EVALUATION OF CRACKING PERFORMANCE OF BRIDGE DECKS WITH AND WITHOUT OVERLAYS AND WITH AND WITHOUT FIBERS

By
Sujan Dhungel
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David Darwin
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A Report on Research Sponsored by

CONSTRUCTION OF LOW-CRACKING HIGH-PERFORMANCE BRIDGE DECKS INCORPORATING NEW TECHNOLOGY
TRANSPORTATION POOLED-FUND PROGRAM
PROJECT NO. TPF-5(392)

Structural Engineering and Engineering Materials
SL Report 23-1
November 2023
Final Submittal May 2024

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

Ninety-three spans on 19 bridges, constructed between 2013 and 2020, were surveyed for cracks. The decks were constructed on either steel or prestressed concrete girders. The spans were constructed with or without overlays, some of which used silica fume as a partial replacement for portland cement, with or without nonmetallic fibers, or with monolithic decks with or without nonmetallic fibers. Of the six bridges with conventional overlays (without silica fume), four contained fibers. All nine of the bridges with silica fume overlays had fibers. Of the four monolithic decks, two had spans with fibers, one did not have fibers, and one had two surveyed units (each with three spans) with fibers and four surveyed units without fibers. The bridge superstructures had from two to seven spans with lengths ranging from 147 to 808 ft (44.9 to 246. m), and roadways with widths ranging from 32 to 70.5 ft (9.8 to 21.5 m). The surveys revealed that decks with concrete overlays crack more than monolithic decks for decks on both steel and prestressed concrete superstructures. Decks with cement paste contents less than 27% of the concrete volume cracked less than decks with a higher volumes of cement paste. More generally, good construction practices are needed for low-cracking decks, and with poor construction practices, even decks with a low paste content, with or without fibers, can exhibit high cracking.

Key words: bridge decks, concrete, construction procedures, cracking, crack density, fibers, reinforced concrete, nonmetallic fibers, paste content, overlays, silica fume

ACKNOWLEDGEMENTS

Funding for this research was provided by the Minnesota Department of Transportation and Kansas Department of Transportation, the latter serving as the lead agency for the "Construction of Low-Cracking High-Performance Bridge Decks Incorporating New Technology" Transportation Pooled Fund Study, Project No. TPF-5(392). On-site support and data on the bridge decks were provided by the Minnesota Department of Transportation.

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CHAPTER 1: INTRODUCTION

1.1 GENERAL

In the United States, bridges serve a major role in the nation's infrastructure. While the number of bridges keeps increasing; with 617,000 bridges in the National Bridge Inventory (NBI) as of 2021, 7.5% of the bridges have been categorized as structurally deficient and in need of replacement or rehabilitation (ASCE 2021).

Cracking in concrete bridge decks accelerates deterioration by allowing oxygen, water, and deicing chemicals to penetrate the deck more easily. Over the past sixty years, transportation agencies and researchers have attempted to minimize cracking in concrete bridge decks by employing crack-reducing technologies. The use of concrete overlays, described as "overlays" in this report, on bridge decks has been popular because the high-density concrete used in the overlays has a lower chloride permeability than conventional concrete (Schmitt and Darwin 1995), although the effects of using the overlays has resulted in higher crack densities than exhibited by monolithic decks (Lindquist et al. 2005). The use of fibers has also been one of the methods used by state departments of transportation (DOTs) as a crack-reducing technology, although results show that it can only slightly alleviate cracking (Feng and Darwin 2020, Bahadori et al. 2022) and is, at times, used to improve durability, ride quality, and as a preservation tool. In this study, the effectiveness of different technologies, such as conventional overlays, silica fume overlays, and monolithic decks, with and without fibers, are studied, based on crack surveys of 19 bridge decks constructed between 2013 and 2020. The crack survey method used is described first, followed by information on the decks in this study. The survey results, presented in Chapter 3, are converted to equivalent crack densities at 36 months of age to provide a fair comparison between decks. The results are discussed in Chapter 6. The summary and conclusions are presented in Chapter 7.

1.2 CRACK SURVEY METHOD

The crack surveys were performed using a standardized procedure, described next and in Appendix A.

1.2.1 Crack Survey Procedure

Crack surveys are conducted on a day with a minimum air temperature of 60 °F (16 °C), with weather that is mostly sunny. Crack surveys are only conducted when the bridge deck surface is completely dry. Crack survey results obtained under conditions that do not meet these requirements are invalid.

A plan view of the deck for drawing the crack map, with a scale of 1 in. = 10 ft (25.4 mm = 3.1 m) and a 10 × 10 ft (3.1 × 3.1 m) grid, is prepared before conducting the cracking survey. To establish the scaled length and location of the cracks, a 5 ft × 5 ft (1.5 m × 1.5 m) grid with a scale of 1 in. = 10 ft (25.4 mm = 3.1 m) is printed separately and is placed underneath the crack map. The grid should be aligned so that the grid points spaced at 5 ft × 5 ft (1.5 m × 1.5 m) match the grid lines on the crack map. The crack map also indicates the north compass direction to further assist the crack survey crews.

State department of transportation (DOT) crews provide traffic control by closing at least one lane to traffic. The surveyors start marking the grids on the deck using sidewalk chalk in 40-ft (12.1-m) increments in the longitudinal and 5-ft (1.5 m) increments in the transverse directions corresponding with the scaled crack map. The surveyors mark cracks with sidewalk chalk that are visible when bending at the waist to waist height as they walk over the deck. Once a crack is observed, surveyors are allowed to bend closer to the deck to complete marking the crack. Once a crack is marked, surveyors must resume identifying cracks that are only visible from waist height. Each portion of the deck is surveyed by at least two surveyors. The cracks marked on the bridge deck are transferred to the crack map, using the 5 ft × 5 ft (1.5 m × 1.5 m) grid map. The hand-drawn map is used to calculate the crack density of the bridge deck.

To calculate crack density, the hand-drawn map is scanned and converted into an AutoCAD file, and the crack lengths are measured using the built-in AutoCAD command, Data Extraction. The output is an Excel file in a CAD output folder showing the measured crack lengths of the individual cracks (in AutoCAD units). The summation of these measurements is the total crack length in AutoCAD units. Two scaling factors are defined to convert the AutoCAD unit measurements. One scaling factor is defined as the ratio between the actual bridge length and the length of the bridge drawn in AutoCAD (measured after scanning the hand-drawn crack map into AutoCAD). Similarly, the second scaling factor is defined as the ratio between the actual bridge width and the width of the bridge in AutoCAD. The average of these two scaling factors is used for the calculations. The actual crack lengths are obtained by multiplying the crack lengths in AutoCAD units by the average scaling factor. The crack density is calculated by dividing the crack length by the deck area and reported in m/m^2.

1.2.2 Crack Width

A number of randomly selected cracks from the bridge deck are measured for crack width. Cracks are selected so as to be representative based on length (short or long), orientation (transverse, parallel, or diagonal to traffic), and shape (straight or nonlinear). The width of cracks generally increases along with crack density. The widest point of the crack is measured as the crack width. A bank card-sized crack width comparator, with an accuracy of 0.001 in. (0.025 mm), is used for the measurements.

1.2.3 Student's t-test

Student's t-test is used to determine if the difference between the means of two small data sets, X_1 and X_2, drawn from two normally distributed populations, with unknown means and standard deviations, is due to random variation or represents an actual difference in the populations. The means of two samples are often compared on the basis of the *p*-value, which indicates the probability that the difference between two means is due to chance at a preselected significance level α when, in fact, they are the same. Thus, the smaller the value of p, the lower the probability that the observed difference is due to chance. A value of p less than a significance level of 0.05, for example, indicates that the probability that the test mistakenly identified the two population means as different is 5% when, in fact, they are not. A *p*-value greater than the significance level, in this case 0.05, would indicate that the difference between two means is likely to have been due to chance. Values of $p \leq 0.05$ are usually taken as indicating that the difference between two means is statistically significant.

CHAPTER 2: MINNESOTA BRIDGE DECKS

This section provides information regarding the bridge decks surveyed in this study, including location, type, mixture proportions, fiber properties, and crack maps.

2.1 BRIDGE DECK INFORMATION

The Minnesota Department of Transportation (MnDOT) identified 93 spans on 19 bridge decks, listed in Table 2.1, with either conventional or silica fume overlays, with and without nonmetallic fibers and monolithic decks with and without nonmetallic fibers constructed between 2013 and 2020 to be surveyed. A conventional overlay in Minnesota consists of a low-slump dense concrete wearing course produced by a mobile mixer and placed with a twin screed exerting compaction pressure and vibration. Of the decks with conventional overlays (without silica fume), four contained fibers. All decks with overlays containing silica fume had fibers. Of the four monolithic decks, two had spans with fibers, one did not have fibers, and one had two surveyed units (each with three spans) with fibers and four surveyed units without fibers. Of the four monolithic decks, two contained fibers, one did not have fibers, and one had two surveyed units (each with three spans) with fibers and four surveyed units without fibers. The bridge decks in this study are supported by steel girders, precast concrete girders, or a post-tensioned slab.

Table 2.2 summarizes the geometry of the bridge decks. The number of spans ranges from two to seven. The lengths of the bridges range from 147.4 to 807.6 ft (44.9 to 246.1 m), and the roadway widths range from 32 to 70.5 ft (9.8 to 21.5 m). For the decks constructed in multiple placements, the order of the placement is not available, except for bridge 27133. Cracking performance of each deck is expressed in terms of crack density in m/m^2.

Table 2.1: Bridge Deck Information

Bridge Number	Location	County	Girder Type	Technology	Date of Construction
7263	France Ave. over T.H. 62	Hennepin	Steel	Monolithic-Fibers	5/29/2019
7268	Penn Ave. (C.S.A.H. 32) over T.H. 62	Hennepin	Steel	Monolithic-No Fibers	9/10/2013
9071	C.S.A.H. 19 over US 61	Washington	Steel	Conventional Overlay-No Fibers	8/2/2017, 8/7/2017
9689	I-90 WB over BNNR RR: C.S.A.H. 4	Rock	Prestressed	Silica fume Overlay-Fibers	8/11/2017, 8/17/2017
10004	TH 101 over Minnesota River- Unit 4	Carver	Prestressed	Monolithic-No Fibers	10/7/2015
	TH 101 over Minnesota River- Unit 5		Prestressed	Monolithic-Fibers	10/8/2015
	TH 101 over Minnesota River- Unit 7		Prestressed	Monolithic-No Fibers	8/21/2015
	TH 101 over Minnesota River- Unit 8		Prestressed	Monolithic-No Fibers	8/28/2015
	TH 101 over Minnesota River- Unit 9		Prestressed	Monolithic-Fibers	9/3/2015, 9/4/2015
	TH 101 over Minnesota River- Unit 10		Prestressed	Monolithic-No Fibers	9/11/2015
19004	US 61 over Mississippi River - North Bound	Dakota	Post-Tensioned Slab	Conventional Overlay-No Fibers	8/1/2013[a]
	US 61 over Mississippi River - South Bound				
22801	C.S.A.H. 1 over I-90	Faribault	Steel	Silica fume Overlay-Fibers	5/8/2020
22802	C.S.A.H. 5 over I-90	Faribault	Steel	Silica fume Overlay-Fibers	7/27/2019
27133	CENTRAL Ave over US 12	Hennepin	Steel	Monolithic-Fibers	9/24/2019, 10/8/2019
46824	C.S.A.H. 59 over I-90	Martin	Prestressed	Silica fume Overlay-Fibers	7/24/2019
46831	TWP 40 over I-90	Martin	Prestressed	Silica fume Overlay - Fibers	7/26/2019
46835	I-90 WB over Center Creek	Martin	Prestressed	Silica fume Overlay-Fibers	7/25/2019
46836	I-90 EB over Center Creek	Martin	Prestressed	Silica fume Overlay-Fibers	6/11/2020

[a]Only the year of construction is known. 1st of August assumed as the construction date because August is the middle of the construction season in Minnesota

[b] Considering the date of mixture design approval since the date of construction is not available

Table 2.1 (Con't): Bridge Deck Information

Bridge Number	Location	County	Girder Type	Technology	Date of Construction
62038	C.S.A.H. 15 over T.H. 51	Ramsey	Prestressed	Monolithic-No Fibers	6/2/2015[b]
62652	Summit Ave over AYD Mill RD	Ramsey	Prestressed	Silica fume Overlay-Fibers	8/20/2020, 8/21/2020
62924	I-35E NB over BNSF RR	Ramsey	Steel	Conventional Overlay-No Fibers	6/3/2015, 6/8/2015, 6/11/2015, 6/16/2015, 6/18/2015
62925	I-35E SB over BNSF RR	Ramsey	Steel	Conventional Overlay-No Fibers	8/25/2015[b]
83026	T.H. 4 over MN 60	Wantonwan	Prestressed	Conventional Overlay-No Fibers	5/2/2019, 5/3/2019, 5/6/2019
83027	C.S.A.H. 12 over MN 60	Wantonwan	Prestressed	Conventional Overlay- No Fibers	8/3/2018, 8/6/2018

[a]Only the year of construction is known. 1st of August assumed as the construction date because August is the middle of the construction season in Minnesota

