U.S. Department of Transportation
Federal Highway Administration

SUSTAINABLE PAVEMENTS PROGRAM

HIGH-PERFORMANCE CONCRETE PAVEMENTS PROVIDE SUSTAINABILITY BENEFITS IN MINNESOTA

FHWA-HIF-19-086

The Minnesota Department of Transportation implemented a long-life concrete pavement program in the early 2000s that is now providing a number of sustainability benefits for the State. This is demonstrated by a 2004 long-life concrete pavement reconstruction project on I-94, a 6-lane divided interstate northwest of Minneapolis.

WHAT WAS THE MOTIVATION?

The Minnesota Department of Transportation (MnDOT) strives to design and construct pavements that meet societal demands of increasing traffic while coping with higher construction costs and reduced availability of high-quality raw materials. However, in the 1990s some of MnDOT's concrete pavements exhibited reduced service lives due to material durability issues related to freeze-thaw damage and alkali-silica reactivity (ASR) (Burnham, Izevbekhai, and Rangaraju 2006; Sutter, Moulzolf, and Masten 2018). During this period (prior to 1996), MnDOT utilized a prescriptive, strength-based concrete mixture specification that did not directly address durability. Mixture proportioning focused solely on achieving a minimum design compressive strength and nearly all concrete mixture designs were supplied by MnDOT to the contractors, further restricting innovation. These premature failures were costly and wasteful, and MnDOT was concerned that the situation was non-sustainable given budgets and constraints on the availability of high-quality materials.

As a result, MnDOT launched a multi-year effort to improve its concrete material standards and pavement designs and move from a 35-year design life to a 60-year design life. The long-life pavement approach has significant benefits that touch on the three pillars of sustainability (economic, environmental, and social), through reductions in future maintenance and rehabilitation costs (economic), reductions in consumption of increasingly scarce high-quality aggregate materials (environmental), reductions in construction zone congestion and crashes (economic, environmental, social), and improved ride quality over the life cycle (economic, environmental, social).

WHAT WAS DONE?

In the late 1990s, MnDOT carried out a multi-year effort to develop a long-life concrete pavement referred to at the time as high-performance concrete pavement (HPCP). Key features of MnDOT's HPCP include (Burnham, Izevbekhai, and Rangaraju 2006; MnDOT 2018):

- Slab thickness near 13 inches with 15-ft transverse joint spacings.
- Solid foundation featuring a 4-inch dense graded, crushed granular base course and a frost-resistant select granular subbase (minimum 36 inches).

- Stainless steel, corrosion-resistant dowel bars (1.5-inch diameter bars that are 15 inches long and spaced at 12 inches on center).
- Use of a high-performance concrete mixture (described below).
- Rigorous construction inspection and quality assurance program that includes the following unique elements:
  - AASHTO T 318 *Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying* to monitor the water content of concrete placed onsite.
  - Use of a MIT-SCAN-T2 nondestructive testing device to monitor concrete thickness as well as locate pavement reinforcement and dowel bars.
- Artificial turf or broom drag texture.
- Membrane curing (poly-alpha-methylstyrene or linseed oil), with additional provisions for cold weather curing.
- Incentive/disincentive pay schedule for aggregate quality, well-graded aggregate, water-to-cementitious ratio (*w/c*), and initial ride quality.

Since 2000, MnDOT has constructed more than a dozen HPCP projects and adopted the 60-year HPCP design method as standard practice for high-volume urban highways. A 6.1-mile section of I-94 constructed in 2004 serves as an excellent example of the agency's HPCP experience. It is located between U.S. 169 and State Highway 252 (see figure 1) and was constructed under two separate contracts. The design features of the I-94 HPCP are summarized in table 1.

© 2018 Google Earth; Data: SIO, NOAA, US Navy, NGA, GEBCO, INEGI, Landsat/Copernicus. The lines marking the project limits and the labels were added for this case study.

Figure 1. I-94 project location.

Table 1. Design features for I-94 HPCP (data source: Sutter, Moulzolf, and Masten 2018).

Design Feature	Description
Concrete Slab	13-inch JPCP
Base Type	4-inch MnDOT Class 5 granular material
Subbase Type	48-inch MnDOT select granular
Transverse Joint Spacing	15-ft
Transverse Joint Sealant	Preformed elastomeric compression seal
Load Transfer Devices	Stainless steel-solid, stainless steel clad
Surface Texture	Broom drag with 0.08-inch average depth as measured using ASTM E965

Key elements of MnDOT's concrete mixture specification used on the I-94 HPCP include:

- Maximum *w/cm* of 0.40 to reduce permeability and increase durability.
- Optimized aggregate grading using the 8-18 percent "haystack" to reduce water demand and improve workability.
- Up to 30 percent cement replacement with fly as to mitigate ASR and chemical deicer attack.
- Target air content of 7.0 ± 1.5 percent to protect against freeze-thaw damage.
- Payment incentives and disincentives:
  - Actual *w/cm* based on the microwave test (AASHTO T 318).
  - High-quality coarse aggregate.
  - Well-graded aggregate (optional incentive).

