2013 MnROAD Construction Report

Minnesota Department of Transportation

RESEARCH SERVICES & LIBRARY

Office of Transportation System Management

MnROAD Office of Materials

Dave Van Deusen, Principal Investigator
Office of Materials and Road Research
Minnesota Department of Transportation

October 2014

Research Project
Final Report 2014-35

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2014-35		

4. Title and Subtitle	5. Report Date
2013 MnROAD Construction Report	October 2014
	6.
7. Author(s) Bruce Tanquist, Benjamin Worel, Tom Burnham, Bernard Izevbekhai, Leonard Palek, Dave Van Deusen	8. Performing Organization Report No.
9. Performing Organization Name and Address Minnesota Department of Transportation Office of Materials and Road Research 1400 Gervais Avenue Maplewood MN, 55109	10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No.
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899	13. Type of Report and Period Covered Final Report; June-July 2013 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/PDF/201435.pdf

16. Abstract (Limit: 250 words)

In June and July 2013, MnDOT constructed three new concrete pavement test sections or cells at the MnROAD facility. On MnROAD’s Interstate 94 mainline, a 7.5 inch thick sustainable concrete pavement was constructed using a 75% recycled concrete aggregate (RCA) mix, to study the performance of recycled aggregates in new concrete. Geocomposite transverse joint drains and preformed neoprene joint seals were also incorporated into this test section. Also on the MnROAD mainline, new bonded concrete overlays of distressed asphalt pavement (BCOA) test sections were built. These BCOA or whitetopping test cells were built with 4 and 5 inch thick fiber reinforced concrete slabs. On MnROAD’s Low Volume Road loop, a 3 inch thick ultra-thin unbonded concrete overlay was constructed over two different thicknesses of geotextile fabric interlayer. The concrete overlay also contained structural fibers in the mix. This report documents the design, construction, field testing, sampling and testing, and sensor instrumentation associated with these new test sections.

Additionally, a thin 5 inch concrete pavement (cell 32) on the low volume road was repaired and retrofitted with unique load transfer devices; post-repair diamond grinding was performed. The pervious concrete overlay test cell (Cell 39) was ground to ascertain 1) whether slurry from grinding operations significantly impair the permeability.

Details about the cells:

- Mainline sustainable concrete pavement and whitetopping: Cells 613, 140 & 240, and 160-163 (SP 8680-169)
- Low-volume thin unbonded concrete overlay with geosynthetic interlayer and pervious pavement rehab: Cells 32, 39 (SP 8680-170)

17. Document Analysis/Descriptors	18. Availability Statement
Concrete pavements, Concrete overlays, Drainage, Pavement design, Paving, Highway engineering, Whitetopping, Rehabilitation (Maintenance) or Pavement maintenance, Load transfer	No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	92	

2013 MnROAD Construction Report

Final Report

Prepared by:

Bruce Tanquist
Benjamin Worel
Tom Burnham
Bernard Izevbekhai
Leonard Palek
Dave Van Deusen
Minnesota Department of Transportation
Office of Materials and Road Research

October 2014

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGEMENTS

The authors gratefully acknowledge contributions from the following people to a successful construction project:

- MnROAD operations staff.
- Maureen Jensen – For leadership and managerial support.
- Propex, Inc. – Donated the fabric interlayers and helped guide the installation. Propex also provided support related to the development of the concrete mix designs. Greg Halvorson acted as the manufacturer's representative on the project.
- Concrete Paving Association of Minnesota (CPAM) provided neoprene sealant used on the project. Ben Jacobus of D.S. Brown Company acted as the industry contact.
- Tensar International Corp. – Provided RoaDrain™ material and assistance with installation during construction.
- University of Missouri and the University of North Dakota – Provided fiber optic sensors installed into the ultra-thin unbonded concrete overlay through a National Science Foundation grant.
- PNA Construction Technologies, Inc. – Provided assistance with installation of the CoVex plate dowel slots.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

In June and July 2013, MnDOT constructed three new concrete pavement test sections (cells) at the MnROAD facility. On MnROAD's Interstate 94 mainline, a 7.5-inch thick concrete pavement was constructed using a 75% recycled concrete aggregate (RCA) mix to study sustainability and the performance of recycled aggregates in new pavement. Geocomposite transverse joint drains and preformed neoprene joint seals were also incorporated into this test section. New bonded concrete overlay cells were constructed on existing distressed asphalt pavement. The two overlays, or whitetopping cells, were built with 4- and 5-inch thick fiber-reinforced concrete slabs. On MnROAD's low-volume road loop, a 3-inch thick ultra-thin unbonded concrete overlay was constructed over two different thicknesses of geotextile fabric interlayer. Structural fibers were incorporated into the mix.

Additionally, on the low-volume road, a thin, 5-inch concrete section (cell 32) was repaired and retrofitted with unique load transfer devices; post-repair diamond grinding was performed to restore ride. The pervious concrete overlay test cell (cell 39) was ground to ascertain 1) whether slurry from grinding operations significantly impair the permeability and 2) impacts to acoustic properties and ride quality.

This report documents the design, construction, materials sampling, field and laboratory testing, and sensor instrumentation associated with these new test cells.

CHAPTER 1 – INTRODUCTION

1.1 MnROAD Facility

The Minnesota Road Research Project (MnROAD) was constructed by the Minnesota Department of Transportation (MnDOT) in 1990-1993 as a full-scale accelerated pavement testing facility, with traffic opening in 1994. Located 40 miles northwest of St. Paul, MN, MnROAD is one of the most sophisticated pavement test facilities of its type in the world. Its design incorporates thousands of electronic in-ground sensors and an extensive data collection system that provide opportunities to study how traffic loadings and environmental conditions affect pavement materials and performance over time. MnROAD consists of two unique road segments located parallel to Interstate 94. The first is a 3.5-mile mainline interstate roadway carrying "live" traffic averaging 29,700 vehicles per day with 13.0% trucks. The second is a two lane, two way, 2.5-mile closed-loop low-volume road. Between August 1994 (the initial opening of MnROAD) to approximately July 2008, traffic loads were applied to both lanes of the low-volume road sections: four days per week the MnROAD-operated 18-wheel, 5-axle, tractor-trailer loaded to 80,000 lbs. trafficked the inside lane of the loop; one day per week the same truck was loaded to 100,000 lbs. and traveled the outside lane. Since July 2008 overloaded truck traffic has been suspended on the outside lane; it has essentially become an environmental lane.

Over time, many of the original test sections (cells) have met the end of their service or research life. Several new research test sections have been constructed at MnROAD since 1994, including a large number completed in 2008. This effort was considered MnROAD's second phase of research, which is expected to continue until 2016.

Most MnROAD test cells are approximately 500 feet long. Subgrade, aggregate base, and surface materials, as well as roadbed structure and drainage methods vary from cell to cell. All data presented herein, as well as historical sampling, testing, and construction information can be found in the MnROAD database and in various publications. The layout and designs studied as part of MnROAD Phase 2 are shown in Appendix A. Additional information on MnROAD can also be found on the following web site: www.dot.state.mn.us/mnroad.

1.2 MnROAD Instrumentation and Performance Database

Data collection at MnROAD is accomplished using a variety of methods to help describe pavement response to vehicle loads and the environment. Layer response data is collected from a number of different types of in-situ instrumentation located within the top pavement layer, as well as subsequent sub-layers. The instrumentation measures variables such as temperature, moisture, strain, deflection, and frost depth. Data flows from this instrumentation to several roadside cabinets, which are connected by a fiber optic network that is fed into the MnROAD database for storage and analysis. MnROAD staff also monitors and records pavement performance on a regular basis. Monitoring data includes ride quality, surface distress, rutting, transverse joint faulting, surface friction, falling-weight deflectometer (FWD) deflections, findings from forensic trenches, and laboratory testing of materials. Data from the sensors or monitoring activities contained in the MnROAD database can be requested by contacting MnDOT researchers. Data releases are also available on the MnROAD website.

1.3 MnROAD Cell Numbering

Each unique pavement test section at MnROAD is assigned a "cell" number. Often, new cell numbers are variations of previous test cell numbers, due to the fact they are associated with certain historical locations on one of the MnROAD test tracks. Table 1.1 shows the test cells that were removed or reconstructed, as well as the new cells constructed in June and July of 2013.

Table 1.1 – 2013 reconstructed/rehabilitation test cells.

State Project No.	Test Cells Removed/Reconstructed	New Test Cells Constructed
8680-170	**Cell 32** 5 inch undoweled PCC (rehabilitation)	**Cell 32** Concrete full-depth repair and DBR Diamond grinding
	Cell 39 4 inch pervious PCC (rehabilitation)	**Cell 39** Diamond grinding
8680-169	**Cells 113, 213, 313, 413, 513** Thin concrete designs MnROAD mainline (I-94) 2008 - 2013	**Cell 613** 75% recycled coarse aggregate Concrete mix MnROAD mainline (I-94)
	Cell 40 Concrete thickened edge MnROAD low-volume road 1993 - 2013	**Cells 140, 240** Ultra-thin unbonded fiber reinforced Concrete overlay with fabric bond breaker MnROAD low-volume road
	Cells 60, 61, 62, 63 Concrete overlay of existing asphalt (whitetopping) MnROAD mainline (I-94) 2004 - 2013	**Cells 160, 162** Fiber-reinforced concrete overlay of existing asphalt pavement (whitetopping) MnROAD mainline (I-94)

CHAPTER 2 – PROJECT BACKGROUND

2.1 Pavement Condition Prior to 2013 Construction

The pavement condition described below is a verbal description of the condition of the test cells before any construction or rehabilitation was completed. The before and after performance data is documented later in this report.

2.1.1 Cell 32

Cell 32 was originally built in in June 2000 to better understand the minimum requirements for a low-volume concrete road. Much of the pavement within the inside lane was in need of significant repair to address cracked panels and faulting. Figure 2.1 and Table 2.1 show the accumulated traffic and changes in International Ride Index (IRI, or roughness), respectively, leading up to the 2013 construction. The outside lane exhibited less faulting and cracking due to receiving a lower number of load repetitions. This test cell is 550 feet long and built on MnROAD's low-volume road. The 5-inch concrete with 10x12 foot undoweled panels was placed on the existing gravel road section of which the upper 5 inches was removed. After removal the remaining pavement section consisted of approximately 8 inches of aggregate base material over the original clay loam subgrade.

2.1.2 Cells 113, 213, 313, 413, 513

Cells 113, 213, 313, 413, 513 were built in 2008 as part of the MnROAD Phase 2 initiative. These test cells were designed and constructed to support a study on concrete pavement thickness optimization. The cells ranged in thickness from 5 to 6.5 inches. Placement on the interstate mainline portion of MnROAD was chosen to provide accelerated loading to "thin" pavements, and to rapidly identify potential failure mechanisms and performance issues.

The thinnest cells, 113 and 213, reached the end of their service life by 2012. Figure 2.2 and Table 2.2 show the accumulated traffic and changes in IRI, respectively, prior to the 2013 construction. Additional performance analysis of these test cells was outlined in a report by Burnham and Izevbekhai (Burnham & Izevbekhai, 2011). Frequent repairs and new research initiatives warranted replacement of these cells as soon as possible.

2.1.3 Cell 40

Cell 40 is located on MnROAD's low-volume road. The test cell was originally constructed in 1993, and consisted of a thickened edge design (5.5 to 7 inch) jointed plain concrete pavement. The pavement was built over 5 inches of dense graded (MnDOT Class 5) aggregate base and a clay subgrade. The transverse joints were undoweled, skewed at 2 feet in a 12 foot lane, and spaced at 15 foot intervals. Accumulated traffic loadings and roughness are shown in Figure 2.3 and Table 2.2. Cell 40 was exhibiting significant transverse joint faulting, as well as a number of cracked panels. It was deemed to be a suitable candidate for supporting an unbonded concrete overlay.

2.1.4 Cells 60-63

Cells 60-63, located on the mainline interstate traffic portion of the MnROAD facility, were constructed in 2004 and consisted of 4 and 5 inch thick bonded concrete overlays placed over existing asphalt pavement (whitetopping). The asphalt, placed in 1993, was originally 13 inches thick, but was milled and overlaid with various whitetopping test sections since 1997. Panel size for cells 60-63 was 5 feet long by 6 feet wide. Joints within cells 60 and 62 were sealed with hot-pour sealant while cells 61 and 63 were left unsealed.

Figure 2.1 – Changes in roughness prior to 2013 construction for cell 32.

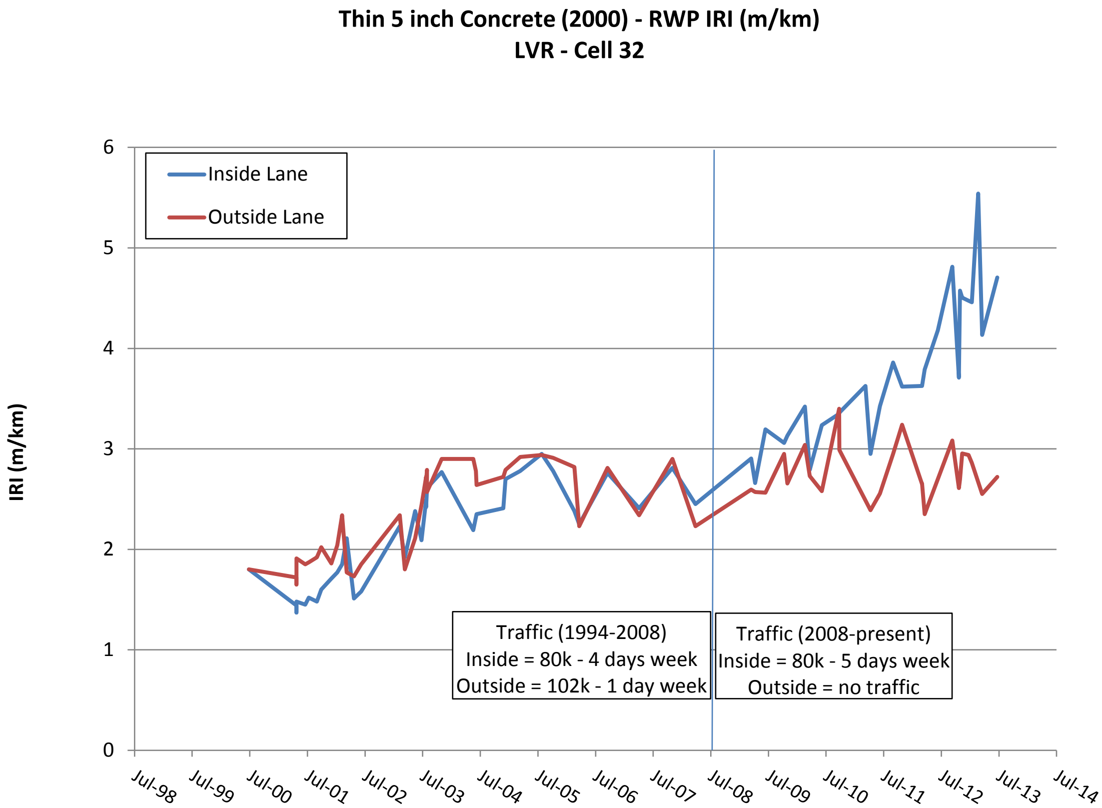


Table 2.1 – Accumulated traffic on low-volume road cells 32, 39, and 40.

	LVR Loadings		**Inside Lane - 80k Truck**		**Outside Lane - 102k Truck**	
Cell	**Start**	**End**	**Loadings** (Laps)	**Rigid ESALS** (3.74 ESALs/pass)	**Loadings** (Laps)	**Rigid ESALS** (11.63 ESALs/pass)
32	6/15/2000	6/15/2013	82,760	309,522	14,559	169,321
39	10/31/2008	6/15/2013	29,329	109,690	-	-
40	8/1/1994	6/15/2013	128,420	480,291	28,159	327,489

Figure 2.2 – Changes in roughness prior to 2013 construction for cells 113-513.

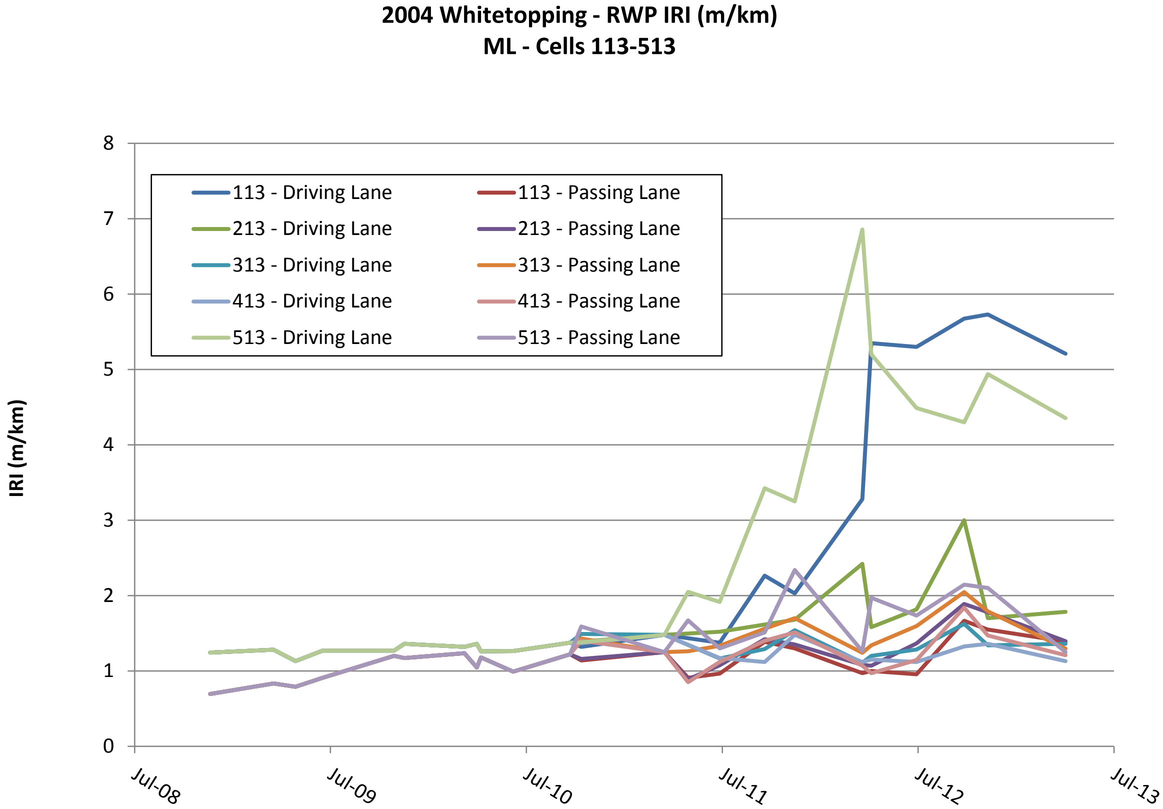
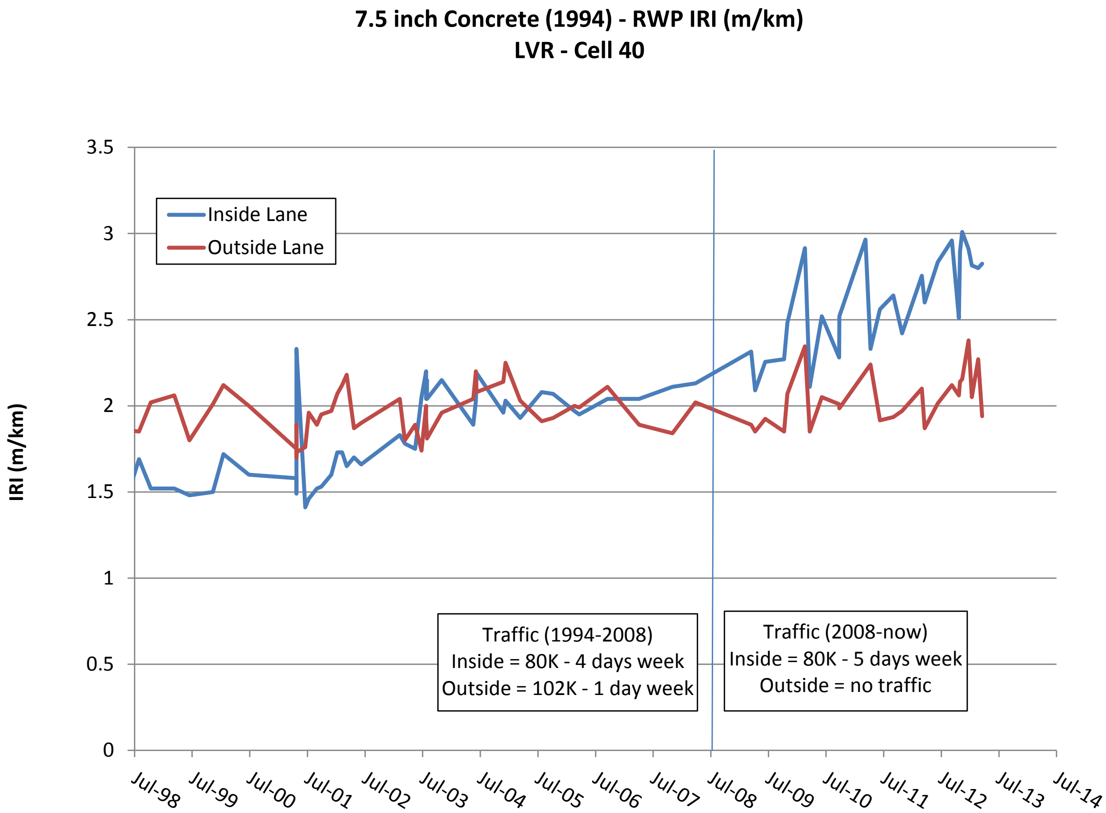


Table 2.2 – Accumulated traffic on mainline cells 113-513.

Start date	10/31/2008	1,689	Total days
End date	6/15/2013	1,156	Full traffic days

	Passing	Driving	Total
No. vehicles	15,656,856	15,541,184	31,198,040
No. Trucks	961,312	3,431,620	4,392,932
ADT	13,544	13,444	26,988
HCADT	832	2,969	3,801
%Trucks	6	22	14
BESALs	773,272	3,144,952	3,918,224
CESALs	1,166,237	4,765,888	5,932,125

Figure 2.3 – Changes in roughness prior to 2013 construction of cells 140 and 240.



Cell 63, a 4 inch thick whitetopping section, experienced significant panel cracking by 2010. In that same year the joints were sealed and the cell underwent 40 full-depth panel replacements and diamond grinding in 2011 to maintain service. Cells 60-62 had a small number of panels with longitudinal cracks near the outside wheel path, but otherwise in good condition.

Figure 2.4 and Table 2.3 show the accumulated traffic and changes in roughness, respectively, prior to construction in 2013.

After 8 years, and approximately 8 million CESALs, it was decided that these sections had provided enough useful data to satisfy their research objectives. Due to good condition and sufficient thickness of the underlying asphalt layers, this area was determined to be capable of supporting another set of bonded concrete overlay over existing asphalt pavement (whitetopping) test sections.

2.2 Overview of Construction

The focus of the 2013 construction projects was concrete rehabilitation and sustainability. An overview of each project is as follows.

Under SP 8680-169 the proposed construction for cells 140 and 240 consisted of an ultra-thin, 3 inch thick, fiber-reinforced unbonded concrete overlay placed on a drainable fabric interlayer. In cells 160-163, existing 4 and 5 inch thick whitetopping sections were removed and replaced with fiber-reinforced concrete whitetopping sections. For cell 613, the existing thin concrete sections were removed and replaced with a new 7.5 inch concrete pavement containing 75% recycled concrete aggregate in the mix.

Figure 2.4 – Changes in roughness prior to 2013 construction of cells 60-63.

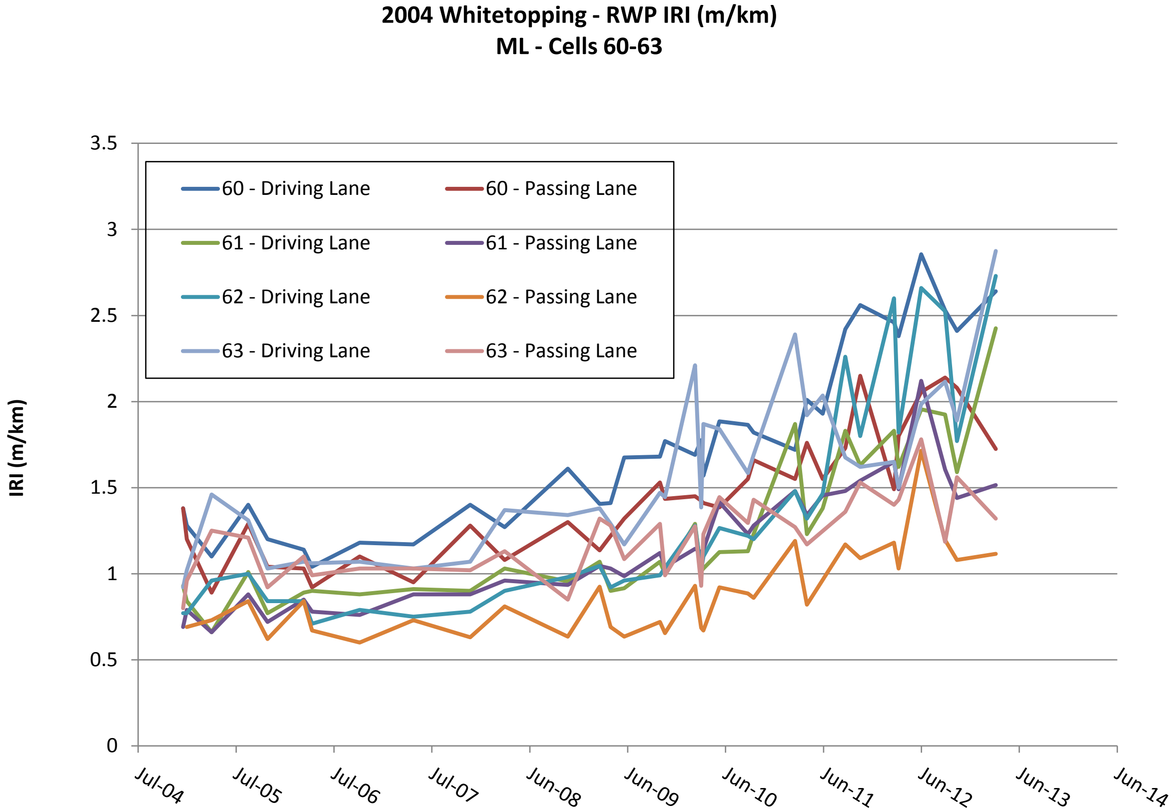


Table 2.3 – Accumulated traffic on mainline cells 60-63.

Start date	11/17/2004	3,133	Total days
End date	6/15/2013	2,142	Full traffic days

	Passing	Driving	Total
No. vehicles	29,310,583	29,518,724	58,829,307
No. Trucks	1,750,195	6,232,144	7,982,339
ADT	13,684	13,781	27,465
HCADT	817	2,909	3,726
%Trucks	6	21.1	13.6
BESALs	1,427,368	5,718,133	7,145,501
CESALs	2,157,490	8,643,022	10,800,512

The construction contract was let on February 22, 2013 and awarded to CS McCrossan on March 6, 2013. Construction started May 21, 2013 and was completed on July 11, 2013. MnDOT hired WSB & Associates, Inc. to assist with the construction inspection and contract administration. Materials sampling and testing was done under contract with American Engineering Testing, Inc. Sensors were installed by MnDOT staff, as well as researchers from the Missouri University of Science and Technology and North Dakota State University.

Construction under SP 8680-170 performed rehabilitation on cells 32 and 39 with the objective of investigating different retrofit load transfer devices and restoration approaches for pervious pavement. Several different dowel bar retrofit methods were installed in the 5 inch concrete pavement of cell 32; ride was reestablished by diamond grinding. The pervious concrete overlay in cell 39 was diamond ground to restore ride.

The construction contract was let on February 22, 2013 and awarded to Diamond Surfacing, Inc. on March 6, 2013. Construction started September 21, 2013 and completed on July 11, 2013. MnDOT performed construction inspection and contract administration. Materials sampling and testing was done under contract with American Engineering Testing, Inc. No additional sensors were installed during this effort.

CHAPTER 3 – RESEARCH CONCEPT, DESIGN AND MATERIALS

3.1 Cell Overview and Strategy

3.1.1 Cells 140 & 240

The existing concrete pavement was overlaid with an ultra-thin, unbonded concrete overlay. Two different thickness of non-woven geotextile fabric served as an interlayer. A thin (8 oz.) fabric was placed on cell 140 and standard weight (15 oz.) fabric was used on cell 240. Interlayers were placed full-width, including the shoulders. To reduce stresses and tendencies toward panel warp and curl, 6 by 6-foot panels were constructed. Structural fibers were added to the concrete mix to determine their contribution toward strength, fatigue capacity, and improvement in joint load transfer. To reduce the amount of variables affecting this test section, all joints were sealed with bituminous hot pour. Texture was provided by longitudinal tining. Shoulders were constructed of asphalt millings salvaged from another MnROAD cell; the millings were placed directly on top of the interlayer fabric.

Areas of Research

Stress Relief from Interlayer Fabric

One of the main areas of research for this test cell is the non-woven geotextile fabric, which will be used as an interlayer between the existing concrete substrate and the concrete overlay. This interlayer serves several purposes: stress relief, bond inhibitor and drainage. It has been theorized that this fabric can absorb a substantial amount of vertical (load-related) and horizontal stresses associated with movement along cracks and joints in the existing concrete substrate, and in turn, prevent cracks from reflecting up in to the new concrete layer. Cushioning between the two concrete layers is also needed to prevent the ultra-thin concrete overlay slabs from “snapping” when the panels curl up off the underlying concrete pavement.

The benefit of the fabric interlayer relative to reflective cracking will be monitored through distress surveys. To measure the stress attenuation provided by fabric interlayer, strain gauges were retrofitted into the existing pavement in locations directly below strain gauges placed in the new concrete layer above the fabric. The gauges were positioned such that the response due to loading measured around a joint or crack in the existing pavement can be compared to the response at the mid-panel of the existing pavement, to determine if the fabric is providing such benefit. If the two locations (crack versus no crack) show the same, or similar, response, it would be clear that the fabric is absorbing much of the damaging stresses.

Interlayer Fabric Drainage

Besides stress relief, the fabric interlayer is designed to aid in the drainage of water which has infiltrated the new concrete overlay. The drainage of water not only prevents water from standing in the joints, but also reduces potential hydraulic pressures from water trapped between the concrete layers.

Sufficient drainage is only accomplished if there is a continuous path for the water to flow out of the structure. At MnROAD this was done by ensuring contact between the fabric strips from the centerline of the traveled lanes to the outer edge of the shoulders. This is often called “daylighting” the fabric.

While it has been recently demonstrated that fabric interlayers can provide substantial drainage in concrete overlay tests conducted in a laboratory (Lederle, et al 2013) documented full-scale performance in the field is lacking. Similar to the instrumentation used to monitor stress, sensors were installed in the MnROAD sections to detect moisture in the region of the fabric interlayer.

Variable Thickness for Fabric Interlayer
There is interest in understanding the performance of ultra-thin slabs on a geotextile fabric interlayer. If the self-weight of the thin, small panels is not substantial enough to significantly compress the fabric, the panels could essentially “float” above the fabric and be susceptible to rocking movements caused by traffic loading. To test this theory, two different fabric thicknesses were installed the test cells. Standard weight (15 oz.) fabric was installed in cell 140; lighter (8 oz.) fabric was used in cell 240. Other than a difference in interlayer fabric weight, the test cells are identical, thus allowing a direct comparison of their performance.

Fabric Color and Installation Technique
As with other interlayer types, their behavior during the paving process must be considered. In order to reduce the potential for wicking moisture out of the fresh concrete, or overheating and causing significantly differences in thermal gradients in the very thin overlay slabs, interlayer materials must be chosen to suit various temperature conditions. This is most prevalent with dark interlayer materials on very warm days with direct sunlight. In these conditions, the interlayer must be sprayed with enough water to cool the surface, but not so much as to add moisture into the new concrete above. An alternative approach, and the one taken on this project, is to use a white fabric interlayer.

