

MnROAD Cells 16-23 (Phase II): Forensic Investigation into Recycled Unbound Base and Asphalt Surface Materials

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FINAL REPORT

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EXECUTIVE SUMMARY

This report presents the findings from an eight-year performance evaluation of eight cells (Cells 16-23) built at the Minnesota Road Research Facility (MnROAD) in 2008. The constructed cells were used for two performance evaluation studies of: 1) unbound base materials (i.e., recycled asphalt pavement (RAP), recycled concrete aggregate, and taconite) and Class 5 aggregate as the road base material and 2) surface materials that include warm mix additives (WMAs), RAP, and different binders with different performance grades.

The eight cells were tested via a surface distress survey, rutting tests, falling weight deflectometer tests, international roughness index (IRI) tests, and friction tests. Disk-shaped compact tension (DCT) tests also were performed using the mixture samples, and the performance of the unbound base materials (Cells 16-19) was evaluated using light-weight deflectometer (LWD), dynamic cone penetrometer (DCP), and gradation tests. During the performance monitoring period from 2008 to 2016, the cells did not experience any extreme weather events, and the traffic levels, i.e., the equivalent single-axle loads (ESALs) and truck percentages, also were in the normal range. The fatigue life and rutting life of the pavements predicted by MnPAVE ranged from 9 to 50 years and 6 to 11 years, respectively. After eight years of service (approximately 5.6 million ESALs), the fatigue and rutting exhibited by the cells did not exceed the failure threshold.

All the data presented in this report, as well as the sampling, testing, and construction information, can be found in the MnROAD database and various publications. Additional information about MnROAD can be found on the MnROAD website at <http://www.dot.state.mn.us/mnroad/index.html>. The following conclusions and recommendations were reached based on the field and laboratory test results.

Conclusions:

- Overall, after eight years of service, the cells were in good condition relative to surface distresses, rutting, stiffness, IRI values, and friction. Consequently, it was difficult to compare the performance differences among the various unbound materials and mixtures.
- A correlation between DCT fracture energy and the thermal low-temperature performance of the mixtures could not be found due to the limited number of cracks in the cells.
- The unbound recycled materials and taconite performed as well as the Class 5 aggregate base material in terms of the gradation, DCP, and LWD test results.
- All mixture types, regardless of RAP content, binder grade, or the presence of WMA, exhibited similar performance.

Recommendations:

- Additional research is required to validate the findings from these studies. Laboratory tests using core samples currently are being conducted, and a separate report will be generated to expand on this report.

- MnPAVE updates are required for the unbound base materials. Resilient modulus values and seasonal variations of the unbound base materials need to be found.
- Further research regarding a temperature correction model for TONN 2010 needs to be conducted to refine the existing model. Significant seasonal variations with back-calculated stiffness values were noted even after being corrected for 72°F.

CHAPTER 1: INTRODUCTION

1.1 PROJECT BACKGROUND AND OBJECTIVES

Low-temperature cracking is the major surface distress type found in asphalt pavements that experience cold weather climates, such as the climate of Minnesota. As the temperature drops, the restrained pavement tries to shrink. Tensile stress builds up as the restrained pavement attempts to shrink at low temperatures, and a crack forms at a critical point. The current low-temperature specifications consider only the asphalt binder performance grade (PG), and thus, specifications must be developed for the asphalt mixture as well (2). The primary objective of this study is to validate the current laboratory test procedures, models, and pavement design procedures. A fracture mechanics approach was used in this study to investigate the detrimental effects of aging and moisture on the fracture resistance of asphalt materials.

This report presents the findings from an eight-year performance evaluation of eight cells (Cells 16-23) built at the Minnesota Road Research Facility (MnROAD) in 2008. The constructed cells were used for two performance evaluation studies of: 1) unbound base materials, i.e., recycled asphalt pavement (RAP), recycled concrete aggregate (RCA), and taconite, and Class 5 aggregate as the road base material, and 2) surface materials that include warm mix additives (WMAs), RAP, and different binders with different PGs.

Minnesota has a long history of using recycled materials in all of the pavement layers in pavement construction. The Minnesota Department of Transportation (MnDOT) specification 3138 (2016) allows recycled materials, including, e.g., RAP and recycled Portland concrete cement (PCC), etc. as the base material (1). However, the material properties (strength, stiffness, unsaturated properties, etc.) of these materials are not well understood. In 2004, MnDOT began a partnership with the Minnesota Department of Natural Resources to evaluate Mesabi Select aggregate as a base material. A follow-up project in conjunction with the Natural Resources Research Institute at the University of Minnesota at Duluth included new construction using taconite aggregate, which is commonly used as railroad ballast (2). For the current long-term study, these material properties were monitored during construction and throughout the pavement life to determine their effects on pavement performance. Specifically, the objective of this study is to monitor the performance of the MnROAD cells that were constructed using recycled materials in the granular base layers; these materials include recycled materials blended with virgin materials (Cell 17) and 100 percent recycled asphalt (Cell 18), recycled concrete pavement materials (Cell 16), and Mesabi Select aggregate (Cell 23).

MnROAD partnered with the National Center for Asphalt Technologies (NCAT) in the fall of 2015. This partnership initiated one of the first pavement research efforts to develop and implement asphalt performance tests to predict cracking for common distresses found in pavements in North America. As a result, both MnROAD and NCAT started to develop test sections for their research partnership. MnROAD Cells 16 through 23 are the only existing cells that meet the requirement (i.e., eight consecutive cells on

the MnROAD mainline test road) for these test sections. As of November 2016, Cells 16 through 23 (Phase II, constructed in 2008) were removed for new construction.

1.2 PREVIOUS STUDIES OF MNROAD PAVEMENTS

Several research studies of the asphalt pavements at MnROAD have been conducted in the past to investigate low-temperature cracking, the performance of RAP and recycled unbound materials, surface characteristics, the benefits of the Phase II research, and construction. The titles, report numbers, and brief summaries of the studies performed using Cells 16 through 23 are presented in the following subsections.

1.2.1 Investigation of Low-Temperature Cracking in Asphalt Pavements (Report No. 2007-43)

Marasteanu et al. conducted research into the development of experimental and analytical methods to investigate the fracture resistance of asphalt materials and the fracture performance of asphalt pavements at MnROAD. Marasteanu et al. reached the following conclusions based on their research (3):

- Asphalt binder properties are among the major factors used to design asphalt mixtures that are resistant to low-temperature cracking. However, low-temperature cracking cannot be predicted with sufficient reliability using the current asphalt binder test methods.
- The effects of temperature and loading rate are significant for low-temperature tests on asphalt mixtures. Furthermore, the mixture coefficient of thermal contraction is a critical parameter that is needed to estimate low-temperature cracking in the field.

1.2.2 2008 MnROAD Phase II Construction Report (Report No. 2009-22)

Johnson et al. documented the MnROAD Phase II construction, which was begun in 2007 and continued through 2008. The construction involved the reconstruction of Cells 2, 3, 4, 5, 6, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, and 23 on MnROAD's 'mainline' test section and Cells 24, 39, 53, 85, 86, 87, 88, and 89 on MnROAD's low-volume test road. Funding for the construction and research came from many partners, both locally and nationally, and the total budget was \$10.9 million. The core research areas were mechanistic design, innovative construction, preventive maintenance, recycled materials, pavement rehabilitation, surface characteristics, and other non-pavement research (2). Table 1-1 through Table 1-5 provide summaries of the material properties for Cells 16 through 23 obtained at the time of construction.

Table 1-1 Proctor test data for Class 5 material

Cell	Opt. Moisture (%)	Max Density (pcf)
19	9.1	128.3
20	9.3	129.2
21	8.9	129.3
22	10.3	128.1

Table 1-2 Proctor test data for unbound recycled material

Cell	Material	Opt. Moisture (%)	Max Density (pcf)
16	100% recycled PCC	11.7	118.0
17	50% recycled PCC 50% virgin Class 5	10.4	123.2
18	100% RAP	6.7	124.4

Table 1-3 Proctor test data for Select Granular material

Cell	Material	Opt. Moisture (%)	Max Density (pcf)
16	Select Granular	8.1	131.5
17	Select Granular	8.1	130.6
18	Select Granular	7.9	130.1
19	Select Granular	7.7	131.4
20	Select Granular	8.5	129.6
21	Select Granular	8.3	129.2
22	Select Granular	8.4	128.6
23	Select Granular	7.6	131.4

Table 1-4 Material properties for subgrade (clay loam)

Cell	Optimum Moisture	Max Density	Liquid Limit	Plastic Limit	Plasticity Index	R-Value
16	13.6	117.1	30.5	19.3	11.2	25.8
17	14.9	113.5	33.8	20.8	13.0	18.9
18	13.9	114.2	33.8	20.5	13.3	20.9
19	15.6	112.1	29.8	21.9	8.0	28.2
20	15.2	113.2	30.3	15.5	14.8	22.9
21	16.4	108.9	32.6	18.1	14.5	25.4
22	15.7	112.6	30.9	18.5	12.4	23.0
23	16.5	109.7	34.1	20.5	13.7	18.5

Table 1-5 Average density and air void results for hot mix asphalt core samples

Cell	Description	% Density	Air Voids
15-19, 23	WMA non wear	93.4	6.6
15-19, 23	WMA wear	92.0	8.0
20	RAP non wear	95.6	4.4
20	RAP wear	92.5	7.5
21	FRAP non wear	95.0	5.0
21	FRAP wear	92.3	7.7
22	FRAP non wear	95.4	4.6
22	FRAP wear	93.6	6.4

1.2.3 Use of Taconite Aggregates in Pavement (Report No. 2010-24)

Clyne et al. investigated the use of taconite aggregate for pavement applications. Clyne et al. reported the following major findings (4):

- Taconite aggregate can be used as a quality aggregate base for asphalt and concrete pavement base layers. The test sections composed of taconite aggregate at MnROAD showed good performance.
- The laboratory test results also indicated good performance of the asphalt mixture that contained taconite aggregate compared to the asphalt mixtures composed of conventional aggregate.

1.2.4 Investigation of Low-Temperature Cracking in Asphalt Pavements National Pooled Fund Study - Phase II (Report No. 2012-23)

Marasteanu et al. conducted research that was a continuation of their 2007 work to investigate low-temperature cracking. Based on their research, Marasteanu et al. reached the following conclusions (5):

- Disk-shaped compact tension (DCT) tests and semi-circular bending laboratory tests of asphalt mixtures showed that fracture tests could distinguish between different mixtures.
- A 15 percent increase in fracture energy to account for mixture aging and a higher fracture energy threshold are suggested. The DCT test validation showed that the test could reasonably predict the initial field performance data.
- The new ILLI-TC thermal cracking model is a significant improvement over current models in handling fracture simulations. The researchers also developed a thermal stress model that accounts for the glass transition and physical hardening of asphalt mixtures, thereby providing a foundation for developing mixtures that resist cracking through multiple temperature cycles.

1.2.5 Recycled Unbound Materials (Report No. 2012-35)

Edil et al. characterized the properties of RCA and RAP as unbound base materials without stabilization (6). This project included laboratory specimens, large-scale model tests, and the evaluation of field data from MnROAD test sections constructed using recycled materials. In addition, the study employed recycled unbound materials from other states, i.e., California, Colorado, Michigan, Minnesota, New Jersey, Ohio, Texas, and Wisconsin. A conventional base course was used as the control material. Overall, RCA and RAP were determined to be suitable materials for unbound base layer applications and could provide equal or superior performance compared to natural aggregates in terms of stiffness, freeze-thaw and wet-dry durability, and toughness. Additional major findings from the Edil et al. report are as follows:

- The mechanical properties of RAP and RCA that were determined under different climatic conditions indicate that both RAP and RCA have higher stiffness values than Class 5 aggregate base material regardless of the number of freeze-thaw cycles.
- Effects of temperature on the resilient modulus of RCA and natural aggregate at 7°C, 23°C, 35°C, and 50°C were not evident; however, a decrease of approximately 30 percent of the resilient modulus was observed in two of the three RAP specimens tested between 23°C and 35°C. This finding suggests that the service life of a pavement constructed with RAP/RPM may be shorter than the service life of a pavement that has a natural crushed aggregate base in terms of rutting due to the combined effects of decreasing stiffness and increasing plastic deformation that result from the temperature increase.
- Based on their measured unsaturated hydraulic conductivity values, the RAP and RCA showed greater drainage capacity than the Class 5 material.
- Falling weight deflectometer (FWD) tests have been conducted at MnROAD cells since construction (2009-2012). All of the pavement layers below the surface layer (i.e., the base, sub-base, and subgrade) have retained a relatively constant level of stiffness regardless of the temperature. Moreover, no deterioration of the modulus was evident over the subsequent four years (to 2016).

1.2.6 MnROAD Study of RAP and Fractionated RAP (Report No. 2012-39)

Johnson et al. evaluated and compared the laboratory and field performance of RAP and fractionated RAP (FRAP) by monitoring test cells at MnROAD between 2008 and 2012. Based on their research, Johnson et al. reached the following conclusions (6):

- Overall, only limited amounts of distress were observed in Cells 16, 20, 21, and 23. With regard to experimental variables, Cell 21 (PG 58-28 FRAP) developed 13 feet of longitudinal cracking.
- The IRI results were similar within study groups, i.e., WMA, FRAP, and recycled base material. The rutting test results revealed that rutting was not an issue for any of the cells, as measured by an Automated Laser Profile System (ALPS) laser.

1.2.7 Hot Mix Asphalt Surface Characteristics Related to Ride, Texture, Friction, Noise and Durability (Report No. 2014-07)

McDaniel et al. investigated 25 asphalt-surfaced roadway test sections at MnROAD to develop a model to predict on-board sound intensity (OBSI) on hot mix asphalt (HMA) pavements. The model indicated that, in order to achieve a low-noise pavement, a smooth surface with a low stiffness value is preferable. Pavements with chip or surface seals have greater texture and result in higher noise levels than warm mix asphalt and low-volume traffic mixtures that generally have lower stiffness values and produce less noise (7).

1.2.8 Benefits of MnROAD Phase II Research (Report No. 2015-19)

Worel and Van Deusen reported the benefits of the MnROAD Phase II research (2007 -2016). They reported that the estimated annual savings and benefits were over \$10 million. The major benefits reported in the study that relate to Cells 16 through 23 are as follows (8):

- Findings from the study, *Investigation of Low Temperature Cracking in Asphalt Pavements*, led to enhanced pavement life due to the reduced rate of low-temperature cracking occurrences and the reduction in damage and resultant efficiency of maintenance and construction costs.
- Three cells built in 2008 incorporated higher than standard recycled asphalt content, and these cells performed well. The findings were able to lead to improvements in the pavement life cycle and cost-effectiveness due to the more sustainable use of existing resources.
- In 2008, six test cells on the I-94 mainline roadway were constructed using warm mix technology. These sections were the first MnROAD sections to demonstrate WMA usage on a high-volume roadway. This work helped foster a sense of confidence in using WMA on a wider scale across Minnesota.
- The study, *HMA Surface Characteristics Related to Ride, Texture, Friction, Noise, Durability*, evaluated several asphalt surface types, including porous, dense-graded, ultra-thin bonded, and taconite. The key findings led to the determination of the characteristics of each these surfaces with respect to level of sound absorption, friction, ride, and longevity when subjected to Minnesota's climate extremes.

1.2.9 DCT Low Temperature Testing Pilot Project (Report No. 2015-20)

Johanneck et al. reported the use of the DCT test to measure the thermal fracture properties of asphalt mixtures in five asphalt paving projects in Minnesota during the 2013 construction season. The five construction projects represented different climatic conditions, construction practices, and asphalt binder PGs. DCT tests were conducted using both adjusted and unadjusted production mixes to verify the mixes' fracture energy requirement of 400 J/m². Preliminary distress survey results indicated that the samples with mill and overlay experienced more cracking compared to samples that contained reclaimed or virgin binder. Additional key findings from the study are as follows (9):

- Differences in materials can greatly affect fracture energy; thus, specimens prepared for DCT testing must match the material to be used during production.
- The presence of polymer-modified binder did affect the fracture energy.
- The test temperature for DCT test specimens is recommended to be 10°C warmer than the asphalt binder PG low temperature required for 98 percent reliability as determined by LTPPBind 3.1 software.

1.3 REPORT ORGANIZATION

This report is organized into four chapters. Chapter 1 provides the research background, objectives, and a summary of previous research conducted using MnROAD Cells 16 through 23. Chapter 2 describes the experimental study conducted to evaluate unbound recycled base materials and mixture low-temperature cracking performance. Chapter 3 discusses the findings from the eight-year performance evaluation of the eight test cells. The conclusions from this research and future research recommendations are given in Chapter 4.

All the data presented herein, as well as the sampling, testing, and construction information, can be found in the MnROAD database and various publications. Additional information about MnROAD also can be found on the MnROAD website at <http://www.dot.state.mn.us/mnroad/index.html>.

CHAPTER 2: EXPERIMENTAL EVALUATION

2.1 CONSTRUCTION

2.1.1 Site information

The MnDOT's pavement test track (MnROAD) is located 40 miles northwest of Minneapolis/St. Paul and contains over 50 individual test sections. All of the test sections, each approximately 500 feet long, are owned and operated by MnDOT and its partners. Two separate roadway segments that also are included are the 3.5-mile Interstate-94 mainline roadway and bypass and a 2.5-mile low-volume roadway. This report focuses on eight test sections (Cells 16-23) that were constructed in 2008 on the east end of the 3.5-mile Interstate-94 mainline test section.

