Lessons learned from Mn/ROAD (1992 – 2007): Five-Inch Concrete Pavement Study

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Abstract

This paper examines the design and performance to date of the 125-mm [five-inch] concrete pavement test cell (Cell 32) constructed in 2000 on the MnROAD low-volume road (LVR). After seven years of service, this pavement has since been subjected to more than 170,000 80-kN [18-kip] ESALs by a 5-axle tractor-trailer loaded to as much as 454 kN [102 kips]. It would take more than 50 years to accumulate this many ESALs on residential streets and many lower volume roads. Few distresses have developed and the pavement ride quality remains acceptable for lower volume road applications. The performance of this pavement section suggests that accepted design procedures for low-volume concrete roads may be quite conservative.

Introduction

A 125-mm [5-inch] thick concrete pavement was constructed without dowels or drains over 175 mm [7 inches] of crushed rock and silty-clay subgrade on the low-volume road (LVR) test loop at the MnROAD site in 2000. After seven years of service, this pavement has since been subjected to more than 170,000 80-kN [18-kip] ESALs by a 5-axle tractor-trailer loaded to as much as 454 kN [102 kips]. It would take more than 50 years to accumulate this many ESALs on residential streets and many lower volume roads. Few distresses have developed and the pavement ride quality remains acceptable for lower volume road applications.

Research Significance

The results of this study provide a point of validation concerning the sufficiency of existing concrete pavement design procedures for low volume roads. It also provides evidence of the apparent efficacy of certain design features (i.e., reduced panel size, well-compacted foundation) in helping to ensure good performance, even in the presence of heavy loads and the absence of typical performance-enhancing features, such as dowels, drains and deep foundation layers.

The MnROAD Project – A Brief Overview

The Minnesota Road Research Project (MnROAD), a full-scale pavement test facility located about 30 miles northwest of Minneapolis, is one of the most sophisticated,

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independently operated pavement test facilities of its type in the world. The facility includes two separate, heavily instrumented road segments that are located adjacent and parallel to the westbound lanes of Interstate 94: a 5.6-km [3.5-mile] mainline interstate roadway carrying traffic diverted from I-94 (averaging 23,500 westbound vehicles per day with 12% trucks in 2004), and a 4.0-km [2.5-mile] closed-loop low-volume roadway carrying a facility-controlled 5-axle tractor-semi-trailer (Worel 2006, Burnham 2005). The mainline and LVR sections can be seen in figure 1.

When originally constructed (1991 – 1994) and opened to traffic (August 1994), it featured 40 test sections or "cells", including 14 constructed using jointed concrete pavement, 22 with asphalt surfacing, and 4 with aggregate surfacing. Each original test section is about 150 m [500 ft] long and contains numerous instruments for measuring pavement responses to applied loads and environmental effects. The performance of the original MnROAD concrete pavement test cells is discussed in a report to be published by the American Concrete Pavement Association (Snyder, 2008).

Figure 1. Aerial photo of MnROAD
(image courtesy of Minnesota Department of Transportation).

Several more concrete test sections have been added to the MnROAD facility since 1994, including several sections of whitetopping on the mainline pavement (discussed in a different article in this series), a section of thin (130-mm [5-in]) concrete on the low-volume test loop (the subject of this article), and a section with alternative dowel materials on the low-volume test loop.

Data are collected from the test sections in many ways, from automated and triggered sensor records (e.g., for layer strain and temperature data) to manually collected data (e.g., pavement distress and friction data). The MnROAD Data Base Guide (Worel 2006) provides details concerning data collection protocols.

Detailed descriptions of the concept, design, construction, instrumentation and performance of MnROAD can be found in many of the references listed at the end of this paper, as well as at the official Minnesota Road Research website, http://www.mrr.dot.state.mn.us/research/Mnresearch.asp

Design and Construction of Cell 32

Cell 32 was originally constructed in 1993 as an aggregate-surfaced pavement consisting of 150 mm [6 in] of MnDOT Class 1 aggregate (surfacing) over 150 mm [6 in] of Class 1c special (base) over a silty-clay subgrade (R-value = 12). The gradations of these materials are shown in Table 1. The cell was reconstructed using the same materials and thicknesses in 1996. The test cell is 500 ft [150m] long.

Table 1. Aggregate Gradations (% Passing) for Classes 1 and 1c (special) Aggregate (MnDOT 1993 Specification).

