Report on 2017 MnROAD Construction Activities

May 2018

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The National Road Research Alliance (NRRA), a multi-state pooled-fund program, exists to provide strategic implementation of pavement engineering solutions through cooperative research. NRRA is led by an Executive Committee of state DOT partners, and supported by numerous agency and industry partner representatives. Members provide expertise to NRRA, from the selection of research topics, to communication, and implementation. NRRA consists of five project teams: Flexible, Rigid, Geotechnical, Preventive Maintenance, and Technology Transfer. The 2017 construction season at MnROAD saw construction of 35 new and unique pavement test sections. The sections, designed to address NRRA high-priority research topics, were conceived and planned by NRRA project teams. This report details development, design, and construction of each research project and the test sections supporting them. Individual study details are left to future reports generated by the individual research contracts and their respective teams.

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REPORT ON 2017 MNROAD CONSTRUCTION ACTIVITIES

FINAL REPORT

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Wisconsin Department of Transportation
Federal Highway Administration
Minnesota Local Road Research Board

Associate Member Organizations

3M Transportation Safety Division
Aggregate and Ready Mix Association of Minnesota
American Engineering Testing, Inc.
Asphalt Pavement Alliance (APA)
Asphalt Recycling and Reclaiming Association
BASF
Braun Intertec Corporation
Cargill Industrial Specialties
Center for Transportation Infrastructure Systems
Collaborative Aggregates LLC
Concrete Paving Association of Minnesota
Diamond Surface, Inc.
First State Tire Recycling
Flint Hills Resources, LP
GSE Environmental
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Mathy Construction Company
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LIST OF ABBREVIATIONS AND TECHNOLOGY TERMS

ALPS, ALPS2	Automated Laser Profile System, v1 and v2
CCPR	Cold Central Plant Recycling
DCP	Dynamic Cone Penetrometer
DIV	Digital inspection vehicle
ESAL	Equivalent single axle load
FRC	Fiber-reinforced concrete
FWD	Falling-weight deflectometer
LISA	Lightweight inertial surface analyzer
LSSB	Large-stone subbase
LVR	Low volume road at MnROAD
LWD	Lightweight deflectometer
MnDOT	Minnesota Department of Transportation
MnROAD	Minnesota Road Research Project
MIRA	Ultrasonic pulse echo device
NCAT	National Center for Asphalt Technology
NMAS	Nominal maximum aggregate size
NRRA	National Road Research Alliance
PCC	Portland cement concrete pavement
PEM	Performance engineered mixtures
RAB	Recycled aggregate base
RAP	Recycled asphalt pavement
RAS	Recycled asphalt shingles
RCA	Recycled concrete aggregate
RDM	Rolling Density Meter
RSR	Residual Strength Ratio
UTBWC	Ultra-thin bonded wearing course
UTEP	University of Texas El Paso
VA	Virgin aggregate
VMA	Voids in mineral aggregate

EXECUTIVE SUMMARY

The National Road Research Alliance (NRRA), a multi-state pooled-fund project, is an innovative endeavor for the Minnesota Department of Transportation, Office of Materials Road Research. The NRRA exists to:

- Evaluate pavement materials, equipment, and methods under real-world conditions
- Leverage knowledge, skills, and resources from participating partners to advance pavement research and implementation efforts
- Establish industry standards and develop performance measures for improving pavement performance
- Develop and/or revise specifications and recommendations
- Study and promote innovative techniques and technologies that will save agencies money, improve safety, and increase efficiency
- Support the exchange of information and ideas through collaborative research efforts that provide opportunities for public agencies to share experiences
- Support technology transfer that highlights the implementation of research results and the associated benefits

Led by an Executive Committee of DOT Agency Partners, the NRRA consists of five technical project teams: Flexible, Rigid, Geotechnical, Preventive Maintenance, and Technology Transfer.

The 2017 construction season at MnROAD saw construction of 35 new and unique test sections. These sections, designed to address NRRA high-priority research topics, were conceived and planned by the five NRRA technical team members.

This report details the development of the individual long-term research area projects, the pavement sections designed to meet those needs, and the construction of them. Each specific group of test sections support long-term research contracts. Details and results of each individual study are left to future reports generated by the individual research contracts and their respective teams. Each of the research projects are discussed in individual chapters.

CHAPTER 1: INTRODUCTION

1.1 MNROAD FACILITY

The Minnesota Road Research Project (MnROAD) is a pavement test facility owned and operated by the Minnesota Department of Transportation (MnDOT). The facility, located on westbound I-94, northwest of the Twin Cities metropolitan area, was constructed in 1990-1993 and opened to traffic in 1994. With the 2017 construction described in this report, MnROAD now has four separate experimental roadway segments:

- 2.7-mile, two-lane, westbound I-94 mainline with live traffic. This segment averages 26,500 vehicles per day with 13 percent trucks and provides approximately 750,000 flexible and 1,000,000 rigid equivalent single axle loads (ESALs) per year.
- 2.5-mile, two-lane closed loop Low-Volume Road (LVR). Traffic on the LVR is provided by an 80-kip, 5-axle, tractor/trailer combination. The combination averages approximately 70 laps a day and is restricted to the inside lane only. The outer lane of the LVR is preserved for the study of environmental effects.
- 1000-foot long, two-lane roadway in the MnROAD stockpile area. This area has been utilized for testing the impact of implements of husbandry on low-volume roads and is periodically used by contractors to test placement methods before proceeding to test sections on the mainline or LVR.
- Newly constructed in 2017 is a series of asphalt overlay and partial-depth spall repair test sections on the original westbound concrete pavement lanes of I-94. This pavement segment is 2.7 miles in length and originally constructed in 1973. These test sections receive the same traffic stream as mainline MnROAD test sections but only seven days per month, on average, when traffic is diverted from the MnROAD mainline for monitoring or construction. As a result, the cumulative ESALs on this roadway are about one-third of the amount that mainline I-94 experiences.

MnROAD has progressed through two phases since it was originally constructed. Phase-I (1994-2007) primarily investigated concrete and asphalt structural (thickness) designs. Phase-II (2008-2015) focused on partnerships with government, academia, and industry, led by MnDOT through the former Transportation Engineering and Road Research Alliance.

Construction in 2016 marked the beginning of MnROAD Phase-III, with the creation of a partnership with the National Center for Asphalt Technology (NCAT). This partnership resulted in the construction of eight flexible pavement sections as part of a National Cracking Performance Test experiment.

The 2017 construction season at MnROAD saw the addition of 35 new and unique test sections. These sections, designed to address National Road Research Alliance (NRRA) high-priority research topics, were conceived and planned by NRRA Rigid, Flexible, Preventive Maintenance, and Geotechnical team members.

1.2 NATIONAL ROAD RESEARCH ALLIANCE (NRRA)

The NRRA is a multi-state pooled-fund program led by MnDOT. The NRRA was conceived to provide guidance for the MnROAD Phase III research program with the objective of strategic implementation through cooperative pavement research. NRRA is led by an Executive Committee of DOT Agency Partners, and supported by numerous agency and industry partner representatives, as shown in Tables 1.1 through 1.4. Together, representatives from these organizations provide their expertise to NRRA to plan and oversee the entire lifecycle of MnROAD research, from the selection of research topics to communication and implementation of results. NRRA consists of five project teams: Flexible, Rigid, Geotechnical, Preventive Maintenance and Technology Transfer.

In addition to state DOT sponsors, associate members from industry and academic sectors provide key perspectives. Associate members provide expertise throughout the research process by giving input on long-term technology trends, identifying innovative solutions to research problems, and determining the viability of research results by actively participating in projects. Members also have an opportunity to provide or obtain materials for testing and to propose design approaches based on field experience.

Planning for the NRRA 2017 construction began January, 2016. During the experiment planning and design phase, the five NRRA project teams developed the following high-priority research projects shown in Table 1.5. An overall time frame for construction is given in Appendix A.

Sections constructed at MnROAD were designed to address these research topics; maps in Figures 1.1 and 1.2 show the general location of the sections. It can be seen that the Rigid Pavement team sections are located on both the MnROAD mainline and LVR. Flexible Pavement team sections are located on both original westbound I-94 and LVR. The Preventive Maintenance team sections were constructed on MnROAD mainline. Finally, the Geotechnical team sections are located on the LVR.

Table 1.1 NRRA Executive Committee Members.

AGENCY	REPRESENTATIVES
Caltrans	Joe Holland, Ron Jones
Illinois Department of Transportation	Brian Pfeifer, Charles Weinrank
Michigan Department of Transportation	Steve Bower, Curtis Bleech
Minnesota Department of Transportation	Greg Ous, Glenn Engstrom
Missouri Department of Transportation	John Donahue, Dave Ahlvers
Wisconsin Department of Transportation	Barry Paye, Steve Krebs
Federal Highway Administration	Bob Orthmeyer
Minnesota Local Road Research Board	Lyndon Robjent (Carver County) Paul Oehme (City of Chanhassen)

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Minnesota Department of Transportation
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Melissa Cole
Tim Clyne
Shannon Fiecke
Eddie Johnson
Dave Van Deusen
Michael Vrtis
Ben Worel
Tom Zimmerman

Table 1.5 High-priority research topic areas identified by NRRA project teams.

TEAM	TOPICS	MnROAD CELLS
Flexible Pavement	-Asphalt Overlay of Concrete and Methods of Enhancing Compaction -Cold Central Plant Recycling	984-995 133, 233, 135, 235
Rigid Pavement	-Fiber Reinforced Concrete Pavements -Early Opening Strength to Traffic -Optimizing Cement Content for Concrete Mixes	705, 805, 506, 606, 706, 806, 139, 239 124, 224, 324, 424, 524, 624 138, 238
Geotechnical	-Recycled Aggregate Bases -Subgrade Stabilization with Large-sized Aggregates	185, 186, 188, 189 127, 227, 328, 428, 528, 628, 728
Preventive Maintenance	-Maintaining Poor Pavements -Partial Depth Repairs	101, 201, 115, 215 94001-94015

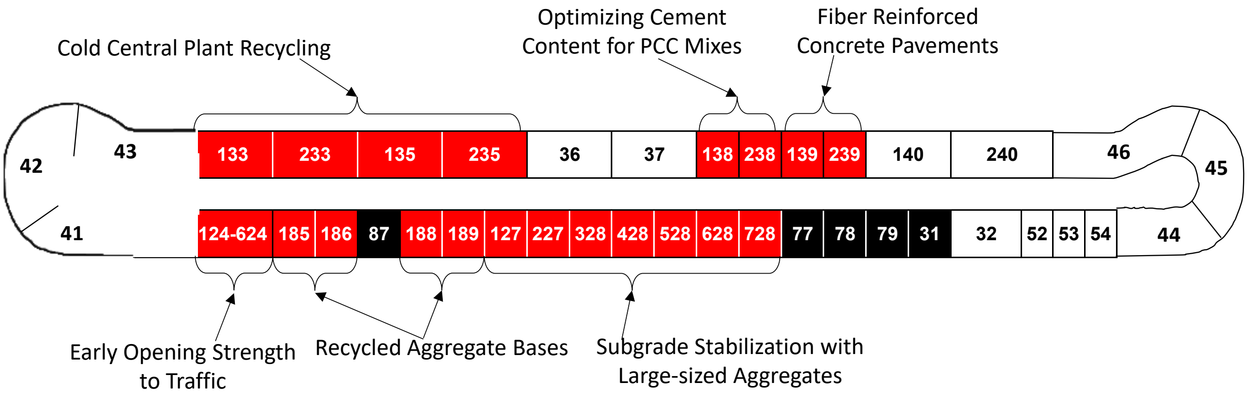


Figure 1.1 MnROAD Low Volume Road (LVR) NRRA sections.

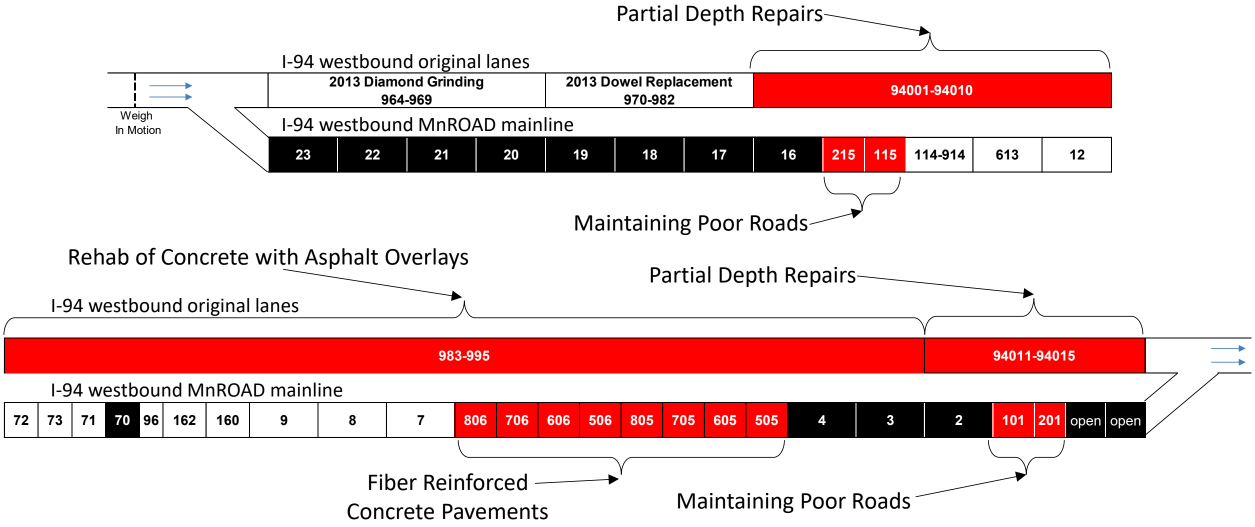


Figure 1.2 MnROAD I-94 WB (original and mainline) NRRA sections.

1.3 REPORT OBJECTIVES

This report documents the objectives of each particular project, along with design considerations, and construction experiences of the sections built in support of them. Each specific group of test sections support long-term research contracts (see Table 1.6). The details and results of each individual study are left to future reports generated by the individual research contracts and their respective teams. Each of the research projects are discussed in individual chapters. Chapter 10 describes performance monitoring and in place sensor measurements that are common among all of the projects.

Table 1.6 NRRA long-term research projects and investigators.

NRRA TEAM	RESEARCH PROJECT	CONTRACTOR
Flexible	Developing Best Practices for Rehabilitation of Concrete with Hot Mix Asphalt (HMA) Overlays related to Density and Reflective Cracking	Dr. Eshan Dave, University of New Hampshire
	Cold Central Plant Recycling (CCPR)	David Rettner, American Engineering Testing, Inc.
Rigid	Fiber Reinforced Concrete Pavements	Dr. Manik Barman, University of Minnesota Duluth
	Early Opening Strength to Traffic	Dr. Lev Khazanovich, University of Pittsburgh
	Optimizing the Mix Components for Contractors	Dr. Peter Taylor, Iowa State University
Geotechnical	Recycled Aggregate Base and Large Subbase	Dr. Bora Cetin, Iowa State University
Preventive Maintenance	Maintaining Poor Pavements	Joe Korzilius, SRF Consulting
	Partial Depth Repairs	Matt Oman, Braun Intertec, Inc.

CHAPTER 2: COLD CENTRAL PLANT RECYCLING

2.1 OBJECTIVES

The use of cold central plant recycling (CCPR) as an economical way to rehabilitated asphalt pavements is becoming more common. CCPR is similar to Cold In place Recycling (CIR) in that it utilizes a high percentage (typically 100 percent) of recycled asphalt pavement (RAP) in a cold mix. Furthermore, it is paved with standard paving equipment. Where it differs from CIR is that it is done centrally, either using millings from an active project or stockpile material. In the case of the latter, CCPR has gained momentum in states that have large surpluses of stockpile material. Nationally, several state agencies are using stockpiled RAP materials in cold mixing applications for stabilized base layers. In particular, Virginia DOT has made significant advances in the design and construction of CCPR [Diefenderfer, et al, 2017] and their specifications were used as the prototype for the NRRA project.

The NRRA experiment will confirm the viability of the CCPR process as well as compare performance of two different:

- Recycling processes (foamed and emulsified asphalt);
- Binders with low-temperature cracking (LTC) specification (PG XX-28 and PG XX-34); and
- Asphalt-based surfaces (asphalt overlay and double chip seal).

Data collected during construction and following years of performance will be used to support the NRRA CCPR research study. The research contractor selected (American Engineering Testing, Inc.) for this project will analyze field testing and performance data, and perform laboratory mixture testing. The findings will be used by each NRRA state member for consideration within their local pavement design and construction practices.

2.2 DESIGN

Four CCPR test cells were planned and designed as part of the 2017 NRRA construction. The new test sections were constructed in an area previously occupied by Cells 33-35 on the LVR. Those sections were originally constructed in 2007; however, existing aggregate base and subgrade were originally constructed in 1994. Total length available for the new sections was about 1,700 feet making each new section approximately 425 feet in length. Existing asphalt pavement was removed and the in place aggregate base prepared for the CCPR layer. Millings from the existing sections were not permitted for use in the new experiments as they were deemed non-representative of field conditions. First, the mixes were acid-modified and second, they had not experienced a significant amount of aging. Contract proposal required the Contractor to provide both a RAP source and four separate CCPR mix designs. Design details for each cell are summarized in Table 2.1. Project special provisions stipulated the performance requirements summarized in Tables 2.2 and 2.3. A summary of the mixture design results are shown in Table 2.4.

Table 2.1 CCPR mixture design and production parameters.

CELL	SURFACE	CCPR SPEC	CCPR BINDER	LTC requirement
133	Double chip seal FA-3/FA-2.5 (CRS-2P)	Emulsion (58S-28)	CIR-EE (H)	-21.4 °C*
233	Double chip seal FA-3/FA-2.5 (CRS-2P)	Foam (58S-28	PG 58S-28	-21.4 °C*
135	1.5 inch asphalt 12.5 mm, PG 58S-34	Foam (XX-34)	PG 52-34	-21.4 °C
235	1.5 inch asphalt 12.5 mm, PG 58S-34	Emulsion (XX-34)	CIR-TEC M	-21.4 °C

*Low-temperature cracking performance testing was not a mix design requirement for Cells 133 and 233. However, test results were required for informational purposes.

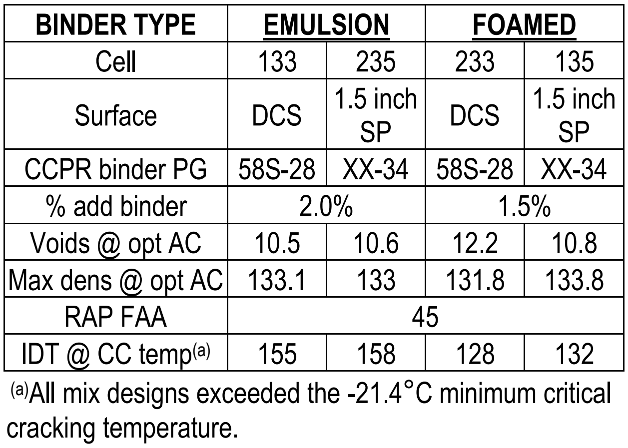
Table 2.2 CCPR mixture design requirements – emulsified asphalt.

ITEM	TEST METHOD	CRITERIA
1	Moisture Density Relations AASHTO T 180, Method D	Determined by design
2	Marshall Stability Test ASTM 5581 (6 inch specimens), AASHTO T 245 (4 inch specimens)	2500 lbs minimum (6 inch specimen), or 1250 lbs (4 inch specimen)
3	Retained Stability ASTM 5581 (6 inch specimens), AASHTO T 245 (4 inch specimens)	70% of results from #2
4	Raveling Stability (ASTM D 7196)	Maximum 2%
5	Thermal Cracking (Indirect Tensile Test, AASHTO T 322)	The critical cracking temperature will be less than or equal to -21.4 °C
6	Hamburg Wheel Track Test, AASHTO T 324-16	Info only

Table 2.3 CCPR mixture design requirements – foamed asphalt.

ITEM	TEST METHOD	CRITERIA
1	Moisture Density Relations AASHTO T 180, Method D	Determined by design
2	Dry Indirect Tensile Strength (ITS), AASHTO T 283 Section 11	45 psi minimum
3	Retained Indirect Tensile Strength, AASHTO T 283 Section 11	Minimum, 70% of the dry ITS
4	Expansion Ratio. Wirtgen 2012 Cold Recycling Manual	10 times when aggregate temperature is 50 °F to 77 °F; 8 times when aggregate temperature is greater than 77° F
5	Half-Life. Wirtgen 2012 Cold Recycling Manual	6 second minimum

Table 2.4 Summary of CCPR mix design results.



BINDER TYPE	**EMULSION**		**FOAMED**	
Cell	133	235	233	135
Surface	DCS	1.5 inch SP	DCS	1.5 inch SP
CCPR binder PG	58S-28	XX-34	58S-28	XX-34
% add binder	2.0%		1.5%	
Voids @ opt AC	10.5	10.6	12.2	10.8
Max dens @ opt AC	133.1	133	131.8	133.8
RAP FAA	45			
IDT @ CC temp[(a)]	155	158	128	132

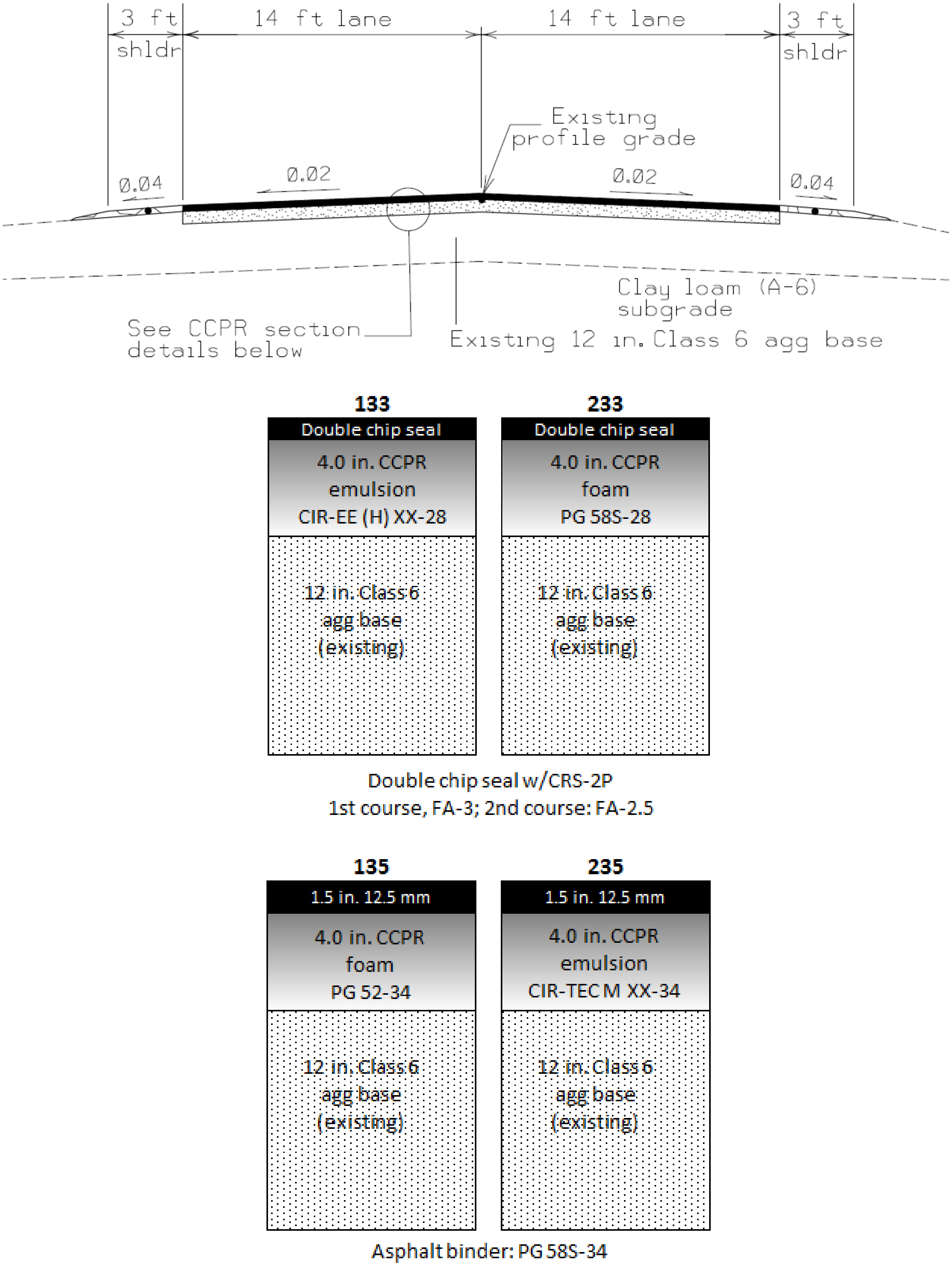
[(a)] All mix designs exceeded the -21.4°C minimum critical cracking temperature.

The asphalt surfacing on the existing sections was 4 inches thick with 12 inches of Class 6 aggregate base. In place subgrade soils are clay loam (A-6). Total asphalt width was 28 feet with 3 feet of aggregate shouldering adjacent to each lane. Section designs are shown in Figure 2.1. The new sections perpetuate this typical.

Two different types of surfacing were constructed. Surfacing on Cells 135 and 235 consisted of 1.5 inches of 12.5 mm asphalt mixture (PG 58S-34 binder). Project specifications for the chip seals called for CRS-2P binder emulsion, with MnDOT FA-3 and FA-2.5 aggregate sizes for the first and second chip courses, respectively. The Contractor was also required to perform a mix design and submit a recommendation report prior to placement. The recommended aggregate and binder application rate ranges were as follows:

- First course
  Binder: 0.25 to 0.35 gal/SY
  Aggregate: FA-3, granite source, 0.375-inch max size, 23 lbs/SY
- Second course
  Binder: 0.18 to 0.26 gal/SY
  Aggregate: FA-2.5, granite source, 0.25-inch max size, 12 lbs/SY

The binder application rates above are based on an anticipated traffic volume of 1,500 AADT which is consistent with the loading rate of the MnROAD LVR assuming about 10 percent heavy commercial traffic. Typically the binder application rate would be adjusted upwards on surfaces with high porosity and/or relief.



Double chip seal w/CRS-2P
1st course, FA-3; 2nd course: FA-2.5

Asphalt binder: PG 58S-34

Figure 2.1 NRRA CCPR research section designs, Cells 135 and 235.

2.3 CONSTRUCTION

Existing asphalt layers were removed by cold-milling. Material was stockpiled at the MnROAD stockpile yard for further processing and eventual use as aggregate shouldering on a number of the constructed sections. It was found that, upon completion of milling operations, the in place aggregate base was in very good condition. A modest amount of shaping and compaction were still performed.

During milling operations it was determined that Cell 235 needed to be shortened by about 50 feet to account for a pavement exception in the transition between Cells 35 and 36.

Construction of the double chip seal took place the week of September 4, 2017. Prior to placement on the project, the Contractor was required to construct a test strip. This was required for the first course only and was constructed on the access road to the MnROAD pole barn. Due to the fact that CCPR mixes have fairly high air voids, a slightly higher initial binder rate was selected: 0.38 gal/SY. The FA-3 cover aggregate was applied at a rate of 19 lbs/SY.

Based on the performance of the test strip it was decided to increase the binder rate slightly – 0.40 gal/SY for placement on Cells 133 and 233. Approximately one dozen passes each with two pneumatic rollers were made starting immediately after placement. Excess chips were swept about one hour after placement.

The second and final course of aggregate was then placed using binder and aggregate rates of 0.28 gal/SY and 18 lbs/SY, respectively. Subsequently, only 4 passes with each of two pneumatic rollers were made.

Final sweeping and fog seal of the double chip seal sections was performed the week of September 18, 2017. Asphalt paving took place the week of September 18, 2017. Prior to paving the CCPR surface was tacked.

2.4 SAMPLING AND TESTING

The asphalt surfacing of the preceding sections (Cells 33-35) were originally constructed in 2007; however, the existing aggregate base and subgrade were originally constructed in 1994. A substantial amount of routine falling-weight deflectometer testing on the preceding pavement sections exists. These data will be analyzed to provide data on the aggregate base and subgrade and will benefit CCPR section performance interpretation.

Several rounds of deflection testing were performed on the exposed in place aggregate base prior to CCPR paving.

Intelligent compaction validation runs were also performed by Ingios Geotechnics before and after CCPR paving. The results are contained in a separate report [White and Vennapusa, 2017].

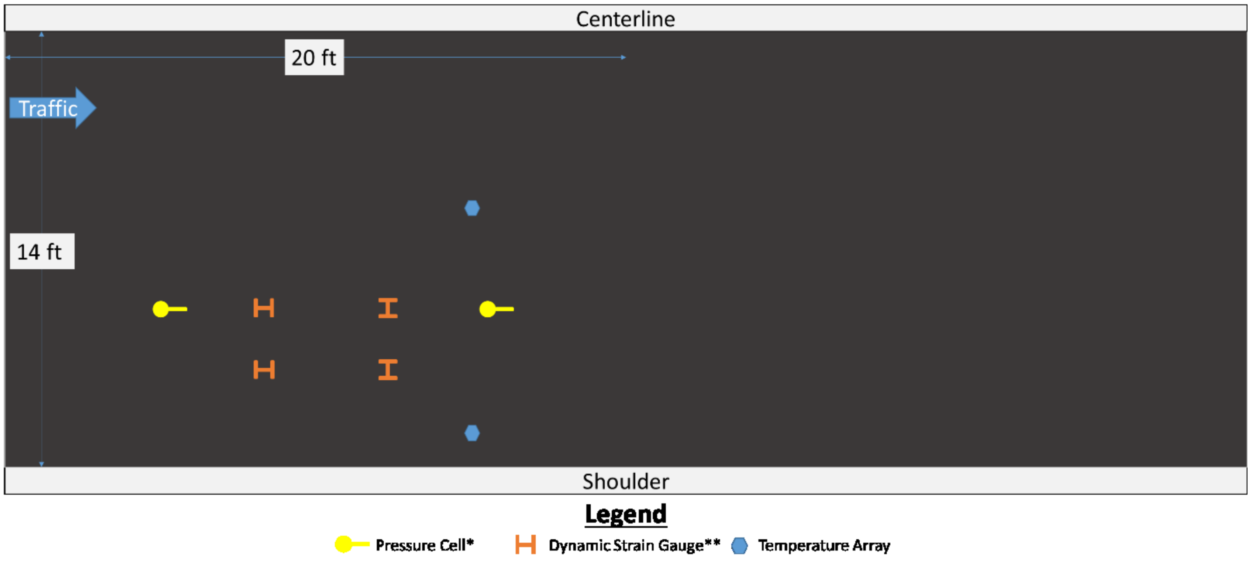
On CCPR production days both RAP and asphalt binder were sampled at the Contractor's plant site. In addition, a limited amount of production mix was sampled at the plant site and test sections. RAP, asphalt binder, and production samples are designated for the NRRA CCPR contract. Additionally, one set of production mix samples were retained for binder extraction and properties testing. These materials will be used for the NRRA long-term research study on CCPR.

Density measurements using a Seaman C-300 (DT-8) portable density meter, in backscatter mode, were performed as part of construction of CCPR sections for both contractor test strips and LVR Cells 133, 233, 135, and 235. General approach was to monitor the density growth curve with successive roller passes. This method was also used for the asphalt surfacing construction of Cells 135 and 235.

The double chip seal was constructed the week of September 4, 2017, a date that is outside the permitted window according the MnDOT specifications. However, conditions were ideal with warm air temperatures and abundant sunshine. After CCPR paving, several rounds of FWD deflection testing were performed. This was again repeated after the surfacing layers were constructed.

2.5 SENSORS

Thermocouple temperature arrays, pressure cells, and pavement strain response sensors were installed as part of the experiment. Cell 133 contains only temperature sensors while Cell 235 has temperature arrays, pressure cells, and longitudinal and transverse asphalt strain transducers. Descriptions of all the sensor types installed with the NRRA construction are contained in Chapter 10. Pressure cells were placed within the aggregate base layer, asphalt strain transducers in Cell 235 were placed at the bottom of the CCPR layer while temperature arrays were positioned within asphalt, CCPR, base, and subgrade layers to a depth of 6 feet. Appendix C lists the as-built locations of the sensors while Figure 2.2 displays a plan view of sensor locations.



* Pressure cells placed at approximately 12 in. from surface
**Strain gauges placed at bottom of CCPR

Figure 2.2 Sensor layout for Cell 235.

CHAPTER 3: BEST PRACTICES FOR REHABILITATION OF CONCRETE WITH HOT MIX ASPHALT OVERLAYS

3.1 OBJECTIVES

Maintenance and rehabilitation of existing roadway pavements constitute a significant portion of available construction resources. It is imperative for agencies to use the most effective tools and approaches to provide the required level of service and long-term performance within the available resources. As infrastructure ages, agencies responsible for maintaining the system are looking for economical ways to meet customer needs while addressing problems that impact the roadways. Agencies face the challenge of maintaining or improving the ride quality of these pavements while managing treatment costs and limiting travel delays due to construction.

Asphalt overlays are commonly used to rehabilitate deteriorated concrete pavements; however, mechanically or thermally-driven movements at joints and cracks in the underlying pavement usually lead to the development of reflective cracks in the overlay. The formation and propagation of reflective cracking is largely controlled by displacements of the underlying concrete pavement. However, the mechanical properties of the asphalt, as well as layer thickness and composition, also play a role in mitigating reflective cracking and resultant benefits to long-term performance.

Current state-of-practice for asphalt overlay design is often policy-based and lacks an engineered selection and design approach. There is need for a) establishing an engineering practice for design of overlays, b) assessment of pre-overlay concrete pavement condition, and c) recommendations for improvements to existing pavement prior to overlay construction.

This study will evaluate the cost, constructability, and benefit of rehabilitating concrete pavements with asphalt overlays that vary in thickness and composition. The ability to reduce pavement distresses (i.e. reflective cracking, joint bumps, slippage failures, etc.) and improve ride quality will be measured between test sections and evaluated based on cost, impact of construction, and service life of each technique. Besides varying the thickness and composition, other options will be considered where applicable, including: highly modified or high strength asphalt pavement, the use of permeable asphalt courses as a first lift, and stabilization of subsurface concrete pavement support placed prior to an overlay.

In support of the NRRA construction efforts, a research contract is underway to achieve the goal of establishing the standard of practice described. The research contract will consider laboratory performance tests on asphalt mixtures from the test sections and will incorporate field performance data, performance modelling, and life cycle cost analysis to develop best practices for rehabilitation of concrete with asphalt overlays. This research will provide specific guidance on the best materials and techniques to use in the rehabilitation of concrete pavements with asphalt overlay.

Specific objectives of the proposed study are to develop a simple decision tree based tool for selecting suitable asphalt mixtures and overlay designs to prolong overlay lives by lowering reflective cracking and improving in-situ density. Recommended guidance from this study will incorporate consideration of constructability (time and effort), performance over time, and life cycle and cost-benefit analysis. It is anticipated that implementation of the tools and materials recommended from the results of this study will translate to savings in construction costs and time, improved serviceability of the roadways for users, and reduced life cycle costs.

The research contractor (University of New Hampshire) will analyze field testing data, including in situ density, intelligent compaction measurements, and laboratory performance testing to calibrate the mechanistic overlay model, and explain how these results affect the observed pavement performance. The recommendations will address each NRRA state DOT partner considering their pavement design method and construction specifications.

The study will also examine whether enhanced density may improve the performance of asphalt overlays. States across the country have been adjusting asphalt mixes in a variety of ways to try to attain better overall mixture performance by achieving higher in place field density. Many research projects have shown the benefit of higher in place density with respect to cracking, rutting, and durability. There have been many approaches to improving field density including, air void regression, reducing gyrations, modifying design air void targets, film thickness, minimum asphalt contents, compaction additives, etc. As part of this study, two specific mixtures based on different mixture design methods that have potential to increase field density were constructed in an effort to quantify impacts on density, cracking, rutting, and overall pavement performance. These are the Superpave5 and regressed air void design approaches proposed by Indiana and Wisconsin, respectively.

Recently, Indiana has proposed a new mixture design approach called Superpave5. This approach, originally a French concept, is accomplished by adjusting the gradation of the aggregates in the mix design while keeping effective binder content the same. Gradation changes to create additional voids in the mineral aggregate (VMA) are also necessary. Three gyration levels are typically used depending on the traffic level: 30, 50, or 70. The overall goal is consistency with traffic loads, and density from design to construction, i.e., design and construct the mixture to 5.0 percent air voids.

The concept of regressed air voids is to design a conventional gyratory mix (4.0 percent design air voids) and then increase the amount of additional virgin asphalt binder to obtain 3.0 percent air voids. This typically increases the design asphalt content up to 0.4 percent. Several states have done this to address the issue of dry mixes, most notably Illinois and Michigan in the Midwest. It is believed the method also improves mixture compaction, and therefore improves the density of the mat. The objective is a more durable pavement.

3.2 DESIGN

A variety of asphalt overlay concepts were considered by the NRRA flexible team. The resulting recommendation consisted of twelve different designs with the goal of examining the performance of different materials, layer configurations, and mix design approaches. One 500 foot section was left in its existing form to serve as a control section (Cell 983).

The roadway selected for these rehabilitation alternatives was the original alignment of I-94 westbound. This section has been in place since the early 1970s and consists of 27-foot jointed (skewed, doweled), reinforced concrete pavement. Exceptions to this exist, however. During past rehabilitation jobs, several areas within the limits had received concrete repairs including full-depth joint replacements and complete panel replacements. In these instances the newly established joints are perpendicular to center line and are less than the original design of 27 feet. The location and condition of transverse joints within the experimental sections were documented prior to overlay construction.

The most recent rehabilitation project (2013) included diamond grinding in the driving lane only. The pavement was in fair condition with the primary distress being faulting, although mid-panel cracks and spalling were also present.

Although an asphalt patching item was included in the contract, only a minimal amount pre-overlay patching was required. MnDOT maintenance personnel had done a significant amount of asphalt patching work in the months leading up to NRRA construction.

The overlay sections are divided into single and two-lift construction. Binder used in all mixes was PG 58H-28, and tack material/rate were conventional, except as noted. Table 3.1 summarizes the designs in this experiment.

Cells 984-986, 994, and 995 are single-lift overlay designs. All were constructed with dense-graded asphalt (Superpave) with the exception of Cell 995, which received a 0.625-inch layer of ultra-thin bonded wearing course (UTBWC). Binder used in the UTBWC was PG 58V-34. Both Cells 986 and 995 were placed with a spray paver that applies a fairly heavy tack. The overlay in Cell 994 was preceded by a polyurethane compaction grouting and void filling process. Voids under a slab can result in high deflections at joints and cracks in a concrete pavement. By filling these voids prior to an overlay, the differential movement between slabs may be significantly reduced or eliminated which, in turn, may reduce or eliminate reflective cracking and allow for a thin, single-lift overlay treatment to be used.

Cells 987-993 were all two-lift designs with varying layer thicknesses and compositions. Total asphalt design thicknesses were 4 inches for Cells 987-991 and 2.5 inches for Cells 992-993. A coarse, 19.0-mm NMAS mix was constructed as the first lift in Cells 987-991 and paved at 2.5 inches thick for Cell 987 and 2.25 inches thick in Cells 988-991.

Surface lifts for Cells 987, 988, and 991 were dense-graded mixes designed for 4.0 percent air voids. Cell 987 had a 9.5 mm NMAS surface layer mix paved 1.5 inches thick. Cells 988 and 991 had 12.5 and 9.5 mm NMAS, respectively, paved at 1.75 inches thick.

Cells 989 and 990 employed alternate mix designs for the surface course. The second lift of Cell 989 was a Superpave5 mix designed to 5.0 percent air voids and compacted to 95.0 percent density in the field. Surface lift in Cell 990 was a regressed 3.0 percent air voids mix, with field target density at 93.0 percent. Mix proportions were attained by holding the aggregate gradation constant and supplying additional asphalt binder to achieve 3.0 percent design voids.

Asphalt mix placed on the shoulders is the same as the mix placed for each particular lift on the adjacent travel lanes. The inside shoulder was paved concurrent with the passing lane. Transition areas for core sampling and other evaluations were included at either end of the test sections. A layout of the test sections and summary of designs are shown below in Figures 3.1 through 3.3. Except as noted, the following hold true for all lifts and mixes in these sections:

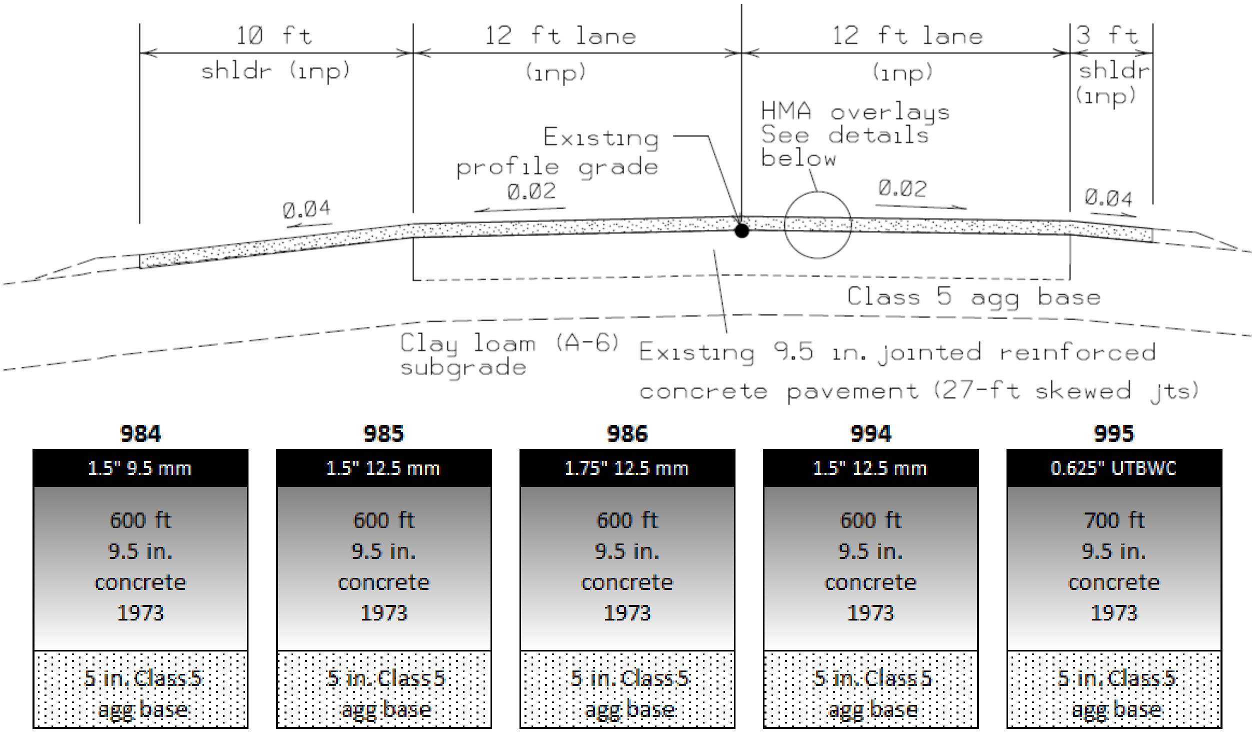
- Tack coats specified as conventional MnDOT rates and material;
- Mixes placed with conventional paving equipment;
- Asphalt binder PG 58H-28; and
- Mixes designed to 4 percent air voids.

