining distinct factor behind Ideal CT testing on the field cores is the presence of the longitudinal joint. In fact, the test was set up so that the vertical load was applied along the joint line, as shown in the example in Figure 7.26 . Therefore, it is hypothesized that the joint generated a weaker interface where the core would more likely fail. Additionally, the presence of two asphalt layers may result in shear failure at the interface instead of the characteristic fracture (under indirect tension) behavior exhibited by lab compacted specimens.

**Figure 7.26: Ideal CT Testing Along the Longitudinal Joint.**

To further confirm this hypothesis, a similar analysis was performed for Wood and Sheboygan counties, with results presented in Figure 7.27 and Figure 7.28, respectively. Findings for the three counties are in agreement, as the shape of the load displacement curve was not governed by air void content – regardless of the presence of rumble strips. Instead, the cracking behavior of field cores is driven by the presence of the joint along the test plane.

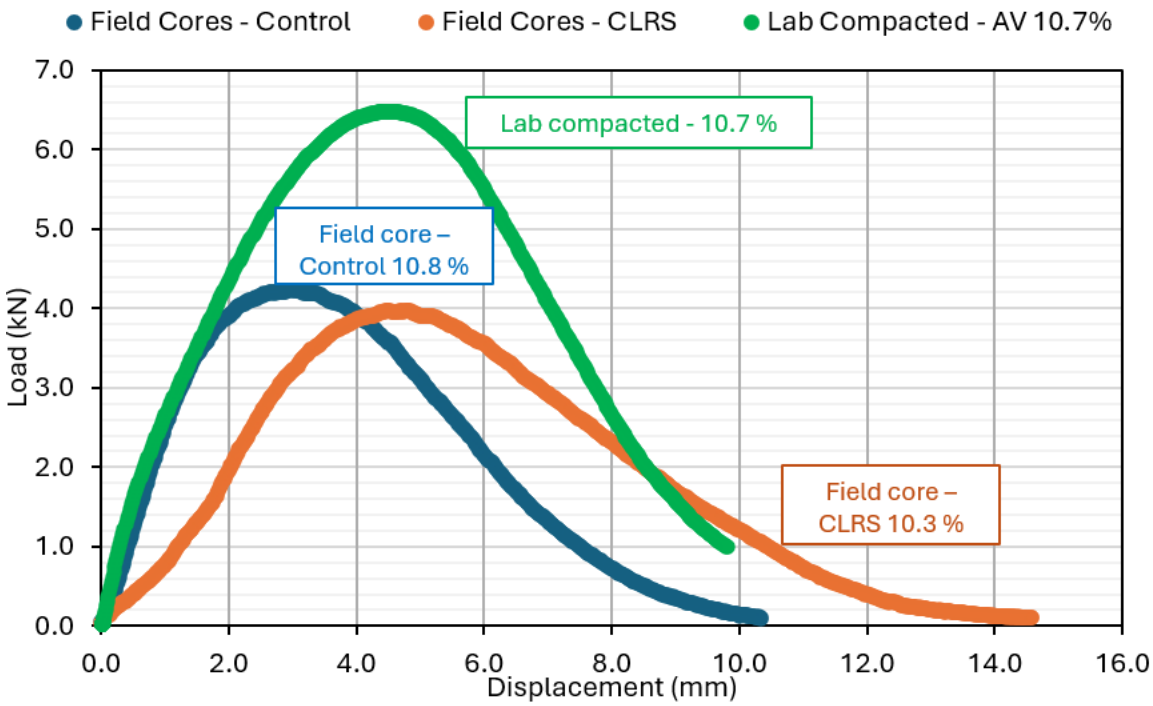



**Figure 7.27: Load Displacement Curves for Lab Specimens and Field Cores at Multiple Air Void Contents - Wood Co.**

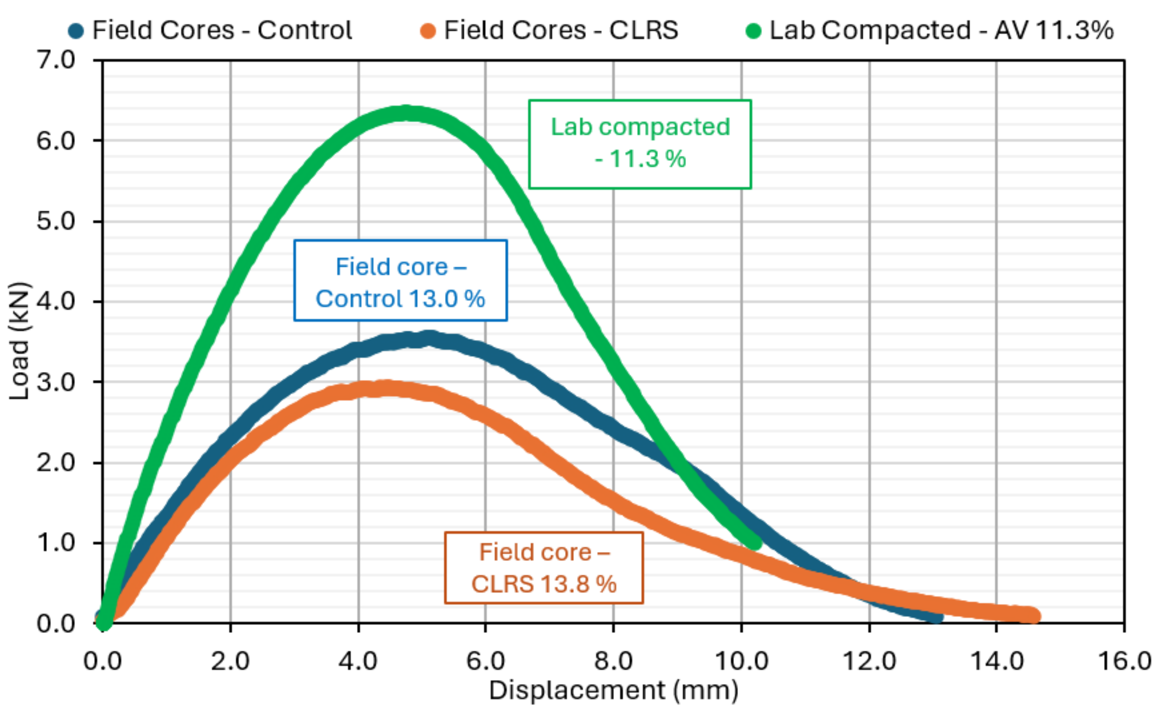



**Figure 7.28: Load Displacement Curves for Lab Specimens and Field Cores at Multiple Air Void Contents - Sheboygan Co.**

Overall, the above analysis of load displacement curves provided an important finding for this study: when compared against lab compacted specimens, the magnitude of the CT Index was not governed by air void content, thickness, or presence of rumble strips on field cores. Results showed that testing along the joint line (i.e., a weaker vertical plane) caused a distinct cracking behavior with lower peak loads, higher displacement at peak and flatter post-peak slope.