[b] Date of mixture design approval; date of construction is not available

Table 2.2: Bridge Geometry

Bridge No.	No. of Spans	Skew	Length		Roadway Width	
			ft	m	ft	m
7263	4	-9º20'53"	188.6	57.6	70.5	21.5
7268	2	0º0'0"	148.0	45.0	48.0	14.6
9071	4	0º0'0"	178.0	54.2	35.0	10.4
9689	5	52º28'45"	378.8	118.2	39.4	12.0
10004	3	0º0'0"	315.2	96.0	64.0	19.5
	3	0º0'0"	315.2	96.0	64.0	19.5
	3	0º0'0"	315.2	96.0	64.0	19.5
	3	0º0'0"	315.2	96.0	64.0	19.5
	3	0º0'0"	315.2	96.0	64.0	19.5
	3	0º0'0"	315.2	96.0	64.0	19.5
19004-NB	5	Various[a]	551.9	168.2	33.3	10.1
19004-SB	5	Various[b]	552.2	168.3	36.5	11.1
22801	4	0º0'0"	300.6	91.6	46.5	14.2
22802	4	0º0'0"	298.0	91.0	32.0	9.8
27133	3	7º40'54"	278.8	84.9	60.0	18.3
46824	4	0º0'0"	299.6	91.4	32.0	9.8
46831	4	0º0'0"	299.2	91.2	36.0	10.9
46835	3	29º27'54"	147.4	44.9	40.5	12.3
46836	3	28º53'03"	147.4	44.9	40.5	12.3
62038	2	0º0'0"	181.8	55.4	48.0	14.6
62652	2	-21º25'12"	216.5	65.9	54.0	16.5
62924	6	Various[c]	703.6	214.4	Various[d]	Various[d]
62925	7	Various[e]	807.6	246.1	Various[f]	Various[f]
83026	4	-23º11'35"	305.7	93.2	68.5	20.9
83027	4	55º22'39"	356.0	108.4	70.5	21.5

[a] 0°3’16” to 12°45’42”; [b] 0°3’16” to 12°45’42”; [c] -7°22’11” to 54°40’2.5”; [d] 89’7½” to 139’4⅝” (27.3 m to 42.5 m)
[e] -7°22’11” to 46°38’9”; [f] 90’3” to 120’0½” (27.5 m to 36.6 m)

2.2 CONCRETE MIXTURE PROPORTIONS

The mixture proportions for the decks are presented in Tables 2.3, 2.4, and 2.5. Table 2.3 presents the mixture proportions of the subdecks with conventional overlays and of the conventional overlays. All of the decks with conventional overlays had a 2-in. overlay with the mixture proportions shown in Table 2.3. Table 2.4 presents the mixture proportions of the overlays of the decks with silica fume overlays only; the mixture proportions of the subdecks were not available. Table 2.5 presents the mixture proportions of the monolithic decks.

The total weight of the cementitious materials was 836 lb/yd^3 for the conventional overlay and ranged from 573 to 743 lb/yd^3 for conventional overlay subdecks, 595 to 650 lb/yd^3 for silica fume overlays, and 540 to 600 lb/yd^3 for monolithic decks. The water-to-cementitious material (*w/cm*) ratio of overlays ranged from 0.32 to 0.43 and for the monolithic decks and the conventional overlay subdeck, the *w/cm* ratio ranged from 0.35 to 0.43. The *w/cm* ratio of the subdecks with a silica fume overlay is not known. The paste content (volume fraction of cementitious materials and mixing water) was 31.8% for the conventional overlay, and ranged from 25.9 to 30.4 % for the conventional overlay subdecks, from 26.9 to 29.9 % for the silica fume overlays, and from 22.7 to 27.1% for the monolithic decks. The mixture proportions of subdecks of bridge 9071, 83026, and 83027 were not provided by MnDOT.

Table 2.3: Design Mix Proportions of
Subdecks with Conventional Overlays and Conventional Overlay

Bridge No.	Cementitious Material Content (lb/yd^3)	Water Content (lb/yd^3)	*w/cm* Ratio	Paste Content (%)	Cementitious Material Percentage[b]	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Fiber dosage (lb/yd^3)
9071	-[a]	-[a]	-[a]	-[a]	-[a]	-[a]	-[a]	0
62924	573	241	0.42	25.9	71%C 29%FA-C	1687	521/859[c]	0
19004-NB	743	260	0.35	30.4	77%C 20%FA-C 4%SF	1650	1205	0
19004-SB	743	260	0.35	30.4	77%C 20%FA-C 4%SF	1650	1205	0
62038	581	250	0.43	26.4	70%C 15%FA-F 15%S	1726	1302	0
83026	-[a]	-[a]	-[a]	-[a]	-[a]	-[a]	-[a]	0
83027	-[a]	-[a]	-[a]	-[a]	-[a]	-[a]	-[a]	0
62925	573	241	0.42	25.9	71%C 29%FA-C	1687	521/859[c]	5 [e]
2-in. Conventional Overlay	836	270	0.32	31.8	100% C	Variable	1415	0

[a] Data is not available
[b] Percentages by total weight of cementitious material; C = portland cement;
S = Grade 100 slag cement; FA-F = Class F fly ash; FA-C = Class C fly ash;
SF = Silica Fume
[c] Two types of aggregates
[d] Actual dosage not available. Based on the best-recommended dosage; Note: 1 lb/yd^3 = 0.593 kg/m^3
[e] Fibers in Subdeck

Table 2.4: Design Mix Proportions of Silica Fume Overlays[a]

Bridge No.	Cementitious Material Content (lb/yd^3)	Water Content (lb/yd^3)	*w/cm* Ratio	Paste Content (%)	Cementitious Material Percentage[b]	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Fiber dosage (lb/yd^3)
22801	600	252	0.42	26.9	75%C 20%FA-C 5%SF	1617	1346	3
22802	600	252	0.42	26.9	75%C 20%FA-C 5%SF	1617	1346	3
46824	600	252	0.42	26.9	75%C 20%FA-C 5%SF	1617	1346	3
46831	600	252	0.42	26.9	75%C 20%FA-C 5%SF	1617	1346	3
46835	600	252	0.42	26.9	75%C 20%FA-C 5%SF	1617	1346	3
46836	600	252	0.42	26.9	75%C 20%FA-C 5%SF	1617	1346	3
62652	615	258	0.42	28.0	66%C 30%FA-F 4%SF	1473	881/585[c]	3
9689	650	279	0.43	29.9	70%C 25%FA-F 5%SF	1727	1091	3

[a] Proportions for subdeck are not known

[b] Percentages by total weight of cementitious material; C = portland cement; S = Grade 100 slag cement; FA-F = Class F fly ash; FA-C = Class C fly ash; SF = Silica Fume

[c] Two types of aggregates

Note: 1 lb/yd^3 = 0.593 kg/m^3

Table 2.5: Design Mix Proportions of Monolithic Decks

Bridge No.	Cementitious Material Content (lb/yd^3)	Water Content (lb/yd^3)	*w/cm* Ratio	Paste Content (%)	Cementitious Material Percentage[a]	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Fiber dosage (lb/yd^3)
7268	540	205	0.38	22.7	70%C 10%FA-C 20%S	1680	1200/310	0
10004-U4	570	228	0.40	24.8	72%C 14%FA-C 14%S	1670	1114/309	0
10004-U7	570	228	0.40	24.8	72%C 14%FA-C 14%S	1670	1114/311	0
10004-U8	570	228	0.40	24.8	72%C 14%FA-C 14%S	1670	1114/312	0
10004-U10	570	228	0.40	24.8	72%C 14%FA-C 14%S	1234/464	1083/309	0
7263	600	252	0.42	27.1	70%C 30%FA-F	1731	1249	5
27133	575	241	0.42	26.0	75%C 20%FA-C 5%SF	1775	1271	4
10004-U5	570	228	0.40	24.8	72%C 14%FA-C 14%S	1670	1114/310[b]	2.5[c]
10004-U9	570	228	0.40	24.8	72%C 14%FA-C 14%S	1670	1114/313[b]	2.5[c]

[a] Percentages by total weight of cementitious material; C = portland cement; S = Grade 100 slag cement; FA-F = Class F fly ash; FA-C = Class C fly ash; SF = Silica Fume
[b] Two types of aggregates
[c] Actual dosage not available. Based on the best-recommended dosage; Note: 1 lb/yd^3 = 0.593 kg/m^3

Table 2.6 lists the type of fibers used in some of the bridge decks in this study. All the decks with fibers had macro fibers. The length of the fibers ranged from 1.5 to 2.1-in. (38.1 to 53.3-mm) and the specific gravity of the fibers was 0.91.

Table 2.6: Properties of fiber reinforcement

Bridge No.	Dosage (lb/yd^3)	Type	Length (in.)	Specific Gravity	Material
7263	5	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
9689	3	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
10004-U5	Fibers	MasterFiber MAC 2200 CB/Macro	2.1	0.91	Polymer Resin
10004-U9	Fibers	MasterFiber MAC 2200 CB/Macro	2.1	0.91	Polymer Resin
22801	3	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
22802	3	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
27133	4	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
46824	3	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
46831	3	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
46835	3	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
46836	3	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
62652	3	Forta Ferro/Macro	1.5	0.91	Virgin Copolymer/Polypropylene
62925*	4	Propex Novomesh 950/Macro	2	0.91	Polypropylene/Polyethylene

Note: 1-in. = 25.4-mm.
*Fibers in post-tensioned slab

2.3 CONCRETE PROPERTIES

The properties of the concrete were not provided by MnDOT.

CHAPTER 3: CRACK SURVEY RESULTS

The cracking performance of the 19 bridge decks surveyed in this study is described in this chapter.

3.1 BRIDGE 7263 (MONOLITHIC WITH FIBERS)

Bridge 7263 has a monolithic deck incorporating fibers constructed in one placement on May 29, 2019. The bridge carries two-way traffic on France Ave. over T.H. 62 in Hennepin, Minnesota. The concrete supplier and the contractor were Aggregate Industries and Kraemer North America, respectively. The bridge has four spans with lengths of 36 ft-11 ⅞ in. (11.3 m), 57 ft-4 in. (17.5 m), 57 ft-4 in. (17.5 m), and 36 ft-11 ⅞ in. (11.3 m), with a total length of 188 ft-7 ¾ in. (57.6 m). The deck has a 70 ft-6 in. (21.5 m) wide roadway, a 1 ft-3 in. (380 mm) wide barrier, and a 10 ft (3.0 m) sidewalk on each side, for a total deck width of 92 ft (28.0 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by steel girders with a skew of -9º 20’53”. The crack survey was performed at a deck age of 26.6 months, and the deck had a crack density of 0.144 m/m^2. The crack map is shown in Figure 3.1.

Only 46.5 ft (14.2 m) of the east half of the deck width was surveyed. Short cracks of length less than 1 ft (305 mm), possibly caused by plastic shrinkage, were distributed throughout the deck and constituted 46% of the total crack length. The longer cracks were mostly transverse, except for some longitudinal cracks near the abutment. The use of fibers did not seem effective in limiting crack formation, as shown in Figure 3.2. Span 2 exhibited the highest crack density of 0.204 m/m^2, and span 4 exhibited the lowest crack density of 0.074 m/m^2. Although only 46.5 ft (14.2 m) of the deck width was surveyed, the rest of the deck, which was not surveyed, was observed to have similar cracking. Crack widths ranged from 0.003 in (0.076 mm) to 0.030 in. (0.762 mm), with an average of 0.012 in. (0.305 mm).