Table 3.1 Summary of NRRA flexible pavement overlay test sections (Cells 983-995).

STUDY	CELL	LIFT	THICK. (in.)	MIX DESCRIPTION (NMAS, mm)	BINDER	DESIGN VOIDS (%)	TARGET FIELD DENSITY (%)
Concrete Pavement Rehab	983	-	-	-	-	-	-
	984	1/1	1.50	Fine mix (9.5)	58H-28	4.0	93.0
	985	1/1	1.50	Typical mix (12.5)	58H-28	4.0	93.0
	986	1/1	1.75	Typical mix (12.5) w/spray paver	58H-28	4.0	93.0
	987	1/2	2.50	Coarse leveling (19.0)	58H-28	4.0	93.0
		2/2	1.50	Fine mix (9.5)	58H-28	4.0	93.0
Compaction Study	988	1/2	2.25	Coarse leveling (19.0)	58H-28	4.0	93.0
		2/2	1.75	Typical mix (12.5)	58H-28	4.0	93.0
	989	1/2	2.25	Coarse leveling (19.0)	58H-28	4.0	93.0
		2/2	1.75	Superpave 95/5 (12.5)	58H-28	5.0	95.0
	990	1/2	2.25	Coarse leveling (19.0)	58H-28	4.0	93.0
		2/2	1.75	Regressed voids design (12.5)	58H-28	3.0	93.0
	991	1/2	2.25	Coarse leveling (19.0)	58H-28	4.0	93.0
		2/2	1.75	Fine mix (9.5)	58H-28	4.0	93.0
Concrete Pavement Rehab	992	1/2	1.00	Crack inhibiting interlayer (4.75)	58E-34	2.0-3.0	-
		2/2	1.50	Fine mix (9.5)	58H-28	4.0	93.0
	993	1/2	1.00	PASSRC-permeable interlayer mix	64S-22	-	-
		2/2	1.50	Fine mix (9.5)	58H-28	4.0	93.0
	994	1/1	1.50	Fine mix (9.5) pre-overlay slab treatment	58H-28	4.0	93.0
	995	1/1	0.75	UTBWC w/spray paver	58V-34	-	-

	Control	Single lift			Two lifts							Single lift	
Cell	983	984	985	986	987	988	989	990	991	992	993	994	995
Length (ft)	500	700	600	600	600	600	600	600	600	600	600	600	700

Figure 3.1 Rehabilitation with asphalt overlays test section layout (original westbound lanes of I-94).



Except as noted:
1. Binders PG 58H-28
2. Mixes 4.0% design voids
3. Conventional tack rates
4. Target field density 93% of maximum

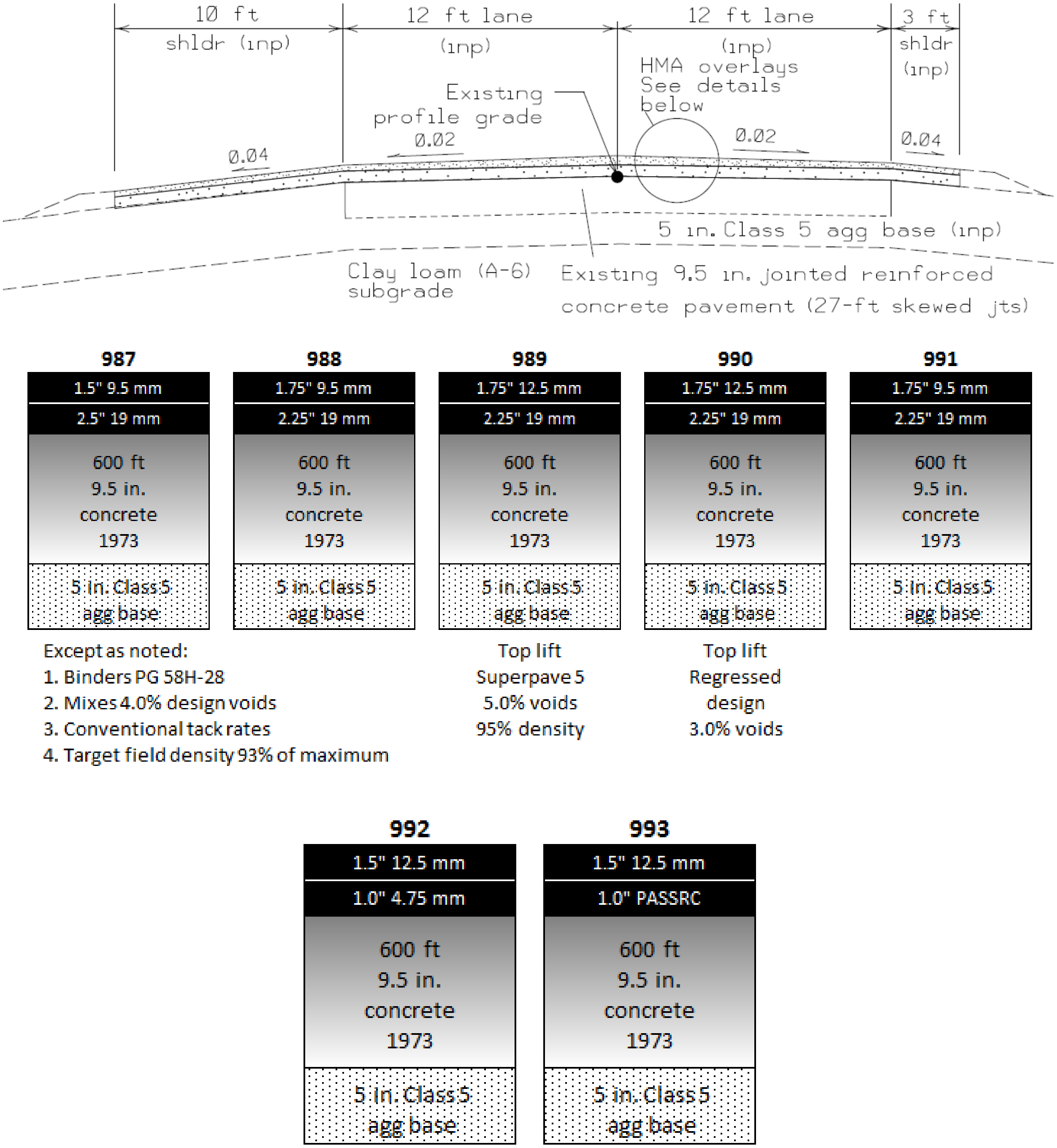
986: Spray paver tack 0.17-0.23 gal/sy

994: Pre-overlay compaction grouting + joint underseal

995: PG 58V-34 Spray paver tack 0.17-0.23 gal/sy

Figure 3.2 Single lift asphalt overlay section designs.

Adequate tack coat is a crucial component in the long-term performance of asphalt pavements. During construction of these sections the tack coat rate, based on residual asphalt, was evaluated using ASTM D2995-14 (with modifications). Residual asphalt of an emulsified asphalt tack coat refers simply to the amount of asphalt binder that remains after breaking and curing. Several states have implemented residual tack rate specifications. However, MnDOT specifies an application rate range; tack coat is considered incidental to the contract. Table 3.2 shows residual tack coat rate requirements from Illinois DOT. Tables 3.3 and 3.4 summarize the MnDOT standard tack coat specifications that were in effect for construction of the project. Table 3.5 provides a comparison between distributor (application) and residual rates. As can be seen, MnDOT application rates, when translated to residual rates, are in very close agreement to Illinois DOT.



Except as noted:
1. Binders PG 58H-28
2. Mixes 4.0% design voids
3. Conventional tack rates
4. Target field density 93% of maximum

989: Top lift
Superpave 5
5.0% voids
95% density

990: Top lift
Regressed
design
3.0% voids

992: Bottom lift
1.0"
interlayer
PG 58E-34
2-3% voids

993: PASSRC
PG 64S-22

Figure 3.3 Two lift asphalt overlay section designs.

Table 3.2 Illinois DOT specifications - residual asphalt contents for tack coat emulsions.

TYPE OF SURFACE	RESIDUAL ASPHALT CONTENT (gal/SY)
Milled asphalt, aged non-milled asphalt, milled concrete, and non-milled concrete	0.05
HMA lifts	0.03

Table 3.3 MnDOT typical residual asphalt contents for tack coat emulsions (2016 Standard Specification 2357).

Table 2357-1 RESIDUAL ASPHALT CONTENT (percent)		
	Minimum Residual Asphalt Content	
Emulsion	Undiluted	Diluted (7:3)
CSS-1 or CSS-1h	57%	40%

Table 3.4 MnDOT tack coat rates for various surface types (2016 Standard Specification 2357).

Table 2357-2 TACK COAT APPLICATION RATES			
	Application Rates (gal/SY)		
Surface Type	Undiluted Emulsion	Diluted Emulsion (7:3)[1]	MC Cutback[2]
New Asphalt	0.05 to 0.07	0.08 to 0.10	0.05 to 0.07
Old Asphalt[3] and concrete	0.08 to 0.10	0.13 to 0.15	0.09 to 0.11
Milled Asphalt and Milled concrete	0.07 to 0.11	0.10 to 0.13	0.09 to 0.11

1- As provided be the asphalt emulsion supplier

2- Use when approved by the Engineer

3- Older than 1 year

Table 3.5 MnDOT tack coat rates expressed in terms of residual asphalt.

Surface Type	Undiluted		Diluted	
	Distributor (a) (gal/SY)	Residual (b) (gal/SY)	Distributor (a) (gal/SY)	Residual (b) (gal/SY)
New Asphalt	0.060	0.034	0.090	0.036
Old Asphalt or concrete	0.090	0.051	0.140	0.056
Milled Asphalt or concrete	0.090	0.051	0.120	0.048

(a) Rates taken from mid-point of ranges shown in Table 2357-2.

(b) Residuals calculated using (a) and residuals in Table 2357-1

The procedure detailed in ASTM D2995 involves the placement of absorbent geosynthetic fabric squares on the pavement surface prior to passage of the tack coat distributor. The fabric pieces are first weighed before tack coat is applied, and subsequently after the applied tack has fully cured and the water driven off. The ASTM procedure prescribes that the saturated squares be heated in an oven to fully drive off the water in the emulsion. It was found that it was unnecessary to dry the fabric/tack specimens in an oven as the difference was at most +/- 0.001 gal/SY.

An asphalt-rich, polymer-modified, crack-resistant interlayer was constructed as the first lift of Cell 992. The special provisions contained performance requirements for which the Contractor had the responsibility of meeting. See Table 3.6.

Table 3.6 Asphalt interlayer performance requirements for Cell 992.

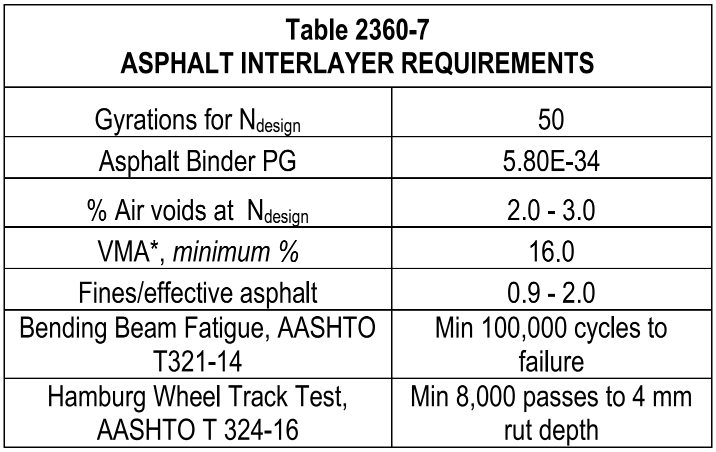


Table 2360-7
ASPHALT INTERLAYER REQUIREMENTS

Gyrations for N_{design}	50
Asphalt Binder PG	5.80E-34
% Air voids at N_{design}	2.0 - 3.0
VMA*, *minimum %*	16.0
Fines/effective asphalt	0.9 - 2.0
Bending Beam Fatigue, AASHTO T321-14	Min 100,000 cycles to failure
Hamburg Wheel Track Test, AASHTO T 324-16	Min 8,000 passes to 4 mm rut depth

3.3 ASPHALT MIXTURE PERFORMANCE TESTING

As part of the NRRA long-term research needs, asphalt mixture performance testing will be performed on the mixes from the newly constructed sections. Asphalt mixture performance testing presents an opportunity to promote innovation while ensuring a pavement with sufficient performance characteristics is achieved. Additionally, not all XX-34 binders are created equal (modified vs. neat, crude source properties, modification method, etc.). Research has shown binder tests alone are not sufficient to predict low temperature cracking performance in the field [Marasteanu, et al, 2007]; testing asphalt mixtures is helpful to obtain performance comparisons. A listing of performance tests to be conducted by NRRA state partners is shown in Table 3.7.

3.4 CONSTRUCTION

Table 3.8 provides a detailed timeline broken down by mixture and test section. It can be seen that paving was completed by mid-October, 2017.

Table 3.7 Summary of asphalt mixture performance testing.

DISTRESS TYPE	TEST	DESCRIPTION
Cracking	E*	Dynamic modulus
	S-VECD	Simplified, visco-elastic continuum damage
	IFIT	Illinois Flexibility Index Test
	IDEAL-CT	Ideal Cracking Test
	Texas OT	Texas Overlay Tester
	DCT	Disc-shaped Compact Tension
Rutting	Flow number (E*)	Part of dynamic modulus test
	HWTT	Hamburg Wheel Track Test
Moisture susceptibility	TSR	Tensile Strength Ratio
	HWTT	Hamburg Wheel Track Test
	MiST	Moisture Induced Stress Tester

Table 3.8 Detailed timeline of construction by test section, lift, and mixture.

STUDY	CELL	LIFT	THICK. (in.)	MIX DESCRIPTION (NMAS, mm)	DATE PAVED
Concrete Pavement Rehab	983	-	-	-	
	984	1/1	1.50	Fine mix (9.5)	10/18/2017
	985	1/1	1.50	Typical mix (12.5)	10/14/2017
	986	1/1	1.75	Typical mix (12.5) w/spray paver	10/12/2017
	987	1/2	2.50	Coarse leveling (19.0)	10/13/2017
		2/2	1.50	Fine mix (9.5)	10/18/2017
Compaction Study	988	1/2	2.25	Coarse leveling (19.0)	10/13/2017
		2/2	1.75	Typical mix (12.5)	10/14/2017
	989	1/2	2.25	Coarse leveling (19.0)	10/13/2017
		2/2	1.75	Superpave 95/5 (12.5)	10/17/2017
	990	1/2	2.25	Coarse leveling (19.0)	10/13/2017
		2/2	1.75	Regressed voids design (12.5)	10/17/2017
	991	1/2	2.25	Coarse leveling (19.0)	10/13/2017
		2/2	1.75	Fine mix (9.5)	10/18/2017
Concrete Pavement Rehab	992	1/2	1.00	Crack inhibiting interlayer (4.75)	10/13/2017
		2/2	1.50	Fine mix (9.5)	10/18/2017
	993	1/2	1.00	PASSRC-permeable interlayer mix	10/13/2017
		2/2	1.50	Fine mix (9.5)	10/18/2017
	994	1/1	1.50	Fine mix (9.5) pre-overlay slab treatment	10/18/2017
	995	1/1	0.75	UTBWC w/spray paver	10/12/2017

3.5 SAMPLING AND TESTING

The ancillary data described in this section will be provided to the research contractor for analysis and comparison against pavement performance.

A number of pre-overlay evaluations were performed to document conditions of the concrete pavement prior to construction. See Chapter 10 for a full discussion of all the various performance evaluation approaches utilized at MnROAD. The pre-overlay evaluations included deflection load-transfer efficiency testing using the falling-weight deflectometer and distress surveys made using Pathway Services, Inc. Digital Inspection Vehicle (DIV).

At the time of construction, samples of all mixtures were collected for performance tests described in Table 3.7 of this chapter. In place properties were also characterized by various methods, including nuclear density gauge, coring, rolling density meter (RDM), thermal profiling, and intelligent compaction. In support of the asphalt mixture performance testing program, samples of production mix were bulk sampled from delivery trucks as shown in Figure 3.4. Figure 3.5 shows how the samples were then transferred to individual, 3.5-gal containers from the bulk sample.

Tack coat residual rates were determined during the paving operations in each cell utilizing 12-inch by 12-inch geosynthetic fabric squares mounted to impervious plates. Just prior to tack coat application, the fabric/plate assemblies were weighed, and then placed on the road. After the tack distributor had passed, the assemblies were brought inside, permitted to cure, and subsequently weighed. It was found that, based on the determined residual asphalt tack rates and requirements shown in Table 3.5, adequate tack coverage was attained.

Figure 3.4 Bulk sampling approach for NRRA asphalt mixtures.

Figure 3.5 Transferring bulk samples to containers for distribution to NRRA participants.

Project special provisions required the contractor to employ paver mounted thermal profiling and intelligent compaction technology to monitor the surface temperature and compaction effort, respectively.

In place density measurements were obtained from a limited number of randomly located, density acceptance cores taken from each lift of each section and nuclear density measurements calibrated with density cores from transition areas. Nuclear density measurements with a Seaman C-300 (DT-8) portable density meter were made in backscatter mode. Calibrated nuclear density measurements (with associated cores), shown in Figure 3.6, were made within the transition areas of selected sections to identify a relationship for each unique mix. Eight points were tested for calibration prior to coring, at 6-ft and 10-ft offsets from the centerline joint, in the driving lane. After the calibration points were measured with the gauge, supplementary cores were taken from each point in the grid. Bulk specific gravity determinations were made in the laboratory. In addition, three sets of four points were tested using the nuclear density gauge only (no coring) within each test section. Using these relationships, a series of standalone nuclear density readings were made within each lift of each test section. Respective calibrations were applied based on the particular mix.

The MnDOT RDM system was used to survey the compacted asphalt lifts. Interpreted electromagnetic signal reflections are used to estimate the surface dielectric of the asphalt material. These values have been shown to correlate well with compacted asphalt mixture volumetric properties [Hoegh and Dai, 2017].

Figure 3.6 Typical layout for density calibration cores and nuclear density testing.

3.6 SENSORS

Both joint-opening (JO) sensors and thermocouples (TC) were installed in four of the 12 sections: Cells 983, 984, 989, and 992. Two JO sensors and a single temperature array were installed in Cell 983. The remaining cells have three JO sensors and one temperature array each, Figures 3.7 and 3.8 show the sensor layout used in these sections. Detailed location information is summarized in Appendix C. Refer to Chapter 10 for a discussion of sensors installed.

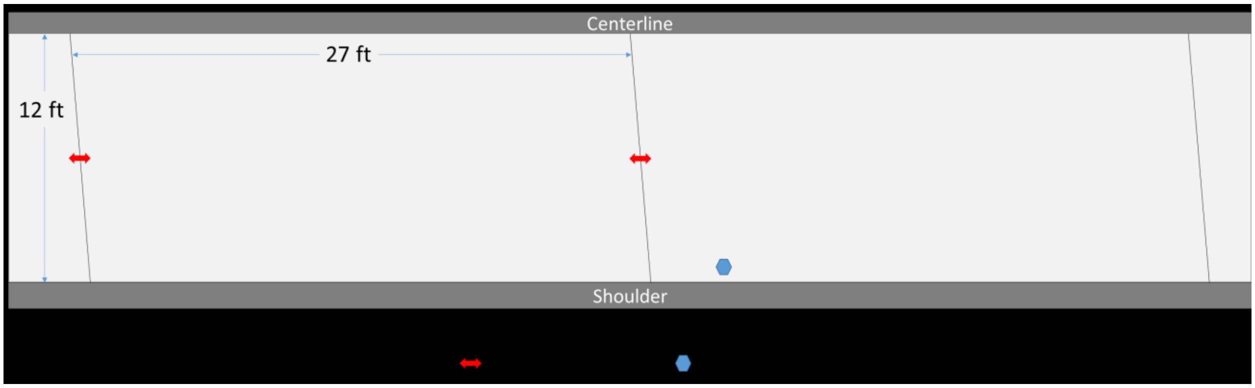


Figure 3.7 Sensor layout for Cell 983.

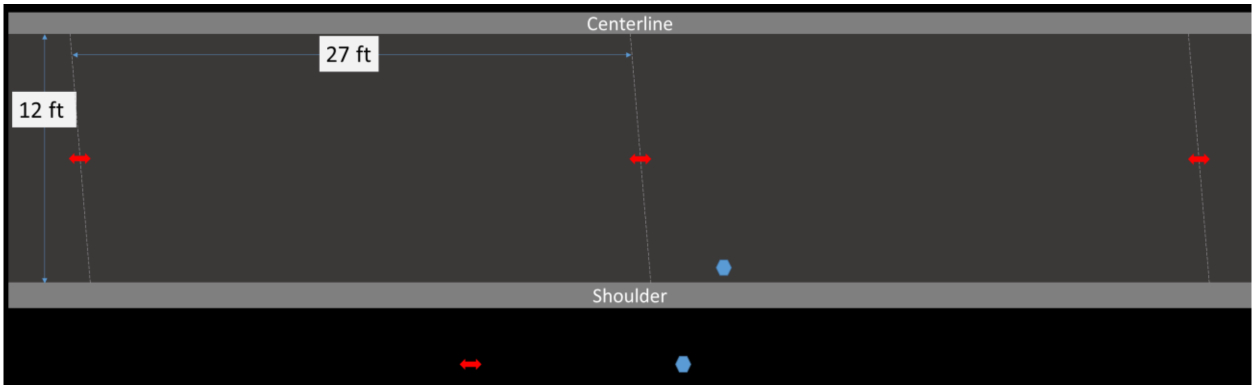


Figure 3.8 Typical sensor layout for Cells 984, 989, and 992.

CHAPTER 4: FIBER-REINFORCED CONCRETE PAVEMENT

4.1 OBJECTIVES

Due to increasing budget constraints, there is interest in economizing concrete pavement structures by either reducing panel thickness or increasing the panel size, while continuing to provide satisfactory long-term service life. Past research and network performance has demonstrated there are definite limits to both of these parameters for conventional, jointed, undoweled, plain concrete pavement, as well as concrete overlays. One potential solution to achieving these goals might be to utilize fiber-reinforced concrete (FRC) pavement. The research need arises in understanding the contribution of structural fibers in improving the performance of both thinner concrete pavements (on grade), as well as various concrete overlays.

The primary objectives in constructing new FRC test cells at MnROAD include quantifying the ability of structural fibers to improve the performance of thin concrete pavement and overlays by holding cracks tight, as well as transferring wheel loads between adjacent slabs. This will be accomplished by determining the contribution of fibers related to three behavioral aspects:

- Reducing and/or arresting fatigue cracking;
- Maintaining joint load transfer and mitigating joint faulting;
- Optimization of panel size and thickness for specific applications (i.e. slabs on grade, overlays);

The new test cells will also provide field performance data for comparison and validation of associated studies examining the characteristics and recommended fiber dosages rates for FRC pavements.

4.2 DESIGN

To accomplish the objectives of the FRC study, eight new MnROAD test cells were designed and constructed in 2017. Table 4.1 summarizes the general pre- and post-construction descriptions of these cells. Table 4.2 lists design and as-built components for each cell. Fiber type and dosages were determined by the contractor through flexural strength testing in accordance with ASTM C1609. In particular, calculated residual strength ratio (RSR) was used. Of particular note are some changes that occurred during the construction of cells 606, 705, and 805. These changes will be described in further detail in Section 4.3.

Constructed on the LVR portion of MnROAD, Cells 139 and 239 consist of FRC designed for 3 and 4 inch thicknesses, respectively. The sections were constructed on a new 6-inch thick Class 6 aggregate base and 4-inch thick clay loam common borrow subgrade layer. Figure 4.1 depicts the general cross-sectional design of the new cells. Both lanes were sawn into 6 x 6 foot panels as shown in Figure 4.2. All single saw-cut joints were sealed with MnDOT Spec 3725 hot-pour asphalt sealant. Shoulders were constructed using recycled asphalt pavement stabilized with asphalt emulsion.

The fiber dosage chosen for these two cells was based on meeting a 30 percent RSR based on ASTM C1609 testing. This higher than typical dosage rate was selected for Cells 139 and 239 in anticipation of the need for extra reinforcement with ultra-thin slabs.

Table 4.1 Pre- and post-construction design summary.

PREVIOUS SECTIONS	NRRA FRC SECTIONS
Cells 305 and 405 Thin Unbonded Concrete Overlay on Concrete with PASSRC Interlayer. Located on MnROAD Mainline (I-94) Life span: 2008 – 2017	**Cells 705 and 805** Thin FRC Unbonded Concrete Overlay on Existing Concrete Pavement with Fabric Interlayer.
Cells 306 and 406 Thin Concrete Pavement on Drainable but Stable Base. Located on MnROAD Mainline (I-94) Life span: 2011 - 2017	**Cells 506 – 806** Thin FRC Pavement on Base.
Cell 39 Pervious Thin Bonded Concrete Overlay on Concrete. Located on MnROAD LVR Life span: 2008 - 2017	**Cells 139 and 239** Ultra-thin Fiber Reinforced Concrete Pavement on Base (Street Design).

Table 4.2 Design details for all FRC cells (as-built dimensions shown in parentheses).

CELL	THICK (in.)	PANEL SIZE (ft) (as-built size shown in parentheses)	MIX	RSR (%), FIBER DOSE (lb/CY)[a]	JOINT SEALING
139	3	6 x 6	3A21F2	30, 8	Hot pour
239	4	6 x 6	3A21F2	30, 8	Hot pour
705	5[b]	Driving: 14W x 12L Passing: 13W x 12L (12W x 12L)[c]	3A21F1	20, 5	-
805	5[b]	Driving: 6W x 12L, 8W x 12L Passing: 6W x 12L, 7W x 12L (6W x 12L, 6W x 12L)[c]	3A21F1	20, 5	-
506	5	6 x 6	3A21FC	None (control)	-
606	5	6 x 6	3A21F1	20, 5	-
706	5	6 x 6	3A21F2	30, 8	-
806	5	6 x 6	3A21F3	NA, 11.66	-

[a] Fiber type: FORTA FERRO®. See Appendix D for specifications.

[b] Placed on 15 ounce non-woven geotextile fabric.

[c] Due to field miscommunication, see Figures 4.5 through 4.7.

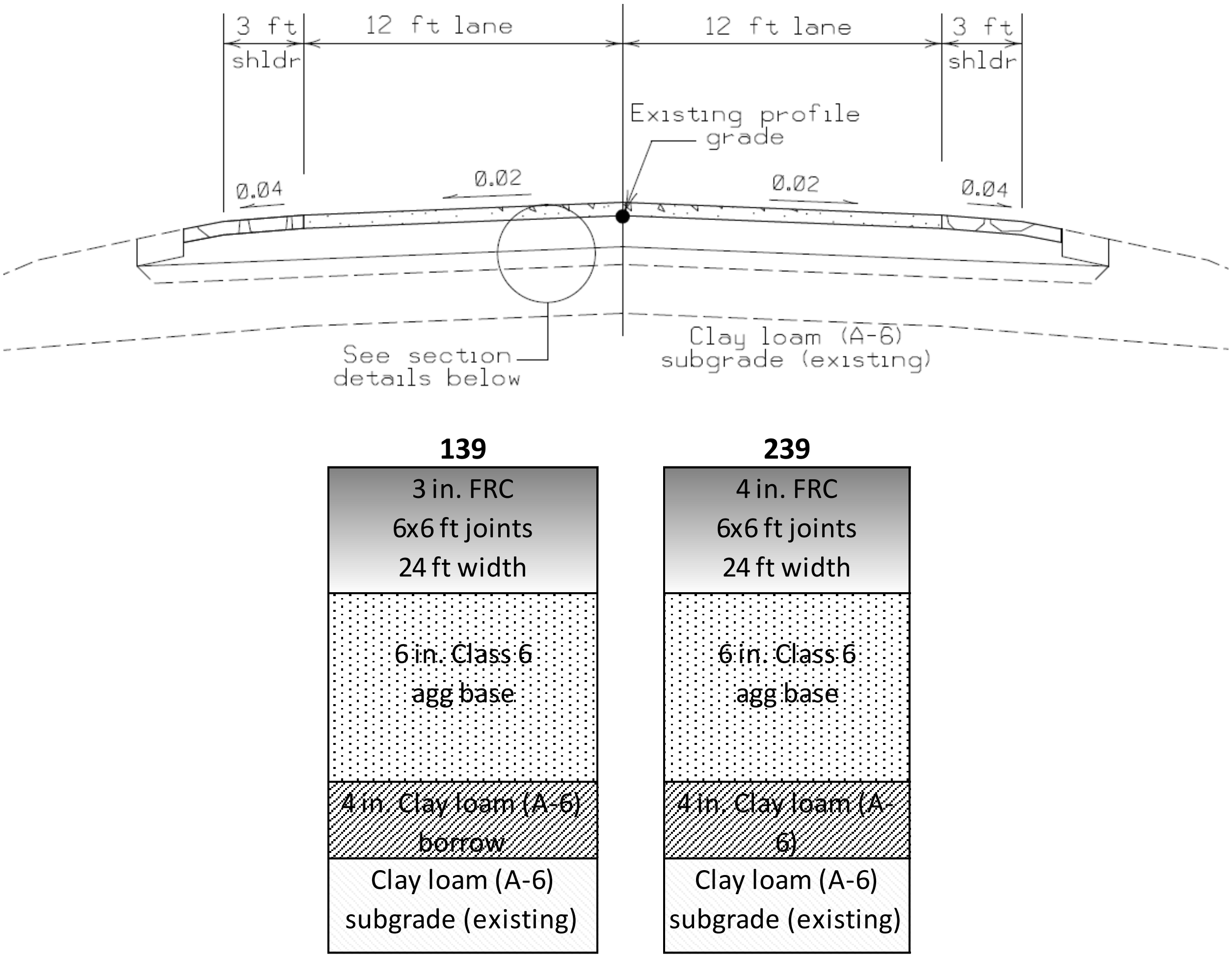


Figure 4.1 Planned section design for FRC Cells 139 and 239.

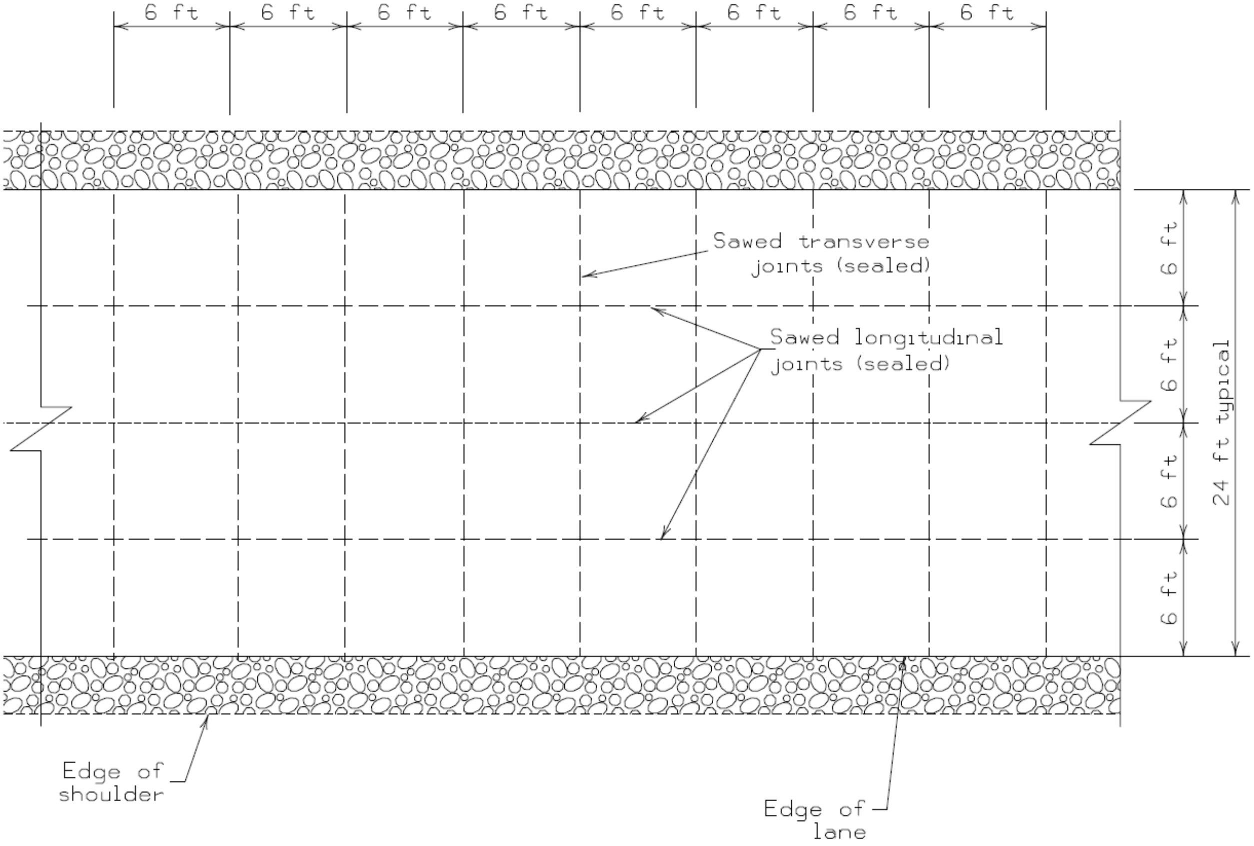


Figure 4.2 Joint layout details for FRC Cells 139 and 239.

Cells 705 and 805, constructed on the mainline interstate portion of MnROAD, consist of 5-inch thick FRC placed on a 15 ounce non-woven geotextile fabric interlayer adhered to a 7.5-inch thick concrete pavement originally constructed in 1992. Figure 4.3 depicts the general cross-sectional design of the new cells. The driving lane of the 1992 section consisted of 14 foot wide by 15 foot long panels, while the passing lane panels were 13 feet wide by 15 feet. The fiber dosage chosen for these two cells was based on meeting a typical RSR of 20 percent from ASTM C1609 testing.

The new FRC overlays in Cell 705 and 805 were paved at 30 feet in width. Transverse joints were all spaced at 12 feet. In Cell 705, proposed longitudinal joints were to be made at centerline and 13 feet from centerline (1 feet outside the passing lane, inside shoulder). Proposed longitudinal joints in Cell 805 were to be made at centerline, 6 feet offset from centerline, either side, and 13 feet from centerline, outside the passing lane (inside shoulder). See Figures 4.4 and 4.5. Inadvertent deviations from the planned joint layouts occurring during construction are discussed in Section 4.3.

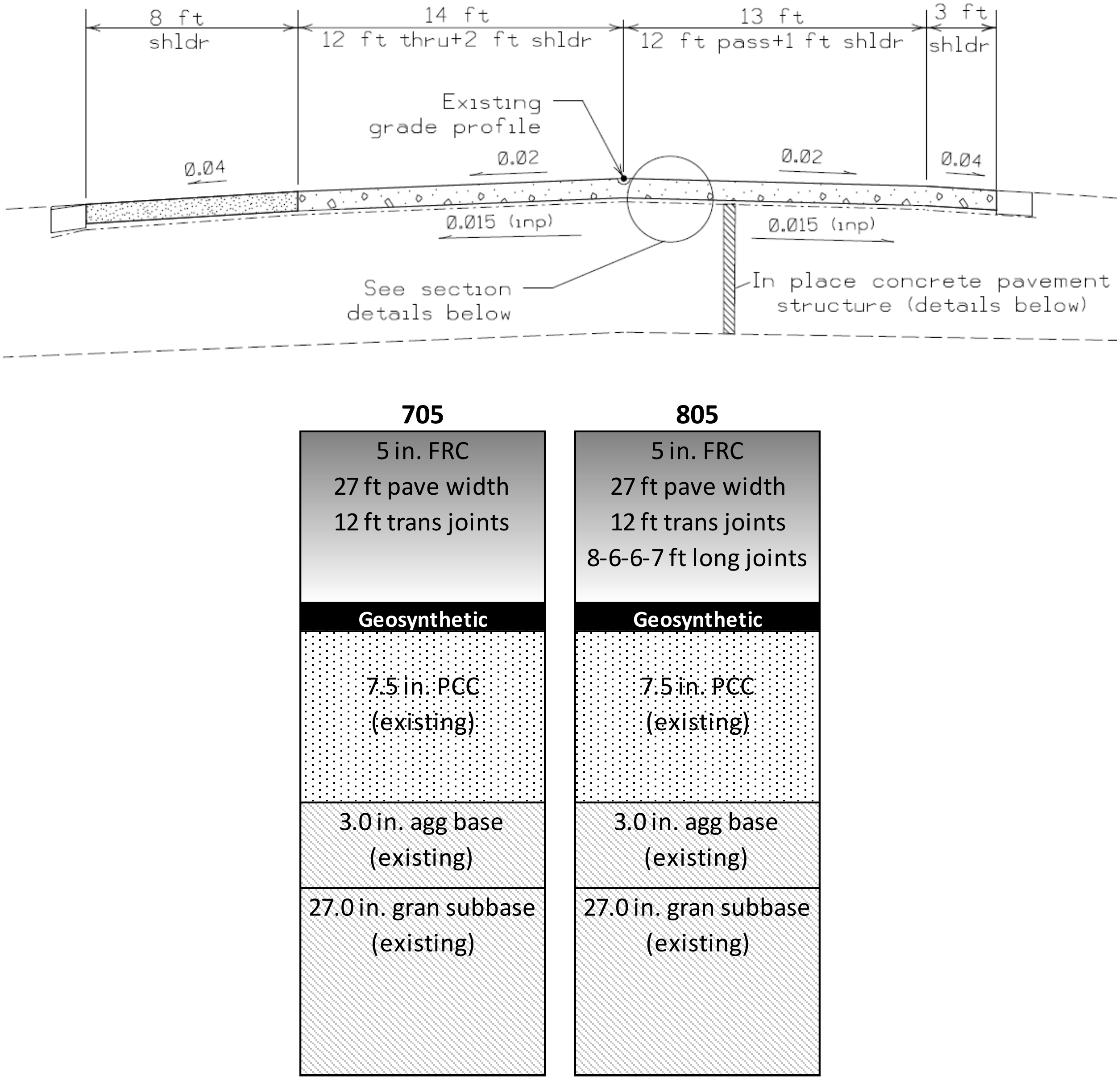


Figure 4.3 Planned section design for FRC Cells 705 and 805.

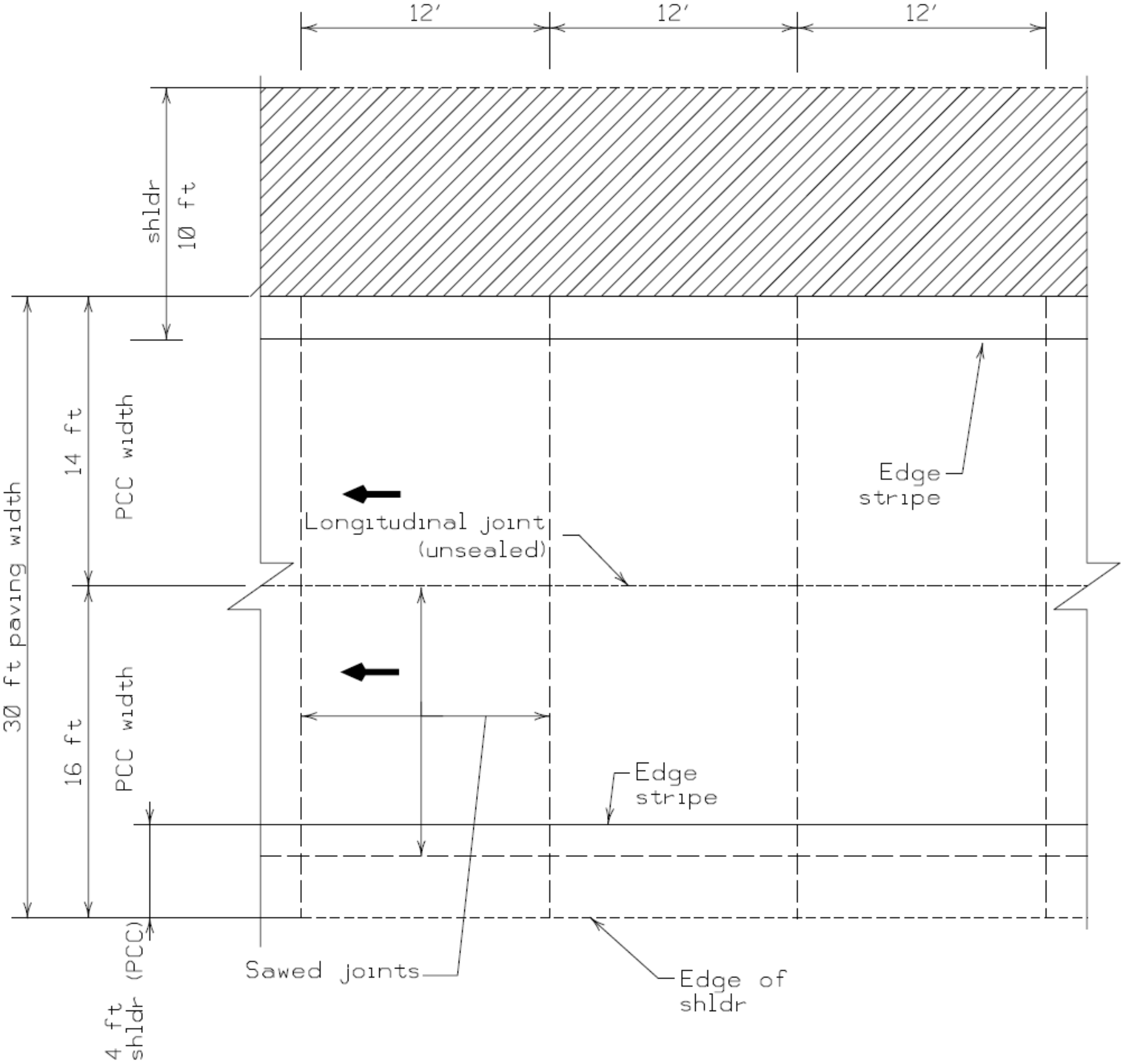


Figure 4.4 Planned joint layout for FRC Cell 705.