Following the observed trends, the research team studied the effect of rumble strips and material treatments on peak load, displacement at peak and post peak slope for every field project. A statistical analysis was performed at a 95% confidence level, where each treatment was compared against the untreated counterpart.

Figure 7.29 shows the results for peak load of every test section in Rock Co., and statistical significance is detailed in Table 17 below. When looking at the control sections, every treatment caused a statistically significant reduction in peak load, suggesting a reduction in cracking resistance (i.e., earlier crack initiation). Every material treatment, especially VRAM, increased binder content and reduced air voids, which would presumably improve cracking resistance along the joint. However, the reduction in peak load would indicate a worse cracking performance, despite the greater binder content.

On the other hand, CLRS sections saw an increase in peak load with most treatments, which would suggest the joint would withstand greater stress levels prior to cracking. It is also worth highlighting that the untreated CLRS section presented a considerably lower peak load, which might be a result of the milling of rumble strips debilitating the joint. Thus, Rock Co. test sections showed that material treatments successfully mitigated the effects of rumble strips on cracking resistance.

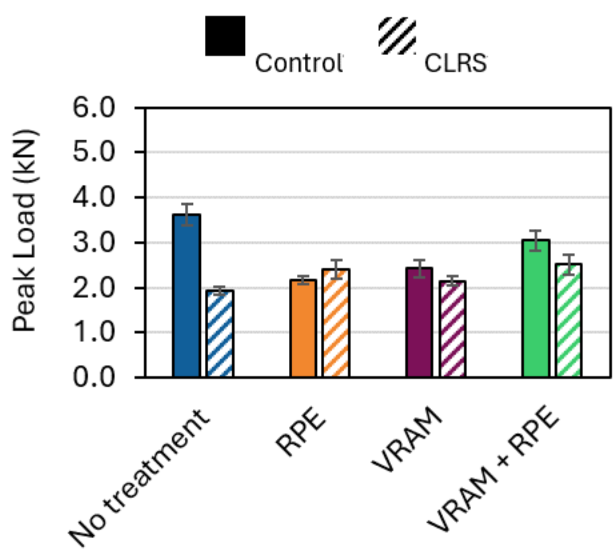



**Figure 7.29: Peak Load Results for Control and CLRS Sections - Rock Co.**

**Table 17: Statistical Analysis for Peak Load Results - Rock Co.**

| | Control | | | | CLRS | | | |
|---|---|---|---|---|---|---|---|---|
| **Treatments** | **Mean (kN)** | **Standard Deviation** | **Grouping** | | **Mean (kN)** | **Standard Deviation** | **Grouping** | |
| **No treatment** | **3.6** | **0.24** | **A** | | **1.9** | **0.09** | | **B** |
| VRAM + RPE | 3.0 | 0.23 | B | | 2.5 | 0.23 | A | |
| RPE | 2.2 | 0.09 | | C | 2.4 | 0.20 | A | |
| VRAM | 2.4 | 0.19 | | C | 2.1 | 0.12 | A | B |

Peak load results for Wood Co. and their statistical significance are presented in Figure 7.30 and Table 18, respectively. Unlike Rock Co., the milling of CLRS did not cause a considerable reduction in peak load. However, RPE and VRAM+RPE also led to a significant reduction in peak load for the control sections, while VRAM had no significant effect. For this field project, material treatments had no effect on peak load after the milling of rumble strips: while VRAM increased peak load and RPE and VRAM+RPE reduced it, no statistical significance was observed, thus crack initiation was predominantly unchanged.

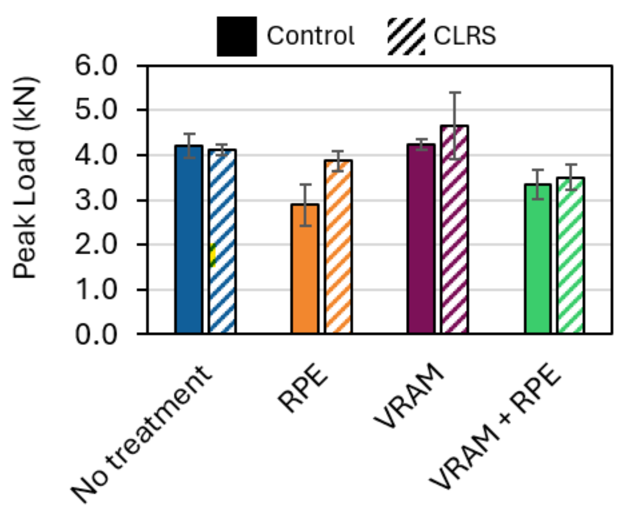



**Figure 7.30: Peak Load Results for Control and CLRS Sections - Wood Co.**

Table 18: Statistical Analysis for Peak Load Results - Wood Co.

| Treatments | Control | | | | CLRS | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean (kN) | Standard Deviation | Grouping | | Mean (kN) | Standard Deviation | Grouping | |
| **No treatment** | **4.2** | **0.27** | **A** | | **4.1** | **0.12** | **A** | **B** |
| VRAM + RPE | 3.3 | 0.32 | | B | 3.5 | 0.28 | | B |
| RPE | 2.9 | 0.46 | | B | 3.9 | 0.22 | A | B |
| VRAM | 4.2 | 0.12 | A | | 4.7 | 0.74 | A | |

Similar results were found for Sheboygan Co., as shown in Figure 7.31 and Table 19 below. No statistical significance was observed on peak load after the application of material treatments, on sections with and without rumble strips.

Overall, results for peak load showed no significant effects of material treatments for the Wood and Sheboygan field projects, while results for Rock Co. showed RPE and VRAM + RPE mitigated the effect of rumble strip milling by increasing peak load relative to the untreated section.

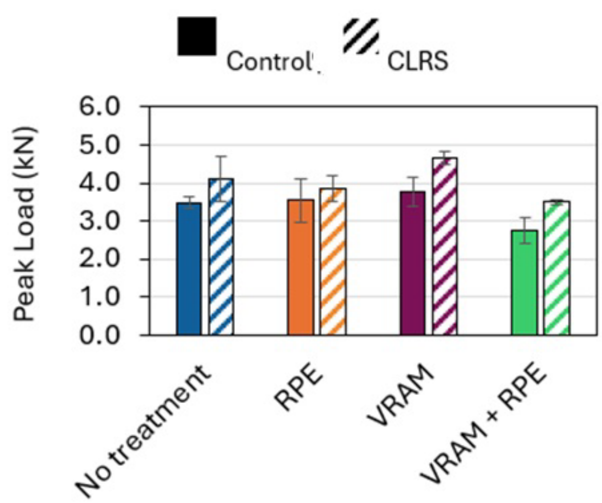



Figure 7.31: Peak Load Results for Control and CLRS Sections - Sheboygan Co.