Sieve Size	% Passing	
	Class 1	Class 1c (special)
19mm [¾ in]	100	100
9.5 mm [3/8 in]	65 – 95	65 – 90
4.75 mm [#4]	40 – 85	40 – 70
2.00 mm [#10]	25 – 70	25 – 50
425μm [#40]	10 – 45	10 – 30
75μm [#200]	8 – 15	4 – 12
PI		0 – 6 max
Crushing		Crushed particles not allowed.

In June 2000, the top 125 mm [5 inches] of the surface aggregate was removed and replaced with 125 mm [5 inches] of jointed plain concrete pavement. The resulting foundation consists of 25 mm [1 in] of MnDOT Class 1 aggregate and 150 mm [6 inches] of MnDOT Class 1c (special) aggregate, as shown in Figure 2.

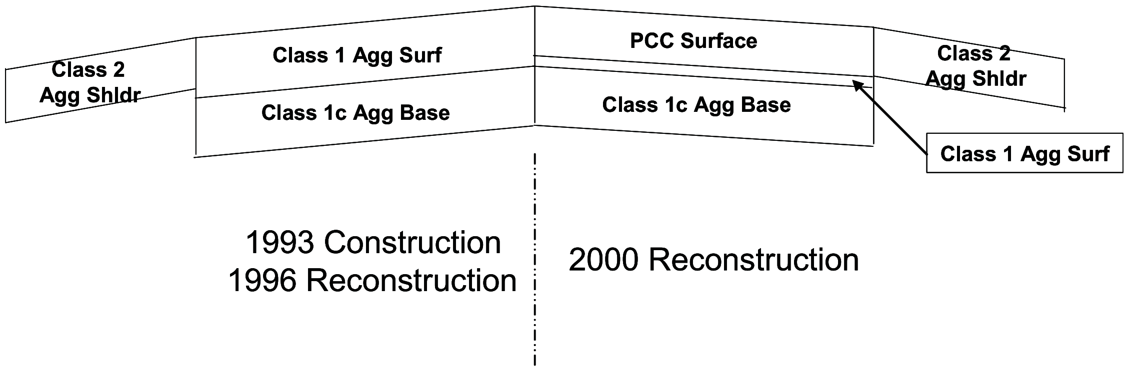

Figure 2. Cross-section of Cell 32 in 1993 (original aggregate construction) and 2000 (PCC reconstruction).

The slab thickness measured during construction (by probing behind the paver) averaged 130 mm [5.13 in] and ranged from 121 – 140 mm [4.75 – 5.50 in]. Seven cores retrieved after construction averaged 140 mm [5.4 in] in length, with a range of 120 – 150 mm [4.7 – 6.0 in].

There are no pavement drains in this cell. The travel lanes are 3.6 m [12 ft] wide and the undoweled transverse joints are cut perpendicular to the centerline and are spaced 3.1 m [10 ft] apart. The panel joints were sealed with a hot-pour asphalt joint sealant, and the shoulders are comprised of 125 mm [5 in] of MnDOT Class 2 aggregate. Figure 3 shows a recent photo of Cell 32.

Figure 3. Photograph of Cell 32 (foreground) in 2003, looking southeast (image courtesy of the Concrete Paving Association of Minnesota).

The concrete mixture used in test Cell 32 was proportioned as follows (Burnham, 2001):

- Coarse Aggregate (3/4-in-plus [19-mm-plus], oven-dry): 615 lb/yd^3 [366 kg/m^3]
- Coarse Aggregate (3/4-in-minus [19-mm-minus], oven-dry): 760 lb/yd^3 [452 kg/m^3]
- Coarse Aggregate (#7, oven-dry): 360 lb/yd^3 [208 kg/m^3]
- Sand #1 (oven-dry): 950 lb/yd^3 [565 kg/m^3]
- Sand #2 (“safety grit,” oven-dry): 440 lb/yd^3 [262 kg/m^3]
- Type I Cement: 384 lb/yd^3 [228 kg/m^3]
- Granulated Ground Blast Furnace Slag: 206 lb/yd^3 [122 kg/m^3]
- Water: 218 lb/yd^3 [130 kg/m^3]
  - Resulting water-cement ratio (w/c) = 0.57
  - Resulting water-cementitious materials ratio (w/(c+p)) = 0.37
- Water reducer: 5 oz/100 lb cement (325 ml/100kg cement)

The resulting concrete had average compressive strengths (companion cylinders) of 14.2 MPa [2057 psi] at 3 days, 18.8 MPa [2729 psi] at 7 days, 27.5 MPa [3988 psi] at 28 days, and flexural strengths of 3.0 MPa [441 psi] at 3 days, 3.9 MPa [564 psi] at 7 days and 4.9 MPa [714 psi] at 28 days.