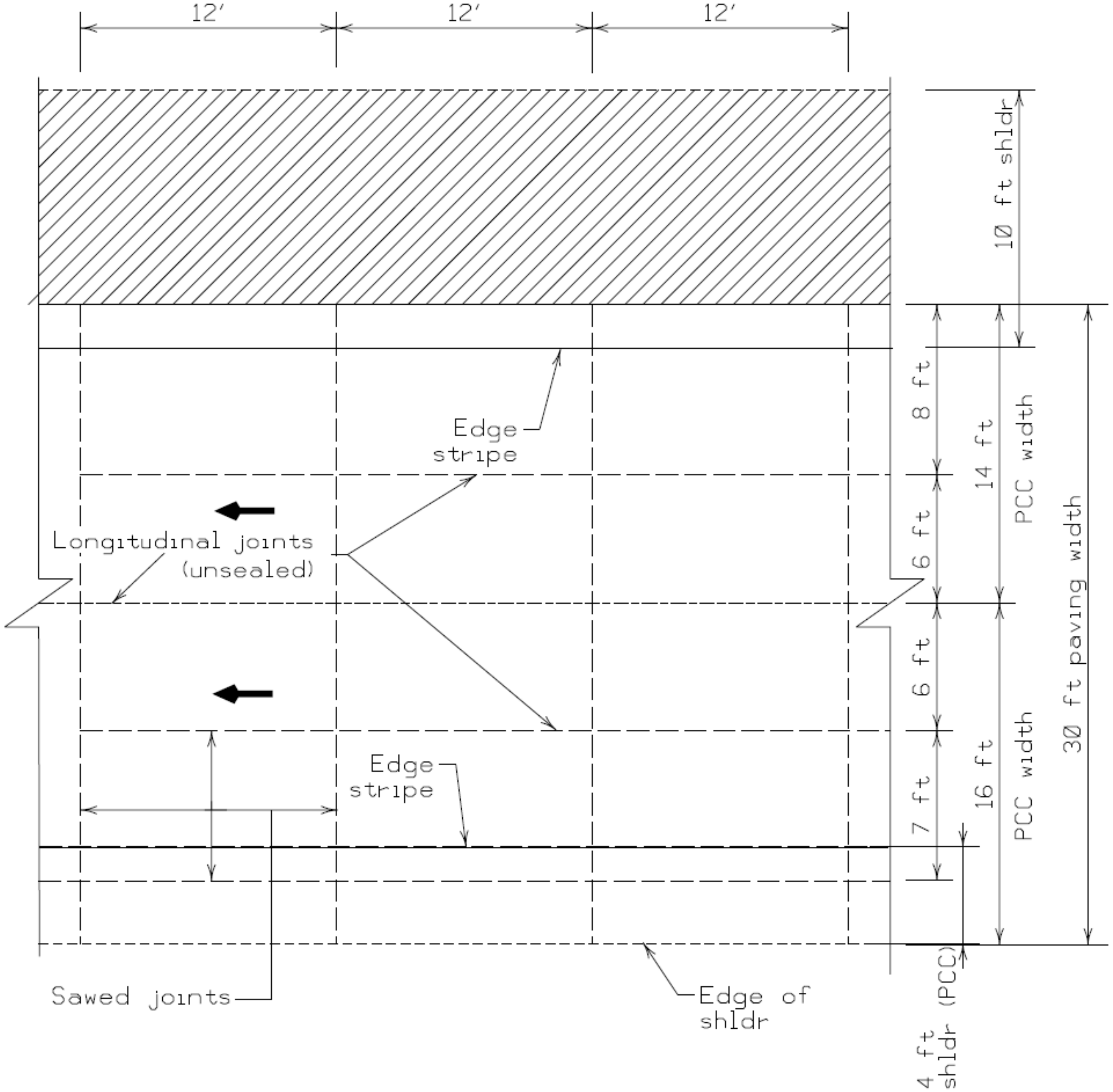


Figure 4.5 Planned joint layout for FRC Cell 805.

The single saw-cut joints in Cell 705 and 805 were not sealed. Asphalt shoulder pavement, 8 feet in width, was placed adjacent to each cell outside the driving lane. Non-woven geotextile fabric extended approximately 2 feet beyond the paved shoulders, ending beneath the outer edge of aggregate surfacing placed outside the shoulders on either side.

Cells 506 through 806 are 5-inch thick designs on new 11-inch thick Class 5Q aggregate base. The sections utilize approximately 3 inch of in place Class 5 aggregate base remaining after existing pavement removal (originally constructed in 1992). Figure 4.6 depicts the general cross-sectional design of the new cells. Cells 606 through 806 each had a different fiber content, as listed in Table 4.2. The fiber dosages in these sections were designed to meet RSR values of 20 and 30 percent, respectively, based on ASTM C1609 testing. The fiber dosage of 0.75 percent by volume was chosen for Cell 806 based on results from lab testing, where this dosage rate provided diminishing returns on improving RSR, as well increasing the potential for fiber "balling." The concrete mixture in Cell 506 is non-FRC and will serve as a control section for the study.

The paving width for Cells 506-806 was 24 feet; both lanes were sawn into 6 x 6 feet panels as shown in Figure 4.7. The single saw-cut joints were not sealed. Both inside and outside shoulders were paved with asphalt.

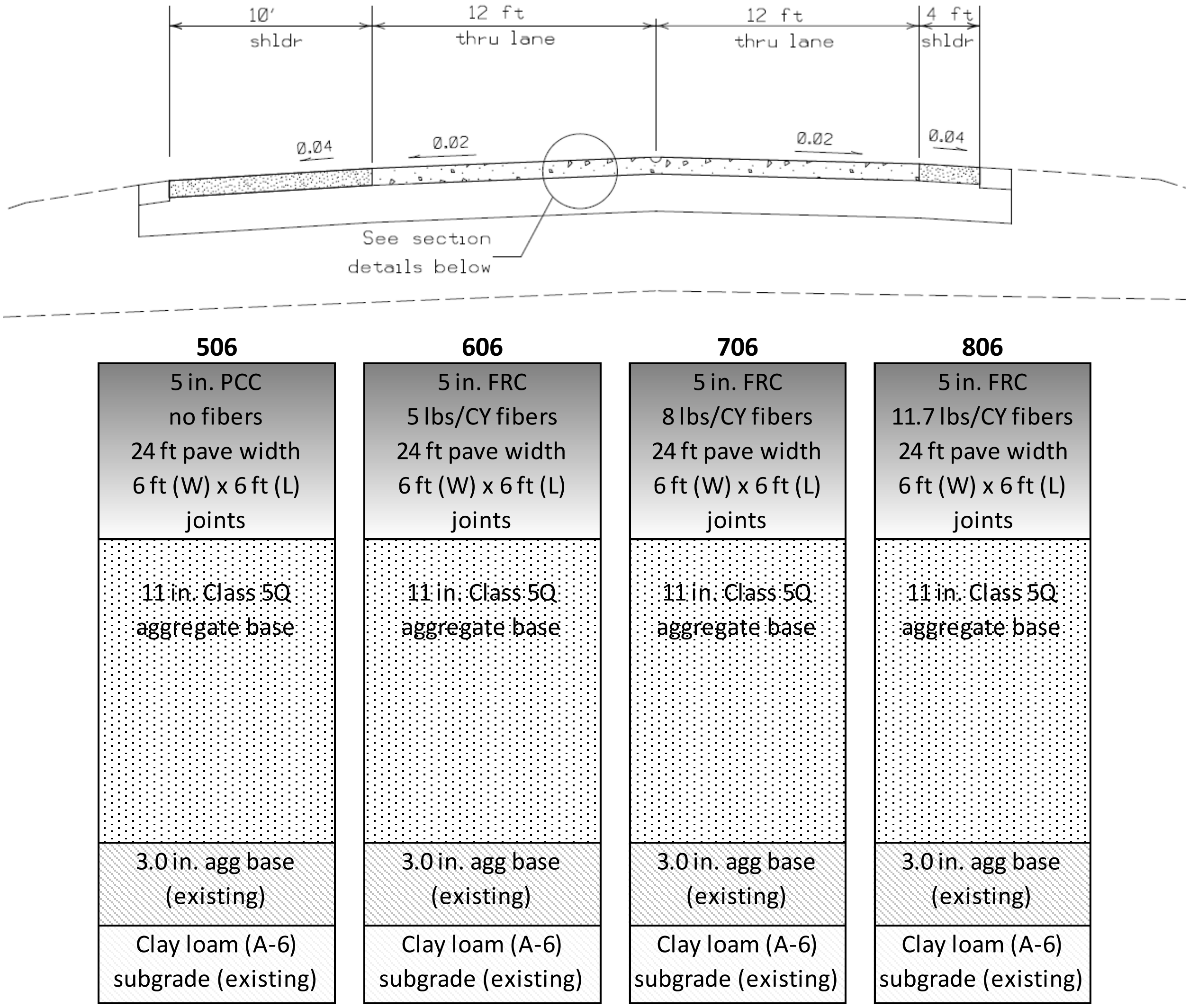


Figure 4.6 Planned section design details of FRC Cells 506 - 806.

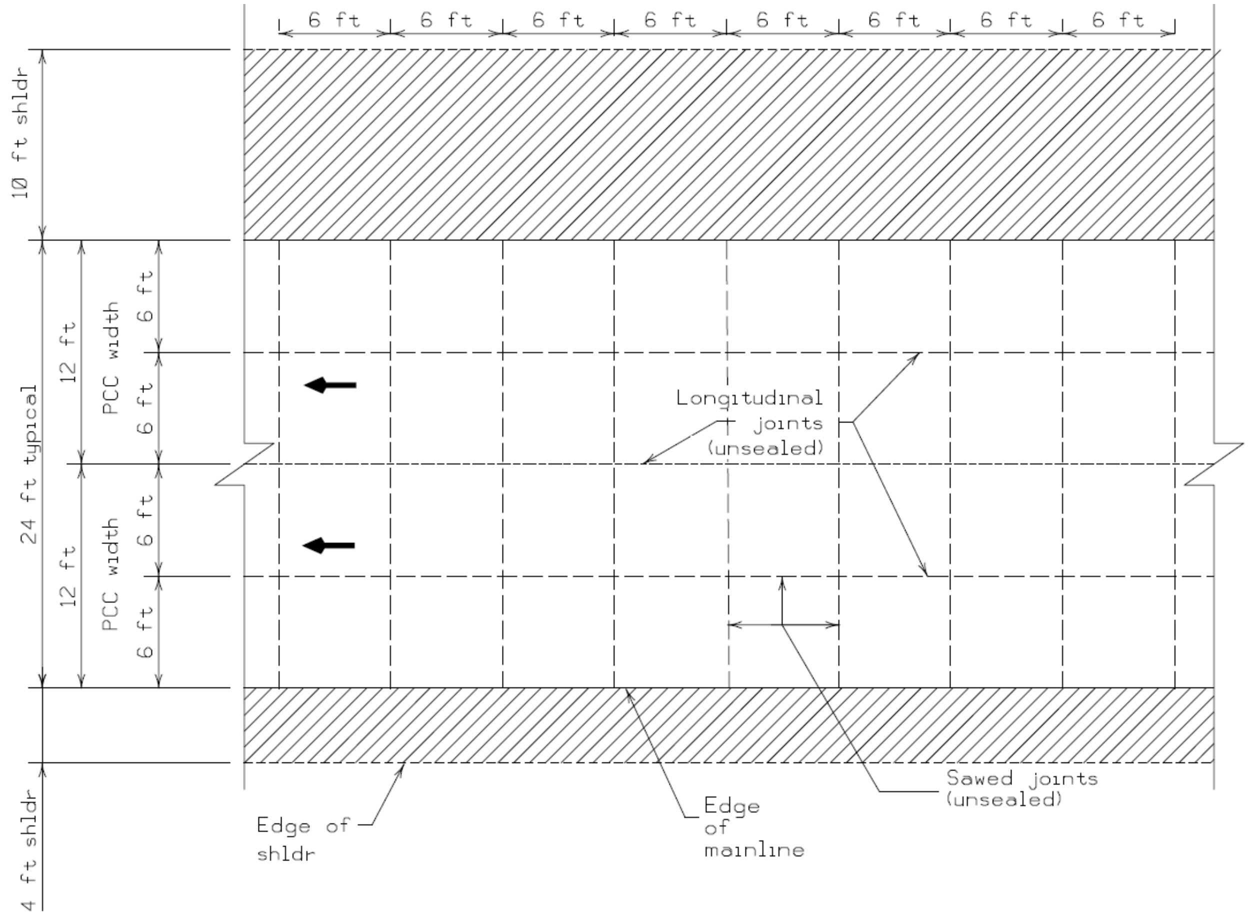


Figure 4.7 Planned joint layout of FRC Cells 506 - 806.

Table 4.3 lists the materials and proportions for the 4 concrete mixtures used in this study. The four mixes included:

- MR-3A21FC: Control mix with no fibers, consisting of typical MnDOT materials and proportions. Used in Cell 506.
- MR-3A21F1: Standard fiber dosage = 20 percent RSR based on Illinois DOT specification determined by ASTM C1609 test results. Used in Cells 705, 805, and 606.
- MR-3A21F2: Enhanced fiber dosage = 30 percent RSR determined by ASTM C1609 test results. Used in Cells 139, 239, and 706.
  MR-3A21F3: Maximum fiber dosage = 0.75 percent by volume. Determined in lab testing to be dosage rate where there are diminishing returns on improving RSR, as well limiting the potential for fiber “balling.” Used in Cell 806.

To facilitate documentation of early and long-term measurements, all transverse joints in the new cells were assigned unique joint numbers. Joint numbers for the FRC cells are listed in Table 4.4.

Table 4.3 Mix designs for FRC Cells (includes control mix with no fibers)

MIX/CELL	AIR (%)	WATER (lbs)	CEMENT (lbs)	FLY ASH (lbs)	FLY ASH (%)	W/C RATIO	FA #1 (lbs)	CA #1 (lbs)	FIBERS (lbs/CY)	SLUMP RANGE (in.)
MR-3A21FC 506	7.0	239	400	170	30	0.42	1222	1798	-	0.5 - 3
MR-3A21F1 705, 805, 606		248	413	177			1204	1773	5	
MR-3A21F2 139, 239, 706		252	420	180			1196	1761	8	
MR-3A21F3 806		258	430	185			1184	1743	11.66	

Table 4.4 Transverse joint numbering for new MnROAD FRC cells.

CELL	BEG JT NO.	END JT NO.
139	2800	2844
239	2845	2890
705	2900	2909
805	2910	2918
506	2500	2523
606	2524	2546
706	2547	2568
806	2569	2591

4.3 CONSTRUCTION

Construction began in Cells 139 and 239 with removal of the existing pavement structure. Note that the in place pavement was slightly deeper than the proposed NRRA section and therefore several inches of common borrow matching the in place subgrade were required. Excavation proceeded to the planned depth. It was noted that the upper several inches of the exposed grade contained remnants of the previously in place aggregate base mixed in with the subgrade.

The contractor scarified the in place material to a depth of about 6 inches and compacted. Next was hauling and placement of 4 inch of clay loam common borrow, followed by 6 inches Class 6 aggregate base.

To document as-built concrete thickness and variability, numerous metal target plates were placed before paving the surface layer of each cell. During the paving, the contractor used a probe to check the thickness to the plates. After the paving, both the Contractor and MnROAD staff used a MIT-Scan-T2 device to document the as-built thickness over each plate. Results are listed in Appendix B.

During concrete paving, it was noted that the base deflected under the ready-mix trucks. The contractor utilized a drum roller to level and compact the surface ahead of the paver. It is expected that the wheel ruts in the base resulted in deviations from the planned 3 and 4-inch design thicknesses throughout the cell.

To the extent possible, construction traffic was routed around the new sections, due to their thin nature and susceptibility for damage. Certain amounts of traffic were entirely unavoidable, however. Early age damage to Cell 139 likely occurred from shouldering operations around August 8, 2017. Loading also occurred around August 25, 2017 when excavated materials were being hauled across Cell 139 to other cell locations on the LVR. Further loads occurred on September 19, 2017 due to asphalt paving operations on other areas of the LVR. See Figures 4.8 and 4.9 for examples of cracking observed.

Construction of the overlays in Cells 705 and 805 began with removal of the existing concrete overlay in early July and was completed during the first week of September.

Prior to installation of the non-woven geotextile fabric interlayer, the existing surface was swept with a power broom. The fabric was secured to the original concrete pavement using a clear spray adhesive, 3M Holdfast 70, shown in Figure 4.10.

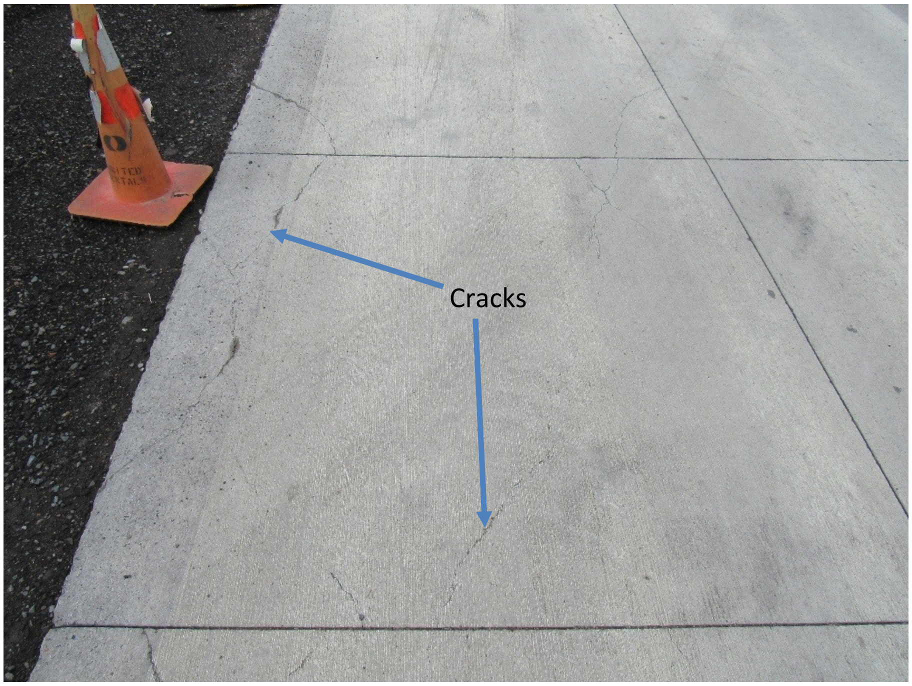


Figure 4.8 Damage to Cell 139 by construction traffic.

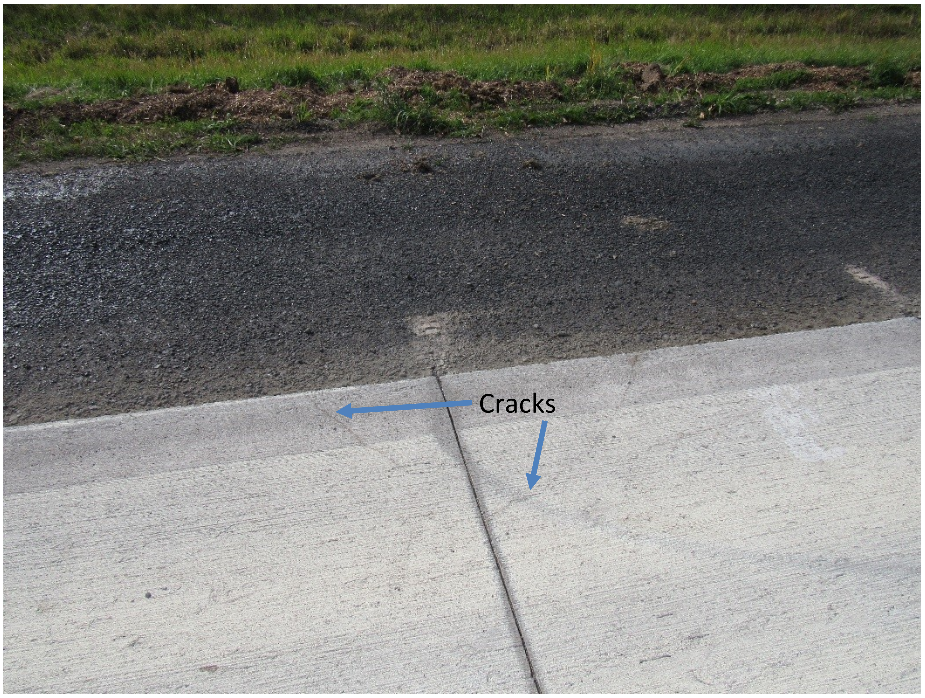


Figure 4.9 Damage to Cell 139 by construction traffic.

Figure 4.10 Adhesive used to secure non-woven geotextile fabric in Cells 705 and 805.

Due to miscommunication during sawing operations, the longitudinal joint intended for 13 feet from centerline (1 feet outside the passing lane/shoulder joint) was sawed at 12 feet from centerline. See Figure 4.11. Due to the underlying 13 feet wide concrete slab, the inside shoulder is now supported for a width of 1 feet, as opposed to fully lying over the base supporting the remainder of the shoulder. As-built joint layout diagrams are shown in Figures 4.12 and 4.13.

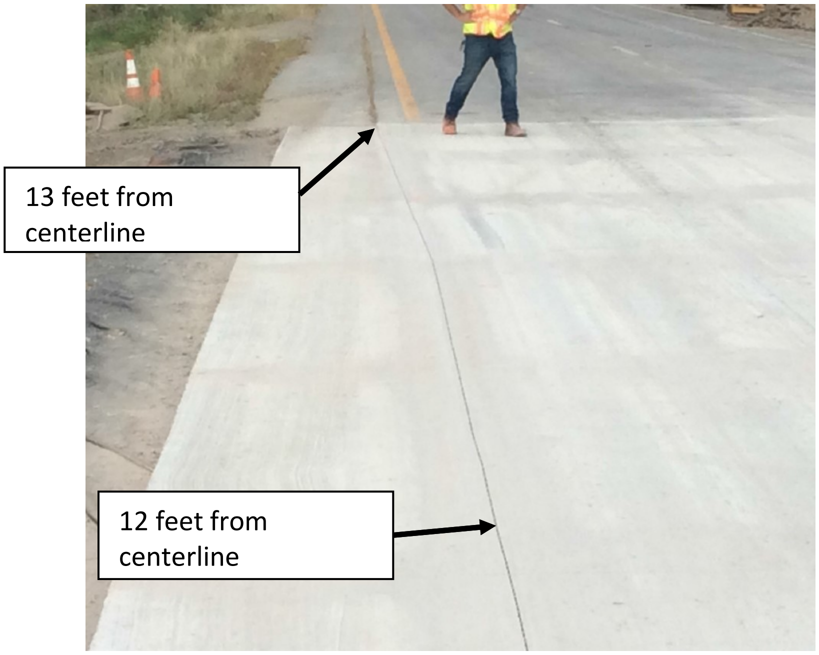


Figure 4.11 Inadvertent longitudinal sawcut misplacement in FRC Cells 705 and 805.

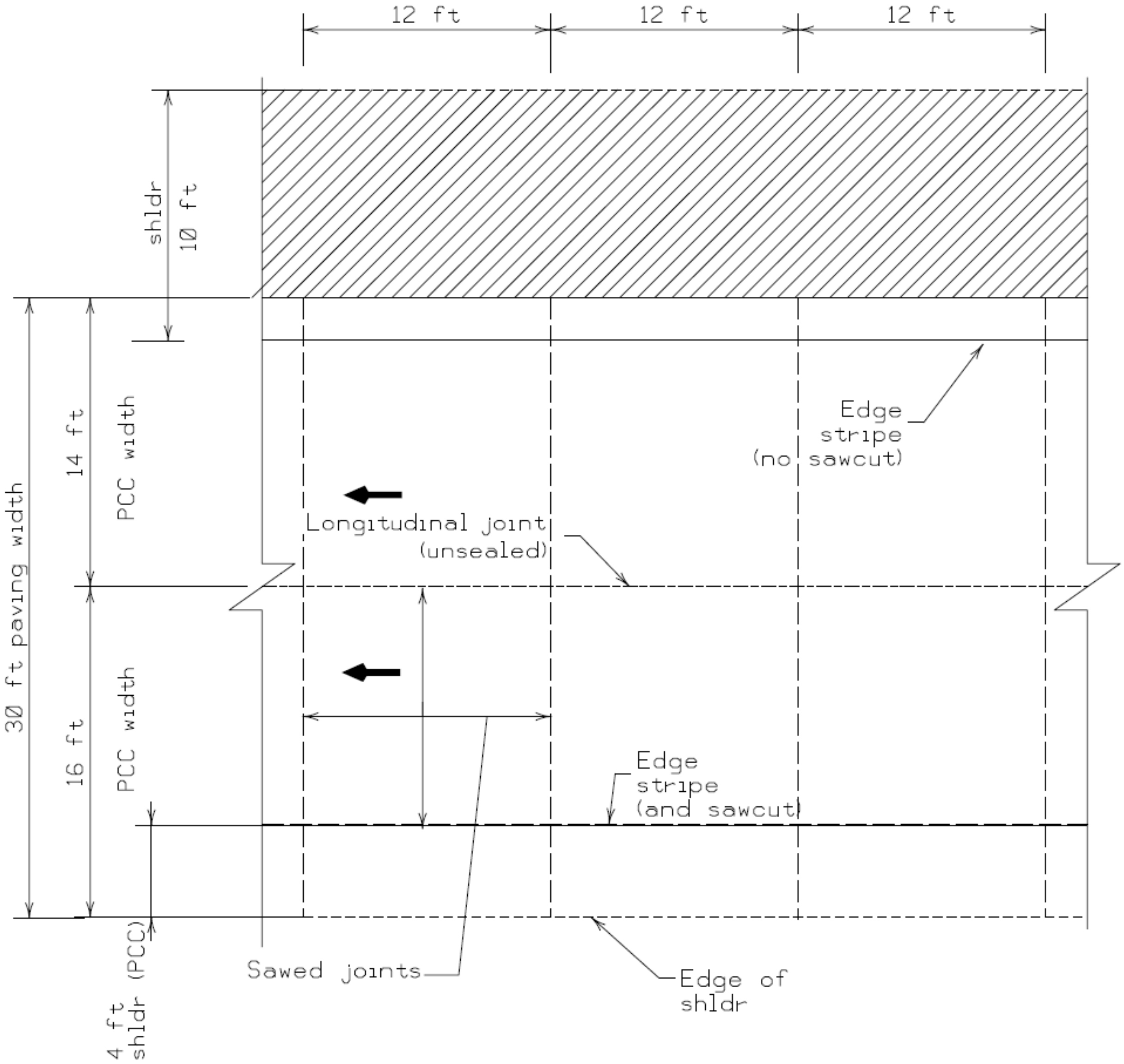


Figure 4.12 As-built joint layout for FRC Cell 705.

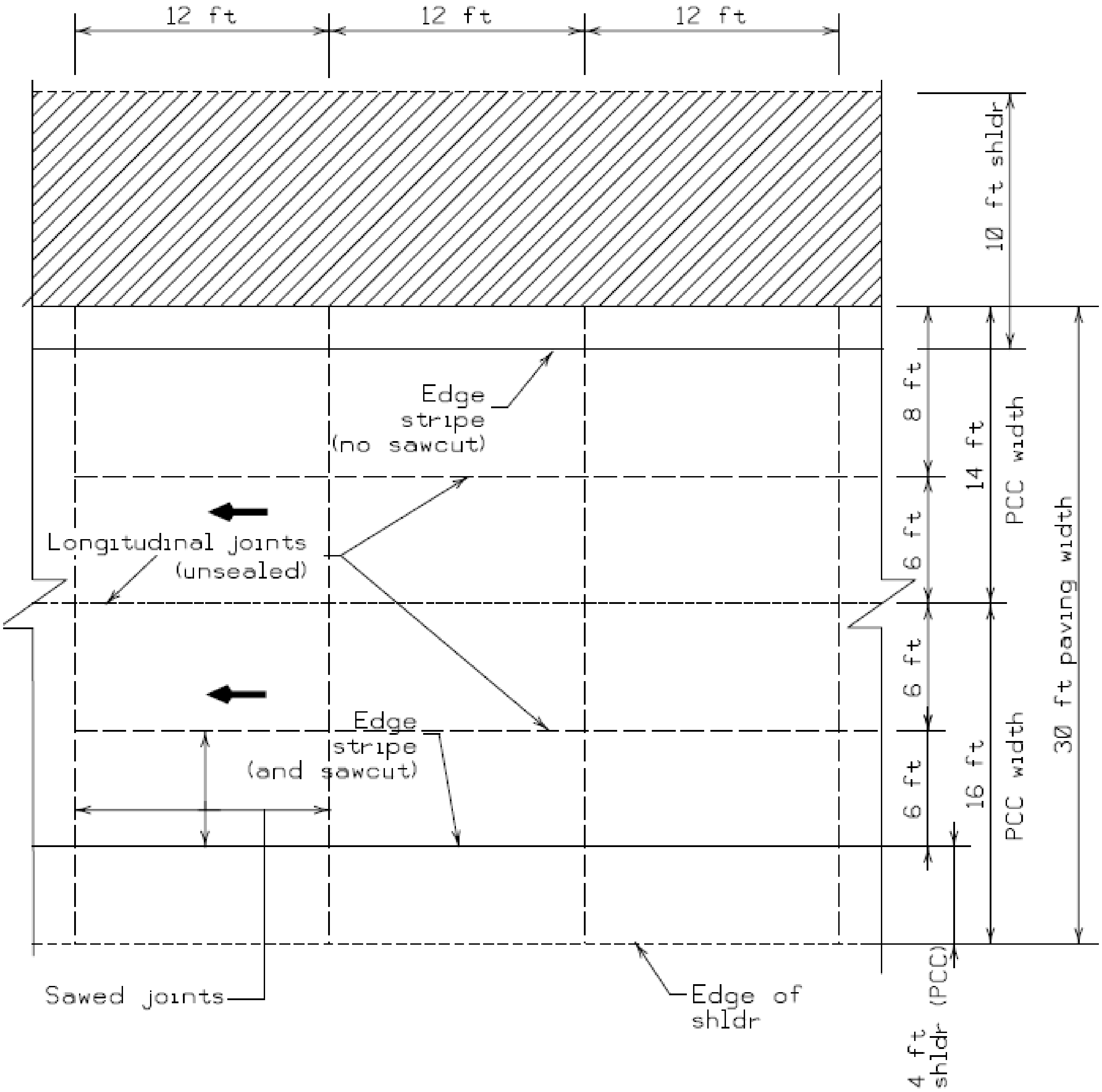


Figure 4.13 As-built joint layout for FRC Cell 805.

Construction of Cells 506-806 began with removal of existing concrete pavement and aggregate base. This was followed by placement of 11 inches of Class 5Q aggregate base.

Paving proceeded starting with Cell 506 and progressed eastward to Cell 806. Each of the four FRC sections were paved on separate days permitting time for equipment cleaning, preparing for changes to the fiber content, and sensor installations.

MnDOT did not initially install its own T2 plates in Cells 506 and 606 as this is typically the Contractor's responsibility. At the time Cell 606 was being paved, field personnel observed thick pavement being placed. The contractor placed two T2 plates which indicated thickness well in excess of the planned 5-inch thick section with readings of 6.2 and 6.4 inches measured. Unfortunately, these T2 plates were located near the end of paving in Cell 606. MnROAD personnel decided to install additional T2 plates for subsequent paving of Cells 706 and 806 to better characterize thickness uniformity/variability. The thickness for these sections ranged from 4.6 to 5.9 inches, and averaged 5.3 inches.

Paving of Cell 806 was more difficult due to the heavy dosage of fibers. Despite this issue, the contractor was able to work it into a satisfactory surface as shown in Figure 4.14.

Figure 4.14 Contractor working on Cell 806 with 0.75 percent by volume fiber mix.

4.4 SAMPLING AND TESTING

As with all new concrete pavement test cells at MnROAD, a comprehensive sampling and testing program was implemented for the new cells. A list of the fresh concrete testing, as well as laboratory tested specimens can be found in Tables 4.5 and 4.6. MnDOT construction inspection staff also gathered and tested concrete specimens to satisfy MnDOT contract quality assurance requirements. In addition, the contractor also tested the surface texture after paving.

Table 4.5 Fiber Reinforced Concrete sampling and testing plan for new MnROAD Cells 506-806.

TEST(S)	SAMPLE AGE(S), days	SPEC TYPE	SPEC SIZE	NO. SPECIMENS	CURE PROCEDURE	CURE TIME, days/weeks
Box and SAM Test	---	---	1 SAM and Box per mix	---	---	---
ASTM C39, Compressive Strength	3, 7, 28	cyl	6x12-in., set of 2	6	Moist Room	Per test age
ASTM C78, Flexural Strength	3, 7, 28	beam	6x6x20-in., one per age	3	Lime-water immersion	Per test age - will test at MnROAD
AASHTO T336, Coefficient of Thermal Expansion	28	cyl	4x8-in.	1	Moist room	28 days
ASTM C469, Modulus of Elasticity and Poisson's	28	cyl	6x12-in.	1	Per test method	28 days
ASTM C215, Dynamic Modulus	7, 28	cyl	4x8-in.	Use ASTM C469 cylinder before testing	Moist room	28 days
Wenner Probe Resistivity	28	cyl	4x8-in.	Use ASTM C469 cylinder before testing	Per test method	28 days
ASTM C1609, Residual Flexural Strength	7, 28	Beam	6x6x20-in.	1 set of 4, three for test and one for trial	Moist room	Testing at UMD
ASTM C457, Air Void Analysis of Hardened Concrete	>=14	cyl or core	4x8-in. cylinders	1	At least 14 days moist cure	At least 14 days moist cure
ASTM C157, Drying Shrinkage	56	beam	4x4x11-1/4-in. beams with pins	1	28 days lime-saturated water	28 days

Table 4.6 Sampling and testing plan for new MnROAD Cells 705,805, 139, and 239.

TEST(S)	SAMPLE AGE(S), days	SPEC TYPE	SPEC SIZE	NO. SPECIMENS	CURE PROCEDURE	CURE TIME, days/weeks
Box and SAM Test	---	---	2 SAM and 1 Box per mix	---	---	---
ASTM C39, Compressive Strength	3, 7, 28	cyl	4x8-in., set of 3	9	Moist room	Per test age
ASTM C78, Flexural Strength	3, 7, 28	beam	6x6x20-in., one per age	3	Lime-water immersion	Per test age - will test at MnROAD
Wenner Probe Resistivity	28	cyl	4x8-in.	Use ASTM C39 cylinder before testing	Per test method	28 days
ASTM C1609, Residual Flexural Strength	28	beam	6x6x20-in.	1 set of 4, three for test and one for trial	Moist room	Testing at UMD
ASTM C457, Air Void Analysis of Hardened Concrete	>=14	cyl or core	4x8-in. cylinders	2	At least 14 days moist cure	At least 14 days moist cure

In an effort to characterize all aspects of the new test cells, several test procedures were performed by MnROAD research staff within the first few weeks after paving. Surface profiles, joint deployment, and transverse joint movement were observed and documented. Surface profiling was conducted using both the MnROAD Lightweight Inertial Surface Profiler (LISA) and the MnROAD Automated Laser Profile System, version 2 (ALPS2) device, which primarily captures slab warp and curl. Transverse joint deployment was accomplished through visual inspection of the edge of the slabs prior to placement of the shoulders. Results from this testing will be used by the principal investigator of the research contract. Others can obtain the data from the MnROAD website, or by contacting MnROAD staff.

4.5 SENSORS

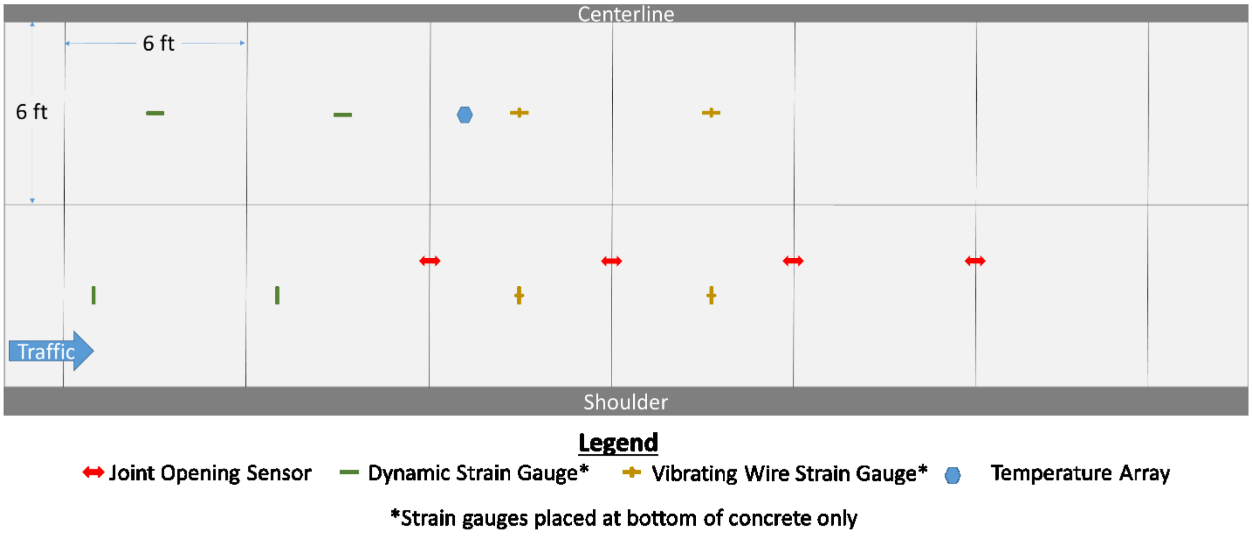
Instrumentation for the FRC cells focused on measuring the following responses:

- Temperature (slab and supporting layers);
- Strain in slab caused by concrete shrinkage and environmental effects (temperature, moisture);
- Strain in slab caused by vehicular loads; and
- Joint movement caused by shrinkage and temperature.

Table 4.7 lists the type and quantities of the sensors installed in the FRC cells. Figures 4.15 through 4.22 depict the general layout of the sensors in each test cell. A discussion of each sensor type may be found in Chapter 10. The as-built location of each sensor, including depth and offset from centerline, can be found in Appendix C.

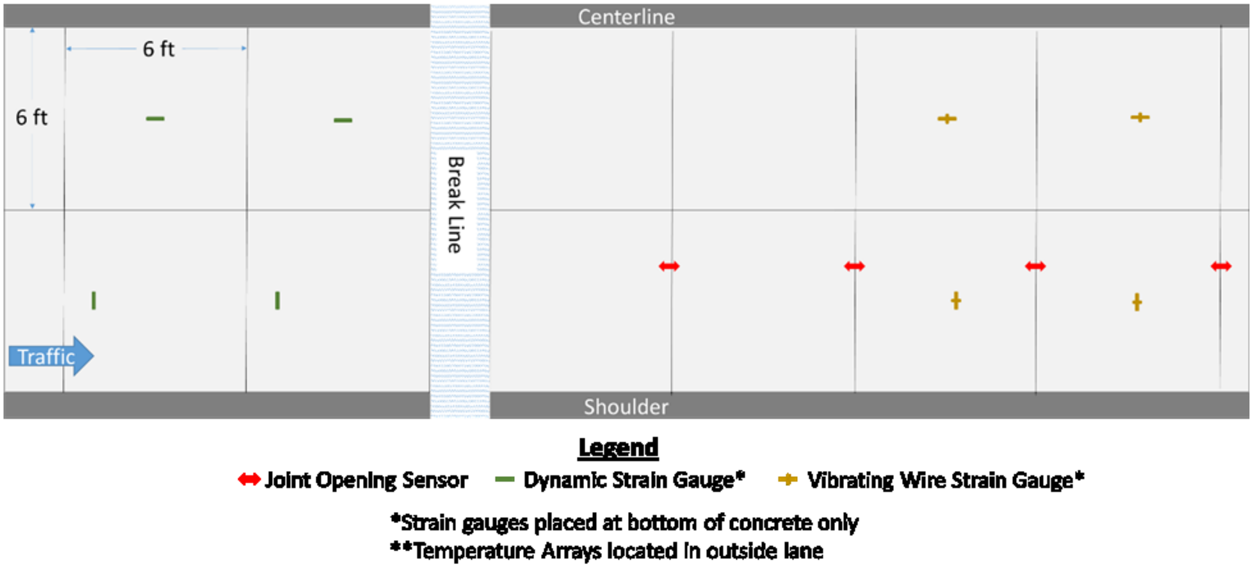
Table 4.7 Instrumentation installed into FRC cells.

CELL	TEMPERATURE (TC)	SHRINKAGE/ ENVIRONMENTAL STRAINS (VW)	DYNAMIC STRAIN (CE)	TRANSVERSE JOINT OPENING (JO)
139	16	4	4	4
239	16	4	4	4
705	8	8	8	4
805	12	8	8	4
506	-	4	4	3
606	8	4	4	3
706	12	4	4	3
806	-	4	4	3



*Strain gauges placed at bottom of concrete only

Figure 4.15 Sensor layout for FRC Cell 139.



*Strain gauges placed at bottom of concrete only
**Temperature Arrays located in outside lane

Figure 4.16 Sensor layout for FRC Cell 239.

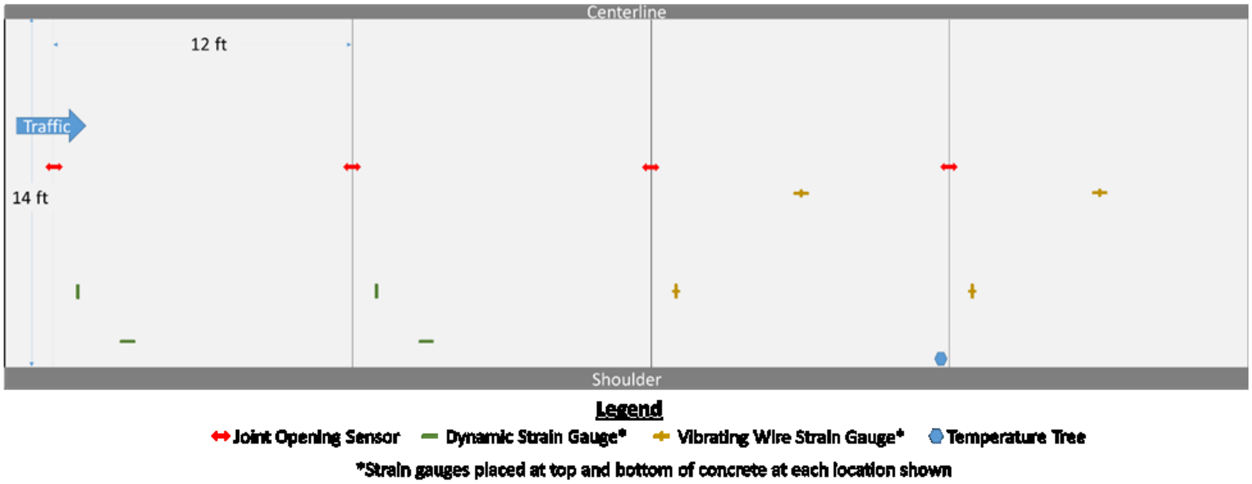


Figure 4.17 Sensor layout for FRC Cell 705.