Table 19: Statistical Analysis For Peak Load Results - Sheboygan Co.

| | Control | | | | CLRS | | |
|---|---|---|---|---|---|---|---|
| Treatments | Mean (kN) | Standard Deviation | Grouping | | Mean (kN) | Standard Deviation | Grouping |
| **No treatment** | **3.5** | **0.15** | **A** | **B** | **2.3** | **0.60** | **A** |
| VRAM + RPE | 2.7 | 0.34 | | B | 3.0 | 0.06 | A |
| RPE | 3.6 | 0.58 | A | B | 2.9 | 0.34 | A |
| VRAM | 3.8 | 0.39 | A | | 2.7 | 0.17 | A |

The second parameter under consideration was displacement at peak. Results for Rock Co. and the corresponding statistical analysis are presented in Figure 7.32 and Table 20, respectively. In this case, the effectiveness of material treatments was different for sections with and without rumble strips. While no statistical difference was observed between treated and untreated sections with rumble strips, VRAM and VRAM+RPE showed a significant increase in displacement at peak for the control sections, suggesting a higher strain tolerance. As a result, the joint would withstand greater deformation prior to cracking, improving cracking resistance.

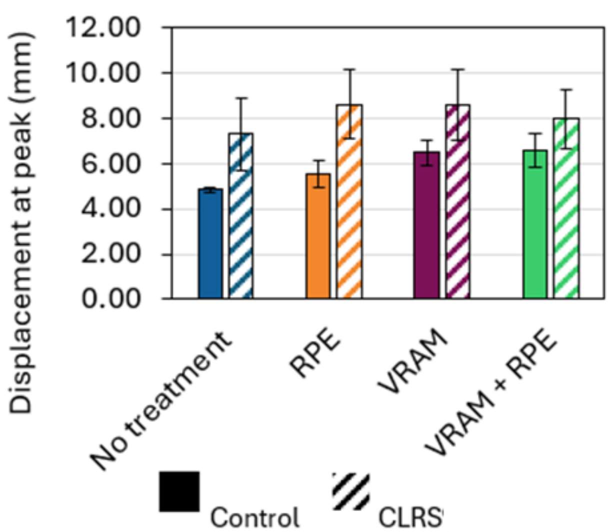



Figure 7.32: Displacement at Peak Load for Rock Co. Test Sections.

Table 20: Statistical Analysis for Displacement at Peak Load - Rock Co.

| | Control | | | | CLRS | | |
|---|---|---|---|---|---|---|---|
| **Treatments** | **Mean (mm)** | **Standard Deviation** | **Grouping** | | **Mean (mm)** | **Standard Deviation** | **Grouping** |
| **No treatment** | **4.84** | **0.10** | | **B** | **7.32** | **1.60** | **A** |
| VRAM + RPE | 6.58 | 0.71 | A | | 7.98 | 1.30 | A |
| RPE | 5.55 | 0.62 | A | B | 8.62 | 1.55 | A |
| VRAM | 6.48 | 0.57 | A | | 8.62 | 1.57 | A |

Similar trends were observed for Wood Co. test sections, with results and statistical analysis presented in Figure 7.33 and Table 21, respectively. No statistical significance was observed for rumble strips sections, which would indicate that material treatments provided no additional benefits. On the other hand, RPE and VRAM + RPE caused a significant increase in displacement at peak for the control sections, thus potentially contributing to an improved strain tolerance that would enhance cracking resistance along the joint.

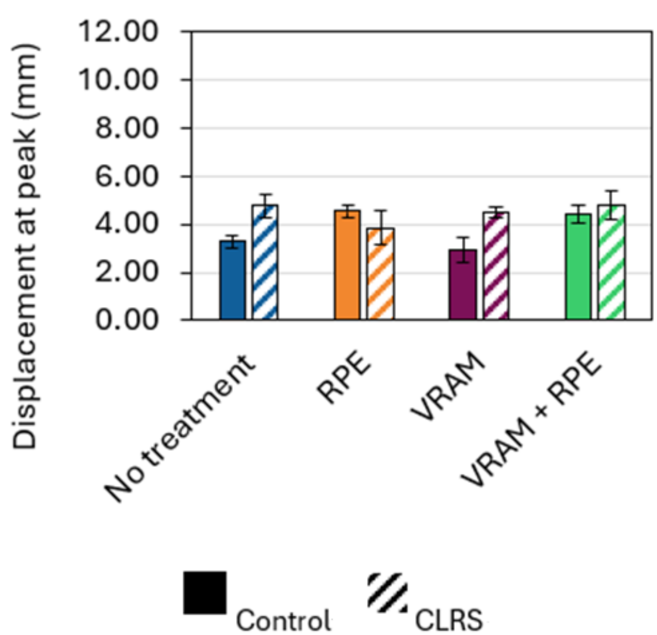



Figure 7.33: Displacement at Peak Load For Wood Co. Test Sections.

**Table 21: Statistical Analysis for Displacement at Peak Load - Wood Co.**

| | Control | | | | CLRS | | |
|---|---|---|---|---|---|---|---|
| **Treatment** | **Mean (mm)** | **Standard Deviation** | **Grouping** | | **Mean (mm)** | **Standard Deviation** | **Grouping** |
| **No treatment** | **3.28** | **0.29** | **B** | | **4.76** | **0.50** | **A** |
| VRAM + RPE | 4.42 | 0.37 | | A | 4.80 | 0.59 | A |
| RPE | 4.53 | 0.24 | | A | 3.86 | 0.71 | A |
| VRAM | 2.92 | 0.54 | B | | 4.49 | 0.26 | A |

Finally, results for displacement at peak for Sheboygan Co are shown in Figure 7.34 with statistical significance in Table 22. Like Rock and Wood counties, material treatments did not cause significant changes on displacement at peak of CLRS sections. On the other hand, VRAM and VRAM+RPE significantly improved displacement at peak relative to the untreated section without rumble strips. This trend was also observed in Rock Co. and can be attributed to highly polymer modified binder on VRAM that contributed to the higher strains on the sample prior to failure.