Additional information concerning the design and construction of this test cell (including test cell materials and instrumentation) can be found in a report by Burnham (2001).

In general, the design of this test cell (5 in [125mm] of undowelled concrete pavement with short joint spacing built over a thin granular subbase) can be considered to be representative of many city streets and other lower-volume roads built in Minnesota (and throughout the U.S.) in the 1940s and 1950s. More recent designs for these applications have generally featured thicker slabs (e.g., 6 inches [150 mm] minimum).

Environmental Conditions

MnROAD is located in an area that experiences a wide range of environmental conditions. Temperatures as warm as 39C [102F] and as cold as -42C [-43F] have been observed in the area. Precipitation averages 69.9 cm [27.5 in] per year (including snowfall that averages 113 cm [44.5 in] per year) over 109 days per year. (Source: www.weatherbase.com)

Traffic Loadings

All traffic loadings on the Mn/ROAD LVR section are accomplished by passes of standard 5-axle tractor-trailer trucks that are loaded to 355 kN [80,000 lbs] in the inner lane and 453 kN [102,000 lb] in the outer lane. The axle loads for these two configurations are:

- 355-kN [80-kip] configuration: 53-kN [12-kip] single axle, 151-kN [34-kip] dual-tandem axle, 151-kN [34-kip] dual-tandem axle

- 453-kN [102-kip] configuration: 55-kN [12.5-kip] single axle, 199-kN [44.75-kip] dual-tandem axle, 199-kN [44.75-kip] dual-tandem axle

The 355-kN [80-kip] lane is generally trafficked 4 days each week and, as of the end of 2007, had been subjected to approximately 46,300 vehicle passes and 173,000 ESALs since construction of Cell 32 in June 2000. The 453-kN [102-kip] lane is generally trafficked 1 day each week and, as of the end of 2006, had been subjected to approximately 13,700 vehicle passes and 164,000 ESALs since the construction of Cell 32 in June 2000.

Performance Observations

After more than 7 years of service in Minnesota's harsh climate, Cell 32 remains in very good condition. The ride quality has not deteriorated greatly, it exhibits relatively little distress (especially considering the traffic loads and pavement thickness) and has required no significant maintenance.

Ride Quality

Pavement profile measurements have been obtained in the outer wheel path of each lane at least three times per year since construction using a laser-based system that obtains 6 measurements per cm [16 per inch] and processes that data using moving averages to produce a profile at 7.5-cm [3-in] intervals. The pavement profile data are used to compute an International Roughness Index (IRI) value for each lane of each test section at each point in time. The IRI is calculated as the ratio of the accumulated vertical motion of a standard ¼-car suspension model to the distance traveled over the measured profile at a speed of 80 km/h [50 mph]. IRI is typically expressed in units of inches (of suspension movement or "roughness") per mile (meters/kilometer) and is strongly correlated (inversely) with Present Serviceability Rating, or PSR, the ride quality and performance measure used as the basis for all AASHTO pavement design guides since the early 1960s. Details concerning the IRI can be found in ASTM E 1926.

Figure 4 presents a summary of IRI data since construction for the PCC version of Cell 32. It shows that the ride quality of this cell has not deteriorated greatly (especially given the heavy traffic and thin pavement section). It also shows that the roughness of this section has always been higher than would be desired for highway pavement construction, but is probably acceptable for lower volume road applications.