2.1.2 Recycled unbound pavement materials (Cells 16-19, 23)

The construction of the cells began in May 2008. First, the existing pavement was milled, followed by the placement of Select Granular and Class 3 materials. In late August and early September 2008, the aggregate base layers were constructed, and the cells were paved on September 17 and 18. The construction of Cell 23 required the placement of fabric on top of the Class 3 aggregate base. Mesabi Select aggregate was then placed by having a dozer push it into place and then rolled vigorously to compact the aggregate. This compaction effort was found to cause the aggregate particles in the bottom layer to fracture. It should be noted also that the HMA overran by approximately 30 percent on the bottom lift due to loss into the Mesabi Select aggregate voids. Table 2-2 provides a summary of the major construction activities and dates performed.

Cells 16 to 18 all had a 5-inch asphalt wearing course with PG 58-34 binder. These cells were built as 12 inches of recycled base course material over 12 inches of Class 3 material that was over 7 inches of select granular material. Cell 19 was similarly constructed overall, but used virgin Class 5 aggregate base material as the control. The recycled base materials were 100% recycled PCC for Cell 16, 50% recycled PCC and 50% virgin Class 5 material for Cell 17, and 100% RAP for Cell 18.

Figure 2-1 presents cross-sections of Cells 16 to 19 and 23. The subgrade material for all the cells was determined to be predominantly clay loam (AASHTO A-6) according to soil tests of 240 specimens collected from the entire MnROAD site, as shown in Table 2-1. The material properties for the subgrade materials obtained from the 2008 construction report are provided in Chapter 1.2.2 .

Materials for MnDOT laboratory testing were obtained during the construction of the roadway cells at the MnROAD test facility in Monticello, Minnesota to investigate the field behavior. RAP was milled from the roadway surface of previously constructed cells at MnROAD. The RCA was obtained from a stockpile maintained by the Knife River Corporation at their pit located at 7979 State Highway 25 NE in Monticello, Minnesota.

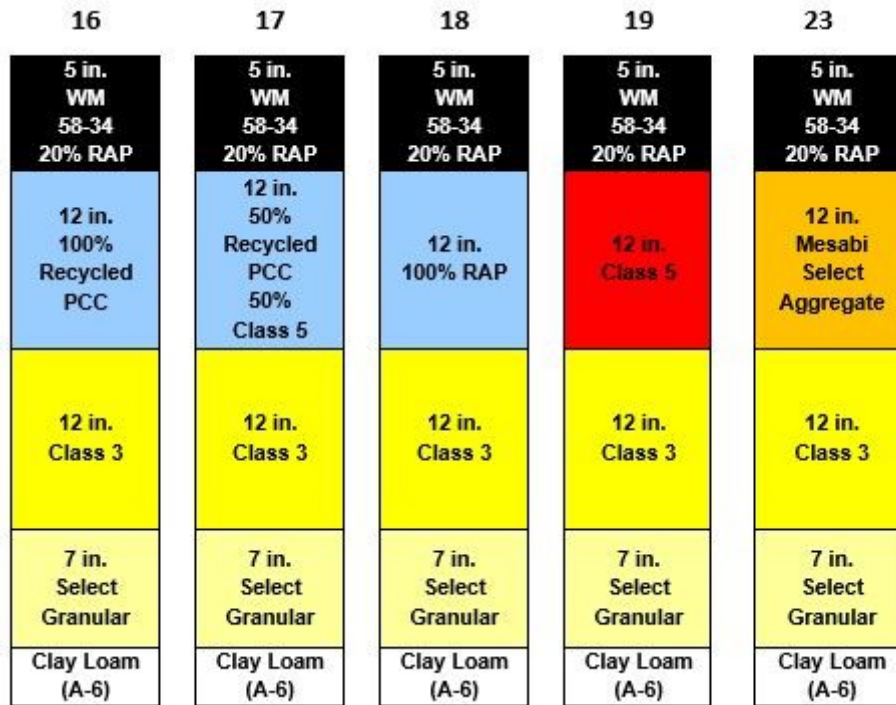


Figure 2-1 Typical cross-sections for Cells 16 to 19 and 23.

Table 2-1 MnROAD soils test results

OCCURRENCES	Classification (No. of Occurrences)							Grand Total
	A-1-B	A-4	A-6	A-7-6	CL	L	SA	
AASHTO GROUP	5	9	97	9				120
TEXTURAL CLASS					70	45	5	120
Grand Total	5	9	97	9	70	45	5	240

Table 2-2 Major construction activities and dates for Cells 16 to 19 and 23 in 2008

Cell	Milling	Select Granular Placement	Class 3 Placement	Recycled Base Course Placement	Paving
16	May 7 – 8	Jun 26	Jun 27	Aug 28	Sep 17 - 18
17	May 7 – 8	Aug 20	Aug 20 – 21	Aug 28 – Sep 3	Sep 17 - 18
18	May 7 – 9	Aug 25 – 26	Aug 26 – 27	Sep 9	Sep 17 - 18
19	May 7 – 9	Jun 25	Jun 26 – 27	Sep 3	Sep 17 - 18
23	May 7 – Jun 2	Jun 25	Jun 26	Sep 8 – 9	Sep 17 - 18

2.1.3 Low-temperature cracking performance (Cells 20-22)

Milling was completed in early June 2008. Select granular material was placed starting June 17 and 18. In late June, Class 3 and Class 5 aggregate base materials were placed. The first lift and second lift of the HMA were constructed on September 5 and 10, respectively. **Error! Reference source not found.** provides a summary of the major construction activities and dates performed.

Table 2-3 Major construction activities and dates for Cells 20 to 22 in 2008

Cell	Milling	Select Granular Placement	Class 3 Placement	Class 5 Placement	Paving
20	May 7 – Jun 2	Jun 17	Jun 19	Jun 23	Sep 5 & 10
21	May 7 – Jun 2	Jun 18	Jun 20	Jun 23	Sep 5 & 10
22	May 7 – Jun 2	Jun 18	Jun 20	Jun 23	Sep 5 & 10

Figure 2-2 presents cross-sections of Cells 16 through 19 and 23. Cells 20 to 22 all had the same 5-inch asphalt wearing course but Cell 22 had a different PG; the PG for Cells 20 and 21 was 58-28, whereas the PG for Cell 22 was 58-34. These cells were built on 12 inches of virgin Class 5 material over 12 inches of Class 3 material, which were over 7 inches of select granular material. Cell 20 included 30 percent non-fractional RAP material in the mixture whereas Cells 21 and 22 had a 30 percent fractionated RAP split on the quarter-inch screen in the mixture. All cells had clay loam (AASHTO A-6) as the subgrade material.

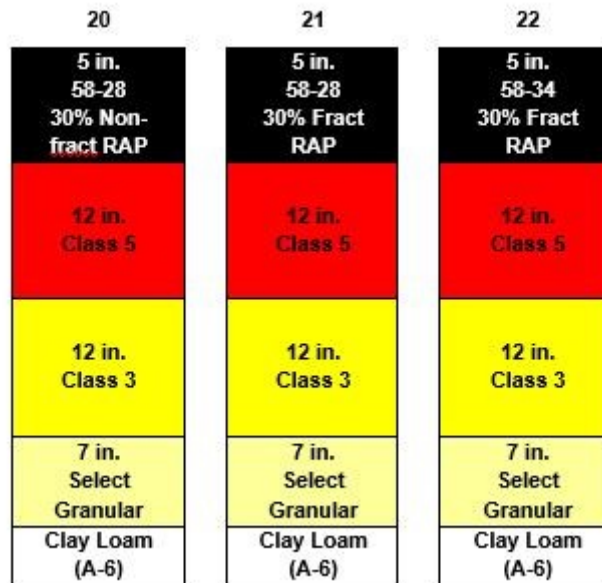


Figure 2-2 Typical cross-sections for Cells 20 to 22.

2.2 WEATHER AND TRAFFIC DATA

MnROAD is located in Wright County, Minnesota. Like most locations in Minnesota, the Wright County area experiences temperature extremes. Weather information for Wright County was obtained from the

National Oceanic and Atmospheric Administration (NOAA), as shown in Figure 2-3 and Figure 2-4 that present the high/low monthly temperatures and the monthly accumulated precipitation, respectively. Figure 2-4 presents the high and low temperatures for each day in a month that were averaged from January 2009 to August 2016. This figure shows the average temperature (47.05 °F) from 1981 to 2010. Figure 2-3 also shows that July and January are the hottest and coldest months of each year, respectively. Figure 2-4 shows that the rainiest months are in the spring (May) and summer (July). The average annual precipitation from 1981 to 2010 was 32 inches, and the only year from 2008 to 2016 that experienced above average annual precipitation (36 in.) was 2015. Overall, the MnROAD cells did not experience any extreme weather events during the performance evaluation period (2008 – 2016).

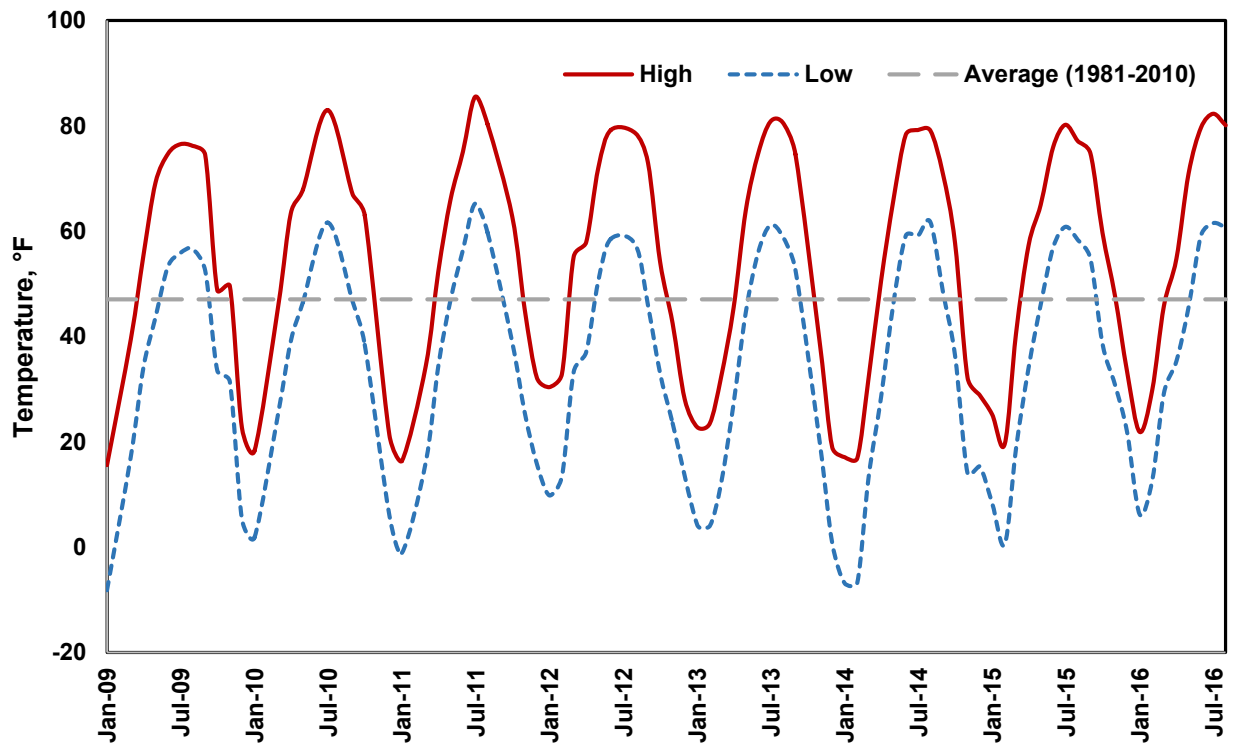


Figure 2-3 Average high and low temperatures by month in Wright County, Minnesota

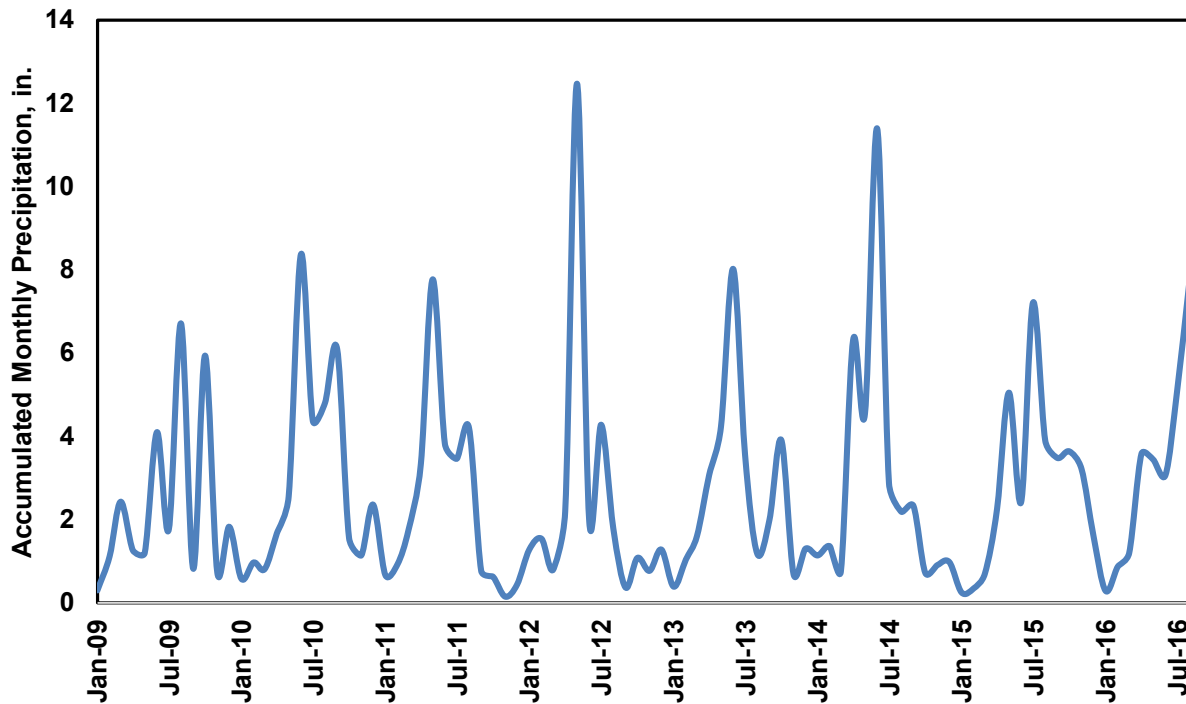


Figure 2-4 Accumulated monthly precipitation by month in Wright County, Minnesota

The MnROAD mainline ESALs were determined from two weigh-in-motion devices located at MnROAD. Table 2-4 provides a summary of the average annual daily traffic (AADT), ESALs, and the percentage of trucks ('% Truck') in both the driving and passing lanes. Approximately 75 percent of all monitored traffic was on the cells. MnROAD cells experienced approximately 5.6 million ESALs during the monitoring period (2008 – 2016).

Additional information about MnROAD can also be found on the MnROAD website at <http://www.dot.state.mn.us/mnroad/index.html>.

Table 2-4 Traffic data for driving and passing lanes in MnROAD mainline westbound (WB) lanes

Interstate-94 Mainline WB Lanes	Driving			Passing		
	AADT	ESALs	% Truck	AADT	ESALs	% Truck
2009	10,770	773,095	21.9	10,939	196,919	6.7
2010	8,333	583,177	20.8	8,404	141,483	5.6
2011	8,183	632,002	23.0	8,033	149,516	6.1
2012	9,718	719,264	21.7	10,125	178,117	5.9
2013	12,200	921,873	23.0	11,840	245,983	6.6

2014	10,839	827,056	22.5	11,230	219,653	6.3
2015	11,843	875,172	22.1	12,426	237,183	6.4
2016	6,539	416,001	22.2	6,680	94,027	6.4
Total	N/A	5,747,640	N/A	N/A	1,465,881	N/A

2.3 TEST METHODS

For this study, pavement field performance was measured and quantified using FWD tests, rutting tests, IRI values, friction tests, and surface distress evaluations after construction each year for eight years. Also, DCT tests were conducted to evaluate the mixtures with respect to their resistance to crack formation and propagation. In addition, LWD tests, DCP tests, gradation analysis, and moisture tests were utilized to assess the performance of the base materials. All of the field test methods were performed at certain intervals throughout the year. The other tests, i.e., the LWD tests, DCP tests, gradation analysis, and moisture tests, were conducted on an as-needed basis. Table 2-5 summarizes all the test methods employed for this study and the data collection frequency for each test method. Additional information about these test methods and data processing also can be found on the MnROAD website at <http://www.dot.state.mn.us/mnroad/data/index.html>.

Table 2-5 List of test methods and data collection frequency

Test	Annual Frequency
Falling Weight Deflectometer (FWD)	3
Distress Survey	2
Ride Quality	2
Friction	2
Rutting (ALPS)	3
Disk-Shaped Compact Tension (DCT)	*
Asphalt Mixture Volumetric Properties	*
Light-Weight Deflectometer (LWD)	*
Dynamic Cone Penetrometer (DCP)	*

Moisture Content	*
Rutting (ALPS2)	*
Gradation	*

* During construction and occasional forensic activities

2.3.1 Field testing

2.3.1.1 Surface distress survey

A surface distress survey was carried out to monitor the field performance of the cells. The data collected from the survey included the distress type, extent or amount of the distress, and severity of the distress. The surface distress types for a pavement include surface-initiated or top-down cracking, transverse thermal cracking, and longitudinal cracking at construction joints.