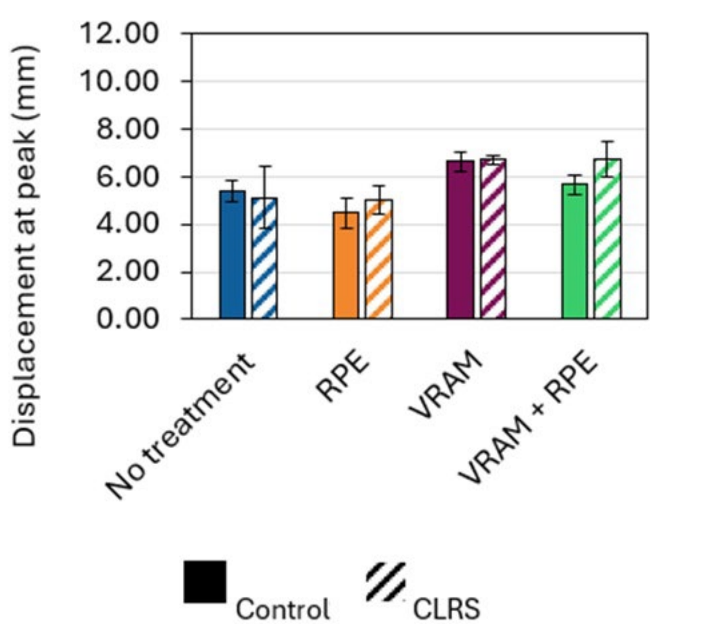



**Figure 7.34: Displacement at Peak Load for Sheboygan Co. Test Sections.**

Table 22: Statistical Analysis for Displacement at Peak Load - Sheboygan Co.

| Treatment | Control | | | | CLRS | | |
|---|---|---|---|---|---|---|---|
| | Mean (mm) | Standard Deviation | Grouping | | Mean (mm) | Standard Deviation | Grouping |
| **No treatment** | **5.40** | **0.42** | | **B** | **5.13** | **1.31** | **A** |
| VRAM + RPE | 5.65 | 0.40 | A | B | 6.74 | 0.75 | A |
| RPE | 4.49 | 0.63 | | B | 5.02 | 0.60 | A |
| VRAM | 6.65 | 0.41 | A | | 6.70 | 0.15 | A |

The last Ideal-CT parameter under consideration was post-peak slope, which may be related to crack propagation and ductility of the joint. The longitudinal joint of two-lane highways is not subjected to considerable traffic loading; therefore, a more ductile joint is preferred over a stiffer joint. A more ductile joint, with a lower post peak slope, would delay crack propagation – including non-load related cracks likely to occur along the joint.

Results for Rock Co. test sections and their statistical analysis are presented in Figure 7.35 and Table 23, respectively.

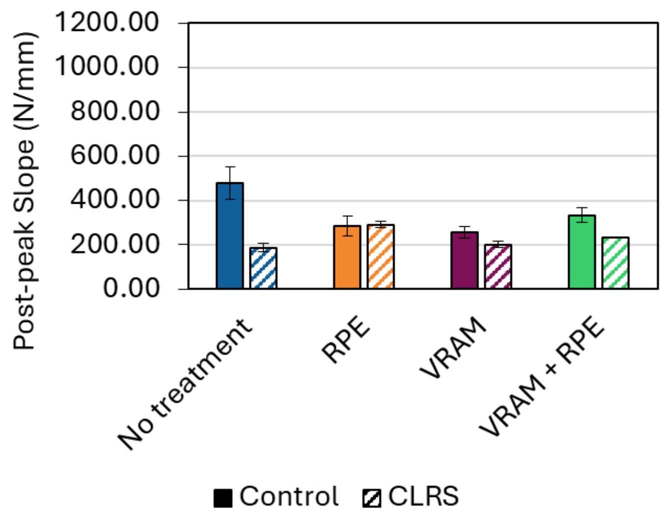



Figure 7.35: Post-Peak Slope for Rock Co. Test Sections.

**Table 23: Statistical Analysis for Post-Peak Slope - Rock Co.**

| | Control | | | | CLRS | | | |
|---|---|---|---|---|---|---|---|---|
| **Treatment** | **Mean** | **Standard Deviation** | **Grouping** | | **Mean** | **Standard Deviation** | **Grouping** | |
| **No treatment** | **478.4** | **73.8** | **A** | | **187.4** | **18.0** | | **C** |
| VRAM + RPE | 333.7 | 32.2 | | B | 234.2 | 3.0 | | B |
| RPE | 285.6 | 45.9 | | B | 290.9 | 13.5 | A | |
| VRAM | 255.4 | 25.7 | | B | 200.9 | 14.1 | B | C |

A significant reduction in post-peak slope was observed on treated sections without rumble strips, which suggests these treatments lead to a more ductile behavior of the joint, with a slower crack propagation. However, the treated sections with rumble strips did not show such a clear trend. In fact, a significant increase in post peak slope was observed on sections with RPE and VRAM+RPE, suggesting a more brittle behavior of the joint. It is worth noting, nevertheless, that the post peak slope of the untreated CLRS test section is considerably lower than the control without rumble strips. This would indicate milling of rumble strips improved the ductile behavior of the joint, which goes against the hypotheses put forward in this work.

Post peak slopes for Wood Co. are presented in Figure 7.36 and their statistical analysis in Table 24 below. As with Rock Co., material treatments for Wood Co. caused a significant reduction in post peak slope of the control sections, potentially indicating their effectiveness at delaying crack propagation. On the other hand, only the VRAM+RPE treatment significantly reduced post peak slope among the CLRS sections. These findings would indicate VRAM+RPE successfully delayed crack propagation along the joint, improving its durability, regardless of the presence of rumble strips.

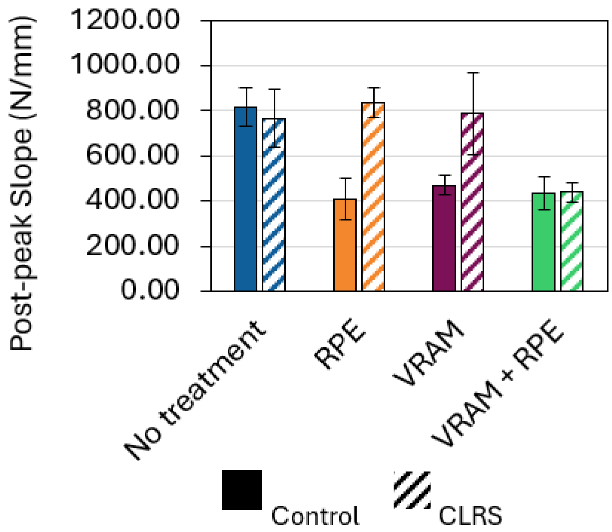



**Figure 7.36: Post-Peak Slope for Wood Co. Test Sections.**

**Table 24: Statistical Analysis for Post-Peak Slope - Wood Co.**

| | Control | | | | CLRS | | | |
|---|---|---|---|---|---|---|---|---|
| **Treatment** | **Mean** | **Standard Deviation** | **Grouping** | | **Mean** | **Standard Deviation** | **Grouping** | |
| **No treatment** | **818.1** | **86.1** | **A** | | **764.9** | **127.2** | **A** | |
| VRAM + RPE | 435.3 | 70.0 | | B | 437.9 | 45.8 | | B |
| RPE | 407.9 | 94.7 | | B | 836.9 | 64.7 | A | |
| VRAM | 468.6 | 43.2 | | B | 789 | 181 | A | |

Finally, results for post peak slopes of Sheboygan Co. test sections are presented in Figure 7.37 and Table 25 shows their statistical analysis.