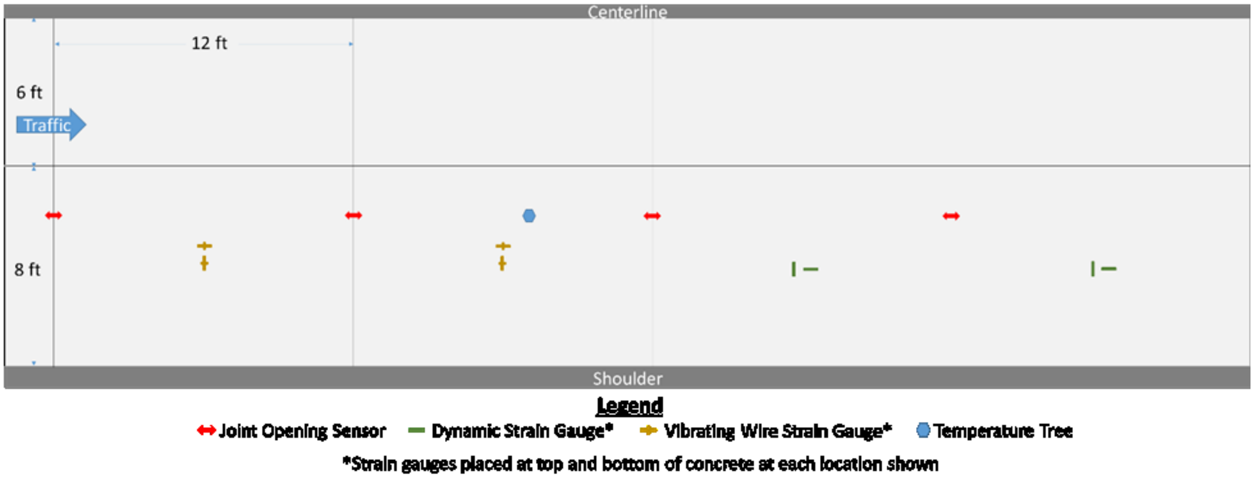


Figure 4.18 Sensor layout for FRC Cell 805.

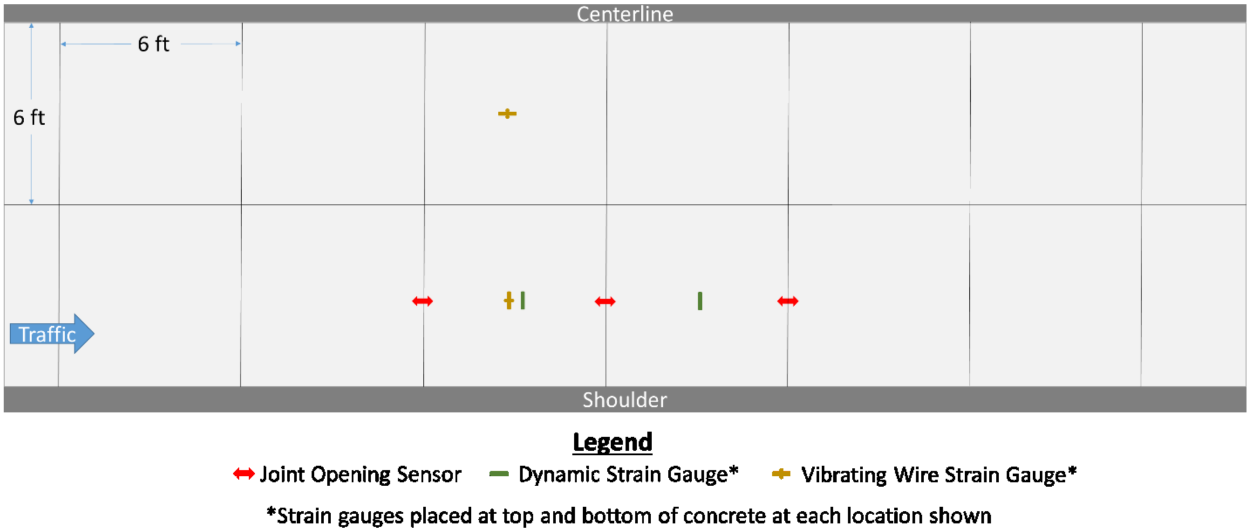


Figure 4.19 Sensor layout for FRC Cell 506.

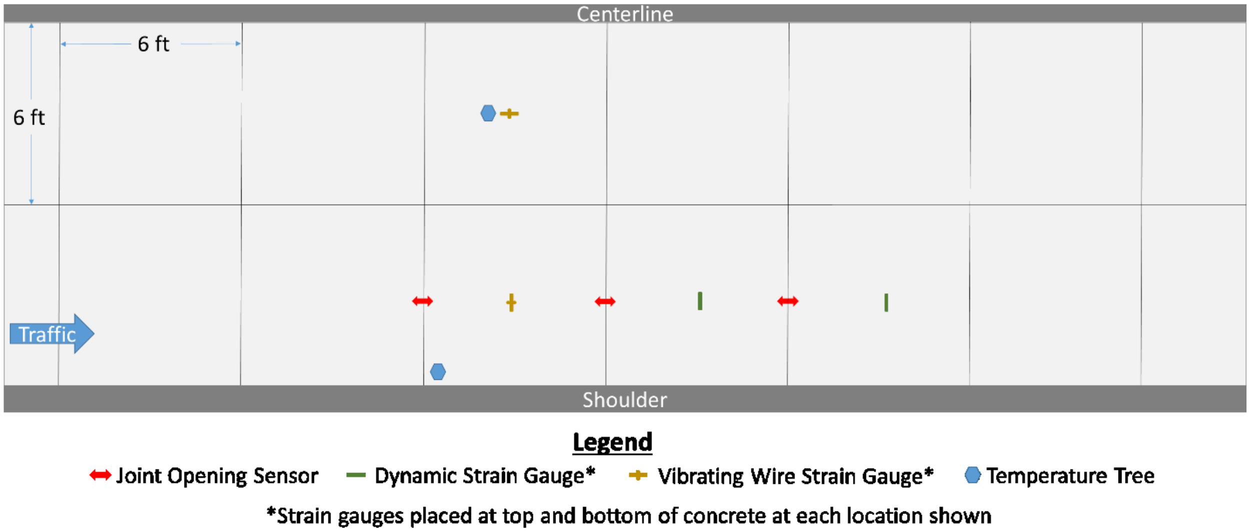


Figure 4.20 Sensor layout for FRC Cell 606.

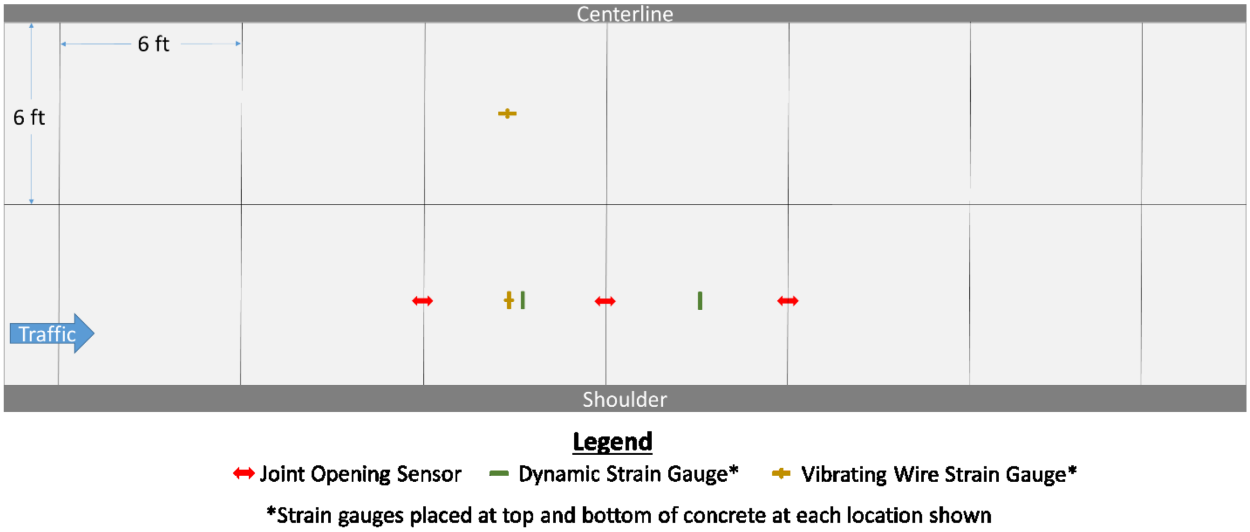


Figure 4.21 Sensor layout for FRC Cell 706.

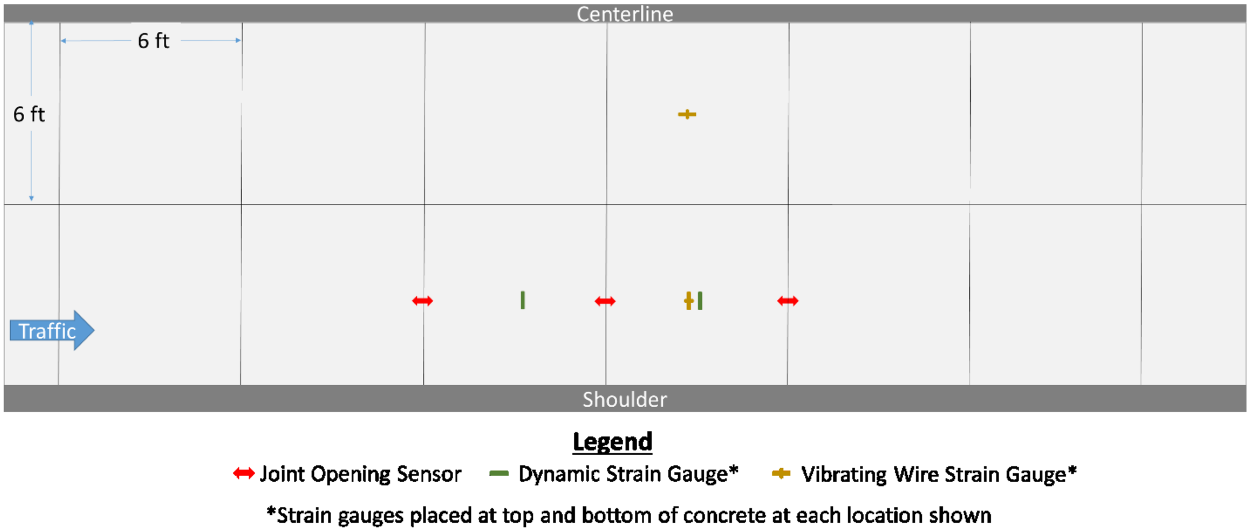


Figure 4.22 Sensor layout for FRC Cell 806.

In addition to sensors, joint opening measurement pins were installed in select cells. Two small Allen head socket screws were installed into drilled holes, located approximately 1 inch to either side of a joint. Measurements are made with a caliper equipped with special points to fit into the screw head. This data, to be collected 2 to 3 times per year, will supplement the joints containing joint opening (potentiometer) sensors. Joints containing the pins are listed in Table 4.8.

Table 4.8 Joints in FRC cells with joint opening measurement pins

CELL	JOINT NUMBERS w/MEASUREMENT PINS									
506	2502	2505	2508	2510	2513	2515	2517	2522		
606	2526	2527	2530	2531	2533	2534	2536	2541	2543	2545
706	2549	2550	2552	2553	2555	2559	2560	2562	2567	
806	2570	2571	2572	2573	2576	2579	2583	2585	2587	2590
138	2707	2708	2710	2714	2715					
238	2719	2720	2725							
139	2806	2809	2812	2815	2822	2824	2829	2834	2838	
239	2847	2849	2858	2864	2869	2875	2877	2880	2883	2886

CHAPTER 5: EARLY OPENING STRENGTH TO TRAFFIC

5.1 OBJECTIVES

There is a prevailing process among agencies to use a 3,000 psi compressive strength as a requirement for opening a newly constructed concrete pavement to traffic. Depending on the temperature, weather, and mix design, it can take from 7 to 28 days to attain the required strength and that has huge implications on user costs that add to the overall cost. The concrete paving industry and many DOTs are often searching for cost-effective, low-risk solutions to reduce the time a conventional concrete pavement is closed for construction without compromising long-term performance. The question is, what strength is actually needed prior to opening the pavement to traffic?

To answer this question, MnDOT and the NRRA collaborators decided to conduct a real-time experiment at the MnROAD research facility to determine strength at opening to traffic. An experimental plan involving a new section with six sub cells (Cells 124-624) was constructed on the LVR. In addition to establishment of a means for determining early opening time, this project will study and monitor the very early-age fatigue damage and associated long-term distress in concrete pavement subjected to early opening. At a minimum, this project seeks to verify early-opening methodologies recent research has proposed [Freeseman, et al, 2016], and thus, ultimately may result in reduced time for opening to traffic and potentially total construction time as well. The end result will be cost savings and improved user satisfaction.

The approach adopted in this study includes:

- Create an experimental design, preferably a stepwise loading scenario, to replicate and simulate early loading of concrete (new construction and rehabilitation) in a sequence that maximizes and accentuates quantifiable damage to the concrete pavement
- Determine the immediate and long-term damage (visible and intrinsic) from early loading using measurements and imbedded sensors
- Recommend a minimum strength at opening or other measurable variables associated with this parameter based on damage assessment of early loading and statistical analysis
- Recommend strategies for avoidance, mitigation, or remediation of damage while outlining what level of damage is of any consequence

To accomplish these objectives, each cell will be monitored for warp and curl as well as ruts in the wheel path. Additionally, researchers will use a MIRA, an Ultrasonic Low Frequency Tomography device, loaned by NRRA member, University of Minnesota Department of Civil, Environmental and Geological Engineering. This non-destructive test will be used to determine if the consistency of the concrete has been compromised by early loading. MIRA facilitates evaluation of damage condition of the interior of the pavement. Petrographic analysis will also be utilized to show if aggregates have been pushed apart during early loading.

5.2 DESIGN

The section was designed as a 6-inch thick concrete pavement with 1-inch diameter dowels and sawed, non-skewed joints established at 15-foot intervals. Aggregate base was Class 6 aggregate at 6 inches thick. Section details can be seen in Figure 5.1 and the planned joint layout is in Figure 5.2.

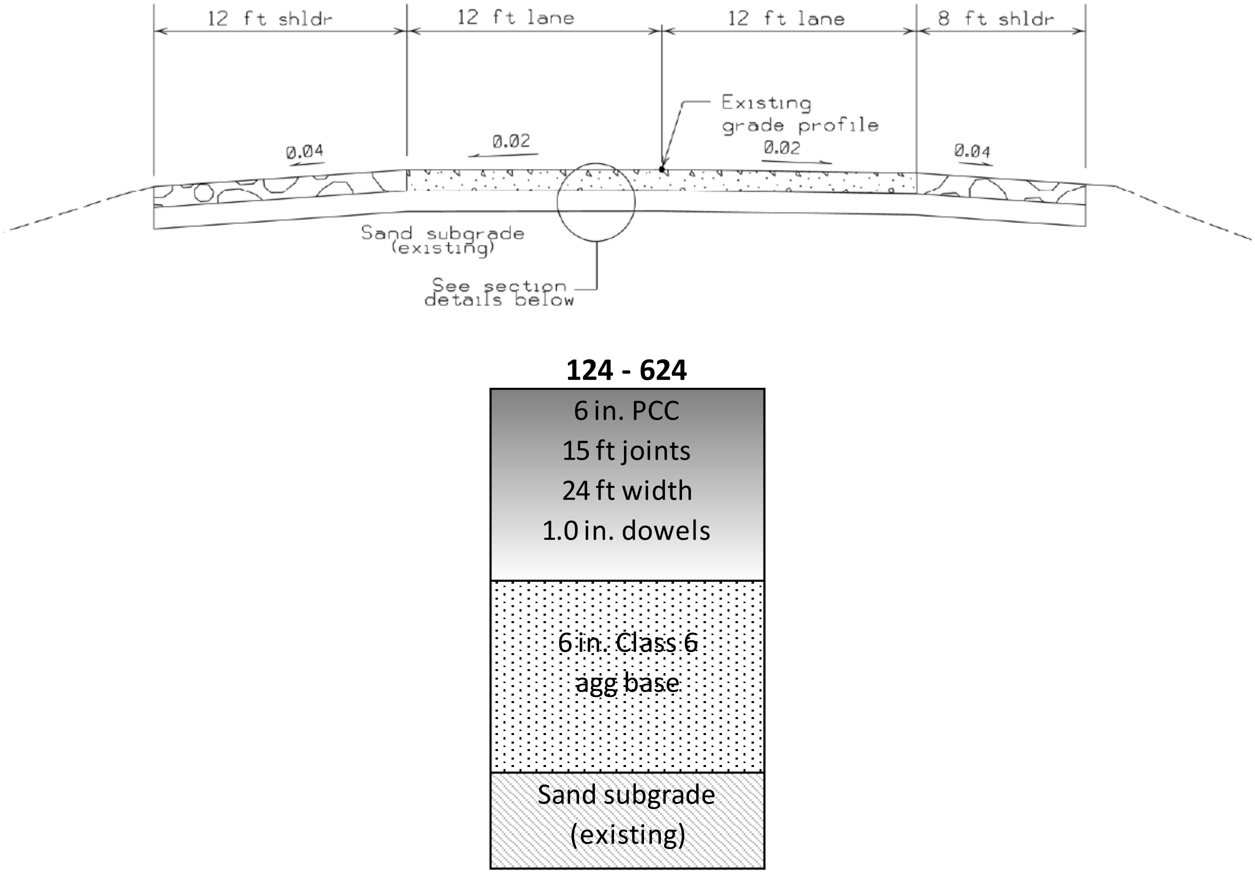


Figure 5.1 Concrete pavement section design for early opening experiment (Cells 124-624).

The experiment created four cells that were sequentially loaded and a fifth that acted as the control. On the first day of paving the loading sequence proceeded in an easterly direction, such that Cells 124, 224, 324, and 424 each received 8, 6, 4, and 2 load repetitions, respectively. Loads were applied by a ¾-ton pickup truck on the outside lane, and an unloaded MnDOT snow plow truck on the inside lane. Cell 524 served as control (not loaded on the first day). In Cell 624, ruts were imparted by a ¾-ton pickup truck traversing across the plastic pavement to study the impact that visible ruts impart when drivers erroneously drive on freshly placed concrete. The loading sequence is shown schematically in Figure 5.3.

Trial mixing was performed prior to submission of mix design for approval. The trial mixing examined slight variants of the mix design meeting the requirements of a 3A21 traditional contractor mix with conventional pozzolanic substitution. Table 5.1 shows the final mix design utilized in this section.

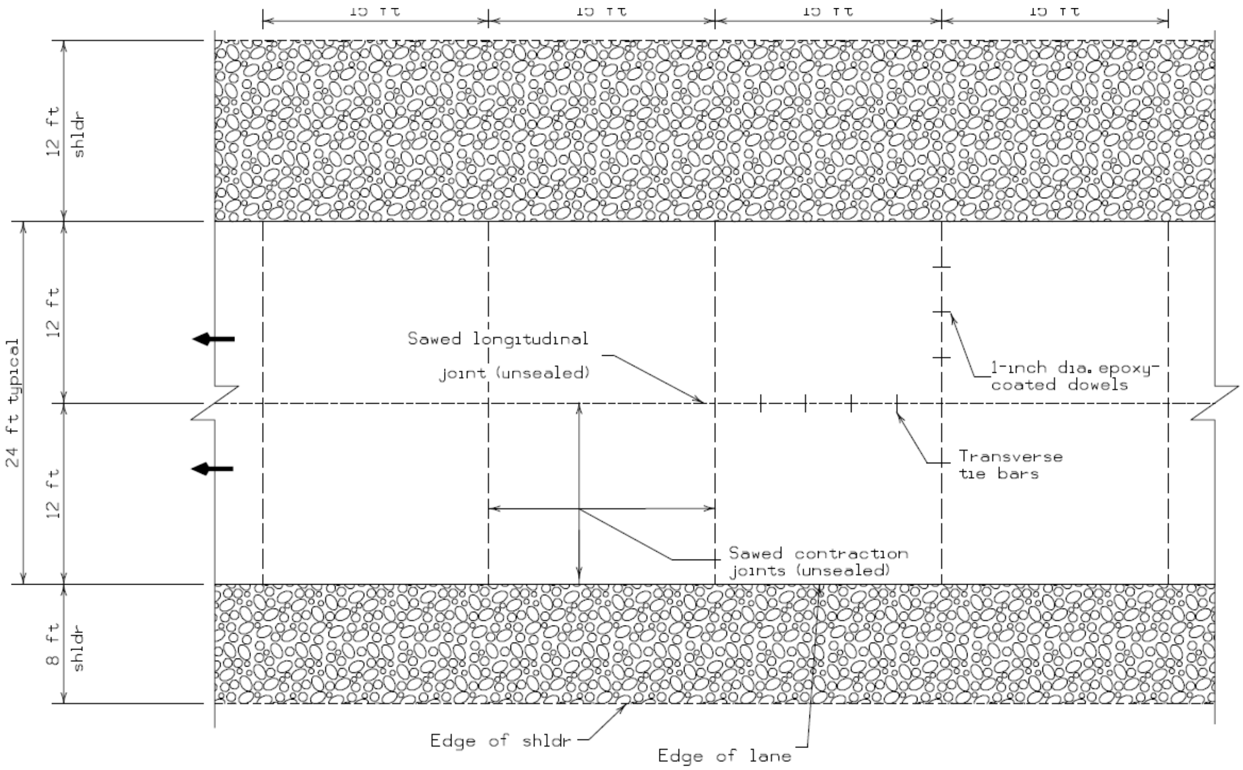
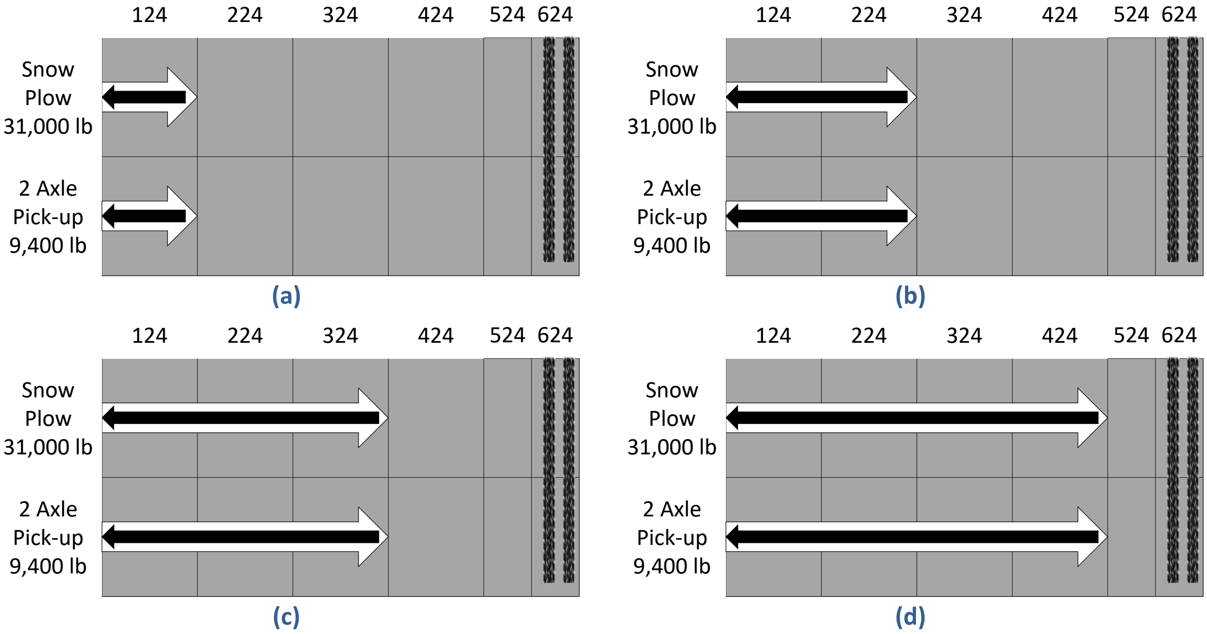


Figure 5.2 Concrete pavement joint plan for early opening experiment (Cells 124-624).



(a)

(b)

(c)

(d)

Figure 5.3 Primary loading scheme: day one.

Table 5.1 Mix design for early opening experiment concrete (Cells 124-624).

MIX/CELL	AIR (%)	WATER (lbs)	CEMENT (lbs)	FLY ASH (lbs)	FLY ASH (%)	W/C RATIO	FA #1 (lbs)	CA #1 (lbs)	CA #2 (lbs)	CA #3 (lbs)	SLUMP RANGE (in.)
MR-3A21 124-624	7.0	228	400	170	30	0.40	1173	562	1015	305	0.5-3

5.3 CONSTRUCTION

Cells 124 through 624 were constructed with a slip form paver maintained at a production width of 24 feet thus paving both lanes simultaneously. Paving commenced at approximately 9:00 am on July 5, 2017. Starting at the east end (Cell 624) the paving proceeded at a reasonable pace westward to Cell 124. Note that this direction was opposite the direction of reducing sequence of loading repetitions and time of loading. Loading began on Cell 124 which had not developed as much maturity as Cell 224. This design provided a framework to intensify disparity between consecutive cells in the direction of loading.

Paving ended at approximately 12:00 pm on July 5, 2017. Transverse and longitudinal joints were established by mechanical sawing in the night after the first round of loading. It should be noted then that joint sawing preceded the second set of loading. Figures 5.4 shows the sections after construction and prior to early loading.

Figure 5.4 Panoramic view of Cells 124 to 624 pavement after placement and application of curing compound.

5.4 SAMPLING AND TESTING

This section discusses the various rheological and mechanical tests as well as other tests conducted. Within this project, American Engineering Testing, Inc., was contracted to perform sampling, rheological testing, early strength, and early mechanical strength testing. The current performance engineered mixture tests were performed by the contracted consultant. The materials testing matrix is summarized in Table 5.2 below. Test results will be utilized in subsequent NRRA research projects and will be made available to researchers upon request.

MnROAD personnel performed early loading in a sequence based on maturity of the concrete, shown schematically in Figure 5.3, to evaluate effects of curing (maturity of strength) on pavement response. Maturity is calculated, or read, as a function of internal temperature of the concrete and time. Loading began with passage of a 2-axle pickup in Cell 624 approximately 2 hours after paving (to induce visible damage) as shown in Figures 5.5 and Figures 5.6. Load response sensors were not utilized for this stage of loading.

Table 5.2 Testing requirements for Cells 124 through 624 early-opening experiment.

TEST(S)	SAMPLE AGE(S), days	SPEC TYPE	SPEC SIZE	NO. SPECIMENS	CURE PROCEDURE	CURE TIME, days/weeks
Box and SAM Test	---	---	1 SAM and box per mix	---	---	---
ASTM C39, Compressive Strength	2, 3, 7, 28	cyl	6x12-in., set of 2	8	Moist Room	Per test age
ASTM C78, Flexural Strength	2, 3, 7, 28	beam	6x6x20-in., one per age	4	Lime-water immersion	Per test age - will test at MnROAD
ASTM C666, Proc. A Freezing and Thawing in Water	MnDOT decides	cores	3 to 4-in. dia. cores x 9-10 inch	1	Field cores	In pavement
AASHTO T336, Coefficient of Thermal Expansion	28	cyl	4x8-in.	1	Moist room	28
ASTM C469, Modulus of Elasticity and Poisson's	28	cyl	6x12-in.	1	Per test method	28
ASTM C215, Dynamic Modulus	7, 28	cyl	4x8-in.	Use ASTM C469 cylinder before testing	Moist room	28
Wenner Probe Resistivity	28	cyl	4x8-in.	Use ASTM C469 cylinder before testing	Per test method	28
ASTM C856, Petrographic Examination of Hardened Concrete	MnDOT decides	core	3 to 4-in. dia. cores x 6 in.	1	Field core	In pavement
ASTM C157, Drying Shrinkage	56	beam	4x4x11-1/4-in. beams with pins	1	28 days lime-saturated water	28 days

Figure 5.5 Preparation in the second hour for application of rut on sub-Cell 624 plastic concrete.

Figure 5.6 Rut depth ranged from 0.25 inch in the outside lane to 1.5 inches at the edge of inside lane.

From that point forward, and throughout the remainder of the day, the vehicles traversed each sub cell in a staggered fashion as shown previously in Figure 5.3. Pavement response sensors were monitored for these stages of loading. The outside lane was loaded with a ¾-ton, 2-axle pick-up while in the inside lane it was an unloaded tandem snow plow truck. The timing of each stage depicted in Figures 5.3a-5.3d were selected based on measured maturity. When the pavement reached a maturity of 100 °C-hr, both trucks traveled easterly on Cell 124 right up to the edge of the cell and then reversed back over it (Figure 5.3a). Likewise when the maturity reached 200 °C-hr, Cells 124 and 224 were loaded traveling easterly (Figure 5.3b). This proceeded in a similar fashion until all four cells were loaded. That meant Cell 124 had eight passes from each vehicle while Cell 424 had two.

Early testing included MIRA, a magnetic imaging tomographic device. MIRA spot tests were performed at 20 determined locations. These were compiled along with the GPS locations and kept on file. Cores were taken at the locations corresponding to the MIRA sweep. A total of 20, 4-inch diameter cores were retrieved from Cells 124 to 424 on day two. A second set of cores were taken after day 6 loadings. Core identification nomenclature was carefully observed so as to preserve location details when the test results are read.

Summarily, the tests conducted included the following:

- Concrete maturity: monitored in each sub cell for 28 days so that actual compressive strength and flexural strength derived from preliminary correlation tests are deduced;
- Load testing, day one: testing with dynamic strain sensors 1 to 8 recording (odd number top even number bottom in each of cells 124, 224, 324 and 424;
- MIRA, day two: a MIRA sweep of locations on, and between, each wheel track in each lane of each sub cell as shown in Figure 5.7;
- Coring, day two: Cores were taken adjacent to MIRA test locations in each lane of each sub cell;
- Loading, days two to six: 5 repetitions of the loaded snow plow, forward and backward, over Cells 124 to 424, inside lane only;
- MIRA, day six: A MIRA sweep was conducted on the same panels that were tested on the second day to evaluate the effect of additional repetitions on each of the 4 sub cells;
- Coring, day six: After the MIRA data collection sweeps, cores were taken from each tested panel, ensuring a valid comparison of loaded (wheel track) and unloaded (between wheel track) locations;
- Strain due to environment: Continuously recorded for days two through six;
- Warp and curl measurements, day seven: Performed using the MnROAD ALPS2 device;
- Ride measurements, day fifteen: Performed using the MnROAD LISA device; and
- Load testing, day 120 and beyond: Testing with dynamic strain sensors for comparison to day one, inside lane only.

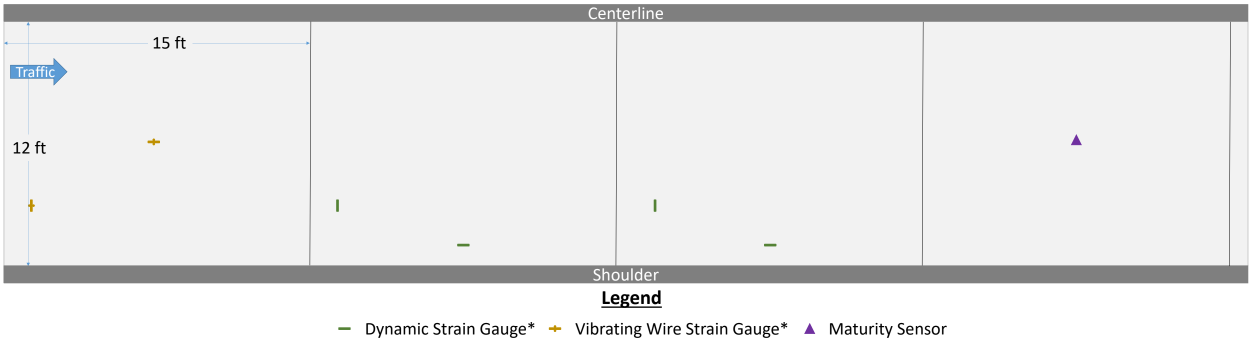
The MIT-SCAN-T2 was utilized for determination of as-built concrete thickness. Results are presented in Appendix A, Table A.1. The average concrete paving thickness for Cells 124-624 was 6.2 inches with a range of 5.8 to 6.6 inches.

Figure 5.7 MIRA sweep being conducted adjacent to wheel rut in Cell 624.

5.5 SENSORS

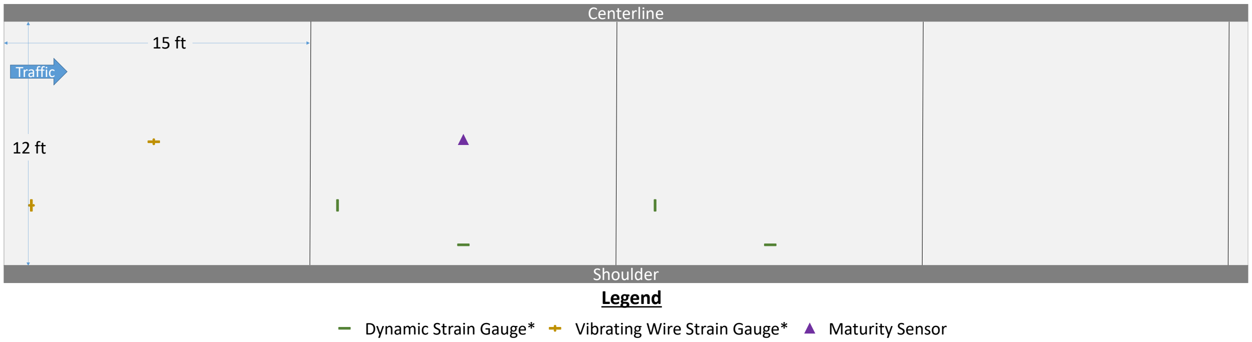
To facilitate timing decision for early loading, the maturity of the sub cells was monitored. They were consequently instrumented with maturity data loggers. Irrespective of locations within the sub cell, each maturity datalogger was installed at mid-depth, not less than 2 feet from pavement edge, and identified by the sub cell and lane in the maturity meter/reader. Maturity dataloggers were initialized with the readers early enough to facilitate the early loading decision. Eight dynamic sensors and eight environmental sensors were installed in each of Cells 124 to 424 according to the sensor layout. Sensor layouts are shown in Figures 5.8 through 5.11

It should be noted that, during a storm in October, 2017, lightning destroyed the datalogger cabinet and sensors associated with Cell 324. However, this did not affect the dynamic and static sensor readings within each sub cell collected up to that point.



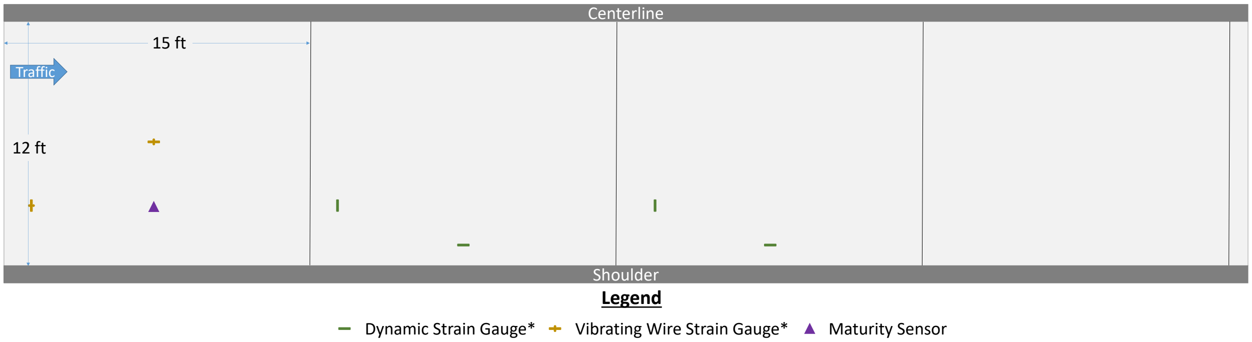
*Strain gauges placed at top and bottom of concrete at each location shown
**Temperature Trees and additional Maturity Sensor located in outside lane

Figure 5.8 Sensor layout for Cell 124.



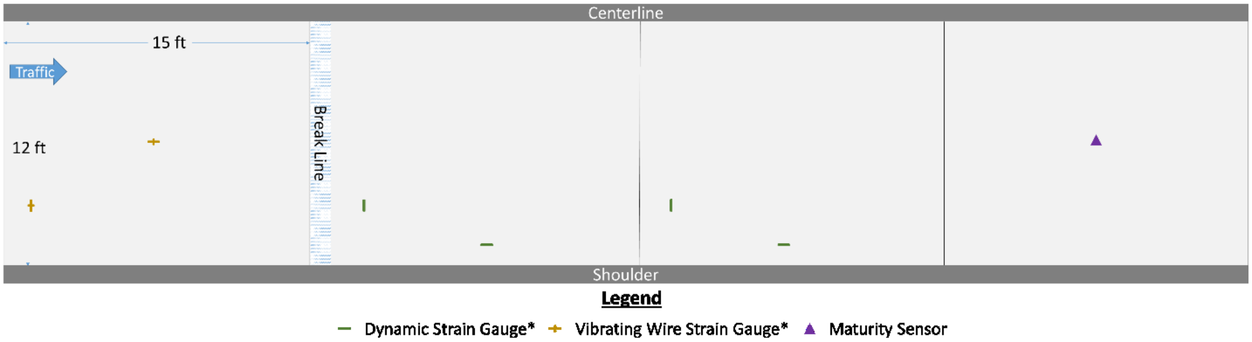
*Strain gauges placed at top and bottom of concrete at each location shown
**Temperature Trees and additional Maturity Sensor located in outside lane

Figure 5.9 Sensor layout for Cell 224.



*Strain gauges placed at top and bottom of concrete at each location shown
**Temperature Trees and additional Maturity Sensor located in outside lane

Figure 5.10 Sensor layout for Cell 324.



*Strain gauges placed at top and bottom of concrete at each location shown
**Temperature Trees and additional Maturity Sensor located in outside lane

Figure 5.11 Sensor layout for Cell 424.

CHAPTER 6: OPTIMIZING THE MIX COMPONENTS FOR CONTRACTORS

6.1 OBJECTIVES

High cementitious content is typically associated with pronounced autogenous shrinkage. Shrinkage creates uneven stresses in the surface that are resisted disproportionately in the matrix as the mortar and quasi-mortar phases transition from plastic to semi-plastic state inhibited by the network of coarse aggregate. Nevertheless, the mortar component of the concrete plays the primary role of deploying the aggregate into a uniform matrix called concrete. As the proportion of the mortar to the aggregate or, more definitely, the cement factor, contributes to the strength gain with time, excessive cement factor while accelerating strength gain is associated with increased shrinkage resistance and internal micro cracking. These distresses inhibit the durability of concrete. Izevbekhai's invention of the aggregate avoidance method of evaluating strength in the vicinity of the aggregate mortar interface lends credence to the role of mortar in the ability of concrete to resist cracking [Akkari, Izevbekhai, and Olson, 2015]. Although the time domain evaluation hypothetically explains early aggregate avoidance, thus negating the time domain precedence of shrinkage cracks to structural cracks. Certain enhancements have been shown to increase the strength of the interfacial transition zone [Akkari, Izevbekhai, and Olson, 2015; Izevbekhai, 2015]. The cement factor cannot be ignored in the macro to nano-crystalline formation of the matrix.

In transportation structures in general, and bridge decks and pavements in particular, achievement of required strength has never been as elusive as attainment of durability. Certain factors associated with high cement content (high cement factor) are durability limiting though more cement content increases strength. An optimum cementitious content is therefore required to minimize shrinkage and its concomitants while ensuring that sufficient strength is available. This initiative seeks to reduce the cement content to the barest minimum below the typical 570 lb/CY to 500 lb/CY (low cementitious content) and further to 470 lb/CY (lower cementitious content). To minimize confounding phenomena, variables such as pozzolanic substitution, the admixtures, aggregate sources and time of paving are kept constant.

To facilitate this study two sub cells were designed and constructed on the LVR in the section previously occupied by Cell 38. Extensive evaluation will compare the performance of this cell to one in which a standard cement factor has been utilized. MnROAD Cell 524, also built in 2017, has been chosen for this comparison.

6.2 DESIGN

This initiative consists of two sub cells (138 and 238) that were paved with lower, and low cementitious concrete mixtures, respectively. Both of the sub cells are 8-inch thick jointed dowelled plain concrete built over a nonstandard base material. Plans called for removal of existing concrete and leaving in place the existing aggregate base. The base material was originally a material meeting the requirements of

MnDOT Class 3 [Minnesota Department of Transportation, 2018] but due to non-separation of layers, interfacial mixing had occurred over the last 24 years. The material was scarified from its over-consolidated state and recompacted. Difficulty in achieving adequate density was evident as observed by pumping phenomena during construction. The pavement was characterized by non-skewed joints and 1.25-inch diameter dowels spaced at 1-foot intervals. Longitudinal joints were tied with 30-inch long, 0.5-inch diameter rebars. Design section and plan details are shown in Figures 6.1 and 6.2, respectively.

As a materials based experiment, most of the expected responses are durability related. In consequence, the MIRA will be used to evaluate damage over time by monitoring changes in pulse velocity. The cells will also be evaluated for visible damage and cores will be taken periodically to facilitate petrographic analysis. Results of these sub cells will be compared to the control cell (Cell 524).