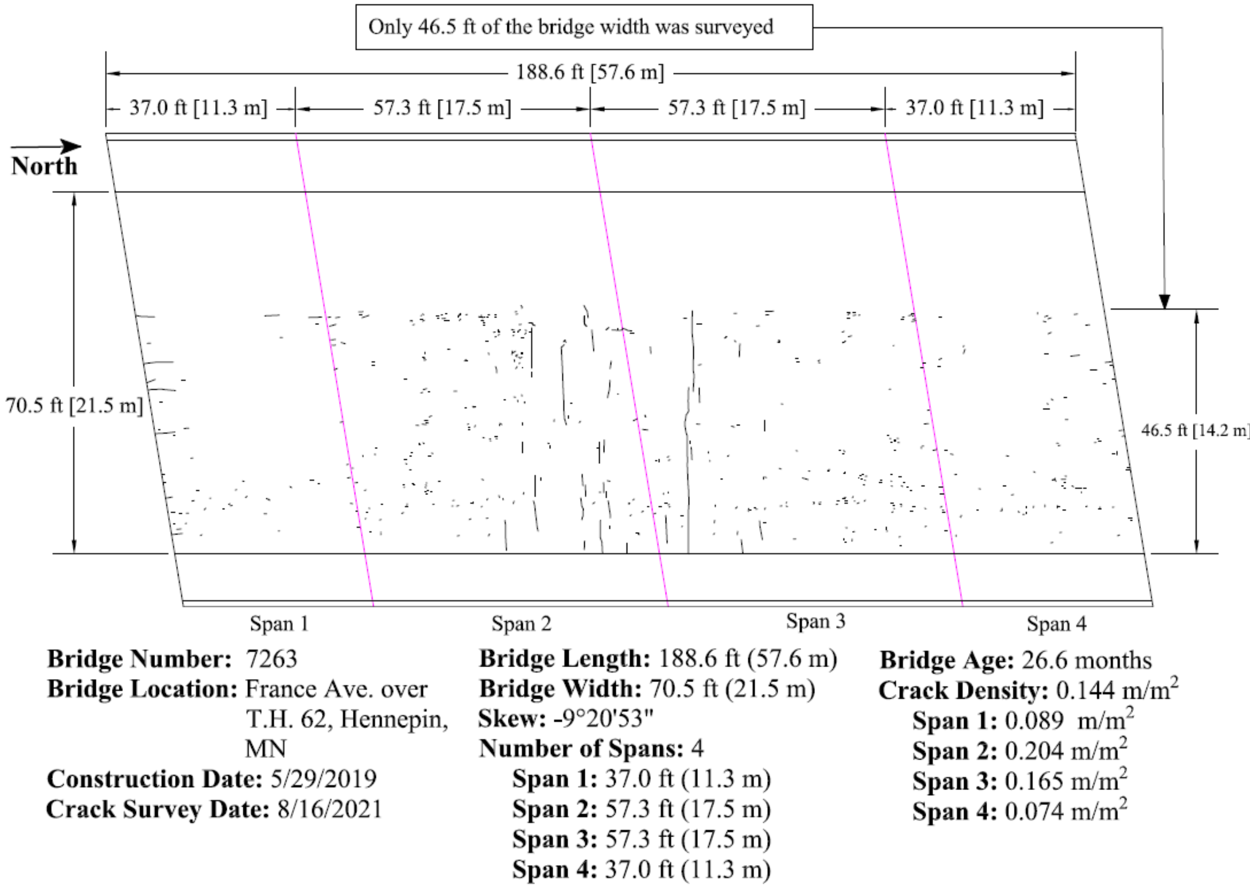


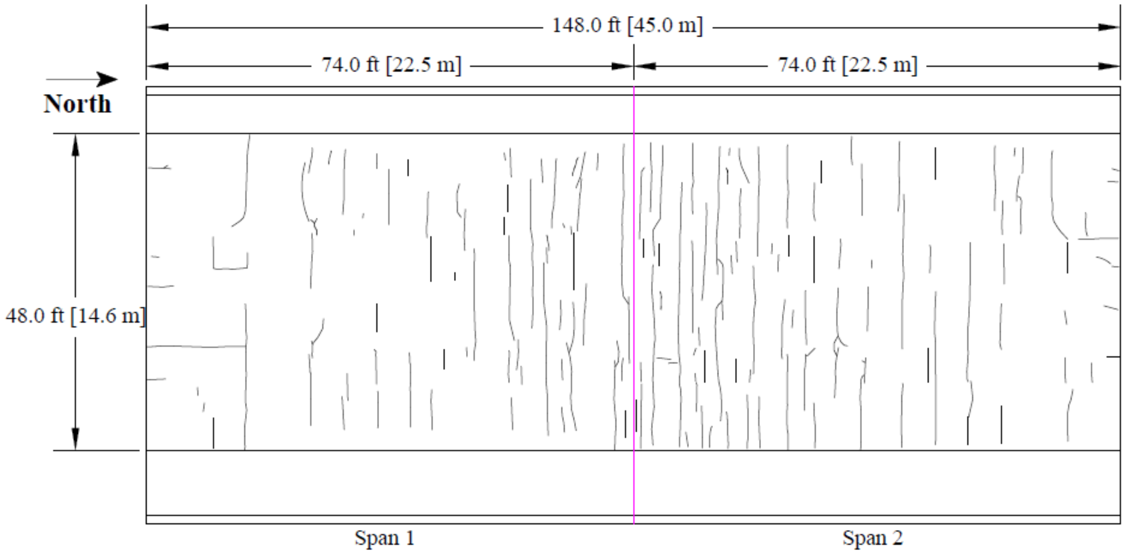
Figure 3.1: Crack Map of bridge 7263

Figure 3.2: Crack propagation in the presence of fibers

3.2 BRIDGE 7268 (MONOLITHIC WITHOUT FIBERS)

Bridge 7268 has a monolithic deck without fibers constructed in one placement on September 10, 2013. The bridge carries two-way traffic on Penn Ave. over T.H. 62 in Hennepin, Minnesota. The concrete supplier and the contractor were AVR Inc. and Lunda Construction Co., respectively. The bridge has two spans each with a length of 74 ft (22.5 m) with a total length of 148 ft (45.0 m). The deck has a 48 ft (14.6 m) wide roadway, a 1 ft-2 in. (360 mm) wide barrier, and a 10 ft (3.0 m) sidewalk on the east side and a 6 ft (1.8 m) on the west side, for a total deck width of 66 ft-4 in. (20.2 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by steel girders with no skew. The crack survey was performed at a deck age of 95.2 months, with a crack density of 0.547 m/m^2. The crack map is shown in Figure 3.3.

Only the roadway of the deck was surveyed. Significant transverse cracking was found throughout the deck and some cracks extended almost throughout the width of the deck. Cracking was higher around the negative moment region of the deck near the central pier. The rest of the deck, except near the piers, had less cracking. Longitudinal cracks were observed mostly near the abutments, the lengths of which ranged from approximately 1 ft (305 mm) to 10 ft (3.0 m). Ninety-nine percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.003 in (0.076 mm) to 0.060 in. (1.524 mm), with an average of 0.025 in. (0.635 mm).



Bridge Number: 7268
Bridge Location: Penn Ave. (C.S.A.H. 32) over T.H. 62, Hennepin, MN
Construction Date: 9/10/2013
Crack Survey Date: 8/16/2021

Bridge Length: 148.0 ft (45.0 m)
Bridge Width: 48.0 ft (14.6 m)
Skew: 0°
Number of Spans: 2
Span 1: 74.0 ft (22.5 m)
Span 2: 74.0 ft (22.5 m)

Bridge Age: 95.2 months
Crack Density: 0.547 m/m^2
Span 1: 0.450 m/m^2
Span 2: 0.645 m/m^2

Figure 3.3: Crack map of bridge 7268

3.3 BRIDGE 9071 (CONVENTIONAL OVERLAY DECK WITHOUT FIBERS)

Bridge 9071 has a conventional overlay without fibers constructed in two placements on August 2, 2017, and August 7, 2017. The north half of the bridge was placed on the latter date and utilized a hydroseeding mulch cure in place of traditional wet curing with burlap. Both passes of the overlay were wet cured according to the 4-day standard in which the wet cure is applied after AMS curing compound and after the concrete is sufficiently set up to prevent marring of the tined texture. The bridge carries two-way traffic on C.S.A.H 19 over US 61 in Washington, Minnesota. The mixture design concrete supplier, and contractor for this deck were not provided by MnDOT. The bridge has four spans with lengths of 35 ft-6 in. (10.8 m), 53 ft-6 in. (16.3 m), 53 ft-6 in. (16.3 m), and 35 ft-6 in. (10.8 m) with a total length of 178 ft (54.2 m). The deck has a 35 ft (10.4 m) wide roadway, a 1 ft-8 in. (510 mm) wide barrier on both sides, and no sidewalks, for a total deck width of 38 ft-4 in. (11.7 m). The nominal deck thickness is 9 in. (230 mm) including a 2 in. (50 mm) conventional wearing course. The bridge deck is supported by steel girders with no skew. The crack survey was performed at an average overlay age of 47.7 months, and the deck had a crack density of 1.147 m/m^2. The crack map is shown in Figure 3.4.

Transverse and longitudinal cracks were observed throughout the deck. Some of the transverse cracks were observed to span the entire width of the deck. Some interconnected cracks were observed along almost the entire span length. The longitudinal cracks were more prevalent near the middle third of the deck width. Ninety-five percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.003 in (0.076 mm) to 0.060 in. (1.524 mm), with an average of 0.021 in. (0.533 mm).

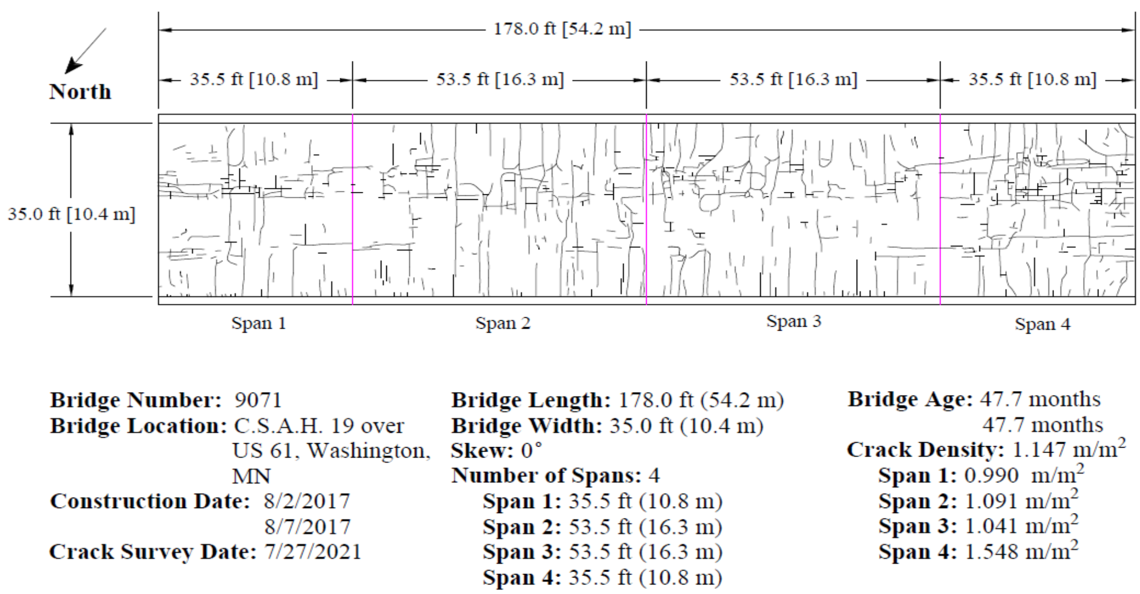


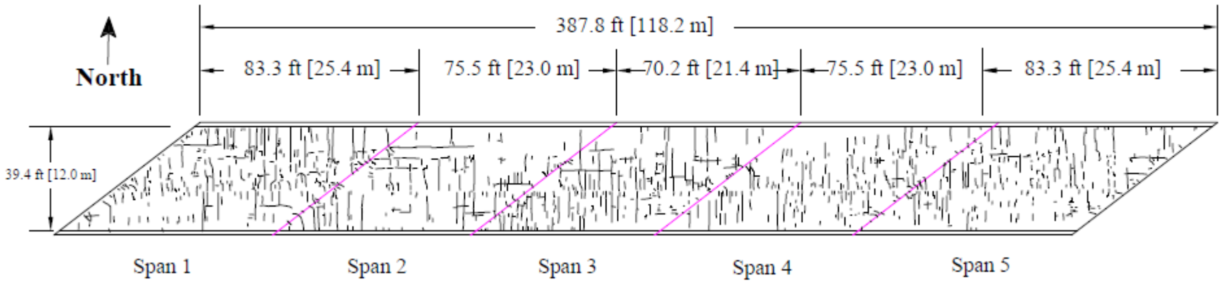
Figure 3.4: Crack map of bridge 9071

3.4 BRIDGE 9689 (SILICA FUME OVERLAY DECK WITH FIBERS)

Bridge 9689 has a silica fume overlay incorporating fibers constructed in two placements on August 11, 2017, and August 17, 2017. The order of the placements, however, is not known.

The bridge carries two-way traffic on westbound I-90 over BNNR RR: C.S.A.H. 4 in Rock, Minnesota. The concrete supplier and the contractor were Buffalo Ridge Concrete and PCI Roads, respectively. The bridge has five spans with lengths of 83 ft-4 in. (25.4 m), 75 ft-6 in. (23.0 m), 70 ft-2 in. (21.4 m), 75 ft-6 in. (23.0 m), and 83 ft-4 in. (25.4 m) with a total length of 378 ft-10 in. (118.2 m). The deck has a 39 ft-5 in. (12.0 m) wide roadway, a 1 ft-8 in. (0.51 m) wide barrier on both sides, and no sidewalks, for a total deck width of 42 ft-9 in. (13.0 m). The nominal deck thickness is 7½ in. (185 mm) including a 2 in. (50 mm) wearing course. The bridge deck is supported by steel girders with a skew of 52º 28' 45". The crack survey was performed at an overlay age of 46.5 months, and the deck had a crack density of 0.622 m/m^2. The crack map is shown in Figure 3.5.

Most of the cracks are transverse and parallel to the top deck reinforcement, not parallel to the skew of the bridge. Longitudinal cracks are also spread throughout the deck, less in number than the transverse cracks. Some diagonal cracks were also observed near the piers. Spans 1 and 3 had similar and higher crack densities, with values of 0.713 and 0.751 m/m^2, respectively, than spans 2, 4, and 5 that had crack densities of 0.539, 0.552, and 0.562 m/m^2, respectively. Crack widths ranged from 0.005 in (0.127 mm) to 0.030 in. (0.762 mm), with an average of 0.014 in. (0.356 mm).



