

MnROAD SHRP2 R21 Composite Concrete Section Performance after Five-Years of Service

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ABSTRACT

The Strategic Highway Research Program (SHRP2) R21 project “Composite Pavements,” completed in 2010 at MnROAD I-94, included both long-term full-scale pavement experiments and the development of new tools for pavement design and analysis. The R21 research focused on both asphalt-over-concrete and concrete-over-concrete (PCC-PCC) pavement systems. This paper focuses on the full-scale PCC-PCC results of the R21 project. Results show that these sections performed very well with no transverse or longitudinal cracking, minimal joint faulting, low IRI values and no obvious durability problems after five years of I-94 traffic. This evaluation also includes analysis of pavement data and a comparison of the PCC-PCC response relative to a conventional single-lift slab. Results indicate very similar performance for similar PCC total thickness and joint design. In addition, the paper also presents the predicted performance of these sections using the AASHTO M-E procedure to the field results at the MnROAD R21 PCC-PCC field sections. This discussion highlights challenges and opportunities in M-E design and performance modeling for PCC-PCC projects.

INTRODUCTION

Rigid pavement construction methods through the 1960s included two-lift construction and the use of a wire mesh between the placement of homogeneous Portland cement concrete (PCC) layers. After the slipform paver was developed in the 1960s, monolithic placement of the slab took over and two-layer paving in the United States was largely forgotten. In spite of the availability of slipform paving, in Europe the use of two-layer PCC pavements (PCC/PCC) continued, in part because some European chose to construct heterogeneous PCC layers, whose properties varied based on available materials and/or desired performance (Darter, 1993; Hall, 2007; Tompkins et al., 2009).

However, in the United States, two-lift paving was not entirely abandoned: in 1978 the Florida Department of Transportation (DOT) constructed multiple full-scale test sections along Florida SR-45 using two-layer concrete slabs, wherein the lower-lift used a low-cement concrete then referred to as “econocrete” (Greene et al., 2010). In the decades to follow in the United States, interest in PCC/PCC has led to additional research, including projects such as:

- the 1992 United States Tour of European Concrete Highways (Darter, 1993);
- the 1992 High Performance Concrete Pavement (HPCP) Test and Evaluation Project 30 (FHWA, 2006), which included experimental PCC/PCC projects in Michigan (Smiley, 1996) and Kansas (Wojakowski, 1998);

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- the 2006 International Technology Scanning Program tour of long-life concrete pavements in Europe and Canada (Hall, 2007); and
- the 2008 demonstration of PCC/PCC construction on I-70 by Kansas DOT, in cooperation with the FHWA (Fick, 2008).

The Strategic Highway Research Program (SHRP2) project R21 “Composite Pavements” is one of the latest and most ambitious of these recent investigations of PCC/PCC. SHRP2 R21 sought to develop construction and design guidelines for PCC/PCC (Rao et al, 2013). To fulfill this objective, the project included the construction of full-scale composite Portland cement concrete (PCC) experimental test sections constructed at the Minnesota Road Research facility (MnROAD). These sections were constructed in May 2010 and opened to live interstate traffic in August 2010.

One of the challenges of any experimental field study of a given pavement is the subject of access and monitoring. One of the advantages of locating the test sections at MnROAD is that the experimental facility allows for controlled test conditions and continuous monitoring of all test cells (Tompkins and Khazanovich, 2006). This includes monitoring traffic loading, environmental conditions, slab response, distress performance, etc. Thus, since opening to traffic in 2010, the data from the R21 PCC/PCC can provide a reliable indication of the response of the PCC/PCC structure to regular truck traffic and environmental conditions.

The purpose of this paper is to follow up on the performance of the MnROAD R21 test sections after five years of service life. Furthermore, given the controlled conditions and the presence of other test sections at MnROAD, the performance of the R21 PCC/PCC sections at MnROAD will be compared with nearby, structurally similar single-lift pavements.

SHRP2 R21 MnROAD PCC/PCC Test Section Construction

Thickness and PCC mix design

The design of the R21 MnROAD test sections is illustrated in Figure 1a and summarized in Table 1. The construction of these test sections at MnROAD is shown in Figure 1b. The tests were built to feature a 3-inch high-quality PCC layer over a 6-inch “structural” PCC lower lift. Here “structural” PCC denotes that the layer functions structurally in the pavement in a manner similar to conventional concretes, yet the structural PCC uses unconventional, alternative, and/or secondary materials. Two kinds of structural PCC were considered: a low-cement, high fly ash concrete with 50% recycled concrete aggregate (RCA) replacement for the coarse aggregate and a low-cement, high fly ash concrete with inexpensive, locally available aggregates.