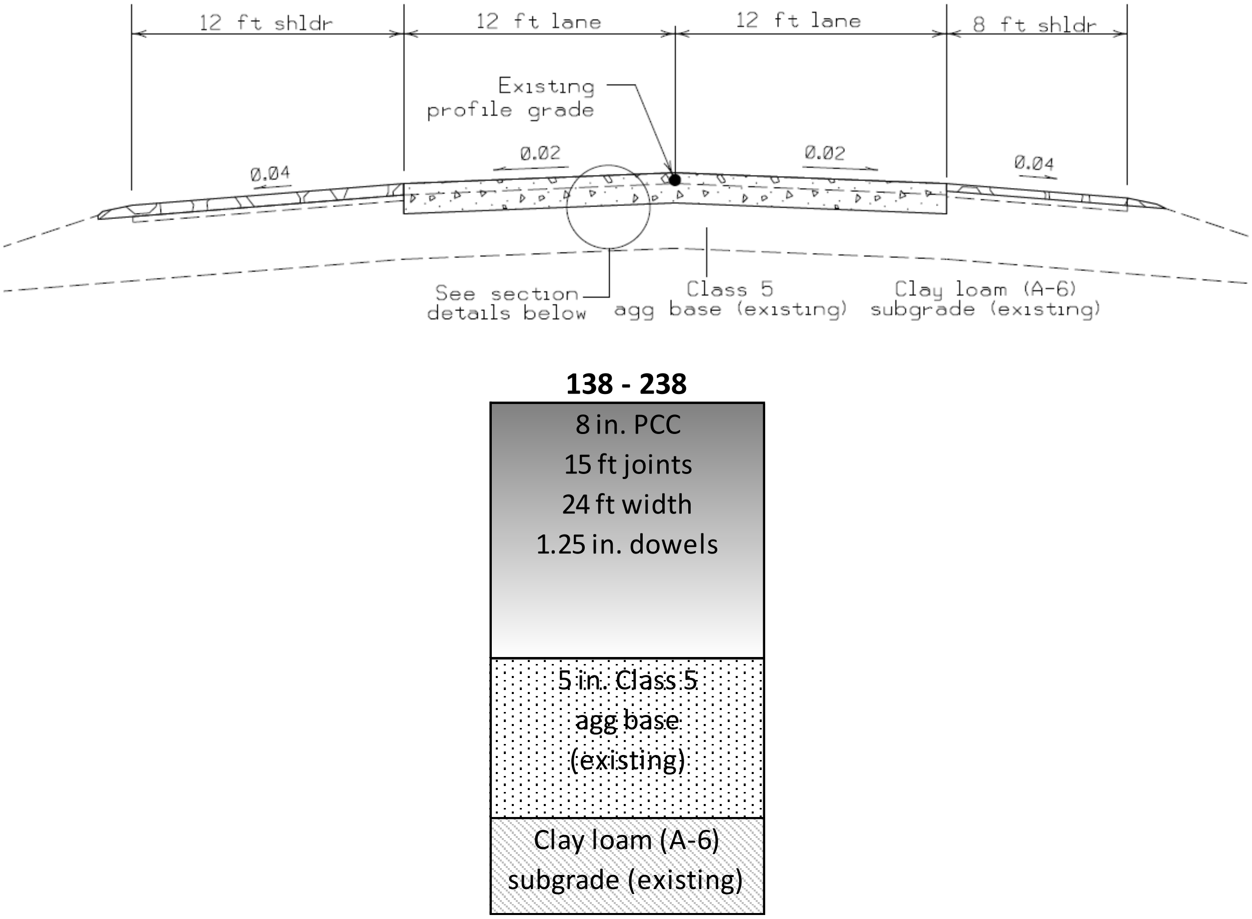


Figure 6.1 Design section details for Cells 138 and 238.

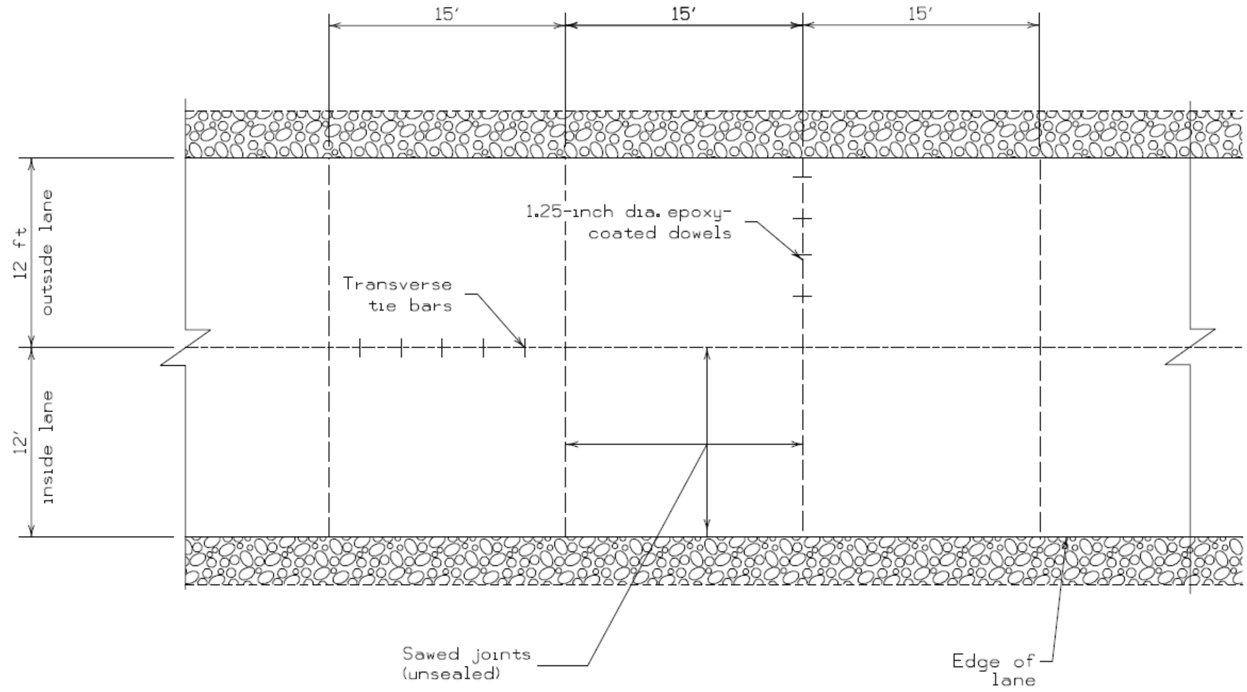


Figure 6.2 Plan detail for Cells 138 and 238.

Trial mixing was performed prior to submission of mix design for approval. The trial mixing examined slight variants of the mix design meeting the requirements of MnDOT 3A21, traditional contractor mix, with conventional pozzolanic substitution. However, for Cell 138 the cementitious content is reduced to 500 lb/CY. A 3A21B mix, with cementitious content further reduced to 470 lb/CY, is utilized in Cell 238. Table 6.1 shows the mix designs utilized for these sections. The table also includes the mix design for Cells 124 through 624 which serve materially as control. Only Cell 524 serves as structural control for cells 138 and 238 since it is built with a conventional mix and not subject to early loading.

Table 6.1 Mix designs for optimized mix concrete (Cells 138 and 238).

MIX/CELL	AIR (%)	WATER (lbs)	CEMENT (lbs)	FLY ASH (lbs)	FLY ASH (%)	W/C RATIO	FA #1 (lbs)	CA #1 (lbs)	CA #2 (lbs)	CA #3 (lbs)	SLUMP RANGE (in.)
MR-3A21 524 (control)	7	228	400	170	30	0.40	1173	562	1015	305	0.5-3
MR-3A21A 238	7	197	353	117	25	0.42	1242	595	1075	323	0.5-3
MR-3A21B 138	7	210	375	125	25	0.42	1218	584	1054	317	0.5-3

6.3 CONSTRUCTION

During preparation of the aggregate base, stability problems were observed, e.g., high deflections and rutting due to construction equipment. The subgrade/base stability issues previously noted for Cells 139 and 239 were more pronounced in this section.

The Contractor performed several iterations of corrective work in an attempt to improve the conditions, beginning with mixing, grading, and compaction of the aggregate base. This approach was unsuccessful. MnROAD personnel were reluctant to call for removal and replacement due to budget and schedule impacts. The Contractor was therefore directed to do the best they could short of removal and replacement. The Contractor then removed the aggregate base, scarified the subgrade to a depth of about 1 foot, to allow for drying.

Figure 6.3 shows a rut left behind after passage of the Ingios intelligent compaction roller at the location of the maximum observed rutting. MnROAD personnel performed DCP testing at two locations: 1) a good area with no yielding observed and 2) the rutted area shown in Figure 6.3. As expected the penetration index values were much higher in the rutted area. Furthermore, it was observed that the problem was due to weak subgrade soils greater than 2 feet from the base surface. Unfortunately, proper resolution of this issue was beyond the budget and scope of this project. To help address the rutting problem and impact to slab uniformity, the Contractor performed rolling in front of the paver as shown in Figure 6.4.

Figure 6.3 Rut in Cell 238 aggregate base due to passage of intelligent compaction steel drum roller.

Figure 6.4 Contractor shaping aggregate base in front of paver with drum roller, Cell 238.

The sub cells were paved on July 14, 2017 with a slip form paver that placed both lanes simultaneously. Paving began at approximately 8:00 am at the east end of Cell 238 with the lowest cementitious (470 lb/CY) mix and progressed westwards until the 250 feet of the cell was completed. The transition to cell 138 was not abrupt, but occurred over a distance of about 10 feet within which the low cementitious mix gradually terminated and the material for the lower (470 lb/CY) cementitious mix commenced. Note that the order of the mixes was changed during paving, and therefore construction plans indicate that the lowest cementitious concrete was to be placed in Cell 138. Throughout paving operations final shaping of the base was continuously done by the contractor.

Transverse (non-skewed) and centerline longitudinal joints were sawn within 12 hours of paving.

6.4 SAMPLING AND TESTING

This section discusses the various rheological and mechanical tests as well as other tests conducted. Within this project, American Engineering Testing, Inc., was contracted to perform sampling, rheological testing, early strength, and early mechanical strength testing. State-of-the-practice performance engineered mixture (PEM) tests were performed by the contracted consultant and Iowa State

University. The materials testing matrix is summarized in Table 6.2 below. Test results will be utilized in subsequent NRRA research projects and will be made available to researchers upon request.

Table 6.2 Testing requirements for Cells 138 and 238 optimized mix experiment.

TEST(S)	SAMPLE AGE(S), days	SPEC TYPE	SPEC SIZE	NO. SPECIMENS	CURE PROCEDURE	CURE TIME, days/weeks
Box and SAM Test	---	---	1 SAM and Box per mix	---	---	---
ASTM C39, Compressive Strength	2, 3, 7, 28	cyl	6x12-in., set of 2	8	Moist Room	Per test age
ASTM C78, Flexural Strength	2, 3, 7, 28	beam	6x6x20-in., one per age	4	Lime-water immersion	Per test age - will test at MnROAD
ASTM C666, Proc. A Freezing and Thawing in Water	MnDOT decides	cores	3 to 4-in. dia. cores x 9-10 inch	1	Field cores	In pavement
AASHTO T336, Coefficient of Thermal Expansion	28	cyl	4x8-in.	1	Moist room	28
ASTM C469, Modulus of Elasticity and Poisson's	28	cyl	6x12-in.	1	Per test method	28
ASTM C215, Dynamic Modulus	7, 28	cyl	4x8-in.	Use ASTM C469 cylinder before testing	Moist room	28
Wenner Probe Resistivity	28	cyl	4x8-in.	Use ASTM C469 cylinder before testing	Per test method	28
ASTM C856, Petrographic Examination of Hardened Concrete	MnDOT decides	core	3 to 4-in. dia. cores x 6 in.	1	Field core	In pavement
ASTM C157, Drying Shrinkage	56	beam	4x4x11-1/4-in. beams with pins	1	28 days lime-saturated water	28 days

The MIT-SCAN T2 was utilized for determination of as-built concrete thickness. Results are presented in Appendix A, Table A.2. The average concrete paving thickness for Cells 138 and 238 was 7.9 inches and ranged from 7.2 to 8.7 inches.

6.5 SENSORS

To monitor progression of strength in each of Cells 138 and 238, maturity sensors and dataloggers were used extensively. Irrespective of locations within the sub cell, each had maturity dataloggers installed at mid-depth, and not less than 2 feet from pavement edge, and were identified by the cell and lane. Maturity dataloggers were initialized with the readers early enough in the strength gain process. Eight dynamic sensors and environmental load sensors were also installed in each of sub cells 138 and 238 according to the sensor layout. Sensor layouts are shown in Figures 6.5 and 6.6. As-built sensor locations are summarized in Appendix C.

Legend

— Dynamic Strain Gauge* + Vibrating Wire Strain Gauge*

*Strain gauges placed top and bottom of concrete at each location shown
**Temperature Trees and moisture gauges located in outside lane

Figure 6.5 Sensor layout for Cell 138.

Legend

— **Dynamic Strain Gauge*** + **Vibrating Wire Strain Gauge***

***Strain gauges placed top and bottom of concrete at each location shown**
****Temperature Trees and moisture gauges located in outside lane**

Figure 6.6 Sensor layout for Cell 238.

CHAPTER 7: DETERMINING PAVEMENT DESIGN CRITERIA FOR RECYCLED AGGREGATE BASE AND LARGE STONE SUBBASE

7.1 OBJECTIVES

Current pavement design methods generally assume that the performance of aggregate base made from recycled materials is similar to the performance of aggregate base made from quarried or mined materials. In addition, large stone subbase (up to 6-inches top size) is being used in some states to provide a more stable construction platform on which to place the overlying layers. Therefore it is necessary to measure and then develop methods to estimate the stiffness, strength, and permeability of aggregate base containing recycled materials and large stone subbase. Deterioration and contamination of these materials also need to be assessed to determine how to best estimate the long-term performance during pavement design.

The research contractor selected to analyze the results from the MnROAD test sections and recommend pavement design criteria for recycled aggregate base and large stone subbase is comprised of a team from Iowa State University (ISU) and the University of Wisconsin-Madison (UW-Madison). In order to determine the pavement design criteria, the research contractor will analyze field testing, including intelligent compaction measurements, and laboratory testing and explain how these results effect the pavement design inputs seasonally. The recommendations will be appropriate for each NRRA state DOT partner considering their pavement design method and construction specifications.

This research project has three main objectives. The first objective is to measure and analyze the field and laboratory performance of the test sections built with recycled aggregate base (RAB) including recycled concrete aggregate (RCA), recycled asphalt pavement (RAP), and virgin aggregate (VA). In addition, similar analyses will be conducted for the test sections built with an 18 inch layer of large stone subbase (LSSB), and with a 9 inch layer of LSSB, which included geogrids and geotextiles. To accomplish this objective, the research team will evaluate both the geomechanical and environmental properties of these pavement systems. It should be noted that the LSSB sections have only one type of aggregate base and the multiple RAB sections do not have LSSB indicating that these experiments are separate. The second objective is to develop a method to estimate the stiffness and permeability of RAB and LSSB designs. This objective will be achieved by establishing correlations between common laboratory test data and both laboratory and field modulus and permeability values. The third objective is to provide mechanistic pavement design input values and recommend construction specifications for roadways built with RAB and LSSB. This objective will be accomplished taking into account the performance and estimated life cycle costs.

The outcome of this research will optimize the use of recycled materials and LSSB designs, while maintaining pavement quality, resulting in cost savings and conservation of natural resources. Specific expected outcomes from this study include optimized pavement design methods and quality management test methods to be implemented in state DOTs specifications.

7.2 DESIGN

Each of the four RAB test sections are approximately 220 feet long. Details are shown in Figures 7.1 and 7.2. All four experimental sections consist of 3.5 inches of 12.5 mm NMAS Superpave over 12 inches of varying types of aggregate base, both VA and RAB. The in place subgrade soils beneath Cells 185 and 186 consist of a clean sand while Cells 188 and 189 are constructed on native MnROAD clay loam (A-6).

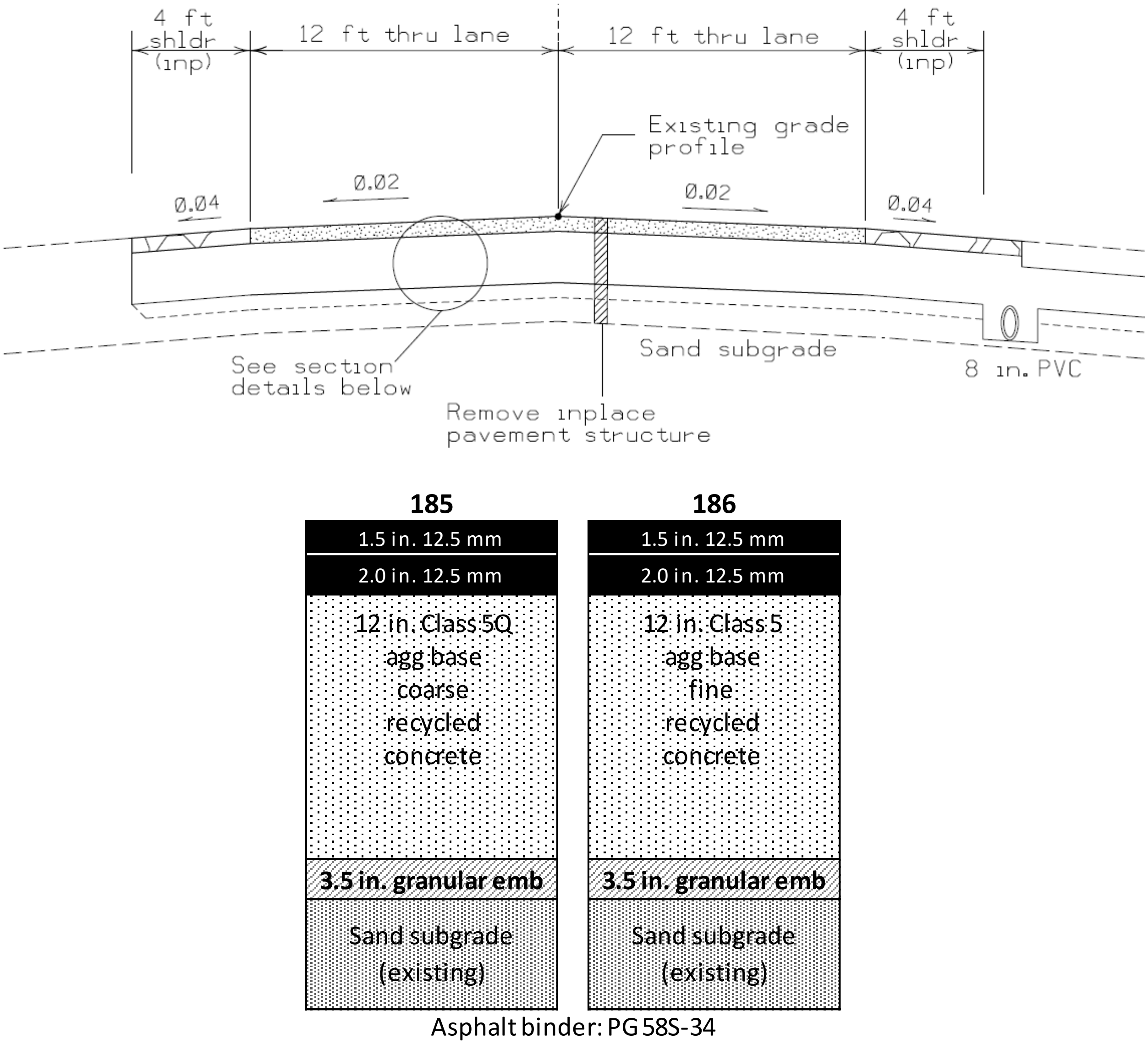
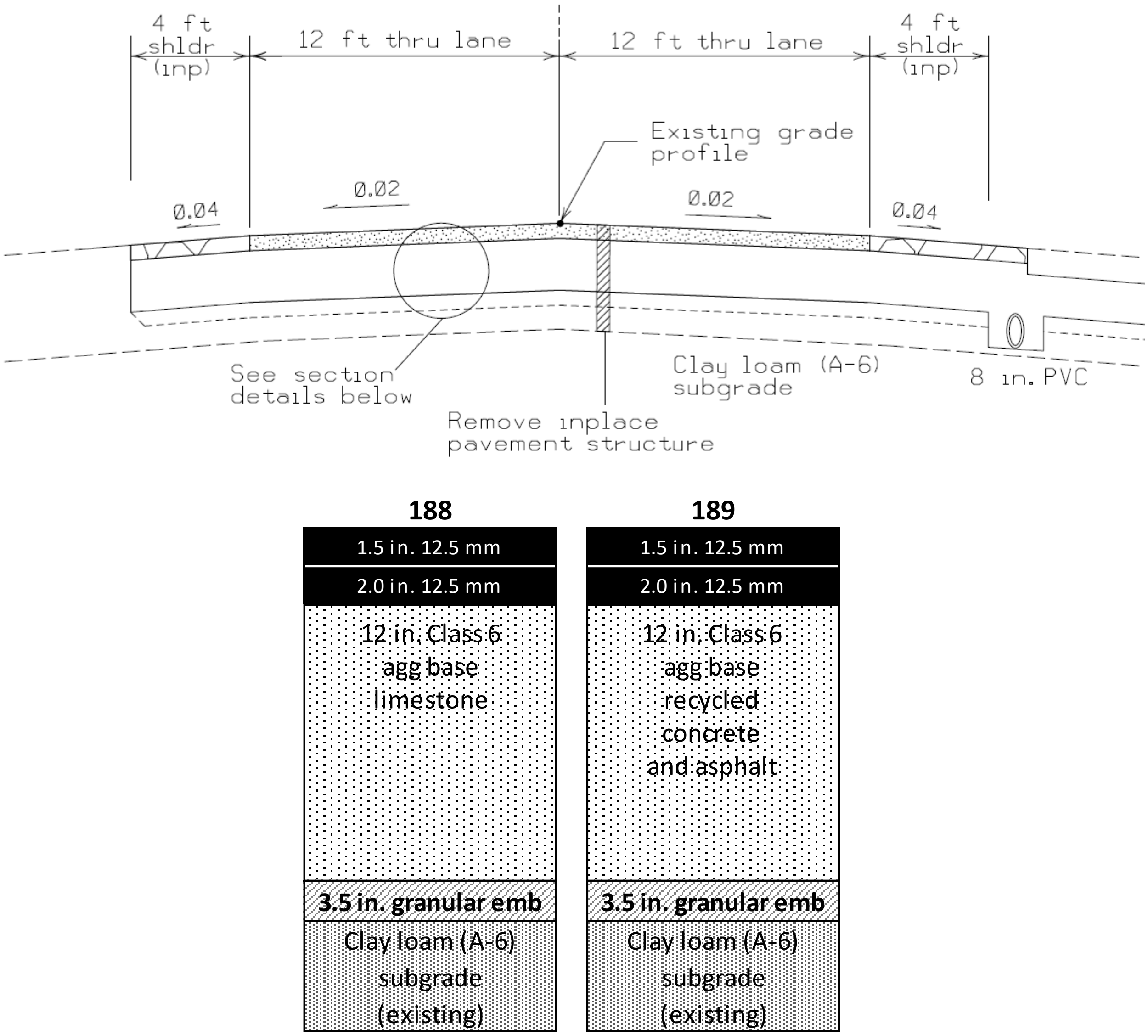


Figure 7.1 Recycled aggregate base sections with sand subgrade (Cells 185 and 186).



188	189
1.5 in. 12.5 mm	1.5 in. 12.5 mm
2.0 in. 12.5 mm	2.0 in. 12.5 mm
12 in. Class 6 agg base limestone	12 in. Class 6 agg base recycled concrete and asphalt
3.5 in. granular emb	**3.5 in. granular emb**
Clay loam (A-6) subgrade (existing)	Clay loam (A-6) subgrade (existing)

Asphalt binder: PG 58S-34

Figure 7.2 Recycled aggregate base sections with clay loam subgrade (Cells 188 and 189).

As originally planned, each of the LSSB test sections were approximately 250 feet long as shown in Figure 7.3 and 7.4.

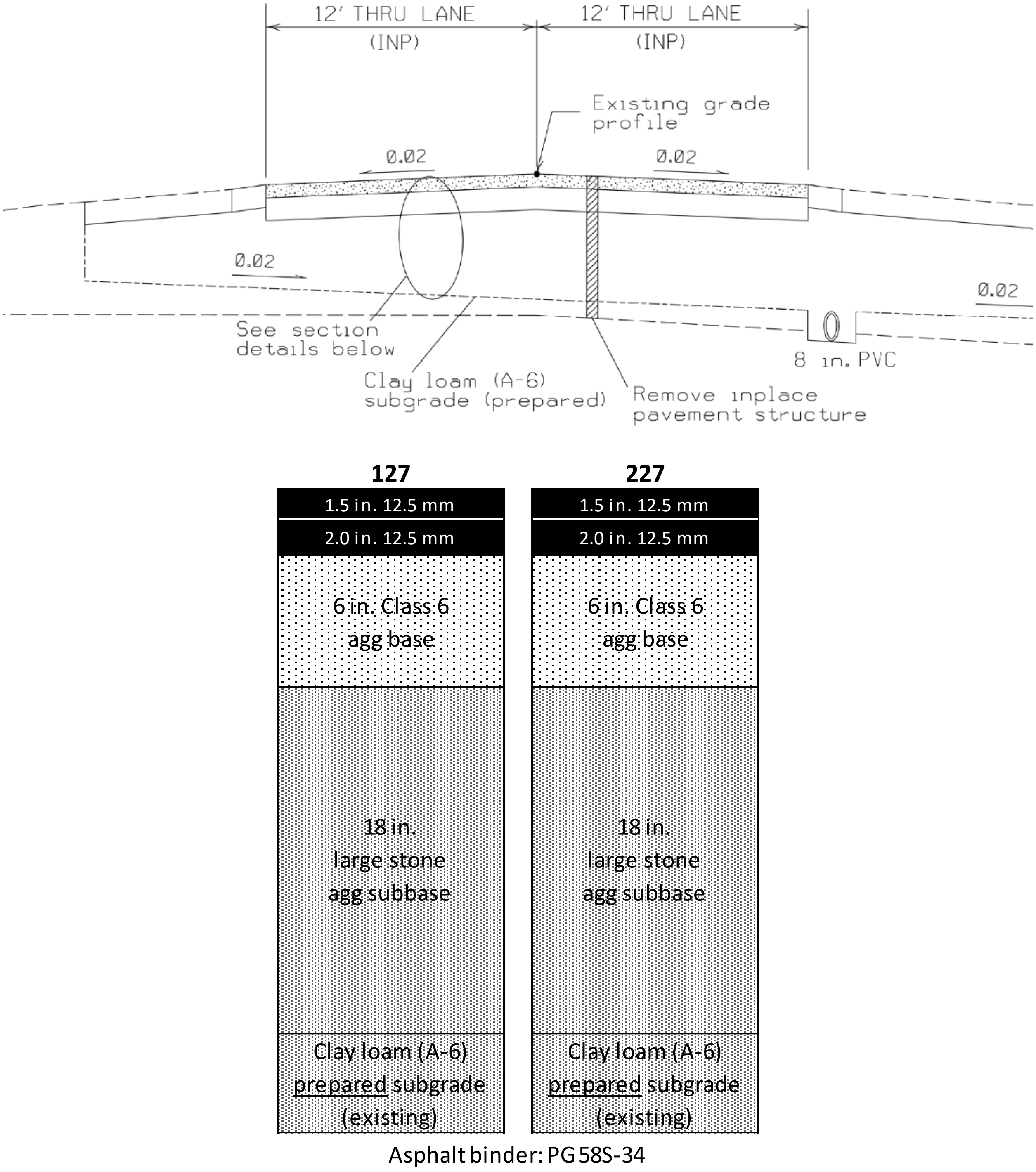


Figure 7.3 Large stone subbase sections: Cells 127 (single lift) and 227 (two-lift) 18-inch thick LSSB.

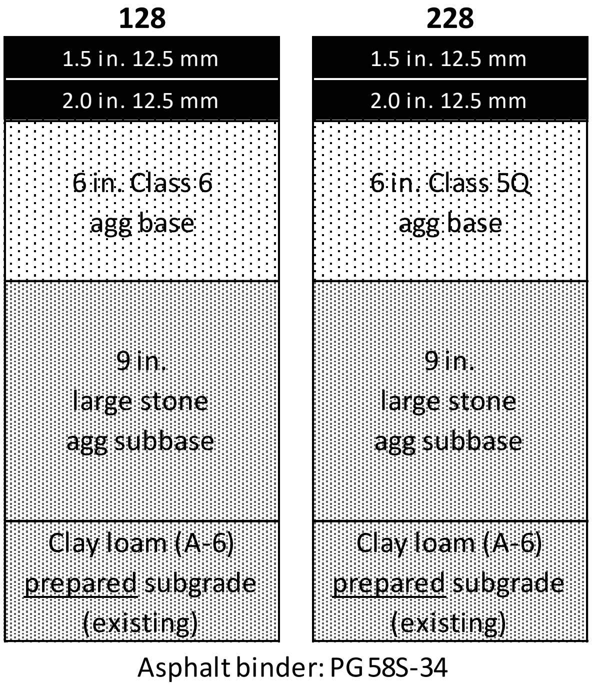
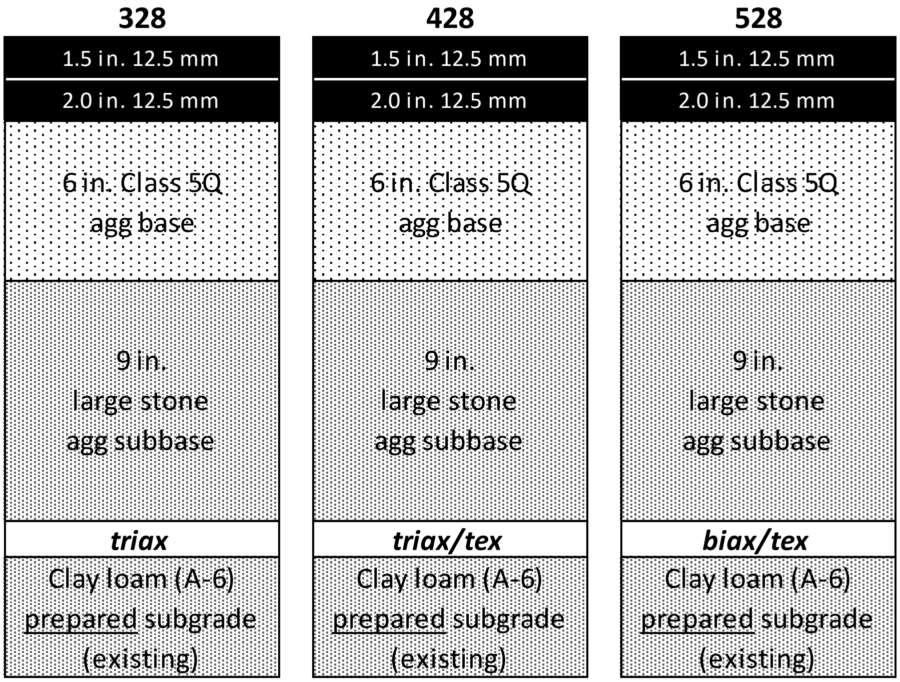


Figure 7.4 Original planned large stone subbase sections: Cells 128, 228 (9 inch LSSB).

Due to failure of the 9 inch sections during construction, cells 128-228 were redesigned as cells 328-728 and reinforced with biaxial geogrid (biax), triaxial geogrid (triax) and/or textile (tex) between the sandy lean clay and the large stone subbase. Details of the redesigned sections are shown below in Figures 7.5a and 7.5b.

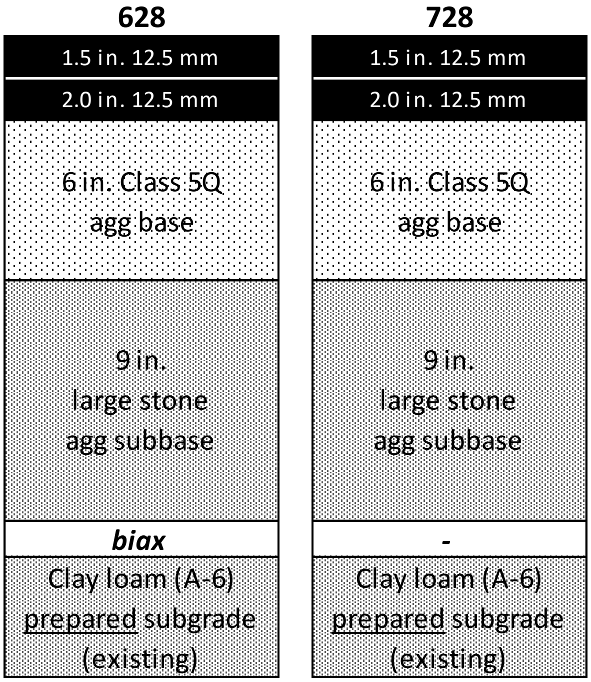
7.3 CONSTRUCTION

Construction timelines for the RAB and LSSB sections are summarized in Tables 7.1 and 7.2, respectively. MnDOT ensured that the construction complied with the plans and special provisions. Inspection included a construction diary with the following information: equipment used, number of lifts to place materials, and number of passes for compaction. Testing included: density, moisture, gradation, classification, dynamic cone penetrometer (DCP), LWD, FWD, and gas permeameter. Samples were collected and shipped to our partner and research contractor’s testing labs.



Asphalt binder: PG 58S-34

Figure 7.5a Redesigned large stone subbase sections: Cells 328, 428, and 528.



Asphalt binder: PG 58S-34

Figure 7.5b Redesigned large stone subbase sections: Cells 628 and 728.

Table 7.1 Construction timeline for recycled aggregate base sections: Cells 185, 186, 188, and 189.

	June				July					August				September				October				
Date/ Activity	5	12	19	26	3	10	17	24	31	7	14	21	28	4	11	18	25	2	9	16	23	30
Erosion control	X																					
Strip topsoil																						
Pavement removal		X	X			X																
Common excavation						X	X															
Subsurface drain							X															
Place conduits and handholes							X															
Place risers and sensors							X			X												
Place aggregate base									X													
HMA paving												X				X						

Table 7.2 Construction timeline for large stone subbase sections: Cells 127/227, 128/228, and 328-728.

	June				July					August				September				October				
Date/ Activity	5	12	19	26	3	10	17	24	31	7	14	21	28	4	11	18	25	2	9	16	23	30
Erosion control	X																					
Strip topsoil							X															
Pavement removal							X															
Common excavation								X	X	X												
Subsurface drain										X												
Place conduits and handholes																						
Subgrade preparation											X											
Place large aggregate subbase											X											
Place risers and sensors																						
Place aggregate base											X											
HMA paving												X										
Remove failed cells													X									
Reconstruct Cells 328-628													X	X								
Final HMA paving																X						

Partnerships with Ingios and University of Texas El Paso (UTEP) mapped the unbound layers using intelligent compaction and also provided other test data. The in situ properties of the test sections were measured during construction quality assurance and will be compared to the properties estimated during pavement design. Construction uniformity was quantitatively measured and recorded using intelligent compaction by our partners Ingios and UTEP. The research contractor will include and utilize this intelligent compaction data and the other test data collected through these partnerships in the contractor's presentations to the technical advisory panel and in the interim and final reports. The research contractor will conduct rigorous statistical analyses to determine whether a reliable and accurate relationship exists between the density and field modulus obtained from intelligent compaction data and the uniformity of the compacted layers. In addition, similar statistical analyses will be conducted to determine the relationship between intelligent compaction data and DCP, LWD, FWD, and permeability results.

The experimental plan for LSSB called for a special subgrade preparation procedure. The objective was to achieve a subgrade meeting a DCP Penetration Index value of 2.5 to 3.5 inches per blow over the upper 1 foot of subgrade.

When the subgrade was constructed to the respective plan vertical elevations, a tracked dozer with shanks mounted to the back loosened subgrade soils to the required depth. See Figure 7.6. Samples for moisture content testing were obtained; it was found that the moisture was well below that of optimum moisture content. Subsequent to the initial passes of the dozer/ripper a water truck capable of spraying the subgrade from across the median was used to provide moisture. Successive passes of the dozer/ripper were made to mix the soils and ensure the water was dispersed within the upper 1 foot. During the operations, MnROAD personnel performed Penetration Index testing with the DCP. Several applications of water were required. Furthermore, the moist, loosened soil was permitted to marinate overnight. In this manner, MnROAD personnel assured that the subgrade met the target strength requirements.

Figure 7.6 Subgrade conditioning with dozer and ripping teeth, MnROAD Cell 228.

The initial construction of Cells 128 and 228 failed during placement of the LSSB. Figure 7.7 shows evidence of subgrade soil pumping up through the LSSB to the surface. In contrast, Cells 127 and 227, with an 18-inch thick LSSB section, performed well during construction. See Figure 7.8. Note that the LSSB section in Cells 127 and 227 were originally intended to be constructed in one lift and two lifts, respectively. In practice, it was found difficult to achieve this. Furthermore, due to the problems experienced with the 9-inch thick LSSB section, both sections were construction with a single, 18-inch thick lift. It was determined that an alternative design was required for Cells 128 and 228 to survive construction and fulfill the objectives of the experiment.

Figure 7.7 Condition of 9-inch deep large stone subbase section after first construction iteration.

Figure 7.8 Comparison of large stone subbase condition: 9-inch thick Cell 128 (foreground) and 18-inch thick Cell 227 (background).

The NRRA Geotechnical team felt it crucial to retain the 9-inch thick LSSB section in the redesigned sections. The arrived at solution involved combinations of geosynthetic separator fabric and/or two types of reinforcing grid.

The originally constructed section was removed to subgrade elevation. Soil loosening was repeated and the geosynthetics were installed immediately prior to placement of the LSSB. See Figure 7.9 for a map of the redesigned Cells 328-728. Note that Cell 728 is actually a remnant from the original Cell 228. Due to near-surface utilities at this location soil ripping was not performed.

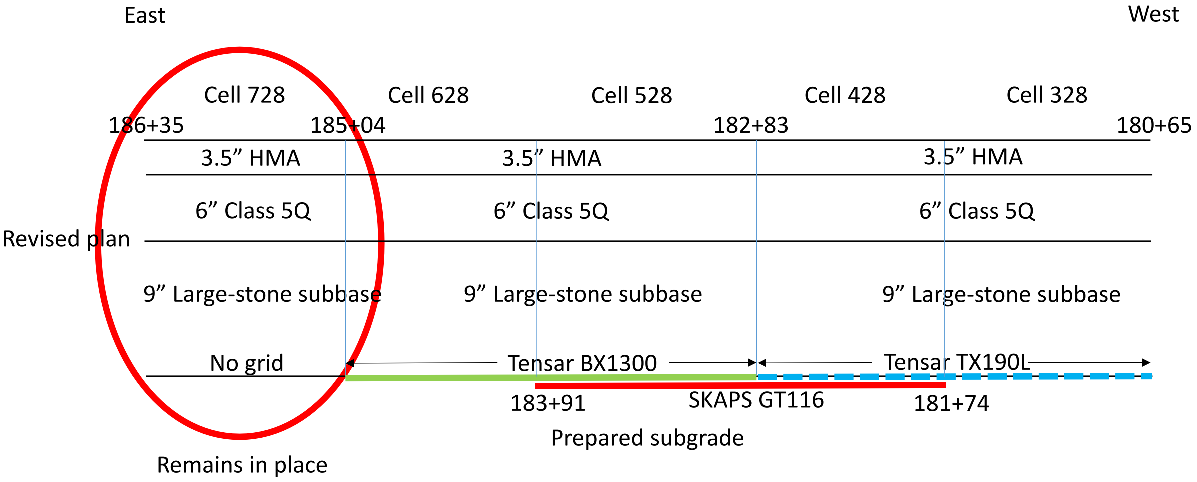


Figure 7.9 Layout of redesigned 9-inch thick LSSB sections: Cells 328-728.

7.4 LABORATORY TESTING AND PERFORMANCE MONITORING

MnDOT and our UTEP partner will perform laboratory testing and provide data to the research contractor. Laboratory tests include density, moisture, gradation, Atterberg limits, hydrometer, classification, and percent crushing. In addition, the research contractor will perform laboratory testing including angularity index and surface texture using image analysis and traditional measurement techniques, which specifically include Illinois DOT test procedures 4791 “Flat and Elongated Particles in Coarse Aggregate” and 5821 “Determining the percentage of Fractured Particles in Aggregate” for all aggregate base and LSSB materials. Our UTEP partner and the research contractor will perform resilient modulus (AASHTO T307) on aggregate base materials (not LSSB). The research contractor will apply existing methods to estimate resilient modulus from more common tests such as density, moisture, gradation, Atterberg limits, hydrometer, classification, percent crushing, angularity index, and surface texture. MnDOT will continue to collect and upload seasonal performance data to the MnROAD database. Seasonal performance data includes falling weight deflectometer and pavement surface condition.

The laboratory investigation will assess the important recycled material characteristics that can impact pavement quality. Since RCA and RAP are not the same as VA materials, quality control and quality assurance target values for RCA and RAP need to be determined. For example, permeability issues and high leachate pH are potentially more problematic for RCA than the stiffness properties, which are comparable or may be even higher than VA. Similarly, the potential for excessive permanent deformation and temperature sensitivity are a greater concern with the use of RAP than the stiffness and permeability. In addition, geotechnical tests will be conducted on sand and sandy lean clay subgrade materials so the mechanistic empirical pavement design methods can be applied to the test sections to investigate the influence of subgrade type and character on the performance of the pavement surface and recycled aggregate base layer.

7.5 SENSORS

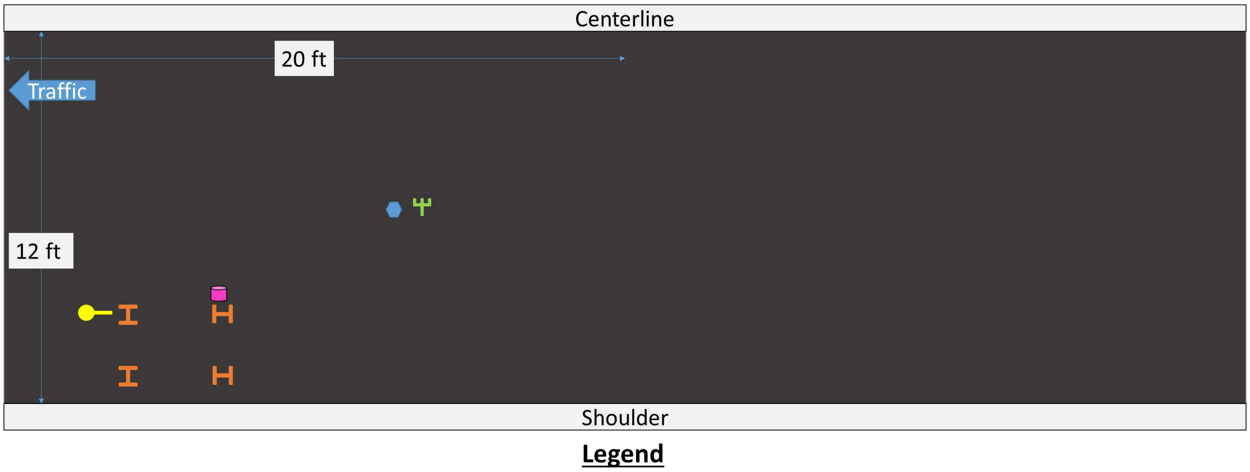
Environmental and load response sensors were installed in Cells 127 and 728 of the LSSB, and Cells 185, 186, 188, and 189 of the recycled aggregate base experiments. Table 7.4 lists the type and quantities of the sensors installed in the cells. Figures 7.10 through 7.12 depict the sensor layout of cells with both environmental and dynamic load sensors. The as-built location of each sensor, including depth and offset from centerline, can be found in Appendix C.