Bridge Number: 9689
Bridge Location: I-90 WB over BNNR RR: C.S.A.H. 4, Rock, MN
Construction Date:
Placement 1: 8/11/2017
Placement 2: 8/17/2017
Crack Survey Date: 6/28/2021

Bridge Length: 387.8 ft (118.2 m)
Bridge Width: 39.4 ft (12.0 m)
Skew: 52°28'45"
Number of Spans: 5
Span 1: 83.3 ft (25.4 m)
Span 2: 75.5 ft (23.0 m)
Span 3: 70.2 ft (21.4 m)
Span 4: 75.5 ft (23.0 m)
Span 5: 83.3 ft (25.4 m)

Bridge Age (Avg.): 46.5 months
Crack Density: 0.622 m/m^2
Span 1: 0.713 m/m^2
Span 2: 0.539 m/m^2
Span 3: 0.751 m/m^2
Span 4: 0.552 m/m^2
Span 5: 0.562 m/m^2

Figure 3.5: Crack map of bridge 9689

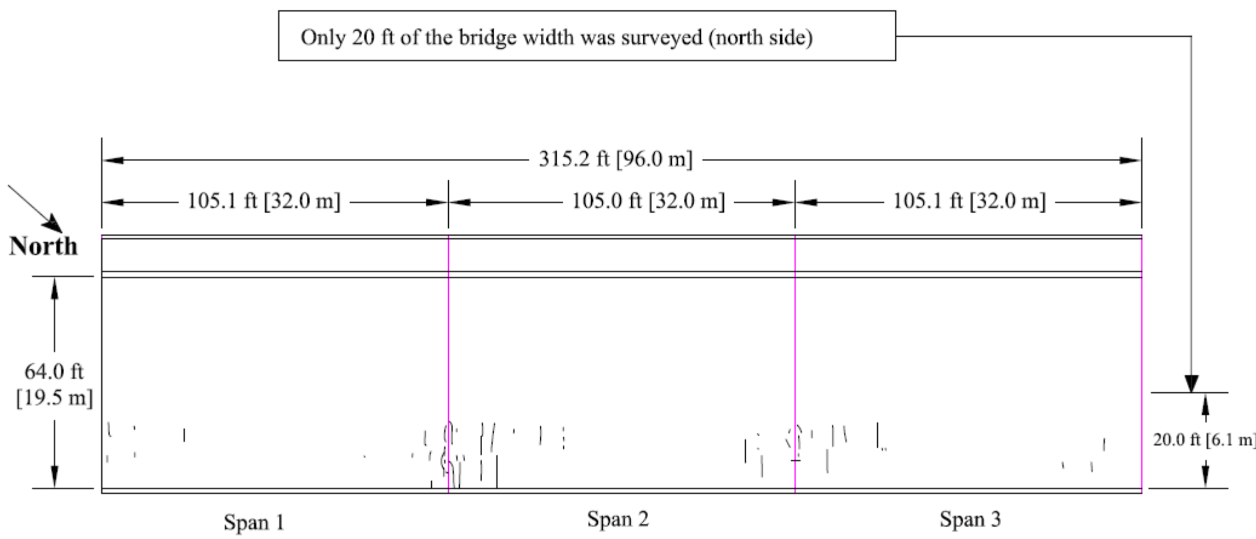
3.5 BRIDGE 10004 (MONOLITHIC WITH AND WITHOUT FIBERS)

Bridge 10004 is a monolithic deck with 13 units incorporating various technologies constructed in 2015. The bridge carries two-way traffic on I-90 TH 101 over Minnesota River in Carver, Minnesota. Units 4, 5, 7, 8, 9, and 10 were surveyed. Each surveyed unit has three spans with lengths of 105 ft-1½ in. (32.0 m), 105 ft (32.0 m), and 105 ft-1½ in. (32.0 m) with a total length of 315 ft-3 in. (96.0 m). The deck has a 64 ft (19.5 m) wide roadway, a 1 ft-8 in. (500 mm), 1 ft-6 in. (450 mm), 1 ft-2 in. (350 mm) wide barriers, and a 10 ft (3.0 m) sidewalk, for a total deck width of 78 ft-4 in. (23.9 m). The nominal deck thickness is 9 in. (230 mm). Units 4, 7, 8, and 10 are monolithic and have no fibers, and Units 5 and 9 are monolithic and incorporate fibers. The concrete supplier and the contractor were AVR-Burnsville and AMES Construction, respectively. The bridge deck is supported by prestressed concrete girders with various skews, but the units surveyed had no skew.

The crack densities of Units 4, 5, 7, 8, 9, and 10 were 0.093, 0.028, 0.110, 0.105, 0.132, and 0.085 m/m^2, respectively. Only 20 ft (6.1 m) of the east side of the deck width was surveyed due to time limitations. The rest of the deck width was observed to have similar cracking.

3.5.1 Unit 4 (With Fibers)

For Unit 4, as shown in Figure 3.6, almost all of the cracks were in the transverse direction, with most of the cracks concentrated within approximately 30 ft (9.1 m) of each pier. Almost no cracking was observed on the rest of the deck. Ninety-five percent of the cracks were longer than 1 ft (305 mm). The crack density of the unit was 0.093 m/m^2. Crack widths ranged from 0.006 in (0.152 mm) to 0.025 in. (0.635 mm), with an average of 0.018 in. (0.457 mm).



Bridge Number: 10004-Unit 4
Bridge Location: T.H. 101 over Minnesota River, Carver, MN
Construction Date: 10/7/2015
Crack Survey Date: 8/18/2021

Bridge Length: 315.2 ft (96.0 m)
Bridge Width: Only 20 ft (6.1 m) was surveyed
Skew: 0°
Number of Spans: 3
Span 1: 105.1 ft (32.0 m)
Span 2: 105.0 ft (32.0 m)
Span 3: 105.1 ft (32.0 m)

Bridge Age: 70.4 months
Crack Density: 0.093 m/m^2
Span 1: 0.065 m/m^2
Span 2: 0.142 m/m^2
Span 3: 0.072 m/m^2

Figure 3.6: Crack Map of bridge 10004-Unit 4

3.5.2 Unit 5 (With Fibers)

Unit 5, as shown in Figure 3.7, had the lowest crack density among the surveyed units of this deck. No cracks were observed near the south end of the unit and only one small transverse crack of length approximately 3 ft (910 mm) from the north end of the unit. A few transverse cracks were observed within approximately 10 ft (3.0m) of the other two piers. No cracks were observed on the rest of the deck. Ninety-five percent of the cracks were longer than 1 ft (305 mm). The crack density of the unit was 0.028 m/m^2. Crack widths ranged from 0.009 in (0.229 mm) to 0.016 in. (0.406 mm), with an average of 0.012 in. (0.305 mm).

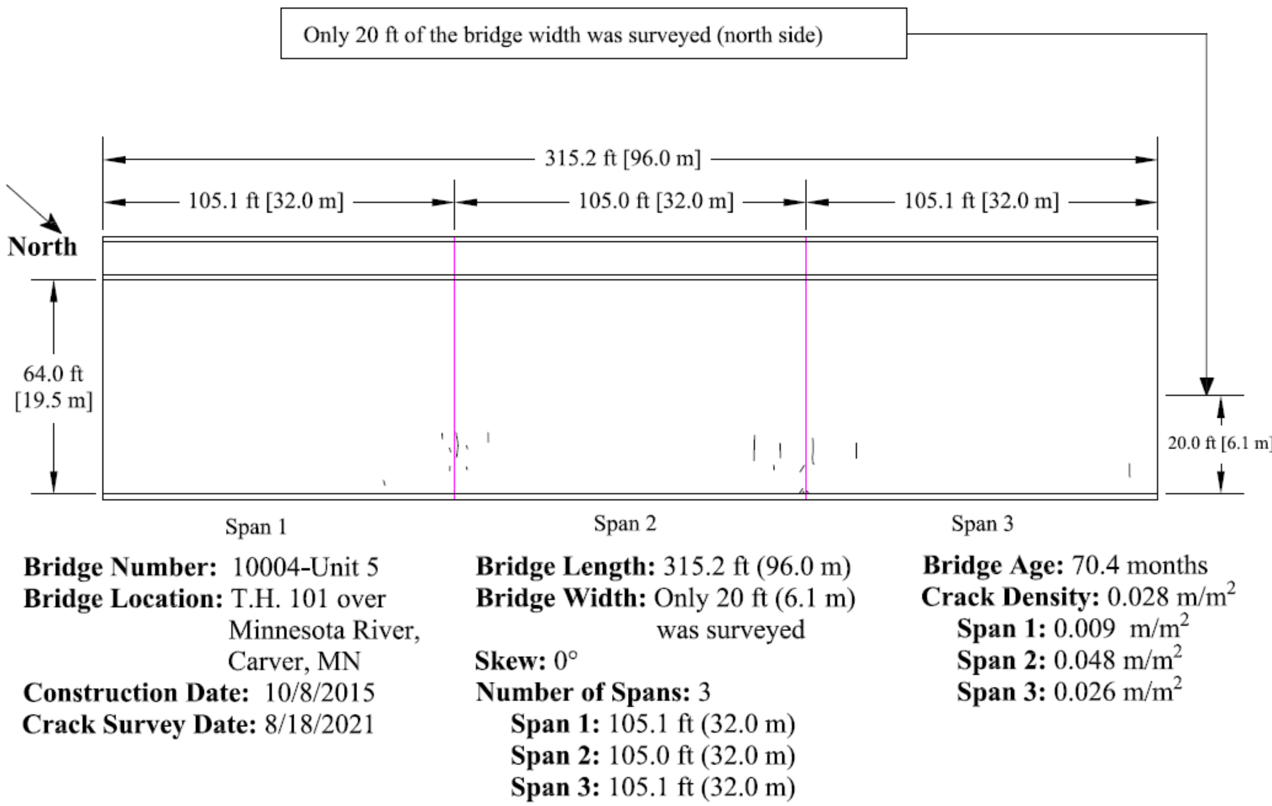
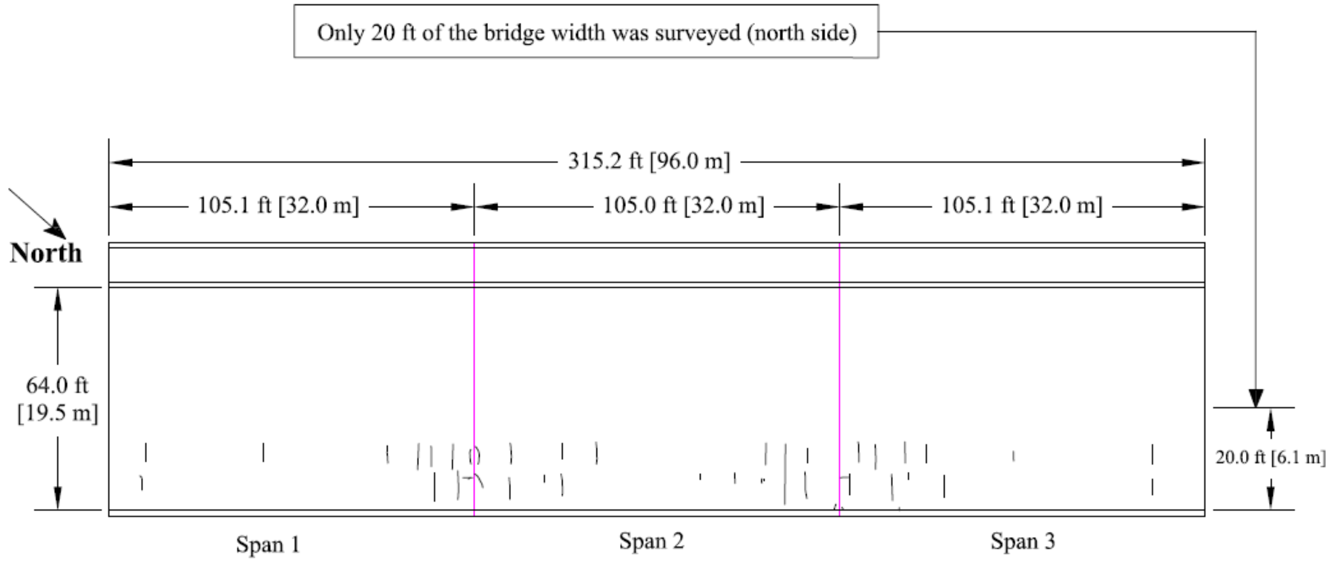


Figure 3.7: Crack Map of bridge 10004-Unit 5

3.5.3 Unit 7 (Without Fibers)

For Unit 7, as shown in Figure 3.8, almost all the cracks were in the transverse direction, with two longitudinal cracks with a length of approximately 1 ft (305 mm) extending near each pier. The cracks were distributed throughout the surveyed portion of the deck width, with higher concentrations near the piers. Ninety-nine percent of the cracks were longer than 1 ft (305 mm). The crack density of the unit was 0.110 m/m^2. Crack widths ranged from 0.009 in (0.229 mm) to 0.013 in. (0.330 mm), with an average of 0.010 in. (0.254 mm).