Table 2 provides average concrete mixture proportions used on I-94. The measured *w/cm* was 0.35, the mixture included 30 percent AASHTO M 85 Class F fly ash[1], and the optimized aggregate grading met the "haystack" 8-18 percent grading requirements.

Table 2. Concrete mix proportions (Source: MnDOT).

Constituent	Quantity (lb/yd^3)
Cement (Type I) (lb.)	405
Fly ash (Class C/F) (lb.)	173
Coarse aggregate (lb.)	1,810
Fine aggregate (lb.)	1,306
Water (lb.)	212
Air content (%)	7.0
Water reducer (oz/cwt)	5
Design *w/cm*	0.37
Measured *w/cm*	0.35

Note: Quantity is the average of two construction contracts.

Figure 2 shows construction of the I-94 project in 2004, including the use of corrosion-resistant stainless-steel dowel bars, prepared grade, slip-form paving, and concrete slab.

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Figure 2. Construction of I-94 in 2004.

[1] Note that the source of fly ash used had chemical properties at the boundary between Class F and Class C fly ash.

WHAT BENEFITS WERE ACHIEVED?

In the conduct of this case study, a number of economic, environmental, and social benefits were identified, some realized at the time of construction and others expected to be realized over the anticipated 60-year service life of the pavements. Some benefits are quantifiable, but most were not documented at the time of construction and only qualitative inferences can be drawn. When evaluating the sustainable benefits, it is important to note that MnDOT's 60-year HPCP is only approximately 1.5 inches thicker than the traditional 35-year design.

PERFORMANCE

After 14 years of service, MnDOT has observed that the HPCP project on I-94 has performed extremely well with minimal-to-no distresses present. In fact, MnDOT is no longer concerned about joint deterioration and other materials-related performance issues that previously plagued some of their concrete pavements.

Figure 3 shows that the average IRI has remained relatively unchanged from the post-construction value of around 80 inches/mi. In addition to providing social benefit through improved riding comfort to the user, smooth pavements have direct economic and environmental benefits by reducing damage to vehicles and goods in transit, improved vehicle fuel efficiency, and reduced emissions (FHWA 2015).

MnDOT uses a surface rating (SR) index as one indicator of pavement condition. Following construction, a concrete pavement will typically have a SR value of 4. The SR for the I-94 HPCP in both directions has not decreased from the post-construction value of 4 after 14 years in service. The pavement continues to maintain excellent ride quality with minimal signs of transverse joint spalling and faulting. Photos of the current condition are provided in figure 4. Such longevity has deferred maintenance well into the future with associated economic and environmental savings. Projections indicated that this will also delay the need for future rehabilitation, resulting in further savings.

> *"Adopting HPCP sounded like a daunting task. Ultimately, the changes needed to create HPCP were fairly subtle. What was once considered HPCP has, for the most part, become our standard specification for concrete pavements. Joint deterioration and other materials related performance issues are no longer considered to be part of our future."*
>
> –Curt Turgeon, State Pavement Engineer

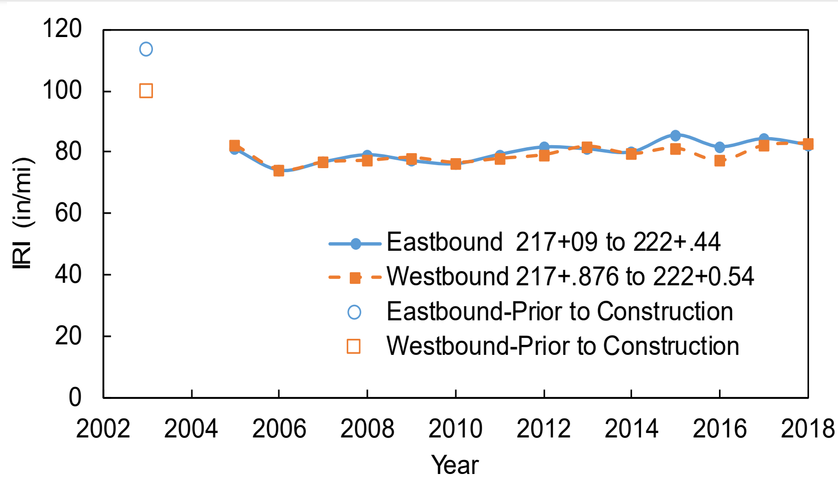

Figure 3. Summary of average IRI for the I-94 HPCP section.

Figure 4. Photos of I-94 showing the current pavement condition.