The other important aspects to consider with fabric interlayers are the placement and fastening techniques. The fabric must be laid as flat as possible with no kinds, folds or ripples, in order to avoid weak zones within the new concrete overlay. The most common fastening method today involves using high powered guns to apply nails at a fixed spacing around the perimeter of the fabric. Success in adequately penetrating into the old concrete surface can often be challenging. Therefore, it was decided to try a new technique to fasten the fabric to the existing concrete in cells 140 and 240.

Recently, the research team discovered a new adhesive designed to “glue” the seams of the fabric together. It was decided to determine whether the adhesive could also be used to secure the fabric to the old concrete pavement. Applied with a handheld sprayer (see Figure 3.1), the adhesive was applied not only to areas where the fabric overlapped, but also near the edges of the existing concrete slabs. Not only was the adhesive effective in holding the fabric in place, but the fabric also stayed in place as the concrete delivery trucks turned their heavy wheels on the fabric. If a “kink” formed in the fabric, the crew was able to simply pull up the fabric and reposition it before the concrete was placed on it.

Structural Fibers in a Thin Overlay
As mentioned earlier, another initiative with this test cell is to determine the effectiveness of using structural fibers in thin overlays as reinforcement. A similar, three inch thick test slab without fibers was built and loaded at the University of Minnesota’s Accelerated Loading Facility (MinneALF). That test slab failed after 1 million loadings, due to a punch-out type failure. One lane of the 3-inch thick overlay in cells 140 and 240 will be loaded with traffic which mimics conditions of lower volume roads. Impending success of this test section to withstand load over a substantial period of time may then be attributed to the benefits provided by the structural fibers within the concrete’s matrix. FWD testing will be done across transverse joints to determine if the structural fibers contribute to increased aggregate interlock and load-transfer efficiency (LTE).

Longitudinal Tined Surface
Surface texture will be attained with longitudinal tining. MnDOT standard specified surface texture is by longitudinal turf drag. On a few occasions, MnDOT has constructed longitudinally tined concrete pavements. While turf drag has proven to provide a safe, durable surface in Minnesota, many other states use longitudinal tining on concrete pavements, with perceived benefits in terms of skid resistance and noise reduction. This test cell will be monitored for ride quality, friction, on-board sound intensity (OBSI), and many other surface characteristics, to confirm the benefits of a longitudinal-tined surface.

Figure 3.1 – Application of geosynthetic adhesive in cells 140 and 240.

3.1.2 Cells 160 and 162

New cells 160 and 162 will continue to study additional parameters associated with bonded concrete overlay of asphalt (whitetopping) pavement design and performance. The previous 4 and 5 inch thick concrete overlays and 1 inch of the underlying asphalt were removed via milling. New 4 and 5 inch thick structural fiber-reinforced concrete overlays were placed. These cells have 6 by 6-foot panels and all joints were sealed with hot-pour asphalt sealant. The surface was textured with a longitudinal tine. The only design differences relative to previous cells 60-63 are the 1-inch thinner underlying asphalt thickness, use of structural fibers in the concrete mix, and sealed joints.

Areas of Research

Benefit of Using Structural Fibers in Concrete Overlays
One of the main areas of research for these test cells is the use of concrete containing structural (macro) fibers. Macro fibers are designed to increase slab flexural capacity by inhibiting the formation of flexural cracking, while providing significant post-cracking toughness. By monitoring the performance of test cells subject to interstate traffic and the extreme climate of Minnesota, the efficacy of using structural fibers in concrete overlays to both decrease slab thickness, as well as provide enhanced load transfer across cracks and joints, can be determined.

Based on the experienced gained by the Illinois DOT, the specification of the type and amount of fibers used in the concrete mix was determined based on laboratory performance testing results. Specifically, the

ASTM C1609 standard was used to approve the mix design for the test cells. To determine the contribution of the structural fibers toward improving load transfer across cracks and joints, dynamic displacement measurements will be taken using both LVDTs and FWD testing. Vibrating wire strain sensors will also measure any differences in thermal response compared to standard concrete mixes. Embedded thermocouples will capture changes in thermal gradients in the structure throughout the seasons.

Panel Size
The past performance history of thin whitetopping has pointed to a 6 by 6-foot panel size as being the most efficient. A remaining perception in the pavement design community claims that this panel size will simply result in “a lot more joints to maintain in the future.” As such, many thin (6 inch) whitetoppings in Minnesota continue to be built with standard 15 foot long by 12 foot wide panels. As panel sizes have grown, so has the use of dowel bars to reduce the tendency toward joint faulting. Unfortunately, anchoring the baskets supporting the dowels has proven to be unreliable, with many projects experience misaligned baskets and dowels. One proposed solution is to leave dowels out during the initial construction of the overlay, and then come back when it develops joint faulting and retrofit dowels and diamond grind the section. Alternately, this experiment seeks to determine whether the joint load transfer can be adequately supplied by the macro fibers in the concrete. To compare the performance between the smaller and larger panels, sensors will be installed to measure the differences in seasonal joint openings.

Longitudinal Tined Surface
These test cells will be finished with a longitudinal tined surface texture. As stated previously, MnDOT standard texture is by the longitudinal turf drag. However, many other states use longitudinal tining on concrete pavements, which is perceived to show benefits in terms of skid resistance and noise reduction. This test cell will be monitored for IRI, friction, OBSI and many other surface characteristics to confirm the benefits of this surface finish.

3.1.3 Cell 613
Cell 613 is intended to be a model for sustainable concrete pavement design. Ideally, it would be preferable to reuse the inplace pavement materials in the newly constructed test cell. In this case, however, recycled material came from the contractor’s stockpile in Maple Grove, MN. This concrete was verified to come from previous pavements produced under MnDOT specifications. Recycled concrete was crushed to a controlled maximum size of 1.5 inch and minimal material passing the No. 200 sieve. Project special provisions further required that there be less than 5% passing the No. 4 sieve. The final mix design included 75% replacement of the coarse aggregate with recycled concrete aggregate. Pavement design consisted of 7.5 inch thick slabs with 15 foot long by 12 wide panels. Transverse joints included 1-inch diameter epoxy coated steel dowels, and longitudinal joints were tied with 1/2 inch diameter, 30-inch long rebars. The original research plan included studying two different narrow width neoprene preformed seals. However, saw cut widths were incompatible with the very narrow seals, so only the wider (1/4 inch wide) seals were installed in the joints.

Recent MnROAD findings indicate that rapidly draining water away from concrete pavement joints is essential to their long term performance in freeze-thaw climates. This drainage is typically accomplished via a well-draining base layer beneath the concrete slabs. The long term stability of such rapid draining bases is, however, sometimes problematic. Another solution is to provide increased drainage capacity near the transverse joints. This was the basis for installing geocomposite material under 6 of the transverse joints in cell 613. Tensar RoaDrain™ material, 15 inches wide, was placed within the dowel bar baskets (on the grade) and extended to “daylight” in the ditch for both the driving and passing lanes. Two of the 6 joints were sealed to act as control joints.

Areas of Research

Instrumentation and Lab Testing
Cell 613 was instrumented with vibrating wire sensors, dynamic strain sensors, temperature sensors, and moisture sensors (in the base). Testing of the base layer during construction included DCP, LWD and FWD testing.

Monitoring Concept
In addition to the standard performance monitoring carried out on every MnROAD test cell, a new monitoring process will be added for cell 613. It will consist of periodic leachate evaluation after the first few minutes of storm water, to ascertain whether the RCA causes more laitance and/or lime leachate, and to detect the presence (or effect) of any existing unmixed paste in the matrix. Initial monitoring will also include monthly readings of the Circular Track Meter (CTM, ASTM E2157) and spikiness (texture orientation) measurement to determine stability of the surface against environmental degradation. All the other typical early-age monitoring tests including warp and curl, ride measurements, acoustic impedance, IRI and FWD were performed. During late fall 2013 the in-situ drainage capacity of the test joints was determined. Monitoring will be ongoing and reported elsewhere.

3.2 Design

3.2.1 Cell 32
Rehabilitation activities in cell 32 consisted of full-depth patching, retrofit load transfer, and diamond grinding. These were performed only on the inside lane and not the outside, environmental lane. Figures 3.2 and 3.3 show the repair and retrofit load transfer layout. Table 3.1 summarizes the items and quantities used for the 2013 construction in cell 32.

3.2.2 Cell 140 & 240
Figures 3.4a and 3.4b show general cross section for the thin fiber reinforced concrete (test cells 140 and 240). Cell 140 contains a thin (8 oz.) geotextile fabric interlayer and cell 240 contains a more standard (15 oz.) geotextile fabric interlayer. These are the only differences between the two test cells. Both fabrics were daylighted beyond the shoulder into the ditch. Each cell is approximately 230 feet long.

Some additional construction details include the following:

- Concrete overlay consists of 6 by 6 foot panels (See Figure 3.4c)
- All joints in the overlay are undoweled
- 6.5 pounds per cubic yard of macro fibers were used in the mix.
- Concrete mix utilized CA-50 concrete coarse aggregate designation, with maximum top size of 0.75 inch to account for the 3 inch thick slabs.
- The concrete was specified to reach 120 psi residual strength according to ASTM C1609
- All transverse and longitudinal joints consist of a single saw cut and bituminous hot-pour sealant.

3.2.3 Cells 160 and 162
The original designs called for four different test cells (160-163) to be constructed with variations in both thickness and sealed/unsealed joints as shown below and in Figures 3.5a and 3.5b:

- Cell 160 – 5 inch concrete overlay, sealed joints with hot pour sealant
- Cell 161 – 5 inch concrete overlay, unsealed joints
- Cell 162 – 4 inch concrete overlay, sealed joints with hot pour sealant
- Cell 163 – 4 inch concrete overlay, unsealed joints

Figure 3.2 – Cell 32 patching and joint load transfer retrofit layout.

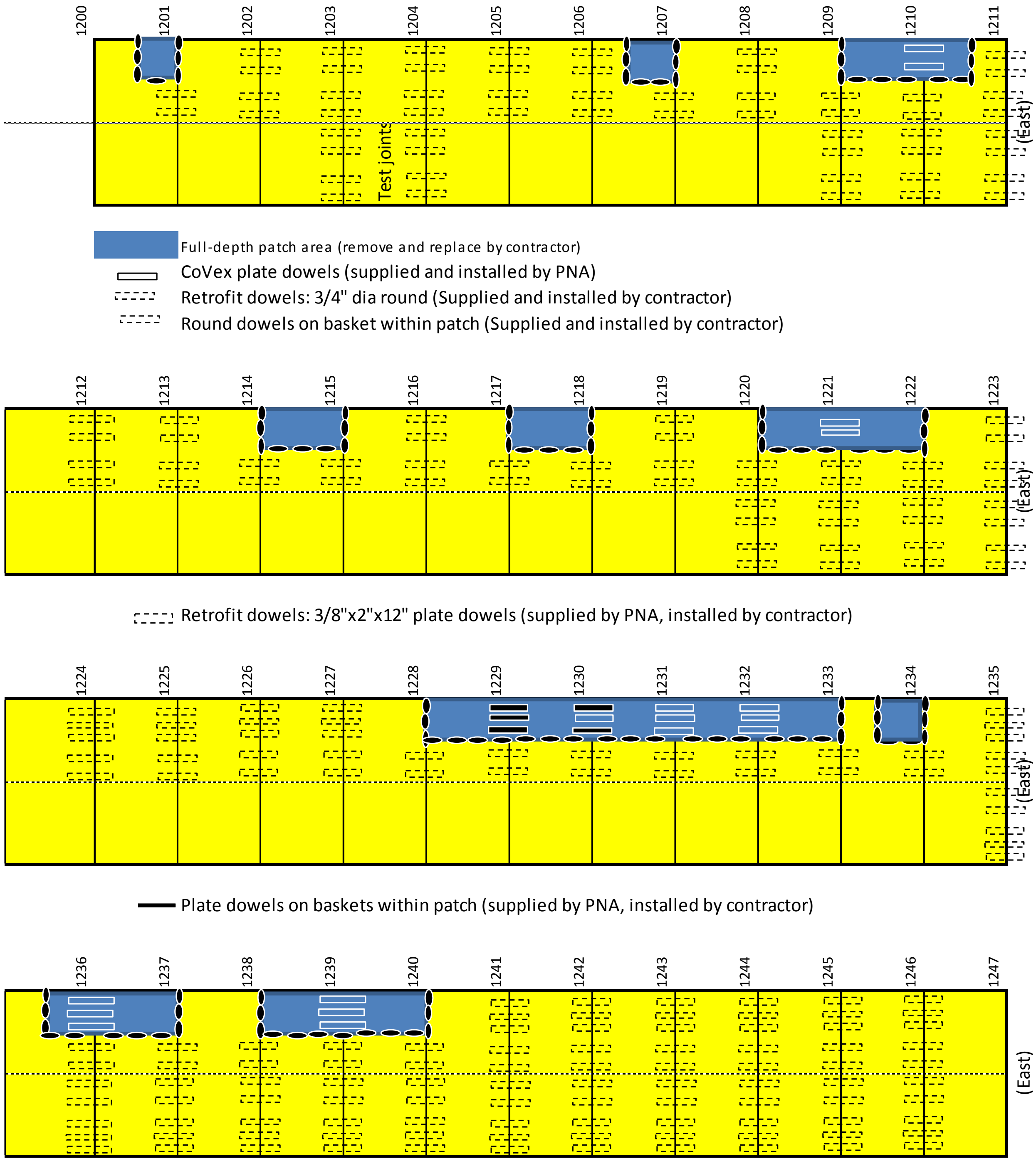


Figure 3.3 – Cell 32 typical CoVex retrofit joint load transfer layout.

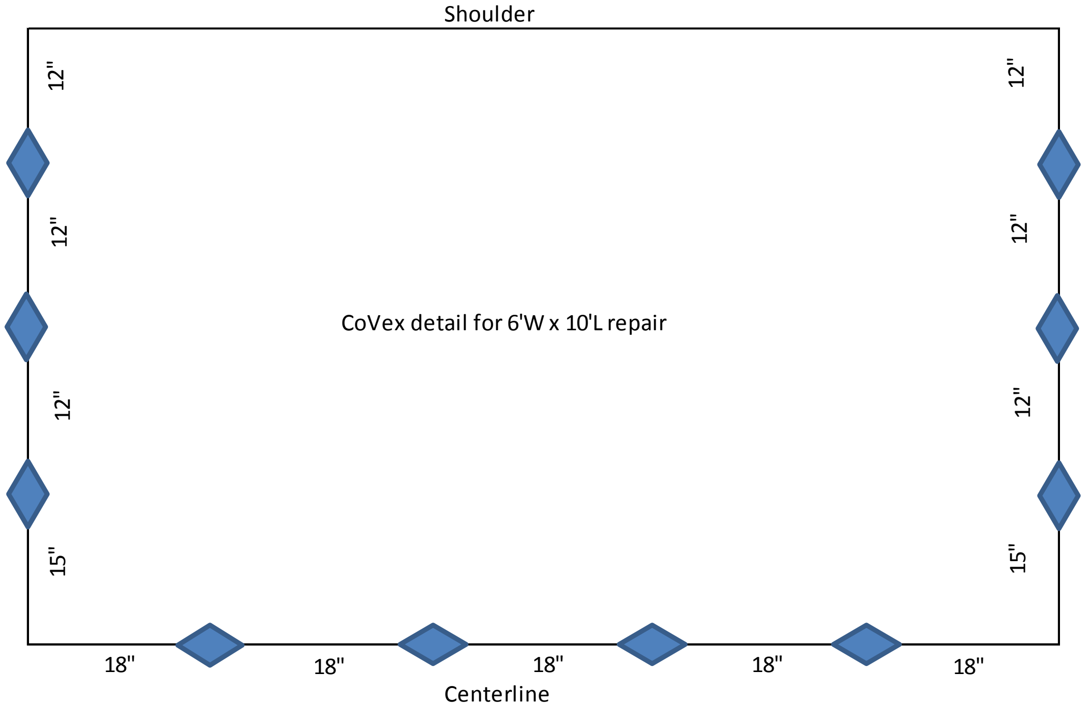
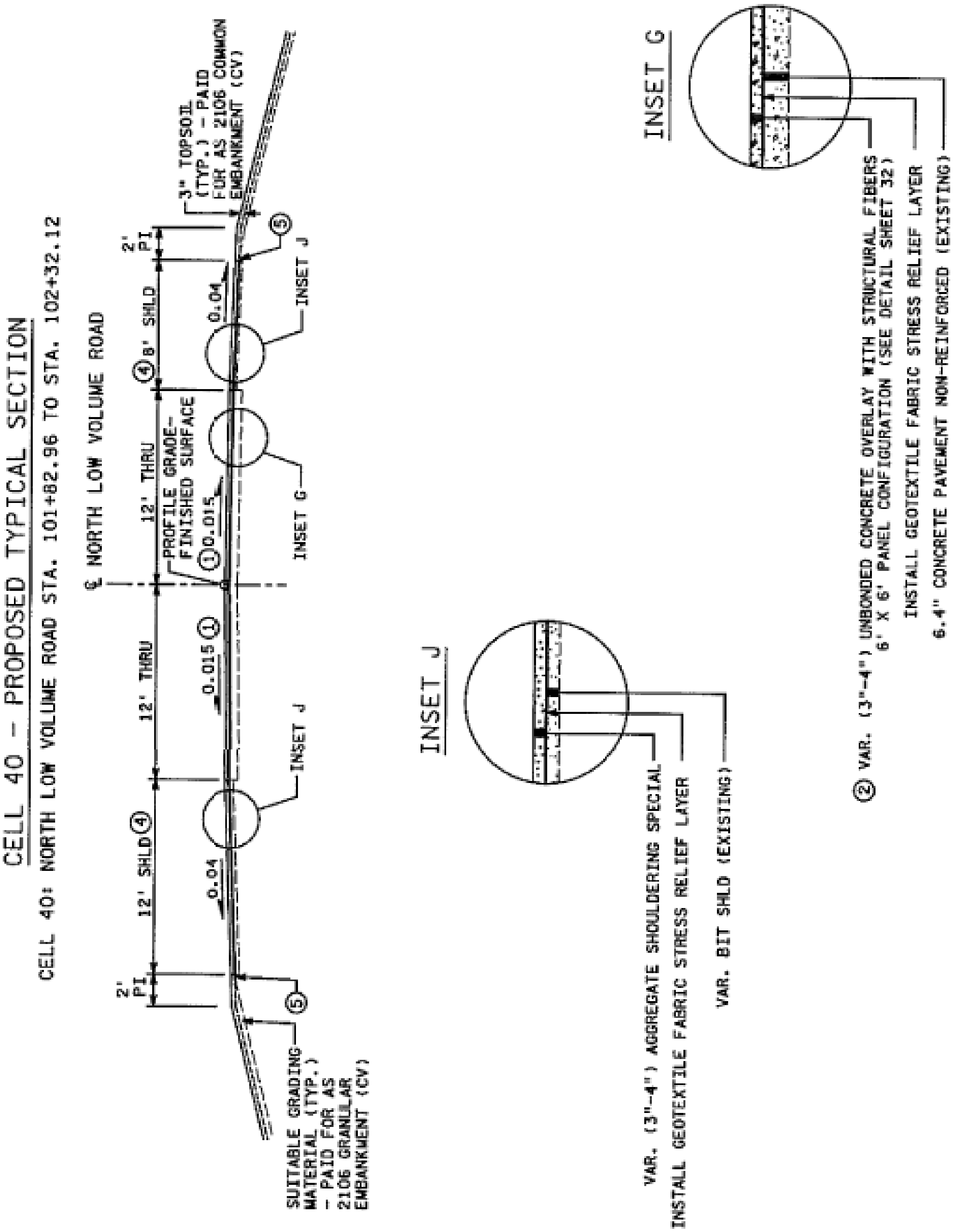


Table 3.1 – Cell 32 typical CoVex retrofit joint load transfer layout.

Quantities	**Items**
122	3/4" dia round retrofit dowels
123	plate retrofit dowels (supplied by MnDOT)
1	mini basket with 2 round dowels (supplied by MnDOT)
1	mini basket with 2 plate dowels
4	mini basket with 3 plate dowels
2	mini basket with 3 round dowels
123	CoVex (supplied and installed by MnDOT)
1004	Full depth PCC panel replacement (square feet)
47	Structural concrete (cubic yards) [added 1 yd^3 for research sampling]
245	Retrofit dowel bar slots (2 widths to accommodate round or plate dowels)

Figure 3.4a – Design section for cell 140.



Fi 3.4b D i ti n f ll 240.

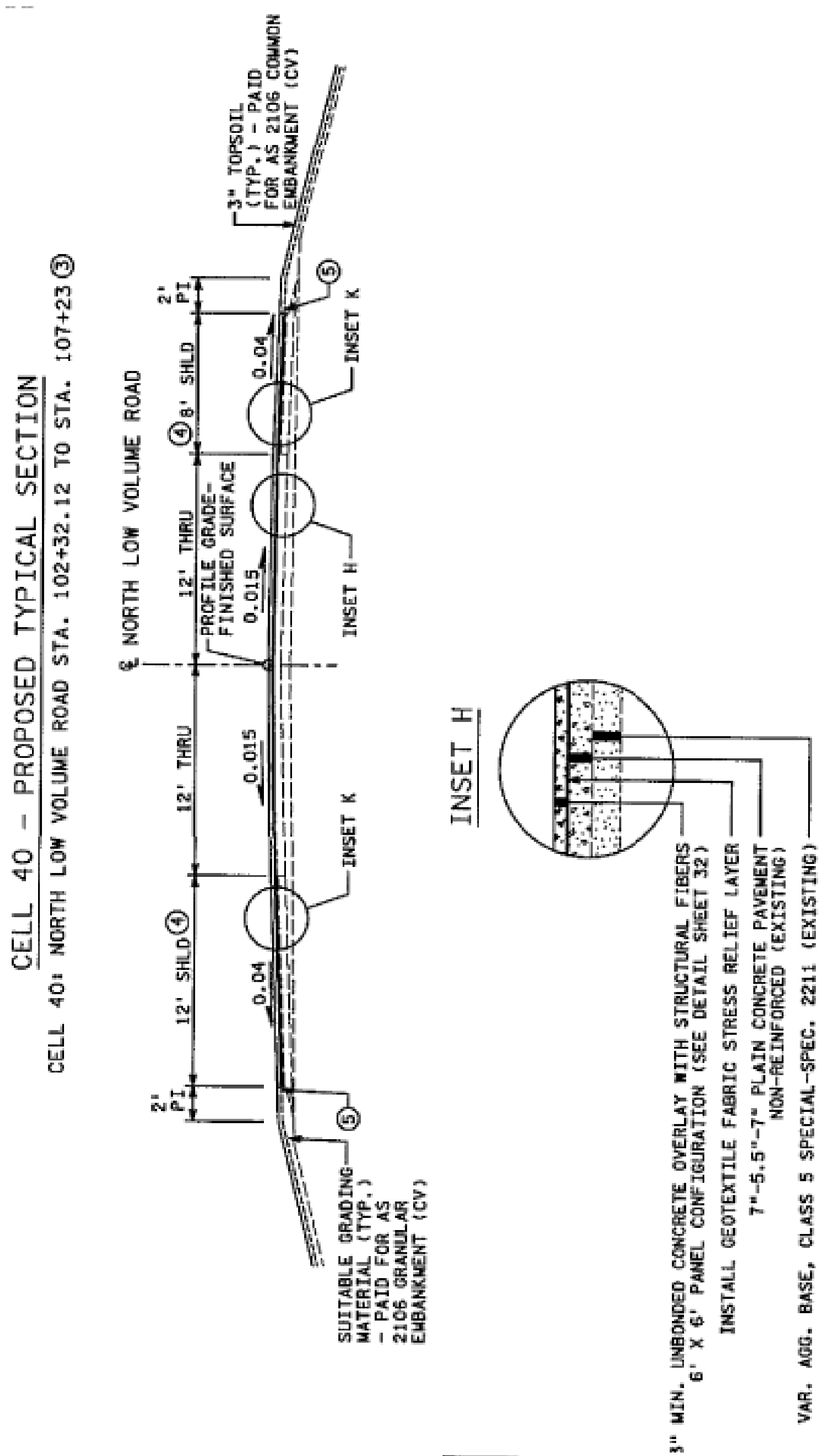
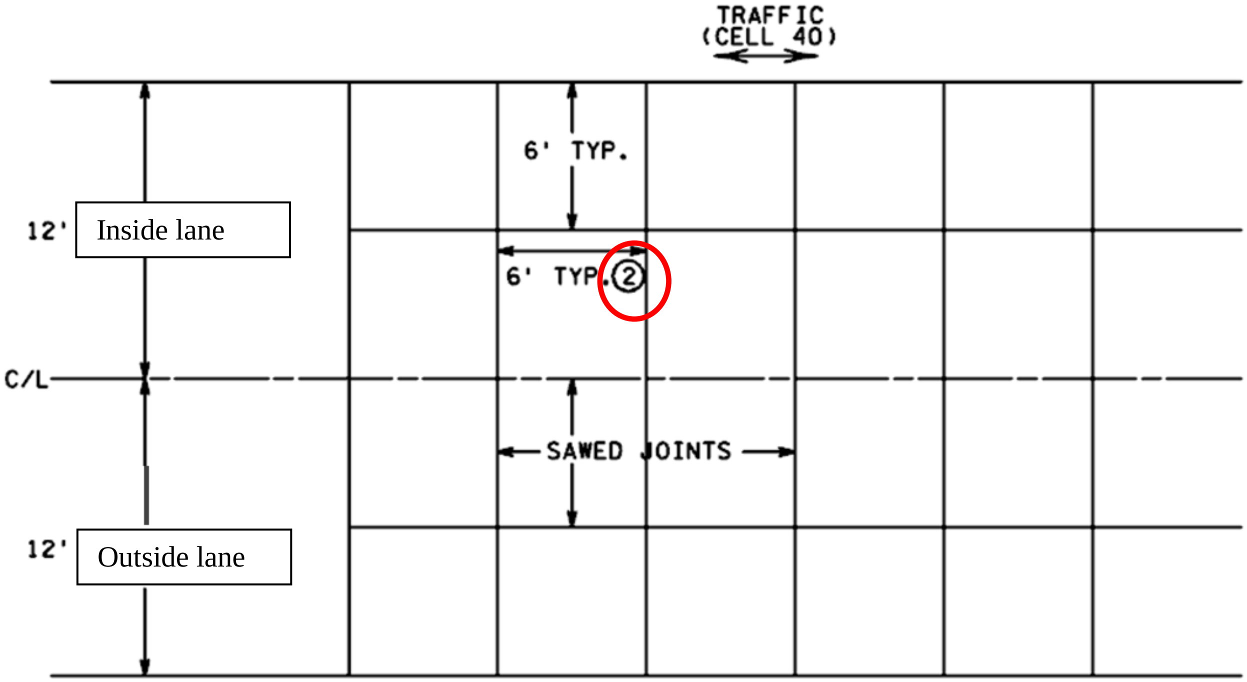


Figure 3.4c – Joint layout for cells 140 and 240.



Joints in cells 161 and 163 were to remain unsealed, however due to miscommunication all joints were sealed in the field. For simplicity of data collection and reporting, cell designations 161 and 163 will be dropped.

Some additional construction details include the following:

- Concrete overlay consists of 6 by 6-foot panels
- All joints in the overlay are undoweled.
- 6.5 pounds per cubic yard of macro fibers were used in the mix.
- Concrete mix utilized CA-35 concrete coarse aggregate designation, with maximum top size of 1.25 inch to account for the 4 inch thick slabs.
- The concrete was specified to reach 120 psi residual strength according to ASTM C1609.
- Transverse and longitudinal joints consist of a single saw cut and bituminous hot-pour sealant.

3.2.4 Cell 613

Figure 3.6 shows the general cross section for the test cell 613. Some additional construction details include the following:

- 15 by 12-foot panels.
- All transverse joints contain 1-inch diameter epoxy coated steel dowels; all longitudinal joints are tied with 3/4 inch diameter tie bars.
- 75% of the coarse aggregate in the concrete mix consists of recycled concrete aggregate from crushed concrete pavements (contractor's stockpile).
- Transverse joints are narrow cut (1/4-inch width) with neoprene (preformed) joint seals.

Figure 3.5a – Design section for cell 160 (note joints in 161 inadvertently sealed).

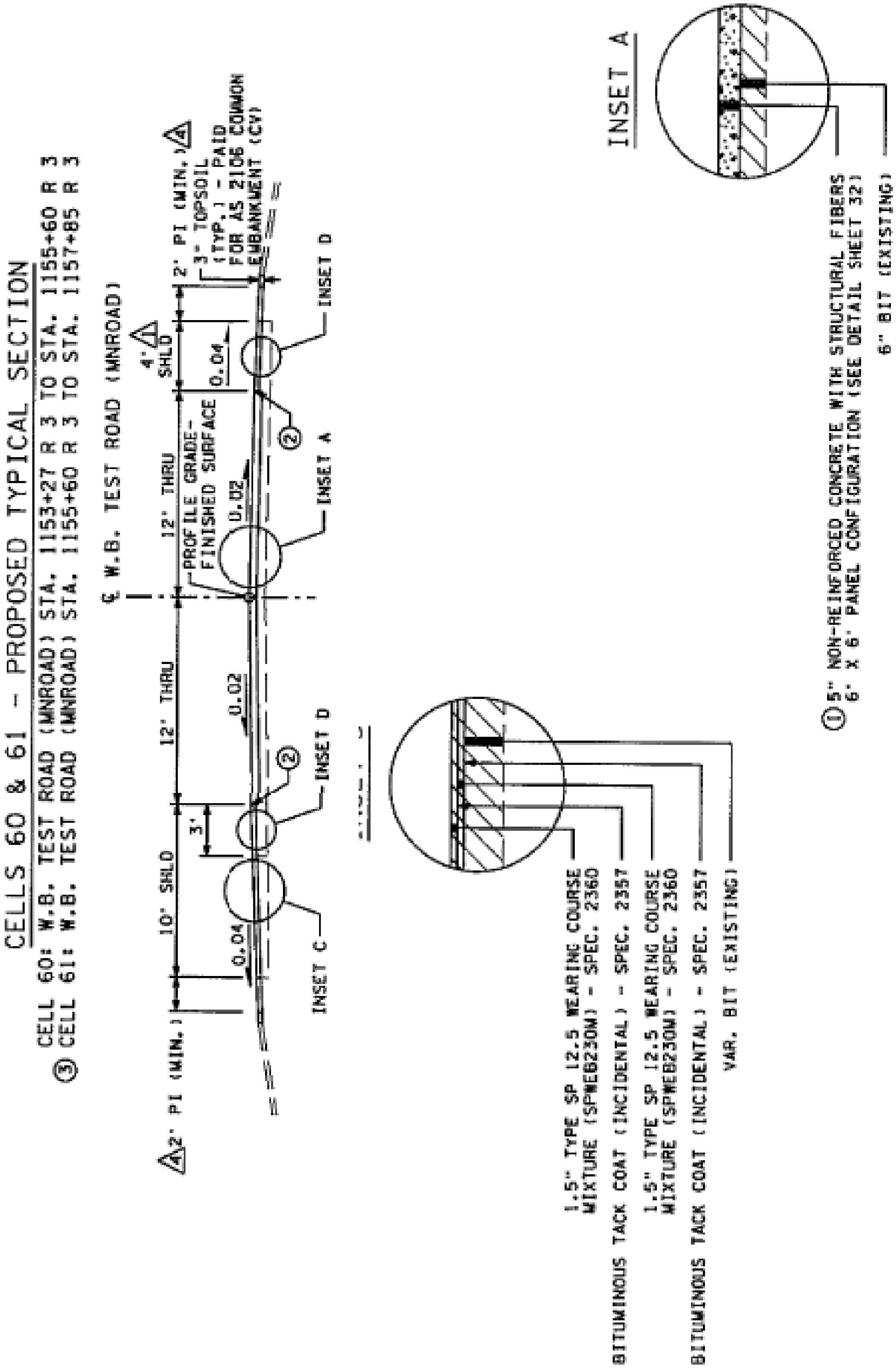


Figure 3.5b – Design section for cells 162 (note joints in 163 inadvertently sealed).

