CONCRETE PAVEMENT WITH OPTIMIZED AGGREGATE GRADATION, COAL ASH, AND SLAG CEMENT IN ILLINOIS

AUTHORS

Sarah Lopez, NCE

Nicole Dufalla, NCE

CONTRIBUTOR

Thomas Van Dam, Wiss, Janney, Elstner Associates, Inc.

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National Concrete Pavement Technology Center
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
cptechcenter.org

Peter Taylor, Director
515-294-3230 / ptaylor@iastate.edu

National Concrete Pavement Technology Center

IOWA STATE UNIVERSITY
Institute for Transportation

Introduction

The Jane Addams Memorial Tollway (I-90) is a heavily traveled, 76 mi Interstate located between Chicago, Illinois, and a northerly point near the Illinois-Wisconsin border, where it feeds into the Wisconsin portion of I-90 leading to Madison, Wisconsin. In 2013, the Illinois State Toll and Highway Authority (Illinois Tollway) embarked on a $2.5 billion project to rebuild and widen 62 mi of I-90 between Chicago and Rockford, Illinois. This project was part of a 16-year, $15 billion capital program to maintain the Illinois Tollway's existing system as well as construct new projects to increase capacity, reduce delays, and strengthen economic activity. From 2015 to 2016, a 24.5 mi portion of the eastern segment of I-90 from the Elgin Toll Plaza to the Tri-State Tollway (I-294) in Chicago was widened and reconstructed using reduced-carbon concrete mixtures (Illinois Tollway 2016). The location of the project is shown in Figure 1.

The following carbon reduction strategies were used in the concrete mixtures:

1. An optimized aggregate gradation was used in the concrete paving mixtures, which allowed for a reduced cementitious materials content while maintaining workability.
2. Coal ash and slag cement were used as supplementary cementitious materials (SCMs) in various percentages in the concrete paving mixtures.