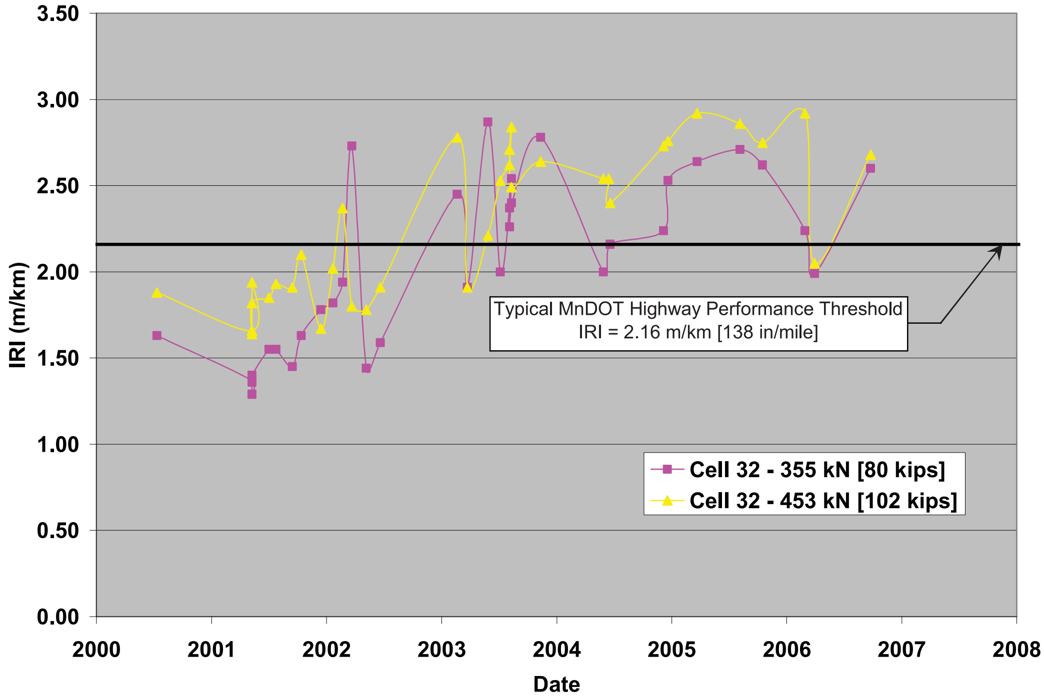

Figure 4. IRI history for Cell 32.

Pavement Distresses

The ride quality (IRI) histories described previously reflect initial construction smoothness, the development of roughness due to long-term environmental effects (i.e., curling and warping), and the development of load-related distresses. The development of load-related distresses has been minimal so far, as described below.

Pavement condition (distress) surveys have typically been performed 3 – 4 times per year using distress measures and definitions described in the FHWA's LTPP Distress Manual (Miller and Bellinger 2003). Summaries of the distresses observed in those surveys is presented in Table 2 and Figure 5.

Table 2. Summary of distresses observed in Cell 32 since reconstruction in 2000.

Distress Type/Severity		80-kip lane				102-kip lane			
	Survey Date	Pre-2005	May-05	Apr-06	Oct-06	Pre-2005	May-05	Apr-06	Oct-06
	ESALs		122,000	143,000	151,000		110,000	132,000	142,000
Long. Crack - Low		0	1.8 m [6 ft] (1 panel, 2%)	0	0	0	5.5 m [18 ft] (2 panels, 4%)	9.1 m [30 ft] (3 panels, 6%)	6.1m [20 ft] (2 panels, 4%)
Long. Crack - Medium		0	0	2.4 m [8 ft] (1 panel, 2%)	2.4 m [8 ft] (1 panel, 2%)	0	0	0	3.0 m [10 ft] (1 panel, 2%)
Trans. Crack - Low		0	0	0	0	0	1.2 m [4 ft] (1 crack)	3.7 m [12 ft] (2 cracks)	3.7 m [12 ft] (2 cracks)
Trans. Jt. Spall - Low		0	0	0	1 (0.6m [2 ft])	0	1 (0.6 m [2 ft])	1 (0.6 m [2 ft])	1 (0.6 m [2 ft])
Trans. Jt. Seal Damage - Low		0	43 joints, 91%	43 joints, 91%	43 joints, 91%	0	45 joints, 96%	45 joints, 96%	45 joints, 96%
Trans. Jt. Seal Damage - Med		0	3 joints, 6%	3 joints, 6%	3 joints, 6%	0	2 joints, 4%	2 joints, 4%	2 joints, 4%
Trans. Jt. Seal Damage - High		0	1 joint, 2%	1 joint, 2%	1 joint, 2%	0	none	none	none