2.3.1.2 Rutting tests

ALPS, which consists of a high-precision distance measurement laser mounted on a carriage, was used to determine the wheel path ruts in the HMA test cells. The ALPS was used to measure the transverse surface profile at intervals of 0.25 inch as the laser traveled across a 14-foot long aluminum beam.

2.3.1.3 Falling weight deflectometer (FWD) tests

An FWD, which consists of a loading plate, weight package, geophone sensors, and data acquisition equipment, can be used to measure the response of a pavement layer or system due to the dynamic load. In this study, FWD tests were conducted according to ASTM D4694, *Standard Test Method for Deflections with Falling Weight Type Impulse Load Devices*. In this test, the plate subsequently applies a dynamic load to the pavement as the weight package is lifted hydraulically and dropped in free fall, with geophone sensors simultaneously recording the deflection basin. The deflection basin can be used to determine the structural capacity of the system as well as to back-calculate the modulus values of the underlying layers.

2.3.1.4 Ride quality

Pavement smoothness is considered a critical factor in evaluating pavement conditions, as it affects the ride quality and thus is the most important factor for the traveling public. The IRI is one of the primary indices used to evaluate pavement smoothness. In this study, profiles of the right wheel paths were collected using dot lasers from Ames Engineering with a sampling rate of four samples per foot. The collected data were analyzed using Profile Viewing and Analysis (ProVAL Version 3.61.17) along with a 10-inch moving average.

2.3.1.5 Friction tests

Surface friction tests are used to measure the force that prevents vehicle tires from sliding on a pavement. Friction resistance includes the properties of the pavement surface characteristics and vehicle tires. In this study, an A KJ Law (Dynatest) 1295 Pavement Friction Tester was used to perform the friction tests at MnROAD in accordance with ASTM E 274, *Specification for Skid Resistance Using a Full-Scale Tire*. A skid trailer was used to obtain the skid number (SN), which is computed as the average coefficient of friction across the test cell intervals. SNs range from 0 to 100, with a higher SN indicating greater friction.

2.3.2 Laboratory testing

2.3.2.1 Disk-shaped compact tension (DCT) tests

DCT tests can be used to determine the fracture energy of brittle materials under tensile stresses, which mirrors the shrinkage of asphalt pavement during the cooling process. ASTM D7313-13 covers the most current DCT test procedure. For this study, the sample preparation and testing were performed according to the 'MnDOT Modified' version of the ASTM standard. This modified version includes updates to the ASTM D7313-13 standard that were made by MnDOT to increase the ease of preparation, conditioning, and testing of samples as well as the practicality of the DCT test and consistency of results.

2.3.3 Trench testing

2.3.3.1 Gradation tests

Sieve analysis or gradation tests can be used to evaluate the particle size distribution in soils using a mechanical shaker. In this study, aggregate gradation sampling and testing were conducted in accordance with Section 5-692.215 (Random Sampling Procedures) and Section 5-692.215 (Sieve Analysis Test Procedure: Gradation) of the MnDOT Grading and Base Manual. The percentage of each particle in a soil sample was determined by shaking the sample through several required sieve sizes. Hence, the soil could be allocated a specific textural classification depending on the percentage of each grain size group in the sample.

2.3.3.2 Light-weight deflectometer (LWD) tests

LWD tests were conducted to determine the stiffness of the unbound materials during construction in accordance with ASTM E 2835-11, *Standard Test Method for Measuring Deflections using a Portable Impulse Plate Load Test Device*. The portable LWD was used to measure the deflection of compacted soil under an applied load. Based on the deflection measured, a modulus value was estimated based on the force required to produce a given deflection for that particular soil type.

2.3.3.3 Dynamic cone penetrometer (DCP) tests

The *in situ* shear strength of soil can be estimated using a DCP, which consists of a lower rod with an anvil and 60° cone tip, with an 8-kg hammer on the upper rod. This test is carried out by dropping the hammer from a distance of 575 mm, whereby it strikes the anvil and drives the cone tip into the soil. The DCP tests were conducted according to ASTM D 6951-03, *Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications*. The dynamic penetration index (DPI) value was calculated as the depth of penetration of the DCP cone per drop of the hammer.

2.3.3.4 Moisture tests

Moisture content is evaluated to control and measure the compaction effort of unbound materials during DCP or LWD tests. The test methods used to determine moisture content are listed in the MnDOT Grading and Base Manual. To prevent the evaporation of any water into the atmosphere, materials often are sampled into a sealed plastic cup or bag. The gravimetric moisture content of the sample is measured as the ratio of the mass of the water to the mass of oven-dried material. In this study, these procedures were followed for moisture content testing.

CHAPTER 3: RESULTS AND ANALYSIS

3.1 MNPAVE ANALYSIS AND RESULTS

MnPAVE is a computer program that combines known empirical relationships with a representation of the physics and mechanics of flexible pavement behavior (<http://www.dot.state.mn.us/app/mnpave/index.html>). The mechanistic portions of the program rely on finding the tensile strain at the bottom of the asphalt layer, the compressive strain at the top of the subgrade, and the maximum principal stress in the middle of the aggregate base layer. MnPAVE consists of three input modules, *Climate*, *Structure*, and *Traffic*, and three design levels, *Basic*, *Intermediate*, and *Advanced*. The level is selected based on the amount and quality of information known about the material properties and traffic data. In basic mode, only general knowledge of the materials and traffic data is required. The intermediate level corresponds to the amount of data currently required for MnDOT projects. The advanced level requires the determination of modulus values for all materials over the expected operating range of moisture and temperature (10).

MnPAVE output includes the expected life of the pavement in terms of fatigue cracking and rutting. The expected life of Cells 16 through 23 was analyzed using MnPAVE (Version 6.304) at the basic design level using materials data collected during construction in 2008. Table 3-1 presents the analysis inputs and results. It should be noted that only limited information (i.e., resilient modulus data) regarding the base material was available for Cells 17 and 23, and the analysis was performed as if 100 percent recycled PCC was used as the base material. Furthermore, different RAP contents and the use of WMA for various cells could not be incorporated into the analysis. Thus, the results should be used only as a rough estimate of the expected life for each cell. In general, cells with stiffer base material showed longer fatigue and rutting expected life. Cells with 100 percent RAP as the base material showed the longest expected life both in terms of fatigue and rutting. Cells with different binder grades (i.e., PG 58-28 vs. 58-34) and binder contents did not show significant differences in expected life.

Table 3-1 MnPAVE (Version 6.304) analysis inputs and results

MnPAVE Inputs	TRAFFIC	STRUCTURE						Expected Life	
								Fatigue	Rutting
Cell	Lifetime (mil. ESALS)	HMA Thickness (in.)	Binder Grade	RAP	Agg. Base	Agg. Sub-base	Existing Soil		
16	14	5	58-34 %AC 5.1, Warm Mix	20%	12 in. 100% Recycled PCC	12 in. Class 3 & 7 in. Select Granular	Clay Loam (A-6)	35	11
17					12 in. 50% Recycled PCC/50% Class 5			35*	11*
18					12 in. 100% RAP			50	17
19					12 in. Class 5			11	8
20			58-28 %AC 5.0	30% Non-fractionated	12 in. Class 5			9	6
21			58-28 %AC 5.6	30%				11	6
22			58-34 %AC 5.4					9	7
23			58-34 %AC 5.1, Warm Mix	20%	12 in. Mesabi Select Aggregate			35*	11*

*Analysis was performed using 100% recycled PCC base as an input.

3.2 DISK-SHAPED COMPACT TENSION TEST RESULTS

Test specimens for the DCT tests were fabricated in 2016 from 150-mm (5.91-in.) gyratory-compacted pills using loose mixture samples collected from all the cells (Cell 16-23) in 2008. The temperature used for the DCT tests in this study was -21.4°C, which is 10°C warmer than the asphalt binder PG low temperature required for 98 percent reliability, as determined by LTPPBind 3.1 software for the MnROAD location. Figure 3-1 presents the DCT test results. In the figure, the cell number indicates the

cell(s) in which each corresponding type of mixture was used. The line represents the ranges, and the number inside the bar represents the average fracture energy value for each mixture type.

The DCT tests were performed from March through May 2016. The average fracture energy values range from 443 J/m² to 546 J/m². The lowest and highest fracture energy values were obtained from specimens with PG 58-28 binder and 30% RAP and from specimens with PG-58-34 binder and 20% RAP, respectively. Based on the traffic level (10 – 300 million ESALs) for the MnROAD cells, the minimum DCT fracture energy required is 450 J/m². Accordingly, the PG 58-34 mixtures met the minimum fracture energy requirement, and the PG 58-28 mixture did not. Statistical analysis was performed to determine the significance of the fracture energy differences among the three mixtures. The fracture energy differences between the PG 58-34 20% RAP specimens and PG 58-28 30% RAP specimens and between the PG 58-34 30% RAP specimens and PG 58-28 30% RAP specimens were statistically significant.

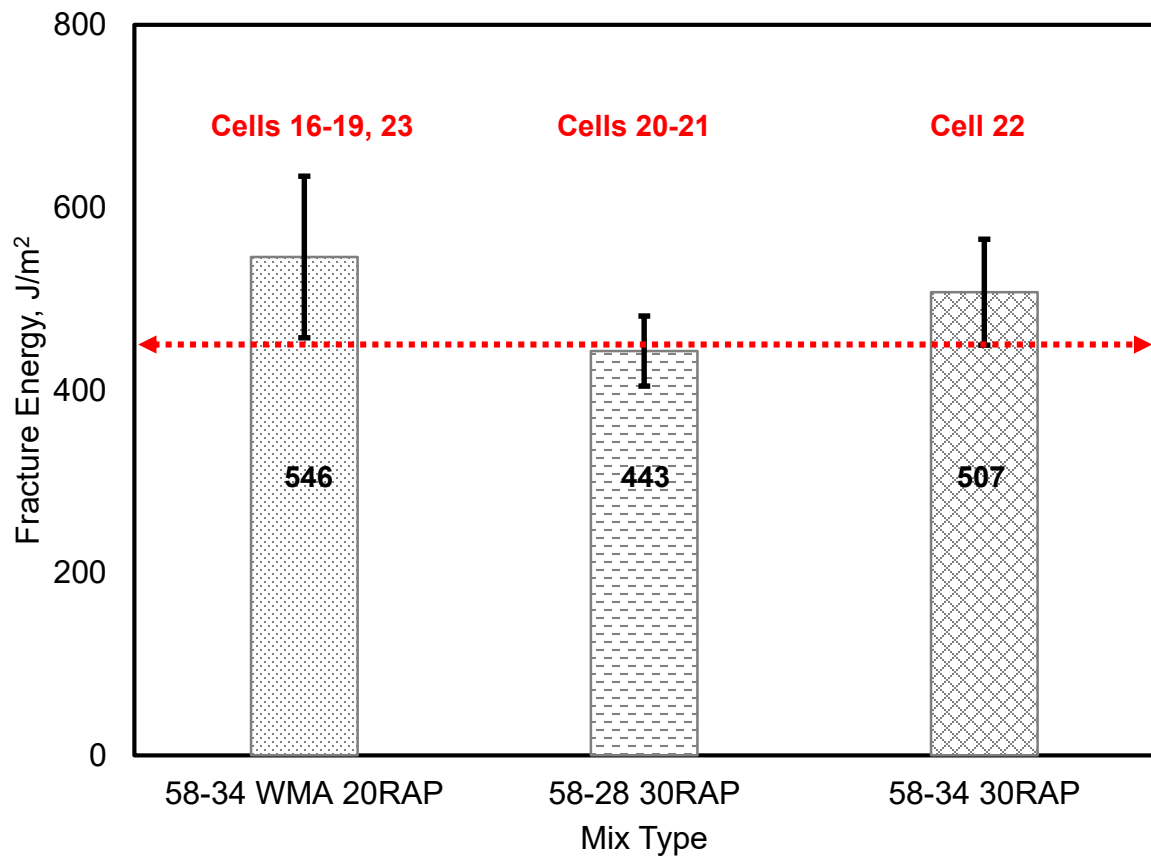


Figure 3-1 Disk-shaped compact tension test results.

3.3 NONDESTRUCTIVE TESTING RESULTS

3.3.1 Surface distress survey results

Surface distress surveys were conducted prior to construction and once or twice each year thereafter. The cracks were categorized in terms of surface distress type: fatigue cracking, block cracking, longitudinal cracking on the wheel path, longitudinal cracking on the non-wheel path, transverse cracking, raveling, and construction joint cracking. The cracks were measured in linear feet. In the case of fatigue cracking, the fatigue crack area was measured in square feet. Table 3-2 presents the year when each type of crack first occurred in each cell. Figure 3-2 to Figure 3-9 show the extent of each crack type for each cell. In each figure, the extent of the crack is presented in terms of each lane (passing and driving) and as a sum of both lanes. Note that in Table 3-2 and Figures 3-2 to 3-9, *WP* is wheel path, *DL* is driving lane, and *PL* is passing lane.

Key findings from the surface distress survey are outlined below:

- In general, most cracks did not occur until 2014. The first crack observed was a transverse crack in Cell 16 (2010). Block cracking did not occur in most cells and exhibited only in Cell 18. Overall, Cell 18 showed the least amount of cracking and Cells 21 and 23 showed the most cracking.
- Relatively more transverse cracks were observed in Cells 20 and 21 compared to the other cells, and most of those cracks were in the driving lane. The mixture type used for Cells 20 and 21 also showed lower fracture energy values than the other two mixtures. However, it should be noted that the extent of the transverse cracking in Cells 20 and 21 was very small, as 200 feet of transverse cracking could be interpreted as one full lane length transverse crack every 50 feet per lane. It is interesting to note that the first transverse crack was observed in Cell 16 and the mixture type used for Cell 16 provided the highest fracture energy value.
- Fatigue cracks first appeared in the driving lanes of Cells 16, 17, 19, 21, and 23 in 2014. Fatigue cracks were observed in Cells 20 and 22 in 2015. The accumulated ESALs for the driving lanes by the end of 2013 and 2014 were 3,629,411 and 4,456,467, respectively. With regard to fatigue cracking, Cell 20 showed the most fatigue cracking and Cell 18 did not show any fatigue cracking. Considering that typical fatigue failure is defined as 20 percent of the total lane area (i.e., 2400 ft²), all cells were well below this criterion.

Overall, Cells 21 and 23 exhibited the greatest extent of surface distresses, and Cell 18 showed the least. However, it should be emphasized that all cells were in relatively good condition, as the total extent of the surface distresses for all the cells was relatively small. Surface distresses were not significant enough in all the cells to assess the relative performance of the unbound materials compared to the virgin Class 5 aggregate base material. Furthermore, the significance of the fracture energy resistance of the different mixtures could not be investigated.

Table 3-2 First occurrence of each type of crack for each cell

Cell	Fatigue	Block	Longitudinal WP	Longitudinal Non-WP	Transverse	Raveling	Construction Shoulder	Construction Centerline
16 DL	2014		2014	2015	2010	2014	2015	2015
16 PL	2015			2015	2010	2014		
17 DL	2014		2014	2013	2012	2011	2012	2013
17 PL	2014				2014	2013		
18 DL			2013			2013		2015
18 PL						2014		
19 DL	2014		2014		2014	2014	2013	2011
19 PL	2014			2014		2014		
20 DL	2015		2015		2011	2014	2012	2014
20 PL	2015		2015	2015	2014	2012		
21 DL	2014	2014	2014		2011	2014	2012	2014
21 PL	2014		2014	2012	2014			
22 DL	2015		2013	2014	2014	2012	2012	2014
22 PL	2015		2014	2015				
23 DL	2014		2014		2014	2012	2012	2012
23 PL	2014			2012	2014	2012		

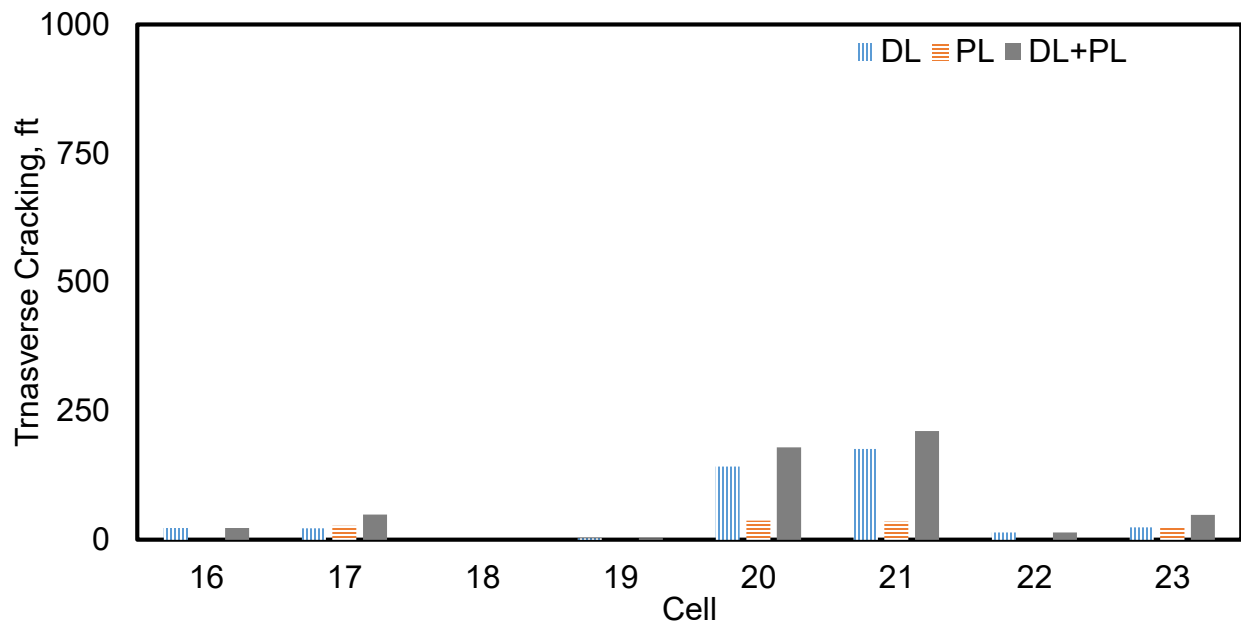


Figure 3-2 Extent of transverse cracking for each cell.