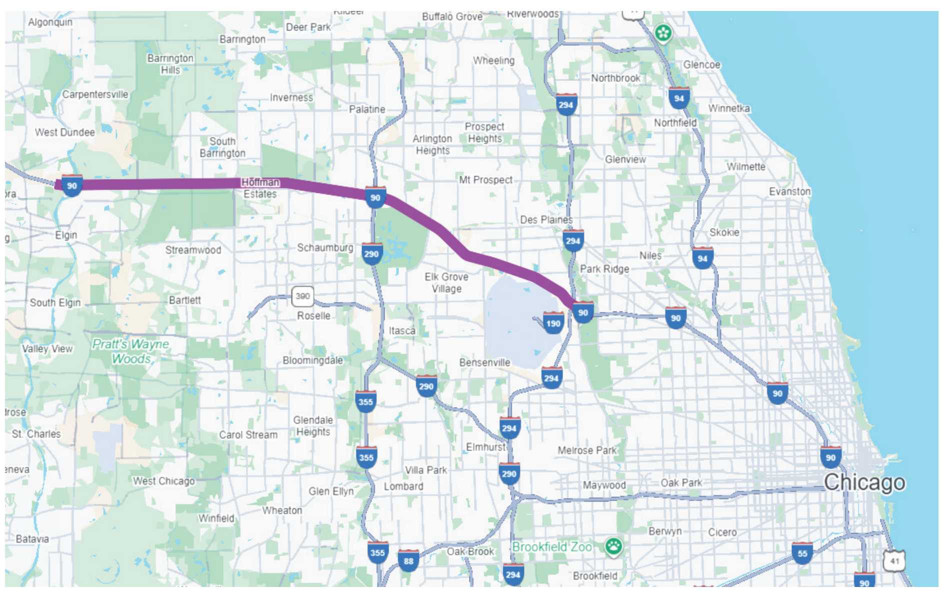


Figure 1. Project location

Pavement Design, Materials, and Construction

Structural Design

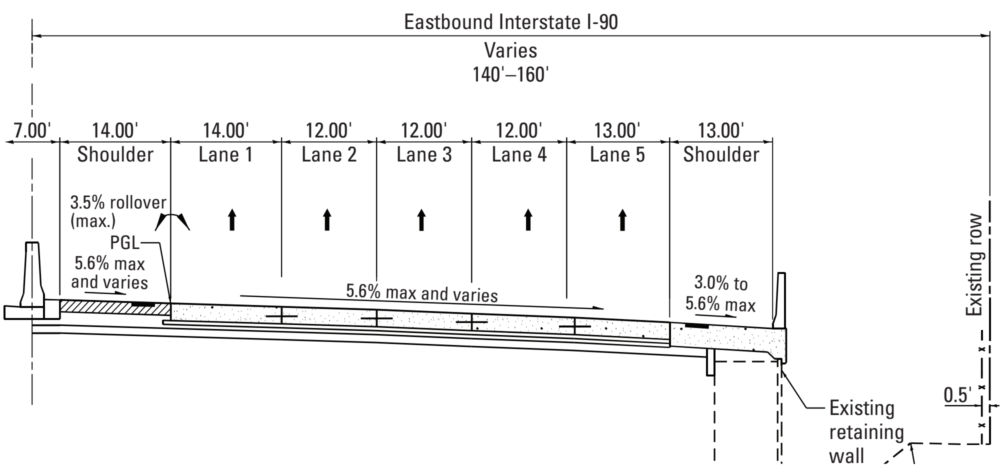
The mainline sections used a typical pavement cross section consisting of 13 in. of portland cement concrete over 3 in. of warm-mix asphalt stabilized subbase over 9 in. of aggregate subgrade. The project included a widened 14 ft inside shoulder to support bus traffic (when needed), a 14 ft inside lane, three 12 ft lanes, a 13 ft outside lane, and a 13 ft outside shoulder (Figure 2).

Paving Materials

Three concrete paving mixtures with optimized aggregate gradations and high replacement percentages of portland cement with SCMs (coal ash and slag cement) were used for the majority of the project. The intent of the optimized aggregate gradations was to allow for lower total cementitious materials contents (i.e., paste contents) while maintaining the workability of the mixtures. The contents of the three mixtures were as follows, with a conventional paving mixture used in 2015 included for comparison:

- I-90 Mixture (35% Cement Replacement): 535 lb/yd³ total cementitious content (15% coal ash, 20% slag), produced at the Ozinga McHenry plant
- I-90 Mixture (39% Cement Replacement): 555 lb/yd³ total cementitious content (27% coal ash, 12% slag), produced at the Prairie Material East Dundee plant
- I-90 Mixture (40% Cement Replacement): 500 lb/yd³ total cementitious content (20% coal ash, 20% slag), produced at the Terrell Route 53 Infield plant
- Conventional Concrete Paving Mixture (25% Cement Replacement): 580 lb/yd³ total cementitious content (25% coal ash)

Table 1 provides additional information on the concrete mixtures.



Illinois Tollway, used with permission

Figure 2. Example cross section of eastbound I-90

Table 1. Mixture proportions for three paving mixtures used on I-90 and a conventional paving mixture used in 2015

Mixture Constituent	I-90 Mix (35% Cement Replacement), per yd³	I-90 Mix (39% Cement Replacement), per yd³	I-90 Mix (40% Cement Replacement), per yd³	Conventional Mix (25% Cement Replacement)
ASTM C150 Type I/II Portland Cement	345 lb	340 lb	303 lb	435 lb
ASTM C618 Class C Coal Ash	80 lb	150 lb	—	145 lb
ASTM C618 Class F Coal Ash	—	—	98 lb	—
ASTM C989 Slag Cement	110 lb	65 lb	99 lb	—
CM 16 Coarse Aggregate	435 lb	350 lb	428 lb	1,807 lb
CM 11 Coarse Aggregate	1,440 lb	1,450 lb	1,650 lb	
FM 2 Fine Aggregate	1,335 lb	1,374 lb	1,186 lb	1,259 lb
Water	230 lb	230 lb	208 lb	242 lb
Water-to-Cementitious Materials (w/cm) Ratio	0.430	0.414	0.416	0.420
Air	6.5%	6.5%	6.5%	6.5%
ASTM C260 Air-Entraining Admixture	4.5 oz	7.3 oz	17 oz	As needed
ASTM C494 Water Reducer	18.7 oz	22.2 oz	20 oz	As needed
Retarder Admixture	10.7 oz	As needed	10 oz	As needed

All three I-90 paving mixtures utilized an optimized aggregate gradation (FHWA 2015), as shown in Figure 3, which was sufficiently dense to allow for lower total cementitious materials contents. The combined gradation for the conventional paving mixture was not available.