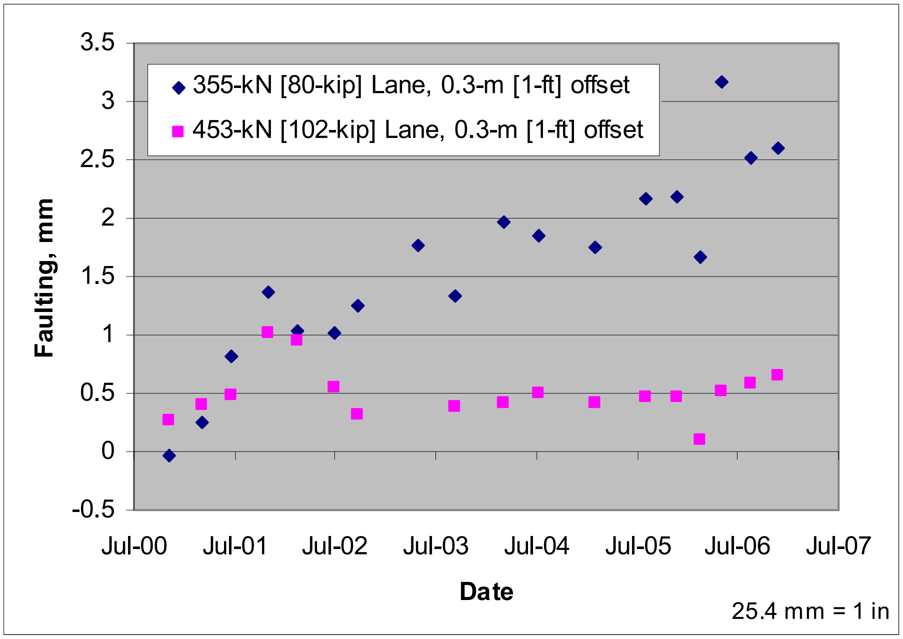

Figure 5. Summary of Cell 32 average faulting measurements.

The most remarkable aspect of this data is that _no significant distress was observed until after 5 years of service under very heavy traffic loading_ (110,000 or more ESALs). Even now, after more than 7 years of service, distress levels are quite low. To summarize, the 355-kN [80-kip] lane has developed no transverse cracking, only one longitudinal crack, one small transverse joint spall, and less than 3 mm [1/8 in] of faulting; the 453-kN [102-kip] lane has developed only two low-severity transverse cracks, three panels (of 47) have a longitudinal crack, there is one small transverse joint spall, and less than 1mm [0.04 in] of faulting. No blowups, corner breaks, D-cracking, map cracking, scaling, popouts or pumping have been observed on either of the lanes of Cell 32.

This performance record is particularly exceptional given that it is for a 125-mm [5-inch] nominal thickness slab built with no performance-enhancing features (e.g., dowels, edge drains, widened lanes or concrete shoulders, etc.) after 7 years of exposure to Minnesota's harsh winter environment and subjected to traffic levels that represent a lifetime (or more) of service for many LVRs. In addition, _no maintenance has been performed whatsoever._

It is interesting to note the difference in faulting development between the two test lanes, as shown in figure 5. While both lanes have similar ESAL accumulations, the more heavily trafficked 355-kN [80-kip] lane shows a greater increase in faulting over time than does the less frequently trafficked 453-kN [102-kip] lane. This suggests that the development of faulting is not well-predicted by ESALs for traffic mixes that are significantly different in composition or load magnitude.

Projected Performance for Typical LVR Applications

The Mn/ROAD LVR loop test cells represent lower-volume pavement structural designs commonly found in practice (i.e., city streets, township and some county roads, etc.). However, the rate of traffic load accumulation on these cells is much more rapid than for many in-service LVRs. The amount of time required to accumulate similar amounts of distress on in-service pavements with similar designs can be estimated by determining the time required to accumulate a similar number of Equivalent Single Axle Loads (ESALs).

Table 3 presents an example of assumptions and calculation results for predicting the amount of time required to accumulate the same amount of ESALs on various classes of in-service pavements as have been accumulated by Dec 2007 on Cell 32 (approximately 170,000 ESALs).

Table 3 suggests that, for the assumed traffic levels, it would take more than 50 years for a 125-mm [five-inch] PCC pavement to accumulate 170,000 ESALs in a typical residential street application if every heavy vehicle was fully loaded, and more than 120 years if more typical (average half-full) vehicle loads are assumed. For a typical collector street, these numbers would be 6.7 years and 16.7 years for the stated assumptions. Values between 0 and 2 years result for more heavily trafficked roads. When using the default traffic volumes and load distributions included in ACPA's StreetPave software for these 4 pavement functional classifications, very similar (but slightly longer) time estimates are obtained.