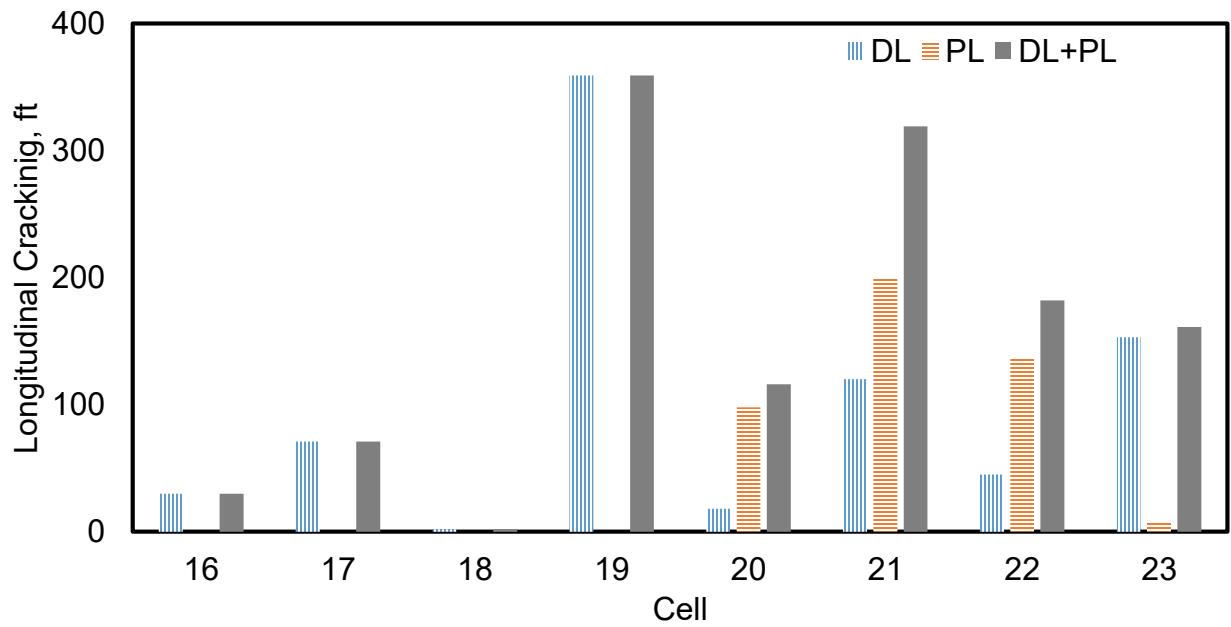


Figure 3-3 Extent of longitudinal cracking in wheel path for each cell.

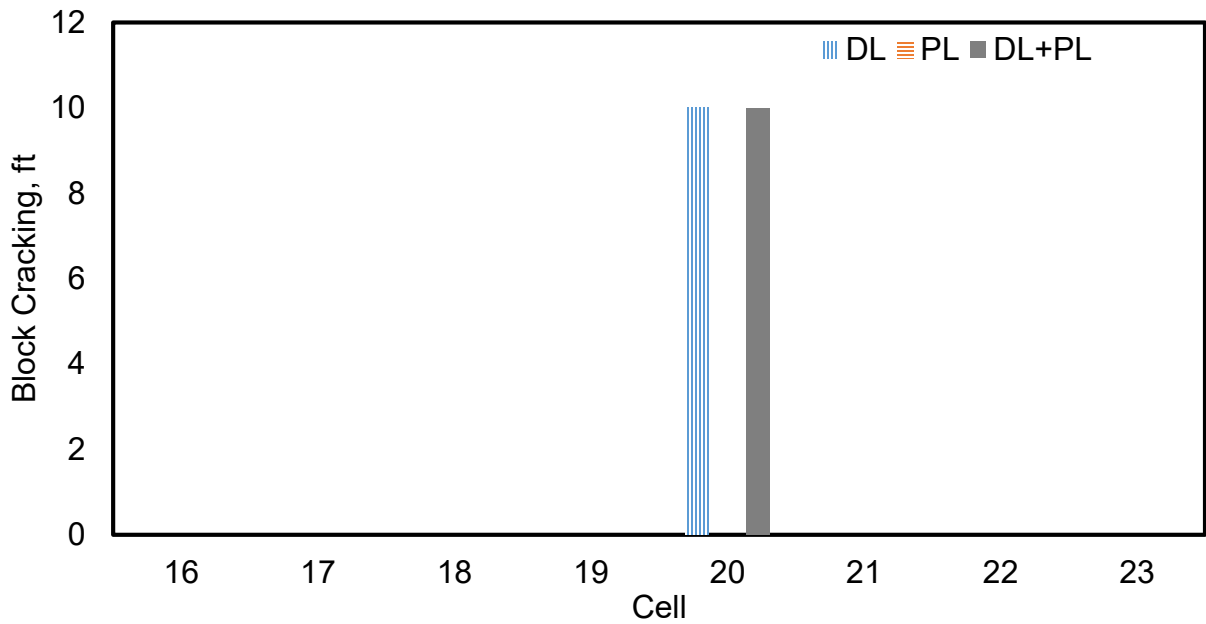


Figure 3-4 Extent of block cracking in wheel path for each cell.

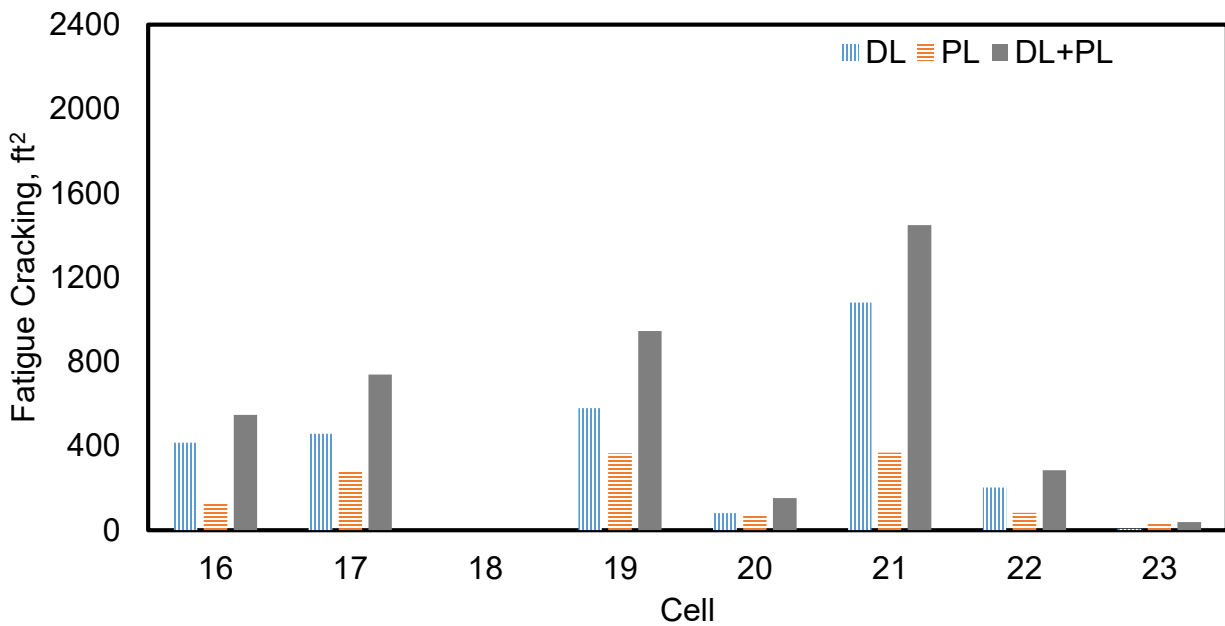


Figure 3-5 Extent of fatigue cracking in wheel path for each cell.

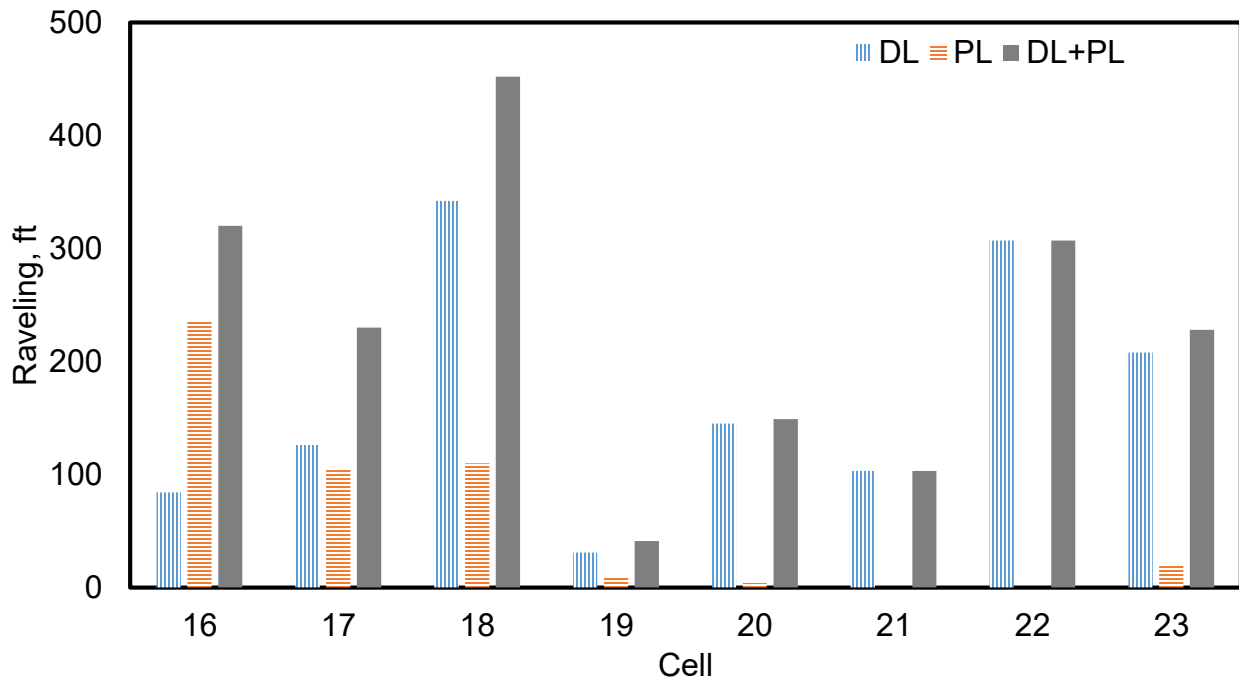


Figure 3-6 Extent of raveling in wheel path for each cell.

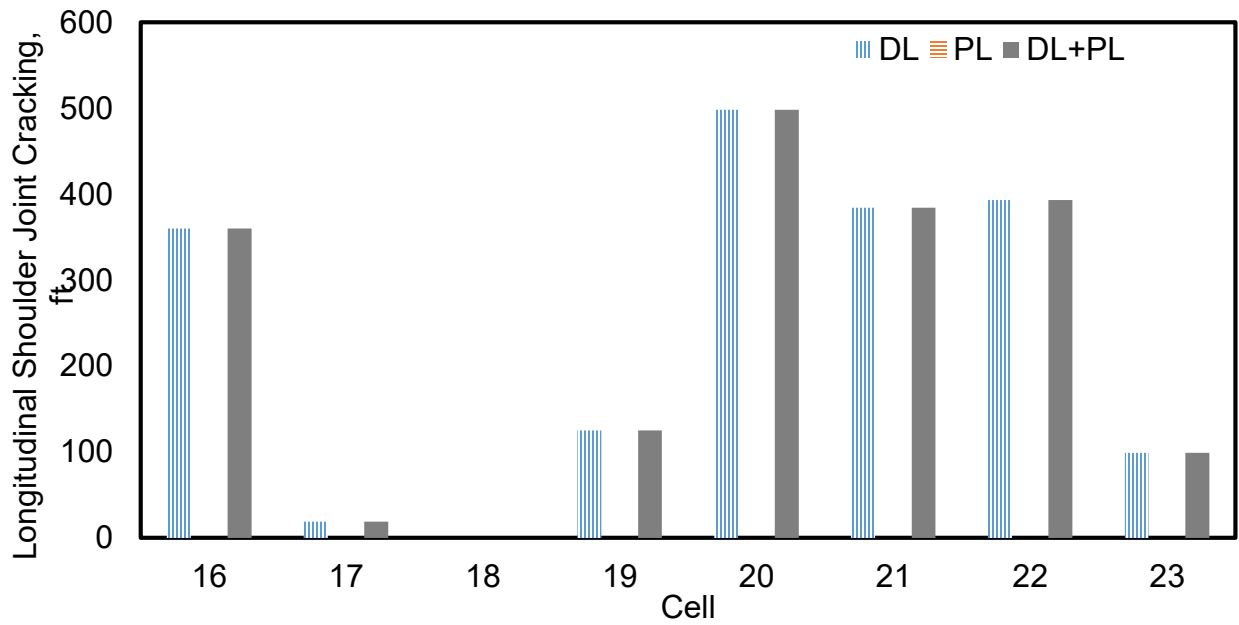


Figure 3-7 Extent of longitudinal shoulder joint cracking for each cell.

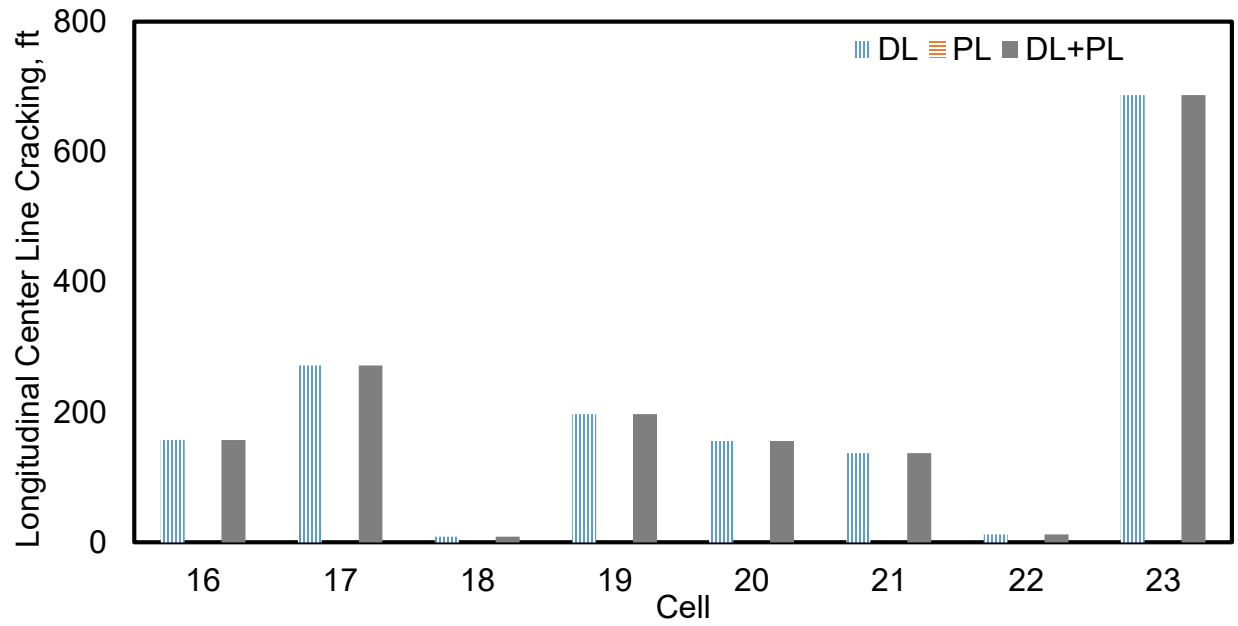


Figure 3-8 Extent of longitudinal centerline cracking for each cell.

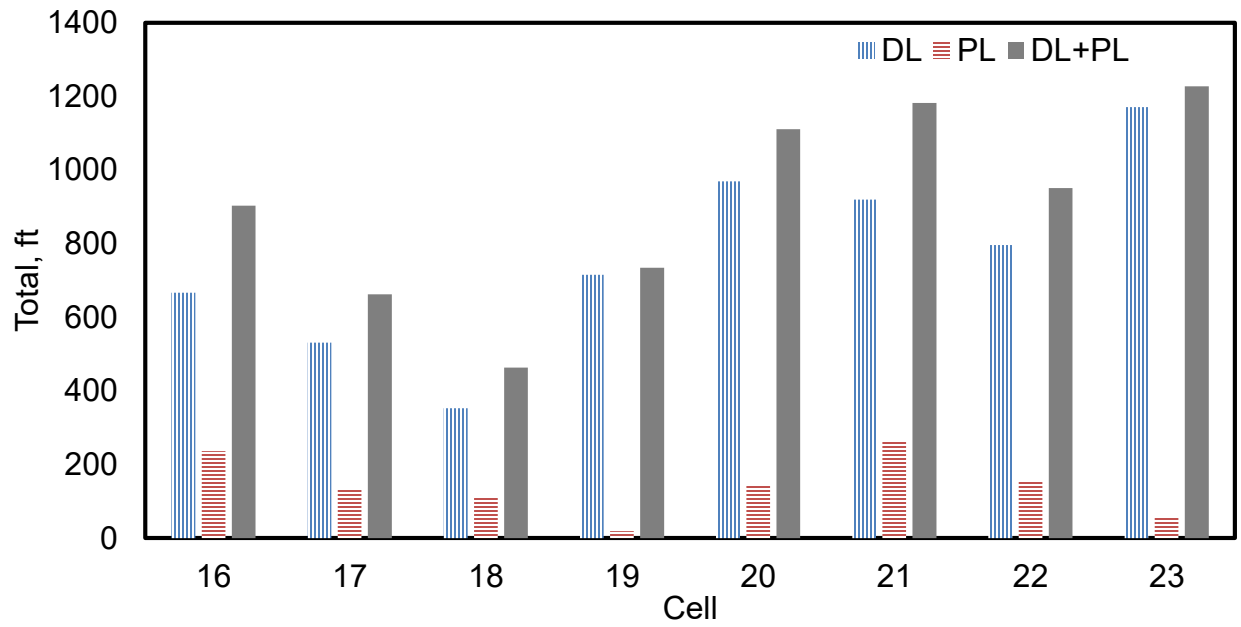


Figure 3-9 Extent of all cracking (except fatigue cracking) in wheel path for each cell.