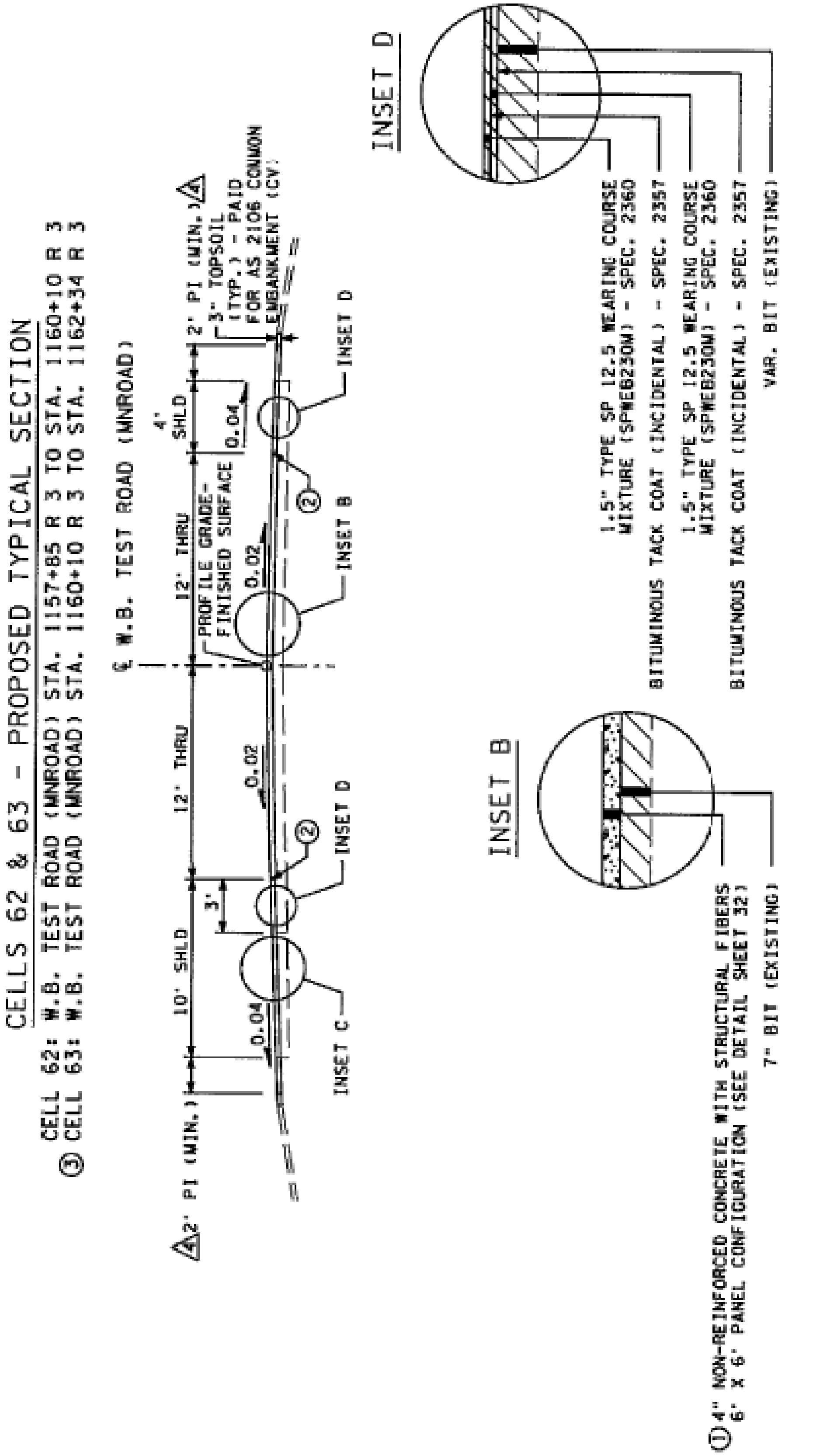
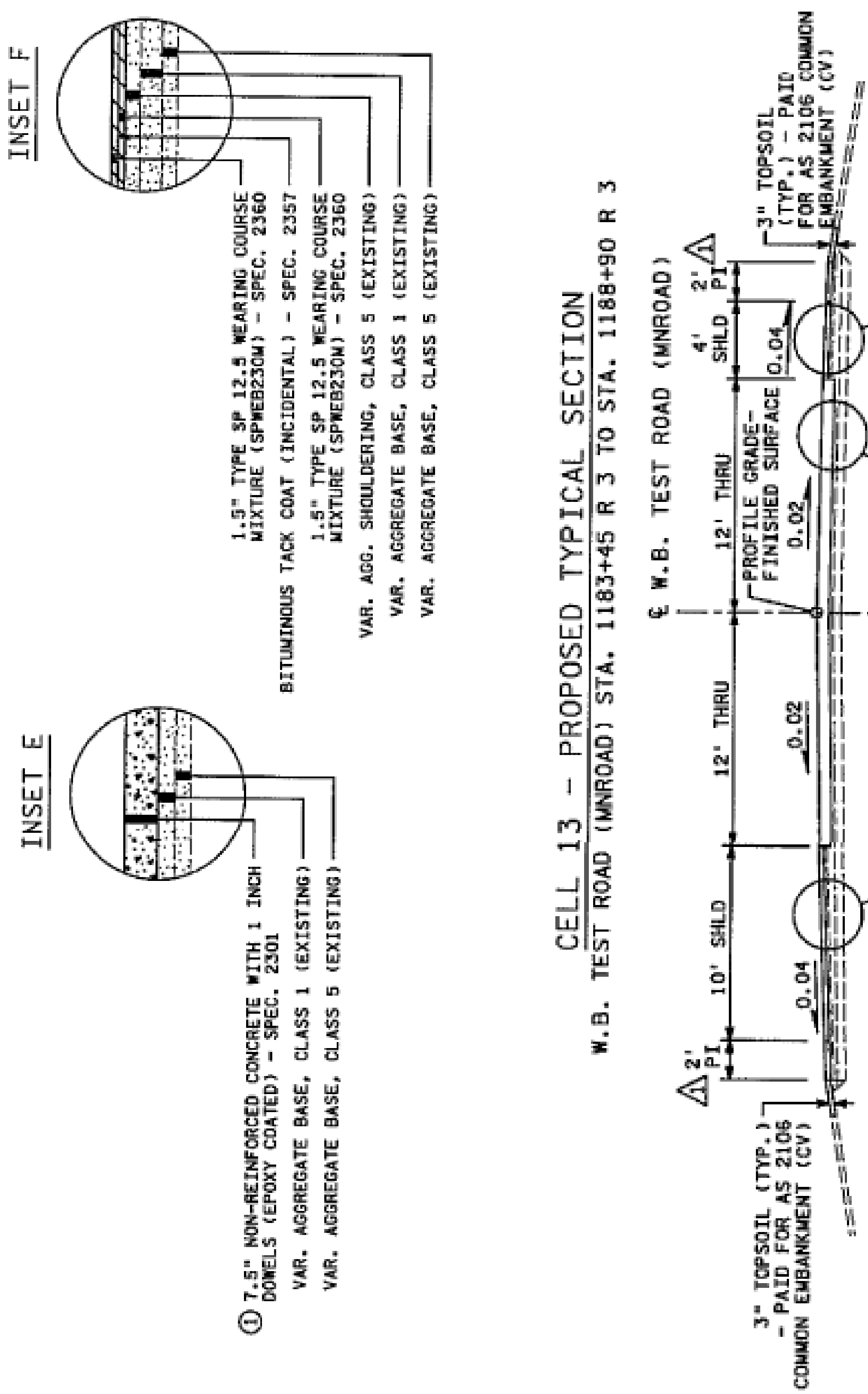


Figure 3.6 – Design section for cell 613.



3.3 Concrete Mixes

Contractor mix designs were required for this project and the prime contractor (McCrossan) retained Aggregate Industries to develop the trial mix designs. The trial mix process and progressive results are available on file in the concrete research group.

3.3.1 Cell 140, 240

The concrete overlay in cells 140 and 240 was paved with structural fiber reinforced mix designated MnDOT Mix MR3A21-2F. The mix designs and material specifications are provided in Tables 3.2a and 3.2b below.

The amount of structural (synthetic) fibers needed was determined by trial mix batches and testing (by the contractor) until the mix met the 120 psi residual strength criteria as determined by the ASTM C1609 procedure. See Appendix D for trial mix results.

3.3.2 Cells 160 and 162

The whitetopping in cells 160-163 was paved with MnDOT mix MR3A21-1F, with the only difference in mix design from cells 140 and 240, being the maximum aggregate size. The mix designs and material specifications are provided in Tables 3.3a and 3.3b below.

Similar to cells 140 and 240, the amount of structural (synthetic) fibers needed was determined by trial mix batches and testing (by the contractor) until the mix met the 120 psi residual strength criteria as determined by the ASTM C1609 procedure. See Appendix D for trial mix results.

3.3.3 Cell 32 Retrofit Load Transfer Patching Mix

MnDOT requires non-shrink rapid set concrete material for dowel bar retrofit repairs meet ASTM C 928-92a. With the exception of four special repairs, Five Start Patching Mix™ was used. On the special repairs D.S. Brown PaveSaver™ was used.

3.4 Cell 613

The concrete in cell 613 was paved with MnDOT Mix MR3A21R75. The contractor proposed, and was approved by MnDOT, to use 75% replacement of the coarse aggregate in the concrete mix with recycled concrete aggregate. Recycled concrete aggregate was provided by the contractor from an existing stockpile of material salvaged from projects originally constructed with MnDOT-based specifications. A MnDOT representative visually inspected the contents of the stockpile both before and during the crushing operation. The mix designs and material specifications are provided below in Tables 3.4a and 3.4b.

3.4.1 SP 8680-169 All Concrete Mixes

The following Table 3.5 provides material sources and specification for all cells constructed during reconstruction.

3.5 Geotextile Fabric Interlayer Specifications

Properties specified for the geotextile interlayer fabric are shown in Table 3.6.

3.6 Surface Texture

3.6.1 Cells 613 and 140, 240: Longitudinal Tine

To achieve the best performance the surface was void of bleed water arising from over-finishing or other unacceptable practices.

Prior to texturing to achieve longitudinal tine, an inverted turf drag pre-texture was applied. Pre-texturing provided a minimum of 1.2 mm mean profile depth (MPD) behind the paver, ahead of the rake bridge. Uniformity of 1.2 to 1.5 mm was the desired setting. Uniform pressure was achieved by the use of a suitable chain placed across the inverted turf, with its weight providing a uniformly distributed load (UDL). The use of aggregate to achieve the UDL was prohibited. The surface was void of scrapings since scrapings that would inhibit subsequent tining were not acceptable.

Table 3.2a – Cell 140, 240 mix design.

Water	228
Cement	420 (70%)
Fly Ash	180 (30%)
Total Cementitious	600
W/CM	0.38
Sand #1	1235 (41%)
CA #1	1790 (59%)
Air Content	7.0
Slump Range, inches	1 – 4
Admix #1 Dos Range	N/A
Admix #2 Dos Range	0 – 5
Admix #3 Dos Range	0 – 12
Admix #4 Dos Range	0 – 6
Propex Structural Fibers	6.5

Note: All weights are in lbs/cy, admixtures dosages are in oz/cy.

Table 3.2b – Cell 140, 240 material information.

	CA #1	Sand #1
Pit Number	71041	71041
Pit Name	Elk River	Elk River
Size/Fraction	#67	Sand
Specific Gravity	2.69	2.63
Absorption	0.013	0.009
Aggregate Class	C	N/A

Table 3.3a – Cells 160 and 162 mix design.

Water	228
Cement	420 (70%)
Fly Ash	180 (30%)
Total Cementitious	600
W/CM	0.38
Sand #1	1165 (38%)
CA #1	580 (19%)
CA #2	1295 (43%)
Air Content	7.0%
Slump Range, inches	1 – 4
Admix #1 Dos Range	N/A
Admix #2 Dos Range	0 – 5
Admix #3 Dos Range	0 – 12
Admix #4 Dos Range	0 – 6
Propex Structural Fibers	6.5 lbs/yd^3

Note: All weights are in lbs/cy, admixtures dosages are in oz/cy.

Table 3.3b – Materials information for cells 160 and 162.

	CA #1	CA #2	Sand #1
Pit Number	71041	71041	71041
Pit Name	Elk River	Elk River	Elk River
Size/Fraction	#4	#67	Sand
Specific Gravity	2.75	2.69	2.63
Absorption	0.009	0.013	0.009
Aggregate Class	C	C	N/A

Table 3.4a – Cell 613 mix design.

Water	228
Cement	400 (70%)
Fly Ash	170 (30%)
Total Cementitious	570
W/CM	0.40
Sand #1	1105 (38%)
CA #1	138 (5%)
CA #2	309 (11%)
CA #3	1340 (46%)
Air Content	7.0%
Slump Range, inches	1 – 3
Admix #1 Dos Range	N/A
Admix #2 Dos Range	0 – 5
Admix #3 Dos Range	0 – 12
Admix #4 Dos Range	0 – 6

Note: All weights are in lbs/cy, admixtures dosages are in oz/cy.

Table 3.4b – Cell 613 material information.

	CA #1	CA #2	CA #3	Sand #1
Pit Number	71041	71041	27005	71041
Pit Name	Elk River	Elk River	McCrossan	Elk River
Size/Fraction	#4	#67	Recycled	Sand
Specific Gravity	2.75	2.69	2.39	2.63
Absorption	0.009	0.013	0.042	0.009
Aggregate Class	C	C	R	N/A

Table 3.5 – Additional material notes.

	Manufacturer/Supplier	**Mill/Pant/ Admix Name**	**Type/Class**	**Specific Gravity**
Cement	Holcim-St. Genevieve	STGBLMO	I/II	3.15
Fly Ash	Headwaters – Coal Creek	COCUNND	C/F	2.50
AEA- Admix #1	Sika AIR 260	SIAIR260	AEA	N/A
Admix #2	Sika Plastocrete 161	SIPC161	A	N/A
Admix #3	Sika Sikament 686	SIKA686	A	N/A
Admix #4	Sika Viscocrete 2100	SIVIS2100	E	N/A
Structural Fibers	Propex Fibermesh® 650	N/A		

Table 3.6 – Geotextile specifications (standard weight fabric only).

Property	**Requirements**	**Test Procedure**
Geotextile type	Nonwoven, needle-punched geotextile, no thermal treatment (calendaring or IR)	Manufacturer Certificate of Compliance
Color	Uniform/nominally same-color fibers (White)	Visual Inspection
Mass per unit area	≥ 450 g/m^2 (13.3 oz/yd^2) ≤ 550 g/m^2 (16.2 oz/yd^2)	ASTM D5261
Thickness under load (pressure)	[a] At 2 kPa (0.29 psi): ≥ 3.0 mm (0.12 in) [b] At 20 kPa (2.9 psi): ≥ 2.5 mm (0.10 in) [c] At 200 kPa (29 psi): ≥ 1.0 mm (0.04 in)	ASTM D5199
Wide-width tensile strength	≥ 10 kN/m (685 lb/ft)	ASTM D4595
Maximum elongation	≤ 60%	ASTM D4595
Water permeability in normal direction under load (pressure)	At 20 kPa (2.9 psi): ≥ 1x10-4 m/s (3.3x10-4 ft/s)	Mod. ASTM D5493 or ASTM D4491
In-plane water permeability (transmissivity) under load (pressure)	[a] At 20 kPa (2.9 psi): ≥ 5x10-4 m/s (1.6x10-3 ft/s) [b] At 200 kPa (29 psi): ≥ 2x10-4 m/s (6.6x10-4 ft/s)	Mod. ASTM D6574 or ASTM D4716
Weather resistance	Retained strength ≥ 60%	ASTM D4355 @ 500 hrs. exposure
Alkali resistance	≥ 96% polypropylene/polyethylene	Manufacturer certification of polymer

The final texture was achieved using a rake that imprinted sufficient longitudinal tines at acceptable intervals to produce a texture to guarantee a MPD of 1.3 to 1.5 mm behind the paver. The rake used produced pavement grooves at a 0.75 inch (19 mm) center-to-center spacing. The tine spacing was perpendicular to the direction of travel. The grooves were 1/8 inch deep or greater to ensure an initial ribbed tire friction number of 45.

3.6.2 Cells 160 and 162: Transverse Broom

Texturing was provided by drawing a broom transversely along the plastic concrete surface. Based on three tests a minimum of 1.2 mm mean profile depth (MPD) was attained behind the paver. Results of initial texture measurements are presented in a subsequent section.

CHAPTER 4 – CONSTRUCTION SEQUENCE

4.1 SP 8680-169 (New Concrete Construction)

Michael Rief and Michael Klasen of WSB & Associates were responsible for the construction inspection and administration for SP 8680-169 that started May 21, 2014 and ended July 21, 2013. A summary of construction activities is presented in Table 4.1 below.

Following construction, it was noted that cells 160-163 did not have a constant cross slope. There was a slight rise at each lane/shoulder edge that prevented complete drainage of surface water after a rain event. The cause was determined to be due to the practice of slightly tipping the wings of the paver up, in anticipation of edge slump after paving. However, the pavement edges in these sections did not slump as expected. Due to concerns about the safety of the traveling public, the contractor was asked to diamond grind the edges to allow complete surface drainage. Grinding was completed on July 21, 2013. Adequate drainage was verified using water from the contractor's water truck.

The thickness of all concrete sections was slightly greater than intended. This is a recurring challenge with paving test sections, because contractors generally pave slightly thicker than the design thickness in order to avoid penalties for not meeting minimum thickness requirements. This is despite informing the contractor that no penalties would be applied, and that it was important to get the thickness as close to design as possible.

A new method for securing a geotextile fabric interlayer was tested in cells 140 and 240. An adhesive normally marketed for connecting sections of geotextile together was used to bond the fabric to the existing concrete surface in lieu of nails. It was deemed successful. The adhesive was applied in a continuous line along the edges of the fabric, and at spots about 3 feet apart in the interior. The fabric was secured to the existing concrete surface on a Friday, and covered with poly to prevent it from becoming saturated by rain that was predicted for the weekend. The fabric was still in place on Monday. During paving, the fabric did not shift under the turning wheels of ready-mix trucks. If a wrinkle formed, it was discovered that the fabric was not difficult to pull up and reposition (additional adhesive was applied during the repositioning process).

The original research plan for cells 161 and 163 called for the transverse joints to remain unsealed. Due to miscommunication, however, the subcontractor sealed all of the joints in cells 160-163. After discussions with a MnDOT contracting specialist and the contractor, it was determined that language in the plans and special provisions did not clearly convey these joint sealing instructions. Due to the difficulty in removing hot-pour asphalt sealant from the single saw cut joints, the research team decided to leave the joints sealed in cells 161 and 163. Since early data was collected using all of the cell numbers, it was also decided to keep all four cell designations for the time being.

To explore the potential for improved drainage underneath transverse concrete pavement joints, a geotextile covered drain material (Tensar RoaDrain™) was installed under six of the joints in cell 613. The manufacturer shipped enough material to place under the joints, however, it was discovered too late that the internal drainage baffles were oriented at a 45 degree angle to the edge of the fabric. It was decided to simply cut the 15 inch wide strips of material at a 45 degree angle, such that the internal baffles were oriented perpendicular to the direction of traffic (in the down slope direction toward the shoulder and ditches). See Figure 4.1.

Additionally, the orientation requirement necessitated splicing of the pieces to span the full width of roadway (two lanes and shoulders) and also be daylighted at the shoulder PI. Splicing was achieved by

Table 4.1 – Field construction notes/daily summary for SP 8680-169.

Date	Notes
5/21/13	McCrossan began concrete pavement removals on original cell 13 STA: 1183+42 - 1185+00. End at 2:30 pm, due to punctured tire on loader. Utilized 3 tri-axle dump trucks to haul rubble off-site to St. Michael Pit. Erickson Builders saw cut concrete and bituminous ends on all Cells. Turf Police: 1 person slicing in silt fence on cell 40. Worked from 9:30 am - 4:30 pm
5/22/13	McCrossan began concrete removals cell 60 - 63 STA: 1153+35 - 1160+00 due to wet conditions on cell 613. Four trucks hauling concrete to St. Michael Pit. Used a 950 loader for concrete removal. Turf Police installed silt fence around cell 60 - 63 along Lt, Rt side they did not finish.
5/23/13	McCrossan finish removing concrete on cell 60 - 63 and finish removing concrete on cell 13. Also milled notches on cell 40 and milled shoulders on cells 60 - 63 & 13, stockpiled all millings in the MnDOT stockpile area. Two trucks used for hauling millings and 4 trucks for hauling concrete to St. Michael Pit. Turf Police: Three personnel continue to install silt fence along cells 160 - 163. MnDOT worked on installing sensors in cells 140, 240, due to schedule change.
5/24/13	McCrossan cleaned up work area and peeled topsoil back in cell 613. Also bladed and sealed with a roller the subgrade in cell 613. End at 10:00 am. Turf Police continued to install silt fence along cell 163 and cells 140, 240. MnDOT continued to work on sensors in cells 140, 240.
5/28/13	McCrossan set up string line for profile milling in cells 160 - 163. Gorman Surveying staked paving hubs on all cells. MnDOT continued to work on instrumentation in cells 140, 240.
5/29/13	McCrossan profile milled bituminous in cells 160 - 163. Average depth of bituminous removed was 1.0 inch +/-, millings were stockpiled in MnDOT stockpile area. Turf Police finished installing silt fence along cells 160 - 163 and along the south side of cells 140, 240. MnDOT continued to work on instrumentation in cells 140, 240.
5/30/13	MnDOT finish initial instrumentation in cells 140, 240.
6/3/13	Turf Police finished installation of silt fence along cells 140, 240 north side. MnDOT installed fabric over sensors in cells 140, 240, covered fabric with 10 mil poly, and began instrumentation installation in cells 160-163.
6/4/13	McCrossan mobilized the concrete paving train and staged it at east end of cells 140, 240. MnDOT continued to work on instrumentation in cells 160 - 163.
6/5/13	McCrossan: No work performed. Results of the concrete mix design trial batch for cell 140, 240 not meeting specs. String line installed along north side of cell 613. MnDOT continued to work on instrumentation in cells 160 - 163.
6/6/13	McCrossan finished string line and checked profile of cells 140, 240. The profile was found to have inconsistencies between what was staked and what was planned. It was determined, in coordination with MnDOT, they would need to field fit the profile so a consistent 3 inch concrete pavement section could be achieved. McCrossan, together with WSB, set the string line to the desired elevation to meet a 3 inch pavement thickness requirement.

Table 4.1 – Field construction notes/daily summary for SP 8680-169, cont.

Date	Notes
6/7/13	McCrossan installed fabric in cells 140, 240 on the concrete part of the roadway only. Covered the fabric with poly for the weekend. The remaining fabric would be placed on shoulder after the concrete paving operations were complete. MnDOT continued to work on instrumentation in cells 160-163.
6/10/13	McCrossan paved cells 140, 240 from east to west, STA: 107+23 - 101+82. Started at 9:00 am and finished around 1:30 pm. Three control beams were cast at the end of the day. Also screened millings in MnDOT stockpile area to create aggregate base special for shouldering. Superior Sawing on-site to saw cut joints in cells 140, 240, approximately 6 hrs after concrete paving operations were completed. MnDOT crews finished installing fiber optic sensors in cells 140, 240, prior to paving. Covered and vibrated concrete around sensors as paving commenced.
6/11/13	McCrossan moved concrete paver to cells 160-163 and set up for paving. Also drained standing water on west end of cells 160-163. MnDOT crews worked on cell 160-163 sensor placements.
6/12/13	McCrossan: no work performed due to rain. MnDOT crews finished cell 160-163 sensor installations.
6/13/13	McCrossan paved cells 160-163. Started at 9:00 am and finished at 3:00 pm. See paving summary spreadsheet. Superior Sawing on-site to saw cut joints in cells 160-163 approximately 6 hrs after concrete paving operations were completed.
6/14/13	McCrossan trimmed and compacted the driving lane in cell 613 so MnDOT could begin sensor placement and installation. McCrossan also cleaned cells 140 and 240 shoulders and extended fabric across them. MnDOT crews worked on sensor placement in cell 613. Also corrected a drainage issue with a vault.
6/17/13	MnDOT crews worked on placing sensors in cell 613.
6/18/13	MnDOT crews continued to work on placing sensors in cell 613.
6/19/13	McCrossan on-site, placing Aggregate Shouldering Material in cells 140, 240, compacting with a rubber tire roller. Then moved to cell 613 to trim the passing lane and compact it. Also, placed dowel baskets in preparation for paving.
6/20/13	McCrossan paved cell 613. Started on the west end of the cell and pave toward the east. Started at 7:00 am and finished at 12:00 pm. Superior Sawing on site to green saw joints around 1:30 pm.
6/21/13	McCrossan on-site to strip sample beams. WSB delivered samples to the Maplewood lab. No other work performed.
6/24/13	Superior Sawing on-site to widen saw cuts in cell 613.
6/25/13	McCrossan hauled Aggregate Base Special from MnROAD stockpile area to cell 140, 240 Shoulders and placed. Also, performed sand patch tests on all cells. Superior Sawing cleaned and sealed joints with hot pour asphalt sealant in cells 140, 240, 160-163.
6/26/13	Superior Sawing cleaned and installed neoprene preformed joint seals in cell 613. The joints were saw-cut too wide on half of the cell from Sta: 1186+17.5 - 1188+90. Therefore they used the same neoprene gasket throughout the entire cell (except for the last 4 joints). In the last 4 joints, STA 1188+90 – 1188+30, they used backer rod and hot-pour asphalt sealant. D.S. Brown, the material supplier, was on-site during the sealing operations.

Table 4.1 – Field construction notes/daily summary for SP 8680-169, cont.

Date	Notes
7/1//13	McCrossan graded shoulders and hauled a few loads of millings from the MnDOT stockpile area ahead of paving. The bituminous crew paved shoulders in cells 160-163, then moved to cell 613. They also fog sealed the shoulders in cells 140, 240. Worked occurred from 7:00 am - 6:30 pm. Erickson Builders placed joint adhesive in shoulder joints along cells 160-163.
7/3/13	McCrossan placed Aggregate Shouldering Special along the outside of the bit shoulders in cells 160-163 and cell 613. One quad axle truck hauled millings from the MnDOT stockpile area. A skid steer and blade was used to place and grade the shoulders. 2’ of additional shouldering material was also placed along cells 140, 240, using a shouldering machine. Worked occurred from 11:00 am - 9:30 pm. Erickson Builders on site at 11:00 am to rout and seal shoulder joints along cell 613.
7/5/13	McCrossan swept cells 13 and 160-163 and started final cleanup of work site.
7/9/13	Rain in the morning. Noticed water ponding on the west end of cell 160 due to the topsoil/slope being high. McCrossan came out with the loader and removed approximately 4 loads of common topsoil and graded inslope along STA: 1153+35 - 1155+50 Rt. Also, loaded rubble piles in MnDOT stockpile area and hauled to their Maple Grove Pit.
7/10/13	McCrossan on-site to apply shoulder tack on cells 160-163, 613 & 140, 240. Turf Police on-site to seed and blanket topsoil inslopes along cells 160-163 & 613.
7/11/13	McCrossan on-site early morning for final walkthrough and cleanup of concrete debris and rills from paving operations. Contract working days expired at the end of the day.
7/12/13	Turf police on-site early to finish final cleanup of silt fence and posts. Also, secured erosion control blanket along the shoulders on TH94.
7/21/13	The outside edges of the concrete travel lanes in cells 160-163 required diamond grinding to facilitate surface drainage. During typical concrete paving, the paver wings are tipped up to accommodate mixture slump at the edge of the pavement. The edges of cells 160-163 did not slump as expected. This created a slight lip near the lane/shoulder edge of the pavement. This lip prevented complete drainage from the surface of the pavement. Diamond grinding was completed at 11:00 p.m.

Figure 4.1 – Installation of drainage fabric under joints in cell 613.

securing the geonets in a butt-joint using strings and subsequently lap-joining the non-woven geofabric (top to top and bottom to bottom) with adhesive.

4.2 SP 8680-170 (Concrete Rehabilitation)

Benjamin Worel and Thomas Burnham of MnDOT were responsible for the construction inspection and staff from MnDOT District 3 helped with the contract administration for SP 8680-170 that started May 21, 2014 and ended July 21, 2013. A summary of construction activities is presented in Table 4.2 below.

A summary of construction field quantity changes are presented in Table 4.3 below.

Table 4.2 – Field construction notes/daily summary for SP 8680-170.

Date	Notes
10/2/2013	**Full Depth Concrete Removals** Weather - Clear and 45F Equipment – Saw, water truck, 2 skid loaders with jackhammers, side dumper, 2 pickups and 5 people. 7:00 am Contractor marked out removals to be cut. Removal areas were adjusted to ease saw cutting. Several areas were widened, therefore slightly increasing replacement quantities. This was approved by MnDOT, and total quantities were measured and documented by Tom Burnham. Ten areas were cut (120.81 square yards), broken into smaller pieces for skidloaders to remove, and then taken off site for disposal. Weep drains were cut in the aggregate shoulder to direct any rain/run-off into the ditch. No standing water occurred in the removal areas, even with a couple rainy days.
10/7/2013	**CoVex Plate Dowels Installed** PNA (MnROAD research partner) cut the CoVex plate dowel slots and epoxied the plate dowels around the perimeter of the repair areas. **Test Joints** Eight dowel bar retrofits were cut and placed by the contractor in the morning. Cores were cut through the load transfer devices in the afternoon, showing both the plate and round dowels had adequate coverage of concrete around the load transfer devises. OK was given to contractor for the rest of the dowel bar retrofits. Final slot dimensions were agreed upon to be 32 inch long x 3.25 inch wide for plate dowels, and 32 inches long x 2.5 inches wide for the round dowels. Both slot types were cut 3 inches deep.
10/8/2013	**Placement of PCC Patches** 10:00-11:25 am - The contractor placed the full-depth concrete patches. The concrete was delivered with a slump of 2.75 inch and an air content of 5.9%. Only the first truckload was tested. Nine laborers plus one foreman. One additional concrete truck had to be ordered to fill the last repair area. There was a 20 minute gap until the remainder of the patch was filled.
10/11/2013	Weather - 70F, cloudy, very windy east wind, storms forecasted but never developed
	Tom at MnROAD in the morning. Ben at MnROAD in the afternoon. Process used by contractor: 1 – Saw Slots 2 – Chip out with jackhammer 3 – Pull out PCC 4 – Air blow 5 – Sand blast 6 – Blow with leaf blower 7 – Seal joints in slots with plaster 8 – Place dowels 9 – Blow again with leaf blower 10 – Wet slot with water before patching 11 – Patch (vibrate, flat trowel) 12 – Cure compound

Table 4.2 – Field construction notes/daily summary for SP 8680-170, cont.

Date	Notes
10/11/2013	**Dowel Bar Retrofit Slots Cut** Equipment – Slot cutter and water truck, semi with low boy trailer, pickup, three staff. 1:30-2:30 pm slots were cut by contractor using a slot cutting machine that would cut 2 or 3 slots across a joint with one pass.
	Dowel Bar Retrofit Removals Equipment - 4 jackhammers, sandblasting, air wand, 2 support trucks, skid loader with pickup, side dumper, ten staff. 2:30-4:30 pm material removed and taken away for disposal. Noted that a couple of slots, the chipping process broke through the bottom of the 5 inch PCC pavement. Compressed air was then used to clean-out each slot area. Between 4:30-5:00 pm slots were sandblasted and blown out using a leaf blower.
	Concrete Sampling American Engineering Testing (4:00 pm) made cylinders and beam samples that will be tested by them after they cure. Air tests were not done since these types of dowel bar patching mixes tend to cause the equipment to clog and damage it. Slump was very high with the patching mix.
	Load Transfer Placement The contractor treated the slots at the joint with sheet-rock mud to prevent patching material working into the existing joints. Flat and round load transfer devices were placed and a final leaf blowing was done before concrete patching.
	D.S. Brown Patching D.S. Brown (three representatives) picked out two joints (one with retrofit plate dowels, one with retrofit round dowels) to install their new patching material as the backfill. Locations were marked on the shoulder to help identify the joints after surface grinding. Details on the patch material can be obtained from D.S. Brown.
	DBR Patching Equipment – one patch truck/mixer, sealant truck, crew of 12 staff. Weather – now 60F, cloudy, and very strong easterly wind. 6:30-7:15 pm. Patching of the outside lane going east, then patching of the inside lane going west. Patching included concrete dropped from patch truck, material pulled into slots, vibration both ends of dowels, hand trowel, cleanup excess, curing compound. Patches set up in 1-2 hours after placement. No issues other than the contractor ran out of materials at the last joint in the outer wheelpath, inside lane to the west was patched with 3U18 mix provided by MnDOT. Contractor cleaned up shoulder weep drains. 7:30 pm everyone left the site.