These estimates represent the time required to accumulate similar ESAL values (and, presumably, similar levels of distress) to those currently accumulated in Cell 32. Since it appears that Cell 32 has several additional years (and ESALs) of performance life remaining, it can safely be assumed that the performance life expectations for in-service applications of this design would be proportionately longer than the estimates provided in Table 3.

It should also be considered that Cell 32 was designed and constructed without dowels, edge support, drainage, stabilized foundation material, or any other performance-enhancing features. It is reasonable to expect that the use of curb-and-gutter edge support and some form of mechanical transverse joint load transfer devices might further increase the performance life of this pavement.

Table 3. Example estimation of time required to accumulate 170,000 ESALs for various traffic levels and distributions.

	Vehicles per Day					Time to 2.8M ESALs, years		Time to 6.4M ESALs, years		Time to 11.7M ESALs, years	
	School Bus	Transit Bus	Garbage Truck	Tractor Semi-Trailer	Other Heavy Trucks	Typ. Max. Load	Typ. Working Load	Typ. Max. Load	Typ. Working Load	Typ. Max. Load	Typ. Working Load
Residential Street	4 per day, 5 days per wk	0	2 per week	1 per week	1 per week	>50	>50	>50	>50	>50	>50
Collector	8 per day, 5 days/week	0	4 per week	2 per week	25 per day	>50	>50	>50	>50	>50	>50
Arterial	20 per day. 5 days/week	20/day, 7 days/week	4 per day	50 per day	100 per day	13	30	29	>50	>50	>50
County Road	4 per day, 5 days per wk	0	0	100 per day	300 per day	7	19	17	44	31	>50
Axle Configuration	Single-Single	Single-Single	Single - Tandem	Single - Tandem - Tandem	Single - Tandem						
Axle Load (kips, typical max)	53 kN - 93 kN [12k - 21k]	67 kN - 125 kN [15k - 28k]	89 kN - 205 kN [20k - 46k]	53 kN - 151 kN - 151 kN [12k - 34k - 34k]	53 kN - 151 kN [12k - 34k]						
ESALs per Vehicle*	2.05	7.24	8.6	3.99	2.09						
Axle Load (kips, typical working)	44 kN - 80 kN [10k - 18k]	53 kN - 111 kN [12k - 25k]	71 kN - 116 kN [16k - 26k]	53 kN - 116 kN - 116 kN [12k - 26k - 26k]	53 kN - 116 kN [12k - 26k]						
ESALs per Vehicle*	1.09	4.2	1.25	1.46	0.826						

* Extrapolated for 125-mm [5-inch] PCC from 1993 AASHTO Guide, Appendix D, Tables D.10 and D.11

* Assumes contribution of passenger cars, vans and light trucks is negligible; assumes no significant additional climate effects.

Note: 1k = 4.448 kN

Many localized failures in low-volume roads result from the settlement of poorly compacted backfill materials in underground utility trenches. Cell 32 contained no utility trenches and cannot be considered representative of the performance of a 125-mm [five-inch] PCC pavement where such trenches exist unless they have been properly constructed and compacted.

Validation of LVR Designs

There are many catalogs, recommendations and other approaches to designing concrete LVRs. The performance (to date) of MnROAD Cell 32 can be used to validate or evaluate these procedures, as shown below for two widely accepted procedures.

AASHTO Low Volume Road Design

The rigid pavement design catalogs presented in table 4.8 and 4.9 of Part II of the 1993 AASHTO Guide for the Design of Pavement Structures recommend slab thicknesses of 130 mm [5 in] for 50 percent reliability and 125 to 150 mm [5 to 6 in] (depending upon foundation support level) for 75 percent reliability for design traffic levels of 50,000 – 300,000 ESALs. These recommendations assume the use of doweled joints, 150 mm [6 in] of granular subbase, and average flexural strength of 4.1 MPa [600 psi].

Cell 32 (with no doweled joints but higher strength concrete) has already carried 170,000 ESALs, which is in the design traffic range suggested for this pavement thickness by the 1993 AASHTO Guide. However, Cell 32 is still performing well and shows no signs of imminent failure; therefore, it may eventually prove the 1993 AASHTO Guide design traffic estimates to be quite conservative.