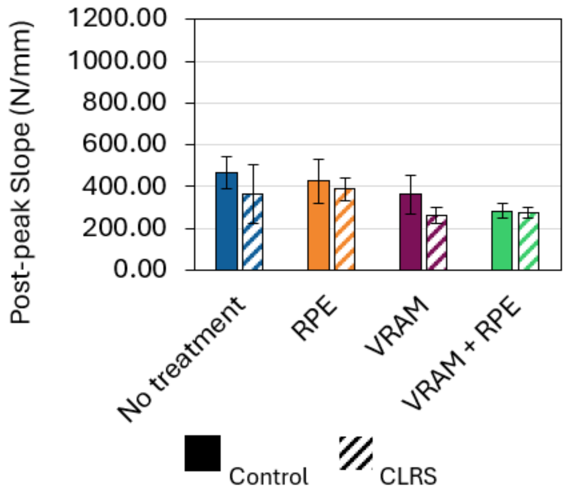



**Figure 7.37: Post-Peak Slope for Sheboygan Co. Test Sections.**

**Table 25: Statistical Analysis for Post-Peak Slope - Sheboygan Co.**

| | Control | | | CLRS | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean** | **Standard Deviation** | **Grouping** | **Mean** | **Standard Deviation** | **Grouping** |
| **No treatment** | **468.5** | **92.5** | **A** | **364.6** | **172.1** | **A** |
| VRAM + RPE | 282.8 | 42.5 | A | 271.9 | 31.4 | A |
| RPE | 425.6 | 130.7 | A | 387.7 | 66.5 | A |
| VRAM | 362.6 | 113.2 | A | 260.4 | 48.1 | A |

The application of material treatments in this project resulted in no significant changes to post peak slope for sections with and without rumble strips. Although VRAM+RPE caused a reduction in post peak slope similar to what was found for both Rock and Wood Co. projects, this was not statistically significant relative to the untreated sections. Results for Sheboygan Co. might indicate that the effectiveness of these treatments is project specific. In addition, it was previously established that the fracture behavior of field cores was governed by the presence of the joint, which introduced a weaker plane of failure. Thus, it could be argued that durability of the joint is most strongly dependent on the quality of the constructed joint, and the application of these treatments is a strategy to increase reliability and mitigate risk of premature failure at the joint.

# Chapter 8: Summary of findings

This project evaluated the efficacy of material methods for improving or enhancing CLRS durability while maintaining safety using full-scale field projects. Testing was conducted on field cores from three, two-lane county highway projects located in Rock Co., Wood Co., and Sheboygan Co., all located in the state of Wisconsin. In addition to the effects of rumble strips, this project evaluated the impacts of material treatments along the joint: RPE, VRAM, and a combination of the two, applied on test sections with and without rumble strips. The complete test plan included permeability testing and cracking performance with the Ideal CT test and the Texas Overlay Test. Extracted binder content, aggregate gradation, and air void content were also determined.

The main findings of this work are summarized as follows:

- Aging of field cores per AASHTO R30 caused binder film drain down and potential core integrity loss, possibly resulting in inaccurate evaluation. Therefore, all field cores in this project were tested in the "as cored" condition.
- Binder content across test sections was consistent with the presence of material treatments. Independent of the mix design binder content, VRAM caused an increase in binder content of between 2-3%, while RPE increased binder content by less than 1%.
- Milling of CLRS did not cause any significant aggregate degradation (i.e., finer gradation curves) indicating the integrity of the mixture at the joint was preserved. The extracted gradations showed overlapping curves across all test sections, with and without rumble strips. This finding indicates that the retrieved field cores were highly representative of the "as built" condition.
- Milling of CLRS increased the air void content along the longitudinal joint relative to the control sections, with the magnitude of change depending on the project. In all projects application of VRAM led to a reduction in air voids relative to the untreated sections, with and without rumble strips.
- The presence of rumble strips did not cause a significant increase in permeability of the joint, although permeability results showed that the three field projects could be considered impermeable. Nevertheless, application of material treatments significantly reduced permeability relative to untreated sections, which provides additional protection against moisture and oxygen ingress – with and without rumble strips.
- Cracking evaluation using the Texas Overlay Test suggests that the Crack Progression Rate (CPR) parameter is better suited for evaluation of cracking performance of the joint relative to the Critical Fracture Energy (CFE) parameter. This study showed that CLRS significantly increased CPR predominantly on the Wood and Sheboygan Co. projects. The application of VRAM and VRAM+RPE significantly reduced CPR on sections with rumble strips, thus mitigating the risk of accelerated deterioration along the joint. The application of RPE had no significant effect on CPR, the reduction in crack propagation was driven by the polymer modified binder in VRAM.
- Cracking evaluation using CT Index derived from the Ideal CT test resulted in considerable challenges as the presence of the joint dominated the fracture behavior of the sample, as

indicated by the load displacement curve. Instead of CT Index alone, cracking performance was analyzed through peak load, displacement at peak and post-peak slope.

- Although very few consistent trends were observed across projects using IDEAL CT test parameters, rumble strip sections exhibited more significant improvements after the application of material treatments. In general VRAM+RPE increased peak load and reduced post peak slope, both trends potentially leading to greater joint durability.
- Results from this study highlight the foremost importance of constructing a high-quality longitudinal joint to ensure durability. Cracking behavior of field cores is primarily controlled by the presence of the joint and not by the milling of rumble strips. Nevertheless, rumble strips can influence joint durability parameters, and the use of VRAM or VRAM+RPE are shown to effectively reduce water permeability and delay crack propagation in these instances and are therefore recommended to increase reliability when used in conjunction with rumble strips.

In support of these findings, a one-page best practices guideline was generated to help facilitate rapid dissemination of project findings and implementation of outcomes. This guide is available as a stand-alone download available on the NRRA project website as well as linked in this report.