3.3.2 Rutting test results

Rut depths were measured at ten different stations for each cell per lane. Figure 3-10 presents the average rut depth measured in 2015 for each cell. Figure 3-11 and Figure 3-12 show the rut depth measurements over time for the driving lane and passing lane, respectively. In general, cells with unbound pavement materials (Cells 16-19, 23) show greater rut depths (deeper ruts) than cells with Class 5 aggregate base material. Cell 23 (taconite base) and Cell 22 (Class 5 base) show the maximum and minimum rut depths, respectively. However, all cells showed good rutting resistance considering that rutting failure typically is defined as a 0.5-inch rut.

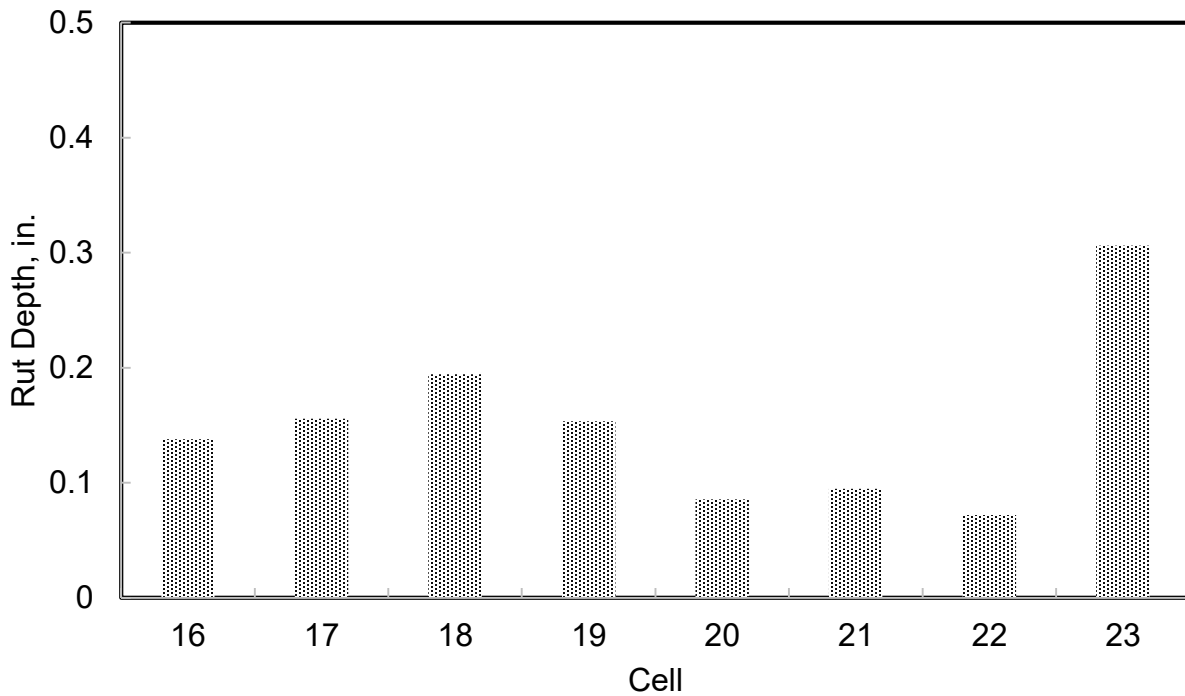


Figure 3-10 Average rut depths in driving lane (2015).

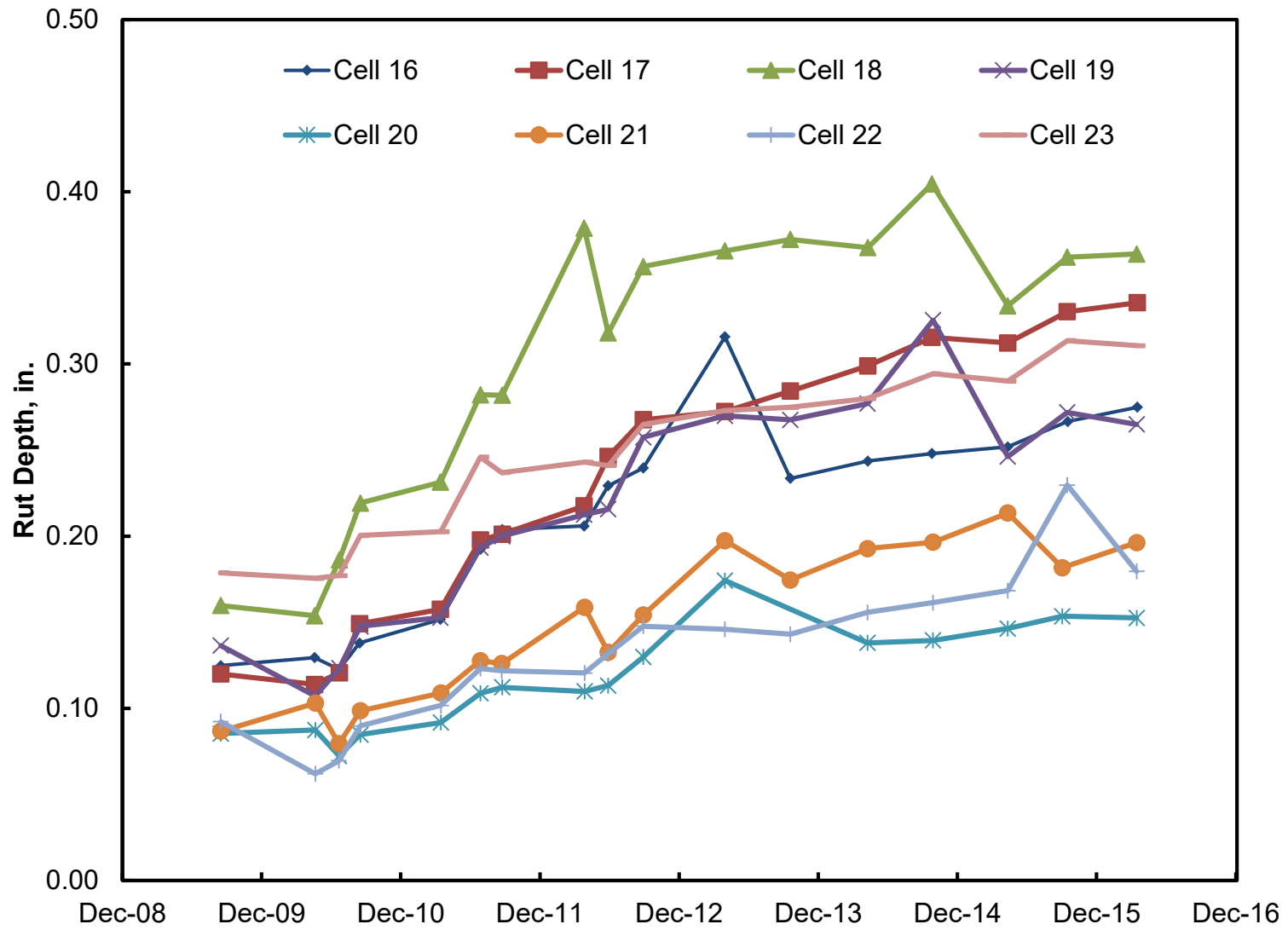


Figure 3-11 Rut depths measured in driving lane.

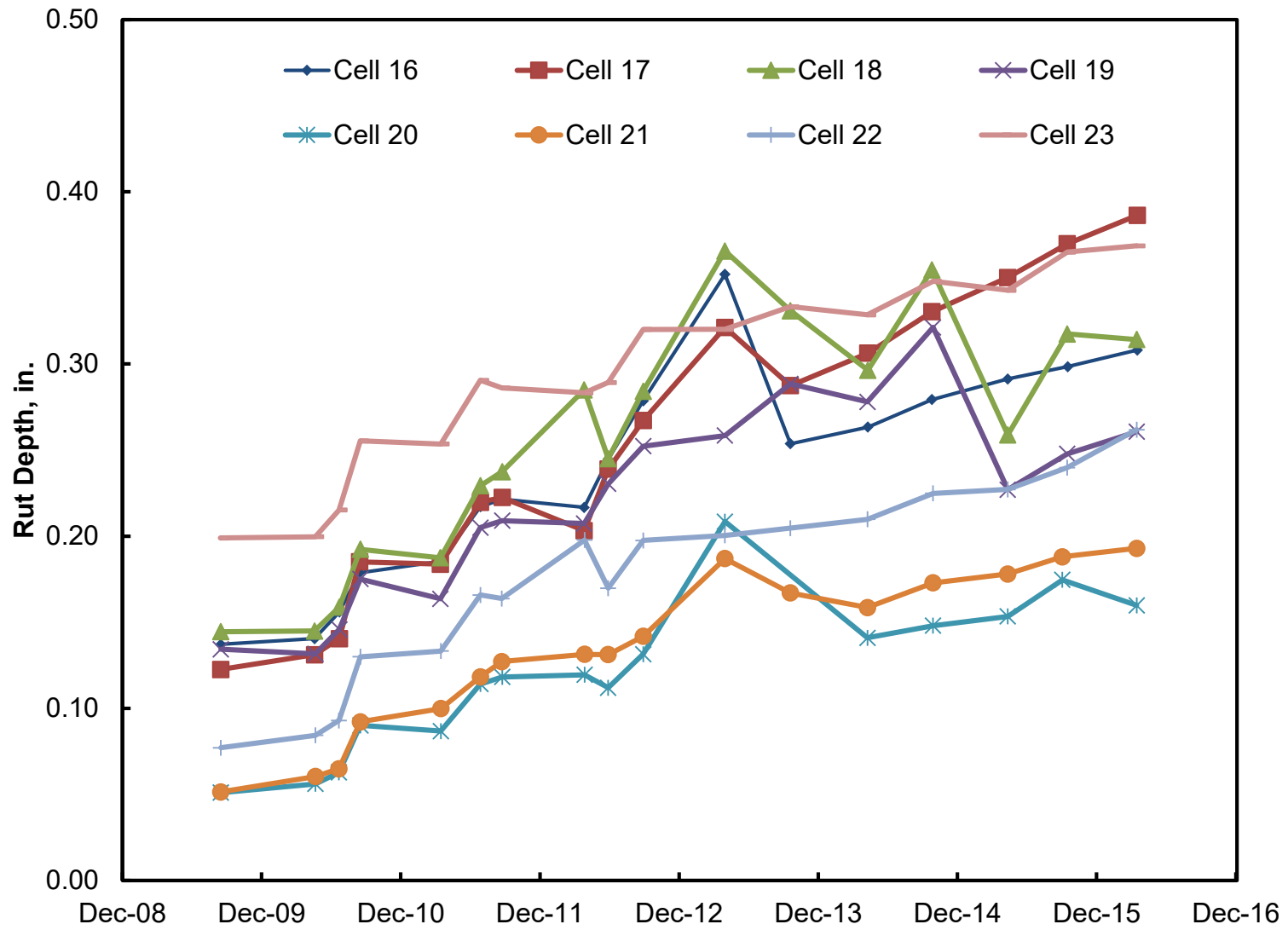


Figure 3-12 Rut depths measured in passing lane.

3.3.3 Falling weight deflectometer (FWD) test results

FWD tests were conducted three times annually to evaluate the structural adequacy of each cell. These tests were performed in the driving and passing lanes at 200-foot intervals. A 9,000-lb (40-kN) load level was used for testing. TONN 2010, a software system developed by the University of Minnesota, was used to calculate the stiffness values and deflections. It should be noted that pavement thickness is one of the major factors that affects the calculation of stiffness values. Table 3-3 presents the average thicknesses of the HMA layers measured by ground penetrating radar (GPR) for the analysis. This table also shows the thicknesses measured from core samples as a reference. Figure 3-13 to Figure 3-18 present the FWD test results that include the stiffness values and surface deflections for each cell.

In general, stiffness tends to decrease during summer and increase during winter. Overall, the cells with Class 5 aggregate as the base material showed lower stiffness values and greater deflections than cells with recycled unbound pavement materials. The cells with recycled unbound pavement materials (Cells 16-18, 23) showed higher stiffness values along with fewer deflections, as illustrated in Figure 3-13. Figure 3-14 indicates that the differences in the stiffness values for those cells (Cells 16-19, 23) were affected primarily by the stiffness of the base materials. Figure 3-15 and Figure 3-16 present the stiffness values of the cells (Cells 20-22) constructed with different binder grades (i.e., PG 58-28 vs. PG 58-34) over the same Class 5 aggregate as the base material. Figure 3-16 shows that Cells 20 through 22 have similar stiffness values for the base layer, which is as expected from the use of the same material for all three cells. Figure 3-15, however, shows that Cell 22 has a lower HMA layer stiffness value than Cells 20 and 21. This outcome can be explained by the use of a stiffer binder grade for Cells 20-21 compared to Cell 22.

Table 3-3 Hot mix asphalt layer thicknesses measured using ground penetrating radar (GPR) and core samples

Cell	GPR	Core Samples (2016)
	Median Thickness, in.	Median Thickness, in.
16	4.63	4.40
17	4.94	4.80
18	5.00	4.50
19	5.03	4.75
20	4.84	4.93
21	4.93	4.81
22	5.32	4.63
23	6.14	6.25

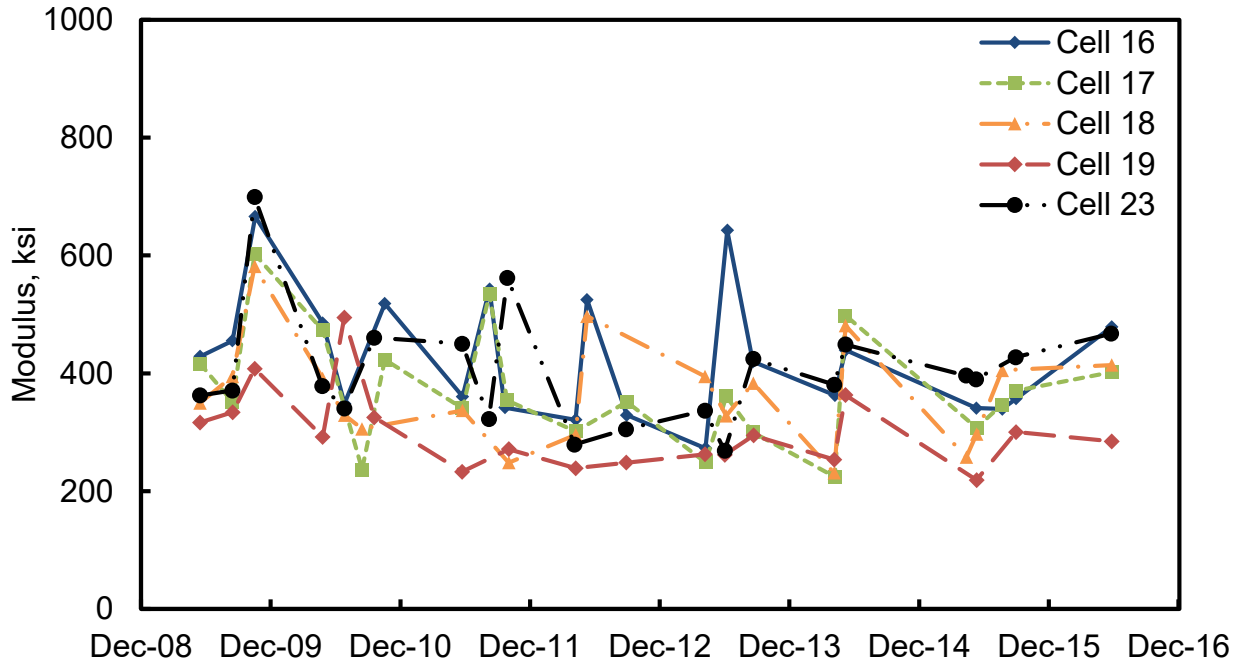


Figure 3-13 Hot mix asphalt layer stiffness values for Cells 16-19 and 23 (TONN 2010).