2009 SHRP-II Composite Pavements		
70	71	72
3" G4-34 Saw/Seal	3" PCC EAC	3" PCC
6" PCC Recycle	6" PCC Recycle	6" PCC Low Cost
8" Class 7	8" Class 7	8" Class 7
Clay 15'x12' 1.25" dowels driving none passing	Clay Innovative DG (driving) Convent. DG (passing) 15'x12' 1.25" dowels	Clay EAC Surface 15'x12' 1.25" dowels
May 10 Current	May 10 Current	May 10 Current



(a)

(b)

Figure 1. (a) SHRP2 MnROAD test section design summary in cross-section and (b) two-lift paving train at MnROAD during SHRP2 construction in 2010

Table 1. SHRP2 R21 design for MnROAD Cells 71 and 72

Section		Two-lift, RCA PCC (71)	Two-lift, Low-Cost PCC (72)
Upper PCC	Thickness	3 in	3 in
	Mix	High portland cement (~550 lb/yd ³) 15% Fly ash, Class C (FAC)	High portland cement (~550 lb/yd ³) 15% FAC
	Coarse Aggregate	Crushed granite (maximum size 3/8 in)	Crushed granite (maximum size 3/8 in.)
Lower PCC	Thickness	6 in	6 in
	Mix	Low portland cement (~250 lb/yd ³) 60% FAC	Low portland cement (~250 lb/yd ³) 60% FAC
	Coarse Aggregate	50% RCA, 50% Mn/DOT Class A Maximum aggregate size 1.25 in	100% Mn/DOT Class A Maximum aggregate size 1.25 in
Base		8 in, Class 5 unbound	8 in, Class 5 unbound
Subgrade		Clay	Clay
Joint spacing		15 ft	15 ft
Doweling		1.25 in (located 4.5 in from top of base)	1.25 in (located 4.5 in from top of base)
Surface texture		Innovative diamond grind	Exposed aggregate

PCC Layer Strength Properties

Table 2 presents average strength data from tests conducted on over 80 specimens of each of the three PCC mixes. Specimens were created using field mix at MnROAD during the construction of a demonstration slab and the two PCC/PCC test sections. Table 2 data includes that of the FHWA Mobile Concrete Lab, which visited the R21 construction site and collected cores and material samples. The general performance of these PCC mix designs was found to be satisfactory, and the performance of RCA mix design in terms of flexural strength was particularly surprising.

Table 2. Average strength data for concretes used in SHRP2 MnROAD test cells

PCC mix	Compressive strength (psi)			Modulus of rupture (psi)	
	7 day	14 day	28 day	7 day	28 day
Upper-lift PCC	5044	5315	5601	739	846
RCA PCC	3599	4117	4509	578	658

Low-cost PCC	3773	4364	5003	468	575
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Surface Texture

Finally, another innovation in the design and construction of the R21 test sections was the use of unconventional surface texturing. The R21 project elected to use an exposed aggregate concrete (EAC) surfacing for the demonstration slab and mainline sections. While EAC has been a successful surface texture in Europe, the SHRP2 R21 was aware of challenges faced by the Kansas and Michigan DOTs in applying these techniques in the United States (6-8). One initial problem that the project team resolved was the specified gradation curve for the PCC mix to be used for the upper lift. The challenge was achieving a gradation curve that attempted to meet the EAC standard observed by the R21 team in Europe yet was within the means of the contractor and its ready-mix supplier. Table 3 describes 1) the allowable maximum and minimum passing for each sieve in the specification and 2) the final gradation curve used for the upper lift PCC by the contractor.