Table 7.3 Instrumentation installed into large stone subbase and recycled aggregate base cells.

CELL	TEMPERATURE (TC)	MOISTURE (EC)	DYNAMIC PRESSURE (PG)	DYNAMIC STRAIN (LE+TE)
185	12	4	-	-
186	12	4	2	4
188	12	4	2	4
189	12	4	2	-
127	12	3	2	-
227	-	-	-	-
328-628	-	-	-	-
728	16	4	2	4

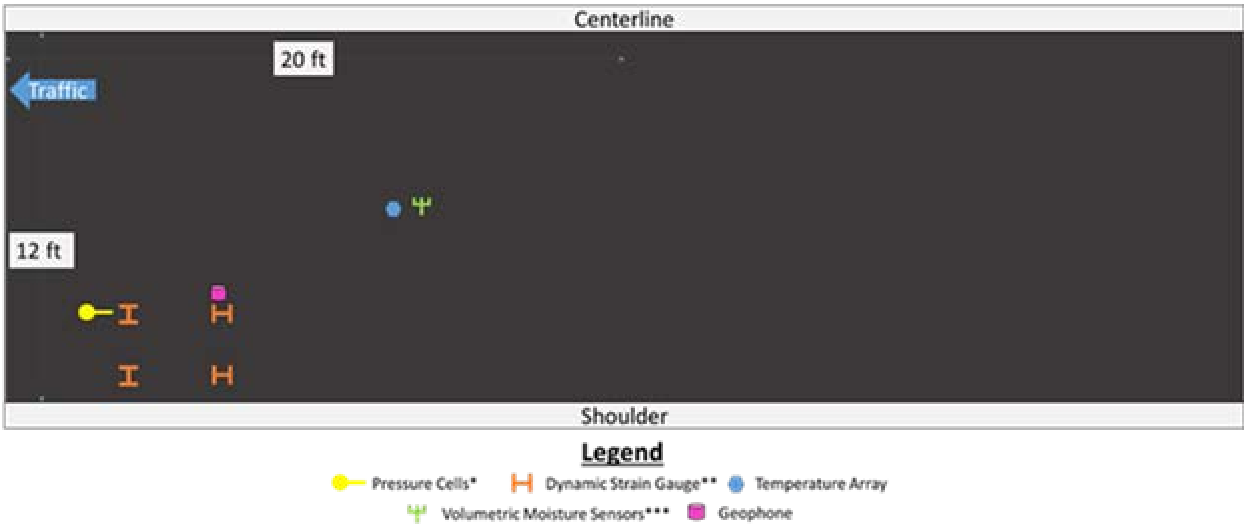
MnDOT purchased, pretested, installed, and verified operation of the sensors. MnDOT also will continue to upload temperature, moisture, and weather data to the database. In addition, MnDOT will measure dynamic asphalt strain seasonally in response to loads applied by the MnROAD truck and falling weight deflectometer and upload the strain data to the database. Finally, MnDOT will continue to record traffic counts and maintain instrumentation to the degree practical during the life of the research project.

The research contractor will analyze temperature, moisture, and dynamic strain data as they relate to pavement design and performance. The research contractor will also analyze and discuss freeze, thaw, and frost depth behavior as they relate to pavement design and performance. Finally, the research contractor will analyze the MnROAD truck loading, FWD, and pavement surface conditions.



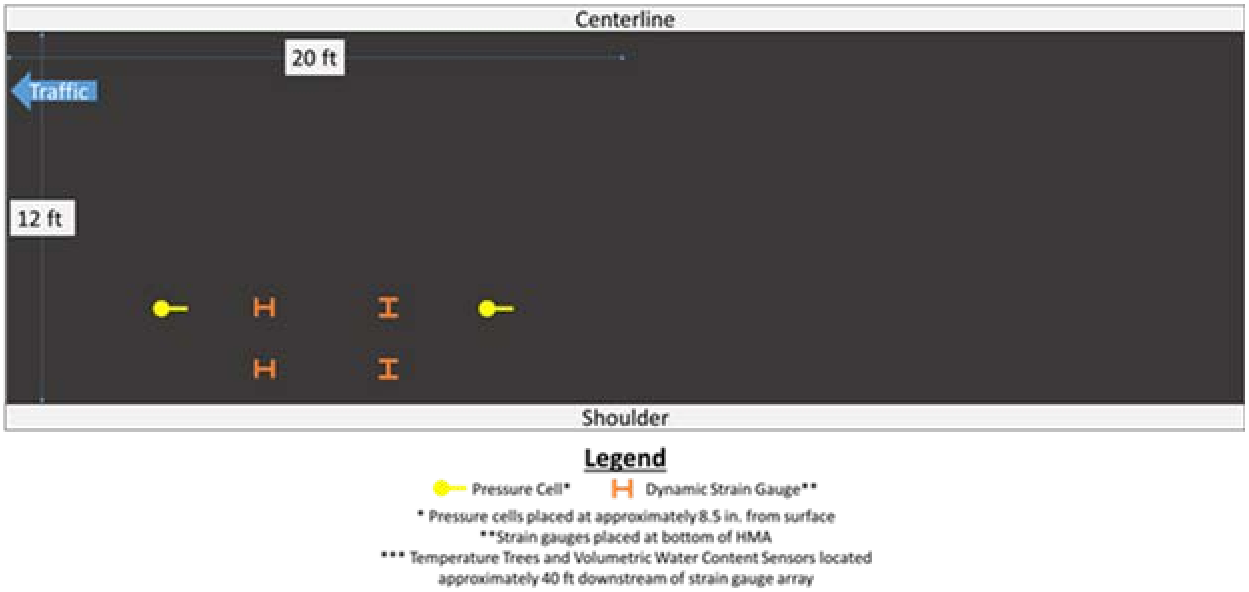
* Pressure cells placed at approximately 15 and 27.5 in. from surface
**Strain gauges placed at bottom of HMA
*** Volumetric Moisture Sensors placed at 5, 14, 17 and 20.5 in. from surface
****Geophone placed at 37.5 in. from surface

Figure 7.10 Sensor layout in Cell 186.



* Pressure cells placed at approximately 15 and 27.5 in. from surface
**Strain gauges placed at bottom of HMA
*** Volumetric Moisture Sensors placed at 5, 14, 17 and 20.5 in. from surface
****Geophone placed at 37.5 in. from surface

Figure 7.11 Sensor layout in Cell 188.



* Pressure cells placed at approximately 8.5 in. from surface
**Strain gauges placed at bottom of HMA
*** Temperature Trees and Volumetric Water Content Sensors located approximately 40 ft downstream of strain gauge array

Figure 7.12 Sensor layout in Cell 728.

CHAPTER 8: MAINTAINING POOR PAVEMENTS

8.1 OBJECTIVES

The overall objective of this NRRA project is to identify performance improvements that can be expected for asphalt roadways, from the application of a variety of thin pavement treatments similar to and including thin lift overlays, fine graded asphalt scratch course with a chip seal, mastic surface correction for cupped cracks with a chip seal, micro surfacing, scrub seals, etc.

The final product will summarize practices being performed in various NRRA member states and to collect performance data and costs related to thin treatments applied to poor condition pavement, intended to extend service life. The project will provide guidance on potential improvements to consider for lower volume roads that are in poor condition, where funds are not available to do a full reconstruction.

This research topic will focus on low volume pavements and rely mostly on existing data obtained from the NRRA member states. However, four sections were constructed on the mainline roadway in support of the study. MnROAD provides a unique location to observe performance on a high volume road.

Data analysis will focus on improvements made to ride quality from the application of various thin treatments and the loss of ride quality over time. Benefits and effectiveness of the treatments will then be evaluated alongside their cost to calculate life cycle benefits for an agency. The outcome will provide agencies with cost information and performance expectations that will enable better decisions for treatment selection and application timing.

8.2 DESIGN

As part of the NRRA effort, four 250-foot test sections were constructed on the MnROAD I-94 mainline. Existing Cells 1 and 15 were divided in two. One half of each cell received a 0.75-in micro-milling followed by a 0.75-inch thick, 4.75 mm NMAS asphalt thinlay. The other half of each cell received a 0.625-inch micro-mill followed by an UTBWC.

Design information is shown in Figures 8.1 and 8.2. Note that the initial conditions of Cells 1 and 15 were significantly different. Both pavement test sections were originally constructed at the same time and have been in service for the same period. Cell 1 is a thinner asphalt pavement structure with a deep granular subbase. Cell 15 is a full-depth asphalt section constructed directly on clay loam (A-6) subgrade soils. Predominant distresses on Cell 1 are structural related (rutting, wheel path cracking, cupped transverse cracks) while for Cell 15 they are environmental (closely spaced thermal cracks).

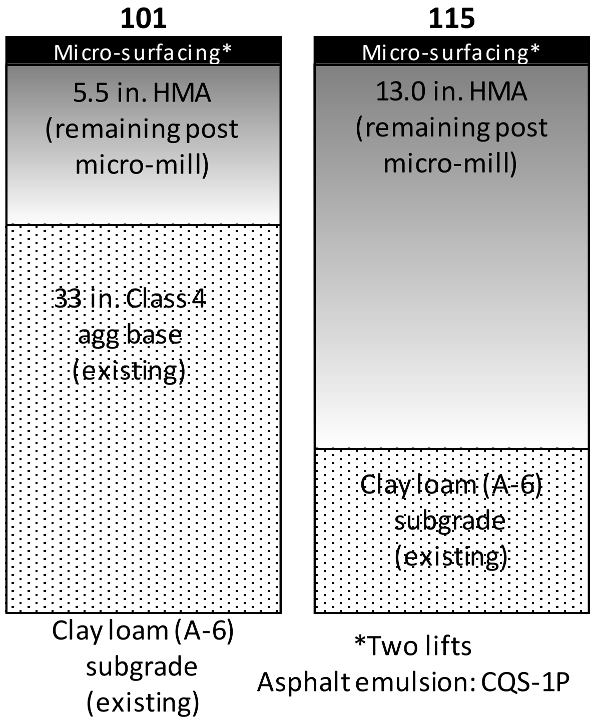


Figure 8.1 Research section details for Cells 101 and 115.

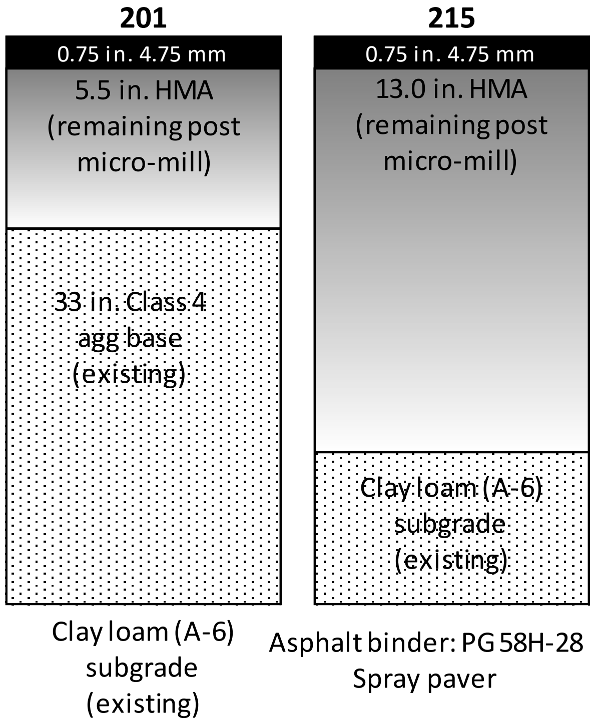


Figure 8.2 Research section details for Cells 201 and 215.

8.3 CONSTRUCTION

Cell 15 was micro-milled in the morning of July 26, 2017. The micro milling machine was 4 feet wide. This required 3 passes to do a lane. The machine started next to, but not on, the centerline. After both lanes and the inside shoulder were milled, a 12 to 18 inch strip by the centerline remained and was milled last. Upon completion of Cell 15, the micro milling machine was loaded on to a trailer and moved to Cell 1. Cell 1 was micro-milled in the afternoon of July 26. The process was similar to cell 15. The passing lane was milled first from close to the centerline toward the yellow edge line. The driving lane was milled next, from close to the centerline toward the white edge stripe.

MnDOT's standard micro-milling special provision requires milling the entire width of the lane in a single pass with a 12.5-ft wide head. Due to difficulty in locating equipment meeting this specification the requirement was not strictly enforced. As a result, the smoothness results of these two test sections may be impacted.

Prior to application of micro-surfacing, the milled asphalt surface was tacked using CSS-1H emulsion. The micro-surfacing was placed in two separate passes: a partial-width scratch course followed by a full-width surface course.

The 0.75-inch thick, 4.75 mm asphalt thinlay was placed with a spray paver applied tack coat. Issues were observed with asphalt mixture quality control testing results: a sample obtained from the plant at production was failed due to high asphalt content and low air voids. MnDOT field personnel also retrieved a sample from the paver hopper at around the same time. However, before a decision regarding the disposition of the failing material was made it was decided to observe the performance of the thinlay after a period of it being subjected to mainline traffic. Traffic was placed on the mainline sections between September 18 and November 2, 2017. Inspection of the thinlay during this period indicated no obvious problems such as rutting or shoving.

Sampling from paver hopper is not the official method for sampling (normally behind the paver); the samples were submitted for testing. Volumetric results from MnDOT samples indicated passing results. A decision was made to accept the thinlay mixture based on these results.

8.4 SAMPLING AND TESTING

Profile measurements using the MnROAD LISA were taken immediately before and after the micro-surfacing, as well as after the treatments were constructed. For the micro-surfacing sections, a limited number of emulsion samples were obtained to perform binder characterization. Additionally, samples of the micro-surfacing mixture were collected for extraction and residual characterization. Samples of asphalt mix were obtained for the two asphalt thinlays for testing as part of the NRRA mixture performance testing long-term project described in Chapter 3.

8.5 SENSORS

Temperature sensors were installed only in the 0.75-inch thick asphalt thinlay sections, Cells 201 and 215. No load response sensors were installed in any of the sections. A detailed listing of all sensors installed is provided in Appendix C.

CHAPTER 9: PATCHING MATERIALS FOR PARTIAL DEPTH REPAIRS OF CONCRETE PAVEMENT

9.1 OBJECTIVES

The objective of this project is to provide a guide for NRRA members and other agencies to establish an effective partial depth repair program. The final report will guide the reader through product selection, installation techniques, equipment needed for completing the repair, typical performance cost, along with the life expectancy of the repair products.

Joint distress or mid panel spalls can range from minor spalling that requires no immediate action to major distresses that can affect large areas of the pavement and significantly disrupt traffic. When immediate action is required, temporary repairs are often made using readily available materials, such as cold mix or other asphalt materials. These temporary materials are oftentimes replaced at a later date with more permanent materials to re-establish the integrity and functionality of the concrete pavement.

When longer-lasting materials are used in the initial repairs, the impact to travelers is reduced and additional costs for temporary materials and subsequent removals are eliminated. Different material types are available for longer-term repairs which vary widely in cost, required skill level for satisfactory placement, and time needed before opening to traffic. The performance of each of these materials can also vary widely making selection and installation of permanent repairs challenging.

Traditionally, repairs have been assumed to last 6 to 8 years, but some agencies have experienced patch service life in excess of 20 years. With the range of products available and performance periods experienced, there is a need to determine the current state-of-the-practice.

9.2 DESIGN

A key focus for this research is to have MnDOT maintenance personnel perform most of the preparation and patching to ensure that the performance of each material reflects work typically done by MnDOT. Another goal is to achieve 3 to 5 years, or longer, of service life from these materials with curing times around two to four hours.

The NRRA Preventive Maintenance team selected the original westbound lanes of I-94 that are adjacent to the MnROAD Road Research Facility. This portion of I-94 was originally constructed in 1973 with a 9-inch thick concrete design and skewed, 27-foot transverse joints.

A total of 15 test sections consisting of three contiguous panels and two transition panels, one at either end were prepared. Seven different patch types were created as shown in Figure 9.1. Thirteen different proprietary products were offered by vendors for evaluation. Additionally, asphalt patching mix was used in two of the 15 sections. MnDOT Research, District, material suppliers, and Braun Intertec personnel were onsite during the preparation and installation process to document the procedures required or used for each product. Documentation collected included equipment needed for preparation, manufacturer guidelines or recommendations for installation of each product, and the Personal Protective Equipment (PPE) needed during preparation and application of the repair product. Nomenclature for each type of repair is shown in the legend beneath Figure 9.1.

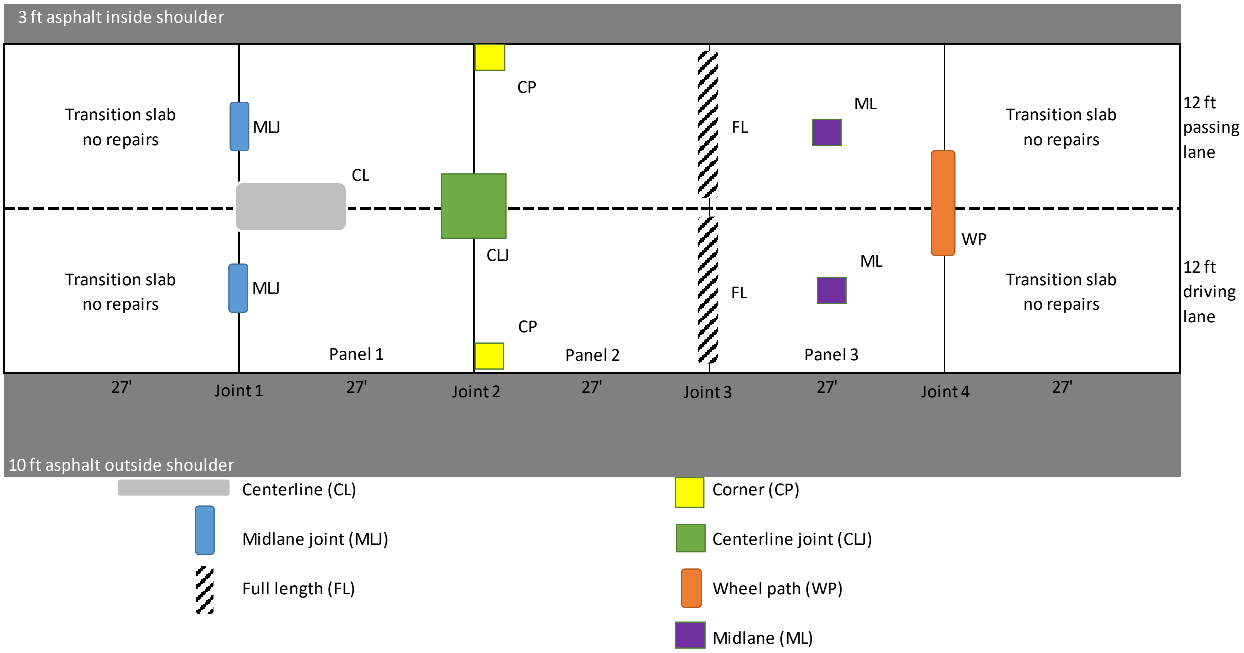


Figure 9.1 Typical layout and definition of patching types for partial-depth repair study.

The general plan for installation and workflow was as follows:

- Concrete joint distresses were created prior to preparation with a small milling machine by a Contractor under a partnership agreement.
- MnDOT District 3 Maintenance staff performed minimal preparation (i.e., sand blasting) and installed patch materials.
- Manufacturers were present onsite in the case of most products, but the intent of the research is to reflect the performance the patch materials under the actual installation conditions.
- Three consecutive panels allocated for each product.

Other information recorded included technical data sheets, manufacturer recommended time to reach required opening strength under varying conditions, adverse conditions and limitations. This information, along with other follow-up data requests, will be compiled, analyzed, and included with the final project report to be prepared by the consultant. Finally, current practices for maintenance joint repairs used by NRRA agency members will be compiled and summarized.

9.3 CONSTRUCTION

The patches were installed during October, 2017. Westbound I-94 traffic was placed on the partial-depth patch sections on November 2, 2017. Traffic remained there until November 21, 2017.

During the installation process, personnel observed and documented material installation. A follow-up questionnaire will be sent to each material supplier to determine the best practices for each product and to determine more detailed information on the installation techniques and preparation needed of the patch.

Patch materials came in a variety of packaging. Some were contained in bags that are not waterproof while some were contained in buckets or waterproof materials. The “shelf life” and storage requirements of each material is an important consideration and will play a role in decisions regarding the appropriateness of each material for storage at maintenance facilities. Details will be provided in the project final report.

It was also noted that some materials required a mixer other than the standard revolving drum mixer that most maintenance crews currently utilize. Several products preferred and some required a mortar or shearing mixer. A few of the products could be mixed with a simple drill mixer with a paddle attachment. The mixing procedures will be detailed in the paragraphs that follow.

The time to opening varied amongst products. This will also be requested in a generalized timeframe at varying temperatures along with the curing procedures for each material.

Re-establishment of joints was an important topic of discussion during the installation. Some suppliers utilized foam board or cardboard or a combination thereof. Some suppliers requested that their patches be sawed. It was observed that during the installation the foam board or cardboard was difficult to use as it would tend to float in the material and require weighing down. Sawing time for some of the materials may have been too long to minimize the potential for cracking.

A milling machine was used to create the patch areas. The process of milling was more aggressive than anticipated which created much larger, both in width and depth, areas that would need patching. The patch was air blasted to remove the loose rubble left after the milling process. The patch was then sandblasted. It should be noted that not all patches were sandblasted which is detailed later in the report in the observations of each individual cell. A final cleaning with a traditional leaf blower was performed before material was placed in the patch. Most patches were sandblasted then cleaned with a high pressure air wand prior to filling. Specific procedures for each patch were documented by field personnel and will be included in the final report.

A typical patch layout is shown in Figure 9.1. Figures 9.2 through 9.20 depict specific patching layouts for each cell. Note that the location of the patch type varies from cell to cell. However, each cell contained each patch type. Refer to the abbreviations in the legend of Figure 9.1.

The patch layout for Cell 94001 (CTS, Rapid Set DOT Repair Mix) is shown in Figure 9.2 This material was a bagged product, weighing 55 lbs. Approximately 1 bucket of 0.375-inch granite chips were added to each bag in the mixer along with approximately 5 quarts of water per bag. The mixture was mixed for 3 minutes in a revolving drum mixer to provide the consistency desired. Then the mixture was placed into a wheel barrow and transported to the patches. Patches were pre-wetted prior to placing the mix.

Finishing was accomplished with traditional concrete tools. Foam board was used to re-establish joints and patches were cured with plastic sheeting.

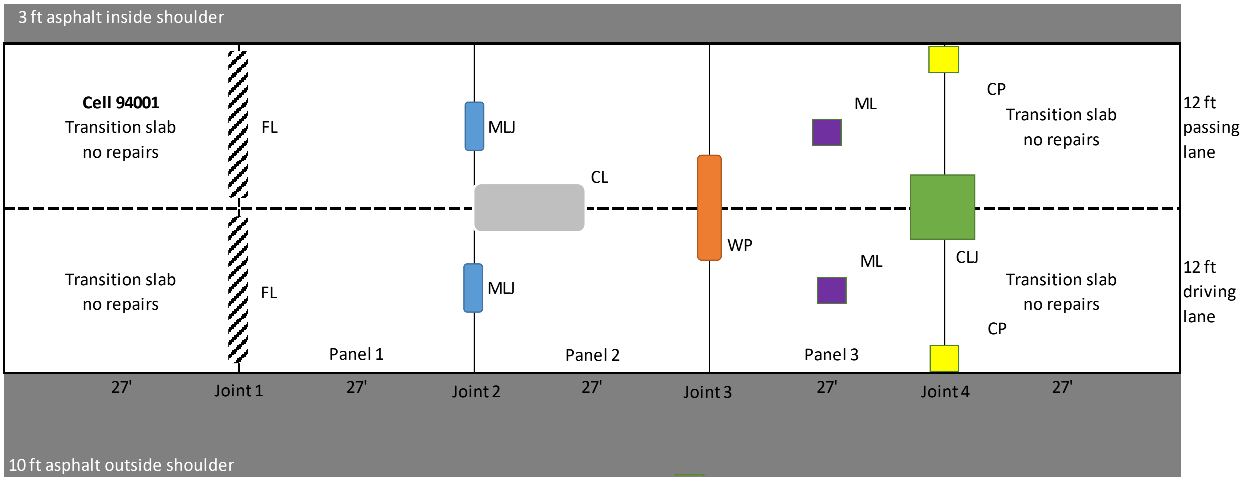


Figure 9.2 Patch layout for Cell 94001 – CTS, Rapid Set DOT Repair Mix.

Figure 9.3 shows the patching layout for Cell 94002 (SpecChem, RepCon 928). Each bag of material weighed 50 lbs. Approximately 2.5 quarts of water per bag were added to each bag in the mixer and mixed for 3 minutes in a revolving drum mixer. The mixture was then placed into a wheel barrow and transported to the patches. The material was finished with traditional concrete tools. The patches were pre-wetted before placing material. Foam board was used to re-establish some joints while others were sawed and patches were cured with plastic sheeting. Some cracking was noted in some patches the next day.

Two materials were used in Cell 94003, both provided by Western Material and Design. Cell 94003(A) utilized Western Material and Design, FasTrac 246 patch material, a product provided in 60 lb bags. The patching layout is shown in Figure 9.4. Approximately 2 quarts of water per bag were added to each bag in the mixer. The supplier utilized their own mixer which was a “screw” type mixer. The mixer attached to the front of a skid steer and was used to mix as well as place the concrete in the patches. The material was finished with traditional concrete tools. The patches were pre-wetted before placing material. Foam board was used to re-establish some joints while others were sawed. The patches were cured with plastic sheeting.

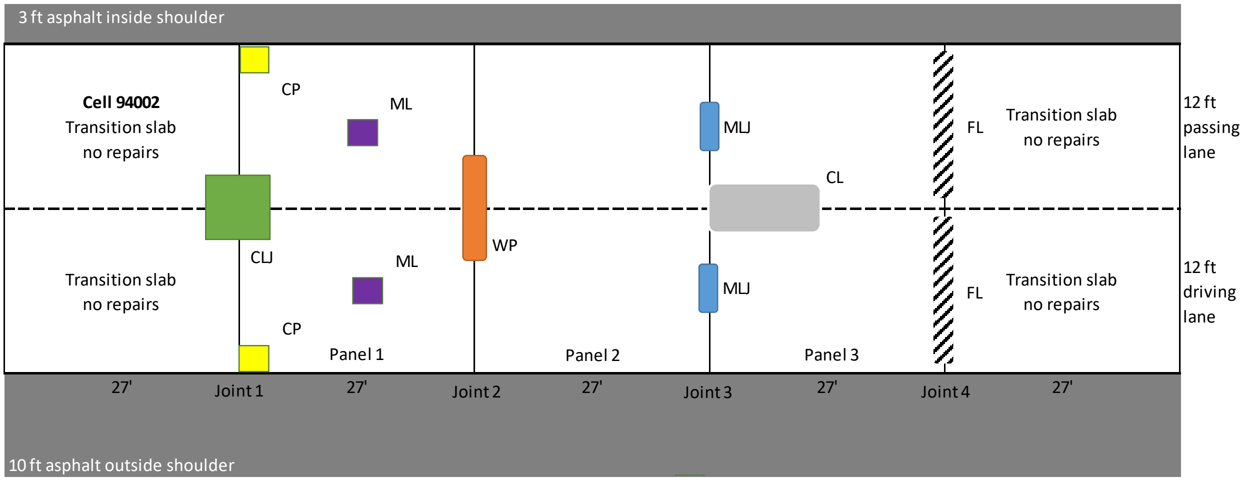


Figure 9.3 Patch layout for Cell 94002 – SpecChem, RepCon 928.

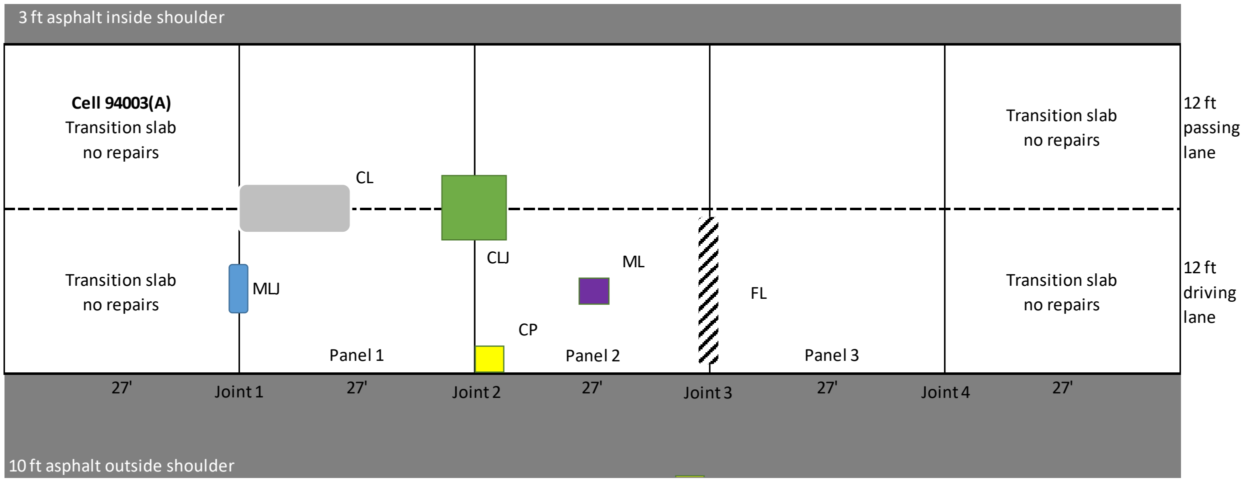


Figure 9.4 Patch layout for Cell 94003(A) – Western Material and Design, FasTrac 246.

Western Material and Design, CE 700 HPC is a 3 part system and was placed in Cell 94003(B). See Figure 9.5 for the patch layout. Before mixing, the material was heated to approximately 70 to 80 °F. Part A (4 gallons) and Part B (4 gallons) were poured into the mixer and mixed for approximately 3 minutes then Part C (aggregate, 12-50 lb bags) was added. The supplier utilized their own mixer which was a “screw” type mixer. The mixer attached to the front of a skid steer and was used to mix as well as place the concrete in the patches. The material was finished with traditional concrete tools. Aggregate was broadcast onto the surface for added slip resistance. Cardboard was used to re-establish joints. The patches were not pre-wetted and were not cured.

The patch layout for Cell 94004 is shown in Figure 9.6. Patching material used in this cell (D.S. Brown, PaveSaver Polymeric Concrete Patch) was a 3 part system. Part A (1 gallon gray liquid) and Part B (1 gallon clear liquid) were poured into a 5 gallon bucket and mixed with a drill mixer having a paddle attachment for 3 minutes. Care was taken to minimize the introduction of air into the mixture; the paddle mixer was placed towards the bottom of the bucket. Part C (aggregate, 2-50 lb bags) was then placed into the bucket while mixing continued until the desired consistency was achieved. The material was poured from the bucket into the patch. The material was finished with traditional concrete tools. Cardboard was used to re-establish joints. The patches were not pre-wetted and were not cured.

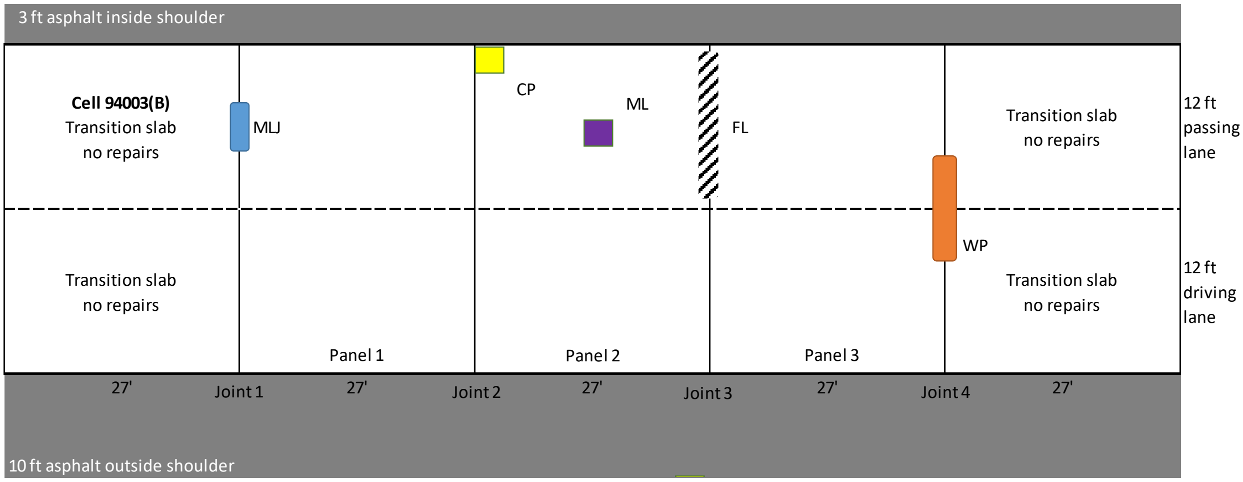


Figure 9.5 Patch layout for Cell 94003(B) – Western Material and Design, CE 700 HPC.

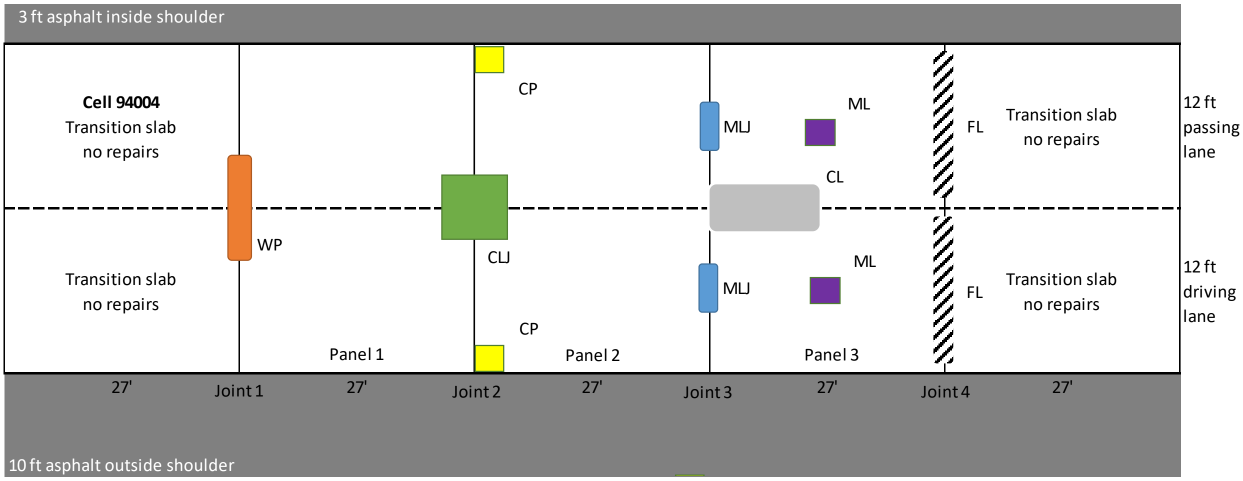


Figure 9.6 Patch layout for Cell 94004 – D.S. Brown, PaveSaver Polymeric Concrete Patch.

Cell 94005, shown in Figure 9.7, was patched with Willamette Valley Company FastPatch. The material was a 3-part system entirely contained in a 5 gallon bucket. Part A (11 liters) and Part B (6 liters) were in separate packets inside the bucket while Part C (2.5 liters) was “loose” in the bucket. The mixing required a drill with a paddle attachment. Part A was added to Part C while mixing for 2 minutes then Part B was added while mixing for an additional 2 minutes. The material was poured from the bucket into the patch and finished with traditional concrete tools. Foam board was used to re-establish the joints. Aggregate was broadcast onto the surface for added slip resistance. The patches were not pre-wetted and were not cured.

Five Star, Rapid Surface Repair Easy Mix was a 3-part system and was the material placed in Cell 94006(A). See Figure 9.8 for the layout. Part A (1.21 liters) and Part B (1.21 liters) were poured into a 5 gallon bucket and mixed using a drill with paddle attachment for approximately 30 seconds. Part C (50 lb aggregate bag) was added and mixed until the desired consistency was achieved. The material was poured from the bucket into the patch. The material was finished with traditional concrete tools. The patches were heated with a propane torch before placing the material. It was observed that the patches were most likely too large for this material at least in the provided material sizes. Thus, the section was split into two with the supplier providing another product for Cell 94006(B). Setting time issues were noted; it was difficult to place the material in more than one lift as the previous lift typically hardened before the second lift could be mixed.

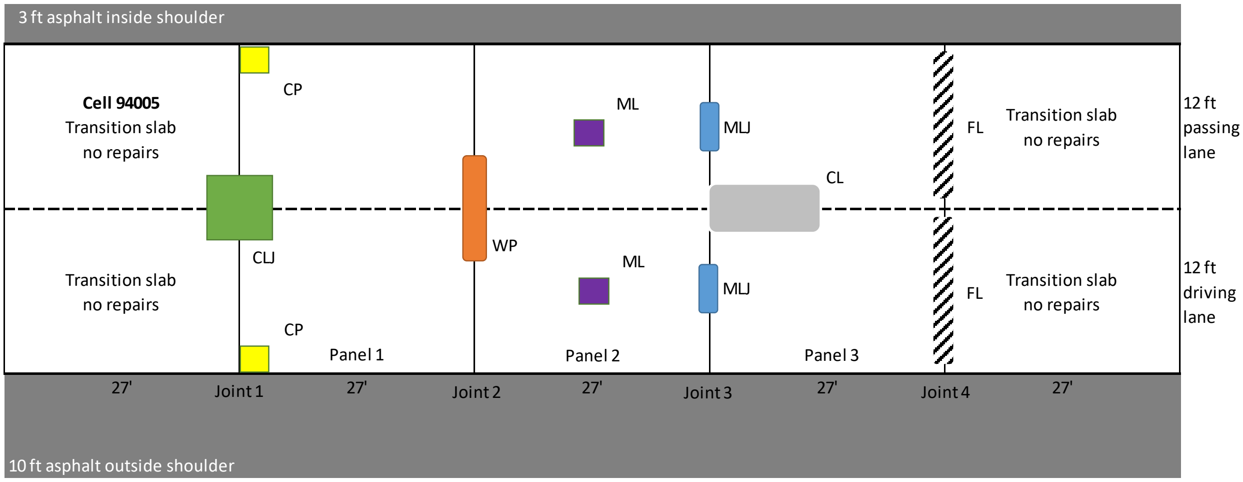


Figure 9.7 Patch layout for Cell 94005 – Willamette Valley Company, FastPatch.

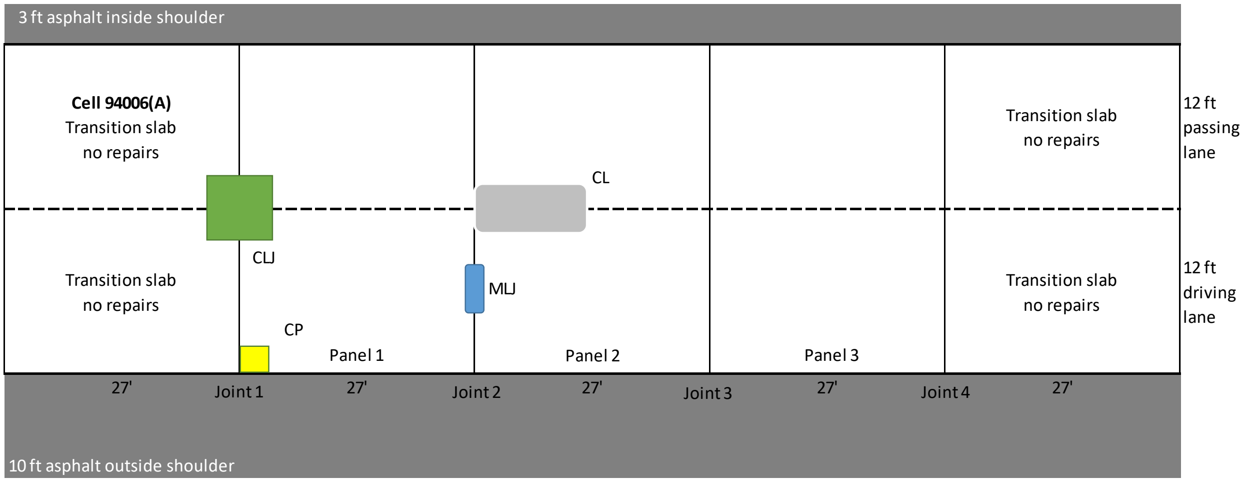


Figure 9.8 Patch layout for Cell 94006(A) – Five Star, Rapid Surface Repair Easy Mix.

Figure 9.9 shows the layout where Five Star, Rapid Surface Repair Epoxy Fix was placed. This material is a 3 part system. Patches were heated with a propane torch before placing the material. Then 0.375-inch granite chips were placed into the patch. The supplier utilized a dispensing system contained in a cargo van. Parts A and B were mixed together and then dispensed onto the granite chips. The mixture filled in the voids in the aggregate to fill the patch. Foam board was used to re-establish joints. Aggregate was broadcast onto the surface to provide texture. The patches were not cured.

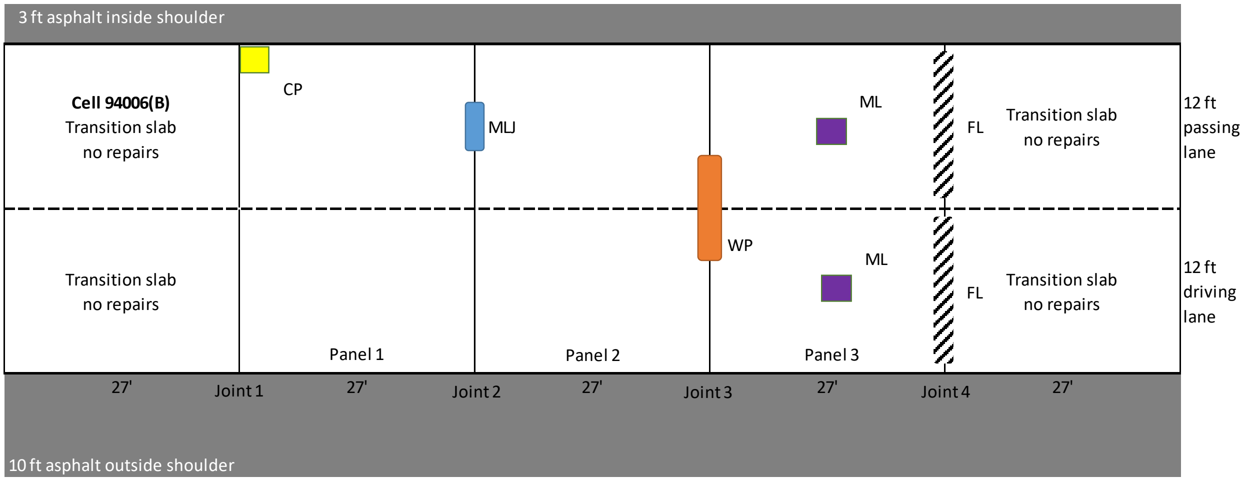


Figure 9.9 Patch layout for Cell 94006(B) – Five Star, Rapid Surface Repair Epoxy Fix.