Bridge Number: 10004-Unit 7
Bridge Location: T.H. 101 over Minnesota River, Carver, MN
Construction Date: 8/21/2015
Crack Survey Date: 8/18/2021

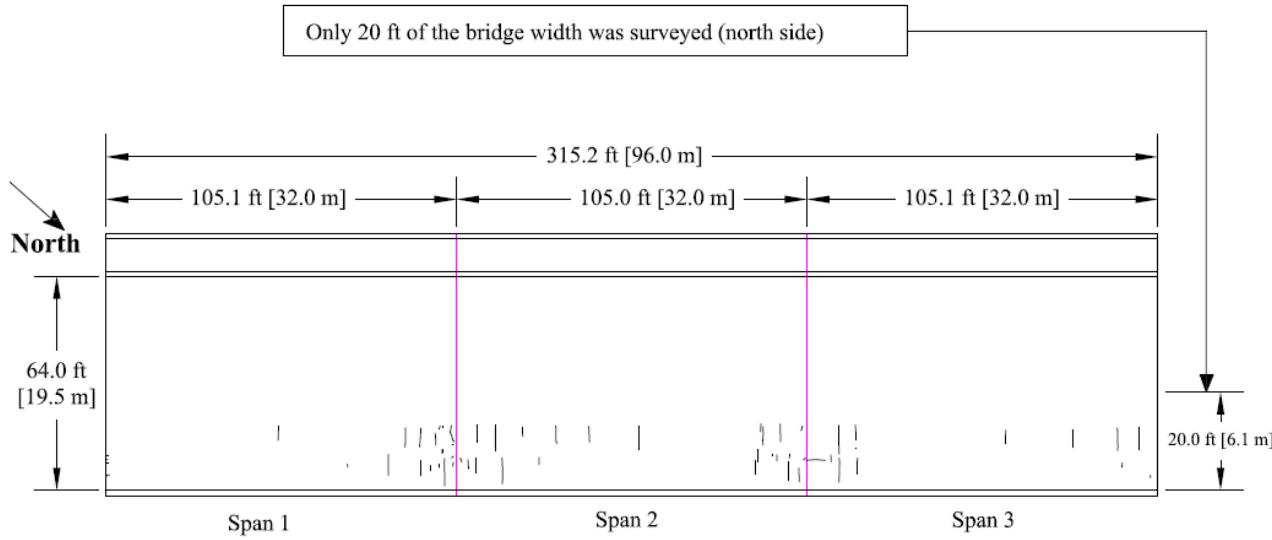
Bridge Length: 315.2 ft (96.0 m)
Bridge Width: Only 20 ft (6.1 m) was surveyed
Skew: 0°
Number of Spans: 3
Span 1: 105.1 ft (32.0 m)
Span 2: 105.0 ft (32.0 m)
Span 3: 105.1 ft (32.0 m)

Bridge Age: 71.9 months
Crack Density: 0.110 m/m^2
Span 1: 0.101 m/m^2
Span 2: 0.132 m/m^2
Span 3: 0.096 m/m^2

Figure 3.8: Crack Map of bridge 10004-Unit 7

3.5.4 Unit 8 (Without Fibers)

For Unit 8, as shown in Figure 3.9, some longitudinal cracks were observed near the piers, although transverse cracks predominated. The transverse cracks were observed mostly near the piers. Three short cracks of length less than 1 ft (305 mm) were observed near the south end pier. Ninety-six percent of the cracks were longer than 1 ft (305 mm). The crack density of the unit was 0.105 m/m^2. Crack widths ranged from 0.009 in (0.229 mm) to 0.025 in. (0.635 mm), with an average of 0.015 in. (0.381 mm).



Bridge Number: 10004-Unit 8
Bridge Location: T.H. 101 over Minnesota River, Carver, MN
Construction Date: 8/28/2015
Crack Survey Date: 8/18/2021

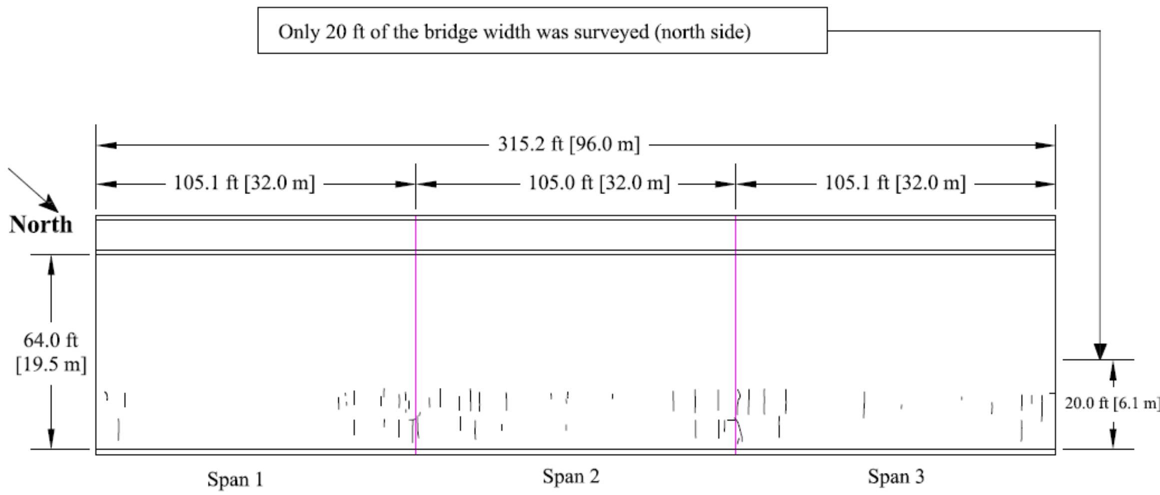
Bridge Length: 315.2 ft (96.0 m)
Bridge Width: Only 20 ft (6.1 m) was surveyed
Skew: 0°
Number of Spans: 3
Span 1: 105.1 ft (32.0 m)
Span 2: 105.0 ft (32.0 m)
Span 3: 105.1 ft (32.0 m)

Bridge Age: 71.7 months
Crack Density: 0.105 m/m^2
Span 1: 0.086 m/m^2
Span 2: 0.137 m/m^2
Span 3: 0.091 m/m^2

Figure 3.9: Crack Map of bridge 10004-Unit 8

3.5.5 Unit 9 (With Fibers)

Unit 9, as shown in Figure 3.10, was constructed in a single placement. Cracking was higher near the piers of the deck. Similar to the rest of the units, transverse cracks were higher in number. Span 1 had the lowest crack density of 0.099 m/m^2. Ninety-nine percent of the cracks were longer than 1 ft (305 mm). The crack density of the unit was 0.132 m/m^2. Crack widths ranged from 0.003 in (0.076 mm) to 0.020 in. (0.508 mm), with an average of 0.012 in. (0.305 mm).



Bridge Number: 10004-Unit 9
Bridge Location: T.H. 101 over Minnesota River, Carver, MN
Construction Date:
Placement 1: 9/3/2015
Placement 2: 9/4/2015
Crack Survey Date: 8/18/2021

Bridge Length: 315.2 ft (96.0 m)
Bridge Width: Only 20 ft (6.1 m) was surveyed
Skew: 0°
Number of Spans: 3
Span 1: 105.1 ft (32.0 m)
Span 2: 105.0 ft (32.0 m)
Span 3: 105.1 ft (32.0 m)
Number of Placements: 2

Bridge Age:
Placement 1: 71.5 months
Placement 2: 71.5 months
Crack Density: 0.132 m/m^2
Span 1: 0.099 m/m^2
Span 2: 0.156 m/m^2
Span 3: 0.140 m/m^2

Figure 3.10: Crack Map of bridge 10004-Unit 9

3.5.6 Unit 10 (Without Fibers)

For Unit 10, as shown in Figure 3.11, a longitudinal crack of length of approximately 50 ft (15.2 m) was observed near the south side of the deck width near the barrier. Most of the transverse cracks were observed near the piers. Some short cracks of length less than 6 in. (152.4 mm) also were observed mostly near the piers. Ninety-six percent of the cracks were longer than 1 ft (305 mm). The crack density of the unit was 0.085 m/m^2. Crack widths ranged from 0.003 in (0.076 mm) to 0.013 in. (0.330 mm), with an average of 0.009 in. (0.229 mm).

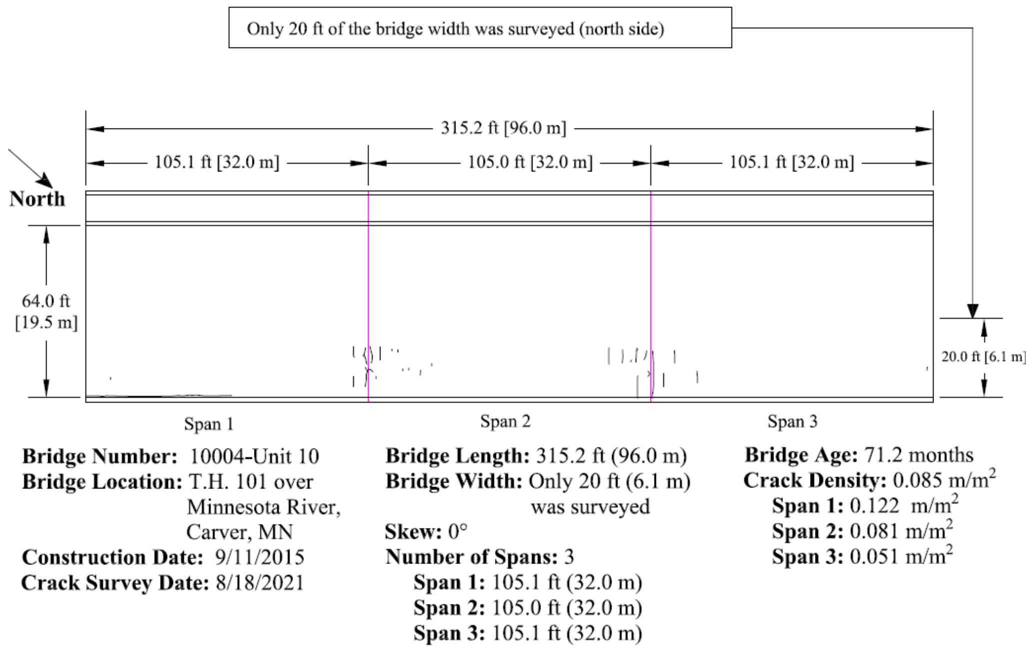


Figure 3.11: Crack Map of bridge 10004-Unit 10

The units were surveyed at ages of 70.4, 70.4 71.9, 71.7, 71.5, and 71.4 months for Units 4, 5, 7, 8, 9, and 10, respectively. The properties of the units are tabulated in Table 3.1.

Table 3.1: Properties of units of bridge 10004*

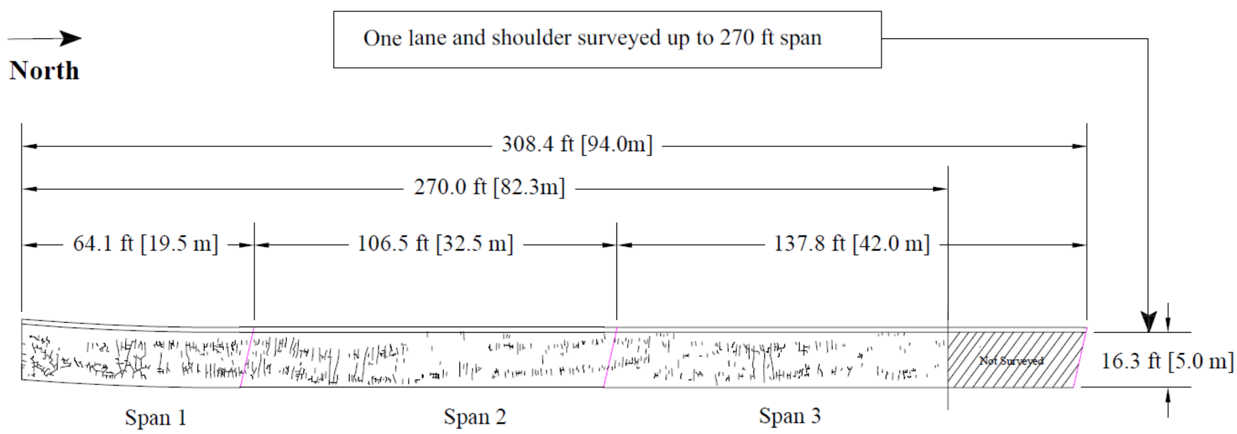
Unit	Unit 4	Unit 5	Unit 7	Unit 8	Unit 9	Unit 10
Spans	11-13	14-16	20-22	23-25	26-28	29-31
Length (ft)	315.3	315.3	315.3	315.3	315.3	315.3
Curing*	1	1	2	1	1	1
Vibration*	1	2	3	3	3	3
Chair Supports*	1	1	1	1	1	1
Presence of Fibers*	1	2	1	1	2	1
Max Agg. Size*	1	1	1	1	1	2
Age	70.4	70.4	71.9	71.7	71.5	71.4
Crack Density (CD, m/m^2)	0.093	0.028	0.11	0.105	0.132	0.085
CD of span 1	0.065	0.009	0.101	0.086	0.099	0.122
CD of span 2	0.142	0.048	0.132	0.137	0.156	0.081
CD of span 3	0.072	0.026	0.096	0.091	0.14	0.051