Table 3. Gradation curve for EAC mix used in R21 MnROAD construction

Designation	12.7 mm (1/2 in.)	9.5 mm (3/8 in.)	6.3 mm (1/4 in.)	4.75 mm (# 4)	2.36 mm (# 8)	1.18 mm (# 16)	.030 mm (# 50)	.015 mm (# 100)	.0075 mm (# 200)
As-written specifications	--	100-95	75-65	55-45	40-30	35-25	13-7	7-1	5-0
Final EAC blend	100	96	68	51	41	38	15	3	1

The finishing platform used for the construction was a GOMACO model TC600 with Power Pavers Inc TC 2700T spray attachment. After paving, a compound was applied to the surface that both acted as a moisture barrier (curing agent) and as a retarder of hydration in the concrete at the surface. This curing/retarder compound was MBT Reveal from BASF Building Systems. Early applications of the surface treatment were delayed due to mechanical problems on the finishing platform, which provided insufficient pressure to the spray nozzles. The treatment was intended to be applied almost immediately after finishing of the placed second lift, however due to frequent delays, the treatment was applied anywhere between 60 and 90 minutes after the completion of paving a given segment.

Brushing was initiated anywhere between 5 and 8 hours after paving of a given section had completed. The extent of brushing was determined using a combination of a sand patch test and an aggregate peak counting test. Though not specified, the aggregate peak counting test was an informal quality control for the brushing adapted from Austrian methods. It aimed for a count of anywhere between 40 and 50 aggregate points per 25 cm² (3.88 in²), according to Haider et al (2006). The sand patch test was conducted according to ASTM E965 at intervals as a quality control measure during brushing to ensure that the depth of brushing was between 0.8 and 1.2 mm (0.03 to 0.05 inches).

In addition to the use of EAC surface texturing (on Cell 72), the driving lane of Cell 71 was textured using diamond grinding. More details on the diamond grind used as a surface texture for Cell 71 can be found in Akkari and Izevbekhai (2012) and Rao et al. (2013).

PCC/PCC SECTION PERFORMANCE AFTER FIVE YEARS

As noted, the R21 MnROAD PCC/PCC test sections (Cells 71 and 72) are situated along the MnROAD “mainline” Interstate 94 and were opened to traffic in August 2010. The sections are shown in Figure 2.



Figure 2. MnROAD Cell 71 (top) and Cell 72 (bottom) as of November 2013

The Minnesota DOT conservatively estimates traffic to be an average of 3559 heavy commercial trucks per day (two-direction), based on WIM data collected between 1994 and 2011 (Peterson, 2011). Thus in the five years since opening, the R21 MnROAD PCC/PCC sections have been subjected to approximately 3 million trucks in the driving lane, not to mention the challenging environmental loads presented by Minnesota’s summer and winter extremes.

As noted in the introduction, in evaluating the performance of the R21 MnROAD test sections, it is important to consider their performance alongside that of a structurally similar single-lift JPCP section. The closest active section at MnROAD that is structurally similar to the R21 PCC/PCC sections is MnROAD Cell 12, a 21-year old JPCP section with a 9.5-inch slab on a substructure very similar to that of the R21 sections. MnROAD Cell 12 is detailed in Table 4.

Table 4. MnROAD Cell 12 design details

Original PCC	Section		Single-lift JPCP Constructed 1992 Opened in 1994
12	PCC	Thickness	9.5 in
9.5" Trans Tined		Mix	Portland cement (~450 lb/yd ³), 15% Fly ash, Class C (FAC)
5" Class 5		Coarse Aggregate	Mn/DOT Class A, Maximum aggregate size 1.25 in
Clay		Base	5 in, Class 5 unbound
15x12	Subgrade		Clay
15x12	Joint spacing		15 ft
1.25" dowel	Doweling		1.25 in
Sep 92	Surface texture		Transverse tining
Current			

Given access to the MnROAD database, one can develop a number of comparisons to evaluate both the general performance of the R21 PCC/PCC sections and their relative performance as an alternative to single-lift paving. The following subsections analyze distress data from this database by JPCP transverse cracking, JPCP joint faulting, and IRI ride quality. In addition, given the incorporation of unconventional surface textures on the R21 sections, noise and friction data are examined for both the R21 sections (Cells 71 and 72) and MnROAD Cell 12, which utilizes the MnDOT conventional texture at the time of its construction (longitudinal tining). For the subsections to follow, the methodology used by MnROAD to observe and/or measure data is excluded – the reader can find more information on MnROAD data collection and the MnROAD database at the MnROAD website (MnDOT, 2016).

Transverse and Longitudinal Cracking

MnROAD engineers have observed no transversely cracked slabs in the first five years of performance on Cells 71 or 72. Additionally, no longitudinal cracking has been observed. Likewise, MnROAD Cell 12 experienced no cracking in its first five years. (Furthermore, as an aside, the only cracking observed in Cell 12's history has been limited longitudinal cracking beginning in its eleventh year, observed in May 2005). The cracking performance of these three sections is not surprising given that the extent of traffic loading is not extreme relative to the composite slab thickness.