Table 4.2 – Field construction notes/daily summary for SP 8680-170, cont.

Date	Notes
10/11/2013	**Diamond Grinding** Equipment – Diamond grinder, water truck, debris truck (tractor-trailer), support truck, flatbed trailer (for grinder), three workers. Diamonding grinding on cell 32 was done with no issues. Bernard Izevbekhai supervised initial grinding process on outer lane of cell 39, from late afternoon into evening. Additional bump grinding using the onsite equipment was also done under this contract in other cell transition areas to allow for smoother ride. It took 3 hours to complete this extra task costing $1,746 overrun.
10/15/2013	**Completed grinding both lanes of cell 39.** Also completed additional bump grinding in other cell transition areas to allow for smoother ride. It took 3 hours to complete this extra task, costing $1,746 overrun.

Table 4.3 – Summary of plan and field quantities.

Item	Plan Quantities	Unit	Field Quantities
MOBILIZATION	1	Lump	1
DOWEL BAR RETROFIT	245	Each	245
JOINT REPAIR (TYPE A2)	1,436	Linear Feet	1,436
CONCRETE GRINDING	1,217	Square yards	1,217* +$1,746.00
PAVEMENT REPLACEMENT (TYPE CX)	112	Square yards	120.81 +$1,776.71

*Bump grinding was done on other transitions on the LVR for 3 hours of extra time above the agreed upon contract. Diamond Surfacing will invoice the contract $1,746 extra costs as agreed. Total contract costs increase is $3,522.71.

CHAPTER 5 – MATERIALS AND SAMPLING

Sampling and testing contract was awarded to American Engineering Testing, Inc. The contract included rheological and mechanical strength tests on concrete from the three sets of test cells in addition to the regular testing.

Concrete field testing included slump and unit weight. The laboratory testing program included compressive and flexural strength, freeze-thaw durability, resistivity, chloride permeability, and coefficient of thermal expansion (COTE).

Certain unconventional tests were required in this contract to ascertain mechanical properties of fiber reinforced concrete and recycled aggregate concrete. These tests, shown in Table 5.1, include the following:

- Coefficient of Thermal Expansion AASHTO TP-90 to ascertain effect of fibers;
- Coefficient of Thermal Expansion Modified with VW sensor for comparison with AASHTO procedure;
- Residual Strength C1609 of fiber reinforced mixes;
- Freeze-Thaw Durability C666 of fiber reinforced mixes and recycled concrete mix;
- Scaling Resistance C672, Drying Shrinkage C157 and Modulus of Elasticity C469 of recycled concrete and fiber concrete;
- Petrographic C856 and Linear Traverse C457 especially for recycled aggregates and fiber reinforced concrete;
- E* (Dynamic Modulus of Elasticity) for HMA Substrate and RCA extraction and chemical analysis for HMA substrate of cells 160 to 163;
- Base evaluation with DCP and LWD (the air permeability device evaluation was performed by others); and
- Slant Shear Test C882 for compatibility of repair materials in cells 32 and 39.

Refer to Appendix B for initial test results.

Table 5.1 – Sampling, field and laboratory testing plan.

Laboratory Test	**ASTM (or other standard)**	**Cells 160-163 and Cell 140, 240**	**Cell 613**
Compressive Strength	C39	16	12
Flexural Strength	C78	16	12
Coefficient of Thermal Expansion (1 set of 3)	AASTHO TP-90	2	2
Coefficient of Thermal Expansion (1 set of 3)	Modified with VW sensor	2	2
Residual Strength	C1609	12	0
Freeze Thaw Durability (1 set of 3)	C666	3	3
Standard Spec for Repair Materials	C928	0	0
Slant Shear Test	C882	0	0
Rapid Chloride Permeability	C1202	3	6
Water/Cementious Determination		0	3
Scaling Resistance	C672	0	3
Drying Shrinkage	C157	0	3

Table 5.1 – Sampling, field and laboratory testing plan, cont.

Laboratory Test	**ASTM (or other standard)**	**Cells 160-163 and Cell 140, 240**	**Cell 613**
Modulus of Elasticity	C469	3	3
Petrographic (set of 3)	C856	1	1
Slump, Air, Temp		10	10
Linear Traverse	C457	3	3
E* for bit substrate		1	0
RCA extraction & chem analysis		1	0
Sampling + Batching		3	3
Base evaluation – DCP and LWD		0	1

CHAPTER 6 – INSTRUMENTATION

During construction sensors were installed within the sections in order to monitor pavement responses and environmental conditions. These include dynamic strain and deflection gages, subsurface moisture content and temperature sensors. The sensing systems are designed to study how traffic loadings and environmental conditions affect pavement materials and performance over time.

Table 6.1 below summarizes information on various sensor types and applications utilized in the 2013 MnROAD research construction efforts. Appendix C contains a detailed listing of each of the sensor types and locations installed at MnROAD.

Table 6.1 – Sensor types and applications used in MnROAD 2013 cell construction.

Sensor Type	Description	Make/Model	Application
CE	Concrete Embedment Strain Gauge	Tokyo Sokki Kenkyujo model PML-60	Used for concrete pavement (PCC) strain response due to dynamic loads. It is an electrical resistance strain gauge hermetically sealed between two thin resin plates. These sensors are embedded into the concrete slab near the top and bottom at various locations throughout a particular panel.
DT	Linear Variable Displacement Transformer	Schaevitz model HCD-500 or Macro GHSAR 750-250	These sensors measure surface layer vertical displacement due to dynamic loads. Displacements are measured relative to a fix reference point (a buried stainless steel or invar rod).
EC	ECH2O-5TE Volumetric Water Content	Decagon	This soil moisture sensor consists of three probes (in one unit) used to measure volumetric water content, temperature, and electrical conductivity in soils. Water content is determined using capacitance/frequency domain technology to measure the dielectric constant of the soil.
HC	Horizontal Clip Displacement Sensor	Tokyo Sokki model TML PI-5	Measures the opening and closing of a PCC transverse contraction joint due to environmental forces.
TC	Thermocouple	Omega Type-T thermocouple wire	Measures the temperature of a material in which it is embedded. A thermocouple sensor is a pair of dissimilar metal alloy wires (copper and Constantine) connected together near the point of measurement. Thermocouples generate an open-circuit voltage that is proportional to the temperature difference between the hot (point of interest) end and a reference junction.
VW	Vibrating Wire Strain Gauge	Geokon model 4200	Measures strain in a PCC slab due to material shrinkage and environmental forces.
WM	WaterMark Matric Potential Sensor	Irrometer Watermark 200-x	Used to measure both soil moisture content and frost depth in base and subgrade layers. The Sensor measures changes in electrical resistance due to changes in the soil moisture content.

CHAPTER 7 – PERFORMANCE MONITORING

This chapter documents the rheological and mechanical test results conducted respectively on plastic as well as hardened concrete at various ages. It also presents the various surface performance tests conducted on the pavements as soon as they were open to traffic. The novelty of the various design and a texture types necessitated careful initial monitoring so that survival characteristics can be better understood with time. The variables measured included mean profile depth. Some of the rheological and mechanical test results are plotted below. Detailed data are presented in Appendix B

7.1 Initial Monitoring Results

Post-construction surface characteristics are presented in this section.

7.1.1 Surface Texture

Surface texture data in the form of mean profile depth (MPD) determined using the CTM are presented in Table 7.1. It is important to observe the following regarding initial MPD data. Tined textures appeared to provide significantly higher MPD as observed in Table 7.1 for cells 40 and 13 in comparison to the transverse broom texture in cells 60 to 63. A MPD of 0.8 mm is not considered sufficient texture but due to the transverse texturing there may be sufficient friction in the cells. Although there is evidence of isolated low FN the overall numbers are comparable to what is common at the network level. Further evaluation and monitoring will be required.

7.1.2 International Roughness Index (IRI)

Post-construction IRI results (m/km) were determined using the lightweight inertial surface analyzer (LISA) are shown in Table 7.2; these values represent the average over each lane for both of the wheelpaths. Details on the LISA and contacts for obtaining data may be found on the MnROAD website at www.dot.state.mn.us/mnroad/data/pdfs/lisa.pdf.

Cell 13 showed an initially high IRI value (1.7 m/km) which may be attributed to the pumping of the base just before paving. Efforts were made to correct this situation during paving but it appears the base remained excessively wet. The suggested need for shorter panels with recycled concrete pavement did not appear to be the cause – when the power spectral density was examined the frequency spikes were not necessarily joint related. Cell 40 and cells 60-63 exhibited very good ride with IRI values less than 1.3 m/km. The shortness of test cells does not allow contractors sufficient length to stabilize their construction operations. In consequence the rate degradation of ride quality will be closely examined.

7.1.3 Surface Friction

Friction numbers in the form of FN40 determined using both smooth and ribbed tires are presented in Table 7.3.

7.1.4 Sound Intensity

Post-construction OBSI data, determined from the average of three separate runs, are presented in Table 7.4. As OBSI values were generally high in cells 140-240, 160 and 162, it is suggested that the fibers may be causal or associated but this will be validated in due course. For the transverse textures in cells 160 and 162 the predicted noise level is commensurate with the measured values. However, with the longitudinal tines it is almost conclusive that they do not approximate to diamond grinding even if the configurations are similar. Waviness and non-uniformity account for this difference.

7.2 Monitoring Plan

Table 7.5 summarizes the planned monitoring of each of the test cells based on research concept. This information will be collected, reviewed, analyzed and placed into the MnROAD database for the benefit and use of researchers.

Table 7.1 – Post-construction mean profile depths (mm) determined from CTM.

Cell	Statistic	Passing Lane	Driving Lane
613	Mean	1.39	1.14
	Largest	2.42	1.87
	Smallest	0.55	0.27
	Range	1.87	1.6
Cell	**Statistic**	**Inside Lane**	**Outside Lane**
140 240	Mean	1.51	1.47
	Largest	2.35	2.61
	Smallest	0.69	0.72
	Range	1.66	1.89
Cell	**Statistic**	**Passing Lane**	**Driving Lane**
160 162	Mean	0.99	0.88
	Largest	1.38	1.84
	Smallest	0.52	0.37
	Range	0.86	1.47

Table 7.2 – Post-construction IRI (m/km) from longitudinal surface profile measurements determined from LISA.

Cell	Statistic	Passing Lane	Driving Lane
613	Mean	1.50	1.70
	Largest	1.62	2.32
	Smallest	1.40	1.38
	Range	0.22	0.94
Cell	**Statistic**	**Inside Lane**	**Outside Lane**
140 240	Mean	1.70	1.33
	Largest	1.78	1.40
	Smallest	1.61	1.21
	Range	0.17	0.19
Cell	**Statistic**	**Passing Lane**	**Driving Lane**
160 162	Mean	1.31	1.51
	Largest	1.74	1.95
	Smallest	1.07	1.22
	Range	0.67	0.73

Table 7.3 – Post-construction friction testing results from 2013 construction.

CELL	LANE	DAY	TIME	FN	PEAK	SPEED (mph)	TIRE
613	Driving	14-Oct-13	10:44	40.9	64.7	40.2	Ribbed
613	Passing	14-Oct-13	10:33	33	43.92	39.8	Smooth
613	Passing	14-Oct-13	10:23	45.7	69.27	40.2	Ribbed
613	Driving	14-Oct-13	10:54	39.4	62.6	40.2	Smooth
140/240	Inside	11/18/2013	11:42	47.4	78.58	40.1	Ribbed
140/240	Inside	11/18/2013	13:10	43.3	77.92	40.4	Smooth
140/240	Outside	11/18/2013	13:14	50.0	83.52	39.1	Ribbed
140/240	Outside	11/18/2013	13:27	55.3	99.17	38.7	Smooth
160	Driving	14-Oct-13	10:45	45.5	69.59	40.6	Ribbed
160	Driving	14-Oct-13	10:55	45.9	70.74	40.6	Smooth
160	Passing	14-Oct-13	10:23	45.2	85.21	40.9	Ribbed
160	Passing	14-Oct-13	10:34	34.7	48.51	40.4	Smooth
161	Driving	14-Oct-13	10:45	47.4	65.96	40.5	Ribbed
161	Driving	14-Oct-13	10:55	45.0	69.35	40.6	Smooth
161	Passing	14-Oct-13	10:23	42.0	89.08	40.6	Ribbed
161	Passing	14-Oct-13	10:34	28.8	48.51	41.0	Smooth
162	Driving	14-Oct-13	10:45	44.9	83.25	39.7	Ribbed
162	Driving	14-Oct-13	10:55	50.1	88.43	39.8	Smooth
162	Passing	14-Oct-13	10:23	43.4	82.93	40.3	Ribbed
162	Passing	14-Oct-13	10:34	28.9	55.36	40.7	Smooth
163	Driving	14-Oct-13	10:45	40.4	63.85	40.2	Ribbed
163	Driving	14-Oct-13	10:55	43.6	63.99	40.2	Smooth
163	Passing	14-Oct-13	10:23	44.3	69.09	40.5	Ribbed
163	Passing	14-Oct-13	10:34	44.4	82.75	40.0	Smooth

Table 7.4 – On-board sound intensity (OBSI) measurement results (dBA) on 2013 constructed sections.

Cell	Statistic	Passing Lane	Driving Lane
613	Mean	104.2	103.4
	Largest	104.3	103.5
	Smallest	104.1	103.3
	Range	0.2	0.2
Cell	**Statistic**	**Inside Lane**	**Outside Lane**
140 240	Mean	103.5	103.0
	Largest	103.8	103.3
	Smallest	103.0	102.4
	Range	0.8	0.9
Cell	**Statistic**	**Passing Lane**	**Driving Lane**
160 162	Mean	105.3	104.9
	Largest	105.9	105.5
	Smallest	104.8	104.3
	Range	1.1	1.2

Table 7.5 – MnROAD typical test cell monitoring plan.

Measurement	Frequency	Description
Distress survey	2 / year	Modified LTPP survey on all cells
Dynamic Load Testing	4 / year	Dynamic load testing of sensors. Loading from MnROAD truck and FWD seasonally.
Joint Faulting/ Shoulder Dropoff	2 / year	Use an automated Georgia Faultmeter per modified LTPP protocol
Friction	1-2 / year	Dynatest Locked Wheel Skid Tester, Grip Tester and Dynamic Friction Tester
Falling-weight Deflectometer	4 / year	Testing schedule varies throughout the year; routine and special testing
Noise (AASHTO TP 76-11)	3 / year	On-Board Sound Intensity (OBSI) measurements and sound absorption
Ride Quality (IRI)	2-4 / year	Pathways and lightweight profiler
Sound Absorption	3 / year	Sound absorption measurements
Surface Texture	1 / year	Circular Track Meter
New OBSI	2 / year	Evaluate two fabrics for Helmholtz Resonance
Leachate of Recycled pavement	2 / year	Evaluate leachate for $CA(OH)_2$ and CSH as well as unreacted pozzolan in leachate

CHAPTER 8 – CONCLUSIONS

The foci of the 2013 MnROAD construction efforts include the following:

1. Performance testing of sustainable concrete pavement rehabilitations and designs;
2. Materials usage as in recycled aggregates and fiber inclusion as well as fabric interlayer;
3. Sustainable designs as in thin overlay with fiber and fabric interlayer;
4. Sustainable rehabilitation techniques using unconventional load transfer devices; and
5. Rehabilitation of an existing pervious overlay.

Former cells 113-513 were replaced with cell 613, a 7.5-inch thick concrete pavement containing a high percentage of recycled concrete aggregates in the mix. Former whitetopping cells 60-63 were removed and replaced with cells 160 and 162. These whitetopping sections are very similar to the former cells, except that a fiber-reinforced concrete mix was used this time. Existing cell 40, exhibiting multiple distresses after 20 years in service, was overlaid with an ultra-thin, 3-inch thick, fiber reinforced unbonded overlay placed on a geotextile fabric interlayer. Although the original idea of a drainable base was not pursued, the installation of the geotextile joint drain was successful and will be monitored continuously for effectiveness in lateral transmissivity of excess moisture.

Based on construction testing and initial data monitoring certain indicators are evident at this time. Initial mechanical property test results show that the coefficient of thermal expansion of the recycled aggregate concrete and the virgin aggregate concrete are not significantly different but are statistically similar. The sensor developed COTE process yielded the same result as the regular AASHTO method. This method has been validated in two prior projects at MnROAD; with the time savings and reliability of this process, AASHTO should consider replacing the traditional method with the sensor method.

The effect of fibers on mechanical properties can also be deduced at this time. There was no shift upwards or downwards in mechanical properties due to fiber content. However, the achievement of the specified residual strength of 120 psi by an increase of dosage to 6.5% is worthy of note.

Durability test results for recycled aggregate indicated that the change in relative dynamic modulus (RDM) was insignificant and comparable to the concrete of virgin aggregates although parallel studies optimize the recycled content at the substitution value 75% used in cell 13. Those parallel studies show that 40% recycled content indicated low mechanical properties.

Some surface performance indicators can also be deduced. The mean profile depth of the pre-textured longitudinal tine achieved the desired texture standard. The transverse broom did not achieve the required texture standard but both textures exhibited friction numbers that are comparable to typical network values.

Slant shear values obtained in the rehabilitation mix were not as high as what is typically obtained in rehabilitation mixes. Bond strength near 50% of the compressive strength of the repair material should have resulted in at least 2,500 psi. Values of 1,500 psi were obtained and indicate either sampling process defects or local damage during testing.

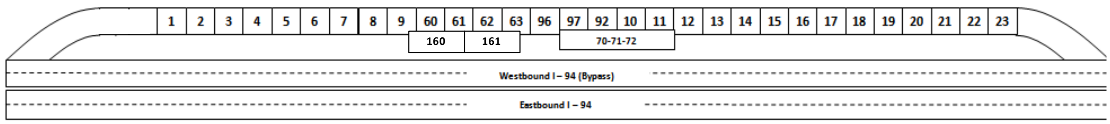
The unusually high IRI values observed in cell 13 are attributed to pumping in the base that resulted in some unevenness in the paved surface. Cell 13 appears to be within a subsurface drainage path as indicated by the geotechnical report (Lauzon, et al, 2012). Otherwise the in-situ efforts to correct the pumping should have been successful.

Appendix A

MnROAD Test Section Layouts

Figure A.1 – MnROAD mainline test cell layout.

MnROAD Mainline



	Original HMA	Stabilized Full Depth Reclamation of Asphalt			Unbonded Concrete Overlay of PCC				Concrete Initiatives		Original Concrete			Whitetopping Bonded Concrete Overlay of Asphalt		
Cell	1	2	3	4	505	605	305	405	306	406	7	8	9	160	162	96
Layers	6" 58 28 75 blow 33" Class 4 Driving Lane 1.5" 52-34 HMA inlay 2006 Micro Surface Aug 2012 Clay	1" TBWC 2 64 34 6" FDR + EE 6" FDR 26" Class 4 Clay	1" TBWC 2 64 34 6" FDR + EE 2" FDR 2" Cl 5 33" Class 3 Clay	1 64 34 2 64 34 8" FDR + EE 9" FDR + Fly Ash Clay	5" UBOL Fabric 7.5" cracked '93 PCC 3"Cl 4 27" Class 3 *6x7 6x6.5 no dowels *Trans Broom *RCC Shlds Clay	5" UBOL Fabric 7.5" '93 PCC 3"Cl 4 27" Class 3 *6x7 6x6.5 no dowels *Trans Broom *RCC Shlds Clay	5" UBOL 1" PSAB 7.5" '93 PCC 3"Cl 4 27" Class 3 15x14 15x13 no dowels Trad Grind Clay	5" UBOL 1" PSAB 7.5" cracked jts '93 PCC 3"Cl 4 27" Class 3 15x14 15x13 no dowels Trad Grind Clay	6" Long Tine 6" OGAB Sp 7" Class 5 Clay 15'x12' 1" dowel RCC Shlds	6" Long Tine 6" OGAB Sp 7" Class 5 Clay 15'x12' 1" dowel RCC Shlds	7.5" Trans Tined 4"PSAB 3"Cl 4 Clay 20x14 20x13 1" dowel 2007 Innovative Grind	7.5" Trans Tined 4"PSAB 3"Cl 4 Clay 15x14 15x13 13' PCC Should 1" dowel 2007 Traditional Grind	7.5" Trans Tined 4"PSAB 3"Cl 4 Clay 15x14 15x13 13' PCC Should 1" dowel 2008 Ultimate Grind	5" BCOA trans broom 6 58 28 93HMA Clay 6x6 Concrete Fibers	4" BCOA trans broom 7 58 28 93HMA Clay 6x6 Concrete Fibers	6" BCOA trans tined 7 58 28 93HMA Clay 6x5 Polypro Fibers 2011 Traditional Grind
Opened	Sep 92	Oct 08	Oct 08	Oct 08	Sep 11	Sep 11	Oct 08	Oct 08	Sep 11	Sep 11	Sep 92	Sep 92	Sep 92	Jul 13	Jul 13	Oct 97
Length (ft)	462	500	454	500	153	146	133	117	261	292	499	500	500	449	449	177
Gap (ft)	97	60	156	75	0	0	0	0	0	21	46	29	26	0	0	0

	2009 SHRP-II Composite Pavements				Original PCC	Recyled PCC	Whitetopping Bonded Concrete Overlay of Asphalt								
Cell	70	71	73	72	12	613	114	214	314	414	514	614	714	814	914
Layers	3 64 34 Saw/Sea 6" PCC Recycle 8" Class 7 Clay 15'x12' Driving 1.25" dowel	3" PCC EAC 6" PCC Recycle 8" Class 7 Clay Innovative Grind (driving) Convent. Grind (passing) 15'x12' 1.25" dowel	3" PCC 6" PCC Low Cost 8" Class 7 Clay Innovative Grind (driving) Convent. Grind (passing) 15'x12' 1.25" dowel	3" PCC 6" PCC Low Cost 8" Class 7 Clay EAC Surface 15'x12' 1.25" dowel	9.5" trans tined 5" Class 5 Clay 15x12 1.25" dowel	7.5" long tined 2.5" Cl 1 5" Class 5 Clay 15'x12' 1.25" dowel Neoprene Sealed	6" BCOA Turf Drag 5 58 28 93 HMA Clay 6'x6' Panels Driving 1" dowels	6" BCOA Turf Drag 5 58 28 93 HMA Clay 6'x6' Panels No Dowels	6" BCOA Turf Drag 6 58 28 93HMA Clay 6'x6' Panels Driving 1" dowels	6" BCOA Turf Drag 6 58 28 93HMA Clay 6'x6' Panels No Dowels	6" BCOA Turf Drag 7 58 28 93HMA Clay 6'x6' Panels Driving 1" dowels	6" BCOA Turf Drag 7 58 28 93HMA Clay 6'x12' Panels Driving plate dowels	6" BCOA Turf Drag 7.5 58 28 93HMA Clay 6'x6' Panels Driving 1" dowels	6" BCOA Turf Drag 8 58 28 93HMA Clay 6'x6' Panels No Dowels	6" BCOA Turf Drag 8 58 28 93HMA Clay 6'x6' Panels Driving 1" dowels
Opened	May 10	May 10	May 10	May 10	Sep 92	Jul 13	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08
Length (ft)	480	267	210	469	499	512	81	24	136	31	36	109	24	24	102
Gap (ft)	0	0	0	3	15	38	0	0	0	0	0	0	0	0	42

	WMA	Recycled Unbound Base, Warm Mix Asphalt				Low Temperature Cracking, Fractionated RAP			WMA, taconite
Cell	15	16	17	18	19	20	21	22	23
Layers	3"WM 58-34 11 64 22 1993 HMA Clay	5"WM 58 34 12" 100% recycle PCC 12" Class 3 7" Select Gran Clay	5"WM 58 34 12" 50% RePCC 50% Class 5 12" Class 3 7" Select Gran Clay	5"WM 58 34 12" 100% RAP 12" Class 3 7" Select Gran Clay	5"WM 58 34 12" Class 5 12" Class 3 7" Select Gran Clay	5 58 28 12" Class 5 12" Class 3 7" Select Gran Clay 30% Non Fract RAP	5 58 28 12" Class 5 12" Class 3 7" Select Gran Clay 30% Fract RAP	5 58 34 12" Class 5 12" Class 3 7" Select Gran Clay 30% Fract RAP	5"WM 58 34 12" Mesabi Ballast 12" Class 3 7" Select Gran Clay
Opened	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08
Length (ft)	500	500	500	500	500	500	500	500	500
Gap (ft)	95	50	70	70	50	90	80	80	

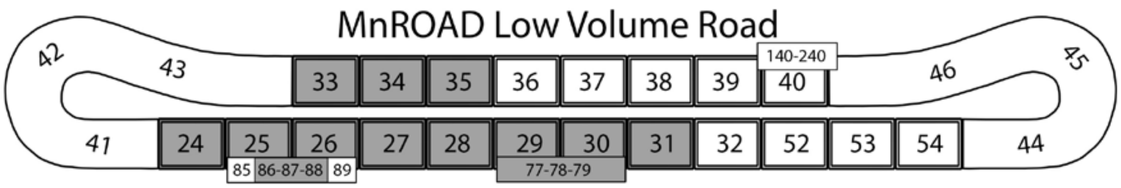
MnROAD Mainline Traffic - ESALS per Year

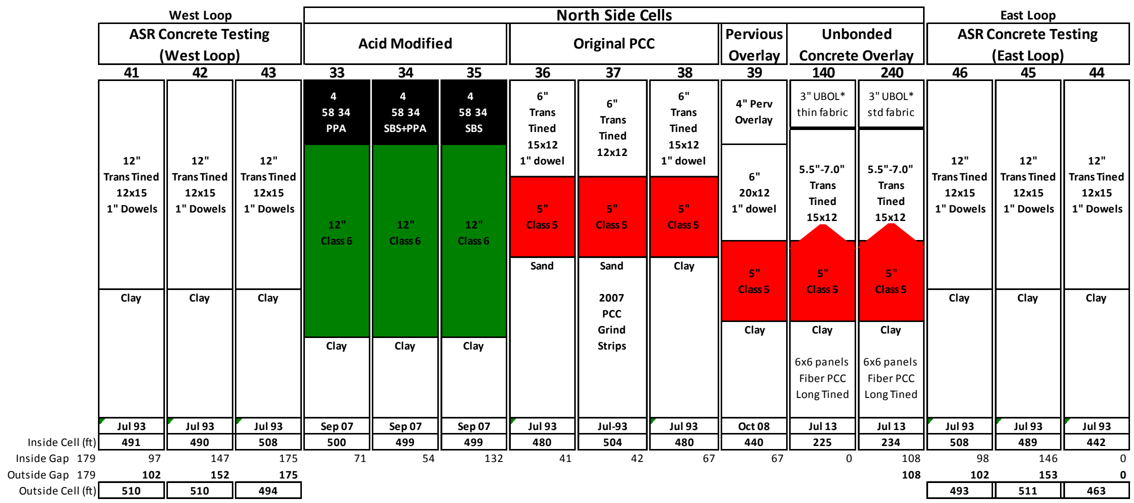
Year	Driving Lane		Passing Lane	
	Flexible	Rigid	Flexible	Rigid
1994	263,499	395,956	67,082	104,717
1995	579,931	877,886	176,791	276,724
1996	532,911	808,851	159,421	248,394
1997	415,828	632,244	110,144	173,507
1998	542,037	821,696	163,020	254,847
1999	641,264	967,499	186,017	289,248
2000	672,845	1,015,504	178,090	272,328
2001	712,973	1,077,422	191,675	291,229
2002	712,316	1,077,750	185,766	282,422
2003	692,453	1,042,991	190,299	288,709
2004	434,937	656,611	111,581	169,923
2005	812,340	1,222,622	215,201	325,195
2006	713,038	1,075,755	184,544	280,287
2007	759,904	1,142,266	188,653	285,853
2008	209,337	318,084	46,074	70,208
2009	773,095	1,170,257	196,919	291,873
2010	583,177	877,282	141,483	215,470
2011	632,002	956,376	149,516	227,038
2012	719,264	1,098,214	178,118	270,145
2013	683,751	1,032,696	191,488	286,612

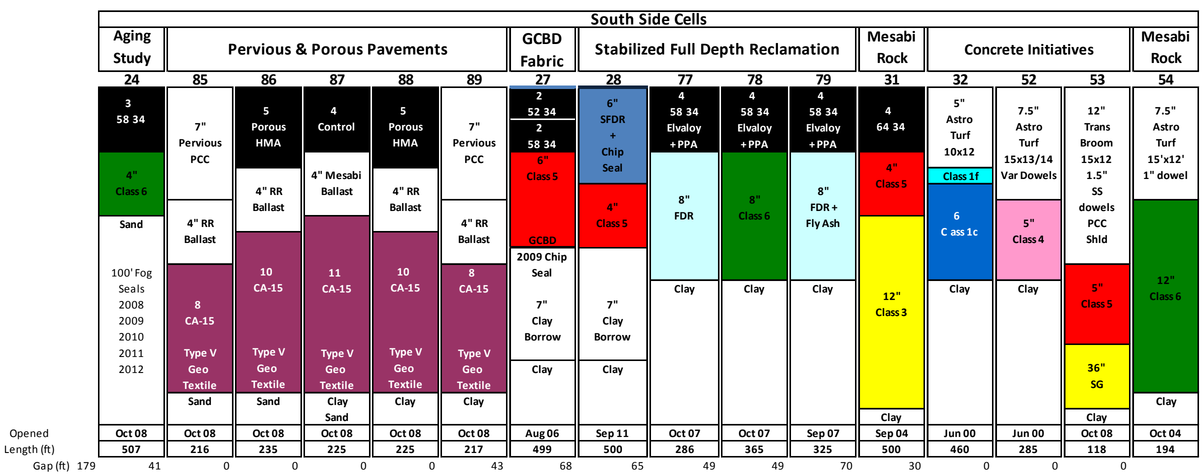
Only for the MnROAD Test cells - lane closure ESALS removed
See the MnROAD Traffic Spreadsheet/Database for more details

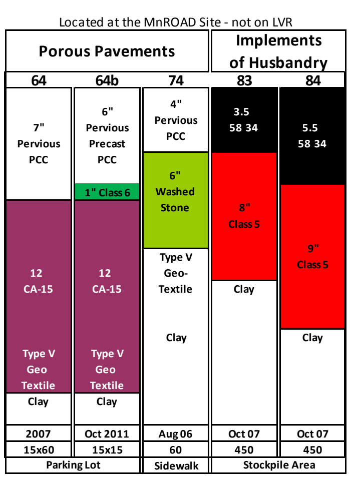
Updated
October 2013

Figure A.2 – MnROAD low-volume road test cell layout.