*Curing: 1-Wet Curing 7 days, 2-Wet Curing 14 days
Vibration: 1-One vibrator per pump, 2-One vibrator per 20' deck width, 3-Gang vibrator
Chair supports: 1- MnDOT specifications, 2-Top Mat of Reinforcement supported at half the standard specifications on chair spacing requirements
Presence of Fibers: 1-Without fibers, 2-With fibers
Max. Aggregate Size: 1- HPC Mix with ¾ in. max size aggregate, 2- HPC Mix with ½ in. max size aggregate

3.6 BRIDGE 19004 (CONVENTIONAL OVERLAY DECK WITHOUT FIBERS)

Bridge 19004 has a conventional overlay without fibers constructed in one placement on August 1, 2013, making it the deck with the oldest overlay in the current study. The year but not the date of construction of the deck is known, and the 1st of August of that year is assumed as the probable date of construction because August is the middle of construction season in Minnesota. The bridge carries two-way traffic on US 61 over the Mississippi River in Dakota, Minnesota. One lane and shoulder spanning 16 ft-4 in. (5.0 m) of the deck width, up to 270 ft (82.3 m) for the northbound deck length, and up to 454 ft-11 in. (138.7 m) for the southbound deck length, starting from the south end of both the bridges were surveyed. The concrete supplier and the contractor were Cemstone Products Company and Lunda/Ames Construction, respectively. The northbound bridge has five spans with lengths of 64 ft-1 ⅝ in. (19.5 m), 106 ft-6 ½ in. (32.5 m), 137 ft-9 ¾ in. (42.0 m), 137 ft-6 ⅞ in. (41.9 m), and 105 ft-10 ⅜ in. (32.3 m) with a total length of 551 ft-11 ⅛ in. (168.2 m). The northbound deck has a 33 ft-3 in. (10.1 m) wide roadway, a 1 ft-5 in. (430 mm) wide barrier on both sides, and a 16 ft-3 in. (5.0 m) sidewalk, for a total deck width of 52 ft-4 in. (16.0 m). The southbound bridge has five spans with lengths of 66 ft-5 ¼ in. (20.2 m), 106 ft-6 ½ in. (32.5 m), 137 ft-9 ¾ in. (42.0 m), 136 ft-1 in. (41.5 m), and 105 ft-3 ¼ in. (32.1 m) with a total length of 552 ft-1 ¾ in. (168.3 m). The southbound deck has a 36 ft-6 in. (11.1 m) wide roadway, a 1 ft-5 in. (430 mm) wide barrier on both sides, and no sidewalks, for a total deck width of 39 ft-4 in. (12.0 m). The thickness of the wearing course is 2 in. (50 mm). The overlay is placed on a thick post-tensioned slab superstructure. The crack survey was performed at an overlay age of 95.9 months for both south and northbound decks. The decks were both heavily cracked with crack densities of 1.065 m/m^2 and 0.787 m/m^2, respectively, for the south and northbound decks. The crack maps for the northbound and southbound decks are shown in Figures 3.12 and 3.13, respectively. Because the superstructure is a large massive slab span, the restraint may be higher than for traditional structural slabs. The crack densities observed on Bridge 19004 are in the upper range of those typically observed for decks with overlays (Lindquist et al. 2005).

For the northbound lanes, only 308.4 ft (94.0 m) of the bridge deck length and only one lane and shoulder of the west side of the deck width spanning 16 ft- 4 in (5.0 m) were surveyed. Most of the cracks were in the transverse direction and these cracks did not reach the barrier. Within 1 ft (305 mm) of the barrier, cracking was relatively low compared to the rest of the deck width. Interconnected cracks are also observed in some locations on all spans. A number of longitudinal cracks were observed near the abutments. Eighty-eight percent of the cracks were longer than 1 ft (305 mm). For the northbound deck, crack widths ranged from 0.003 in (0.076 mm) to 0.010 in. (0.254 mm), with an average of 0.005 in. (0.127 mm).



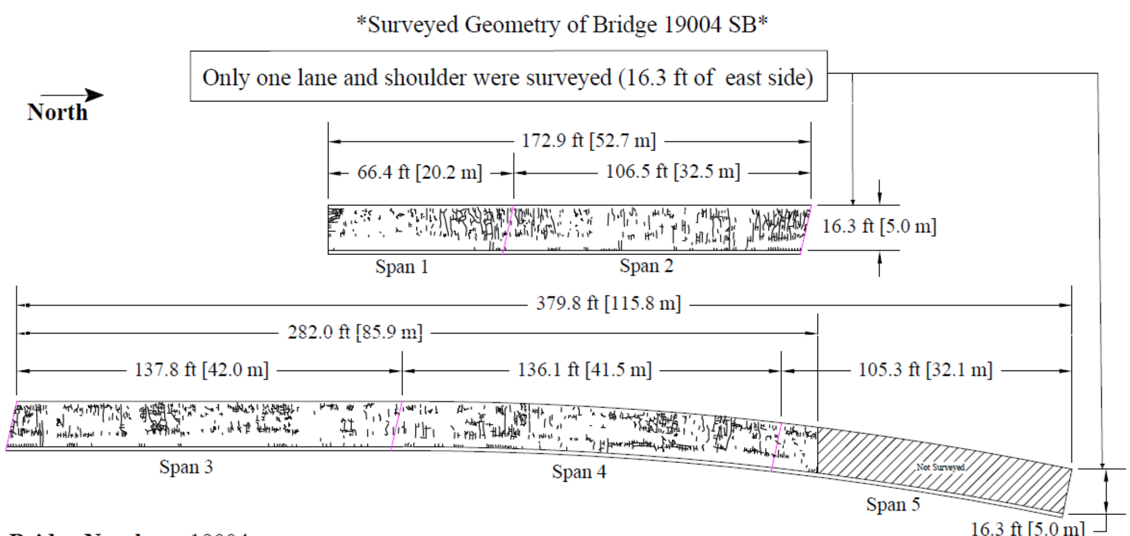
Bridge Number: 19004
Bridge Location: US 61 NB over MISS R; Dakota, MN
Construction Date: 8/1/2013
Crack Survey Date: 7/26/2021

Bridge Length: Only 270.0 ft (82.3 m) was surveyed
Bridge Width: Only 16.3 ft (5.0 m) was surveyed
Skew: Various
Number of Spans: 3 surveyed
Span 1: 64.1 ft (19.5 m)
Span 2: 106.5 ft (32.5 m)
Span 3: 137.8 ft (42.0 m)

Bridge Age: 95.9 months
Crack Density: 0.787 m/m^2
Span 1: 1.111 m/m^2
Span 2: 0.745 m/m^2
Span 3: 0.615 m/m^2

Figure 3.12: Crack map of bridge 19004 Northbound

Similar to the northbound deck, only one lane and the shoulder of the east side of the deck width were surveyed. Along the length, 454.9 ft (138.7 m) of the deck was surveyed. Spans 1 through 4 had crack densities of 1.007, 1.111, 1.051, 1099 m/m^2. Span 5 had a crack density of 0.798 m/m^2. Most of the cracks were in the transverse direction. Interconnected cracks in the transverse and longitudinal directions were observed in discrete locations throughout the span lengths, possibly due to drying shrinkage and plastic shrinkage (Lindquist et al. 2008). Small cracks that extended about 1 ft (305 mm) from the barriers were observed in discrete locations in all the spans. Eighty-five percent of the cracks were longer than 1 ft (305 mm). For the southbound deck, crack widths ranged from 0.003 in (0.076 mm) to 0.013 in. (0.330 mm), with an average of 0.005 in. (0.127 mm).



Bridge Number: 19004
Bridge Location: US 61 SB over MISS R, Dakota, MN
Construction Date: 8/1/2013
Crack Survey Date: 7/26/2021

Bridge Length: Only 460.0 ft (140.2 m) was surveyed
Bridge Width: Only 16.3 ft (5.0 m) was surveyed
Skew: Various
Number of Spans: 5
Span 1: 66.4 ft (20.2 m)
Span 2: 106.5 ft (32.5 m)
Span 3: 137.8 ft (42.0 m)
Span 4: 136.1 ft (41.5 m)
Span 5: 105.3 ft (32.1 m)

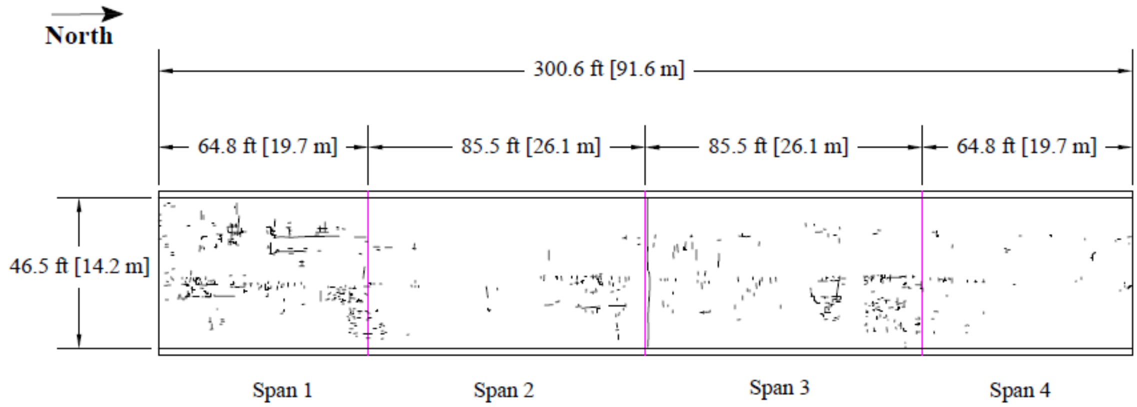
Bridge Age: 95.9 months
Crack Density: 1.065 m/m^2
Span 1: 1.007 m/m^2
Span 2: 1.111 m/m^2
Span 3: 1.051 m/m^2
Span 4: 1.099 m/m^2
Span 5: 0.798 m/m^2

Figure 3.13: Crack map of bridge 19004 Southbound

3.7 BRIDGE 22801 (SILICA FUME OVERLAY DECK WITH FIBERS)

Bridge 22801 has a silica fume overlay incorporating fibers constructed in one placement on May 8, 2020. The bridge carries two-way traffic on C.S.A.H. 1 over I-90 in Faribault, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and PCI Roads, respectively. The bridge has four spans with lengths of 64 ft-10 in. (19.7 m), 85 ft-6 in. (26.1 m), 85 ft-6 in. (26.1 m), and 64 ft-10 in. (19.7 m) with a total length of 300 ft-8 in. (91.6 m). The deck has a 46 ft-6 in. (14.2 m) wide roadway, and a 1 ft-11 in. (585 mm) wide barrier on both sides, for a total deck width of 50 ft-4 in. (15.3 m). The nominal deck thickness is a minimum of 10 in. (255 mm) including the 2-in. (50-mm) wearing course. The deck is supported by steel girders with no skew. The crack survey was performed at an overlay age of 14.2 months. The crack density was 0.159 m/m^2. The crack map is shown in Figure 3.14.

About 33% of the cracks are shorter than 1 ft (305 mm). Span 1 had the highest crack density, 0.326 m/m^2, with some interconnected cracks near the midspan. Span 4 had the lowest crack density, 0.040 m/m^2, with almost all cracks shorter than 1 ft (305 mm). Near the pier between spans 2 and 3, in the negative moment region, a long transverse crack extended throughout the width of the deck. The use of fibers did not seem effective in limiting crack formation, as observed in the crack map. Sixty-seven percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.009 in (0.229 mm) to 0.040 in. (1.016 mm), with an average of 0.018 in. (0.457 mm).