Joint Faulting

Figure 3 illustrates joint faulting measurements for Cells 71 and 72 during the five years after opening to traffic. Reported faulting in Figure 3 is measured in the driving lane at a location three feet from the centerline (of a two-lane section). Figure 4 reports the measured faulting for MnROAD Cell 12 during the five years after it had been opened to traffic. All three sections utilized 15-foot joint spacing and 1.25-inch dowels. Given the low levels of faulting experienced by all three sections, it is safe to claim that the faulting performance is similar. Overall, the low amount of faulting measured in the three sections is not surprising given the doweling, the slab thickness, the substructure, and the traffic volume.

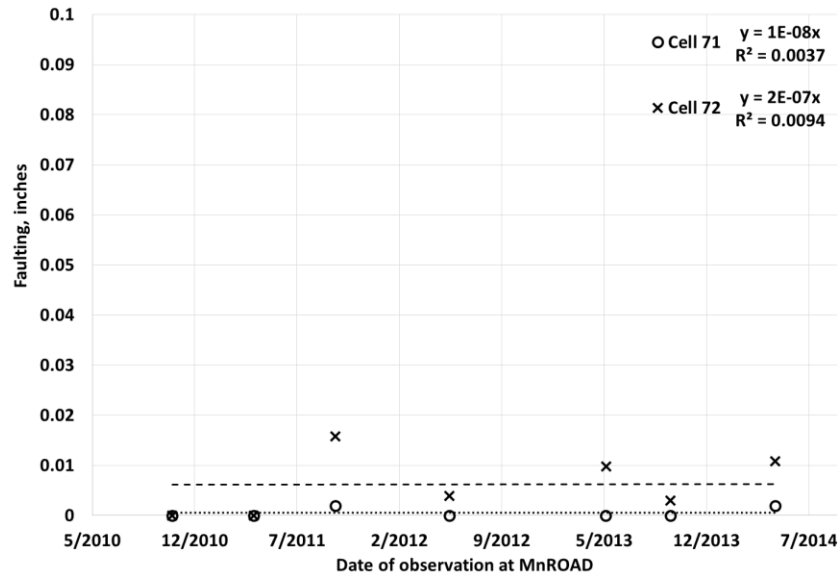


Figure 3. Average joint faulting (measured three feet from the centerline in the driving lane) observed in MnROAD Cells 71 and 72 within five years of opening to traffic

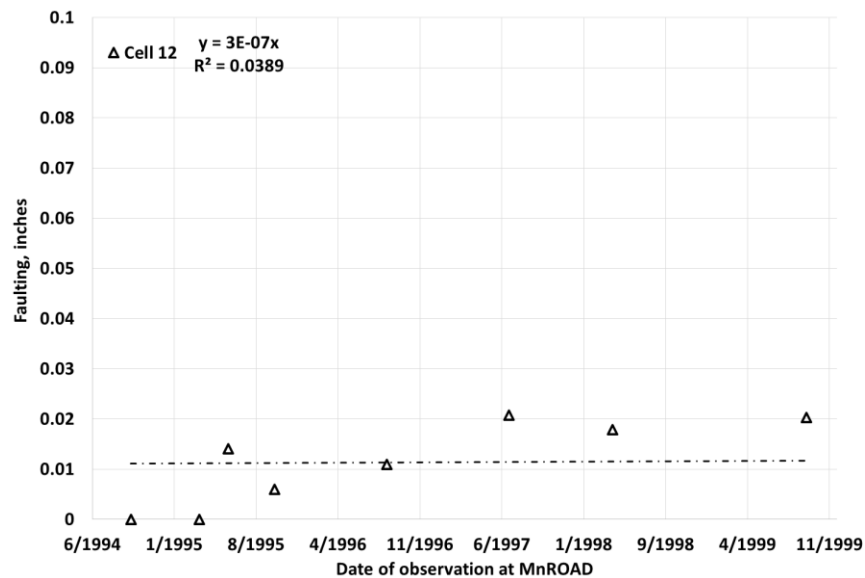


Figure 4. Average joint faulting (measured three feet from the centerline in the driving lane) observed in MnROAD Cell 12 within five years of opening to traffic

IRI Ride Quality

Figure 5 illustrates ride quality as measured in the driving lane of Cells 71 and 72 during the five years after opening to traffic. Figure 6 reports the same information for Cell 12. Some observations of the IRI data are:

- The ride performance of Cell 72 is unusually high for a JPCP given that the section experienced zero cracking and negligible levels of joint faulting. MnROAD engineers have reviewed the Cell 72 IRI data, which was measured using a line laser profilometer, and determined that it is valid.