Construction

Paving for the 24.5 mi portion of I-90 began in 2015 and was completed in 2016. Photographs of the concrete placement are shown in Figure 4, and the finished roadway is shown in Figure 5.

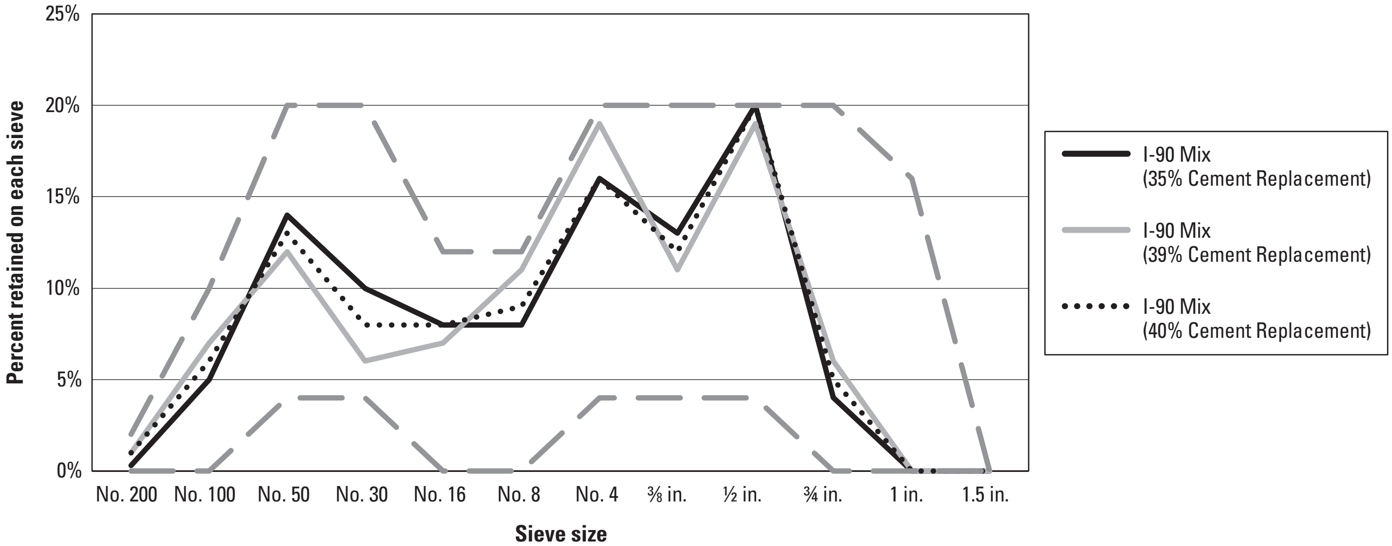


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Figure 3. Comparison of particle size distributions for the three I-90 concrete mixtures

Illinois Tollway, used with permission

Figure 4. Concrete placement on I-90 in 2015

Illinois Tollway, used with permission

Figure 5. Finished roadway in 2016

Trial batches of the three I-90 mixtures were made, and on-site quality control testing was conducted at the respective ready-mix concrete plants where the batches were produced. Compressive and flexural strength testing was performed, and the results are summarized in Table 2. The mixtures were designed to achieve a minimum interim compressive strength of 2,500 psi at 3 days, a minimum ultimate compressive strength of 3,500 psi at 14 days, and a minimum ultimate flexural strength of 650 psi at 14 days. All paving mixtures satisfied these requirements. Additionally, air void system analysis indicated that the trial batch mixtures contained sufficient and properly distributed entrained air.

Carbon Reduction Analysis

Using historical and estimated construction data, an analysis of the global warming potential (GWP) of the four case study mixtures was conducted based on the methodology outlined in the *Guide for Reducing the Cradle-to-Gate Embodied Carbon Emissions of Paving Concrete*, First Edition (AASHTO 2025). A concrete's GWP, in kg CO_2-eq/m^3 of concrete, can be estimated utilizing information from the concrete mix design supplemented with information from environmental product declarations (EPDs).