ENVIRONMENTAL PERFORMANCE

To assess the broader environmental performance of the design and material choices, researchers contracted by FHWA conducted a limited life-cycle assessment (LCA). The LCA examined various design and materials choices comparing the potential environmental impacts of alternatives for the mainline pavement assuming similar use and performance during the design life up to the end of the analysis. The environmental performance is of interest to the Minnesota DOT in helping the agency meet its goals for reduced greenhouse gas emissions, as outlined in the State's *2007 Next Generation Energy Act* and *2017 Statewide Multimodal Transportation Plan*.

In conducting the analysis, the following future treatments were assumed:

- For the standard 35-year design, a concrete pavement restoration (CPR) activity will be performed at year 20, with complete replacement at year 35.
- For the 60-year HPCP, CPR treatments will be performed at years 25 and 35, with reconstruction anticipated at year 60.

The results of the LCA are presented in figure 5 and are annualized to enable a comparison of selected indicators as recommended in the FHWA LCA framework document (FHWA 2016). The HPCP is shown to have a better environmental performance with significantly less potential impact in every category. The main contributor to the results is the need to reconstruct the traditional pavement in year 35 resulting in the use of considerable additional materials, including portland cement in particular. The additional maintenance in year 35 is more than offset by the longer lifespan of the initial construction.

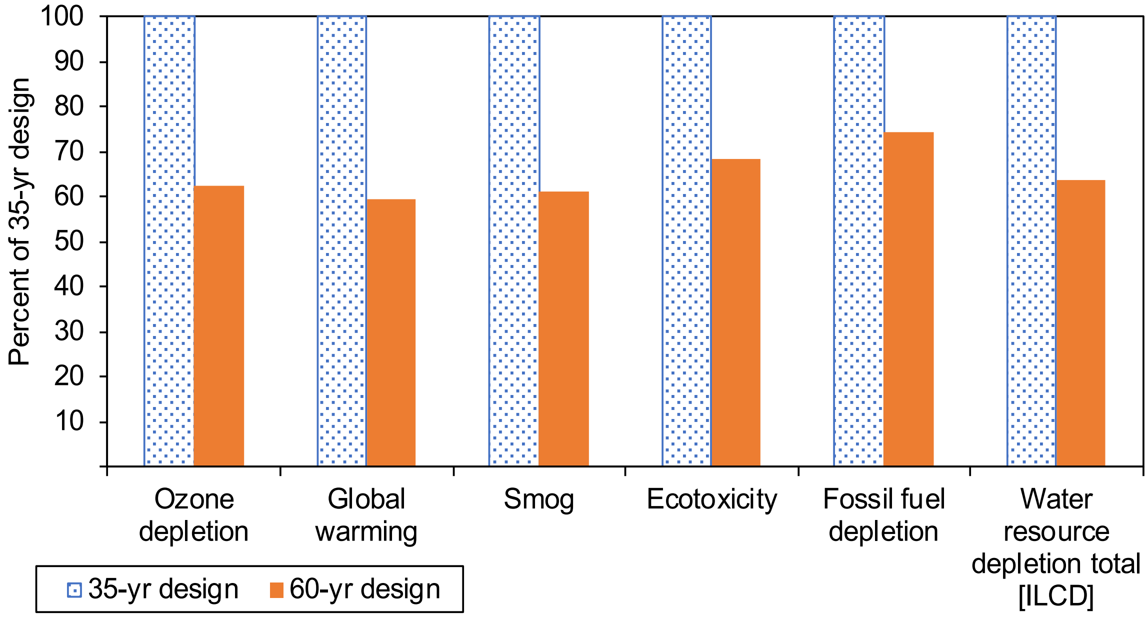

Figure 5. Annualized LCA results conducted as part of this case study.

WHAT WERE THE KEY OUTCOMES AND LESSONS LEARNED?

MnDOT has carried out a multi-year program to develop the HPCP approach featuring a performance-based concrete specification, improved design elements, and enhanced construction quality control and assurance. As a result, MnDOT is realizing the benefits of these long-life concrete pavements. More than a dozen HPCP projects have been constructed in Minnesota with excellent performance. For the I-94 case example highlighted, the following represent key outcomes identified by MnDOT:

- After 14 years of service, the I-94 HPCP has performed extremely well with minimal-to-no distresses present. The MnDOT surface rating value has remained unchanged and IRI remained around 80 inches/mi since the time of construction. This is considered a success.
- MnDOT believes that the modest 5 percent increase in initial construction cost will nearly double the service life of their concrete pavements from 35 years to 60 years. To date, pavement performance data supports this belief. As a result, MnDOT has adopted the use of HPCP as standard practice for high-volume urban highways.
- MnDOT's implementation of HPCP occurred incrementally after recognizing early failures of their traditional concrete pavements were costly and unacceptable. Today's specifications are a result of years of study and have resulted in significant improvement in concrete pavement performance and enhanced overall sustainability.

In addition to the above findings, the limited LCA performed for this case study served to quantify the environmental benefits achieved by switching to HPCP. The results indicated that HPCP designs provided significant environmental benefits across all environmental indicators compared to MnDOT's previous standard practices for the design and construction of concrete pavements.

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