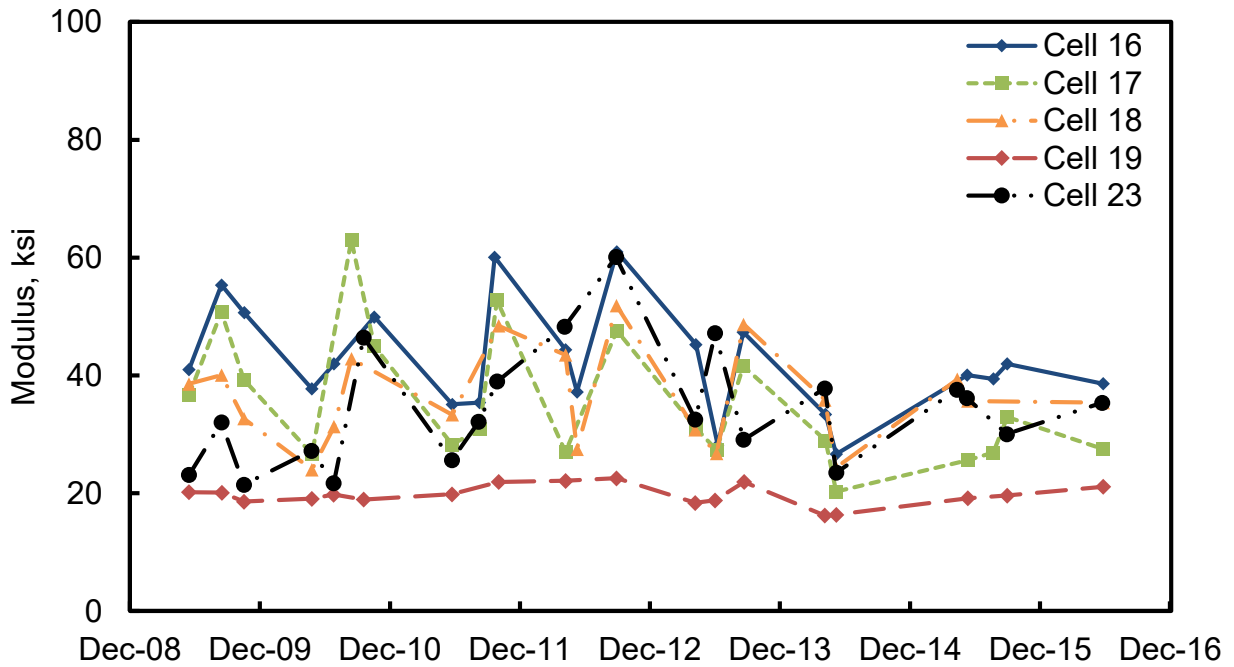


Figure 3-14 Base layer stiffness values for Cells 16-19 and 23 (TONN 2010).

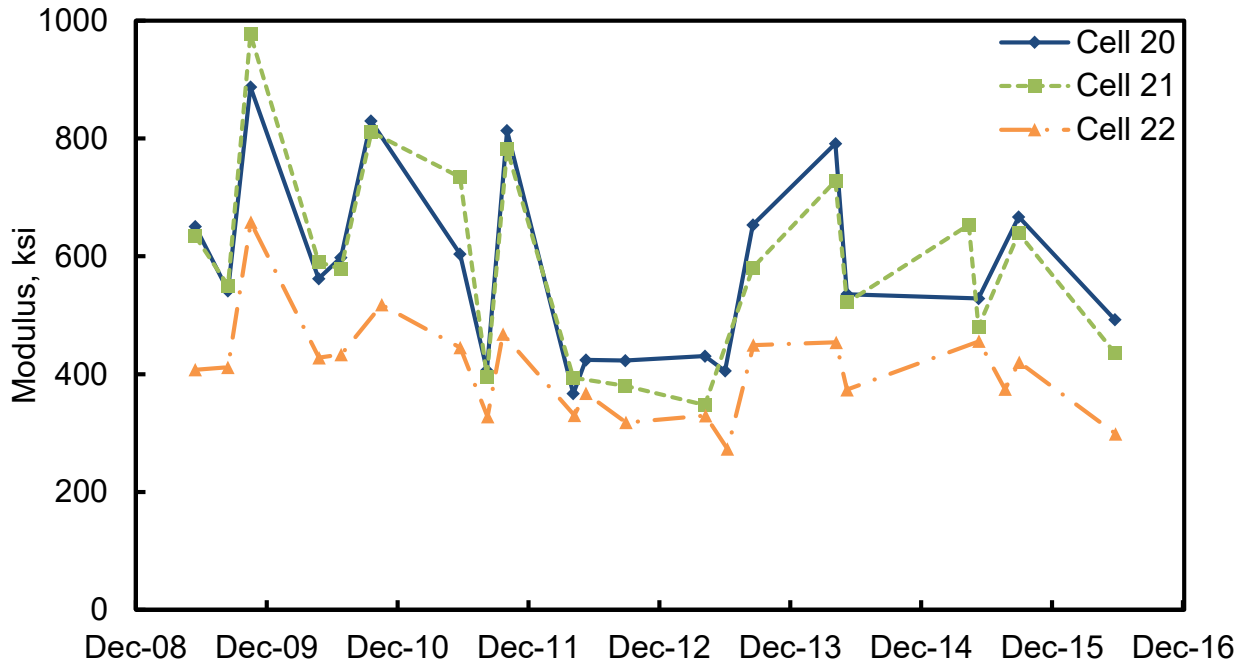


Figure 3-15 Hot mix asphalt layer stiffness values for Cells 20-22 (TONN 2010).

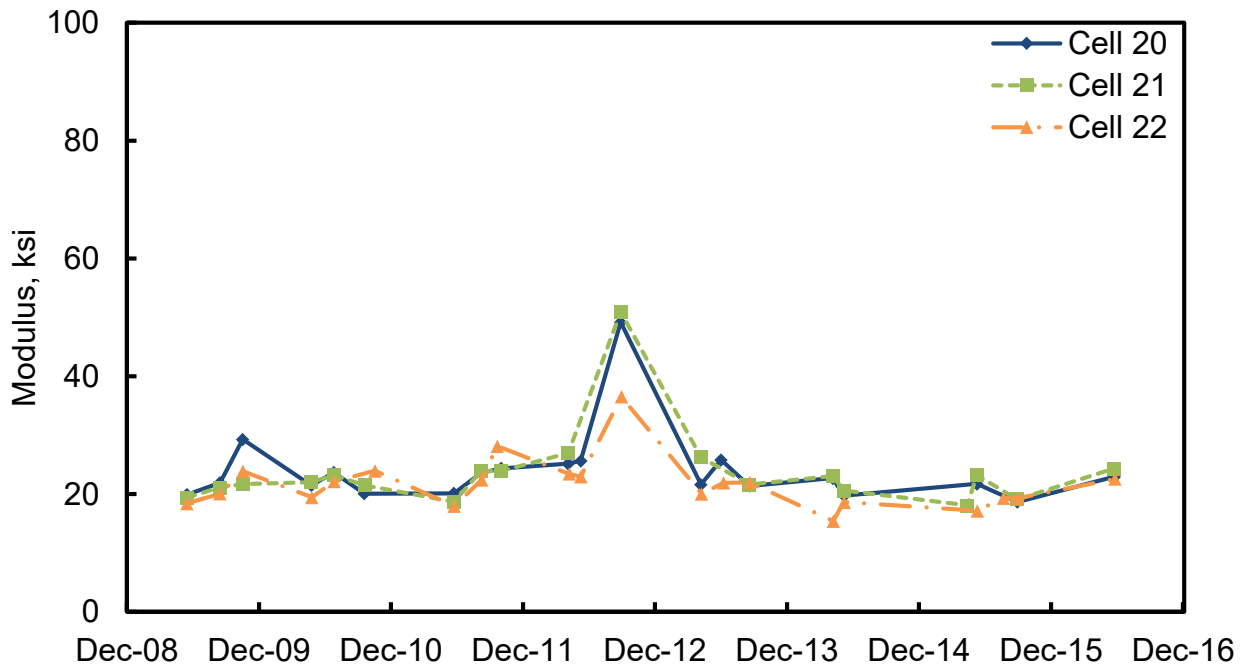


Figure 3-16 Base layer stiffness values for Cells 20-22 (TONN 2010).

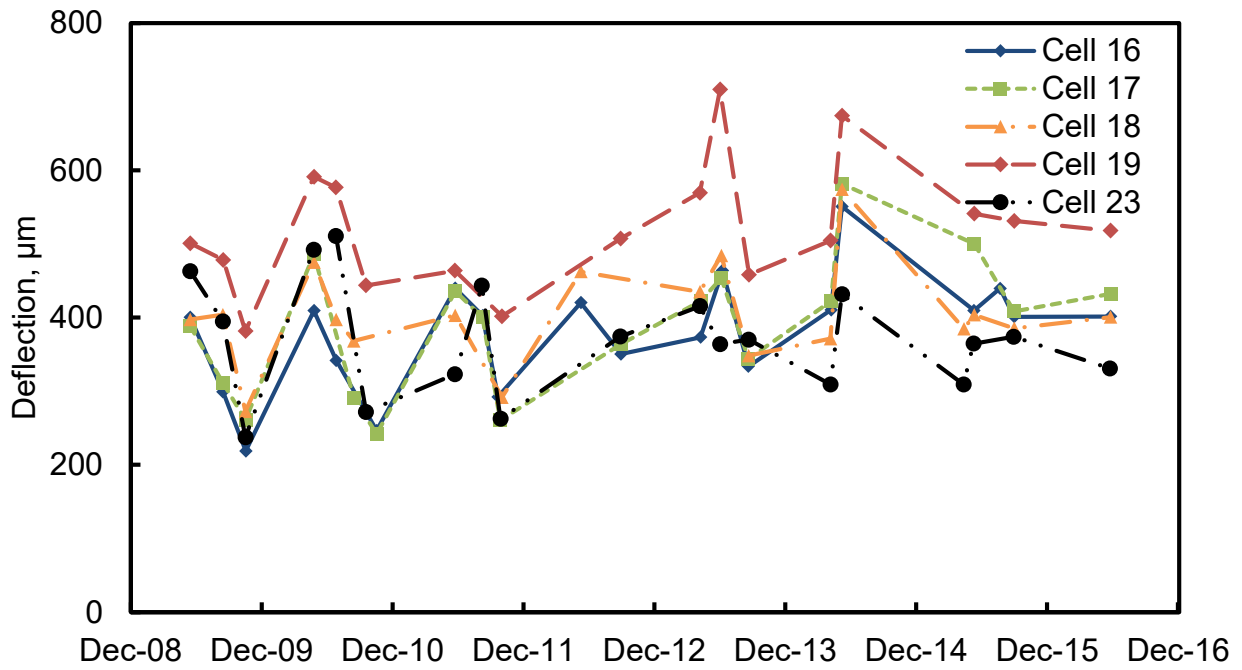


Figure 3-17 Deflections for Cells 16-19 and 23.

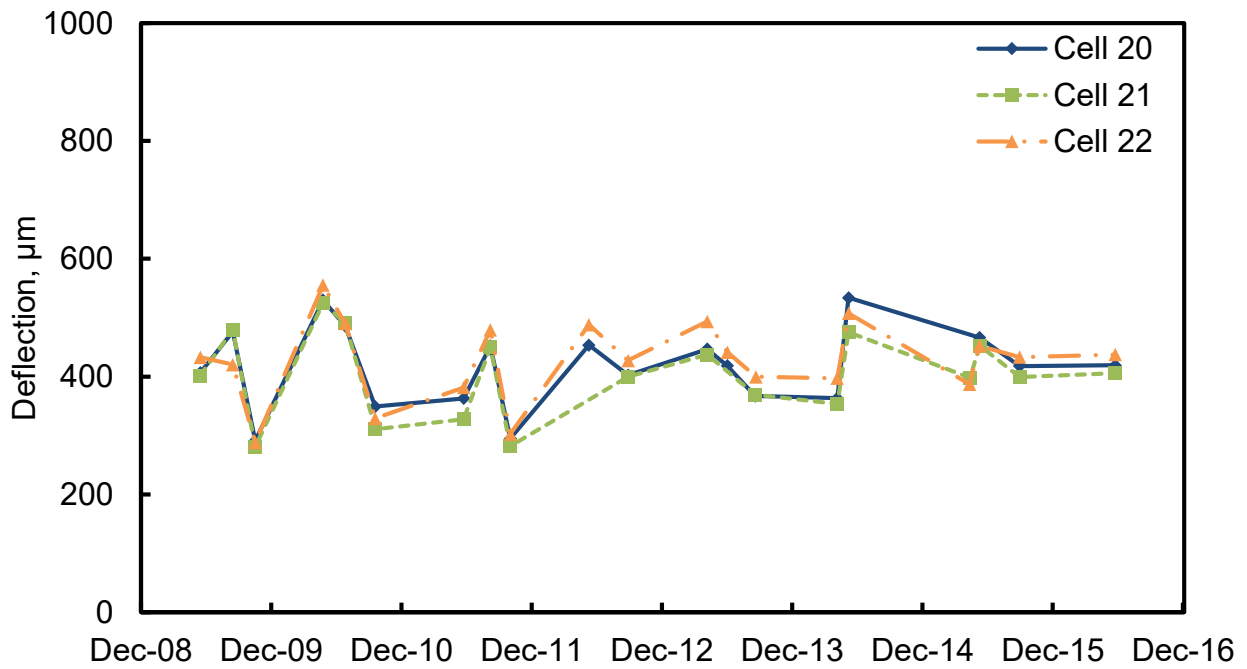


Figure 3-18 Deflections for Cells 20-22.

3.3.4 Ride quality results

Pavement profile data were collected each year to evaluate the functional performance of the test sections. The pavement profiles were analyzed using ProVAL (Version 3.61.17) with a 10-inch (250-mm) moving average to obtain the IRI values. The analysis results are plotted in Figure 3-19 and Figure 3-20.

Overall, most cells show IRI values less than 95 in./mile, which can be considered good condition in terms of ride quality. It is interesting to note that Cells 20 and 21 exhibited the most surface distresses, yet the IRI data do not agree with this observation. Also, Cell 18, which did not exhibit any transverse cracks and had the fewest cracks overall, did not show the lowest IRI values. It can be concluded that the extent of the cracks was not significant enough to affect the ride quality.

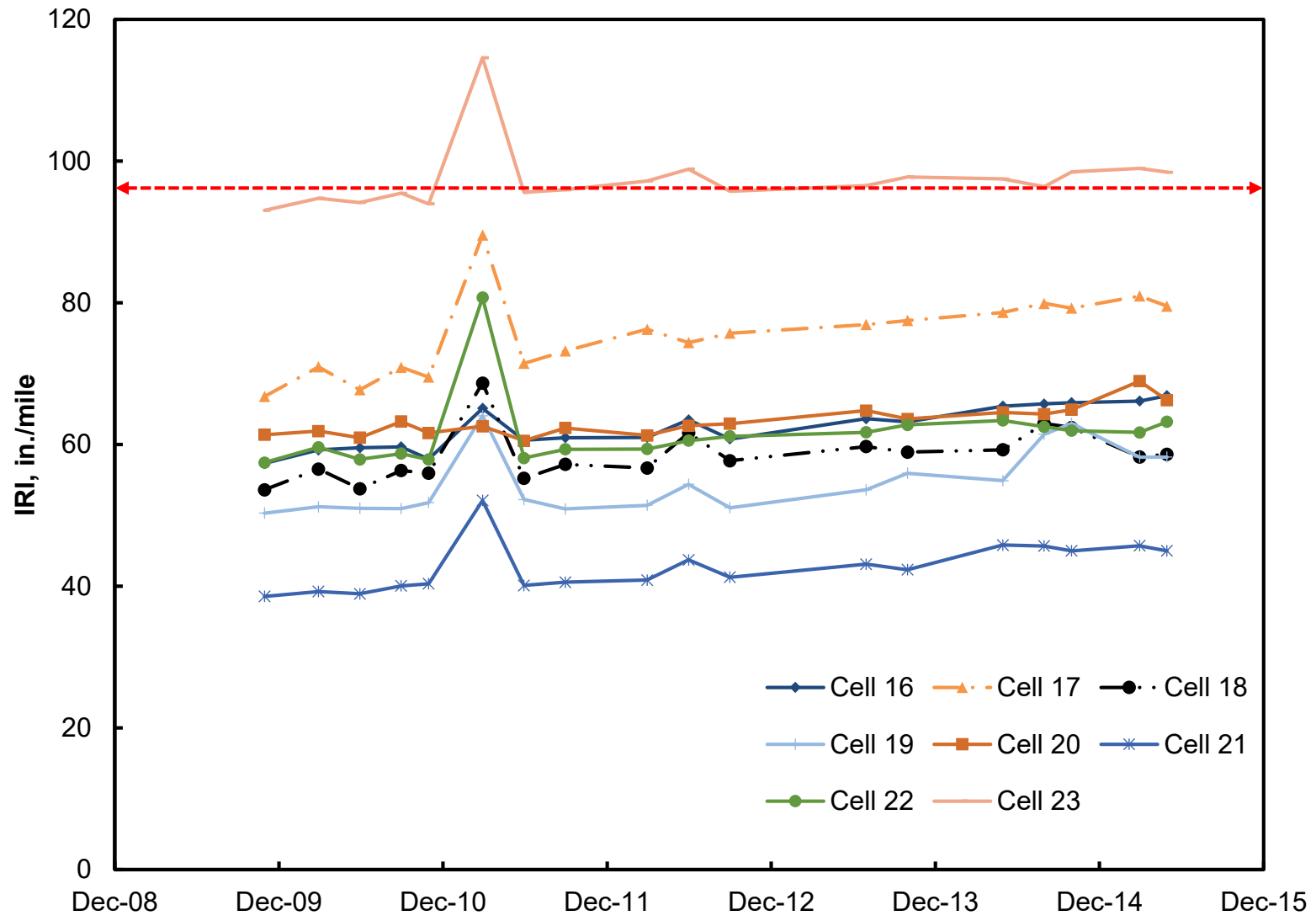


Figure 3-19 International roughness index values for passing lane.