Low Volume Road ESALS per Year

MnROAD 5-Axle Semi Tractor Trailer

Year	Inside Lane (80,000 lbs) Laps	Flexible	Rigid	Outside Lane (102,000 lbs) Laps	Flexible	Rigid
1994	3,283	7,748	12,265	889	6,170	10,357
1995	7,748	18,285	28,947	2,927	20,313	34,100
1996	8,598	20,291	32,122	2,576	17,877	30,010
1997	6,874	16,223	25,681	2,172	15,074	25,304
1998	10,165	23,989	37,976	2,236	15,518	26,049
1999	4,537	10,707	16,950	1,623	11,264	18,908
2000	8,853	20,893	33,075	2,451	17,010	28,554
2001	8,075	19,057	30,168	2,203	15,289	25,665
2002	9,849	23,244	36,796	1,797	12,471	20,935
2003	6,923	16,338	25,864	2,820	19,571	32,853
2004	3,950	9,322	14,757	1,202	8,342	14,003
2005	5,986	14,127	22,364	2,082	14,449	24,255
2006	6,634	15,656	24,785	2,246	15,587	26,166
2007	4,969	11,727	18,564	935	6,489	10,893
2008	2,885	6,809	10,778	Since 2008 MnROAD has not loaded the outside lane to learn more about the environmental deterioration without traffic		
2009	6,229	14,700	23,272			
2010	6,623	15,630	24,744			
2011	5,290	12,484	19,763			
2012	8,447	19,935	31,558			
2013	4,224	9,969	15,781			
	130,142	307,135	486,211	28,159	195,423	328,052

Updated
October 2013

Appendix B

Laboratory Test Results From Initial Field Samples

Table B.1 – Test results for FT tests on MnROAD cell 13 material.

Test Results of ASTM C666 - Procedure A Freezing and Thawing in Water of Concrete Specimens†				
Samples Identification	Freeze-Thaw Cycles	Length Change, %	Mass Change, %	Relative Dynamic Modulus, %
Cell 13 A, B and C	0	0.000	0.00	100
	36	0.000	0.11	101
	72	0.000	- 0.11	101
	108	0.000	- 0.51	100
	144	0.000	- 1.02	101
	180	0.000	- 1.33	100
	216	0.000	- 1.68	101
	252	0.000	- 1.89	102
	288	0.000	- 2.06	103
	300	0.000	-2.08	103
† Values are the average of three specimens.				

Table B.2 – Test results for FT tests on MnROAD cell 32 material.

Test Results of ASTM C666 - Procedure A Freezing and Thawing in Water of Concrete Specimens†				
Samples Identification	Freeze-Thaw Cycles	Length Change, %	Mass Change, %	Relative Dynamic Modulus, %
Cell 32 A, B and C	0	0.000	0.00	100
	30	0.015	0.05	97
	61	0.023	0.01	98
	91	0.026	- 0.02	98
	120	0.024	- 0.09	98
	149	0.032	- 0.25	99
† Values are the average of three specimens.				

Table B.3 – Test results for FT tests on MnROAD cell 40 material.

Test Results of ASTM C666 - Procedure A Freezing and Thawing in Water of Concrete Specimens†				
Samples Identification	Freeze-Thaw Cycles	Length Change, %	Mass Change, %	Relative Dynamic Modulus, %
Cell 40 A, B and C	0	0.000	0.00	100
	36	0.000	0.05	101
	72	0.000	- 0.07	99
	108	0.000	- 0.24	99
	144	0.000	- 0.59	100
	180	0.000	- 0.84	102
	216	0.000	- 1.19	100
	252	0.000	- 1.48	101
	288	0.000	- 1.62	102
	300	0.000	-1.64	102
† Values are the average of three specimens.				

Table B.4 – Test results for FT tests on MnROAD cell 60-63 material.

Test Results of ASTM C666 - Procedure A Freezing and Thawing in Water of Concrete Specimens†				
Samples Identification	Freeze-Thaw Cycles	Length Change, %	Mass Change, %	Relative Dynamic Modulus, %
Cell 60-63 A, B and C	0	0.000	0.00	100
	36	0.000	0.14	102
	72	0.000	0.06	103
	108	0.000	- 0.03	103
	144	0.000	- 0.15	102
	180	0.000	- 0.28	102
	216	0.000	- 0.46	100
	252	0.000	- 0.64	98
	288	0.000	- 0.72	99
	300	0.000	-0.75	98
† Values are the average of three specimens.				

Table B.5 – Compressive strength results (AASHTO T22, ASTM C39) for MnROAD 2013 cells.

Cell 40 (psi)					
Days	Sample #1	Sample #2	Sample #3		Average
7	3880	3690	NA		3800
21	4580	4930	4680		4730
28	4960	5060	5040		5020
Cell 13 (psi)					
Days	Sample #1	Sample #2	Sample #3	Sample #4	Average
3	2890	2780	2870	3030	2890
7	3320	3320	3380	3100	3280
28		4830	4700	4570	4700
Cell 32 (psi)					
Days	Sample #1	Sample #2	Sample #3		Average
7	4630	4910	NA		4770
28	7000	7420	7310		7240
Cell 60-63 (psi)					
Days	Sample #1	Sample #2	Sample #3		Average
3	2670	2720	NA		2700
7	3240	3390	3400		3340
28	4400	4520	4490		4470

Table B.6 – Flexural strength results (AASHTO T97, ASTM C78) for MnROAD 2013 cells.

Cell 40 (psi)					
Days	Sample #1	Sample #2	Sample #3		Average
7	620	625	NA		620
21	780	720	715		740
28	775	775	785		780
Cell 13 (psi)					
Days	Sample #1	Sample #2	Sample #3	Sample #4	Average
7	555	480	475	475	500
21	615	545	600	610	590
28	625	605	595	555	600
Cell 32 (psi)					
Days	Sample #1	Sample #2	Sample #3		Average
7	925	935	855		905
28	1195	1190	1115		1170
Cell 60-63 (psi)					
Days	Sample #1	Sample #2	Sample #3		Average
3	550	590	NA		570
7	495	440	520		490
28	770	735	735		750

Table B.7 – Rapid Chloride Permeabitlity results (AASHTO T 277, ASTM C1202).

Cell 40 (Coulombs)				
Days	Sample #1	Sample #2	Sample #3	Average
28	2060	2310	2030	2130
56	1100	1150	1220	1157
Cell 13 (Coulombs)				
Days	Sample #1	Sample #2	Sample #3	Average
28	1430	1570	1360	1450
56	800	880	840	840
Cell 32 (Coulombs)				
Days	Sample #1	Sample #2	Sample #3	Average
28	4300	4840	4700	4610
Cell 60-63 (Coulombs)				
Days	Sample #1	Sample #2	Sample #3	Average
28	1300	1490	1300	1360
56	610	830	760	733

Table B.8 – Slant shear test results (ASTM C882) for cell 32.

Cell 32 (psi)				
Days	Sample #1	Sample #2	Sample #3	Average
35	1270	1830	1970	1690

Figure B.1 – Freeze-thaw cycles vs. length change of cell 13.

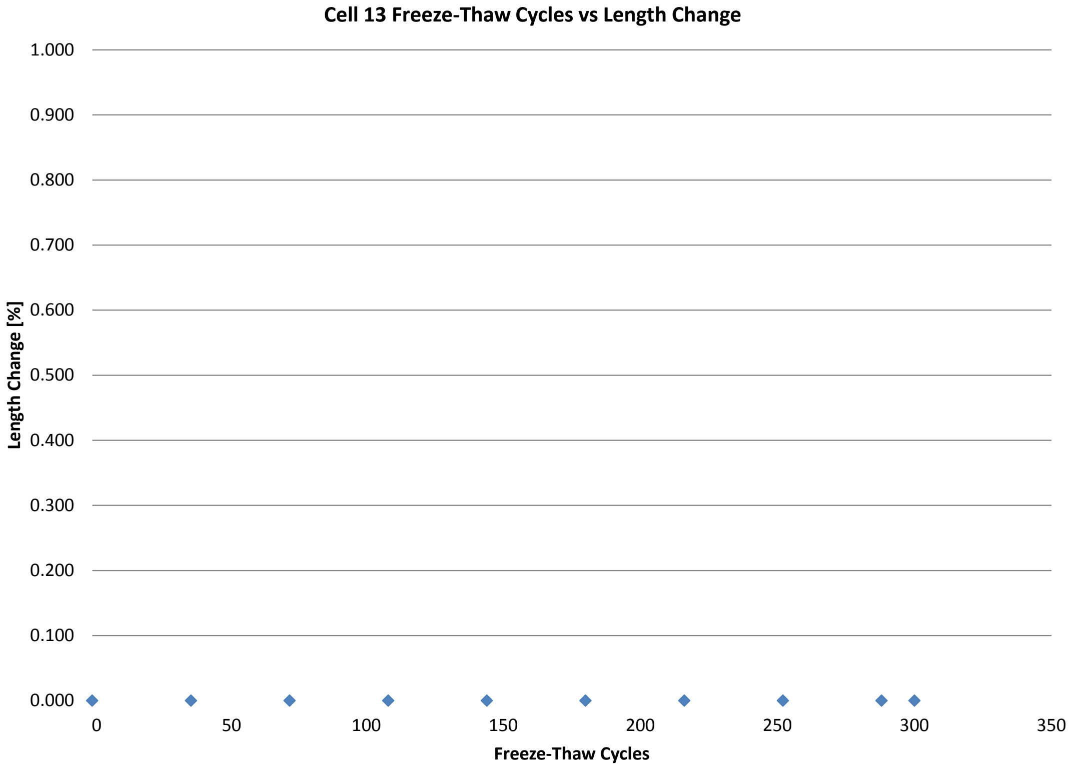


Figure B.2 – Freeze-thaw cycles vs. mass change of cell 13.

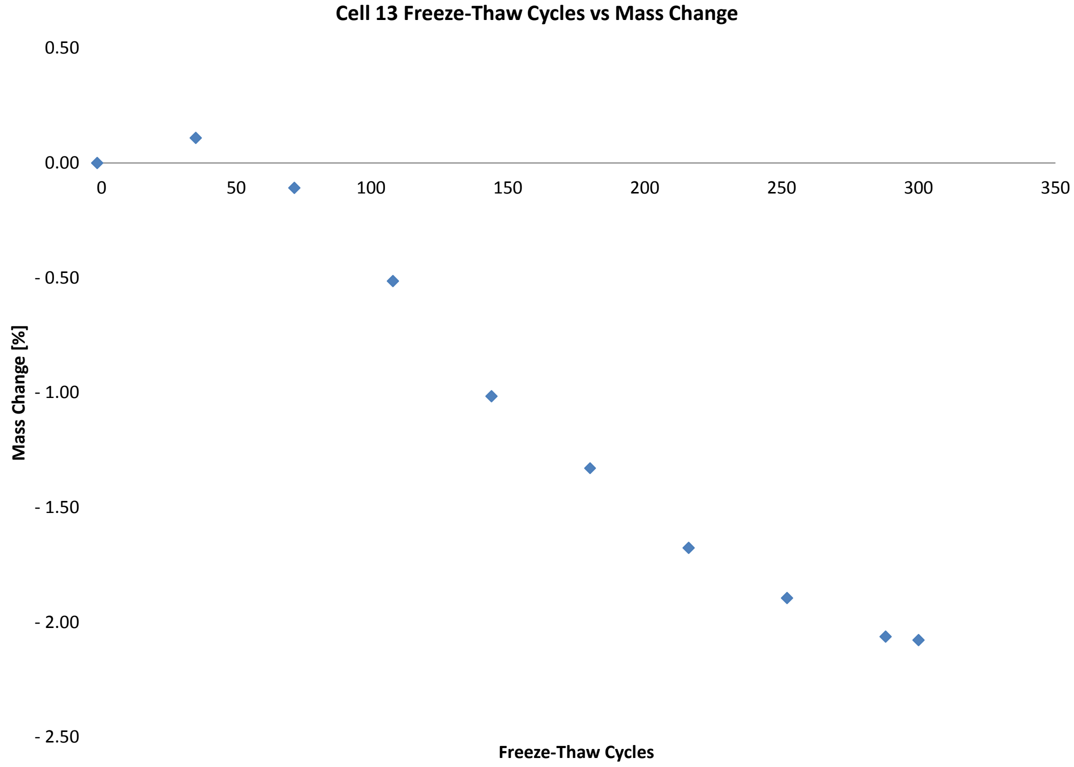


Figure B.3 – Freeze-thaw cycles vs. relative dynamic modulus of cell 13.

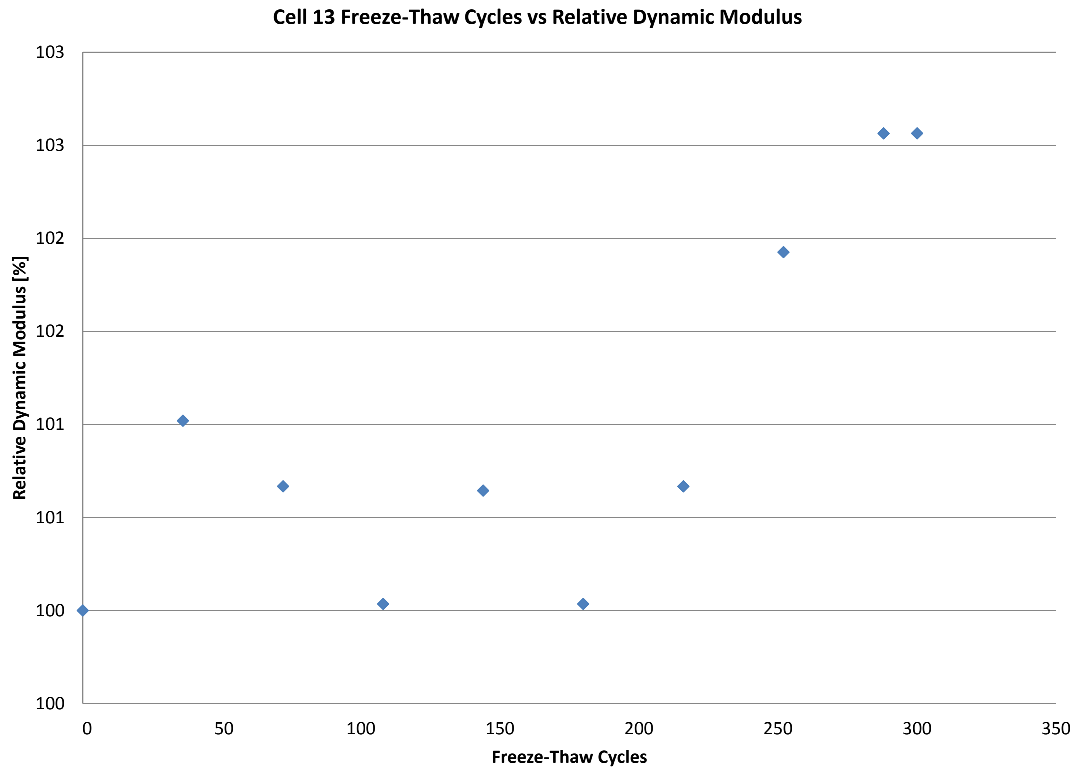


Figure B.4 – Compressive strength test results for cell 13.

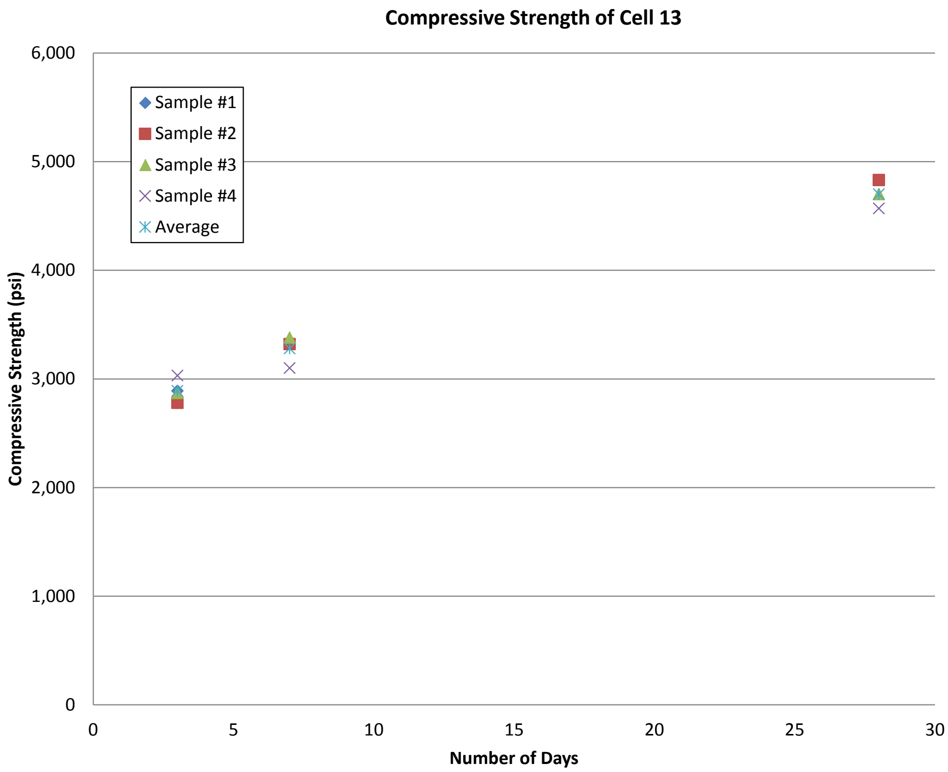


Figure B.5 – Flexural strength test results for cell 13.

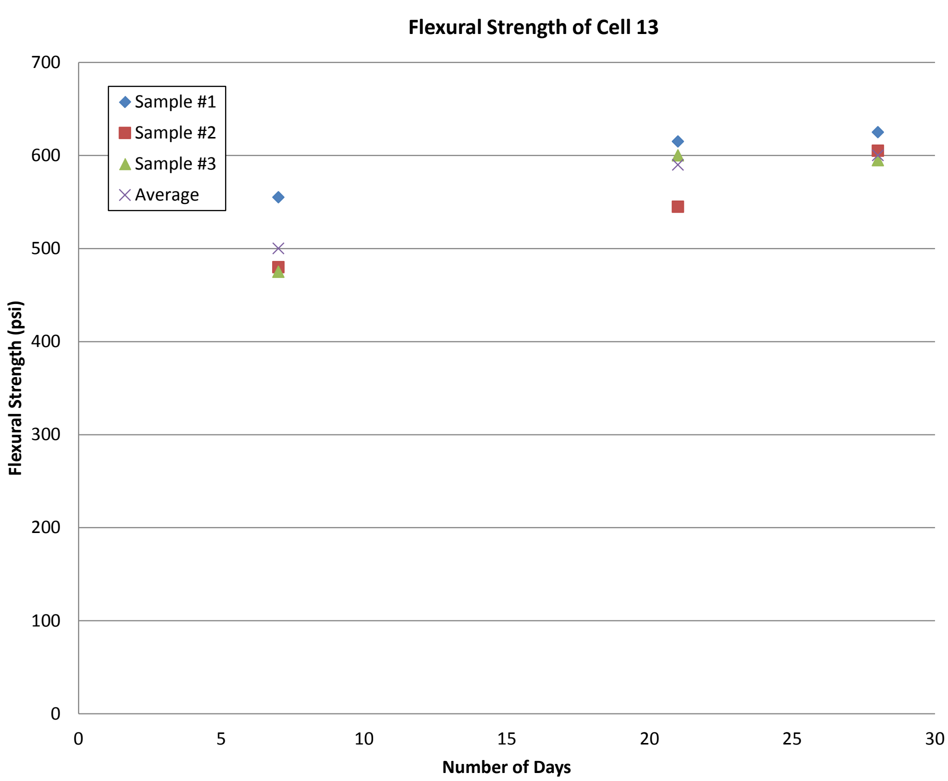


Figure B.6 – Rapid chloride permeability test results for cell 13.

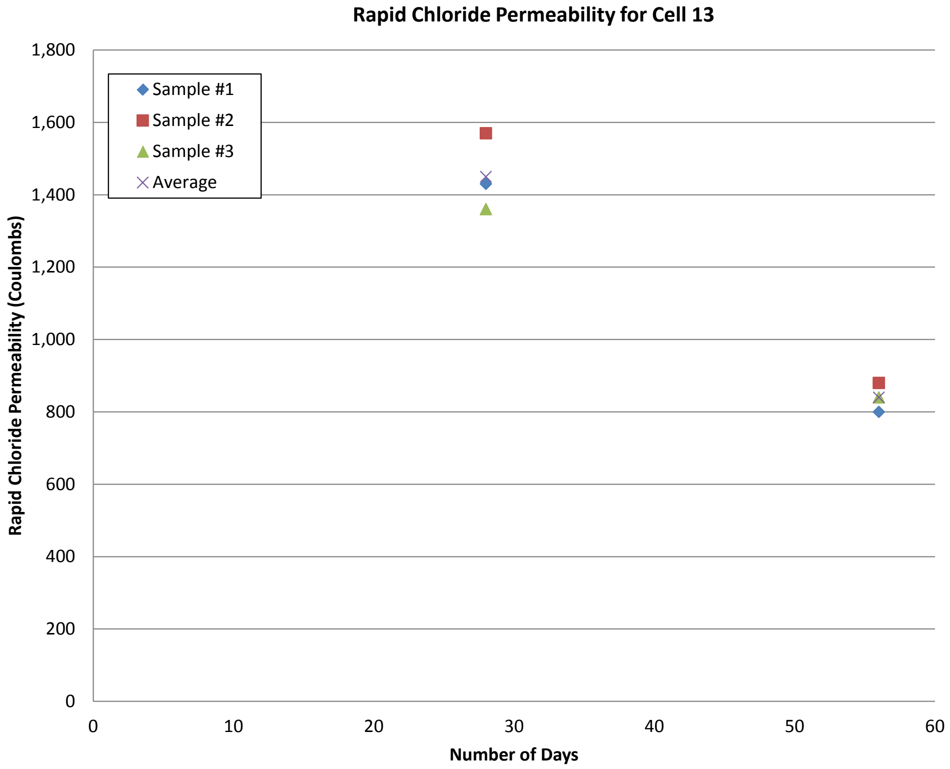


Figure B.7 – Compressive strength test results comparison for all cells.

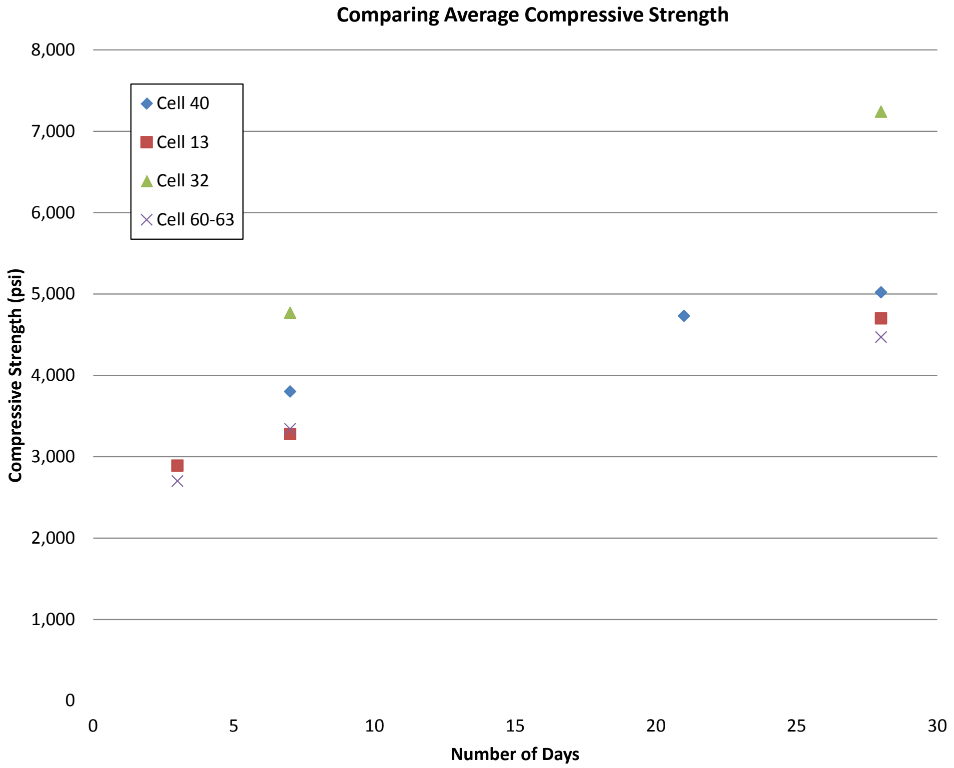


Figure B.8 – Comparing the flexural strength for all cells.

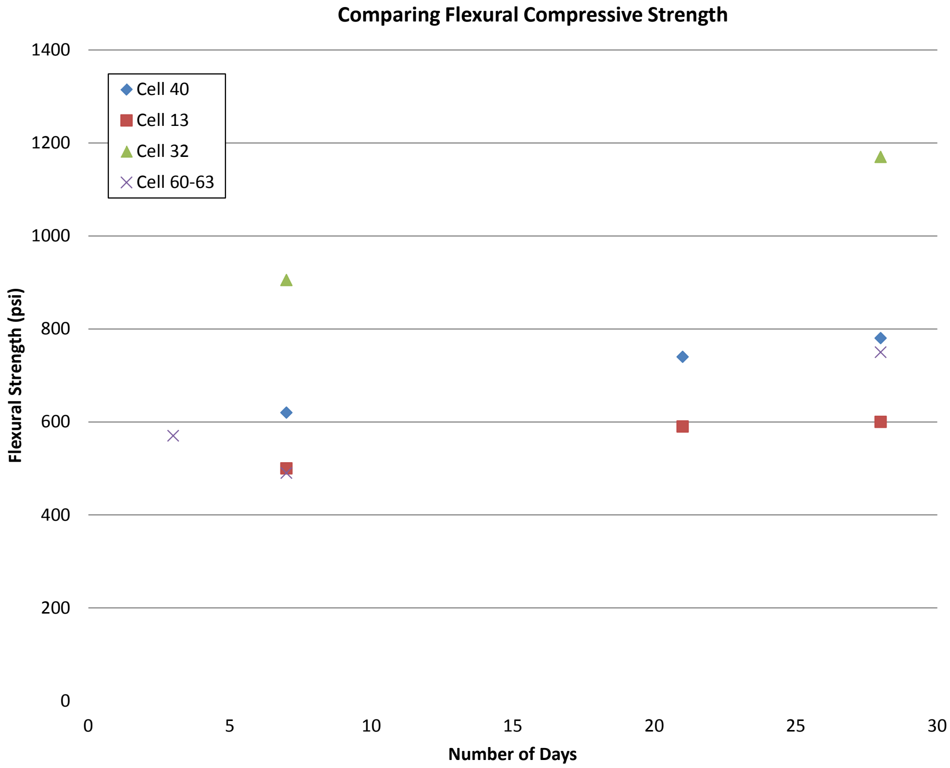


Figure B.9 – Comparing rapid chloride permeability for all 4 groups of cells.

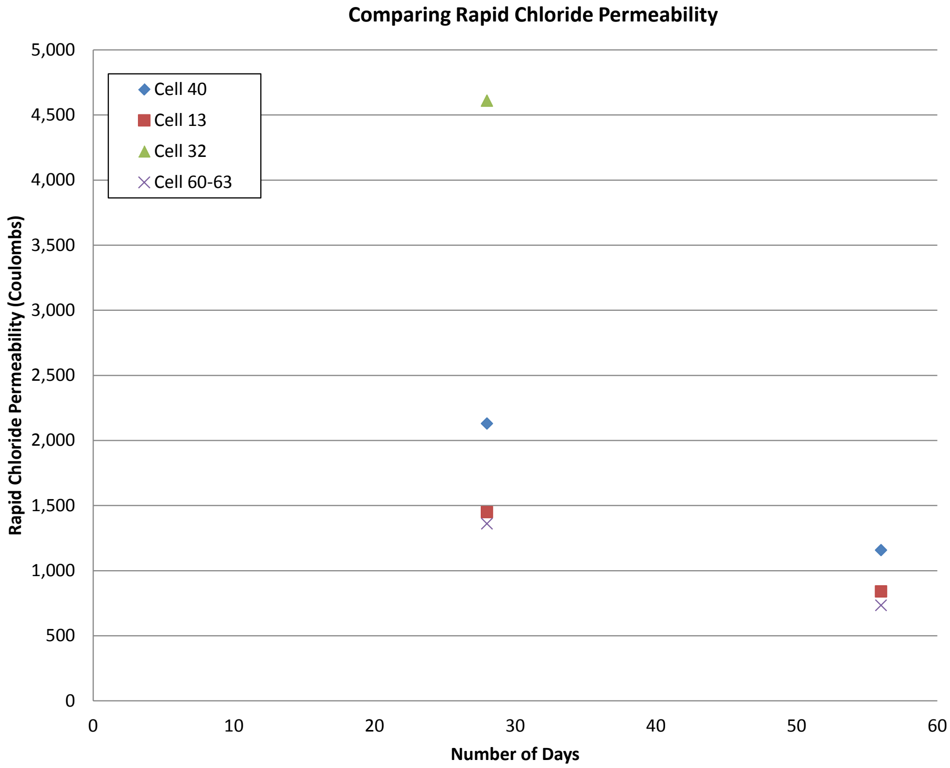


Figure B.10 – Freeze-thaw cycles vs. length change of cell 40.

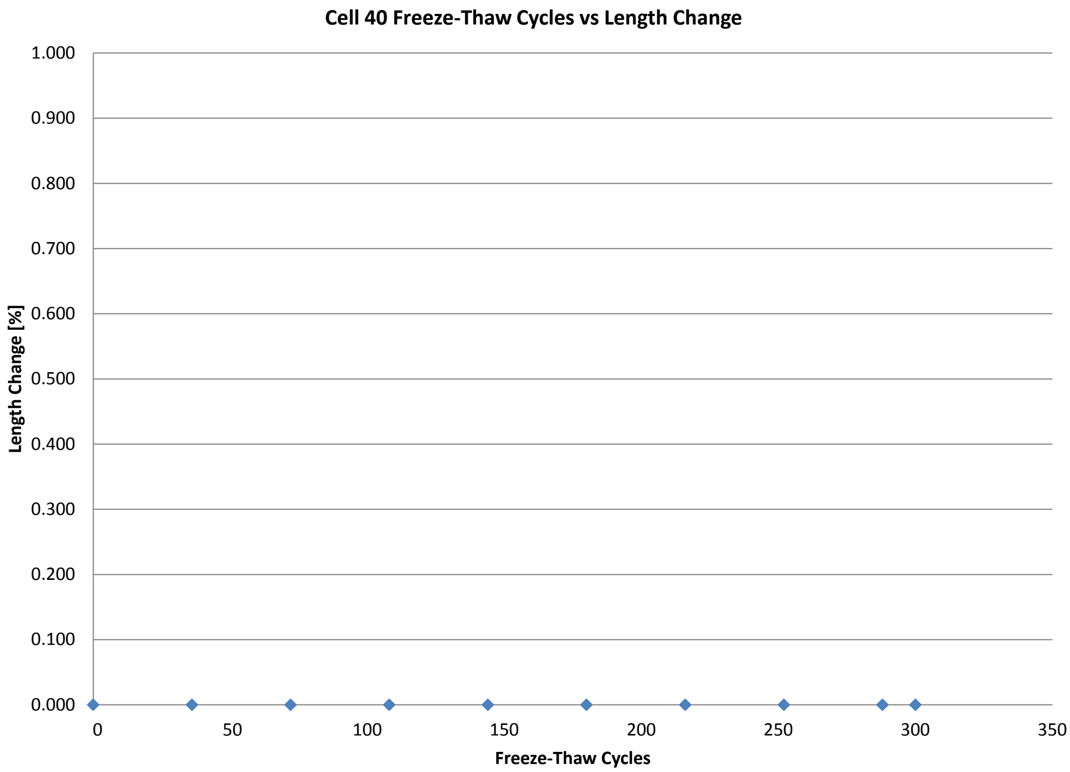


Figure B.11 – Freeze-thaw cycles vs. mass change of cell 40.