- The performance of Cell 71 and Cell 12 is similar, which is expected given the faulting and cracking performance. While there is more variance in the Cell 71 data set ($\sigma^2 = 58.0 \text{ in}^2/\text{mi}^2$) than the Cell 12 data set ($\sigma^2 = 39.8 \text{ in}^2/\text{mi}^2$), the variability can be attributed to a single outlier in the Cell 71 data set (a value of 83 in/mi observed March 2011). If this outlier is removed, the variance for the Cell 71 data becomes $\sigma^2 = 35.8 \text{ in}^2/\text{mi}^2$, which generally agrees with that of Cell 12.

As the IRI on Cell 72 is unusually high from the outset, it is possible that the roughness on that section is due to issues encountered during the construction of the test section. Evidence of these construction issues can be observed in the “patching” in the EAC texture of the passing lane of Cell 72, illustrated in Figure 2 at bottom. It is possible that the issue is not due to construction, but rather the possibility that EAC surfacing (i.e. the associated macrotexture) complicates the profilometer data and the analysis thereof, thus more investigation in this regard is required. Overall, there is little degradation in the ride quality of Cells 71 and 72, evidenced by the linear regression equations fit included in Figure 5. Their performance in the loss of ride quality is similar to that of a conventional JPCP, such as Cell 12 (Figure 6).

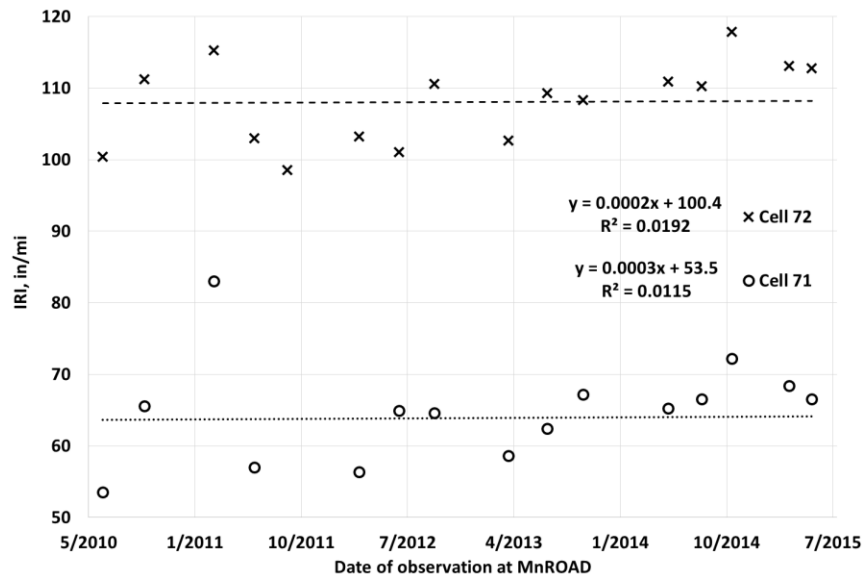


Figure 5. Ride quality in the driving lane observed in MnROAD Cells 71 and 72 within five years of opening to traffic