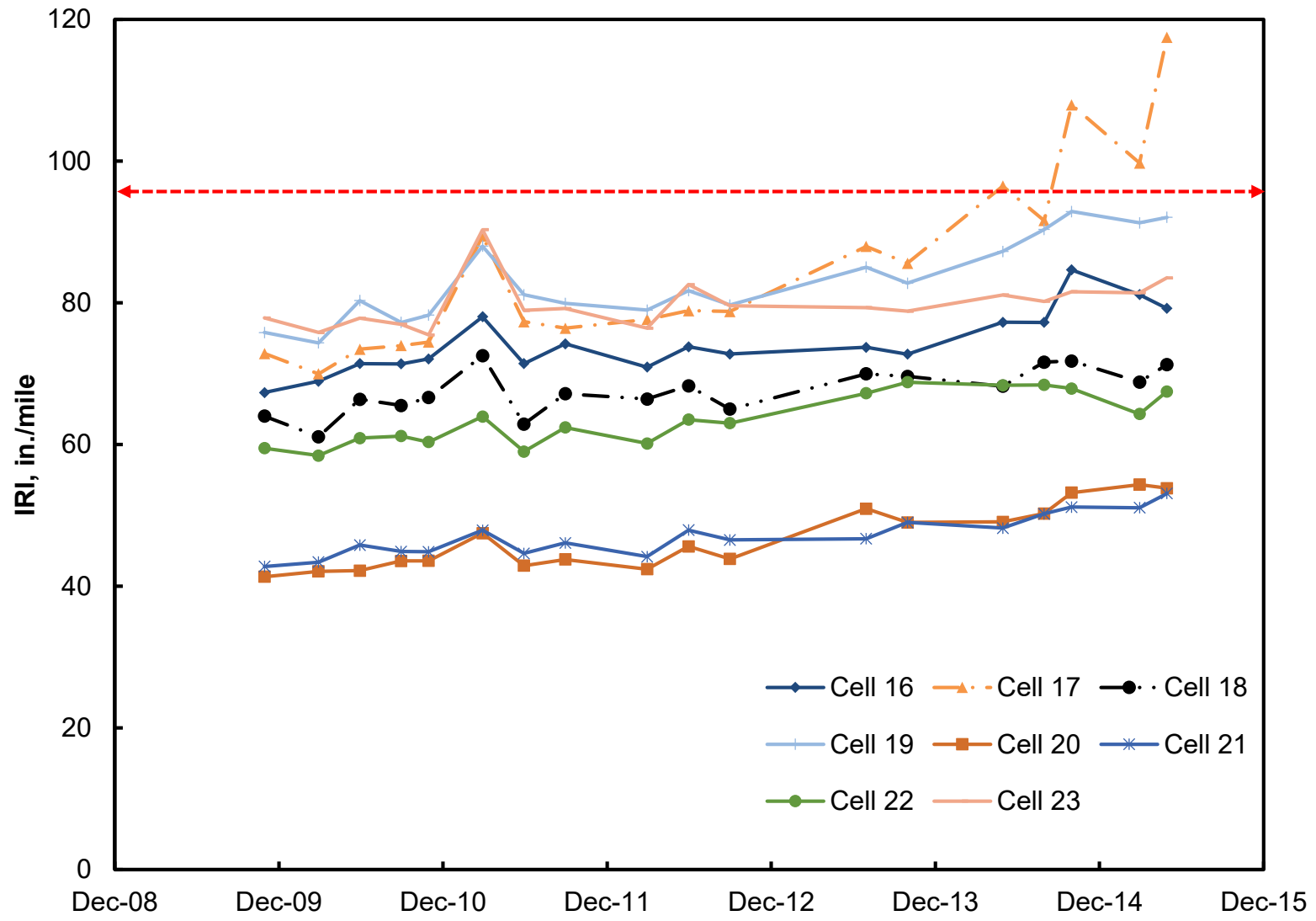


Figure 3-20 International roughness index values for driving lane.

3.3.5 Friction test results

Figure 3-21 presents the friction test results for 2008 and 2015. Based on the SNs for all the cells, it was difficult to assess the performance difference between cells with different base materials or different mixture types. It should be noted that the aggregate used for the mixtures was from a single source.

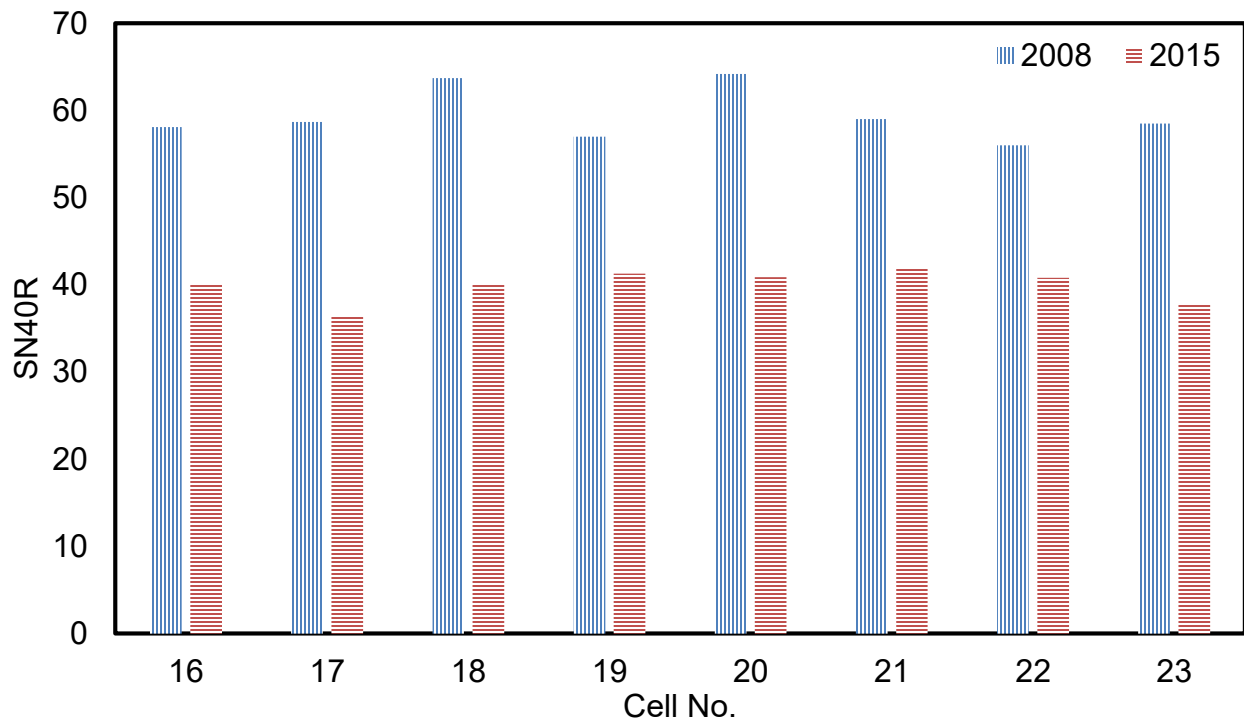


Figure 3-21 Skid numbers measured at 40 mph with ribbed tire.

3.4 TRENCH TESTING (CELLS 16 - 19)

3.4.1 Forensic trenches

Trenches were excavated from the driving lanes of Cells 16 through 19 in July 2016. The trenches were 12 feet by 3 feet. The 12-foot dimension encompassed one 12-foot lane. The 3-foot dimension was chosen to allow access into the trench for *in situ* testing and sample collection. Before the trenches were extracted, ALPS2 was used to measure the trench profile (pre-removal). After the trenches had been removed, the profile (post-removal) was measured again. The trench profiles (before and after extraction) were measured to determine the contribution of rutting from the different HMA lifts and aggregate base layers. However, the correct thickness of the trench panels could not be calculated due to the irregular profile of the base surface. As a result, the rutting performance could not be determined from the trench panels.

3.4.2 Gradation test results

Gradation tests were completed using samples of the original construction material and material gathered during the forensic investigation. The results of these gradation tests were compared to the requirements found in MnDOT specifications. The MnDOT specifications give different gradation requirements depending on the type and content of the recycled unbound material used as the base material (see MnDOT specifications 2016, Tables 3138-3, 3138-4, and 3138-5) (1). Figure 3-22, Figure 3-23, Figure 3-24, and Figure 3-25 present the results of the gradation tests for Cells 16 through 19, respectively, with the maximum and minimum requirements. Figure 3-22 indicates that the recycled PCC base material exceeded the maximum limits for Sieves No. 40 and 200 at the time of construction and after eight years of service. However, the results do not show any significant difference in gradation after eight years of service. Figure 3-23, Figure 3-24, and Figure 3-25 also indicate that the other unbound recycled materials maintained relatively the same gradation over the same period.

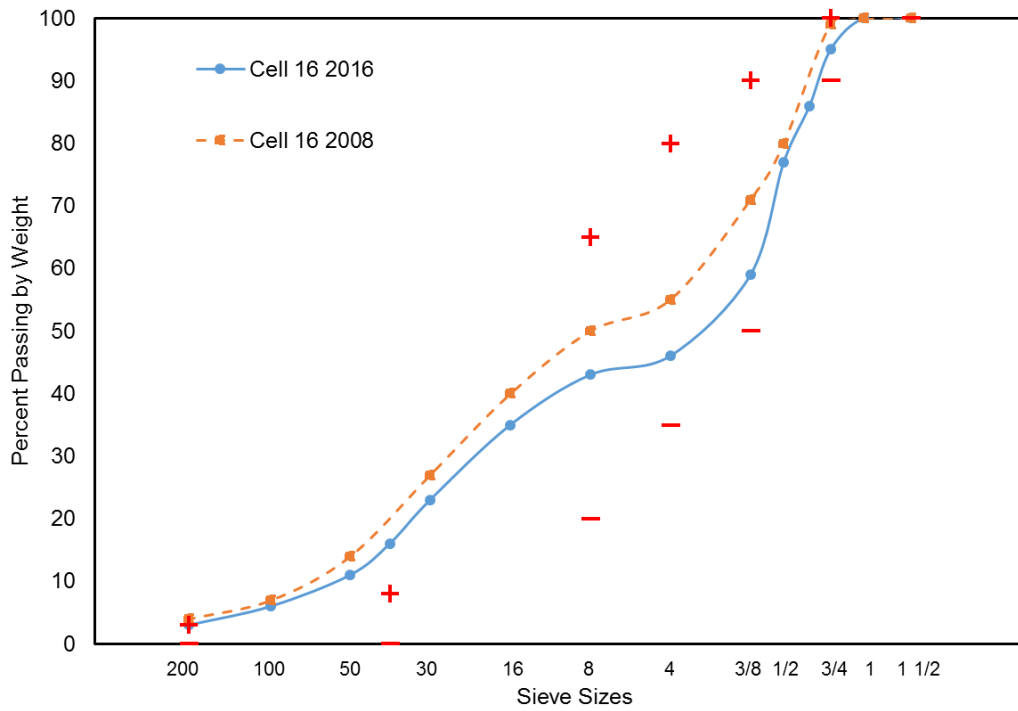


Figure 3-22 Gradations for recycled Portland concrete cement base (Cell 16).

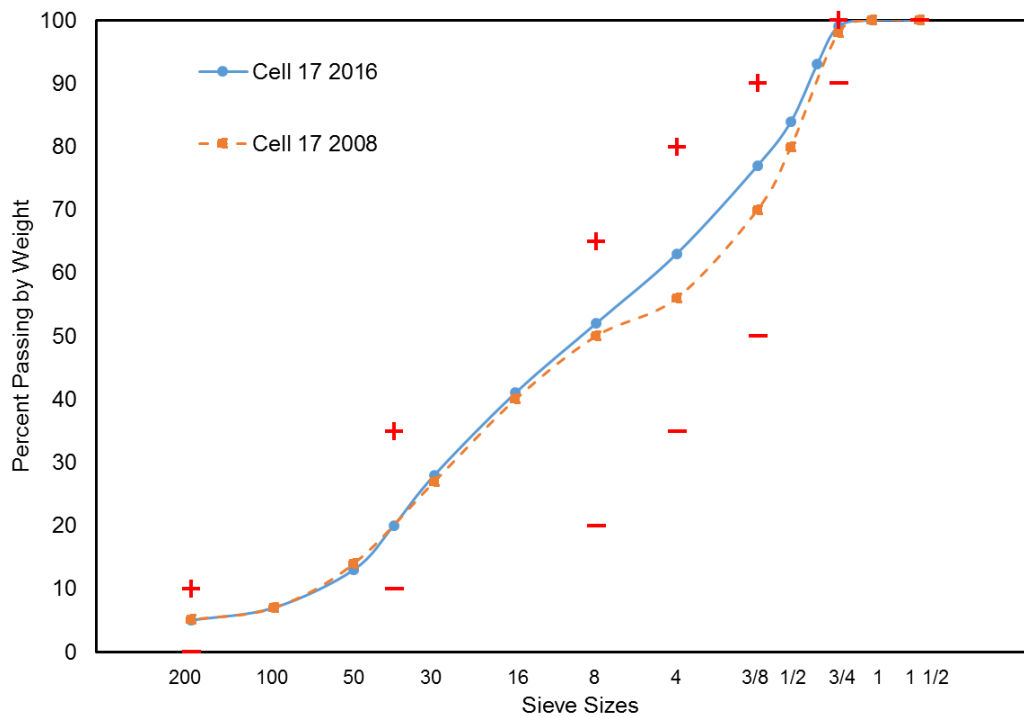


Figure 3-23 Gradations for 50% recycled Portland concrete cement base/50% Class 5 aggregate base (Cell 17).

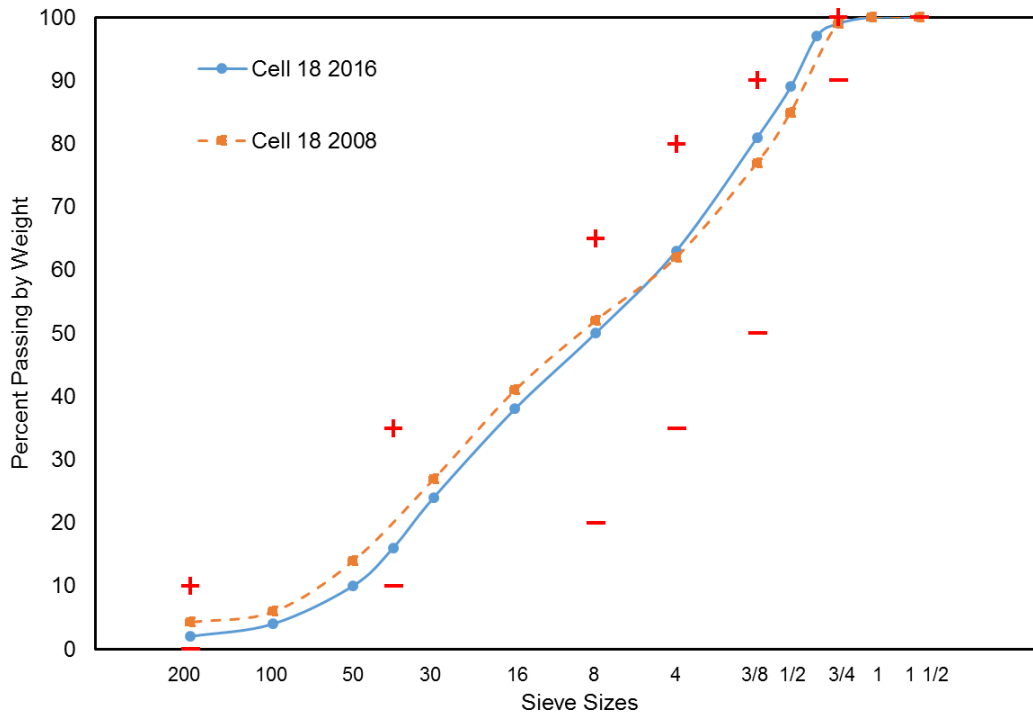


Figure 3-24 Gradations for 100% reclaimed asphalt pavement base (Cell 18).

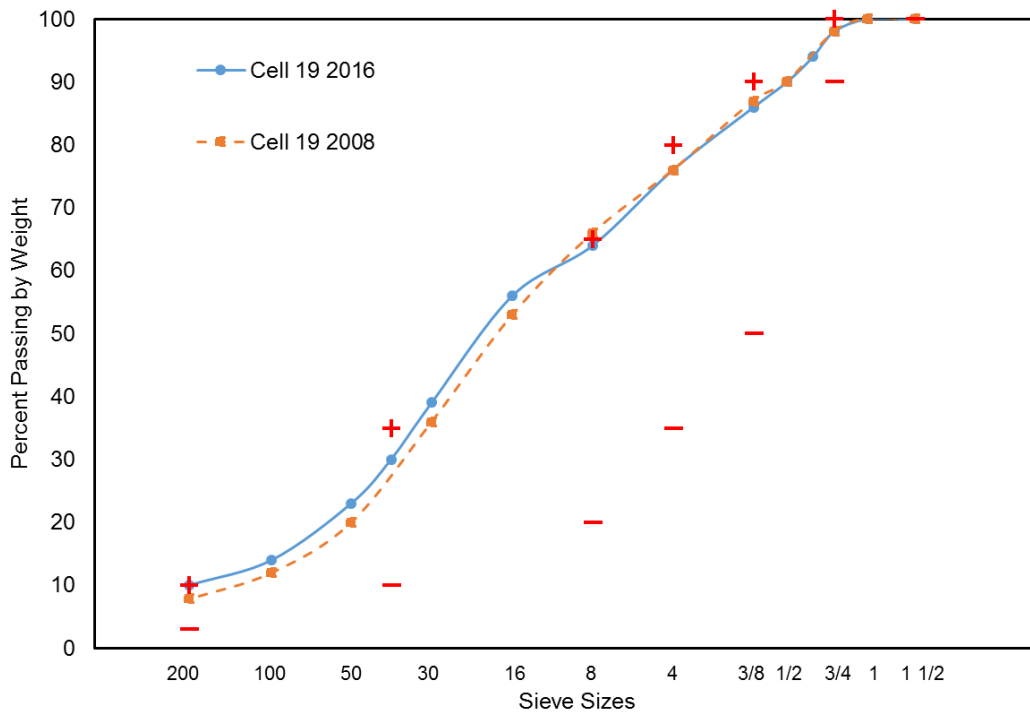


Figure 3-25 Gradations for Class 5 aggregate base (Cell 19).