It can be noted that the nominal 150-mm [6-inch] designs in Cells 36 through 40 (described in the full project report (Snyder 2008)) have carried well over 300,000 ESALs and are also performing well (even those cells without dowels), further suggesting that the 1993 AASHTO Guide design traffic estimates or stated levels of design reliability (or both) may be conservative.

It should also be noted, however, that the MnROAD LVR can be considered to be an accelerated loading facility where traffic loads are applied at a much greater rate than would be typical for most lower-volume streets and roads. The long-term effects of climate (and the interaction of climate and vehicle loads) on pavement distress are probably underrepresented in the performance of all of the MnROAD LVR test cells, which may explain part of why the MnROAD LVR sections are performing better than expected (with respect to the AASHTO Guide estimates).

PCA Simplified Design Procedure

The PCA Simplified Design Procedure presented in Chapter 4 of the Portland Cement Association's Thickness Design for Concrete and Highway Street Pavements (PCA

1984), which is often used for developing designs for local roads where axle load data are not readily available. The tables in this chapter were developed using the same procedures and failure criteria (i.e., fatigue consumption and foundation erosion) used in the standard design procedure for roads with known axle load data. The tables also incorporate "a degree of conservatism" that is not explicitly defined in terms of design reliability (PCA 1984).

Table 11 of this reference is useful in developing undoweled PCC pavement designs for residential streets (PCA Axle-Load Category 1) and table 12b is useful in developing undoweled PCC pavement designs for collector streets and rural roads (PCA Axle-Load Category 2). The following inputs were used in evaluating these design tables:

- Flexural strength of 4.5 MPa [650 psi] (the highest tabulated value; Cell 32 had an average 28-day flexural strength of 4.9 MPa [714 psi])
- "Medium" subgrade-subbase support
- Aggregate interlock joints
- No concrete shoulder or curb
- As-built slab thickness of 125 to 140 mm [5 to 5.5 in]

Using these inputs, table 11 suggests that cell 32 should handle somewhere between 0.4 and 7.5 heavy trucks per day in each direction for 20 years (a total of 2920 to 55,000 heavy trucks) in a residential application. Table 12b recommends using at least 150 mm [6 in] of PCC in collector/rural road applications (to carry about 4 heavy trucks per day in each direction, or less than 15,000 heavy trucks over a 20-year life).

The 355-kN [80-kip] lane of Cell 32 has carried more than 46,000 trucks to date without sign of imminent failure, clearly exceeding the PCA expectations for a 125-mm [5-in] residential pavement (5840 trucks over 20 years) and for a 150-mm [6-in] collector/rural road pavement (<30,000 trucks over 20 years). It could be further noted that MnROAD Cells 36-40 have all carried nearly 100,000 heavy truck loads to date and are also performing well (see separate article in this series for more details).

It can be concluded that Cell 32 has outperformed the expectations of both the AASHTO LVR design catalogs and the PCA Simplified design procedure.

Summary – What Have We Learned?

The performance to date of MnROAD Cell 32 shows that concrete pavement sections as thin as 125 mm [5 inches] can be used successfully on many lower volume roads if the qualities of construction and materials are high and the design is good. This conclusion is supported by the performance of five other MnROAD test sections that are nominally 150 mm [6 inches] thick, have been subjected to the same loads described above for nearly 10 years, and are also performing exceptionally well. It appears that generally accepted design procedures underestimate the potential performance of thinner concrete pavements (or overestimate the required thickness for given design conditions).

For residential streets, it would take 50 years or more to accumulate the number of heavy vehicle loads that Cell 32 has withstood over the last 7 years without experiencing significant amounts of distress. Minor design enhancements such as edge support (tied curb and gutter or shoulders) and dowel bars might result in even longer performance lives.

The ability to obtaining 50 years or more of service from 125 mm [5 inches] of concrete should come as no surprise, however. Many cities throughout the U.S. built residential streets in the 1930s, 40s and 50s using only 125 mm [5 inches] of concrete (often placed directly on the subgrade), and many of these streets are still in service today.

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The contents of this paper reflect the views of the author, who is responsible for the facts and accuracy of the data presented . The contents do not necessarily reflect the official views of the Minnesota Department of Transportation or the American Concrete Pavement Association. This paper does not constitute a standard, specification or regulation.

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