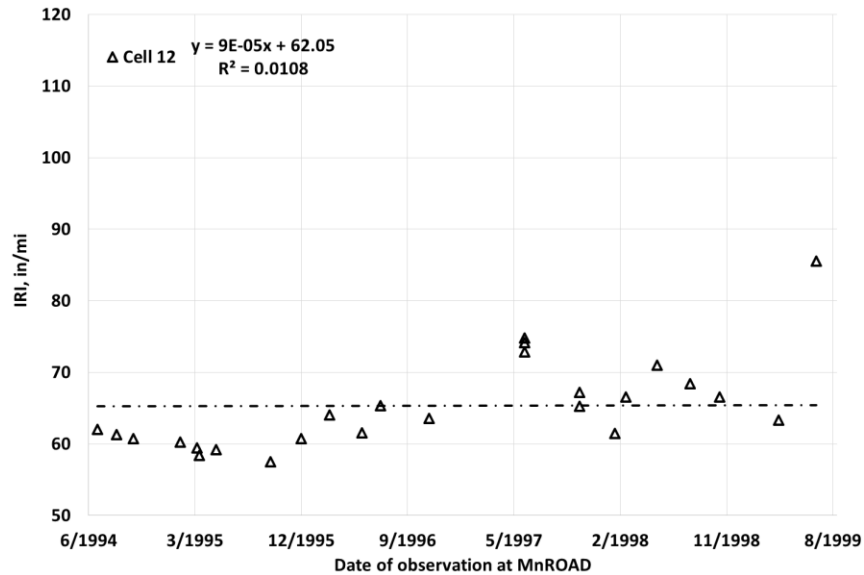


Figure 6. Ride quality in the driving lane for MnROAD Cell 12, observed within five years of opening to traffic

Pavement noise

Figure 7 illustrates the wheel noise in the driving lanes of Cells 71 and 72. These test sections and locations correspond, respectively, to a diamond ground texture (Cell 71) and an EAC texture (Cell 72). Again, more specifics on these textures are provided in Akkari and Izevbekhai (2012) and Rao et al (2013). The noise performance of the EAC texture is in keeping with other experiences in the United States with this technology (Smiley, 1996). That is, the noise performance, while less than that of a conventional texture, is not a dramatically low as observed in Europe (Haider et al, 2006).

A direct comparison of noise performance of the textures on Cells 71 and 72 with that of conventional textures at MnROAD is difficult given that sufficient noise data was not available in the MnROAD database at the time of submission. Thus, the noise performance of Cell 12 in Figure 8 represents the measured wheel noise of that pavement for the same five years depicted in Figure 7. This comparison thus cannot be used to deduce much in terms of the initial performance of these textures. It can be seen, however, that for the same traffic and time span, both the EAC and diamond ground textures on Cells 72 and 71, respectively, are less noisy than the transversely tined Cell 12.

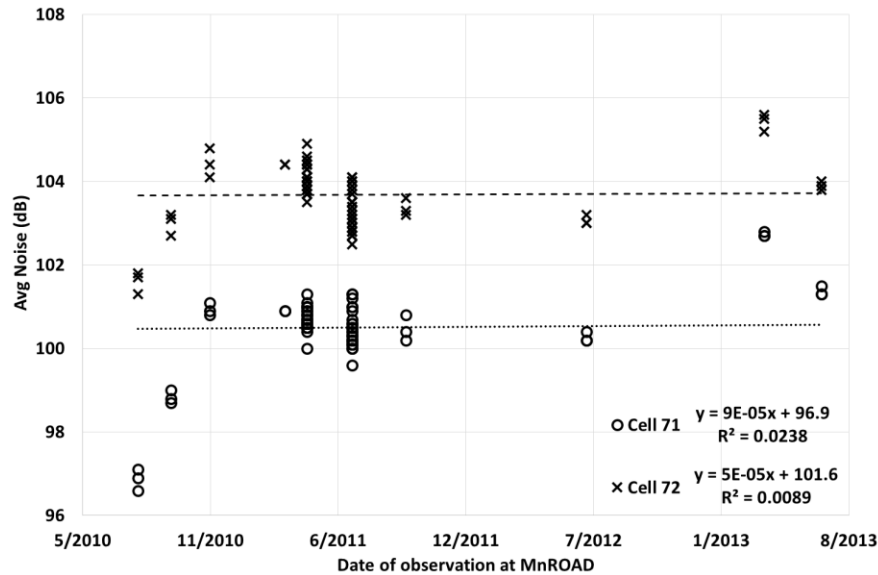


Figure 7. OBSI noise measured in the driving lane of MnROAD Cells 71 and 72, observed within three years of opening to traffic