3.4.3 Light weight deflectometer (LWD), dynamic cone penetrometer (DCP), and moisture content test results

The *in situ* moisture content in the subgrade ranged from 3.6 percent to 10.3 percent for Cells 16 through 19. The maximum allowed DPI value was computed according to the MnDOT Grading and Base Manual and Specification 2211. This calculation uses both moisture content and the ‘grading number’ (the sum of the percentages passing each sieve) to determine the permissible DPI values. LWD and DCP tests were performed in three locations at each excavation site. Table 3-4 presents the results along with the maximum allowed DPI and LWD values (MnDOT specification 2016) (1). The DPI values and LWD deflections in the base ranged from 5 mm/blow to 7.3 mm/blow and from 0.20 mm to 0.29 mm, respectively. Overall, the Class 5 aggregate base material experienced fewer deflections than the unbound recycled materials based on both the DCP and LWD test results. All three recycled unbound materials showed similar test results, and the FWD test results showed the same trend as well. These results indicate that both the Class 5 and recycled unbound materials were in good condition and met the requirements after eight years of service.

Table 3-4 Dynamic penetration index (DPI) and light-weight deflectometer (LWD) test results

Cell	Grading No.	Moisture Content (%)	DPI	Max. Allowed DPI* (mm/blow)	LWD	Max. Allowed LWD* (mm)
16 (RCA)	3.6	10.3	5.3	19	0.21	0.68
17 (RCA + Class 5)	4.2	7.68	5.0	17	0.21	0.61
18 (RAP)	4.1	3.60	5.7	13	0.20	0.46
19 (Class 5)	4.6	6.04	7.3	19	0.29	0.68

*MnDOT specification 2016

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

This report presents the findings from an eight-year performance evaluation of eight cells (Cells 16-23) built at MnROAD in 2008. The constructed cells were used for two performance evaluation studies of: 1) unbound base materials (i.e., RAP, RCA, and taconite) and Class 5 aggregate as the road base material and 2) surface materials that include WMA, RAP, and different binders with different PGs.

The eight cells were tested via a surface distress survey, rutting tests, FWD tests, IRI tests, and friction tests. DCT tests also were performed using the mixture samples, and the performance of the unbound base materials (Cells 16-19) was evaluated using LWD, DCP, and gradation tests. During the performance monitoring period from 2008 to 2016, the cells did not experience any extreme weather events, and the traffic levels, i.e., the ESALs and truck percentages, also were in the normal range. The fatigue life and rutting life of the pavements predicted by MnPAVE ranged from 9 to 50 years and 6 to 11 years, respectively. After eight years of service (approximately 5.6 million ESALs), the fatigue and rutting exhibited by the cells did not exceed the failure threshold.

All the data presented in this report, as well as the sampling, testing, and construction information, can be found in the MnROAD database and various publications. Additional information about MnROAD can be found on the MnROAD website at <http://www.dot.state.mn.us/mnroad/index.html>. The following conclusions and recommendations were reached based on the field and laboratory test results.

4.1 CONCLUSIONS

- Overall, after eight years of service, the MnROAD cells were in good condition with regard to their resistance to surface distresses, rutting, stiffness, IRI values, and friction. Consequently, it was difficult to compare the performance differences between the various unbound materials and HMA mixtures.
- A correlation between DCT fracture energy and the thermal low-temperature performance of the mixtures could not be found due to the limited number of cracks in the cells.
- The unbound recycled materials and taconite performed as well as the Class 5 aggregate base material in terms of the gradation, DCP, and LWD test results.
- All the mixture types, regardless of RAP content, binder grade, and the presence of WMA, exhibited similar performance.

4.2 RECOMMENDATIONS

- Additional research is required to validate the findings from this study. Laboratory tests of core samples are currently being conducted, and a separate report will be generated to expand on this report.
- MnPAVE updates are required for the partial use of unbound base materials (e.g., 50% RAP and 50% Class 5 materials). Also, resilient modulus values and their seasonal variations need to be found.

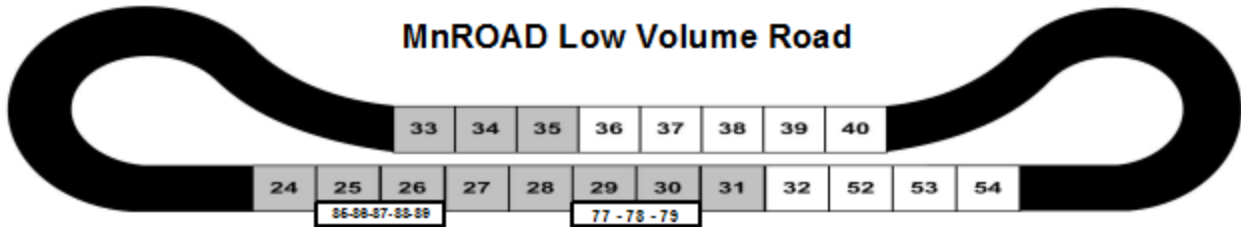
- Further research into a temperature correction model for TONN 2010 needs to be conducted to refine the existing model. Significant seasonal variations with back-calculated stiffness values were noted even after being corrected at 72°F.

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APPENDIX A: MNROAD LAYOUT (2008 CONSTRUCTION)

MnROAD Low Volume Road



Original HMA

Station	24	25	26	27	28	29	30	31	32	33
Top	11" 2S-18	5.5" 2S-18	5.5" 2S-18	13" 2S-18	13" 2S-18	5.5" 2S-18	5.5" 2S-18	13" 2S-18	13" 2S-18	13" 2S-18
Sub	4" C1q	Sub	Clay	11" C1q	17" C1q	10" C1q	12" C1q	12" C1q	4" Class 5	12" C1q
Sub	Sub	Sub	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
Start	Aug 02	Aug 02	Aug 02	Aug 02	Aug 02	Aug 02	Aug 02	Aug 02	Aug 02	Aug 02
End	May 04	May 04	Sep 00	Aug 99	Aug 99	Aug 97	Aug 97	Aug 97	Aug 97	Sep 02

Original Aggregate

Station	25	26	27	28
Top	6" C1-1c	6" C1-1c	6" C1-1c	6" C1-1f
Sub	6" C1-1c	6" C1-1c	6" C1-1c	6" C1-1f
Sub	Clay	Clay	Clay	Clay
Start	Multiple	Multiple	Multiple	Multiple
End	12/95	12/95	12/95	12/95

Original PCC

Station	36	37	38	39	40
Top	6.5" Trans Thd 15x12	6.5" Trans Thd 15x12	6.5" Trans Thd 15x12	6.5" Trans Thd 15x12	6.5"-1.5" Trans Thd 15x12
Sub	2" C1q	12" C1q	5" C1q	1" C1q	1" C1q
Sub	Sub	200' Grd Strip Outside Lane	Clay	Clay	Clay
Start	12/95	Jul 99	Jul 98	Jul 95	Jul 99
End	Current	Current	Current	May 98	Current

Includes traffic most complete information (Report any change)

HMA Constructed

Station	35	36	37	38
Top	15.00 Gravel	4" 2S-18	14" Large Stone	15.00 Gravel
Sub	8" FDR	12" C1q	14" Large Stone	14" Large Stone
Sub	Clay	Clay	Clay	Clay
Start	Sep 00	May 04	Aug 99	Aug 99
End	May 04	Current	Sep 00	Aug 05

PCC Constructed

Station	37	38	39	40
Top	4" Revr Overlay	7.5" Astro Surf 15x12/14	7.5" Astro Surf 15x12/14	12" Trans Room 15x12 1.5" SS
Sub	6" C1-1c	6.5" 2S-18	5" C1q	5" C1q
Sub	Clay	1" dowl	Clay	Clay
Start	Jun 95	Oct 08	Jun 95	Jun 95
End	Current	Current	Current	May 08

Mnshi Hard Rock

Station	53	54
Top	4" G424	7.5" Astro Surf 15x12
Sub	4" C1q	1" dowl
Sub	12" C1q	12" C1q
Start	Sep 04	Oct 04
End	Current	Current

60" Culverts

Station	54
Top	4" 2S-18
Sub	6" Plastic PCC 50x6 Culverts
Sub	Clay
Start	Oct 00
End	Oct 00

Geocomposite Barrier Drains

Station	77	78
Top	4" 2S-14	4" 2S-14
Sub	4" C1-5	4" C1-5
Sub	6" GCB	6" GCB
Sub	7" Clay Barrier	7" Clay Barrier
Start	Aug 06	Aug 06
End	Current	Current

Pervious Full Depth

Station	64	74	85	86	87	88	89
Top	7" Revr RCC	4" Revr RCC	7" Revr RCC	5" Revr NMA	4" Control	5" Revr NMA	7" Revr RCC
Sub	6" Washed Stone	4" RR Ballast	4" RR Ballast	4" RR Ballast	4" RR Ballast	4" RR Ballast	4" RR Ballast
Sub	12" CA-15	Type V Geo-Texile	8" CA-15	Type V Geo-Texile	Type V Geo-Texile	Type V Geo-Texile	Type V Geo-Texile
Sub	Clay	Clay	Clay	Clay	Clay	Clay	Clay
Start	2007	Aug 06	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08
End	Current	Current	Current	Current	Current	Current	Current

Fly Ash Stabilization

Station	77	78	79
Top	4" 2S-14 Ekvay + FFA	5.5" Ekvay + FFA	5.5" Ekvay + FFA
Sub	8" FDR	8" C1q	8" FDR Ry Ash
Sub	Clay	Clay	Clay
Start	Oct 07	Oct 07	Sep 07
End	Current	Current	Current

1999 SuperPave

Station	23	24	25	33	34	35
Top	4" 2S-18	4" 2S-14	4" 2S-14	4" 2S-14 FFA	5.5" 2S-14 SRS	5.5" 2S-14 SRS
Sub	12" C1q	12" C1q	12" C1q	12" C1q	12" C1q	12" C1q
Sub	Clay	Clay	Clay	Clay	Clay	Clay
Start	Jul 99	Jul 99	Jul 99	Sep 07	Sep 07	Sep 07
End	Jul 07	Jul 07	Jul 07	Current	Current	Current

Acid Modified

Station	33	34	35	36	37	38
Top	4" 2S-14 FFA	5.5" 2S-14 SRS	5.5" 2S-14 SRS	4" 2S-14 SRS	1.5" 2S-14	2.5" 2S-14
Sub	12" C1q	12" C1q	12" C1q	12" C1q	8" C1-5	8" C1-5
Sub	Clay	Clay	Clay	Clay	Clay	Clay
Start	Sep 07	Sep 07	Sep 07	Sep 07	Oct 07	Oct 07
End	Current	Current	Current	Current	Current	Current

Implement of Husbandry

Station	83	84
Top	1.5" 2S-14	2.5" 2S-14
Sub	8" C1-5	8" C1-5
Sub	Clay	Clay
Start	Oct 07	Oct 07
End	Current	Current

Agag Study

Station	74
Top	4" C1q
Sub	100' Fog Seal 2008
Sub	100' Chip Seal 2008
Start	Oct 08
End	Current



Original Hot Mix Asphalt													Sewer/Pave Inlets		Misc Surfacing			
5-year design				10-year design									30	31	1999	2002	2004	
6"	6.1"	6.3"	6.1"	10.9"	11.1"	8"	7.9"	7.9"	7.8"	7.8"	7.9"	7.9"	9.2"	2" 55-28	2" 55-28	1999	2002	2004
TS base	24 base	20 base	20 base	7.5 base	7.5 base	2" 55-28	2" 55-28	2" 55-28	2" 55-28	2" 55-28	2" 55-28	2" 55-28	2" 55-28	6" 55-28	6" 55-28	Original Asphalt Binder Type	55-28 = (30958)	64-2 = (34008)
23" C&G	28" C&G	27" C&G	27" C&G	Clay	Clay	28" C&G	28" C&G	28" C&G	28" C&G	28" C&G	28" C&G	28" C&G	28" C&G	2" 55-28	2" 55-28	Warm Mix	Knockout	Duplicate for the most complete information [Report any changes]
Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	W&M	Knockout	Duplicate for the most complete information [Report any changes]
May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02	May 02			

Original Concrete								1997 & 2004 Whitetopping								
5-year design				10-year design				32	33	34	35	36	37	38		
3.5"	7.8"	7.8"	7.8"	7.8"	9.9"	9.9"	9.9"	2.8"	2.8"	2.8"	5.9"	5.9"	5.9"	5"	4" 55-28	4" 55-28
Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed	Trans Thed
2" 55-28	6"	4" 75-28	2.5" 55-28	4" 75-28	4" 75-28	5"	5"	5"	5"	5"	7"	7"	7"	7"	7"	7"
2" 55-28	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14
20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14	20x14
Should	1" d&sd	3007	3007	3007	3007	3007	3007	3007	3007	3007	3007	3007	3007	3007	3007	3007
Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
May 02	May 02	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current

Full Depth Reclamation		
3	4	4
1" 100% RCP	1" 100% RCP	2" 100% RCP
6" FDR treated	6" FDR treated	6" FDR treated
6" FDR	2" FDR	9" FDR - Fly Ash
Clay	Clay	Clay
26" C&G	22" C&G	
Clay		
Oct 08	Oct 08	Oct 08
Current	Current	Current

LTC Overlay		Unbonded Recycled Base				Low Temp Cracking				Mishi Stone Base	
1C	1A	1A	1A	1A	1A	1A	1A	1A	1A	1A	1A
5" WM	5" WM	5" WM	5" WM	5" WM	5" WM	5" WM	5" WM	5" WM	5" WM	5" WM	5" WM
11.1" 64-2	12" 100% Recycle PCC	12" 50% Recycle PCC	12" 100% R&P	12" 100% R&P	12" 100% R&P	12" 100% R&P	12" 100% R&P	12" 100% R&P	12" 100% R&P	12" 100% R&P	12" 100% R&P
Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
59-24 Surface Water	12" C&G	12" C&G	12" C&G	12" C&G	12" C&G	12" C&G	12" C&G	12" C&G	12" C&G	12" C&G	12" C&G
	Select Grs	Select Grs	Select Grs	Select Grs	Select Grs	Select Grs	Select Grs	Select Grs	Select Grs	Select Grs	Select Grs
	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08	Sept 08
Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current

Unbonded PCC Overlay					Comp onite	
185	205	305	405	5	106	206
4"	4"	5"	5"	5"	5"	5"
7.3" cracked 92 PCC	7.3" cracked 92 PCC	7.3" cracked 92 PCC	7.3" cracked 92 PCC	7.3" cracked 92 PCC	7.3" cracked 92 PCC	7.3" cracked 92 PCC
2" 55-28	2" 55-28	2" 55-28	2" 55-28	2" 55-28	2" 55-28	2" 55-28
Clay	Clay	Clay	Clay	Clay	Clay	Clay
20x14	20x14	20x14	20x14	20x14	20x14	20x14
20x14	20x14	20x14	20x14	20x14	20x14	20x14
1" d&sd	1" d&sd	1" d&sd	1" d&sd	1" d&sd	1" d&sd	1" d&sd
OS Long	OS Long	OS Long	OS Long	OS Long	OS Long	OS Long
Clay	Clay	Clay	Clay	Clay	Clay	Clay
Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08
Current	Current	Current	Current	Current	Current	Current

2009 SHRP-II Comp onite Design (Design Stage)		
70	71	72
2" 55-28	2" PCC	2" PCC
8" PCC 15% RAP	8" PCC 15% RAP	8" PCC 15% RAP
1" C&G	1" C&G	1" C&G
Clay	Clay	Clay
12" Road	B&C Surface	B&C Surface
1" d&sd	12" Road	12" Road
no parking	1" d&sd	1" d&sd
	no parking	no parking
2009	2009	2009

Thin Concrete				2008 Whitetopping								
113	113	313	413	114	114	314	414	514	614	714	814	914
5"	5.5"	6"	6.5"	6"	6"	6"	6"	6"	6"	6"	6"	6"
1" C&G	1" C&G	1" C&G	1" C&G	1" C&G	1" C&G	1" C&G	1" C&G	1" C&G	1" C&G	1" C&G	1" C&G	1" C&G
Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
heavy turf	heavy turf	heavy turf	heavy turf	heavy turf	heavy turf	heavy turf	heavy turf	heavy turf	heavy turf	heavy turf	heavy turf	heavy turf
12x12"	12x12"	12x12"	12x12"	12x12"	12x12"	12x12"	12x12"	12x12"	12x12"	12x12"	12x12"	12x12"
no parking	no parking	no parking	no parking	no parking	no parking	no parking	no parking	no parking	no parking	no parking	no parking	no parking
Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08	Oct 08
Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current	Current