Bridge Number: 22801
Bridge Location: C.S.A.H. 1 over I-90, Faribault, MN
Construction Date: 5/8/2020
Crack Survey Date: 7/13/2021

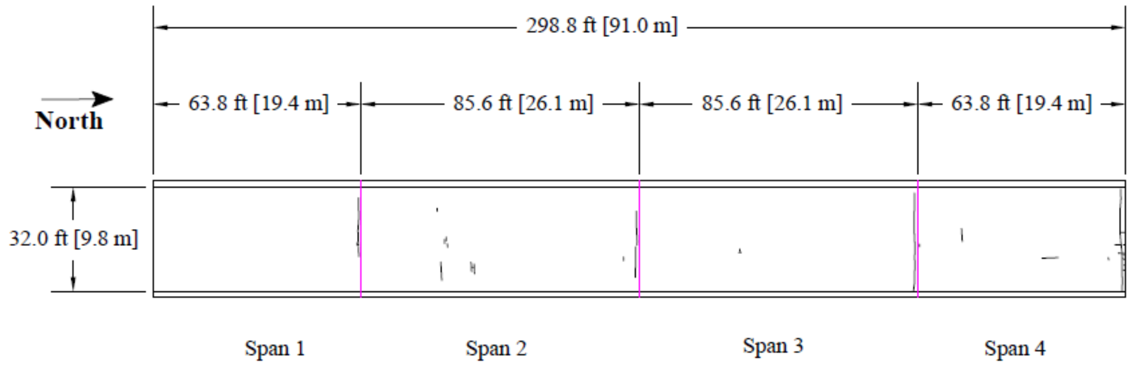
Bridge Length: 300.6 ft (91.6 m)
Bridge Width: 46.5 ft (14.2 m)
Skew: 0°
Number of Spans: 4
Span 1: 64.8 ft (19.7 m)
Span 2: 85.5 ft (26.1 m)
Span 3: 85.5 ft (26.1 m)
Span 4: 64.8 ft (19.7 m)

Bridge Age: 14.2 months
Crack Density: 0.159 m/m^2
Span 1: 0.326 m/m^2
Span 2: 0.083 m/m^2
Span 3: 0.200 m/m^2
Span 4: 0.040 m/m^2

Figure 3.14: Crack map of bridge 22801

3.8 BRIDGE 22802 (SILICA FUME OVERLAY DECK WITH FIBERS)

Bridge 22802 has a silica fume overlay incorporating fibers constructed in one placement on July 27, 2019. The bridge carries two-way traffic on C.S.A.H. 5 over I-90 in Faribault, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and PCI Roads, respectively. The bridge has four spans with lengths of 63 ft-9 in. (19.4 m), 85 ft-7 in. (26.1 m), 85 ft-7 in. (26.1 m), and 63 ft-9 in. (19.4 m), with a total length of 298 ft-10 in. (91.0 m). The deck has a 32 ft (9.8 m) wide roadway, and a 1 ft-11 in. (585 mm) wide barrier on both sides, for a total deck width of 35 ft-10 in. (10.9 m). The minimum nominal deck thickness is 8 in. (200 mm), including the 2-in. (50-mm) wearing course. The bridge deck is supported by steel girders with no skew. The crack survey was performed at an overlay age of 23.5 months. The crack density was 0.047 m/m^2. The crack map is shown in Figure 3.15.



Bridge Number: 22802
Bridge Location: C.S.A.H. 5 over I-90 , Faribault, MN
Construction Date: 7/27/2019
Crack Survey Date: 7/13/2021

Bridge Length: 298.8 ft (91.0 m)
Bridge Width: 32.0 ft (9.8 m)
Skew: 0°
Number of Spans: 4
Span 1: 63.8 ft (19.4 m)
Span 2: 85.6 ft (26.1 m)
Span 3: 85.6 ft (26.1 m)
Span 4: 63.8 ft (19.4 m)

Bridge Age: 23.5 months
Crack Density: 0.047 m/m^2
Span 1: 0.029 m/m^2
Span 2: 0.044 m/m^2
Span 3: 0.038 m/m^2
Span 4: 0.080 m/m^2

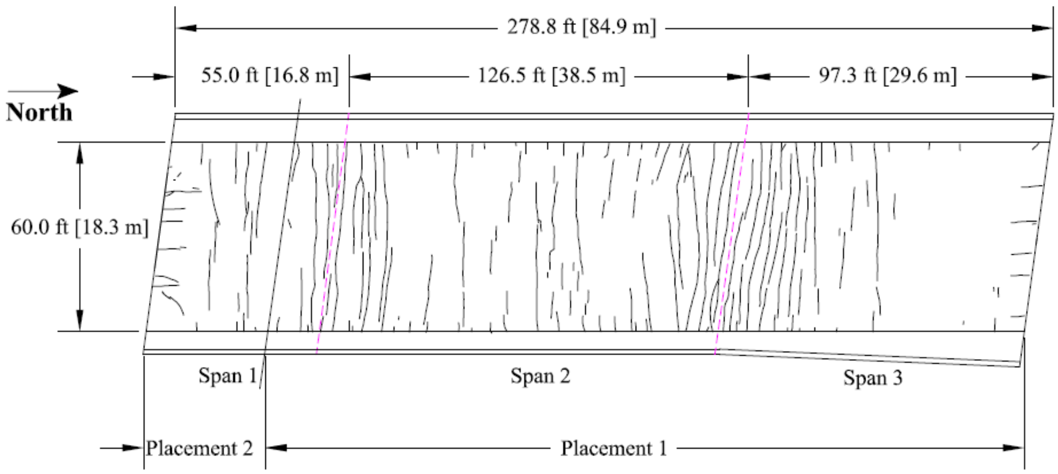
Figure 3.15: Crack map of bridge 22802

Bridge 22802 had one of the lower crack densities among the decks in this study. Most of the cracks were in the transverse direction with a long crack or cracks at each pier and near the abutments. The transverse cracks near the piers and the abutments extended almost the entire width of the deck in the abutment and the piers near the northern end of the deck. No cracks were observed on the abutment in the southern end of the deck. The transverse cracks near the abutments and the piers provided the main contribution to the crack density of the respective spans because the rest of the deck had a maximum of six cracks, all less than 2 ft (610 mm) long. Some longitudinal cracks were also observed near the north abutment. Ninety-four percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.009 in (0.229 mm) to 0.025 in. (0.635 mm), with an average of 0.015 in. (0.381 mm).

3.9 BRIDGE 27133 (MONOLITHIC WITH FIBERS)

Bridge 27133 is a monolithic deck incorporating fibers constructed in two placements on September 24, 2019, and October 8, 2019. The bridge carries two-way traffic on Central Ave over US 12 in Hennepin, Minnesota. The concrete supplier and the contractor were Aggregate Industries and Kraemer North America, respectively. The bridge has three spans with lengths of 55 ft (16.8 m), 126 ft-6 in. (38.5 m), and 97 ft-3 in. (29.6 m) with a total length of 278 ft-9 in. (84.9 m). The deck has a 60 ft (18.3 m) wide roadway with a sidewalk of width 7 ft-6 in. (2.3 m) and 6 ft (1.8 m) on the west and east side, a 1 ft-7 ¾ in. (500 mm) wide barrier on both sides, for a total deck width of 76 ft-5 ½ in. (23.3 m). The minimum nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by steel girders with a skew of 7^{o} 40' 54". The steel superstructure-span arrangement used on this bridge required heavy counterweights at the south abutment because of asymmetric spans, which would tend to induce higher levels of tension in the deck. The crack survey was performed at a deck age of 22.9 and 22.4 months for the first and second placements with crack densities of 0.450 m/m^2 and 0.364 m/m^2, respectively. The overall crack density of the deck was 0.439 m/m^2. The crack map is shown in Figure 3.16.

Bridge 27133 was constructed in two placements, as shown in Figure 3.16. Placement 2 spanned 37 ft- 4 ½ in. (11.39 m) from the south abutment, with Placement 1 covering most of the deck to the northern abutment. Long cracks, many that extended across the full deck width, were observed in both placements spaced approximately 10 ft (3.1 m) apart. Cracking was higher near the piers, with transverse cracks that extended throughout the deck width spaced approximately 2 ft (0.6 m) apart. Longitudinal cracks were almost exclusively near the abutments, likely due to restraint from the abutments (Schmitt and Darwin 1995, Miller and Darwin 2000). Span 3 had the lowest crack density, 0.383 m/m^2. Ninety-nine percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.007 in (0.178 mm) to 0.060 in. (1.524 mm), with an average of 0.029 in. (0.737 mm).



Bridge Number: 27133
Bridge Location: CENTRAL Ave over US 12, Hennepin, MN
Construction Date:
Placement 1: 9/24/2019
Placement 2: 10/8/2019
Crack Survey Date: 8/19/2021

Bridge Length: 278.8 ft (84.9 m)
Bridge Width: 60.0 ft (18.3 m)
Skew: 7°40' 54"
Number of Spans: 4
Span 1: 55.0 ft (16.8 m)
Span 2: 126.5 ft (38.5 m)
Span 3: 97.3 ft (29.6 m)
Number of Placements: 2

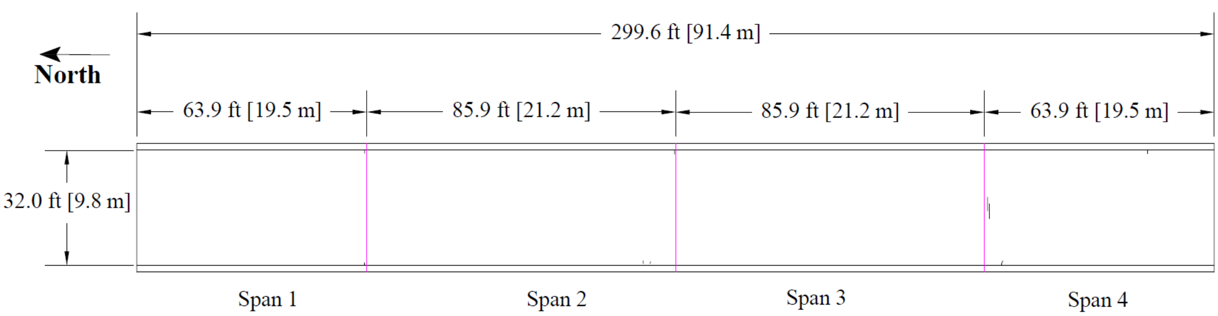
Bridge Age:
Placement 1: 22.9 months
Placement 2: 22.4 months
Crack Density: 0.439 m/m^2
Span 1: 0.428 m/m^2
Span 2: 0.486 m/m^2
Span 3: 0.383 m/m^2
Placement 1: 0.450 m/m^2
Placement 2: 0.364 m/m^2

Figure 3.16: Crack map of bridge 27133

3.10 BRIDGE 46824 (SILICA FUME OVERLAY DECK WITH FIBERS)

Bridge 46824 has a silica fume overlay incorporating fibers constructed in one placement on July 24, 2019. The order of the placement, however, is not known. The bridge carries two-way traffic on C.S.A.H. 59 over I-90 in Martin, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and PCI Roads, respectively. The bridge has four spans with lengths of 63 ft-11½ in. (19.5 m), 85 ft-10 ½ in. (21.2 m), 85 ft-10 ½ in. (21.2 m), and 63 ft-11½ in. (19.5 m) with a total length of 299 ft-8 in. (91.4 m). The deck has a 32-ft (9.8-m) wide roadway, and a 1 ft-11-in. (585-mm) wide barrier on both sides, for a total deck width of 35 ft-10 in. (10.9 m). The minimum nominal deck thickness is 8-¼ in. (210 mm) including a 2 in. (50 mm) silica fume wearing course. The bridge deck is supported by steel girders with no skew. The crack survey was performed at an overlay age of 23.6 months with a crack density of 0.005 m/m^2. The crack map is shown in Figure 3.17.

Bridge 46824 had a very low crack density, with spans 1, 2, and 3 having only one or two cracks of length longer than 1 ft (305 mm). The cracks were in the transverse direction and concentrated near the barriers and the piers in spans 1 and 2. No cracks were observed in span 3. In span 4, two cracks with lengths of approximately 4 ft (1.2 m) were observed near the pier, and no cracks were observed near the abutment. Seventy-three percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.007 in (0.178 mm) to 0.020 in. (0.508 mm), with an average of 0.011 in. (0.279 mm).



Bridge Number: 46824
Bridge Location: C.S.A.H. 59 over I-90, Martin, MN
Construction Date: 7/24/2019
Crack Survey Date: 7/13/2021

Bridge Length: 299.6 ft (91.4 m)
Bridge Width: 32.0 ft (9.8 m)
Skew: 0°
Number of Spans: 4
Span 1: 63.9 ft (19.5 m)
Span 2: 85.9 ft (21.2 m)
Span 3: 85.9 ft (21.2 m)
Span 4: 63.9 ft (19.5 m)

Bridge Age: 23.6 months
Crack Density: 0.005 m/m^2
Span 1: 0.003 m/m^2
Span 2: 0.003 m/m^2
Span 3: 0.000 m/m^2
Span 4: 0.016 m/m^2

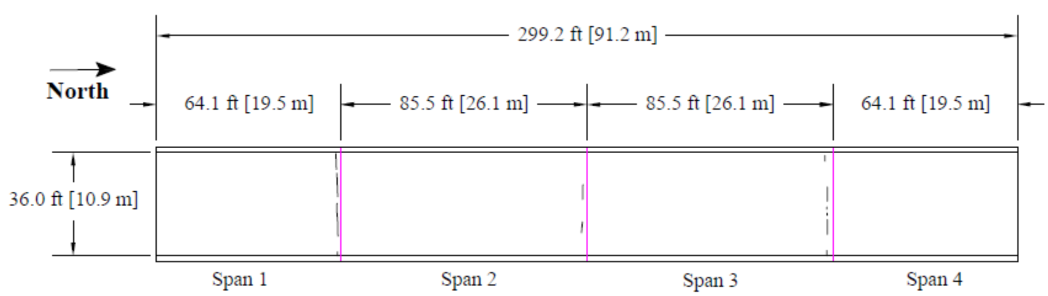
Figure 3.17: Crack map of bridge 46824

3.11 BRIDGE 46831 (SILICA FUME OVERLAY DECK WITH FIBERS)

Bridge 46831 has a silica fume overlay incorporating fibers constructed in one placement on July 26, 2019. The bridge carries two-way traffic on TWP 40 over I-90 in Martin, Minnesota.