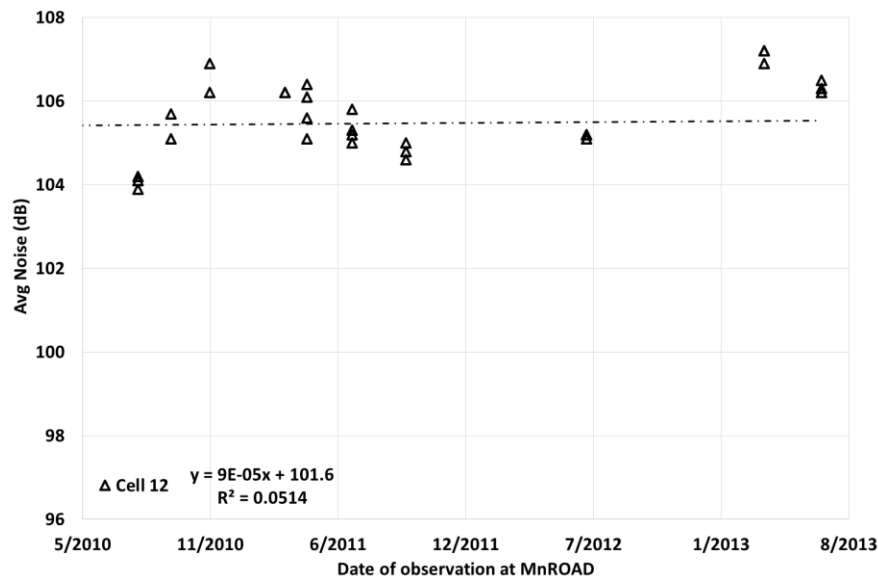


Figure 8. Five years of OBSI noise measurements in the driving lane of MnROAD Cell 12, a transversely tined JPCP that was opened to traffic in 1994

Surface friction

The measured surface friction in the driving lanes (using a ribbed tire for the skid test at 40 MPH) of Cells 71 and 72 for the first five years after opening is illustrated in Figure 9. Again, the surface textures for these test sections are a diamond ground texture (Cell 71) and an EAC texture (Cell 72). The surface friction of the longitudinally-tined Cell 12 for the first five years after opening is illustrated in Figure 10. Some observations on these data sets are:

- While the initial friction in MnROAD Cell 12 is higher, the loss of surface friction is also far more dramatic over the first five years.

- The surface texture for both Cells 71 and 72, in terms of surface friction, appears to be slightly more durable than that of Cell 12. Cells 71 and 72 lost roughly 20% of their initial friction number, whereas Cell 12 lost approximately 35% of its initial friction number.
- The surface friction performance of the exposed aggregate section (Cell 72) is surprising. During the R21 project, the expectation based on the tour of European pavements was that EAC texturing could provide surface friction performance similar to transversely tined pavements. However, the experience at MnROAD is again in keeping with that of I-75 in Detroit, detailed in Smiley (1996), in which both the initial noise and friction performance of EAC sections did not meet expectations.

Overall, the surface friction performance of all three sections is adequate (i.e. a friction number of 40 or higher). Additional study of the surface friction performance is needed to make more specific statements on the performance of these unconventional textures relative to more conventional methods.

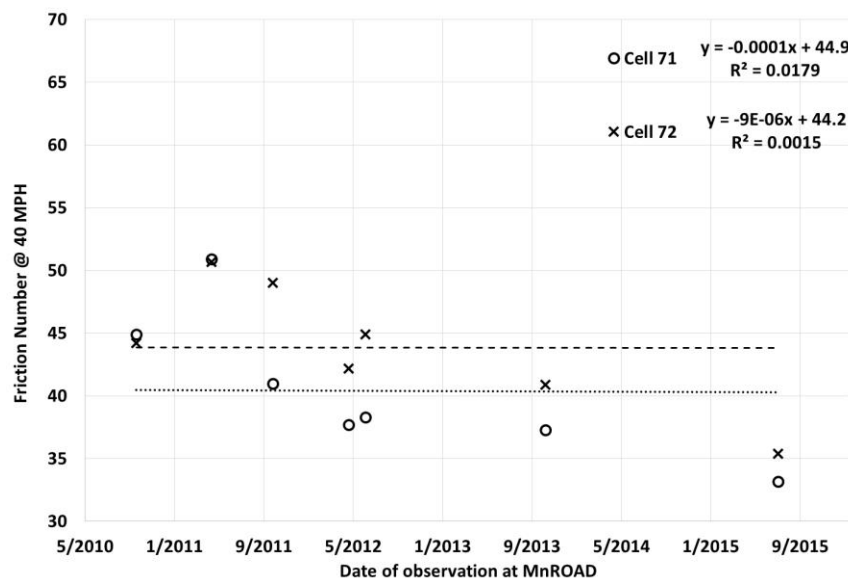


Figure 9. Surface friction, measured at 40 MPH, in the driving lane of MnROAD Cells 71 and 72, observed within five years of opening to traffic