The patching material placed in Cell 94007 was TCC Materials, ProSpec Concrete Patching Mix. Figure 9.10 shows the layout. This product material was provided in 50 lb bags. Approximately 3 quarts of water were added to the mixture per bag. The mixer required for this product was a paddle or mortar mixer. A revolving drum mixer was not suitable. Mixing continued for 2 to 3 minutes until the desired consistency was obtained. The mixture was then placed into a wheel barrow and transported to the patches. The material was finished with traditional concrete tools. Foam board was used to re-establish joints. The patches were pre-wetted before placing material and curing was completed using plastic sheets.

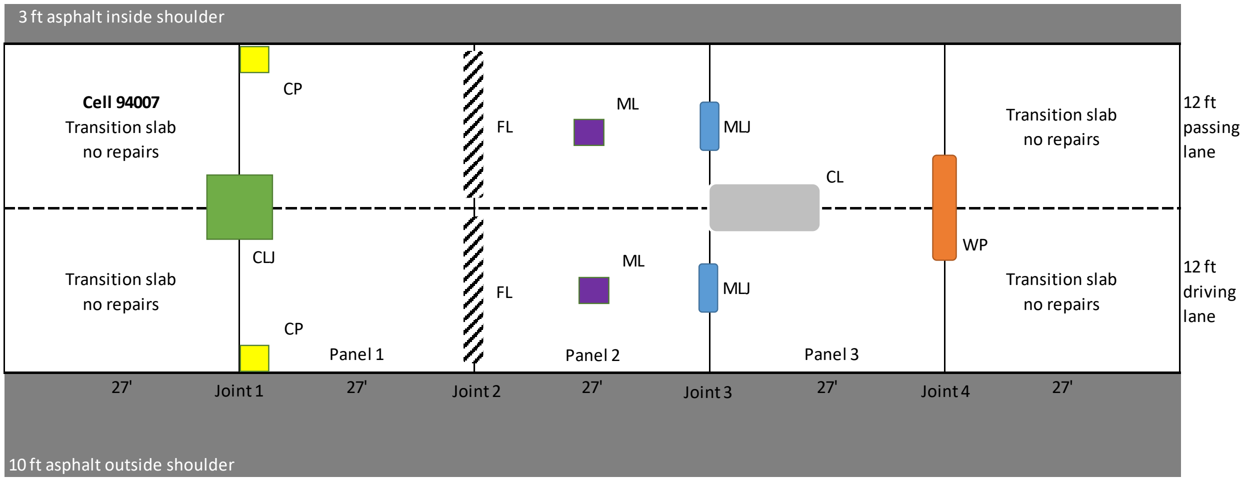


Figure 9.10 Patch layout for Cell 94007 TCC Materials, ProSpec Concrete Patching Mix.

TCC Materials, ProSpec Concrete Patching Mix was provided in 50 lb bags. This material was utilized in Cell 94008(A). Refer to Figure 9.11 for the patch layout. Approximately 3 quarts of water were added to the mixture per bag. The mixer required for this product was a paddle or mortar mixer. A revolving drum mixer was not suitable. In addition to the water, approximately 50 lbs of 0.375-inch granite chips were added per 3 bags of material. The granite was utilized to extend the product to complete patching for this cell. Mixing continued for 2 to 3 minutes until the desired consistency was obtained. The mixture was then placed into a wheel barrow and transported to the patches. The material was finished with traditional concrete tools. Foam board was used to re-establish joints. The patches were pre-wetted before placing material and curing was completed using plastic sheets.

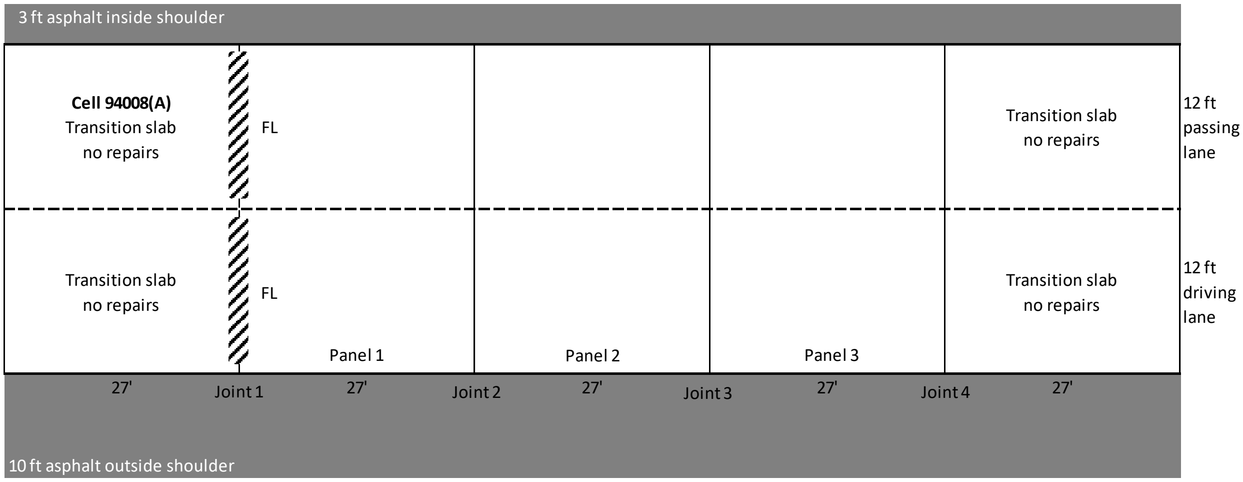


Figure 9.11 Patch layout for Cell 94008(A) TCC Materials, ProSpec Concrete Patching Mix.

Patch material placed in Cell 94008(B), Aqua Patch Road Materials, Aqua Patch, was delivered in 50 lb bags. There was no mixing or finishing required. The material was placed into the patch, water added, and tamped down. Figure 9.12 shows the patch layout for this cell.

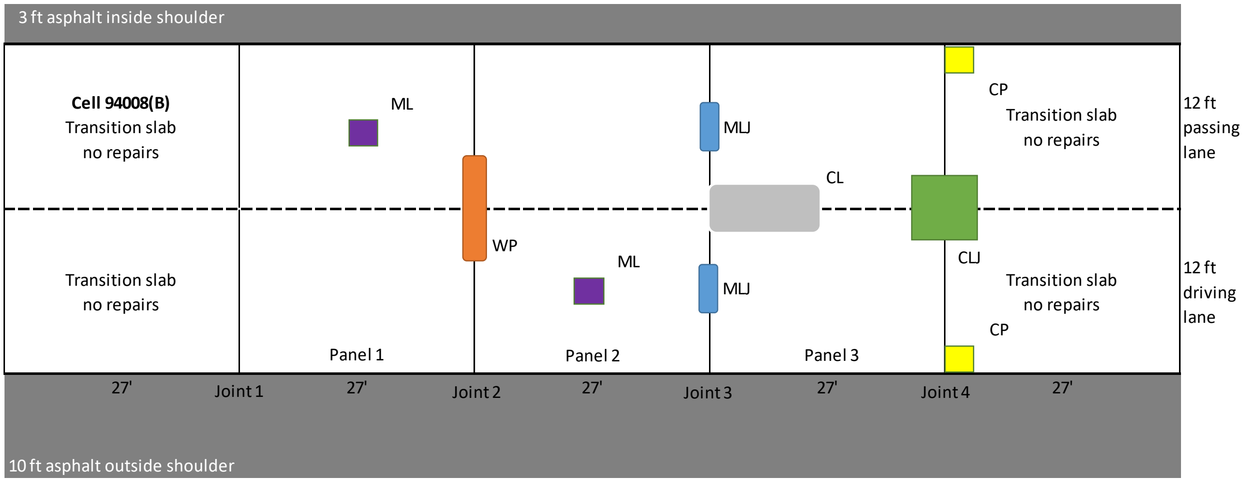


Figure 9.12 Patch layout for Cell 94008(B) Aqua Patch Road Materials, Aqua Patch.

Figure 9.13 depicts the patch layout for Cell 94009, which utilized Crafco, HP Concrete Cold Patch. Each bag of product weighed 50 lbs. The material was placed in 2-inch lifts. Each lift was compacted using a hand tamper. The final layer was placed approximately 0.5 inch above the top of the patch and hand tamped. There was no finishing of the material required. A bond breaker of cement was used on the surface. The supplier then proceeded to drive back and forth over the product for final compaction.

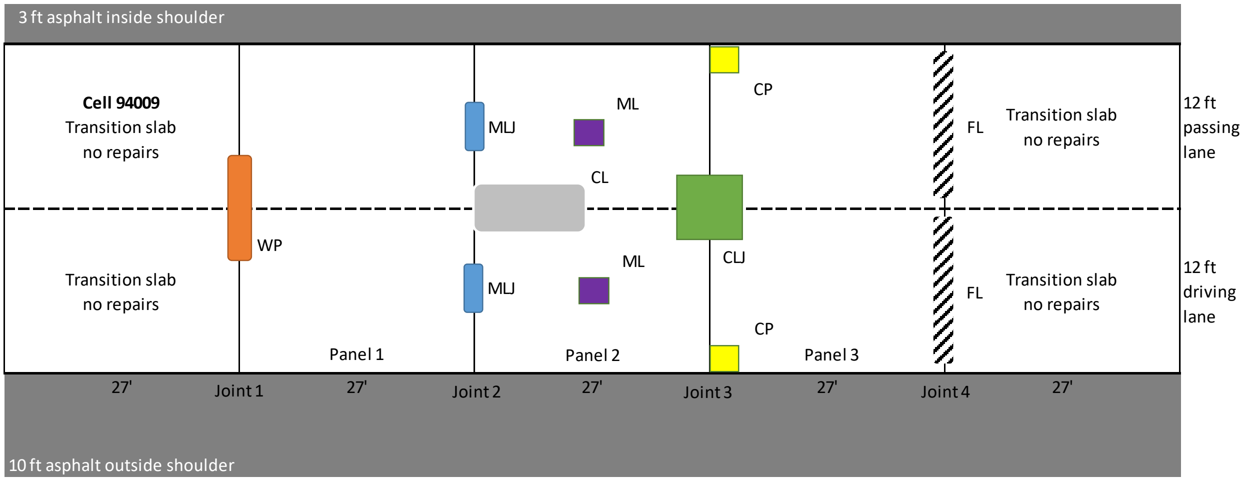


Figure 9.13 Patch layout for Cell 94009 – Crafco, HP Concrete Cold Patch.

Crafco, Techrete-TBR is a hot applied flexible mastic sealant and was the material placed in Cell 94010 shown in Figure 9.14. The material was in meltable bags, 35 lbs, and was heated and mixed in a Crafco melter to approximately 400 °F. The melter used in this application was a Crafco Patcher II. It was reported that most MnDOT districts have an approved melter that is used to apply other materials. A primer was applied to each patch and when dry, the material was placed in the patch. The melter was placed directly over the patch and the material moved down the chute into the patch. Edges were finished with a heated tool, similar to a float used for traditional concrete finishing. Finally, aggregate was broadcast onto the surface to provide texture.

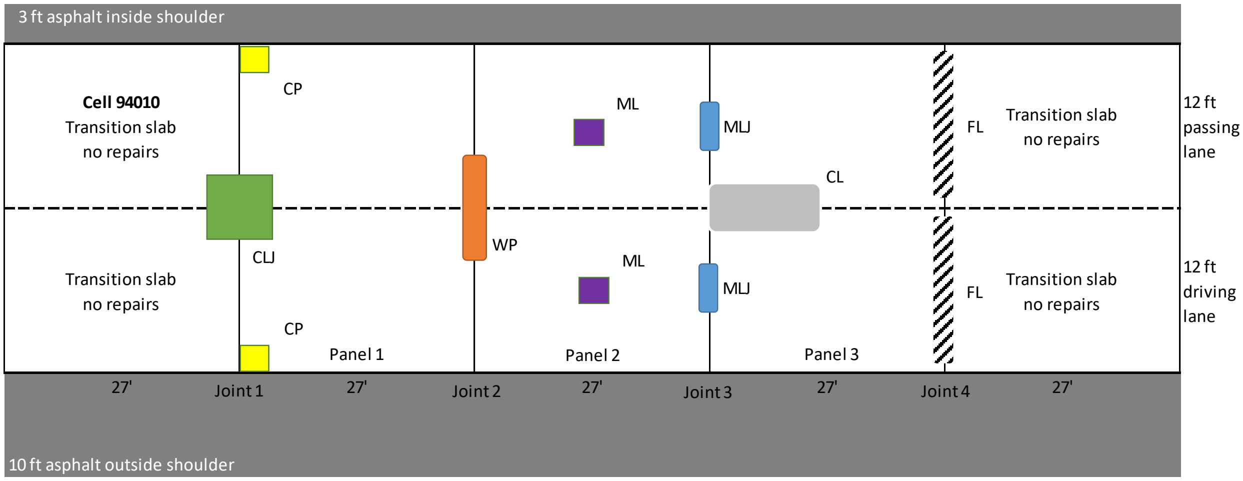


Figure 9.14 Patch layout for Cell 94010 – Crafco, Techrete-TBR.

Figure 9.15 shows the patch layout for Cell 94011 in which TCC, 3U18 Modified material was used. MnDOT Specification 3105 3U18 is a standard mixture for repairing concrete pavement. The material was a 50-lb bagged product. Water was added to the product until an approximate 10 inch slump was achieved continuing the mixing for approximately 6 minutes. A revolving drum mixer was utilized to mix the product. The mixture was then placed into a wheel barrow and transported to the patches. Patches were pre-wetted before placing the material. The material was finished with traditional concrete tools. Curing was completed using plastic sheets. After curing, patches were saw cut to re-stablish joints.

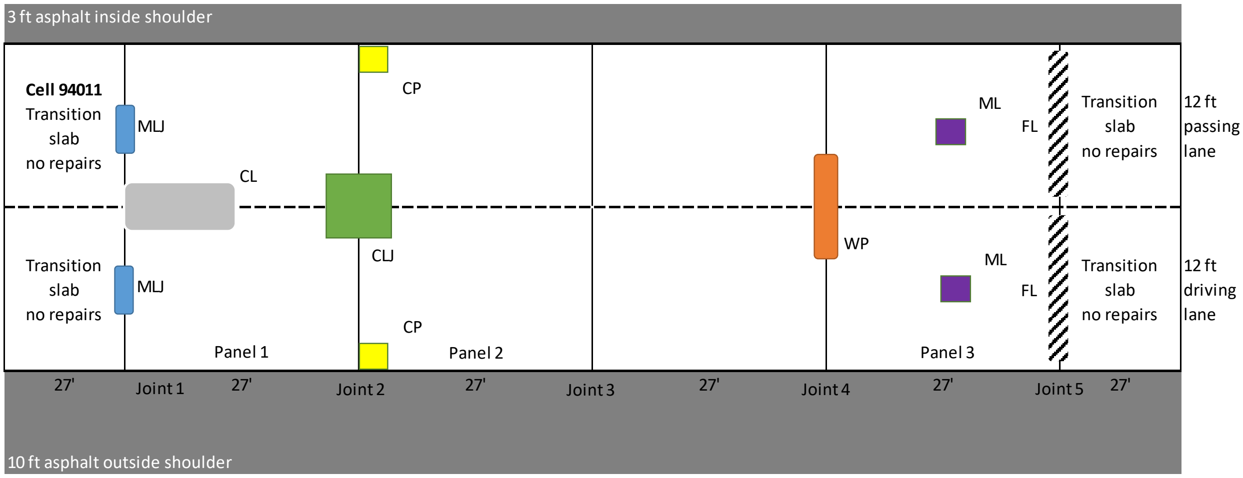


Figure 9.15 Patch layout for Cell 94011 – TCC, 3U18 Modified.

USG Ecofix, placed in Cell 94012, came in 50-lb bags. See Figure 9.16 for the patching layout. Approximately 32.5 lbs of 0.375-inch granite chips and approximately 2.25 quarts of water were added per bag. The mixture was mixed in a revolving drum mixer for 2 to 3 minutes until the desired consistency was obtained. The mixture was then placed into a wheel barrow and transported to the patches. The material was finished with traditional concrete tools. The patches were pre-wetted and saw cutting was utilized to re-establish the joints. The patches were cured with plastic sheets.

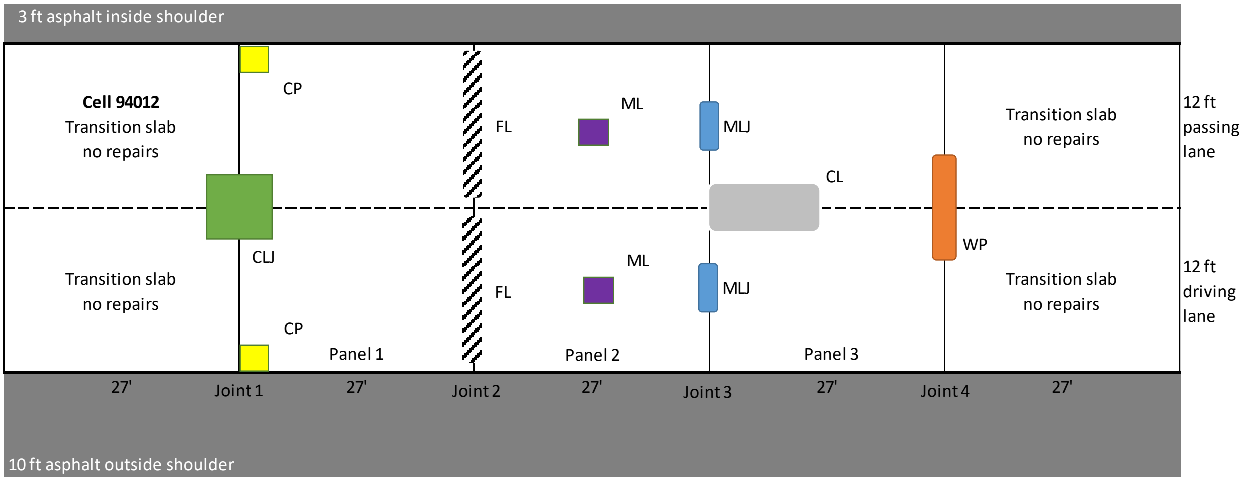


Figure 9.16 Patch layout for Cell 94012 – USG Ecofix.

The patch layout for Cell 94013(A) is shown in Figure 9.17. CTS Rapid Set DOT Repair Mix with Helix 5-25-Standard BA (Zinc Coated) fibers were used. This material was a bagged product, weighing 55 lbs, and was the same used in cell 94001. Approximately 1 bucket of 0.375-inch granite chips were added to each bag in the mixer along with approximately 5 quarts of water per bag. Helix zinc coated fibers were added to the mixture at the rate of 2 lbs per bag. Fibers were added to the granite chips and mixed before addition of the bagged product. Then the mixture was mixed for approximately 3 minutes in a revolving drum mixer to provide the consistency desired. The mixture was then placed into a wheel barrow and transported to the patches. Finishing was accomplished with traditional concrete tools. The patches were pre-wetted before placing material. Foam board was used to re-establish joints and patches were cured with plastic sheeting.

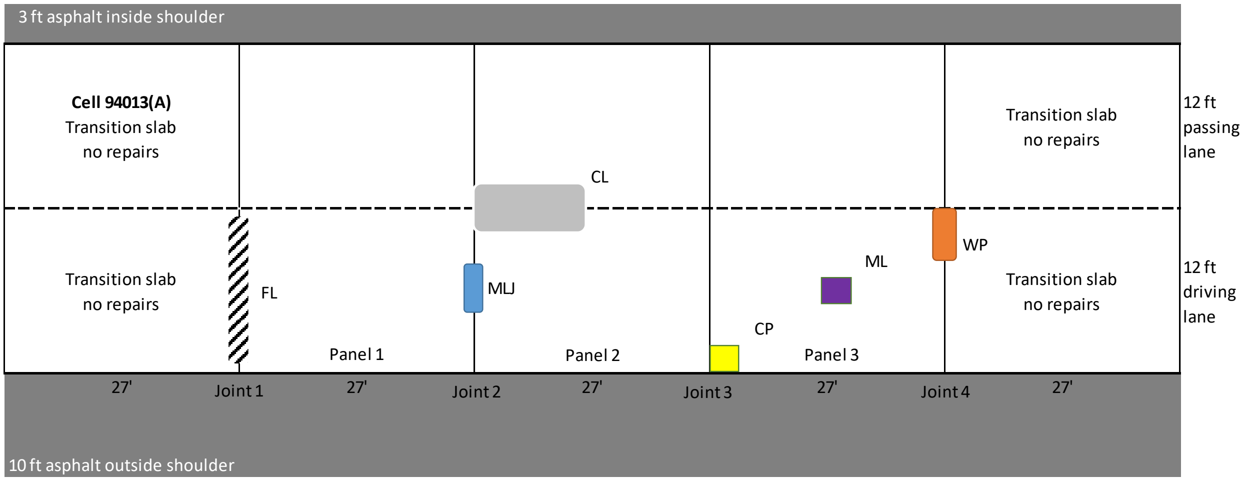


Figure 9.17 Patch layout for Cell 94013(A) – CTS, Rapid Set DOT Repair Mix and Helix 5-25-Standard BA (Zinc Coated).

Steel fibers were also utilized in Cell 94013(B); the layout is shown in Figure 9.18. The patch mix, CTS, Rapid Set DOT Repair Mix, is the same as used in Cell 94001. Reinforcement was provided with Helix 5-25-SS BA (Stainless Steel) fibers. Mixing and placement were accomplished in the same manner as Cell 94013(A).

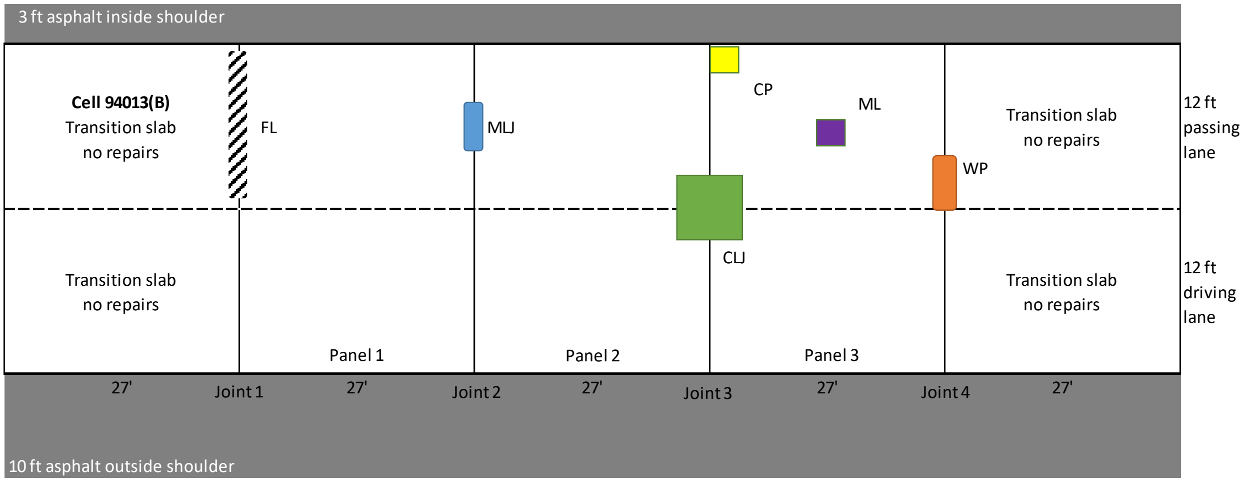


Figure 9.18 Patch layout for Cell 94013(B) – CTS, Rapid Set DOT Repair Mix and Helix 5-25-SS BA (Stainless Steel).

Patches in Cells 94014 and 94015 were completed with hot mix asphalt. See Figures 9.19 and 9.20 for the layouts. The mix was provided by District 3 and installed by MnROAD personnel. All patches were tack coated prior to mix placement. Compaction was achieved with a small drum roller.

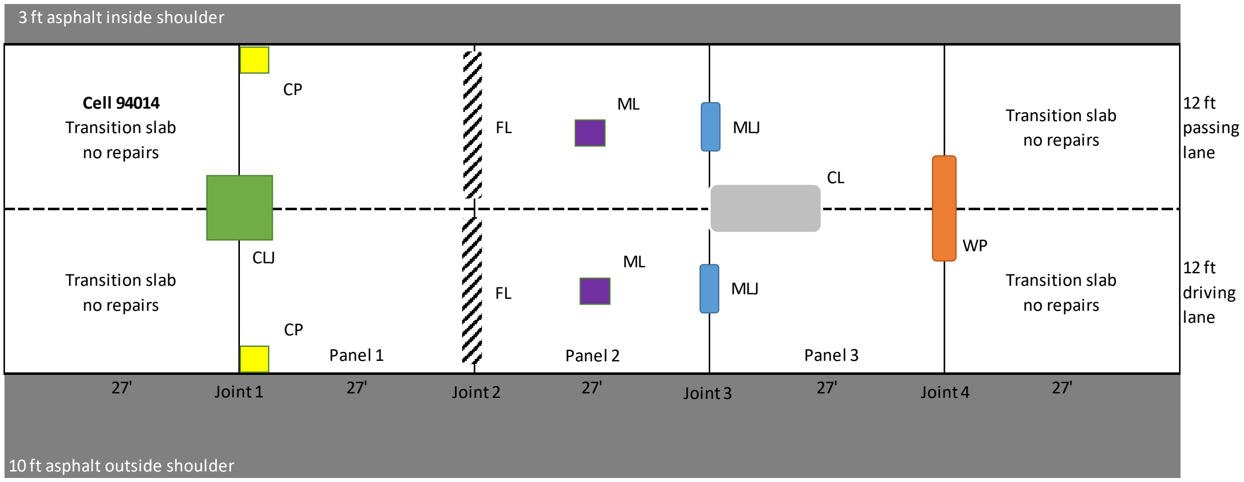


Figure 9.19 Patch layout for Cell 94014 – Hot Mix Asphalt (HMA).

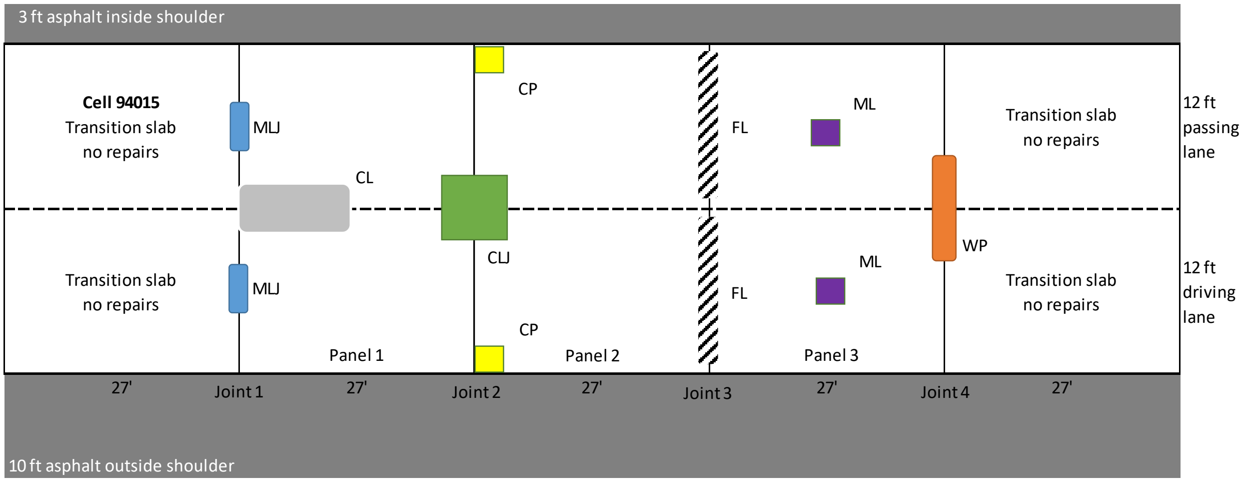


Figure 9.20 Patch layout for Cell 94015 – Hot Mix Asphalt (HMA).

9.4 SAMPLING AND TESTING

During the installation no materials samples were collected for testing. Some unmixed products were retained and are available in the MnDOT cold storage facility if future testing is needed.

9.5 SENSORS

No sensors were installed within these test sections.

CHAPTER 10: PERFORMANCE MONITORING

10.1 BACKGROUND

Performance monitoring over the life of the pavement section is a vital component of the NRRA experiments that were constructed during 2017. Performance monitoring includes surface monitoring, environmental monitoring (temperature, moisture, joint movement, and environmentally induced strain) and dynamic monitoring (FWD and embedded sensors). The prescribed monitoring for each cell has been tailored to the research objectives of each study. This section provides a general summary of the monitoring being conducted and the frequency. It is not intended to be a comprehensive review of each activity. Further documentation on each activity can be found at www.dot.state.mn.us/mnroad/data/index.html.

10.2 SURFACE CHARACTERISTICS MONITORING

Surface monitoring is comprised of visual distress surveys, automated distress and ride surveys, rutting, faulting measurements, warp and curl profiling, and friction measurements.

Visual surface distress surveys are conducted two times per year for all NRRA cells constructed. These surveys document the distress type, the severity, and extent or amount of each distress. Surveys are based on a modified LTPP Distress Manual method for both concrete and asphalt cells. The visual surface distress surveys are conducted less frequently than the automated distress surveys and will be used as a comparison to the automated surveys to verify the outputs of the automated surveys.

Rutting data has previously been collected at MnROAD using the Automated Laser Profile System (ALPS). Profile data have previously been collected three times per year using the Lightweight Inertial Surface Analyzer (LISA). Both the ALPS and LISA have been successfully used at MnROAD. These devices will continue to be utilized however work is currently being done to compare the data generated from the LISA and the ALPS with the data from a Pathways Services, Inc., Digital Inspection Vehicle (DIV). The DIV can be operated at much higher speeds and therefore can be run over then entire MnROAD network more frequently. In addition to the ability to collect distress and ride data more frequently, running the DIV does not require traffic diversions off of the MnROAD tests cells.

The DIV used at MnROAD is shown in Figure 10.1. This vehicle collects distress (amount of cracking/ rutting, extent, severity, etc.) and ride data (roughness, texture, etc.). The DIV collects data on the NRRA cells every two weeks during the spring, summer, and fall months (temperatures need to be greater than 40° F with clear conditions to operate vehicle). After data collection, post-processing is conducted to convert the raw images/ measurements to MnDOT’s Pavement Management classifications for a summary of the overall pavement condition. The DIV and post-processing techniques are identical to the vehicles and processing used by MnDOT’s Pavement Management.

Figure 10.1 MnDOT digital inspection vehicle (DIV).

On concrete sections, a MnROAD modified version of the Georgia Faultmeter is used to measure the amount of faulting between panels. Faulting measurements are taken at least twice per year (typically in the spring and fall) but the frequency may be increased if an increase in faulting is noticed.

Friction is measured several times per year using a Dynatest locked-wheel skid trailer. Testing is done with a standard ribbed tire with the pavement in wet condition (water supplied by testing trailer) according to ASTM E274.

The warp and curl of select concrete test cells is periodically characterized through surface profile measurements using the ALPS2 device. A photo of the device can be seen in Figure 10.2.

10.3 ENVIRONMENTAL AND STATIC RESPONSE SENSORS

Environmental conditions are captured by thermocouples and moisture sensors within the pavement sections as well as by external weather stations. Environmental response sensors measure the movement within the pavement structure that result from the environmentally induced responses. These sensors are used in concrete cells and include joint opening sensors and vibrating wire strain gauges.

MnROAD has two weather stations to record environmental conditions at the site. The stations record air temperature, atmospheric pressure, precipitation, relative humidity, solar radiation, wind speed, and wind direction.

Figure 10.2 MnROAD ALPS2 device measures changes in concrete pavement surface shape due to warp and curl.

Thermocouples are used to measure temperatures within the pavement structure. The thermocouples are fabricated at MnROAD using type T (copper/constantan) thermocouple extension cable. A precision of ±1°C has been achieved with these thermocouples. Prior to construction, a thermocouple array was assembled using a PVC pipe to keep the sensors at fixed, prescribed depths within the pavement structure. The exact depths at which the temperatures are measured vary by individual cell and research objective. Temperatures are read and recorded on 15 minute intervals. This type of sensor is referred to as “TC” on MnROAD data tables.

Volumetric water content gauges were installed in cells 127, 138, 185, 186, 188, 189, and 138. Decagon 5TE gauges were used. These gauges output the volumetric water content (calculated based on dielectric permittivity), the electrical conductivity, and temperature (measured with an internal thermistor). A Decagon 5TE gauge is shown in Figure 10.3. These gauges were installed at varying depths at the same x-y location to measure the moisture content with depth. Data are recorded from these gauges on 15 minute intervals. This type of sensor is referred to as “EC” on MnROAD data tables.

Figure 10.3 Decagon 5TE volumetric moisture content sensor.

Environmentally induced strain responses in concrete pavements are measured by a vibrating wire strain gauge. These gauges consist of a pre-tensioned wire encased in a protective steel tube with the wire anchored at flanges on either end of the steel tube and a resin encapsulated electro-mechanical exciter/reader externally attached to the steel tube. As the concrete slab expands and contracts with temperature changes, the tension in the wire is changed and thus the frequency that the wire vibrates at is also changed. These gauges allow only for a relative comparison of strain over time as the initial strain and frequency are a function of the initial concrete set conditions. A typical installation setup of the VW gauges is shown in Figure 10.4. It can be seen that the gauges are fixed to wooden dowels to keep them near the top and bottom of the concrete slab during placement. The measured resonant frequency and calculated strain are recorded every 15 minutes. This type of sensor is referred to as “VW” on MnROAD data tables.

A new type of sensing system was developed by MnROAD researchers to directly measure the movement that occurs at the joints between concrete panels. A linear potentiometer (Midori America Corporation / LP-20FBS-3/ conductive plastic contact potentiometer) is used to measure the change in transverse joint opening due to changing environmental conditions. The spring potentiometer is inserted into a conduit on one side of the joint, and spans across to an angle-iron bracket mounted on the opposing side of the joint, as shown in Figure 10.5. As the panels expand and contract with temperature, the sensor piston will compress and expand, resulting in a change is resistance. The output data are in mV with 0 at full extension and ~5000 mV at full compression. Data are recorded on 15 minute increments. This type of sensor is referred to as “JO” on MnROAD data tables.

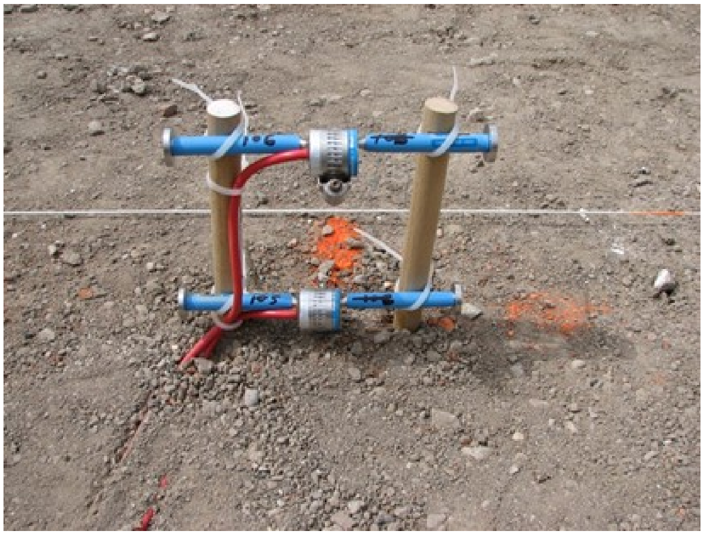


Figure 10.4 Vibrating wire strain gauges.

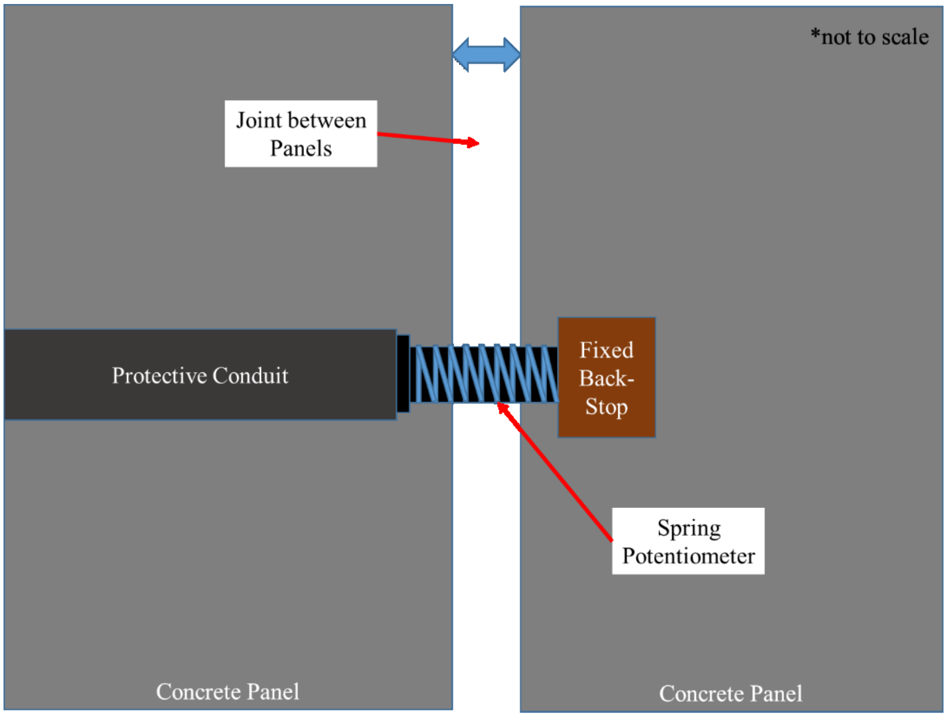


Figure 10.5 Schematic diagram of a joint opening (JO) sensor.

10.4 DYNAMIC PAVEMENT RESPONSE MONITORING

Dynamic pavement response data are collected four times per year (early spring, late spring, summer and fall) to measure how the pavements are responding to vehicle loads over time. The dynamic sensors included in asphalt cells are the pressure cells and asphalt strain gauges. Dynamic responses in concrete cells are captured by the concrete strain gauges. The MnROAD truck, loaded to 80,000 lbs total weight, is used for vehicle load testing data generated on NRRA cells. Load responses are captured at targeted truck speeds of 5 and 40 mph. The testing time (morning or afternoon) is varied to ensure that load responses are gathered at a variety of pavement temperatures. The falling weight deflectometer (FWD) is periodically used to assess both the structural condition of the pavements as well as the response of dynamic load sensors in asphalt cells.

Soil pressure gauges, referred to as PG in MnROAD data tables, are used to measure the vertical pressure in the base and subgrade layers. The pressure gauge consists of two 6 inch diameter plates that are welded together and filled with liquid. A transducer measures the change in pressure from the liquid between the steel plates. Figure 10.6 shows a pressure gauge during installation on Cell 188. In previous MnROAD research, pressure gauges have been used in both concrete and asphalt cells. During the 2017 NRRA construction, pressure gauges were only used in asphalt cells. Pressure gauges were installed in the outside wheel path to measure the resulting pressure under loading. Geokon 3500 Dynamic Soil Pressure Cells with Ashkroft K1 Transducers were used in all cases.

Figure 10.6 Dynamic pressure cells (PG) installed in a MnROAD section.

Geophones were installed by UTEP researchers in each of the recycled aggregate base cells (185, 186, 188, and 189). Four geophones were installed in each cell at depths of approximately 2 feet below surface of subgrade (horizontal and vertical), at 6 inches below the surface of the subgrade, and at 6 inches below the surface of the granular base. The geophones directly measure the velocity along an axis at their given location. The velocity is converted into a displacement value. These sensors were included to provide another measurement to be used during the calibration and validation of the intelligent compaction research being conducted in these cells. Figure 10.7 shows a geophone during installation.

Figure 10.7 Geophone installed in a MnROAD section.

Asphalt dynamic strain gauges are used to measure the dynamic strain response under vehicle loading at the bottom of asphalt layers. These gauges are referred to in the MnROAD system as LE (longitudinal) or TE (transverse) depending on the orientation to the direction of traffic. Asphalt strain gauges have successfully been used at MnROAD since the original MnROAD construction in 1993. Geocomp Model ASG 152 strain gauges were installed during 2017 NRRA construction. These H shaped sensors, shown in Figure 10.8, utilize a full bridge strain transducer mounted to a nylon rod with steel anchors at either end. ASGs were placed near the outside wheel path and were oriented in both the transverse and longitudinal directions. Strain response data will be collected during loading from the MnROAD vehicle four times per year.

Concrete dynamic strain gauges were installed to measure the dynamic response to loading. The gauges used were Tokyo Sokki Kenkyujo model PML-60 and consists of an electrical resistance (quarter-bridge) strain gauge that is hermetically sealed between two thin resin plates. An individual gauge is 150 mm long, 13 mm wide, and 5 mm thick. These gauges are typically placed at the top and bottom of the concrete, except where total thickness only allowed for gauges to be installed at the bottom of the concrete. The typical gauge setup is shown in Figure 10.9. Wooden dowels and thin set wires were used to hold the gauges in position during paving. Data will be collected from these sensors during dynamic load testing of concrete cells. These gauges are referred to as “CE” in MnROAD data tables.

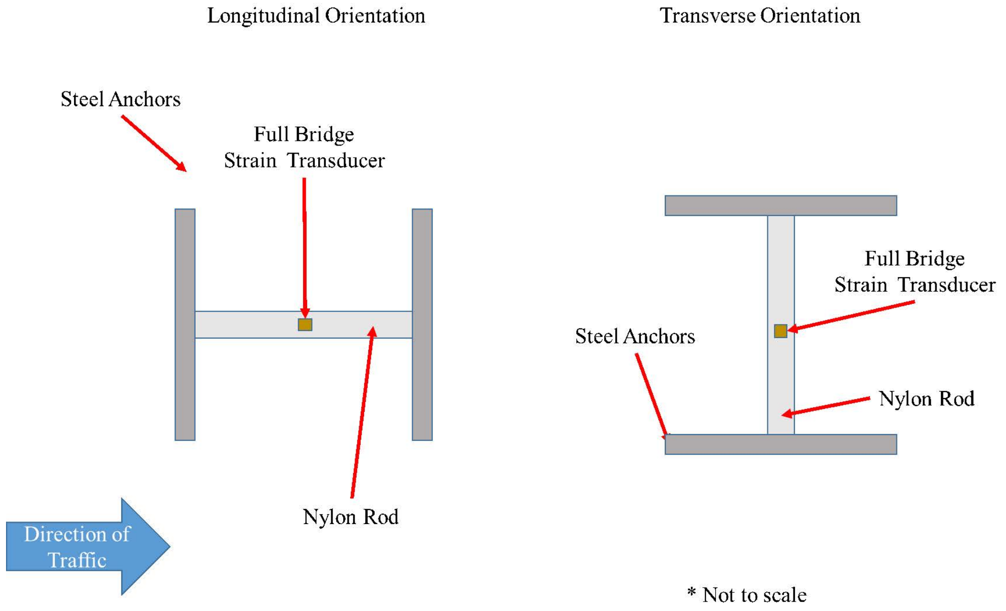


Figure 10.8 Schematic of asphalt dynamic strain gauges used at MnROAD 2017 construction.