Originally, long-term aging and testing of the field cores were planned for this study. However, these plans were abandoned due to issues observed with the field cores after AASHTO R30 aging, such as binder film drain down and potential core integrity loss. Since pavement durability is often discussed in the context of longer-term aging, follow-up research is recommended. This research should focus on aged field cores to validate the findings and trends of this study and to determine if the material treatments remain effective at preserving longitudinal joints.

# Chapter 9: Development of “One-pager” Guidelines Document

In addition to the project report, the research team developed a one-page document that collected the main findings of the study. This “one-pager” intends to facilitate the dissemination of findings, particularly as they relate to implementation of rumble strips. It was framed so that it captured the well-recognized safety benefits of CLRS while addressing the main concerns from agencies and practitioners. To make it a short and easily digestible document, these concerns were presented as simple questions. The answers leveraged the project findings to help the reader with the implementation of CLRS and selection of material treatments and linked the full project report (via QR code) for the complete, in-depth analysis.

The ”one pager” is included for reference below and is also intended to be distributed as a standalone document in addition to being uploaded to the project website.

# Rumble Strips: Fact or Fiction

## Best Practices to Improve Rumble Strip Durability

### We Know Centerline Rumble Strips (CLRS) Save Lives.

CLRS can reduce injury-producing crashes
**by up to 91% on urban two-lane roads and 50% on rural two-lane roads[1].**

### But do milled CLRS impact pavement joint performance? If so, what can be done to protect the joint?

A recent NRRA-funded research project set out to better understand common CLRS concerns and find best practices for utilizing these life-saving tools.

NRRA National Road Research Alliance

*For full project details and reports, scan the QR Code.*

**Does milling CLRS degrade the mix at a joint?**

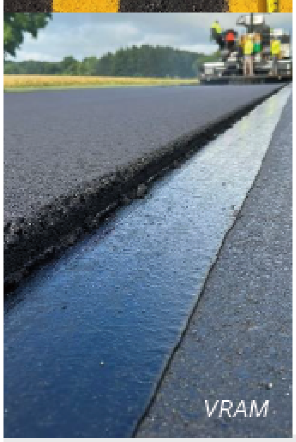
Milling CLRS did not cause significant aggregate breakdown/degradation. No significant difference in gradation with or without CLRS was observed.

**Do rumble strips increase joint permeability?**

CLRS did not increase the permeability at the joint for fine-graded mixtures, although they do provide a small reservoir that may hold water/ice longer than the surrounding pavement.

**Do rumble strips increase the cracking susceptibility of the joint?**

Cracking behavior is driven by the quality of the longitudinal joint. However, CLRS can influence the crack propagation rate.




**What material treatments can increase the performance of the CLRS?**

Void Reducing Asphalt Membrane (VRAM) can help to mitigate the cracking susceptibility of the joint, with or without CLRS. With VRAM, cracks may propagate up to 34% slower compared to control sections. Using VRAM, or VRAM in conjunction with Rapid Penetrating Emulsion (RPE), also reduced permeability relative to control sections.

**Do these treatments impact the safety features of CLRS?**

No. Because VRAM and RPE do not change the shape (geometry) of the CLRS, driver-alerting benefits (internal noise) of the CLRS are maintained. Additionally, these treatments may reduce the external nuisance noise, benefiting the surrounding public!

**Good construction practice is key to a long-lasting, high quality joint. Material treatments such as VRAM and RPE can increase the performance of joints with CLRS, without compromising CLRS safety benefits.**

Asphalt Materials, Inc. | Behnke Materials Engineering | Heritage Research Group

[1]*Torbic, D., et al. Guidance for the Design & Application of Shoulder & Centerline Rumble Strips. Washington D.C. 2009.*

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# Appendix A: Bulk specific gravity of all field cores

# Rock County

**Table 26: Core Denomination and Bulk Specific Gravity for Rock Co.**

| Section ID | Core ID | Bulk specific gravity |
|---|---|---|
| Control (D) | R - D1 | 2.303 |
| | R - D2 | 2.302 |
| | R - D3 | 2.307 |
| | R - D4 | 2.281 |
| | R - D5 | 2.307 |
| | R - D6 | 2.293 |
| | R - D7 | 2.297 |
| | R - D8 | 2.293 |
| | R - D9 | 2.304 |
| | R - D10 | 2.292 |
| | R - D11 | 2.307 |
| | R - D12 | 2.301 |
| Control + VRAM + RPE (B) | R - B1 | 2.229 |
| | R - B2 | 2.241 |
| | R - B3 | 2.239 |
| | R - B4 | 2.230 |
| | R - B5 | 2.228 |
| | R - B6 | 2.231 |
| | R - B7 | 2.238 |
| | R - B8 | 2.255 |
| | R - B9 | 2.235 |
| | R - B10 | 2.231 |
| | R - B11 | 2.248 |
| | R - B12 | 2.214 |
| CLRS (H) | R - H1 | 2.218 |
| | R - H2 | 2.238 |
| | R - H3 | 2.202 |
| | R - H4 | 2.237 |
| | R - H5 | 2.252 |
| | R - H6 | 2.240 |
| | R - H7 | 2.268 |
| | R - H8 | 2.266 |
| | R - H9 | 2.258 |
| | R - H10 | 2.269 |
| | R - H11 | 2.268 |
| | R - H12 | 2.289 |

| Section ID | Core ID | Bulk specific gravity |
|---|---|---|
| CLRS + VRAM + RPE (F) | R - F1 | 2.174 |
| | R - F2 | 2.191 |
| | R - F3 | 2.166 |
| | R - F4 | 2.187 |
| | R - F5 | 2.199 |
| | R - F6 | 2.181 |
| | R - F7 | 2.157 |
| | R - F8 | 2.161 |
| | R - F9 | 2.156 |
| | R - F10 | 2.173 |
| | R - F11 | 2.165 |
| | R - F12 | 2.178 |
| Control + RPE (A) | R - A1 | 2.246 |
| | R - A2 | 2.244 |
| | R - A3 | 2.254 |
| | R - A4 | 2.256 |
| | R - A5 | 2.257 |
| | R - A6 | 2.243 |
| | R - A7 | 2.237 |
| | R - A8 | 2.239 |
| | R - A9 | 2.246 |
| | R - A10 | 2.268 |
| | R - A11 | 2.245 |
| | R - A12 | 2.274 |
| Control + VRAM (C) | R - C1 | 2.251 |
| | R - C2 | 2.236 |
| | R - C3 | 2.236 |
| | R - C4 | 2.234 |
| | R - C5 | 2.245 |
| | R - C6 | 2.249 |
| | R - C7 | 2.226 |
| | R - C8 | 2.258 |
| | R - C9 | 2.248 |
| | R - C10 | 2.255 |
| | R - C11 | 2.247 |
| | R - C12 | 2.253 |