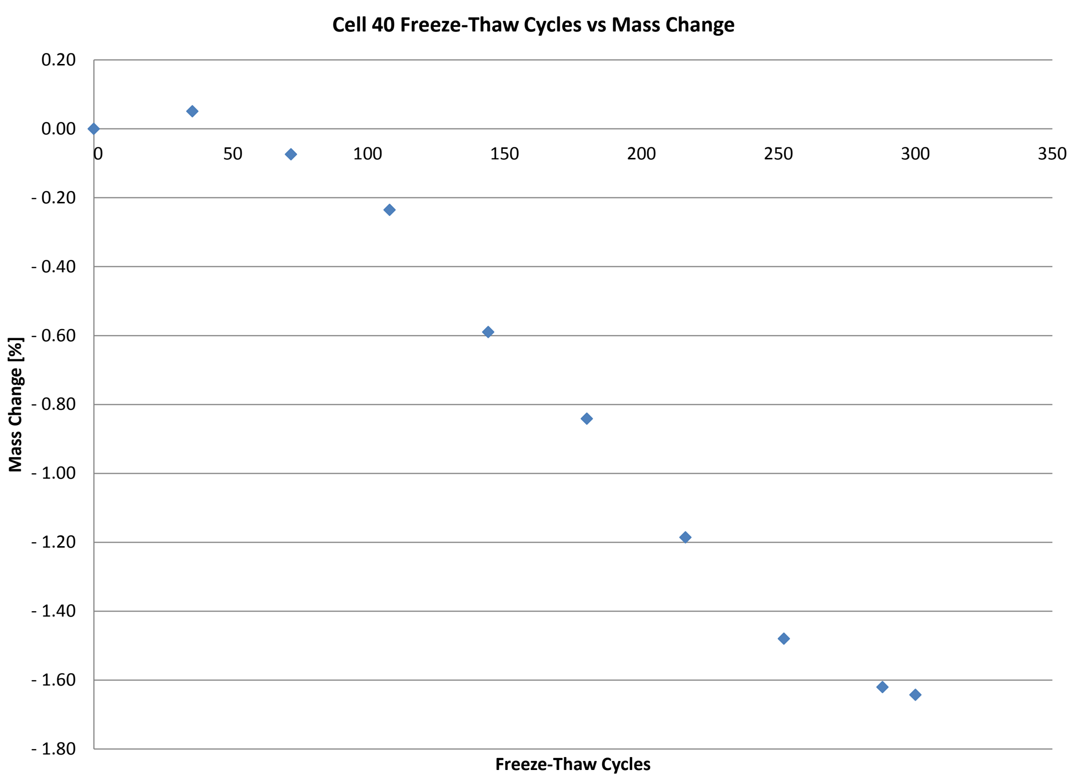


Figure B.12 – Freeze-thaw cycles vs. relative dynamic modulus of cell 40.

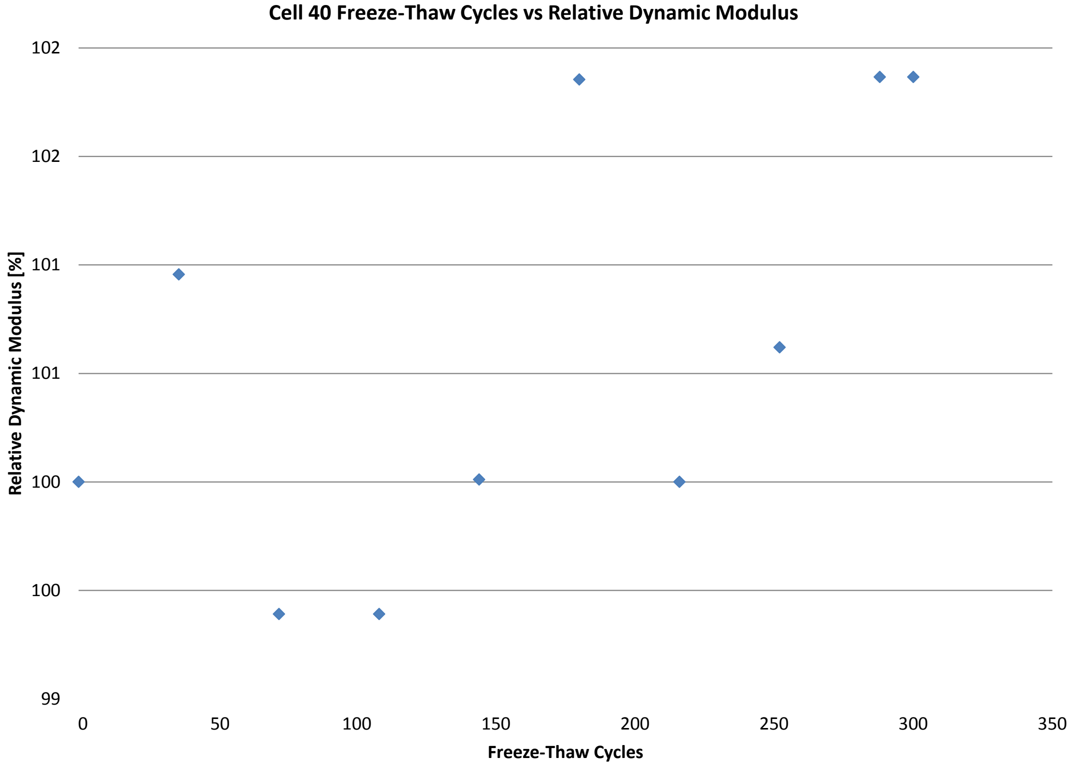


Figure B.13 – Compressive strength of cell 40.

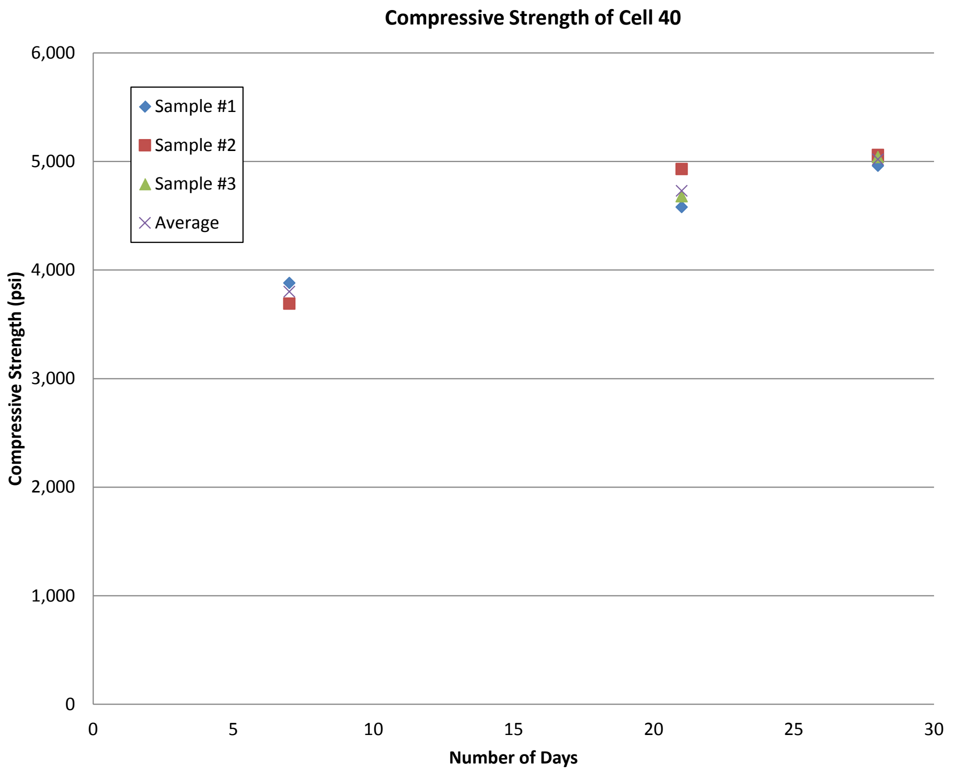


Figure B.14 – Flexural strength of cell 40.

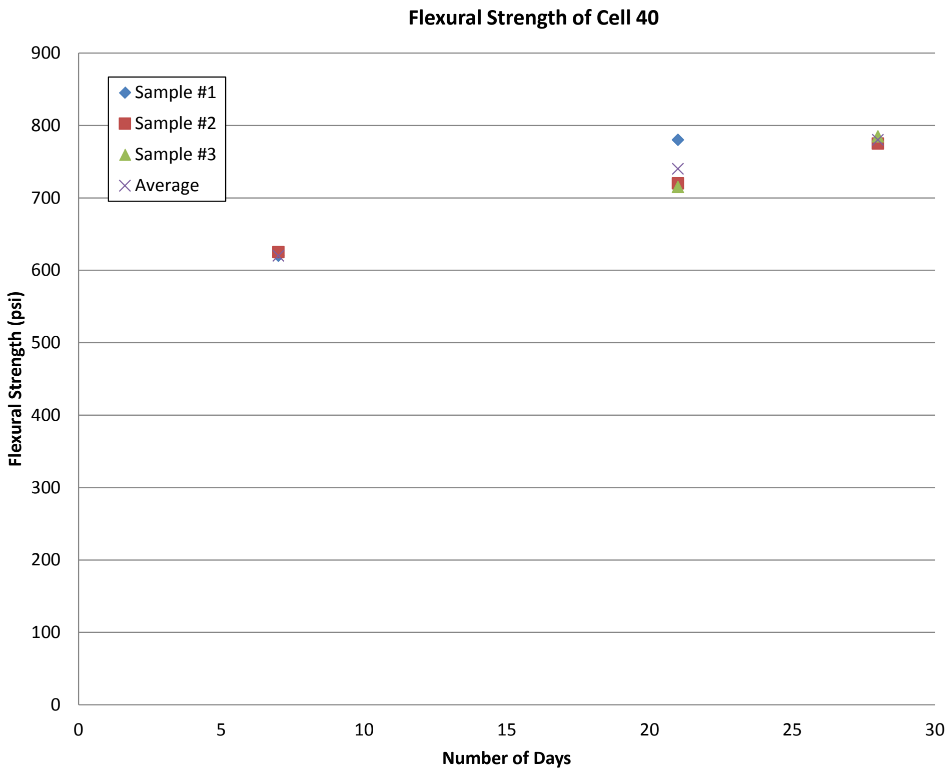


Figure B.15 – Rapid chloride permeability test results for cell 40.

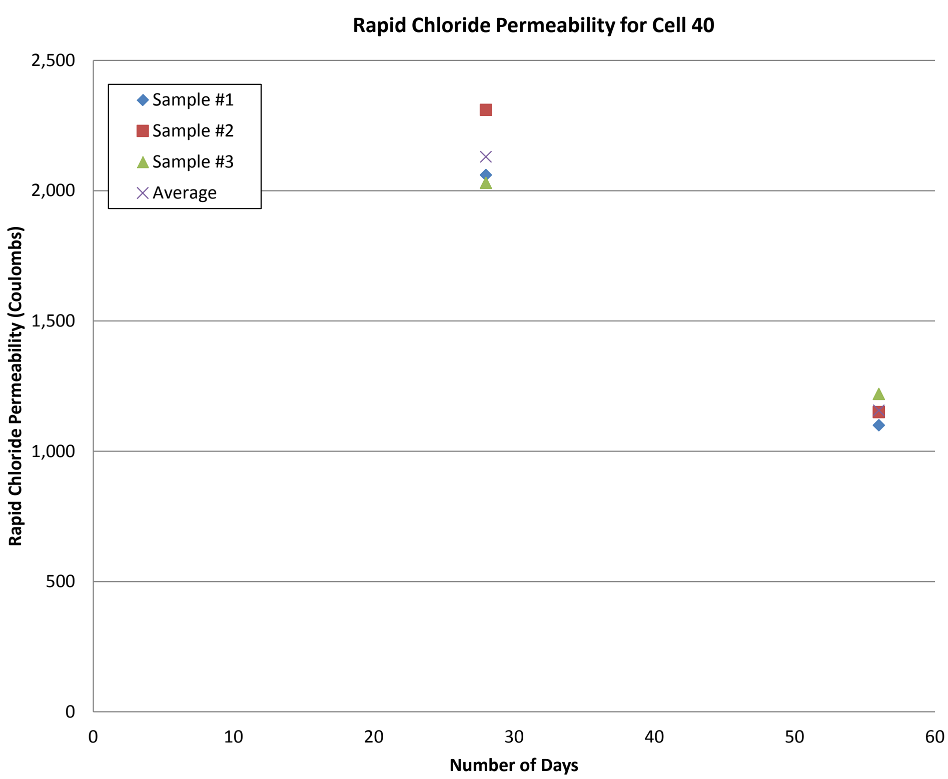


Figure B.16 – Freeze-thaw cycles vs. length change of cells 60-63.

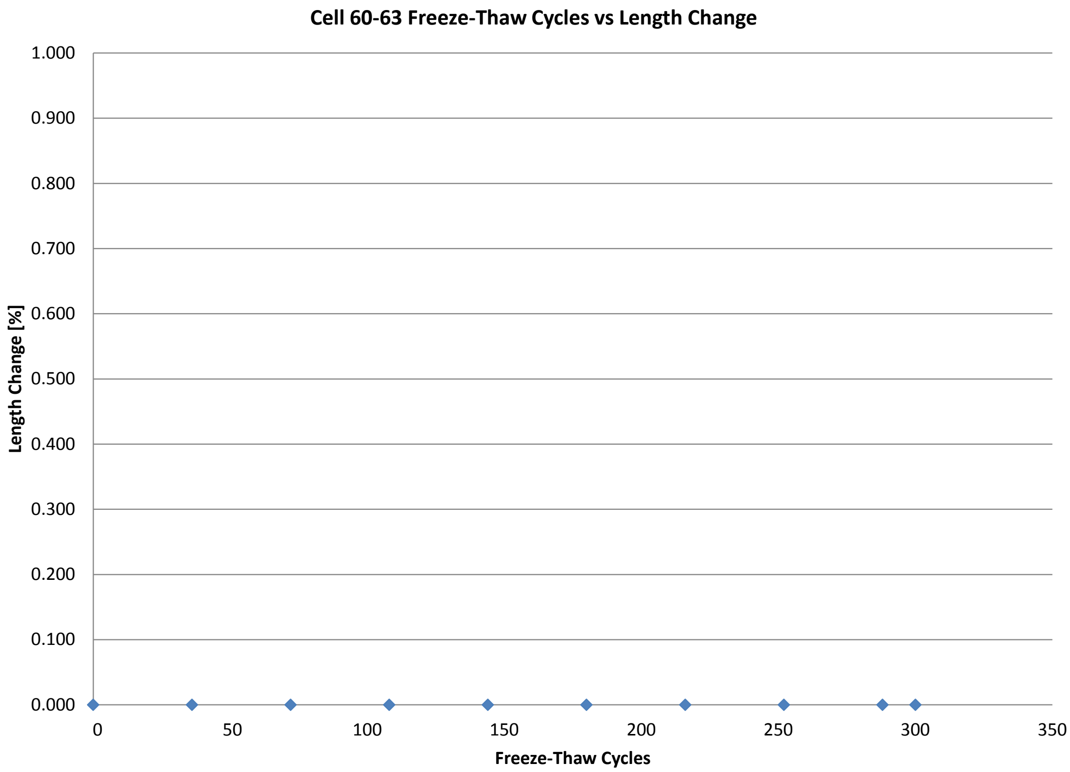


Figure B.17 – Freeze-thaw cycles vs. mass change of cells 60-63.

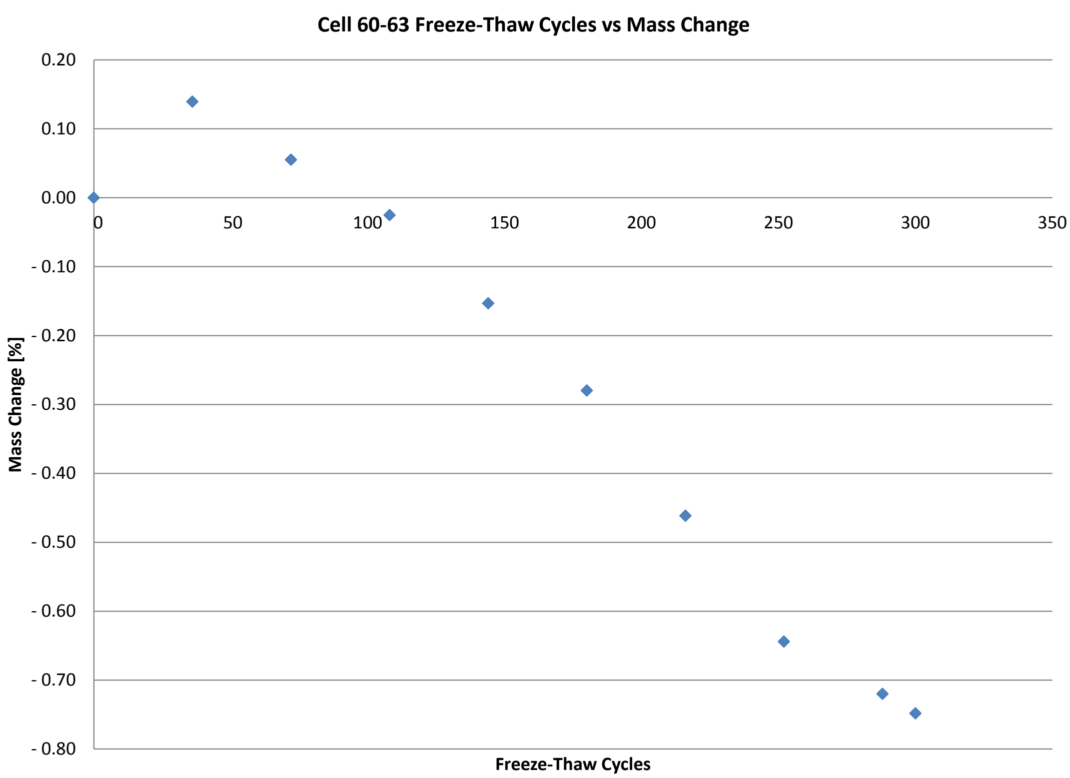


Figure B.18 – Freeze-thaw cycles vs. relative dynamic modulus of cells 60-63.

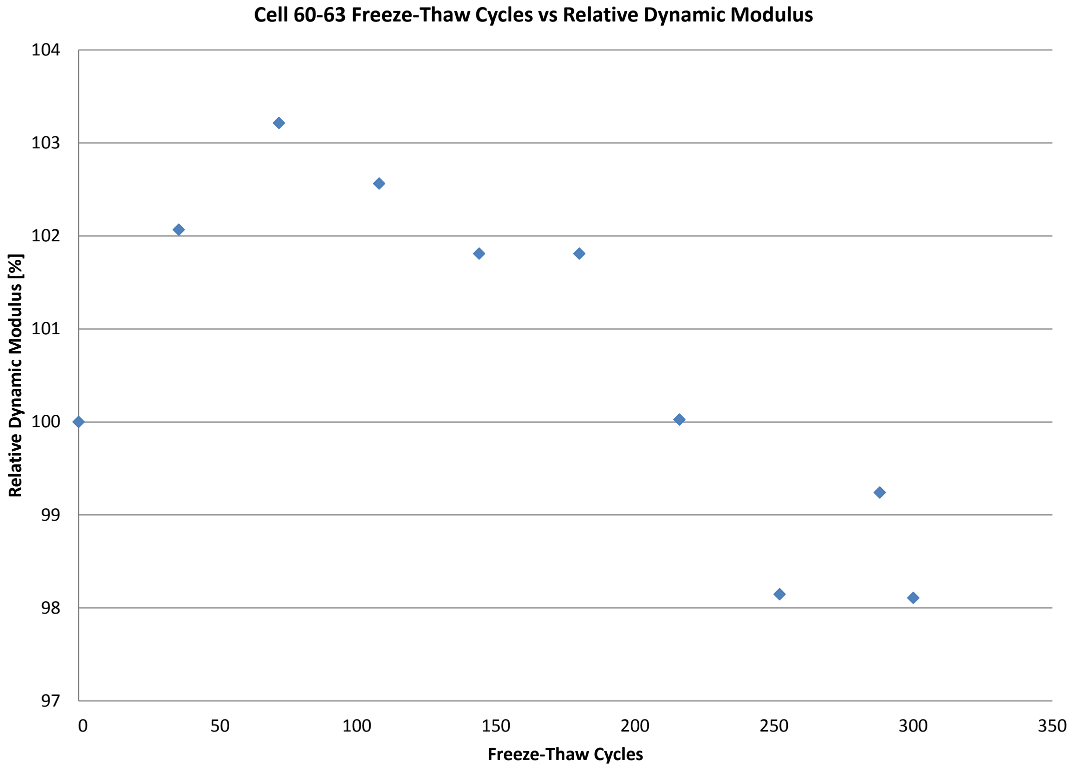


Figure B.19 – Compressive strength of cells 60-63.

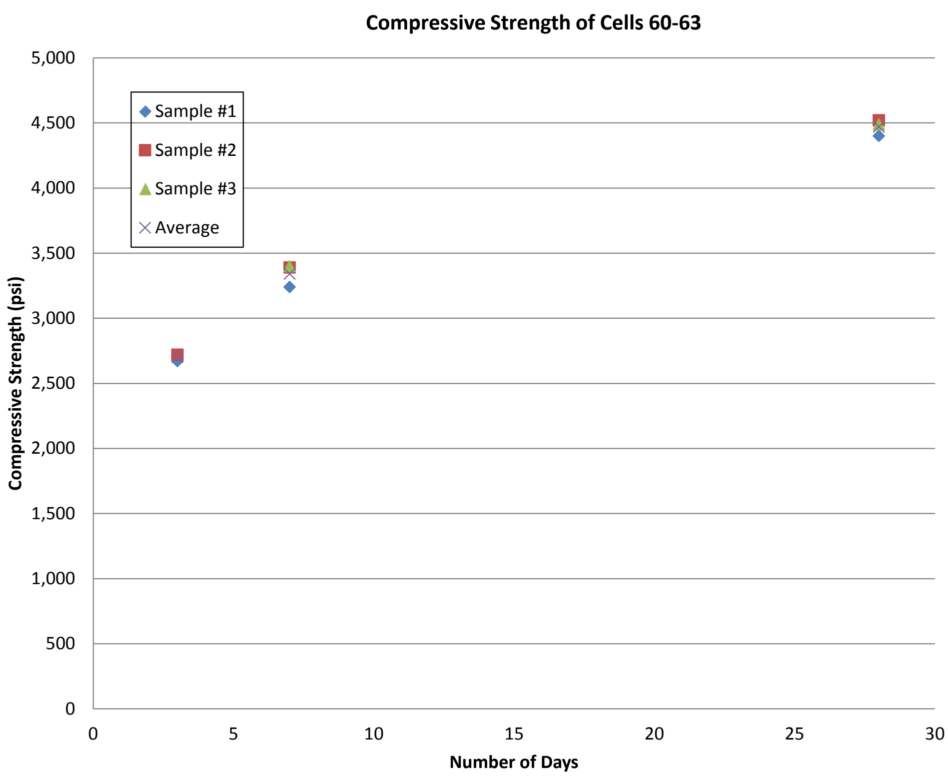


Figure B.20 – Flexural strength of cells 60-63.

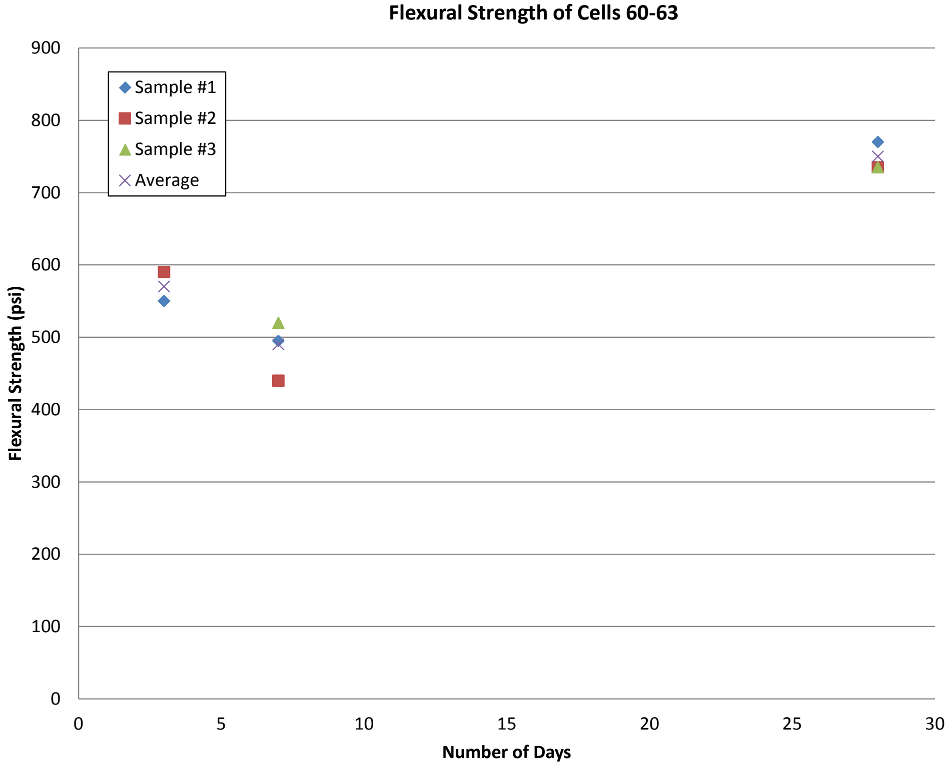


Figure B.21 – Rapid chloride permeability test results for cells 60-63.

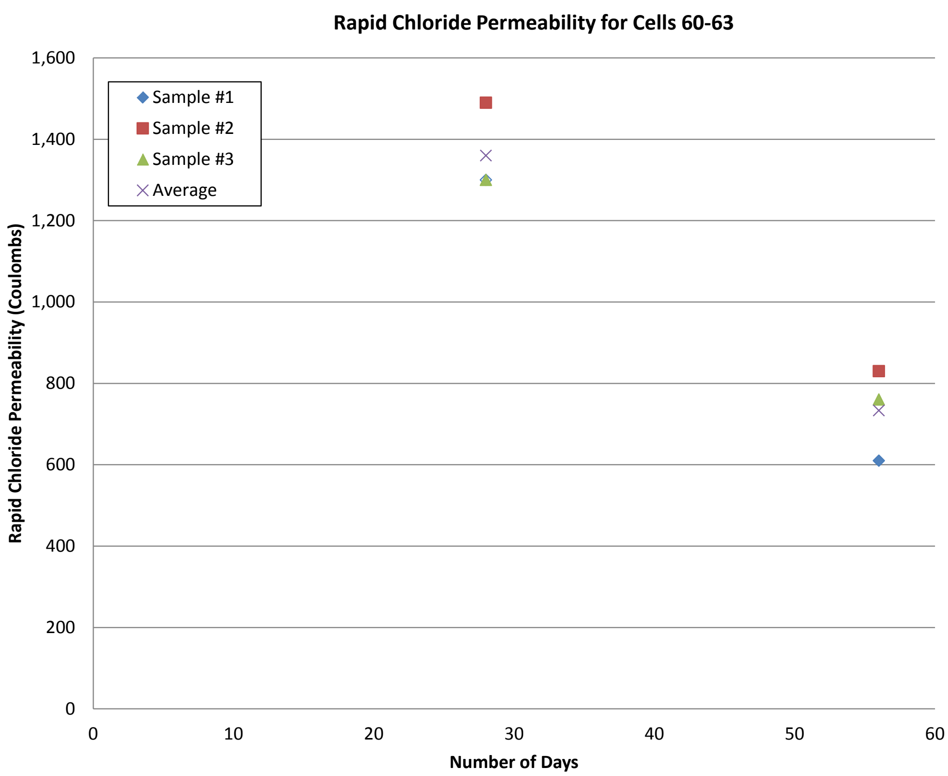


Figure B.22 – Freeze-thaw cycles vs. length change of cell 32.

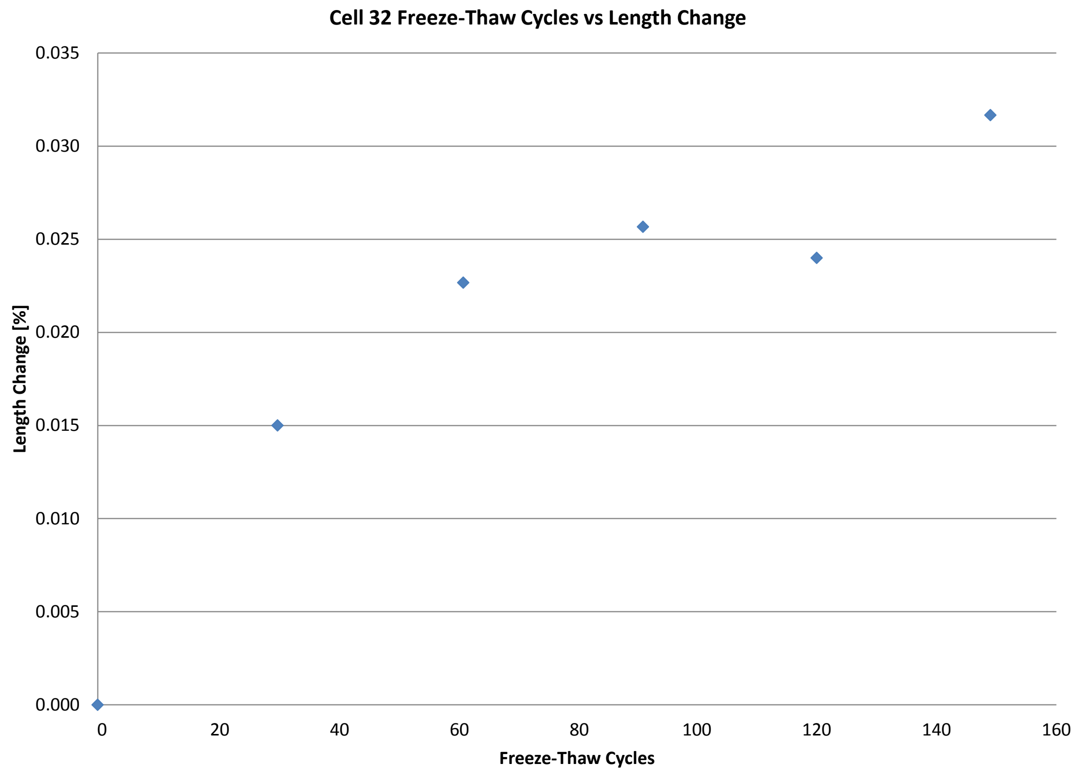


Figure B.23 – Freeze-thaw cycles vs. mass change of cell 32.

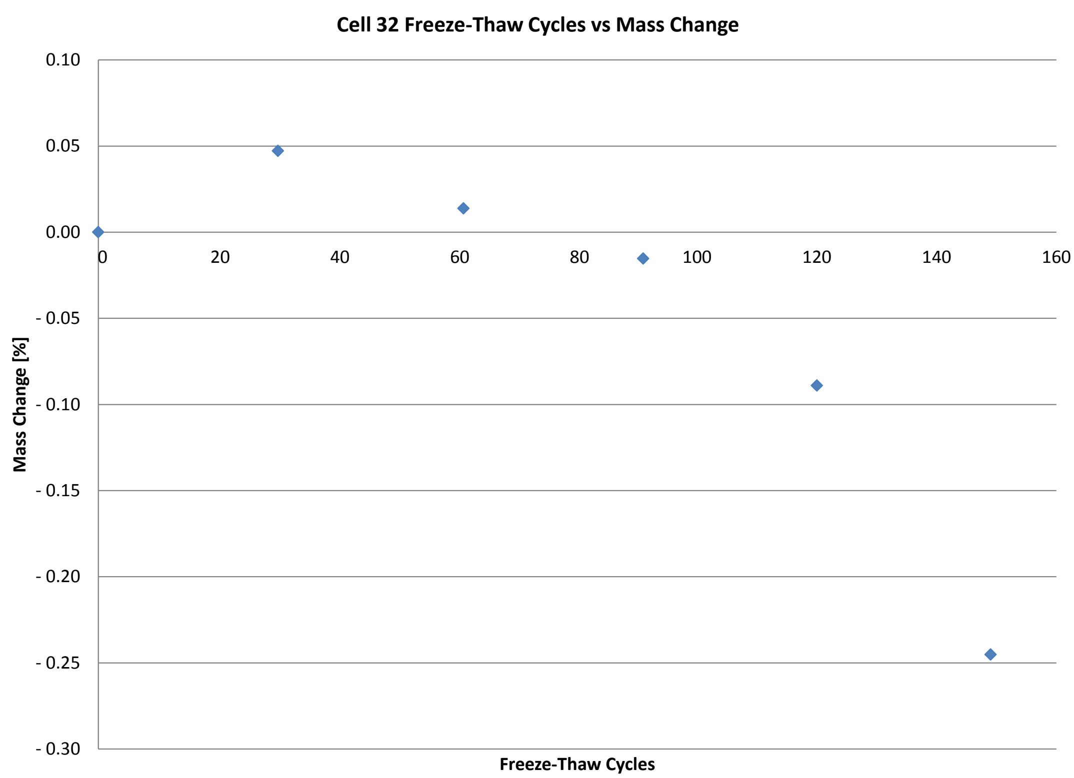


Figure B.24 – Freeze-thaw cycles vs. relative dynamic modulus of cell 32.