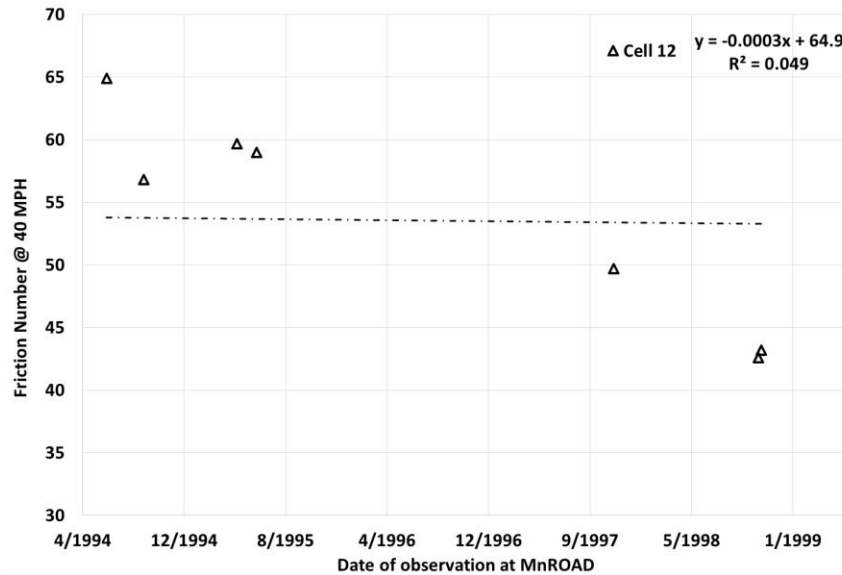


Figure 10. Surface friction, measured at 40 MPH, in the driving lane of MnROAD Cell 12, observed within five years of opening to traffic

PREDICTED PERFORMANCE USING THE AASHTO M-E DESIGN PROCEDURE

One can also view performance data from the first five years of service life alongside predictions made using the AASHTO M-E design procedure for the same time period and traffic volumes. Rao et al (2013) details the design projects developed to simulate MnROAD Cells 71 and 72 in the version of the AASHTO M-E procedure developed during SHRP 2 R21 (MEPDG 1.300:R21). Table 5 compares the predicted performance, taken from Rao et al (2013), with measurements from MnROAD.

Table 5. Comparison of measured performance after five years of service life, as surveyed by MnROAD engineers, with predicted performance from MEPDG 1.300:R21 for MnROAD Cells 71 and 72

		Performance at 5 years		
		Transversely Cracked Slabs (%)	Joint faulting (inches)	Smoothness IRI (in/mi)
Cell 71, Two-lift, RCA PCC	Predicted	0.8	0.02	82.0 ¹
	Measured	0.0	0.00	66.5
Cell 72, Two-lift, Low-cost PCC	Predicted	0.2	0.02	78.0 ¹
	Measured	0.0	0.01	112.8 ²

¹ Designs estimated initial IRI at 63 in/mi; ² High initial IRI attributed to construction

Table 5 illustrates very low measured values of distress and smoothness after five years, which matches the predicted values. The two-layer PCC JPCP were modeled as bonded overlay of existing slab (full friction and bond) in the M-E analysis. The projections actually indicate good performance over a 15 year period and beyond.

CONCLUSIONS

The five year performance results indicate that – after three million heavy trucks in the outer lane – the PCC-PCC JPCP sections at MnROAD are performing very well, with minimal levels of slab cracking, joint faulting, and smoothness. In addition, condition surveys during this time period indicated no obvious durability distress or debonding issues between layers in the harsh Minnesota climate. Overall, the two layer PCC-PCC pavements at MnROAD have performed similarly to a nearby homogeneous slab of approximately the same thickness and base materials over the first five years. A valid question that is often asked of two-lift paving is “Will the two layer PCC-PCC perform the same as, better than, or worse than a single-layer, conventional JPCP?” The answer after five years is that they are performing about the same. In some areas where high quality aggregates are costly, the two layer PCC-PCC will have a lower initial cost. There is no reason to believe that the two layer PCC-PCC will not perform as well as or better than the single layer JPCP pavement.

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