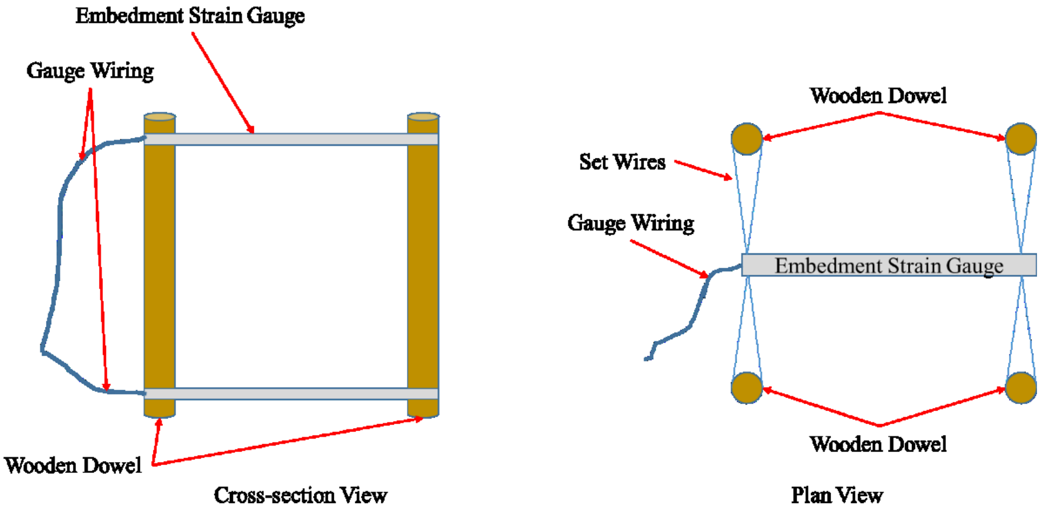


Figure 10.9 Schematic of concrete dynamic load strain gauge used in MnROAD 2017 construction.

FWD testing is conducted throughout the spring, summer, and fall months at MnROAD to characterize the structural response of the pavement. The exact FWD testing protocol is different for concrete and asphalt cells and is often adjusted to address the specific research needs of the study. As previously mentioned, FWD testing is also performed over dynamic sensors during dynamic data collection. Due to locking of the joints, concrete joint load transfer efficiency testing is not conducted during the summer months.

CHAPTER 11: SUMMARY AND FUTURE WORK

The 2017 construction season at MnROAD saw construction of 35 new and unique test sections. These sections, designed to address National Road Research Alliance high-priority research topics, were conceived and planned by NRRA Rigid, Flexible, Preventive Maintenance, and Geotechnical Team Members.

During construction numerous field and laboratory tests were performed, and many pieces of data were collected. Over the next five years, MnROAD personnel will continue to monitor the performance of the sections. The data generated from these efforts will be utilized by researchers performing work for each specific project.

Interested readers are encouraged to stay up-to-date with the latest results of each MnROAD NRRA research teams at: http://www.dot.state.mn.us/mnroad/nrra/structureandteams/index.html.

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APPENDIX A

NRRA TEST SECTION CONSTRUCTION DATES

Table A.1 NRRA test section construction dates.

EXISTING CELL	REMOVAL (pave)	REMOVAL (base)	REMOVAL (subg)	NEW CELL	SUBG.	BASE	PAVE (1st)	PAVE (2nd)
1	7/26/2017	NA	NA	101	NA	NA	7/28/2017	7/31/2017
				201	NA	NA	8/11/2017	NA
15	7/26/2017	NA	NA	115	NA	NA	7/28/2017	7/31/2017
				215	NA	NA	8/11/2017	NA
27	7/25/2017	7/31/2017	8/11/2017	127	8/15/2017	8/19/2017	8/21/2017	9/19/2017
				227				
28				328	8/28/2017	8/31/2017	9/19/2017	9/19/2017
				428				
				528				
				628				
				728	8/15/2017	8/19/2017	8/21/2017	9/19/2017
85	7/10/2017	7/11/2017	7/14/2017	185	7/14/2017	8/10/2017	8/21/2017	9/19/2017
86				186				
88	6/19/2017	7/12/2017		188				
89	6/12/2017			189				
33	7/25/2017	NA	NA	133	NA	8/18/2017	9/6/2017	NA
33/34		NA	NA	233		8/16/2017		
34/35		NA	NA	135		8/16/2017	9/19/2017	
35		NA	NA	235		8/18/2017		
NA	NA	NA	NA	983	NA	NA	NA	NA
				984		NA	10/18/2017	
				985		NA	10/14/2017	
				986		NA	10/12/2017	
				987		NA	10/13/2017	10/18/2017
				988		NA		10/14/2017
				989		NA		10/17/2017
				990		NA		
				991		NA		10/18/2017
				992		NA	10/17/2017	
				993		NA	10/14/2017	
				994*	9/21/2017	9/21/2017	10/18/2017	NA
				995	NA	NA	10/12/2017	

Table A.1 NRRA test section construction dates, cont.

EXISTING CELL	REMOVAL (pave)	REMOVAL (base)	REMOVAL (subg)	NEW CELL	SUBG.	BASE	PAVE (1st)	PAVE (2nd)
24	6/12/2017	6/12/2017	NA	124-624	6/20/2017	6/21/2017	7/5/2017	NA
38	6/12/2017	6/21/2017	7/10/2017	138	NA	7/13/2017	7/14/2017	NA
				238			7/14/2017	
39	6/12/2017	6/19/2017		139	6/30/2017	7/13/2017	7/17/2017	NA
				239			7/17/2017	
305	6/6/2017	NA	NA	705**	NA	8/31/2017	9/5/2017	NA
405				805**		8/31/2017	9/5/2017	
306	6/6/2017	6/8/2017	6/8/2017	506	6/9/2017	6/20/2017	6/26/2017	NA
				606			6/27/2017	
406				706			6/29/2017	
				806			6/30/2017	

APPENDIX B

AS-BUILT CONCRETE PAVEMENT THICKNESS DATA

The following tables summarize as-built pavement thickness data as determined using the MITSCAN-T2 device.

Table B.1 As-built pavement thickness data – Cells 124-624.

CELL	STATION	LANE	OFFSET (ft)	THICKNESS (in.)
124	15850.00	OUTSIDE	10	6.5
124	15850.00	INSIDE	-10	6.3
224	15950.00	OUTSIDE	10	6.1
224	15950.00	INSIDE	-10	5.8
224	16050.00	OUTSIDE	10	-
224	16050.00	INSIDE	-10	5.9
324	16150.00	OUTSIDE	10	6.1
324	16150.00	INSIDE	-10	6.1
424	16250.00	OUTSIDE	10	6.4
424	16250.00	INSIDE	-10	6.0
524	16350.00	OUTSIDE	10	6.6
524	16350.00	INSIDE	-10	6.5

Table B.2 As-built pavement thickness data – Cells 138/238.

CELL	STATION	LANE	OFFSET (ft)	THICKNESS (in.)
138	9200.00	INSIDE	10	8.4
138	9200.00	OUTSIDE	-10	7.9
138	9275.00	INSIDE	10	8.2
138	9275.00	OUTSIDE	-10	7.5
138	9350.00	INSIDE	10	7.7
138	9350.00	OUTSIDE	-10	7.2
238	9450.00	INSIDE	10	7.8
238	9450.00	OUTSIDE	-10	7.7
238	9525.00	INSIDE	10	7.9
238	9525.00	OUTSIDE	-10	7.5
238	9675.00	INSIDE	10	8.7
238	9675.00	OUTSIDE	-10	8.1

Table B.3 As-built pavement thickness data – Cell 139/239.

CELL	STATION	LANE	OFFSET (ft)	THICKNESS (in.)
139	9750.00	INSIDE	10.0	3.1
139	9750.00	OUTSIDE	-10.0	3.1
139	9850.00	INSIDE	10.0	2.6
139	9850.00	OUTSIDE	-10.0	3.1
139	9950.00	INSIDE	10.0	2.9
139	9950.00	OUTSIDE	-10.0	3.0
239	10050.00	INSIDE	10.0	3.7
239	10050.00	OUTSIDE	-10.0	3.7
239	10150.00	INSIDE	10.0	3.8
239	10150.00	OUTSIDE	-10.0	3.8
239	10200.00	INSIDE	10.0	3.5
239	10200.00	OUTSIDE	-10.0	3.8

Table B.4 As-built pavement thickness data – Cells 506-806.

CELL	STATION	LANE	OFFSET (ft)	THICKNESS (in.)
506	113239.00	DRIVING	-2.9	5.2
506	113266.00	DRIVING	-8.7	5.1
506	113294.00	PASSING	7.5	5.0
606	113404.00	PASSING	3.8	6.2
606	113426.00	DRIVING	-2.3	6.4
706	113462.00	PASSING	5.0	4.6
706	113475.00	DRIVING	-10.0	4.8
706	113475.00	PASSING	10.0	5.7
706	113509.00	DRIVING	-10.0	5.2
706	113509.00	PASSING	10.0	5.2
706	113543.00	DRIVING	-10.0	5.2
706	113543.00	PASSING	10.0	5.0
706	113565.00	DRIVING	-6.0	5.0
806	113581.00	PASSING	3.5	5.7
806	113610.00	DRIVING	-10.0	5.9
806	113610.00	PASSING	10.0	5.5
806	113644.00	DRIVING	-10.0	5.6
806	113644.00	PASSING	10.0	5.6
806	113648.00	DRIVING	-5.2	5.5
806	113674.00	PASSING	8.9	5.3
806	113678.00	DRIVING	-10.0	5.6
806	113678.00	PASSING	10.0	5.1
806	113698.00	DRIVING	-4.9	4.8

Table B.5 As-built pavement thickness data – Cells 705/805.

CELL	STATION	LANE	OFFSET (ft)	THICKNESS (in.)
705	112918.00	PASSING	12.6	6.3
705	112920.00	DRIVING	-1.9	6.9
705	112930.00	PASSING	-10	6.9
705	112930.00	DRIVING	-4	6.9
705	112953.00	DRIVING	-4	5.9
705	112953.00	PASSING	6	5.8
705	112954.00	DRIVING	-10	5.9
705	112954.00	PASSING	11	5.9
705	112975.00	DRIVING	-10	5.2
705	112975.00	DRIVING	-4	5.3
705	113007.00	DRIVING	-6.4	4.9
705	113028.00	PASSING	3.8	5.2
805	113090.00	PASSING	11	4.8
805	113094.00	PASSING	3	4.9
805	113107.00	DRIVING	-8.9	5.1
805	113112.00	DRIVING	-5	5.1
805	113112.00	PASSING	5	5.2
805	113114.00	DRIVING	-9	5.2
805	113114.00	PASSING	11	5.3
805	113143.00	DRIVING	-11	4.6
805	113143.00	DRIVING	-4	4.7
805	113159.00	PASSING	9.6	5.2

APPENDIX C

AS-BUILT SENSOR LOCATIONS

Table C.1 As-built locations of sensors installed in fiber-reinforced sections.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
139	CE001	9918.92	9.2	2.5
139	CE002	9920.85	2.8	2.5
139	CE003	9924.97	9.0	2.5
139	CE004	9927.16	3.0	2.5
139	JO001	9930.09	9.1	1.5
139	JO002	9935.84	9.0	1.5
139	JO003	9942.01	9.2	1.5
139	JO004	9947.99	9.1	1.5
139	TC001	9936.85	3.0	0.5
139	TC002	9936.85	3.0	1.5
139	TC003	9936.85	3.0	2.5
139	TC004	9936.85	3.0	3.5
139	VW001	9939.02	9.1	2.5
139	VW002	9939.24	3.1	2.5
139	VW003	9945.09	9.1	2.5
139	VW004	9945.03	3.1	2.5
239	CE001	9979.08	9.1	3.5
239	CE002	9981.05	3.1	3.5
239	CE003	9985.12	9.1	3.5
239	CE004	9987.09	3.0	3.5
239	JO001	10002.04	9.1	2.0
239	JO002	10007.87	9.1	2.0
239	JO003	10013.98	9.1	2.0
239	JO004	10019.97	9.2	2.0
239	TC001	10013.50	-11.5	0.5
239	TC002	10013.50	-11.5	1.5
239	TC003	10013.50	-11.5	2.5
239	TC004	10013.50	-11.5	3.5
239	TC005	10011.09	-8.9	0.5
239	TC006	10011.09	-8.9	1.0
239	TC007	10011.09	-8.9	3.5
239	TC008	10011.09	-8.9	4.5
239	TC009	10011.09	-8.9	9.5
239	TC010	10011.09	-8.9	12.0
239	TC011	10011.09	-8.9	14.0
239	TC012	10011.09	-8.9	24.0
239	TC013	10011.09	-8.9	36.0
239	TC014	10011.09	-8.9	48.0
239	TC015	10011.09	-8.9	60.0
239	TC016	10011.09	-8.9	72.0
239	VW001	10011.00	9.0	3.5
239	VW002	10010.87	3.1	3.5
239	VW003	10017.03	9.2	3.5
239	VW004	10017.02	3.1	3.5
705	CE001	112956.05	-13.1	0.8
705	CE002	112956.05	-13.1	4.5
705	CE003	112957.94	-8.9	0.8
705	CE004	112957.94	-8.9	4.5
705	CE005	112968.09	-13.1	0.8
705	CE006	112968.09	-13.1	4.5
705	CE007	112970.00	-8.8	0.8
705	CE008	112970.00	-8.8	4.5
705	JO001	112934.96	-5.9	2.5
705	JO002	112947.01	-6.0	2.5
705	JO003	112958.98	-5.8	2.5
705	JO004	112970.92	-5.9	2.5
705	TC001	112936.54	-13.6	0.5
705	TC002	112936.54	-13.6	2.5
705	TC003	112936.54	-13.6	4.5
705	TC004	112936.54	-13.6	5.5
705	TC005	112936.54	-13.6	8.8
705	TC006	112936.54	-13.6	12.0
705	TC007	112936.54	-13.6	13.0
705	TC008	112936.54	-13.6	16.0
705	VW001	112929.08	-7.1	0.8
705	VW002	112929.08	-7.1	4.5
705	VW003	112934.02	-8.9	0.8
705	VW004	112934.02	-8.9	4.5

Table C.1 As-built locations of sensors installed in fiber-reinforced sections, cont.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
705	VW005	112940.91	-7.1	0.8
705	VW006	112940.91	-7.1	4.5
705	VW007	112946.00	-8.9	0.8
705	VW008	112946.00	-8.9	4.5
805	CE001	113096.78	-10.8	0.8
805	CE002	113096.78	-10.8	4.5
805	CE003	113096.76	-10.0	0.8
805	CE004	113096.76	-10.0	4.5
805	CE005	113109.15	-10.4	0.8
805	CE006	113109.15	-10.4	4.5
805	CE007	113109.10	-9.8	0.8
805	CE008	113109.10	-9.8	4.5
805	JO001	113102.93	-7.9	2.5
805	JO002	113115.08	-7.7	2.5
805	JO003	113127.04	-7.9	2.5
805	JO004	113139.10	-8.0	2.5
805	TC001	113120.94	-8.2	0.5
805	TC002	113120.94	-8.2	2.5
805	TC003	113120.94	-8.2	4.5
805	TC004	113120.94	-8.2	5.5
805	TC005	113120.94	-8.2	8.8
805	TC006	113120.94	-8.2	12.0
805	TC007	113120.94	-8.2	13.0
805	TC008	113120.94	-8.2	24.0
805	TC009	113120.94	-8.2	36.0
805	TC010	113120.94	-8.2	48.0
805	TC011	113120.94	-8.2	60.0
805	TC012	113120.94	-8.2	72.0
805	VW001	113120.74	-10.3	0.8
805	VW002	113120.74	-10.3	4.5
805	VW003	113120.83	-9.8	0.8
805	VW004	113120.83	-9.8	4.5
805	VW005	113133.10	-10.6	0.8
805	VW006	113133.10	-10.6	4.5
805	VW007	113133.11	-10.0	0.8
805	VW008	113133.11	-10.0	4.5
506	CE001	113278.02	-9.3	0.8
506	CE002	113278.02	-9.3	4.5
506	CE003	113283.63	-9.0	0.8
506	CE004	113283.63	-9.0	4.5
506	JO001	113275.15	-8.9	2.5
506	JO002	113281.16	-8.9	2.5
506	JO003	113286.98	-8.9	2.5
506	VW001	113284.11	-3.1	0.8
506	VW002	113284.11	-3.1	4.5
506	VW003	113284.03	-9.0	0.8
506	VW004	113284.03	-9.0	4.5
606	CE001	113386.01	-8.8	0.8
606	CE002	113386.01	-8.8	4.5
606	CE003	113392.00	-9.1	0.8
606	CE004	113392.00	-9.1	4.5
606	JO001	113389.02	-9.0	2.5
606	JO002	113394.99	-9.1	2.5
606	JO003	113400.93	-8.9	2.5
606	TC001	113397.21	-3.1	0.5
606	TC002	113397.21	-3.1	2.5
606	TC003	113397.21	-3.1	4.5
606	TC004	113397.21	-3.1	5.5
606	TC005	113397.21	-3.1	12.0
606	TC006	113397.21	-3.1	15.0
606	TC007	113397.21	-3.1	18.0
606	TC008	113397.21	-3.1	24.0
606	TC009	113397.21	-3.1	36.0
606	TC010	113397.21	-3.1	48.0
606	TC011	113397.21	-3.1	60.0
606	TC012	113397.21	-3.1	72.0
606	TC013	113400.17	-11.6	0.5
606	TC014	113400.17	-11.6	2.5

Table C.1 As-built locations of sensors installed in fiber-reinforced sections, cont.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
606	TC015	113400.17	-11.6	4.5
606	TC016	113400.17	-11.6	5.5
606	TC017	113400.17	-11.6	8.8
606	TC018	113400.17	-11.6	12.0
606	TC019	113400.17	-11.6	15.0
606	TC020	113400.17	-11.6	18.0
606	VW001	113397.85	-2.8	0.8
606	VW002	113397.85	-2.8	4.5
606	VW003	113397.91	-9.1	0.8
606	VW004	113397.91	-9.1	4.5
706	CE001	113548.04	-9.0	0.8
706	CE002	113548.04	-9.0	4.5
706	CE003	113554.16	-9.0	0.8
706	CE004	113554.16	-9.0	4.5
706	JO001	113545.14	-9.2	2.5
706	JO002	113551.07	-9.1	2.5
706	JO003	113556.93	-9.1	2.5
706	VW001	113554.08	-3.1	0.8
706	VW002	113554.08	-3.1	4.5
706	VW003	113554.65	-9.1	0.8
706	VW004	113554.65	-9.1	4.5
806	CE001	113607.76	-9.3	0.8
806	CE002	113607.76	-9.3	4.5
806	CE003	113613.97	-8.5	0.8
806	CE004	113613.97	-8.5	4.5
806	JO001	113605.11	-9.1	2.5
806	JO002	113611.03	-9.0	2.5
806	JO003	113617.03	-9.1	2.5
806	VW001	113607.88	-3.2	0.8
806	VW002	113607.88	-3.2	4.5
806	VW003	113608.21	-9.2	0.8
806	VW004	113608.21	-9.2	4.5

Table C.2 As-built locations of sensors installed in optimized mix design sections.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
138	CE001	9353.95	11.2	0.8
138	CE002	9353.95	11.2	7.5
138	CE003	9360.01	11.0	0.8
138	CE004	9360.01	11.0	7.5
138	CE005	9368.98	10.8	0.8
138	CE006	9368.98	10.8	7.5
138	CE007	9374.97	10.8	0.8
138	CE008	9374.97	10.8	7.5
138	EC001	9390.73	-5.7	1.0
138	EC002	9390.73	-5.7	4.0
138	EC003	9389.90	-6.0	12.0
138	EC004	9389.90	-6.0	24.0
138	EC005	9389.90	-6.0	30.0
138	TC001	9396.13	-11.4	0.5
138	TC002	9396.13	-11.4	1.0
138	TC003	9396.13	-11.4	4.0
138	TC004	9396.13	-11.4	7.5
138	TC005	9396.13	-11.4	8.5
138	TC006	9396.13	-11.4	10.5
138	TC007	9396.13	-11.4	12.0
138	TC008	9396.13	-11.4	14.0
138	TC009	9390.80	-6.2	0.5
138	TC010	9390.80	-6.2	1.0
138	TC011	9390.80	-6.2	4.0
138	TC012	9390.80	-6.2	7.5
138	TC013	9390.80	-6.2	8.5
138	TC014	9390.80	-6.2	12.0
138	TC015	9390.80	-6.2	14.0
138	TC016	9390.80	-6.2	24.0
138	TC017	9390.80	-6.2	36.0
138	TC018	9390.80	-6.2	48.0
138	TC019	9390.80	-6.2	60.0
138	TC020	9390.80	-6.2	72.0
138	VW001	9384.13	11.0	0.8
138	VW002	9384.13	11.0	7.5
138	VW003	9390.16	6.0	0.8
138	VW004	9390.16	6.0	7.5
238	CE001	9474.07	10.9	0.8
238	CE002	9474.07	10.9	7.5
238	CE003	9480.08	10.9	0.8
238	CE004	9480.08	10.9	7.5
238	CE005	9489.07	10.9	0.8
238	CE006	9489.07	10.9	7.5
238	CE007	9495.02	11.1	0.8
238	CE008	9495.02	11.1	7.5
238	VW001	9459.00	10.9	0.8
238	VW002	9459.00	10.9	7.5
238	VW003	9464.98	6.0	0.8
238	VW004	9464.98	6.0	7.5

Table C.3 As-built locations of sensors installed in early opening to traffic sections.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
124	CE001	15877.51	-11.1	0.5
124	CE002	15877.51	-11.1	5.5
124	CE003	15883.51	-9.1	0.5
124	CE004	15883.51	-9.1	5.5
124	CE005	15892.60	-11.0	0.5
124	CE006	15892.60	-11.0	5.5
124	CE007	15898.57	-9.0	0.5
124	CE008	15898.57	-9.0	5.5
124	TC001	15907.53	6.2	0.3
124	TC002	15907.53	6.2	1.0
124	TC003	15907.53	6.2	3.0
124	TC004	15907.53	6.2	5.5
124	TC005	15907.53	6.2	9.0
124	TC006	15907.53	6.2	12.0
124	TC007	15907.53	6.2	18.0
124	TC008	15907.53	6.2	24.0
124	TC009	15907.53	6.2	36.0
124	TC010	15907.53	6.2	48.0
124	TC011	15907.53	6.2	60.0
124	TC012	15907.53	6.2	72.0
124	VW001	15907.66	-6.1	0.8
124	VW002	15907.66	-6.1	5.5
124	VW003	15913.51	-8.9	0.8
124	VW004	15913.51	-8.9	5.5
224	CE001	15967.66	-11.0	0.5
224	CE002	15967.66	-11.0	5.5
224	CE003	15973.59	-9.0	0.5
224	CE004	15973.59	-9.0	5.5
224	CE005	15982.59	-11.0	0.5
224	CE006	15982.59	-11.0	5.5
224	CE007	15988.57	-8.9	0.5
224	CE008	15988.57	-8.9	5.5
224	TC001	16003.70	11.6	0.3
224	TC002	16003.70	11.6	1.0
224	TC003	16003.70	11.6	3.0
224	TC004	16003.70	11.6	5.5
224	VW001	15997.74	-6.0	0.8
224	VW002	15997.74	-6.0	5.5
224	VW003	16003.70	-8.8	0.8
224	VW004	16003.70	-8.8	5.5
324	CE001	16087.55	-10.9	0.5
324	CE002	16087.55	-10.9	5.5
324	CE003	16093.54	-8.8	0.5
324	CE004	16093.54	-8.8	5.5
324	CE005	16102.68	-11.0	0.5
324	CE006	16102.68	-11.0	5.5
324	CE007	16108.57	-9.0	0.5
324	CE008	16108.57	-9.0	5.5
324	TC001	16124.04	11.2	0.3
324	TC002	16124.04	11.2	1.0
324	TC003	16124.04	11.2	3.0
324	TC004	16124.04	11.2	5.5
324	VW001	16117.43	-5.7	0.8
324	VW002	16117.43	-5.7	5.5
324	VW003	16123.55	-8.9	0.8
324	VW004	16123.55	-8.9	5.5
424	CE001	16192.54	-11.0	0.5
424	CE002	16192.54	-11.0	5.5
424	CE003	16198.46	-9.0	0.5
424	CE004	16198.46	-9.0	5.5
424	CE005	16207.73	-11.0	0.5
424	CE006	16207.73	-11.0	5.5
424	CE007	16213.53	-8.8	0.5
424	CE008	16213.53	-8.8	5.5
424	TC001	16348.76	11.5	0.3
424	TC002	16348.76	11.5	1.0
424	TC003	16348.76	11.5	3.0
424	TC004	16348.76	11.5	5.5
424	VW001	16342.44	-6.1	0.8
424	VW002	16342.44	-6.1	5.5
424	VW003	16348.61	-9.0	0.8
424	VW004	16348.61	-9.0	5.5

Table C.4 As-built locations of sensors installed in cold-central plant recycling sections.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
133	TC001	6530.50	-13.5	0.3
133	TC002	6530.50	-13.5	0.8
133	TC003	6530.50	-13.5	2.5
133	TC004	6530.50	-13.5	4.5
133	TC005	6528.96	-7.1	4.0
133	TC006	6528.96	-7.1	4.5
133	TC007	6528.96	-7.1	6.0
133	TC008	6528.96	-7.1	11.0
133	TC009	6528.96	-7.1	16.0
133	TC010	6528.96	-7.1	18.0
133	TC011	6528.96	-7.1	24.0
133	TC012	6528.96	-7.1	30.0
133	TC013	6528.96	-7.1	36.0
133	TC014	6528.96	-7.1	48.0
133	TC015	6528.96	-7.1	60.0
133	TC016	6528.96	-7.1	72.0
235	LE001	7698.00	11.2	4.0
235	LE002	7698.08	8.8	4.0
235	PG001	7695.18	8.8	12.0
235	PG002	7705.30	8.9	12.0
235	TC001	7705.00	-13.5	0.3
235	TC002	7705.00	-13.5	1.0
235	TC003	7705.00	-13.5	3.0
235	TC004	7705.00	-13.5	5.0
235	TC005	7704.61	-6.2	4.5
235	TC006	7704.61	-6.2	5.0
235	TC007	7704.61	-6.2	6.5
235	TC008	7704.61	-6.2	11.5
235	TC009	7704.61	-6.2	16.5
235	TC010	7704.61	-6.2	18.5
235	TC011	7704.61	-6.2	24.5
235	TC012	7704.61	-6.2	30.5
235	TC013	7704.61	-6.2	36.5
235	TC014	7704.61	-6.2	48.5
235	TC015	7704.61	-6.2	60.5
235	TC016	7704.61	-6.2	72.5
235	TE001	7702.06	11.3	4.0
235	TE002	7702.12	8.8	4.0

Table C.5 As-built locations of sensors installed in recycled aggregate base sections.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
185	EC001	16538.81	-5.8	5.0
185	EC002	16538.81	-5.8	14.0
185	EC003	16538.81	-5.8	17.0
185	EC004	16538.81	-5.8	20.5
185	GP001	-	-	-
185	PG001	16526.83	-8.9	23.5
185	PG002	16526.83	-8.9	15.0
185	TC001	16538.51	-6.4	2.8
185	TC002	16538.51	-6.4	3.8
185	TC003	16538.51	-6.4	9.3
185	TC004	16538.51	-6.4	14.8
185	TC005	16538.51	-6.4	15.8
185	TC006	16538.51	-6.4	18.3
185	TC007	16538.51	-6.4	19.3
185	TC008	16538.51	-6.4	23.8
185	TC009	16538.51	-6.4	35.8
185	TC010	16538.51	-6.4	47.8
185	TC011	16538.51	-6.4	59.8
185	TC012	16538.51	-6.4	71.8
186	EC001	16678.91	-5.6	5.0
186	EC002	16678.91	-5.6	14.0
186	EC003	16678.91	-5.6	17.0
186	EC004	16678.91	-5.6	20.5
186	GP001	-	-	-
186	LE001	16672.04	-11.3	3.0
186	LE002	16672.03	-8.9	3.0
186	PG001	16667.23	-9.7	27.7
186	PG002	16667.23	-9.7	15.0
186	TC001	16678.52	-6.3	3.0
186	TC002	16678.52	-6.3	4.0
186	TC003	16678.52	-6.3	9.5
186	TC004	16678.52	-6.3	15.0
186	TC005	16678.52	-6.3	16.0
186	TC006	16678.52	-6.3	18.5
186	TC007	16678.52	-6.3	19.5
186	TC008	16678.52	-6.3	24.0
186	TC009	16678.52	-6.3	36.0
186	TC010	16678.52	-6.3	48.0
186	TC011	16678.52	-6.3	60.0
186	TC012	16678.52	-6.3	72.0
186	TE001	16667.93	-11.3	3.0
186	TE002	16668.00	-8.7	3.0
188	EC001	17111.75	-4.8	5.0
188	EC002	17111.75	-4.8	14.0
188	EC003	17111.75	-4.8	17.0
188	EC004	17111.75	-4.8	20.5
188	GP001	-	-	-
188	LE001	17110.89	-11.2	3.0
188	LE002	17110.85	-8.8	3.0
188	PG001	17105.92	-8.9	20.1
188	PG002	17105.92	-8.9	15.0
188	TC001	17111.53	-5.5	3.0
188	TC002	17111.53	-5.5	4.0
188	TC003	17111.53	-5.5	9.5
188	TC004	17111.53	-5.5	15.0
188	TC005	17111.53	-5.5	16.0

Table C.5 As-built locations of sensors installed in recycled aggregate base sections, cont.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
188	TC006	17111.53	-5.5	18.5
188	TC007	17111.53	-5.5	19.5
188	TC008	17111.53	-5.5	24.0
188	TC009	17111.53	-5.5	36.0
188	TC010	17111.53	-5.5	48.0
188	TC011	17111.53	-5.5	60.0
188	TC012	17111.53	-5.5	72.0
188	TE001	17107.03	-11.3	3.0
188	TE002	17107.05	-8.8	3.0
189	EC001	17306.24	-4.7	5.0
189	EC002	17306.24	-4.7	14.0
189	EC003	17306.24	-4.7	17.0
189	EC004	17306.24	-4.7	20.5
189	PG001	17287.07	-9.2	28.0
189	PG002	17287.07	-9.2	15.0
189	TC001	17306.11	-5.3	3.0
189	TC002	17306.11	-5.3	4.0
189	TC003	17306.11	-5.3	9.5
189	TC004	17306.11	-5.3	15.0
189	TC005	17306.11	-5.3	16.0
189	TC006	17306.11	-5.3	18.5
189	TC007	17306.11	-5.3	19.5
189	TC008	17306.11	-5.3	24.0
189	TC009	17306.11	-5.3	36.0
189	TC010	17306.11	-5.3	48.0
189	TC011	17306.11	-5.3	60.0
189	TC012	17306.11	-5.3	72.0

Table C.6 As-built locations of sensors installed in large aggregate subbase sections.

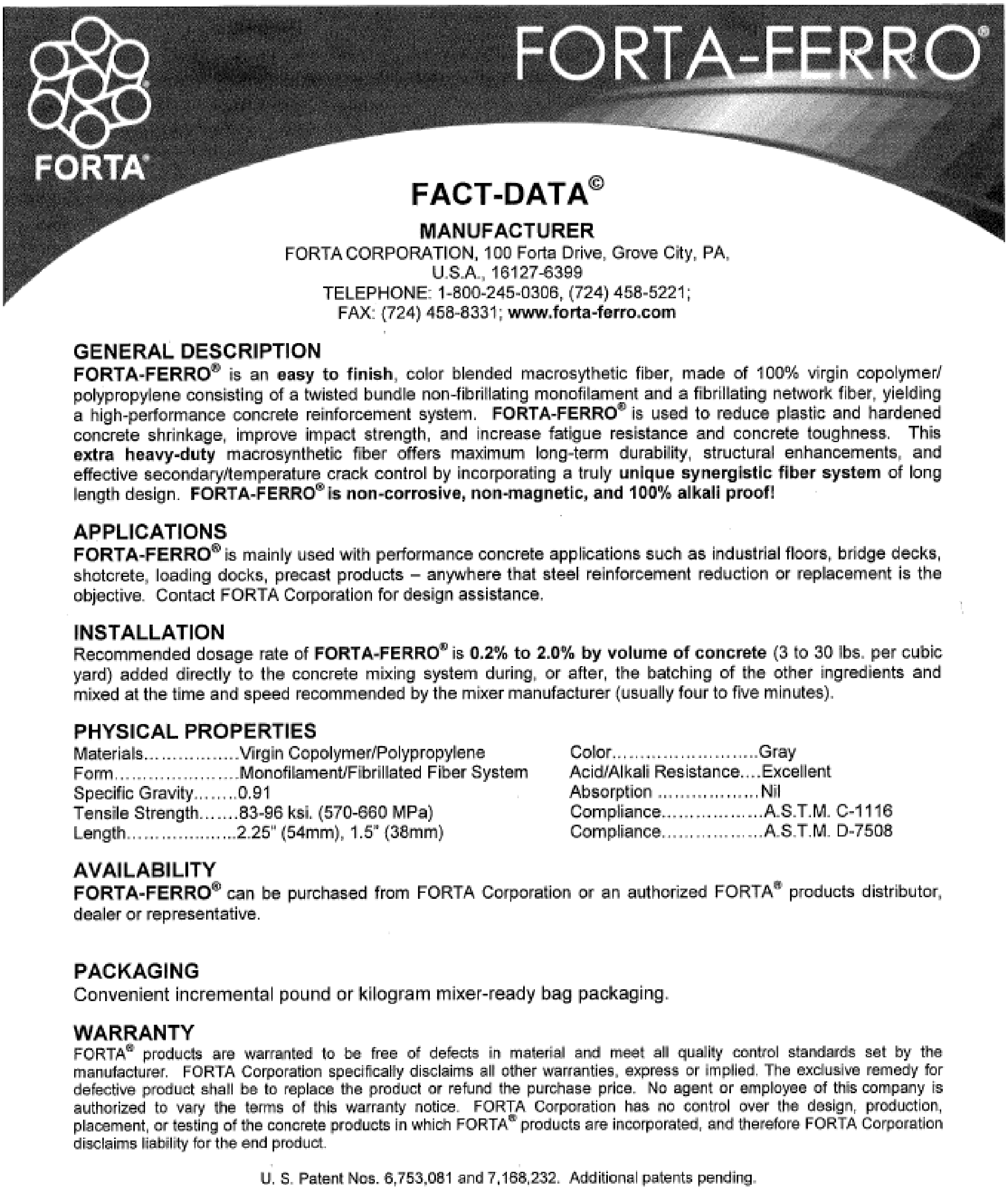
CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
127	EC001	17569.00	-11.0	6.5
127	EC002	17569.00	-11.0	29.0
127	EC003	17569.00	-11.0	36.0
127	PG001	17604.96	-8.5	8.5
127	PG002	17595.10	-8.6	8.5
127	TC001	17569.00	-11.5	3.0
127	TC002	17569.00	-11.5	4.0
127	TC003	17569.00	-11.5	6.5
127	TC004	17569.00	-11.5	9.0
127	TC005	17569.00	-11.5	10.0
127	TC006	17569.00	-11.5	12.0
127	TC007	17569.00	-11.5	18.0
127	TC008	17569.00	-11.5	24.0
127	TC009	17569.00	-11.5	36.0
127	TC010	17569.00	-11.5	48.0
127	TC011	17569.00	-11.5	60.0
127	TC012	17569.00	-11.5	72.0
728	EC001	18544.00	-11.0	8.5
728	EC002	18544.00	-11.0	19.5
728	EC003	18544.00	-11.0	24.0
728	EC004	18544.00	-11.0	36.0
728	LE001	18511.89	-11.3	3.0
728	LE002	18512.03	-8.7	3.0
728	PG001	18515.09	-8.4	8.5
728	PG002	18505.21	-8.4	8.5
728	TC001	18544.05	-11.6	3.0
728	TC002	18544.05	-11.6	4.0
728	TC003	18544.05	-11.6	6.5
728	TC004	18544.05	-11.6	9.0
728	TC005	18544.05	-11.6	10.0
728	TC006	18544.05	-11.6	14.0
728	TC007	18544.05	-11.6	18.5
728	TC008	18544.05	-11.6	24.0
728	TC009	18544.05	-11.6	36.0
728	TC010	18544.05	-11.6	48.0
728	TC011	18544.05	-11.6	60.0
728	TC012	18544.05	-11.6	72.0
728	TC013	18544.10	-11.9	0.3
728	TC014	18544.10	-11.9	1.0
728	TC015	18544.10	-11.9	2.0
728	TC016	18544.10	-11.9	3.0
728	TE001	18508.04	-11.2	3.0
728	TE002	18508.06	-8.8	3.0

Table C.7 As-built locations of sensors installed in asphalt overlay of concrete sections.

CELL	SENSOR	STATION	OFFSET (ft)	DEPTH FROM SURF (in.)
983	JO001	118558.26	-6.0	0.8
983	JO002	118531.27	-6.0	1.0
983	TC001	118529.24	-11.2	0.3
983	TC002	118529.24	-11.2	4.5
983	TC003	118529.24	-11.2	9.0
983	TC004	118529.24	-11.2	12.0
983	TC005	118529.24	-11.2	18.0
983	TC006	118529.24	-11.2	24.0
983	TC007	118529.24	-11.2	36.0
983	TC008	118529.24	-11.2	48.0
984	JO001	117963.87	-6.0	1.8
984	JO002	117937.06	-6.0	1.8
984	JO003	117909.99	-6.0	1.8
984	TC001	117934.88	-11.4	0.5
984	TC002	117934.88	-11.4	1.5
984	TC003	117934.88	-11.4	2.0
984	TC004	117934.88	-11.4	6.3
984	TC005	117934.88	-11.4	10.5
984	TC006	117934.88	-11.4	12.0
984	TC007	117934.88	-11.4	18.0
984	TC008	117934.88	-11.4	24.0
989	JO001	114807.59	-6.0	4.8
989	JO002	114780.35	-6.0	4.8
989	JO003	114753.43	-6.1	4.8
989	TC001	114778.32	-11.4	0.5
989	TC002	114778.32	-11.4	1.0
989	TC003	114778.32	-11.4	2.0
989	TC004	114778.32	-11.4	3.5
989	TC005	114778.32	-11.4	4.5
989	TC006	114778.32	-11.4	8.8
989	TC007	114778.32	-11.4	13.0
989	TC008	114778.32	-11.4	15.0
992	JO001	113025.22	-6.0	3.3
992	JO002	112998.04	-6.1	3.3
992	JO003	112971.30	-6.1	3.3
992	TC001	112995.95	-11.4	0.5
992	TC002	112995.95	-11.4	1.0
992	TC003	112995.95	-11.4	2.0
992	TC004	112995.95	-11.4	2.5
992	TC005	112995.95	-11.4	3.0
992	TC006	112995.95	-11.4	7.3
992	TC007	112995.95	-11.4	11.0
992	TC008	112995.95	-11.4	12.0

APPENDIX D

FORTA-FERRO FIBERS



FORTA®

FORTA-FERRO®

FACT-DATA©

MANUFACTURER

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U.S.A., 16127-6399
TELEPHONE: 1-800-245-0306, (724) 458-5221;
FAX: (724) 458-8331; **www.forta-ferro.com**

GENERAL DESCRIPTION

FORTA-FERRO® is an **easy to finish**, color blended macrosythetic fiber, made of 100% virgin copolymer/polypropylene consisting of a twisted bundle non-fibrillating monofilament and a fibrillating network fiber, yielding a high-performance concrete reinforcement system. **FORTA-FERRO®** is used to reduce plastic and hardened concrete shrinkage, improve impact strength, and increase fatigue resistance and concrete toughness. This **extra heavy-duty** macrosynthetic fiber offers maximum long-term durability, structural enhancements, and effective secondary/temperature crack control by incorporating a truly **unique synergistic fiber system** of long length design. **FORTA-FERRO® is non-corrosive, non-magnetic, and 100% alkali proof!**

APPLICATIONS

FORTA-FERRO® is mainly used with performance concrete applications such as industrial floors, bridge decks, shotcrete, loading docks, precast products – anywhere that steel reinforcement reduction or replacement is the objective. Contact FORTA Corporation for design assistance.

INSTALLATION

Recommended dosage rate of **FORTA-FERRO®** is **0.2% to 2.0% by volume of concrete** (3 to 30 lbs. per cubic yard) added directly to the concrete mixing system during, or after, the batching of the other ingredients and mixed at the time and speed recommended by the mixer manufacturer (usually four to five minutes).

PHYSICAL PROPERTIES

Materials	Virgin Copolymer/Polypropylene	Color	Gray
Form	Monofilament/Fibrillated Fiber System	Acid/Alkali Resistance	Excellent
Specific Gravity	0.91	Absorption	Nil
Tensile Strength	83-96 ksi. (570-660 MPa)	Compliance	A.S.T.M. C-1116
Length	2.25" (54mm), 1.5" (38mm)	Compliance	A.S.T.M. D-7508

AVAILABILITY

FORTA-FERRO® can be purchased from FORTA Corporation or an authorized FORTA® products distributor, dealer or representative.

PACKAGING

Convenient incremental pound or kilogram mixer-ready bag packaging.

WARRANTY

FORTA® products are warranted to be free of defects in material and meet all quality control standards set by the manufacturer. FORTA Corporation specifically disclaims all other warranties, express or implied. The exclusive remedy for defective product shall be to replace the product or refund the purchase price. No agent or employee of this company is authorized to vary the terms of this warranty notice. FORTA Corporation has no control over the design, production, placement, or testing of the concrete products in which FORTA® products are incorporated, and therefore FORTA Corporation disclaims liability for the end product.

U. S. Patent Nos. 6,753,081 and 7,168,232. Additional patents pending.

Figure D.1 Forta-Ferro fiber manufacturer data.