To estimate GWP for a given mixture, the mixture proportions (in metric tons per cubic meter of typical concrete) are multiplied by the production efficiency (in kg CO_2-eq/metric ton), and the sum of these products represents the mixture's GWP (in kg CO_2-eq/m^3). The four concrete mixtures were evaluated using this methodology, and the resulting calculations are shown in Table 3.

All three I-90 mixtures had lower approximated GWP values than the conventional paving mixture, ranging from 16% lower (I-90 mixture with 35% cement replacement) to 26% lower (I-90 mixture with 40% cement replacement). This is a notable difference in approximated GWP, and it was achieved using mixture optimization techniques and increased replacement of portland cement with SCMs.

Table 2. Concrete test results

Test	Testing Age, Days	I-90 Mix (35% Cement Replacement)	I-90 Mix (39% Cement Replacement)	I-90 Mix (40% Cement Replacement)
Compressive Strength (psi)	3	4,060	3,350	3,470
	7	5,160	5,280	4,435
	14	6,220	6,570	—
	28	—	7,960	—
Flexural Strength (psi)	14	885	—	—
	28	—	1,218	—

Table 3. Concrete mixture GWP approximations based on mix designs

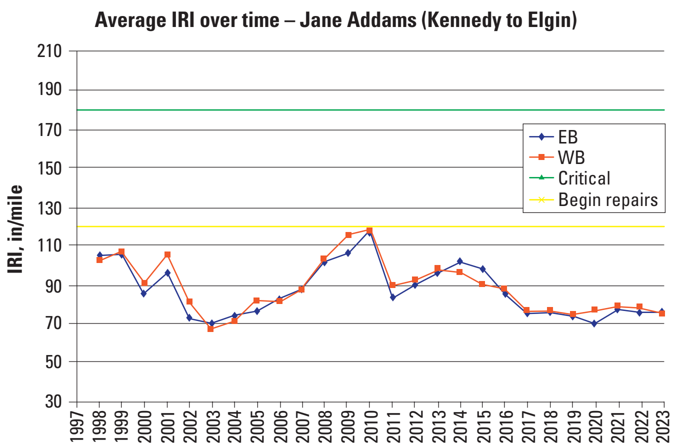
Mixture Constituent	Production Efficiency (kg CO_2-eq/m^3)[1]	I-90 Mix (35% Cement Replacement)		I-90 Mix (39% Cement Replacement)		I-90 Mix (40% Cement Replacement)		Conventional Mix (25% Cement Replacement)	
		Quantity (metric tons/m^3)	Estimated GWP (kg CO_2-eq/m^3	Quantity (metric tons/m^3)	Estimated GWP (kg CO_2-eq/m^3	Quantity (metric tons/m^3)	Estimated GWP (kg CO_2-eq/m^3	Quantity (metric tons/m^3)	Estimated GWP (kg CO_2-eq/m^3
ASTM C150 Cement	919	0.205	188.1	0.202	185.4	0.180	165.2	0.258	237.2
ASTM C618 Class C Coal Ash	50	0.0475	2.373	0.089	4.45	0.0581	2.907	0.0860	4.301
ASTM C618 Slag Cement	147	0.0653	9.593	0.0386	5.669	0.0587	8.634	—	—
ASTM C33 Coarse Aggregate	6.18	0.792	4.895	0.815	5.038	0.704	4.348	0.747	4.616
ASTM C33 Fine Aggregate	5.51	0.136	0.752	0.136	0.752	0.123	0.680	0.144	0.791
Water	0.22	1.112	0.245	1.068	0.235	1.233	0.271	1.072	0.236
Air-Entraining Admixture	439	0.000167	0.0733	0.000271	0.119	0.00063	0.277	—	—
Water-Reducing Admixture	1340	0.000694	0.930	0.000823	1.103	0.00074	0.994	—	—
Retarding Admixture	1530	0.000397	0.607	—	—	0.00037	0.567	—	—
Sum		**207.6**		**202.7**		**183.9**		**247.1**	

[1] *Values from AASHTO 2025*

Pavement Performance and Maintenance History

International Roughness Index (IRI) has been monitored on I-90 since 1998 (Figure 6). Since IRI data collection began, this portion of I-90 has wavered between “good” (less than 95 in./mi) and “fair” (between 95 and 170 in./mi). IRI peaked in 2010 with a value of 118 in./mi, followed by a maintenance overlay later that year. Following the 2015 widening and reconstruction project, IRI has remained at approximately 75 in./mi. As of 2021, the section had an estimated remaining service life of 57 years, with total reconstruction anticipated in 2078.