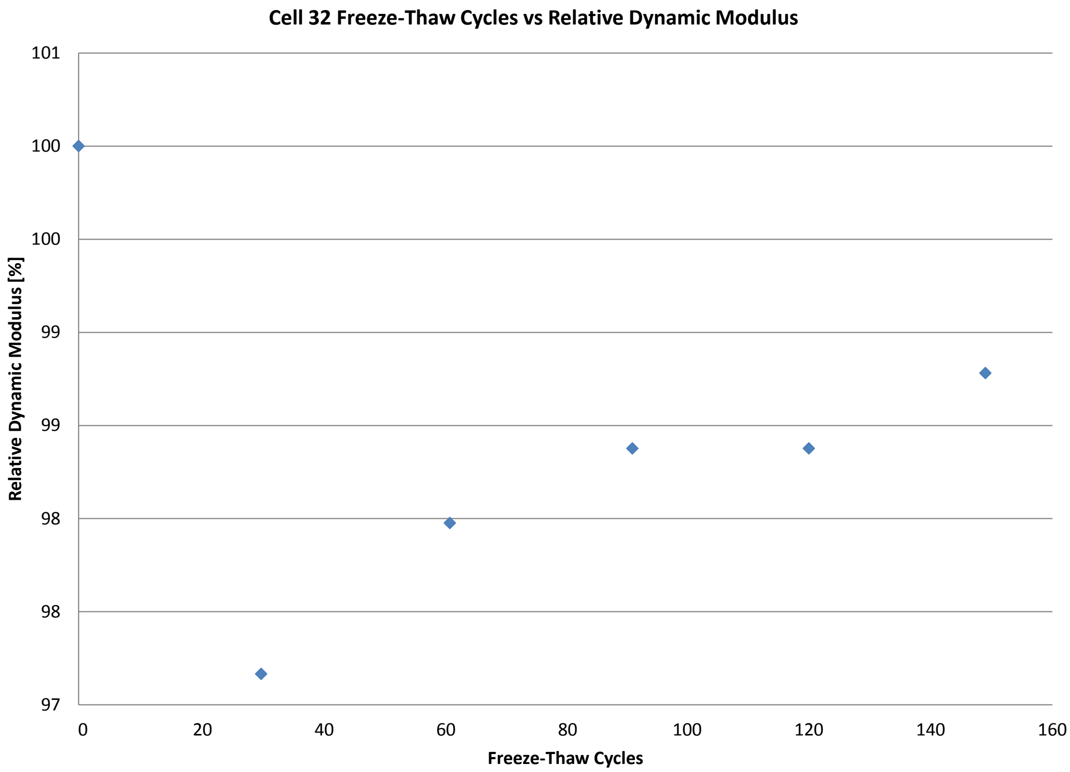


Figure B.25 – Compressive strength test results of cell 32.

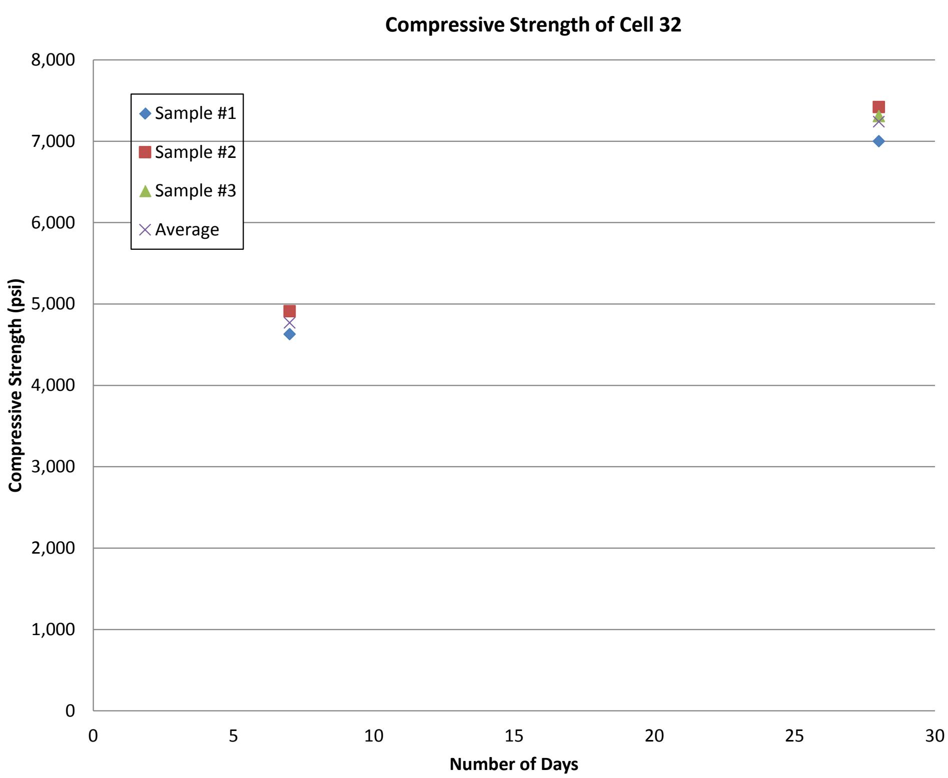


Figure B.26 – Flexural strength test results of cell 32.

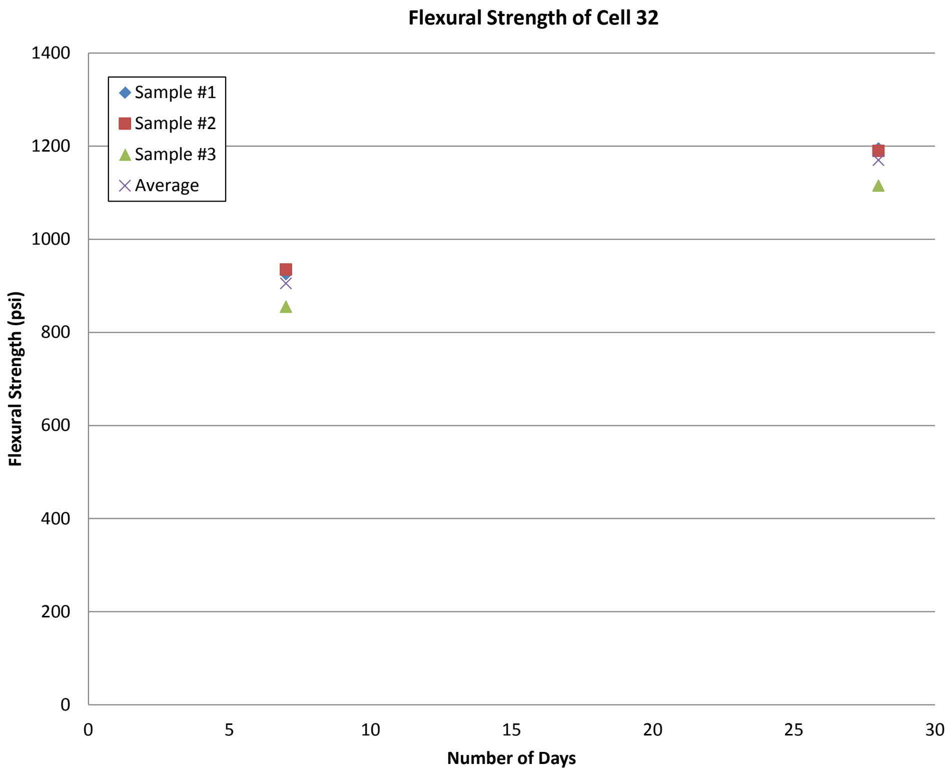


Figure B.27 – Rapid chloride permeability test results for cell 32.

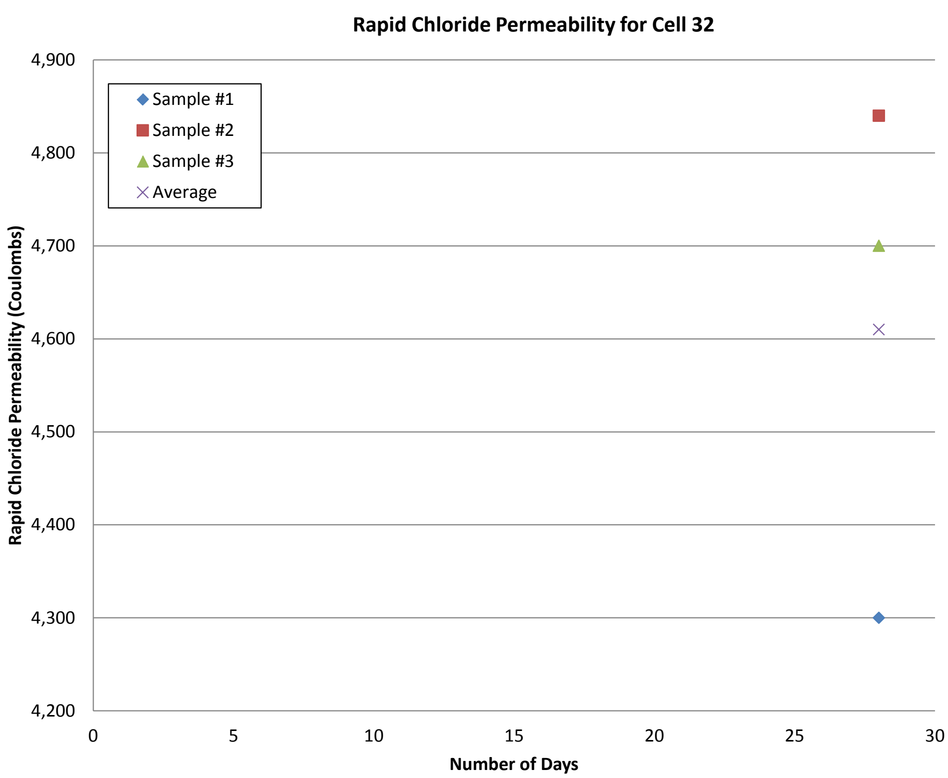
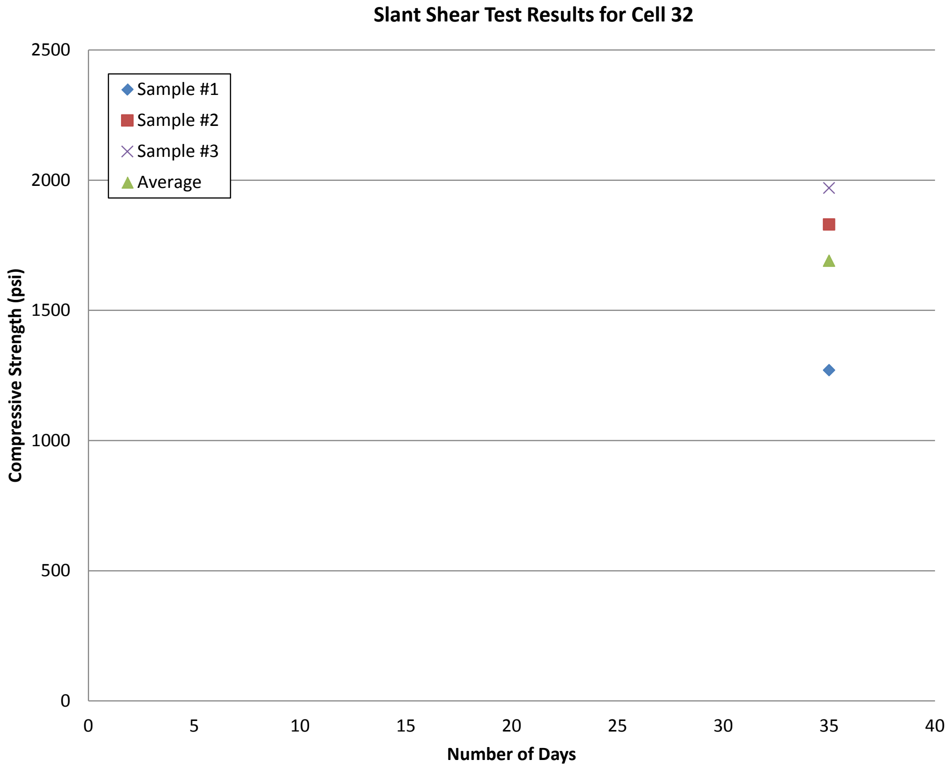


Figure B.28 – Slant shear test results for cell 32.



Appendix C

MnROAD Sensor Field Locations (Source – MnROAD Database)

Table C.1 – Locations of sensors installed during MnROAD 2013 cell construction.

CELL	MODEL	SEQ	DESCRIPTION	DATE INSTALLED	STATION (ft)	OFFSET (ft)	SENSOR DEPTH (in.)	ORIENTATION
140	CE	1	Concrete Embedded Strain Gauge	30-May-13	10446.9	10.0	0.5	Longitudinal
140	CE	4	Concrete Embedded Strain Gauge	30-May-13	10453.8	10.0	0.5	Longitudinal
140	TC	1	Thermocouple	30-May-13	10445.2	11.7	0.5	Vertical
140	VW	1	Vibrating Wire Strain Gauge	30-May-13	10454.3	9.0	0.8	Longitudinal
140	TC	2	Thermocouple	30-May-13	10445.2	11.7	1.0	Vertical
140	TC	3	Thermocouple	30-May-13	10445.2	11.7	1.5	Vertical
140	TC	4	Thermocouple	30-May-13	10445.2	11.7	2.0	Vertical
140	VW	2	Vibrating Wire Strain Gauge	30-May-13	10454.3	9.0	2.3	Longitudinal
140	CE	2	Concrete Embedded Strain Gauge	30-May-13	10446.9	10.0	2.5	Longitudinal
140	CE	5	Concrete Embedded Strain Gauge	30-May-13	10453.8	10.0	2.5	Longitudinal
140	EC	1	ECH2O-5TE Volumetric Water Content	30-May-13	10455.2	9.0	3.0	
140	EC	2	ECH2O-5TE Volumetric Water Content	30-May-13	10455.2	11.0	3.0	
140	TC	5	Thermocouple	30-May-13	10445.2	11.7	3.0	Vertical
140	CE	3	Concrete Embedded Strain Gauge	30-May-13	10446.9	10.0	3.5	Transverse
140	VW	3	Vibrating Wire Strain Gauge	30-May-13	10454.3	9.0	3.8	Longitudinal
140	TC	6	Thermocouple	30-May-13	10445.2	11.7	7.0	Vertical
140	TC	7	Thermocouple	30-May-13	10445.2	11.7	10.0	Vertical
140	TC	8	Thermocouple	30-May-13	10445.2	11.7	13.0	Vertical
160	TC	1	Thermocouple	30-May-13	115527.0	-9.0	0.5	Vertical
160	VW	1	Vibrating Wire Strain Gauge	30-May-13	115533.0	-9.0	0.8	Longitudinal
160	VW	3	Vibrating Wire Strain Gauge	30-May-13	115535.0	-11.0	0.8	Angled
160	VW	5	Vibrating Wire Stain Gauge	30-May-13	115535.7	-9.0	0.8	Transverse
160	TC	2	Thermocouple	30-May-13	115527.0	-9.0	1.0	Vertical
160	TC	3	Thermocouple	30-May-13	115527.0	-9.0	1.5	Vertical
160	TC	4	Thermocouple	30-May-13	115527.0	-9.0	2.0	Vertical
160	DT	1	Linear Variable Displacement Transducer	30-May-13	115469.5	-9.0	2.5	Vertical
160	DT	2	Linear Variable Displacement Transducer	30-May-13	115470.5	-9.0	2.5	Vertical
160	DT	3	Linear Variable Displacement Transducer	30-May-13	115473.0	-9.0	2.5	Vertical
160	HC	1	Horizontal Clip Displacement	5-Jul-13	115530.0	-7.5	2.5	Longitudinal
160	HC	2	Horizontal Clip Displacement Sensor	30-May-13	115530.0	-10.5	2.5	Longitudinal
160	TC	5	Thermocouple	30-May-13	115527.0	-9.0	2.5	Vertical
160	VW	2	Vibrating Wire Strain Gauge	15-Jun-13	115533.0	-9.0	4.3	Longitudinal
160	VW	4	Vibrating Wire Stain Gauge	30-May-13	115535.0	-11.0	4.3	Angled
160	VW	6	Vibrating Wire Stain Gauge	30-May-13	115535.7	-9.0	4.3	Transverse

Table C.1 – Locations of sensors installed during MnROAD 2013 cell construction, cont.

CELL	MODEL	SEQ	DESCRIPTION	DATE INSTALLED	STATION (ft)	OFFSET (ft)	SENSOR DEPTH (in.)	ORIENTATION
160	CE	1	Concrete Embedded Strain Gauge	30-May-13	115473.0	-11.7	4.5	Longitudinal
160	CE	2	Concrete Embedded Strain Gauge	30-May-13	115473.0	-9.5	4.5	Transverse
160	CE	3	Concrete Embedded Strain Gauge	30-May-13	115475.7	-9.5	4.5	Transverse
160	TC	6	Thermocouple	30-May-13	115527.0	-9.0	5.0	Vertical
160	TC	7	Thermocouple	30-May-13	115527.0	-9.0	6.5	Vertical
160	TC	8	Thermocouple	30-May-13	115527.0	-9.0	8.0	Vertical
160	TC	9	Thermocouple	30-May-13	115527.0	-9.0	11.0	Vertical
160	TC	10	Thermocouple	30-May-13	115527.0	-9.0	12.0	Vertical
160	TC	11	Thermocouple	30-May-13	115527.0	-9.0	18.0	Vertical
160	TC	12	Thermocouple	30-May-13	115527.0	-9.0	24.0	Vertical
160	TC	13	Thermocouple	30-May-13	115527.0	-9.0	36.0	Vertical
160	TC	14	Thermocouple	30-May-13	115527.0	-9.0	48.0	Vertical
160	TC	15	Thermocouple	30-May-13	115527.0	-9.0	60.0	Vertical
160	TC	16	Thermocouple	30-May-13	115527.0	-9.0	72.0	Vertical
161	CE	1	Concrete Embedded Strain Gauge	30-May-13	115677.0	-11.7	4.5	Longitudinal
161	CE	2	Concrete Embedded Strain Gauge	30-May-13	115677.0	-9.5	4.5	Transverse
161	CE	3	Concrete Embedded Strain Gauge	30-May-13	115679.7	-9.5	4.5	Transverse
162	TC	1	Thermocouple	30-May-13	115953.0	-9.0	0.5	Vertical
162	VW	1	Vibrating Wire Strain Gauge	30-May-13	115959.0	-9.0	0.8	Longitudinal
162	VW	3	Vibrating Wire Strain Gauge	30-May-13	115961.0	-11.0	0.8	Angled
162	VW	5	Vibrating Wire Strain Gauge	30-May-13	115961.7	-9.0	0.8	Transverse
162	TC	2	Thermocouple	30-May-13	115953.0	-9.0	1.0	Vertical
162	TC	3	Thermocouple	30-May-13	115953.0	-9.0	1.5	Vertical
162	DT	1	Linear Variable Displacement Transducer	30-May-13	115931.5	-9.0	2.0	Vertical
162	DT	2	Linear Variable Displacement Transducer	30-May-13	115932.5	-9.0	2.0	Vertical
162	DT	3	Linear Variable Displacement Transducer	30-May-13	115935.0	-9.0	2.0	Vertical
162	HC	1	Horizontal Clip Displacement Sensor	30-May-13	115956.0	-7.5	2.0	Longitudinal
162	HC	2	Horizontal Clip Displacement Sensor	30-May-13	115956.0	-10.5	2.0	Longitudinal
162	TC	4	Thermocouple	30-May-13	115953.0	-9.0	2.0	Vertical
162	TC	5	Thermocouple	30-May-13	115953.0	-9.0	2.5	Vertical
162	VW	2	Vibrating Wire Strain Gauge	30-May-13	115959.0	-9.0	3.3	Longitudinal
162	VW	4	Vibrating Wire Strain Gauge	30-May-13	115961.0	-11.0	3.3	Angled
162	VW	6	Vibrating Wire Strain Gauge	30-May-13	115961.7	-9.0	3.3	Transverse
162	CE	1	Concrete Embedded Strain Gauge	30-May-13	115935.0	-11.7	3.5	Longitudinal
162	CE	2	Concrete Embedded Strain Gauge	30-May-13	115935.0	-9.5	3.5	Transverse

Table C.1 – Locations of sensors installed during MnROAD 2013 cell construction, cont.

CELL	MODEL	SEQ	DESCRIPTION	DATE INSTALLED	STATION (ft)	OFFSET (ft)	SENSOR DEPTH (in.)	ORIENTATION
162	CE	3	Concrete Embedded Strain Gauge	30-May-13	115937.7	-9.5	3.5	Transverse
162	TC	6	Thermocouple	30-May-13	115953.0	-9.0	4.0	Vertical
162	TC	7	Thermocouple	30-May-13	115953.0	-9.0	7.0	Vertical
162	TC	8	Thermocouple	30-May-13	115953.0	-9.0	10.0	Vertical
163	CE	1	Concrete Embedded Strain Gauge	30-May-13	116073.0	-11.7	3.5	Longitudinal
163	CE	2	Concrete Embedded Strain Gauge	30-May-13	116073.0	-9.5	3.5	Transverse
163	CE	3	Concrete Embedded Strain Gauge	30-May-13	116075.7	-9.5	3.5	Transverse
240	CE	1	Concrete Embedded Strain Gauge	30-May-13	10559.2	10.0	0.5	Longitudinal
240	CE	4	Concrete Embedded Strain Gauge	30-May-13	10566.8	10.0	0.5	Longitudinal
240	CE	7	Concrete Embedded Strain Gauge	30-May-13	10571.1	10.0	0.5	Transverse
240	CE	10	Concrete Embedded Strain Gauge	30-May-13	10573.8	10.0	0.5	Longitudinal
240	TC	1	Thermocouple	30-May-13	10555.8	9.0	0.5	Vertical
240	VW	1	Vibrating Wire Strain Gauge	30-May-13	10573.8	9.0	0.8	Longitudinal
240	TC	2	Thermocouple	30-May-13	10555.8	9.0	1.0	Vertical
240	TC	3	Thermocouple	30-May-13	10555.8	9.0	1.5	Vertical
240	TC	4	Thermocouple	30-May-13	10555.8	9.0	2.0	Vertical
240	VW	2	Vibrating Wire Strain Gauge	30-May-13	10573.8	9.0	2.3	Longitudinal
240	CE	2	Concrete Embedded Strain Gauge	30-May-13	10559.2	10.0	2.5	Longitudinal
240	CE	5	Concrete Embedded Strain Gauge	30-May-13	10566.8	10.0	2.5	Longitudinal
240	CE	8	Concrete Embedded Strain Gauge	30-May-13	10571.1	10.0	2.5	45 Degrees
240	CE	11	Concrete Embedded Strain Gauge	30-May-13	10573.8	10.0	2.5	Longitudinal
240	EC	1	ECH2O-5TE Volumetric Water Content	30-May-13	10566.3	9.0	3.0	Vertical
240	EC	2	ECH2O-5TE Volumetric Water Content	30-May-13	10566.6	11.0	3.0	Vertical
240	TC	5	Thermocouple	30-May-13	10555.8	9.0	3.0	Vertical
240	CE	3	Concrete Embedded Strain Gauge	30-May-13	10559.2	10.0	3.5	Longitudinal
240	CE	6	Concrete Embedded Strain Gauge	30-May-13	10566.8	10.0	3.5	Transverse
240	CE	9	Concrete Embedded Strain Gauge	30-May-13	10571.1	10.0	3.5	45 Degrees
240	CE	12	Concrete Embedded Strain Gauge	30-May-13	10573.8	10.0	3.5	Longitudinal
240	VW	3	Vibrating Wire Stain Gauge	30-May-13	10573.8	9.0	3.8	Longitudinal
240	TC	6	Thermocouple	30-May-13	10555.8	9.0	7.0	Vertical
240	TC	7	Thermocouple	30-May-13	10555.8	9.0	10.0	Vertical
240	TC	8	Thermocouple	30-May-13	10555.8	9.0	13.0	Vertical
613	CE	1	Concrete Embedded Strain Gauge	30-May-13	118562.5	-11.7	0.5	Longitudinal
613	CE	3	Concrete Embedded Strain Gauge	30-May-13	118568.0	-11.7	0.5	Longitudinal
613	CE	5	Concrete Embedded Strain Gauge	30-May-13	118568.0	-10.0	0.5	Angled

Table C.1 – Locations of sensors installed during MnROAD 2013 cell construction, cont.

CELL	MODEL	SEQ	DESCRIPTION	DATE INSTALLED	STATION (ft)	OFFSET (ft)	SENSOR DEPTH (in.)	ORIENTATION
613	CE	7	Concrete Embedded Strain Gauge	30-May-13	118569.7	-10.0	0.5	Transverse
613	TC	1	Thermocouple	30-May-13	118548.0	-6.0	0.5	Vertical
613	TC	13	Thermocouple	30-May-13	118765.5	-11.7	0.5	Vertical
613	VW	1	Vibrating Wire Strain Gauge	30-May-13	118547.5	-7.5	0.8	Longitudinal
613	VW	3	Vibrating Wire Strain Gauge	30-May-13	118553.0	-11.7	0.8	Longitudinal
613	VW	5	Vibrating Wire Strain Gauge	30-May-13	118554.0	-7.5	0.8	Longitudinal
613	VW	7	Vibrating Wire Strain Gauge	30-May-13	118554.7	-10.0	0.8	Transverse
613	HC	1	Horizontal Clip Gauge	30-May-13	118540.0	-10.0	1.0	Longitudinal
613	HC	3	Horizontal Clip Gauge	30-May-13	118540.0	-2.0	1.0	Longitudinal
613	TC	2	Thermocouple	30-May-13	118548.0	-6.0	1.0	Vertical
613	TC	14	Thermocouple	30-May-13	118765.5	-11.7	1.0	Vertical
613	TC	3	Thermocouple	30-May-13	118548.0	-6.0	1.5	Vertical
613	TC	15	Thermocouple	30-May-13	118765.5	-11.7	1.5	Vertical
613	TC	4	Thermocouple	30-May-13	118548.0	-6.0	2.0	Vertical
613	TC	16	Thermocouple	30-May-13	118765.5	-11.7	2.0	Vertical
613	VW	2	Vibrating Wire Strain Gauge	30-May-13	118547.5	-7.5	6.3	Longitudinal
613	VW	4	Vibrating Wire Strain Gauge	30-May-13	118553.0	-11.7	6.3	Longitudinal
613	VW	6	Vibrating Wire Strain Gauge	30-May-13	118554.0	-7.5	6.3	Longitudinal
613	VW	8	Vibrating Wire Strain Gauge	30-May-13	118554.7	-10.0	6.3	Transverse
613	HC	2	Horizontal Clip Gauge	30-May-13	118540.0	-10.0	6.5	Longitudinal
613	HC	4	Horizontal Clip Gauge	30-May-13	118540.0	-2.0	6.5	Longitudinal
613	CE	2	Concrete Embedded Strain Gauge	30-May-13	118562.5	-11.7	7.0	Longitudinal
613	CE	4	Concrete Embedded Strain Gauge	30-May-13	118568.0	-11.7	7.0	Longitudinal
613	CE	6	Concrete Embedded Strain Gauge	30-May-13	118568.0	-10.0	7.0	Angled
613	CE	8	Concrete Embedded Strain Gauge	30-May-13	118570.0	-10.0	7.0	Transverse
613	TC	5	Thermocouple	30-May-13	118548.0	-6.0	7.0	Vertical
613	TC	17	Thermocouple	30-May-13	118765.5	-11.7	7.0	Vertical
613	EC	2	ECH2O-5TE Volumetric Water Content	30-May-13	118540.0	-12.0	8.0	Vertical
613	EC	3	ECH2O-5TE Volumetric Water Content	30-May-13	118540.0	-10.0	8.0	Vertical
613	EC	4	ECH2O-5TE Volumetric Water Content	30-May-13	118547.5	-10.0	8.0	Vertical
613	EC	5	ECH2O-5TE Volumetric Water Content	30-May-13	118555.0	-12.0	8.0	Vertical
613	EC	6	ECH2O-5TE Volumetric Water Content	30-May-13	118555.0	-10.0	8.0	Vertical
613	EC	7	ECH2O-5TE Volumetric Water Content	30-May-13	118562.5	-10.0	8.0	Vertical
613	EC	9	ECH2O-5TE Volumetric Water Content	30-May-13	118570.0	-12.0	8.0	Vertical
613	EC	10	ECH2O-5TE Volumetric Water Content	30-May-13	118570.0	-10.0	8.0	Vertical

Table C.1 – Locations of sensors installed during MnROAD 2013 cell construction, cont.

CELL	MODEL	SEQ	DESCRIPTION	DATE INSTALLED	STATION (ft)	OFFSET (ft)	SENSOR DEPTH (in.)	ORIENTATION
613	EC	12	ECH2O-5TE Volumetric Water Content	30-May-13	118765.0	-12.0	8.0	Vertical
613	EC	13	ECH2O-5TE Volumetric Water Content	30-May-13	118765.0	-10.0	8.0	Vertical
613	EC	14	ECH2O-5TE Volumetric Water Content	30-May-13	118772.5	-10.0	8.0	Vertical
613	EC	15	ECH2O-5TE Volumetric Water Content	30-May-13	118780.0	-12.0	8.0	Vertical
613	EC	16	ECH2O-5TE Volumetric Water Content	30-May-13	118780.0	-10.0	8.0	Vertical
613	EC	17	ECH2O-5TE Volumetric Water Content	30-May-13	118788.0	-10.0	8.0	Vertical
613	EC	19	ECH2O-5TE Volumetric Water Content	30-May-13	118795.0	-12.0	8.0	Vertical
613	EC	20	ECH2O-5TE Volumetric Water Content	30-May-13	118795.0	-10.0	8.0	Vertical
613	TC	6	Thermocouple	30-May-13	118548.0	-6.0	9.0	Vertical
613	WM	1	WaterMark Matric Potential Sensor	30-May-13	118555.5	-26.0	9.0	Vertical
613	WM	5	WaterMark Matric Potential Sensor	30-May-13	118555.5	-17.0	9.0	Vertical
613	WM	9	WaterMark Matric Potential Sensor	30-May-13	118555.5	-12.0	9.0	Vertical
613	WM	13	WaterMark Matric Potential Sensor	30-May-13	118555.5	-6.0	9.0	Vertical
613	WM	17	WaterMark Matric Potential Sensor	30-May-13	118555.5	0.0	9.0	Vertical
613	TC	18	Thermocouple	30-May-13	118765.5	-11.7	9.5	Vertical
613	WM	221	WaterMark Matric Potential Sensor	30-May-13	118780.5	-26.0	9.5	Vertical
613	WM	225	WaterMark Matric Potential Sensor	30-May-13	118780.5	-17.0	9.5	Vertical
613	WM	229	WaterMark Matric Potential Sensor	30-May-13	118780.5	-12.0	9.5	Vertical
613	WM	233	WaterMark Matric Potential Sensor	30-May-13	118780.5	-6.0	9.5	Vertical
613	WM	237	WaterMark Matric Potential Sensor	30-May-13	118780.5	0.0	9.5	Vertical
613	TC	7	Thermocouple	30-May-13	118548.0	-6.0	12.0	Vertical
613	WM	2	WaterMark Matric Potential Sensor	30-May-13	118555.5	-26.0	12.0	Vertical
613	WM	6	WaterMark Matric Potential Sensor	30-May-13	118555.5	-17.0	12.0	Vertical
613	WM	10	WaterMark Matric Potential Sensor	30-May-13	118555.5	-12.0	12.0	Vertical
613	WM	14	WaterMark Matric Potential Sensor	30-May-13	118555.5	-6.0	12.0	Vertical
613	WM	18	WaterMark Matric Potential Sensor	30-May-13	118555.5	0.0	12.0	Vertical
613	TC	19	Thermocouple	30-May-13	118765.5	-11.7	13.3	Vertical
613	WM	222	WaterMark Matric Potential Sensor	30-May-13	118780.5	-26.0	13.3	Vertical
613	WM	226	WaterMark Matric Potential Sensor	30-May-13	118780.5	-17.0	13.3	Vertical
613	WM	230	WaterMark Matric Potential Sensor	30-May-13	118780.5	-12.0	13.3	Vertical
613	WM	234	WaterMark Matric Potential Sensor	30-May-13	118780.5	-6.0	13.3	Vertical
613	WM	238	WaterMark Matric Potential Sensor	30-May-13	118780.5	0.0	13.3	Vertical
613	EC	1	ECH2O-5TE Volumetric Water Content	30-May-13	118540.0	-23.0	14.0	Vertical
613	EC	8	ECH2O-5TE Volumetric Water Content	30-May-13	118570.0	-23.0	14.0	Vertical
613	EC	11	ECH2O-5TE Volumetric Water Content	30-May-13	118765.0	-23.0	14.0	Vertical

Table C.1 – Locations of sensors installed during MnROAD 2013 cell construction, cont.