| Section ID | Core ID | Bulk specific gravity |
| --- | --- | --- |
| CLRS + RPE (E) | R - E1 | 2.254 |
| | R - E2 | 2.243 |
| | R - E3 | 2.242 |
| | R - E4 | 2.244 |
| | R - E5 | 2.263 |
| | R - E6 | 2.253 |
| | R - E7 | 2.260 |
| | R - E8 | 2.248 |
| | R - E9 | 2.243 |
| | R - E10 | 2.217 |
| | R - E11 | 2.236 |
| | R - E12 | 2.214 |
| CLRS + VRAM (G) | R - G1 | 2.165 |
| | R - G2 | 2.177 |
| | R - G3 | 2.224 |
| | R - G4 | 2.183 |
| | R - G5 | 2.164 |
| | R - G6 | 2.173 |
| | R - G7 | 2.172 |
| | R - G8 | 2.212 |
| | R - G9 | 2.162 |
| | R - G10 | 2.182 |
| | R - G11 | 2.169 |
| | R - G12 | 2.200 |

# Wood County

### Table 27: Core Denomination and Bulk Specific Gravity for Wood Co.

| Section ID | Core ID | Bulk specific gravity |
|---|---|---|
| Control (H) | W - H1 | 2.185 |
| | W - H2 | 2.191 |
| | W - H3 | 2.209 |
| | W - H4 | 2.174 |
| | W - H5 | 2.173 |
| | W - H6 | 2.189 |
| | W - H7 | 2.192 |
| | W - H8 | 2.183 |
| | W - H9 | 2.197 |
| | W - H10 | 2.192 |
| | W - H11 | 2.191 |
| | W - H12 | 2.183 |
| Control + VRAM + RPE (B) | W - B1 | 2.116 |
| | W - B2 | 2.119 |
| | W - B3 | 2.100 |
| | W - B4 | 2.134 |
| | W - B5 | 2.132 |
| | W - B6 | 2.130 |
| | W - B7 | 2.106 |
| | W - B8 | 2.120 |
| | W - B9 | 2.142 |
| | W - B10 | 2.159 |
| | W - B11 | 2.174 |
| | W - B12 | 2.130 |
| CLRS (G) | W - G1 | 2.190 |
| | W - G2 | |
| | W - G3 | 2.211 |
| | W - G4 | 2.209 |
| | W - G5 | 2.193 |
| | W - G6 | 2.184 |
| | W - G7 | 2.181 |
| | W - G8 | 2.221 |
| | W - G9 | 2.182 |
| | W - G10 | 2.193 |
| | W - G11 | 2.191 |

| Section ID | Core ID | Bulk specific gravity |
|---|---|---|
| | W - G12 | 2.193 |
| CLRS + VRAM + RPE (E) | W - E1 | 2.123 |
| | W - E2 | 2.109 |
| | W - E3 | 2.161 |
| | W - E4 | 2.142 |
| | W - E5 | 2.137 |
| | W - E6 | 2.151 |
| | W - E7 | 2.195 |
| | W - E8 | 2.121 |
| | W - E9 | 2.132 |
| | W - E10 | 2.116 |
| | W - E11 | 2.178 |
| | W - E12 | 2.121 |
| Control + RPE (A) | W-A1 | 2.053 |
| | W-A2 | 2.055 |
| | W-A3 | 2.085 |
| | W-A4 | 2.071 |
| | W-A5 | 2.081 |
| | W-A6 | 2.068 |
| | W-A7 | 2.070 |
| | W-A8 | 2.083 |
| | W-A9 | 2.075 |
| | W-A10 | 2.080 |
| | W-A11 | 2.060 |
| | W-A12 | 2.060 |
| Control + VRAM (C) | W - C1 | 2.160 |
| | W - C2 | 2.163 |
| | W - C3 | 2.149 |
| | W - C4 | 2.173 |
| | W - C5 | 2.160 |
| | W - C6 | 2.179 |
| | W - C7 | 2.155 |
| | W - C8 | 2.141 |
| | W - C9 | 2.183 |
| | W - C10 | 2.173 |
| | W - C11 | 2.143 |
| | W - C12 | 2.124 |

| Section ID | Core ID | Bulk specific gravity |
|---|---|---|
| CLRS + RPE (F) | W - F1 | 2.202 |
| | W - F2 | 2.204 |
| | W - F3 | 2.208 |
| | W - F4 | 2.185 |
| | W - F5 | 2.196 |
| | W - F6 | 2.033 |
| | W - F7 | 2.200 |
| | W - F8 | 2.194 |
| | W - F9 | 2.215 |
| | W - F10 | 2.200 |
| | W - F11 | 2.190 |
| | W - F12 | 2.194 |
| CLRS + VRAM (D) | W - D1 | 2.139 |
| | W - D2 | 2.162 |
| | W - D3 | 2.181 |
| | W - D4 | 2.173 |
| | W - D5 | 2.188 |
| | W - D6 | 2.192 |
| | W - D7 | 2.198 |
| | W - D8 | 2.190 |
| | W - D9 | 2.188 |
| | W - D10 | 2.189 |
| | W - D11 | 2.200 |
| | W - D12 | 2.198 |

# Sheboygan Co.

**Table 28: Core Denomination and Bulk Specific Gravity for Sheboygan Co.**

| Section ID | Core ID | Bulk specific gravity |
|---|---|---|
| Control (A) | S-A1 | 2.202 |
| | S-A2 | 2.231 |
| | S-A3 | 2.209 |
| | S-A4 (*) | 2.204 |
| | S-A5 (*) | 2.213 |
| | S-A6 | 2.204 |
| | S-A7 | 2.216 |
| | S-A8 | 2.217 |
| | S-A9 | 2.223 |
| | S-A10 | 2.211 |
| | S-A11 | 2.213 |
| | S-A12 | 2.282 |
| Control + VRAM + RPE (G) | S-G1 | 2.167 |
| | S-G2 | 2.179 |
| | S-G3 (*) | 2.200 |
| | S-G4 | 2.210 |
| | S-G5 | 2.204 |
| | S-G6 | 2.184 |
| | S-G7 | 2.190 |
| | S-G8 | 2.192 |
| | S-G9 | 2.191 |
| | S-G10 | 2.195 |
| | S-G11 | 2.181 |
| | S-G12 | 2.182 |
| Control + RPE (E) | S-E1 | 2.293 |
| | S-E2 | 2.274 |
| | S-E3 | 2.287 |
| | S-E4 | 2.294 |
| | S-E5 | 2.308 |
| | S-E6 | 2.300 |
| | S-E7 | 2.307 |
| | S-E8 | 2.308 |
| | S-E9 | 2.311 |
| | S-E10 | 2.239 |
| | S-E11 | 2.274 |
| | S-E12 | 2.282 |