Condition rating survey (CRS) data have also been collected annually since 1998 (Figure 7). The data are reported on a scale of 1.0 to 9.0, where 1.0 represents a completely failed pavement and 9.0 represents a newly constructed pavement (IDOT 2022). CRS values are calculated based on surface type, identified distresses, distress severity levels, IRI, rutting, and faulting. Prior to the 2015 reconstruction and widening project, the CRS values on I-90 were approximately 6.3 in the eastbound direction and 6.4 westbound direction, placing the 24.5 mi section in the “good” category. From 2015 to 2021, the CRS values remained in the “excellent” category. Recently, the CRS values for the section have again been categorized as “good” due to localized joint deterioration and/or patching, as noted in the 2023 CRS survey.



Recreated from ARA 2023

Figure 6. Average IRI values from 1998 through 2023

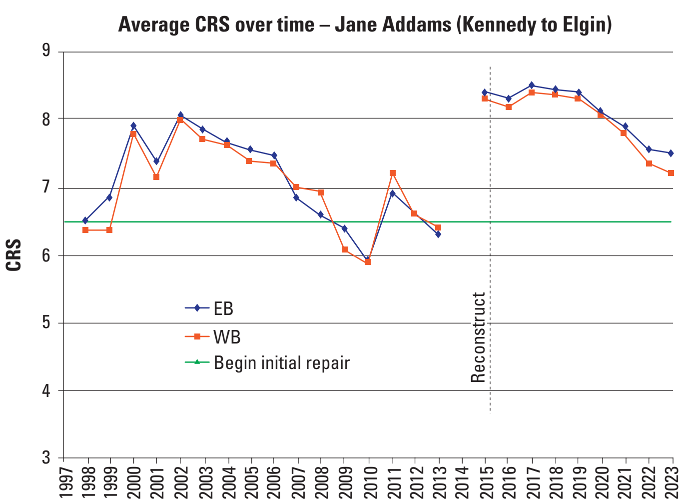


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Figure 7. CRS data from 1998 through 2023

Lessons Learned

The 24.5 mi segment of I-90 from Elgin to Chicago, Illinois, is an excellent example of a reduced-carbon concrete paving project. The concrete mixtures used on this project featured high replacement percentages of portland cement with SCMs (coal ash and slag cement) and optimized aggregate gradations that allowed for a reduction in total cementitious materials (i.e. paste) contents while maintaining workability. The lessons learned from a review of these reduced-carbon concrete mixtures include the following:

- **Low-carbon strategies effectively reduced the estimated greenhouse gas emissions of the concrete mixtures.** The low-carbon concrete mixtures were estimated to have approximate GWPs ranging from 184 kg CO_2-eq/m^3 to 207 kg CO_2-eq/m^3. These values are significantly lower than the estimated GWP of the sample conventional paving mixture, 247 kg CO_2-eq/m^3. As expected, the I-90 paving mixture featuring the lowest total cementitious materials content and the highest cement replacement had the lowest GWP of all the mixtures.
- **The low-carbon concrete paving mixtures met the required performance targets.** The low-carbon concrete mixtures were able to exceed the project strength requirements, and the air void system analysis indicated sufficient and properly distributed entrained air.
- **The low-carbon mixtures are performing well.** IRI results indicate that the 24.5 mi segment has remained in “good” condition since 2015. CRS results show that the segment was in “excellent” condition from 2015 to 2021 and has only recently (as of 2022) crossed into the “good” category.

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About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of developing and implementing innovative technology and best practices for sustainable concrete pavement construction and maintenance.