CELL	MODEL	SEQ	DESCRIPTION	DATE INSTALLED	STATION (ft)	OFFSET (ft)	SENSOR DEPTH (in.)	ORIENTATION
613	EC	18	ECH2O-5TE Volumetric Water Content	30-May-13	118795.0	-23.0	14.0	Vertical
613	WM	3	WaterMark Matric Potential Sensor	30-May-13	118555.5	-26.0	15.0	Vertical
613	WM	7	WaterMark Matric Potential Sensor	30-May-13	118555.5	-17.0	15.0	Vertical
613	WM	11	WaterMark Matric Potential Sensor	30-May-13	118555.5	-12.0	15.0	Vertical
613	WM	15	WaterMark Matric Potential Sensor	30-May-13	118555.5	-6.0	15.0	Vertical
613	WM	19	WaterMark Matric Potential Sensor	30-May-13	118555.5	0.0	15.0	Vertical
613	WM	223	WaterMark Matric Potential Sensor	30-May-13	118780.5	-26.0	15.5	Vertical
613	WM	227	WaterMark Matric Potential Sensor	30-May-13	118780.5	-17.0	15.5	Vertical
613	WM	231	WaterMark Matric Potential Sensor	30-May-13	118780.5	-12.0	15.5	Vertical
613	WM	235	WaterMark Matric Potential Sensor	30-May-13	118780.5	-6.0	15.5	Vertical
613	WM	239	WaterMark Matric Potential Sensor	30-May-13	118780.5	0.0	15.5	Vertical
613	TC	8	Thermocouple	30-May-13	118548.0	-6.0	18.0	Vertical
613	TC	20	Thermocouple	30-May-13	118765.5	-11.7	18.0	Vertical
613	WM	4	WaterMark Matric Potential Sensor	30-May-13	118555.5	-26.0	18.0	Vertical
613	WM	8	WaterMark Matric Potential Sensor	30-May-13	118555.5	-17.0	18.0	Vertical
613	WM	12	WaterMark Matric Potential Sensor	30-May-13	118555.5	-12.0	18.0	Vertical
613	WM	16	WaterMark Matric Potential Sensor	30-May-13	118555.5	-6.0	18.0	Vertical
613	WM	20	WaterMark Matric Potential Sensor	30-May-13	118555.5	0.0	18.0	Vertical
613	WM	224	WaterMark Matric Potential Sensor	30-May-13	118780.5	-26.0	18.0	Vertical
613	WM	228	WaterMark Matric Potential Sensor	30-May-13	118780.5	-17.0	18.0	Vertical
613	WM	232	WaterMark Matric Potential Sensor	30-May-13	118780.5	-12.0	18.0	Vertical
613	WM	236	WaterMark Matric Potential Sensor	30-May-13	118780.5	-6.0	18.0	Vertical
613	WM	240	WaterMark Matric Potential Sensor	30-May-13	118780.5	0.0	18.0	Vertical
613	TC	9	Thermocouple	30-May-13	118548.0	-6.0	24.0	Vertical
613	TC	10	Thermocouple	30-May-13	118548.0	-6.0	36.0	Vertical
613	TC	11	Thermocouple	30-May-13	118548.0	-6.0	48.0	Vertical
613	TC	12	Thermocouple	30-May-13	118548.0	-6.0	60.0	Vertical

Appendix D

Fiber Reinforced Concrete Trial Mix Results

The following pages show the results of ASTM C1609 tests used by the contractor to determine the mix design meeting the 120 psi residual strength results that were specified.

Figure D.1 – Fiber reinforcement mixture design results for cells 140 and 240, specimen 1A.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax: (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of
Propex at a Dosage Rate of 6.5 lb/yd^3 Mixture MR 3A21-2F
Element Project Number - ESP013571P
June 5, 2013

Cells 140 and 240

Test Specimen:		1A			
Length, L	in.	18.0	=	457	mm
Width, b	in.	6.11	=	155	mm
Depth, d	in.	6.29	=	100	mm
P_1	lbf	6382	=	28	N
δ_1	in.	0.0015	=	0.04	mm
f_1	psi	475	=	3.30	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	1410	=	6	N
f^D_{150}	psi	105	=	0.70	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	1683	=	7	N
f^D_{600}	psi	125	=	0.85	MPa
T^D_{150}	in.lb	190	=	21	J
R^{150}_{150}	%	25.0	=	25.0	%
$P_{100,0.4}$	lbf	1538	=	7	N
$f_{100,0.4}$	psi	115	=	0.80	MPa
$P_{100,1.0}$	lbf	1699	=	8	N
$f_{100,1.0}$	psi	125	=	0.85	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	120	=	0.85	MPa

Date Cast: 5/28/13
Age at Test: 8
Date Tested: 6/5/13 Tested By: John Ball

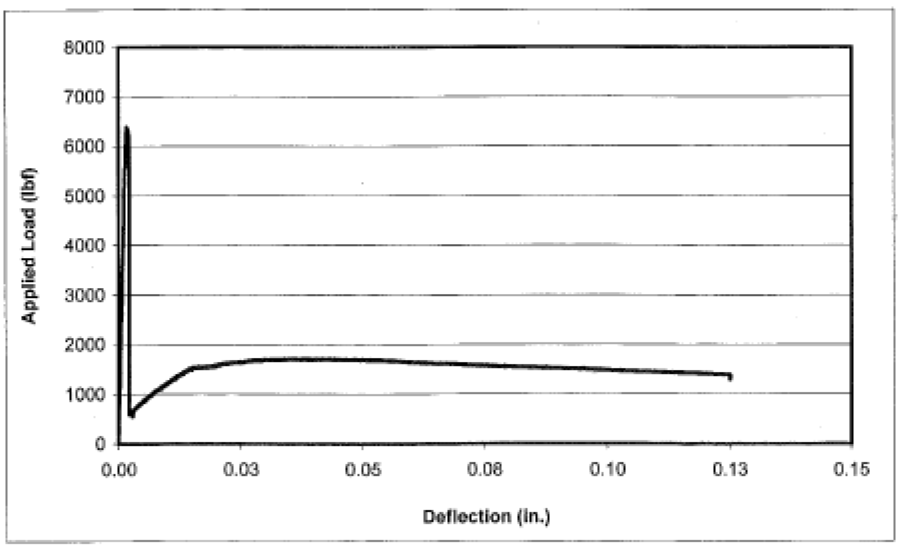


Figure D.2 – Fiber reinforcement mixture design results for cells 140 and 240, specimen 1B.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax: (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of
Propex at a Dosage Rate of 6.5 lb/yd³ Mixture MR 3A21-2F
Element Project Number - ESP013571P
June 5, 2013

Cells 140 and 240

Test Specimen:		1B			
Length, L	in.	18.0	=	457	mm
Width, b	in.	6.11	=	155	mm
Depth, d	in.	5.91	=	100	mm
P_1	lbf	8572	=	38	N
δ_1	in.	0.0030	=	0.08	mm
f_1	psi	725	=	5.00	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	2320	=	10	N
f^D_{150}	psi	195	=	1.35	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	2584	=	11	N
f^D_{600}	psi	220	=	1.50	MPa
T^D_{150}	in.lb	300	=	34	J
R^{150}_{150}	%	29.0	=	29.0	%
$P_{100,0.4}$	lbf	2412	=	11	N
$f_{100,0.4}$	psi	205	=	1.40	MPa
$P_{100,1.0}$	lbf	2602	=	12	N
$f_{100,1.0}$	psi	220	=	1.50	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	213	=	1.45	MPa

Date Cast: 5/28/13
Age at Test: 8
Date Tested: 6/5/13 Tested By: John Ball

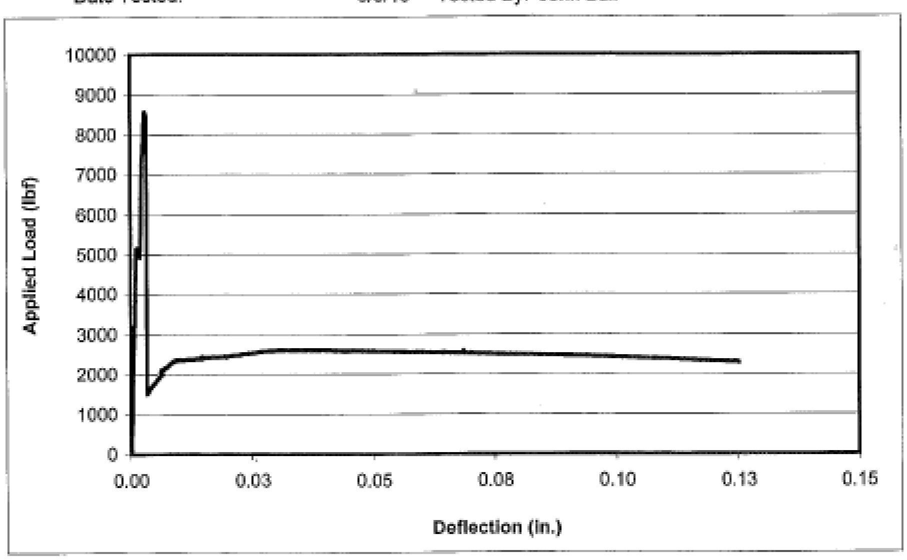


Figure D.3 – Fiber reinforcement mixture design results for cells 140 and 240, specimen 1C.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax: (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of
Propex at a Dosage Rate of 6.5 lb/yd³ Mixture MR 3A21-2F
Element Project Number - ESP013571P
June 5, 2013

Cells 140 and 240

Test Specimen:		1C			
Length, L	in.	18.0	=	457	mm
Width, b	in.	6.09	=	155	mm
Depth, d	in.	6.22	=	100	mm
P_1	lbf	7575.	=	34	N
δ_1	in.	0.0015	=	0.04	mm
f_1	psi	580	=	4.00	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	1443	=	6	N
f^D_{150}	psi	110	=	0.75	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	1654	=	7	N
f^D_{600}	psi	125	=	0.85	MPa
T^D_{150}	in.lb	190	=	21	J
R^{150}_{150}	%	21.0	=	21.0	%
$P_{100,0.4}$	lbf	1601	=	7	N
$f_{100,0.4}$	psi	120	=	0.85	MPa
$P_{100,1.0}$	lbf	1664	=	7	N
$f_{100,1.0}$	psi	125	=	0.85	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	123	=	0.85	MPa

Date Cast: 5/28/13
Age at Test: 8
Date Tested: 6/5/13 Tested By: John Ball

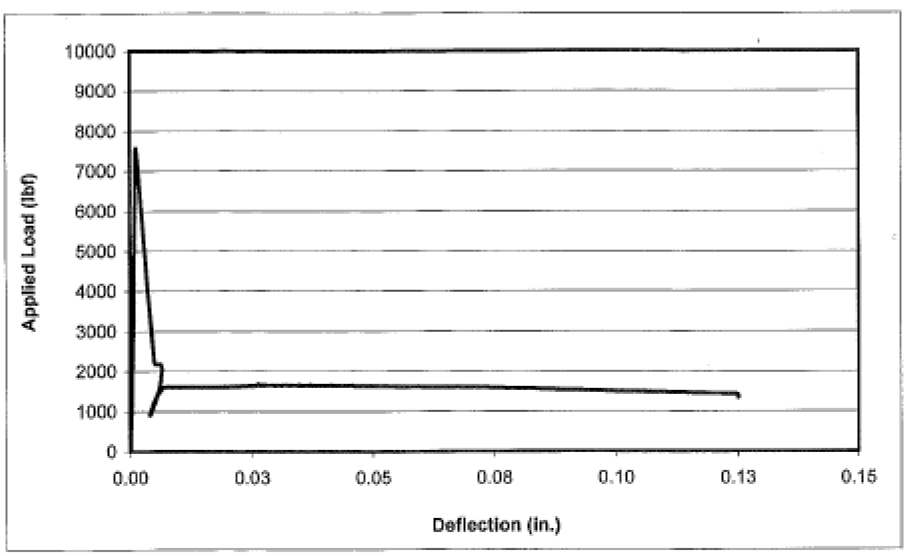


Figure D.4 – Fiber reinforcement mixture design results for cells 140 and 240, specimen 1D.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax: (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of Propex at a Dosage Rate of 6.5 lb/yd³ Mixture MR 3A21-2F
Element Project Number - ESP013571P
June 5, 2013

Cells 140 and 240

Test Specimen:		1D			
Length, L	in.	18.0	=	457	mm
Width, b	in.	6.03	=	153	mm
Depth, d	in.	6.22	=	100	mm
P_1	lbf	8516	=	38	N
δ_1	in.	0.0020	=	0.05	mm
f_1	psi	655	=	4.50	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	1571	=	7	N
f^D_{150}	psi	120	=	0.85	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	1749	=	8	N
f^D_{600}	psi	135	=	0.95	MPa
T^D_{150}	in.lb	190	=	21	J
R^{150}_{150}	%	18.5	=	18.5	%
$P_{100,0.4}$	lbf	1664	=	7	N
$f_{100,0.4}$	psi	130	=	0.90	MPa
$P_{100,1.0}$	lbf	1746	=	8	N
$f_{100,1.0}$	psi	135	=	0.95	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	133	=	0.90	MPa

Date Cast: 5/28/13
Age at Test: 8
Date Tested: 6/5/13 Tested By: John Ball

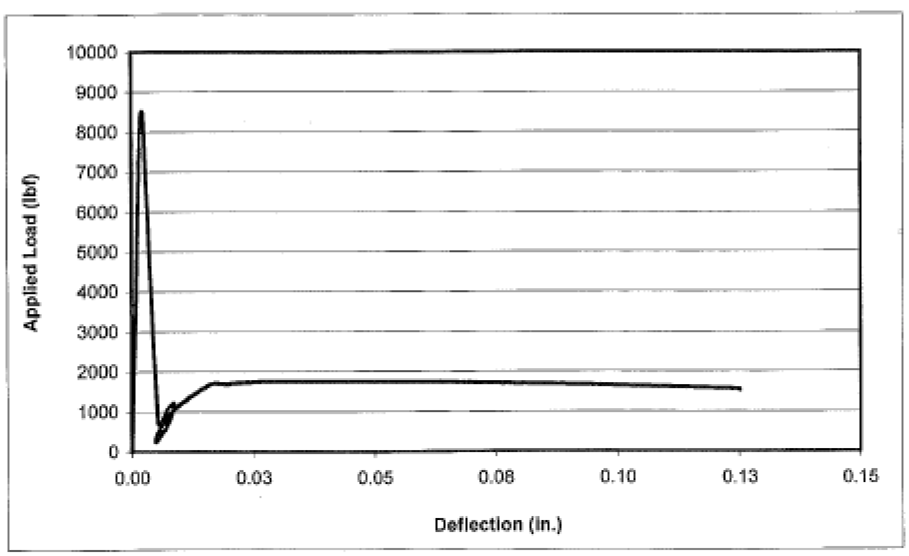


Figure D.5 – Fiber reinforcement mixture design results for cells 140 and 240, specimen 1E.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax: (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of Propex at a Dosage Rate of 6.5 lb/yd³ Mixture MR 3A21-2F

Element Project Number - ESP013571P

June 5, 2013

Cells 140 and 240

Test Specimen:		1E			
Length, L	in.	18.0	=	457	mm
Width, b	in.	6.07	=	154	mm
Depth, d	in.	6.13	=	100	mm
P_1	lbf	8323	=	37	N
δ_1	in.	0.0020	=	0.05	mm
f_1	psi	655	=	4.50	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	1660	=	7	N
f^D_{150}	psi	130	=	0.90	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	1955	=	9	N
f^D_{600}	psi	155	=	1.05	MPa
T^D_{150}	in.lb	220	=	25	J
R^{100}_{150}	%	22.0	=	22.0	%
$P_{100,0.4}$	lbf	1841	=	8	N
$f_{100,0.4}$	psi	145	=	1.00	MPa
$P_{100,1.0}$	lbf	1932	=	9	N
$f_{100,1.0}$	psi	150	=	1.05	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	148	=	1.00	MPa

Date Cast: 5/28/13
Age at Test: 8
Date Tested: 6/5/13 Tested By: John Ball

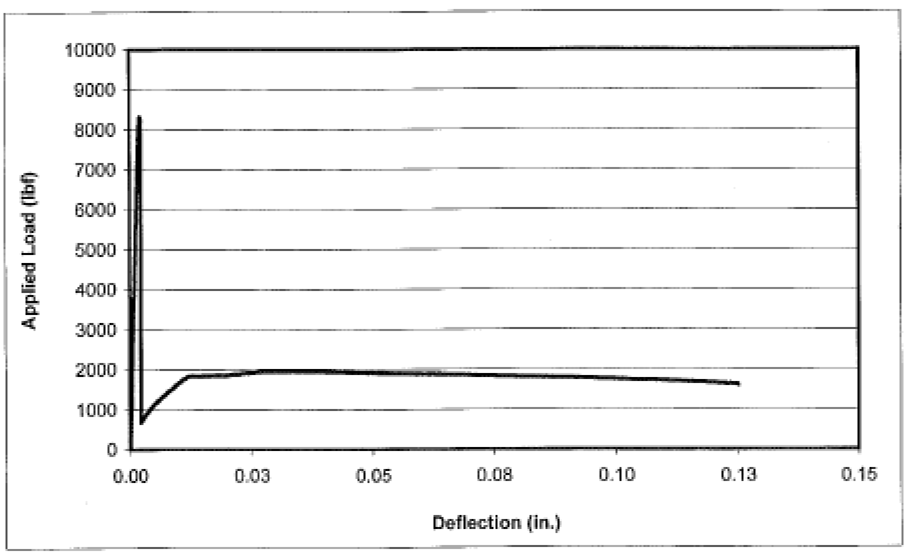


Figure D.6 – Fiber reinforcement mixture design results for cells 160-163, specimen 1A.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax: (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of
Propex at a Dosage Rate of 6.5 lb/yd^3 Mixture MR 3A21-1F
Element Project Number - ESP013571P
June 5, 2013

Cells 160-163

Test Specimen:		1A			
Length, L	in.	18.0	=	457	mm
Width, b	in.	5.98	=	152	mm
Depth, d	in.	6.14	=	100	mm
P_1	lbf	7130	=	32	N
δ_1	in.	0.0020	=	0.05	mm
f_1	psi	570	=	3.95	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	1786	=	8	N
f^D_{150}	psi	145	=	1.00	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	2230	=	10	N
f^D_{600}	psi	180	=	1.25	MPa
T^D_{150}	in.lb	260	=	29	J
R^{150}_{150}	%	30.5	=	30.5	%
$P_{100,0.4}$	lbf	2003	=	9	N
$f_{100,0.4}$	psi	160	=	1.10	MPa
$P_{100,1.0}$	lbf	2319	=	10	N
$f_{100,1.0}$	psi	185	=	1.30	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	173	=	1.20	MPa
I_{20}		#DIV/0!			
I_{50}		#DIV/0!			
$R_{20,50}$		#DIV/0!			

Date Cast: 5/28/13
Age at Test: 7
Date Tested: 6/4/13 Tested By: Nick Holderbaum

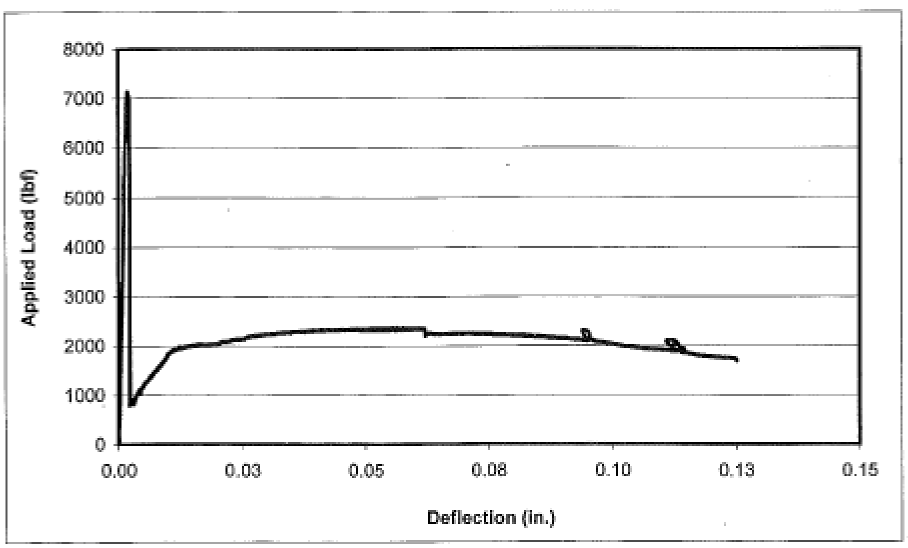


Figure D.7 – Fiber reinforcement mixture design results for cells 160-163, specimen 1B.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax: (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of
Propex at a Dosage Rate of 6.5 lb/yd³ Mixture MR 3A21-1F
Element Project Number - ESP013571P
June 5, 2013

Cells 160-163

Test Specimen:		1B			
Length, L	in.	18.0	=	457	mm
Width, b	in.	5.99	=	152	mm
Depth, d	in.	6.04	=	100	mm
P_1	lbf	7168	=	32	N
δ_1	in.	0.0015	=	0.04	mm
f_1	psi	590	=	4.05	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	1568	=	7	N
f^D_{150}	psi	130	=	0.90	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	1911	=	9	N
f^D_{600}	psi	155	=	1.05	MPa
T^D_{150}	in.lb	210	=	24	J
R^{150}_{150}	%	24.5	=	24.5	%
$P_{100,0.4}$	lbf	1883	=	8	N
$f_{100,0.4}$	psi	155	=	1.05	MPa
$P_{100,1.0}$	lbf	1879	=	8	N
$f_{100,1.0}$	psi	155	=	1.05	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	155	=	1.05	MPa

Date Cast: 5/28/13
Age at Test: 8
Date Tested: 6/5/13 Tested By: John Ball

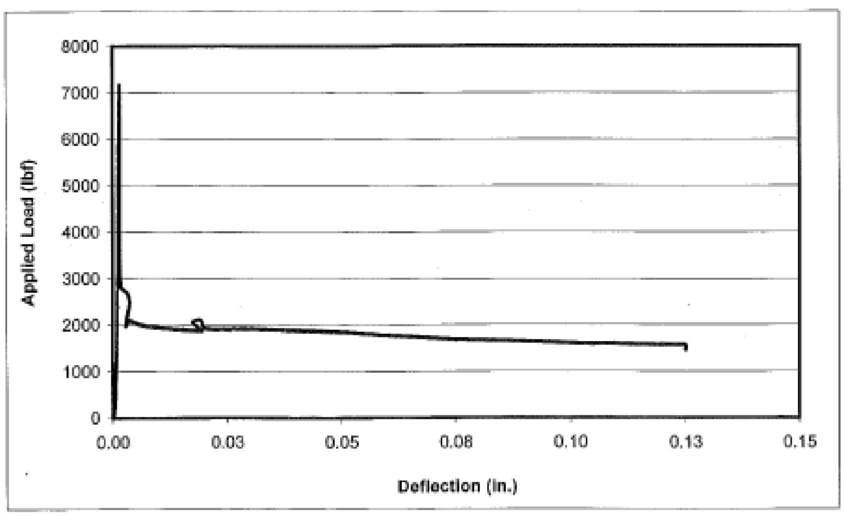


Figure D.8 – Fiber reinforcement mixture design results for cells 160-163, specimen 1C.

element

Element Materials Technology

662 Cromwell Avenue, St. Paul, MN 55114-1776

(651) 645-3601, Fax: (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of Propex at a Dosage Rate of 6.5 lb/yd^3 Mixture MR 3A21-1F

Element Project Number - ESP013571P

June 5, 2013

Cells 160-163

Test Specimen:		1C			
Length, L	in.	18.0	=	457	mm
Width, b	in.	5.93	=	151	mm
Depth, d	in.	6.09	=	100	mm
P_1	lbf	6943	=	31	N
δ_1	in.	0.0015	=	0.04	mm
f_1	psi	570	=	3.95	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	2143	=	10	N
f^D_{150}	psi	175	=	1.20	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	2408	=	11	N
f^D_{600}	psi	195	=	1.35	MPa
T^D_{150}	in.lb	280	=	32	J
R^{150}_{150}	%	33.5	=	33.5	%
$P_{100,0.4}$	lbf	2318	=	10	N
$f_{100,0.4}$	psi	190	=	1.30	MPa
$P_{100,1.0}$	lbf	2452	=	11	N
$f_{100,1.0}$	psi	200	=	1.40	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	195	=	1.35	MPa

Date Cast: 5/28/13

Age at Test: 8

Date Tested: 6/5/13 Tested By: John Ball

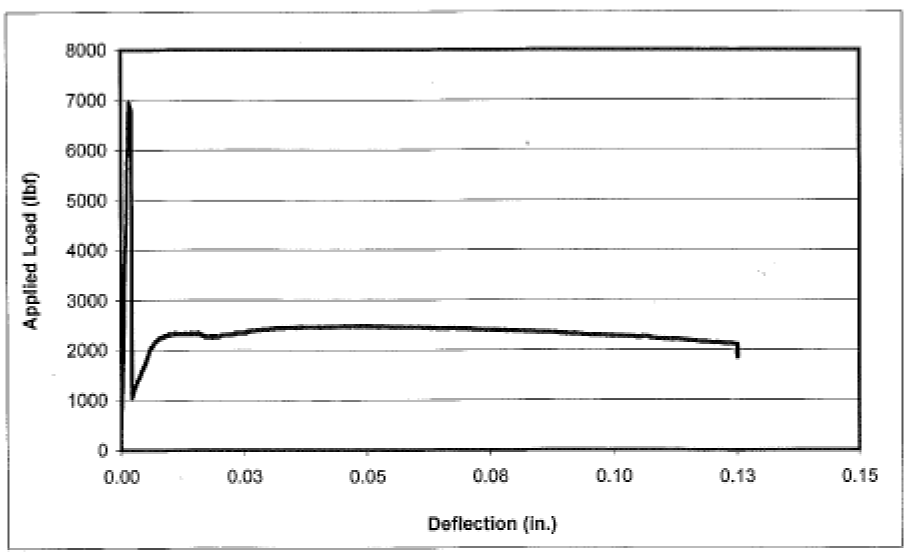


Figure D.9 – Fiber reinforcement mixture design results for cells 160-163, specimen 1D.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax (651) 659-7348

ASTM C1609/C1609M–10 Flexural Performance of Propex at a Dosage Rate of 6.5 lb/yd³ Mixture MR 3A21-1F
Element Project Number - ESP013571P
June 5, 2013

Cells 160-163

Test Specimen:		1D			
Length, L	in.	18.0	=	457	mm
Width, b	in.	5.95	=	151	mm
Depth, d	in.	6.12	=	100	mm
P_1	lbf	6811	=	30	N
δ_1	in.	0.0020	=	0.05	mm
f_1	psi	550	=	3.80	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	1779	=	8	N
f^D_{150}	psi	145	=	1.00	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	2179	=	10	N
f^D_{600}	psi	175	=	1.20	MPa
T^D_{150}	in.lb	250	=	28	J
R^{150}_{150}	%	30.5	=	30.5	%
$P_{100,0.4}$	lbf	2112	=	9	N
$f_{100,0.4}$	psi	170	=	1.15	MPa
$P_{100,1.0}$	lbf	2143	=	10	N
$f_{100,1.0}$	psi	175	=	1.20	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	173	=	1.20	MPa

Date Cast: 5/28/13
Age at Test: 8
Date Tested: 6/5/13 Tested By: John Ball

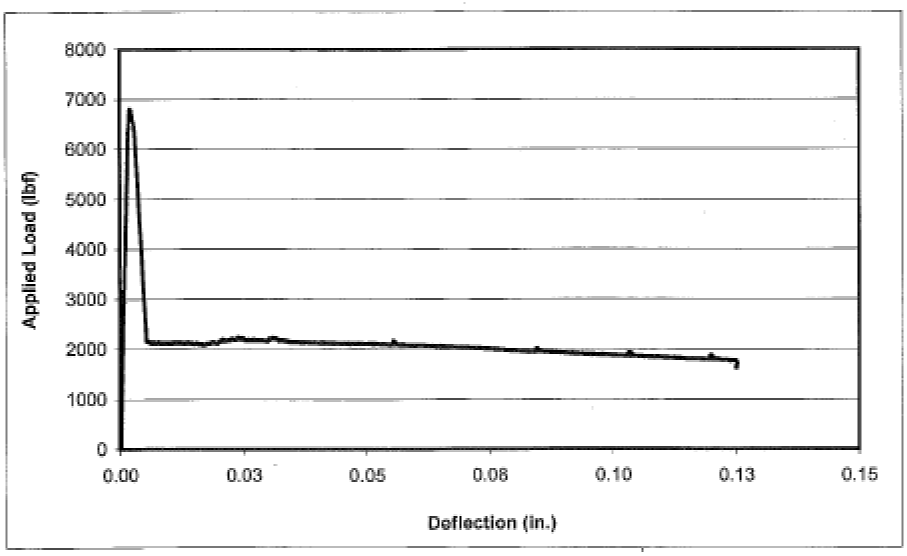


Figure D.10 – Fiber reinforcement mixture design results for cells 160-163, specimen 1E.

element

Element Materials Technology
662 Cromwell Avenue, St. Paul, MN 55114-1776
(651) 645-3601, Fax: (651) 659-7348

Cells 160-163

ASTM C1609/C1609M–10 Flexural Performance of
Propex at a Dosage Rate of 6.5 lb/yd^3 Mixture MR 3A21-1F
Element Project Number - ESP013571P
June 5, 2013

Test Specimen:		1E			
Length, L	in.	18.0	=	457	mm
Width, b	in.	6.03	=	153	mm
Depth, d	in.	6.10	=	100	mm
P_1	lbf	7161	=	32	N
δ_1	in.	0.0020	=	0.05	mm
f_1	psi	575	=	3.96	MPa
δ^D_{150}	in.	0.1200	=	3.05	mm
P^D_{150}	lbf	1775	=	8	N
f^D_{150}	psi	140	=	0.95	MPa
δ^D_{600}	in.	0.0300	=	0.76	mm
P^D_{600}	lbf	1946	=	9	N
f^D_{600}	psi	155	=	1.05	MPa
T^D_{150}	in.lb	230	=	26	J
R^{150}_{150}	%	26.5	=	26.5	%
$P_{100,0.4}$	lbf	1814	=	8	N
$f_{100,0.4}$	psi	145	=	1.00	MPa
$P_{100,1.0}$	lbf	1964	=	9	N
$f_{100,1.0}$	psi	155	=	1.05	MPa
Avg. $f_{100,.4}$ $f_{100,1.0}$	psi	150	=	1.05	MPa

Date Cast: 5/28/13
Age at Test: 8
Date Tested: 6/5/13 Tested By: John Ball