| Section ID | Core ID | Bulk specific gravity |
| --- | --- | --- |
| Control + VRAM (B) | S-B1 | 2.292 |
| | S-B2 | 2.281 |
| | S-B3 | 2.278 |
| | S-B4 | 2.288 |
| | S-B5 | 2.294 |
| | S-B6 | 2.285 |
| | S-B7 | 2.282 |
| | S-B8 (*) | 2.290 |
| | S-B9 | 2.263 |
| | S-B10 | 2.297 |
| | S-B11 | 2.290 |
| | S-B12 | 2.304 |
| Control + VRAM (C) | S-C1 | 2.275 |
| | S-C2 | 2.270 |
| | S-C3 | 2.268 |
| | S-C4 | 2.292 |
| | S-C5 | 2.253 |
| | S-C6 | 2.258 |
| | S-C7 | 2.242 |
| | S-C8 | 2.260 |
| | S-C9 | 2.244 |
| | S-C10 | 2.234 |
| CLRS (I) | S-I1 | 2.200 |
| | S-I2 | 2.240 |
| | S-I3 | 2.198 |
| | S-I4 | 2.202 |
| | S-I5 | 2.161 |
| | S-I6 (*) | 2.176 |
| | S-I7 (*) | 2.186 |
| | S-I8 | 2.178 |
| | S-I9 | 2.159 |
| | S-I10 | 2.195 |
| | S-I11 | 2.139 |
| | S-I12 | 2.162 |
| | S-I13 | 2.133 |

| Section ID | Core ID | Bulk specific gravity |
|---|---|---|
| CLRS + VRAM + RPE (H) | S-H1 | 2.157 |
| | S-H2 | 2.157 |
| | S-H3 | 2.163 |
| | S-H4 | 2.147 |
| | S-H5 | 2.142 |
| | S-H6 | 2.160 |
| | S-H7 | 2.194 |
| | S-H8 | 2.194 |
| | S-H9 | 2.154 |
| | S-H10 | 2.171 |
| | S-H11 | 2.161 |
| | S-H12 | 2.158 |
| CLRS + RPE (F) | S-F1 | 2.178 |
| | S-F2 | 2.194 |
| | S-F3 | 2.215 |
| | S-F4 | 2.259 |
| | S-F5 | 2.238 |
| | S-F6 | 2.244 |
| | S-F7 | 2.243 |
| | S-F8 | 2.240 |
| | S-F9 | 2.255 |
| | S-F10 | 2.266 |
| | S-F11 | 2.289 |
| | S-F12 | 2.278 |
| | S-F13 | 2.284 |
| CLRS + VRAM (D) | S-D1 | 2.167 |
| | S-D2 | 2.224 |
| | S-D3 | 2.206 |
| | S-D4 | 2.189 |
| | S-D5 | 2.191 |
| | S-D6 | 2.173 |
| | S-D7 | 2.193 |
| | S-D8 | 2.200 |
| | S-D9 | 2.207 |
| | S-D10 | 2.226 |
| | S-D11 | 2.232 |
| | S-D12 | 2.219 |

# Appendix B: CT-Index thresholds per state

The research team conducted a literature review to compile CT Index thresholds that have been implemented for Balanced Mix Design. Although these thresholds were not originally developed for joint evaluation, they provide an order of magnitude for comparison with the results obtained in this work. The reported values per state are detailed in Table 30. Additional states such as Maryland, Kansas, Montana, North Dakota, Mississippi, Colorado, Ohio, Maine, and South Dakota are evaluating Ideal CT for implementation or benchmarking mixtures and thus have not developed CT Index thresholds at the time of this report.

**Table 29: CT Index Thresholds for Balanced Mix Design Per State.**

| State | Threshold[1] | Notes |
| --- | --- | --- |
| Arkansas | 50 | Preliminary index, Samples conditioned for 4 hours at 135 °C |
| Missouri | 45 | Samples conditioned for 2 hours at 135 °C |
| Ohio | 80 / 60 based on design and lift type | Based on short-term aged, plant mix lab compacted results |
| Oklahoma | 100 for surface mixtures / 60 for base mixtures | |
| Pennsylvania | 70 / 80/ 90 based on traffic level | Preliminary, report only. |
| New York | 135 | |
| Virginia | 70 | |
| Wisconsin | 30 | Should be increased to 80 for SMA |

[1]All values were retrieved from various published and unpublished sources:

**Table 30 Sources for CT Index Thresholds**

| State | Source |
| --- | --- |
| Arkansas | *Jason Bittner, Elie Y. Hajj, Timothy B. Aschenbrener, Praveen Gopisetti, Heidi Rockwood. FHWA: 2023 Southeast Peer Exchange on Balanced Mix Design Outcomes Summary (2023). Publication No. FHWA-HIF-23-031. April, 2023* |
| Missouri | *William Buttlar, Punyaslok Rath, Jim Meister, Ahmed I.H. Mohamed, Helmut Leodarta, Katie Distelrath. Implementation of Balanced Mixture Design in Missouri Test Sections with Modifiers. Missouri Department of Transportation. November 2024.* |
| Ohio | *Jason Bittner, Elie Y. Hajj, Timothy B. Aschenbrener, Praveen Gopisetti, Heidi Rockwood. FHWA: 2023 North Central Peer Exchange on Balanced Mix Design Outcomes Summary (2023). Publication No. FHWA-HIF-23-032. May, 2023* |
| Oklahoma | *Fan Yin, Randy West. Balanced Mix Design Resource Guide. NAPA. IS-143.* |

| State | Source |
|---|---|
| Pennsylvania | --- |
| New York | *Jason Bittner, Elie Y. Hajj, Timothy B. Aschenbrener, Praveen Gopisetti, Heidi Rockwood. FHWA: 2023 Northeast Peer Exchange on Balanced Mix Design Outcomes Summary (2023). Publication No. FHWA-HIF-23-042. June, 2023* |
| Virginia | *Elie Y. Hajj, Timothy B. Aschenbrener, Derek Nener-Plante. Case Studies on the Implementation of Balanced Mix Design and Performance Tests for Asphalt Mixtures: Virginia Department of Transportation (VDOT). WRSC-TR-21-08. March, 2021* |
| Wisconsin | NAPA. *Lessons Learned: Balanced Mixture Design. Improving Rutting and Moisture Resistance in Wisconsin* |