The concrete supplier and the contractor were Cemstone Products Company and PCI Roads, respectively. The bridge has four spans with lengths of 64 ft-1 in. (19.5 m), 85 ft-6 in. (26.1 m), 85 ft-6 in. (26.1 m), and 64 ft-1 in. (19.5 m) with a total length of 299 ft-2 in. (91.2 m). The deck has a 36-ft (10.9-m) wide roadway, and a 1 ft-11-in. (585-mm) wide barrier on both sides, for a total deck width of 39 ft-10 in. (12.1 m). The nominal deck thickness is 8-½ in. (215 mm) including the 2 in. (50 mm) wearing course. The bridge deck is supported by prestressed concrete girders with no skew. The crack survey was performed at a deck age of 23.6 months with a crack density of 0.016 m/m^2. The crack map is shown in Figure 3.18.

Cracks were exclusively near the piers, in the transverse direction, ranging in length from 1 ft (0.3 m) to 12 ft (3.7 m). No cracks were observed near the abutments. Ninety-seven percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.004 in (0.102 mm) to 0.018 in. (0.457 mm), with an average of 0.011 in. (0.279 mm).



Bridge Number: 46831
Bridge Location: TWP 40 over I-90, Martin, MN
Construction Date: 7/26/2019
Crack Survey Date: 7/12/2021

Bridge Length: 299.2 ft (91.2 m)
Bridge Width: 36.0 ft (10.9 m)
Skew: 0°
Number of Spans: 4
Span 1: 64.1 ft (19.5 m)
Span 2: 85.5 ft (26.1 m)
Span 3: 85.5 ft (26.1 m)
Span 4: 64.1 ft (19.5 m)

Bridge Age: 23.6 months
Crack Density: 0.016 m/m^2
Span 1: 0.038 m/m^2
Span 2: 0.009 m/m^2
Span 3: 0.017 m/m^2
Span 4: 0.000 m/m^2

Figure 3.18: Crack map of bridge 46831

3.12 BRIDGE 46835 (SILICA FUME OVERLAY DECK WITH FIBERS)

Bridge 46835 has a silica fume overlay incorporating fibers constructed in one placement on July 25, 2019. The bridge carries two-way traffic on I-90 WB over Center Creek in Martin, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and PCI Roads, respectively. The bridge has three spans with lengths of 48 ft-3 in. (14.7 m), 50 ft-10 in. (15.5 m), and 48 ft-3 in. (14.7 m) with a total length of 147 ft-4 in. (44.9 m). The deck has a 40 ft-6-in. (12.3-m) wide roadway, and a 1 ft-11-in. (585-mm) wide barrier on both sides, for a total deck width of 44 ft-4 in. (13.5 m). The deck thickness is 10¼ in. (260 mm) including a 2 ¾ in. (70 mm) silica fume wearing course. The bridge deck is supported by prestressed concrete girders with a skew of 29º 27’ 54”. The crack survey was performed at an overlay age of 23.6 months. The crack density was 0.006 m/m^2. The crack map is shown in Figure 3.19.

Bridge 46835 had a very low crack density. Except for a crack in the longitudinal direction of length of approximately 6 ft (18.3 m) close to the east abutment, all other cracks were shorter than 1 ft (305 mm). Short cracks of length less than 1 ft (305 mm) were observed near the abutments and piers at the west end of the deck and barrier near the end of the deck. Seventy-six percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.016 in (0.406 mm) to 0.025 in. (0.635 mm), with an average of 0.020 in. (0.508 mm).

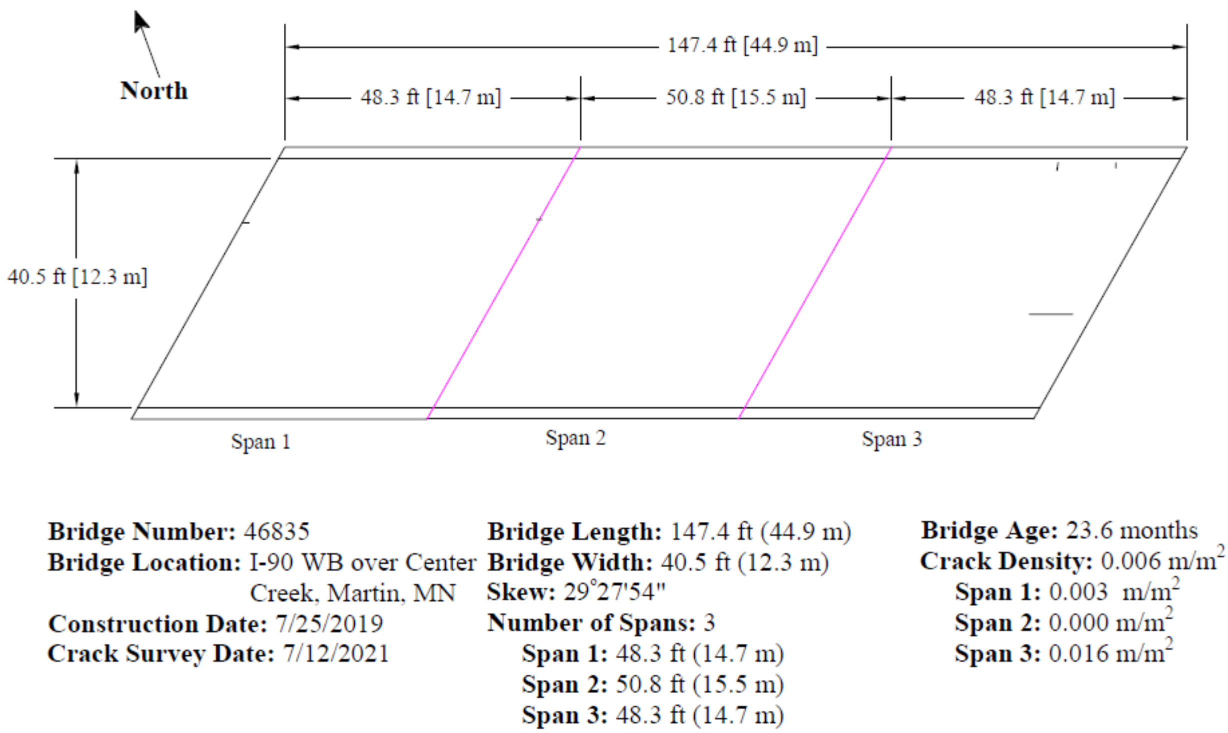
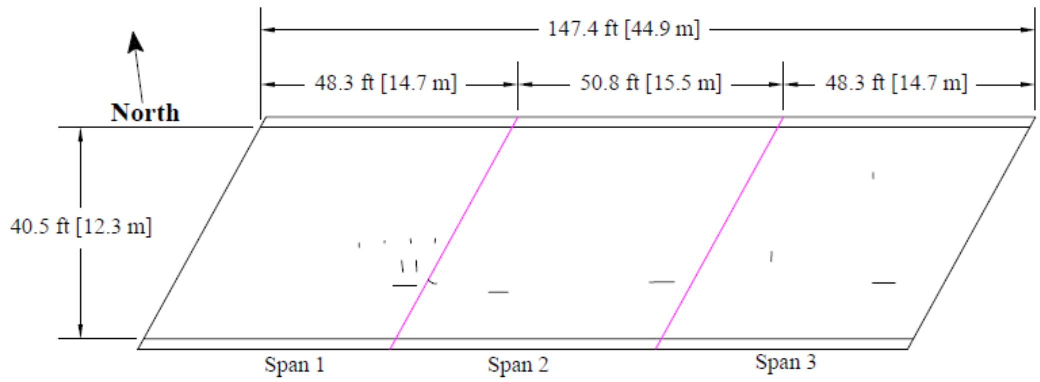


Figure 3.19: Crack map of bridge 46835

3.13 BRIDGE 46836 (SILICA FUME OVERLAY DECK WITH FIBERS)

Bridge 46836 has a silica fume overlay incorporating fibers constructed in one placement on June 11, 2020. The bridge carries two-way traffic on I-90 EB over Center Creek in Martin, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and PCI Roads, respectively. The bridge has three spans with lengths of 48 ft-3 in. (14.7 m), 50 ft-10 in. (15.5 m), and 48 ft-3 in. (14.7 m) with a total length of 147 ft-4 in. (44.9 m). The deck has a 40 ft-6-in. (12.3-m) wide roadway, and a 1 ft-11-in. (585-mm) wide barrier on both sides, for a total deck width of 43 ft-4 in. (13.2 m). The nominal deck thickness is 10¼ in. (260 mm) including the 2 ¾ in. (70 mm) wearing course. The bridge deck is supported by prestressed concrete girders with a skew of 28º 53’ 03”. The crack survey was performed at an overlay age of 12.7 months and had a crack density of 0.016 m/m^2. The crack map is shown in Figure 3.20.

The cracks were almost exclusively located on the southern side of the deck and randomly positioned and distributed in all spans. Longitudinal cracks were higher in number than transverse cracks and of longer length. Spans 1, 2, and 3 had crack densities of 0.020, 0.016, and 0.012 m/m^2, respectively. Ninety percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.002 in (0.051 mm) to 0.020 in. (0.508 mm), with an average of 0.013 in. (0.330 mm).



Bridge Number: 46836
Bridge Location: I-90 EB over Center Creek, Martin, MN
Construction Date: 6/11/2020
Crack Survey Date: 7/1/2021

Bridge Length: 147.4 ft (44.9 m)
Bridge Width: 40.5 ft (12.3 m)
Skew: 28°53'3"
Number of Spans: 3
Span 1: 48.3 ft (14.7 m)
Span 2: 50.8 ft (15.5 m)
Span 3: 48.3 ft (14.7 m)

Bridge Age: 12.7 months
Crack Density: 0.016 m/m^2
Span 1: 0.020 m/m^2
Span 2: 0.016 m/m^2
Span 3: 0.012 m/m^2

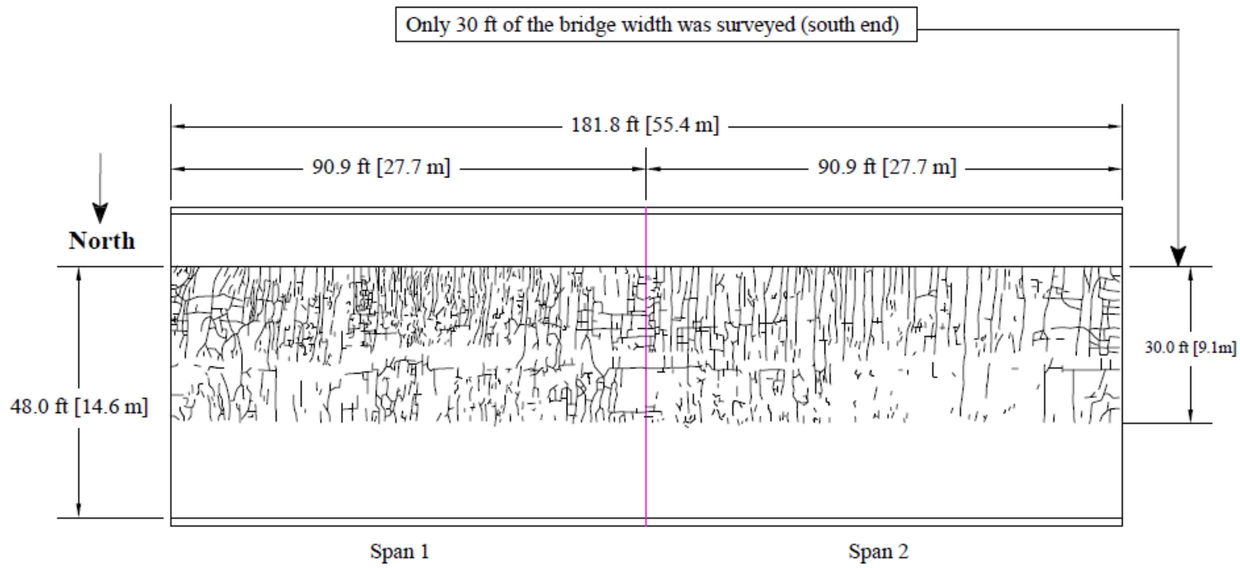
Figure 3.20: Crack map of bridge 46836

3.14 BRIDGE 62038 (CONVENTIONAL OVERLAY DECK WITHOUT FIBERS)

Bridge 62038 has a conventional overlay incorporating no fibers. A construction date of July 2, 2015 is based on the mixture design approval date. The bridge carries two-way traffic on C.S.A.H. 15 over T.H. 51 in Ramsey, Minnesota. The concrete supplier and the contractor were Cemstone-Childs Plant and Redstone Construction, respectively. The bridge has two spans with lengths of 90 ft-11 in. (27.7 m), and 90 ft-11 in. (27.7 m) with a total length of 181 ft-10 in. (55.4 m). The deck has a 48-ft (14.6-m) wide roadway, a sidewalk and a barrier with widths of 10 ft and

1 ft- 3 in. (3.0 m and 380 mm) on the south side, respectively, and a barrier with a width of 1 ft-8 in. (510 mm) on the north side, for a total deck width of 60 ft-11 in. (18.6 m). The minimum deck thickness is 9 in. (230 mm) including a 2 in. (50 mm) conventional wearing course. The bridge deck is supported by prestressed concrete girders with no skew. The crack survey was performed at an overlay age of 73.4 months and had a crack density of 1.916 m/m^2. Only 30 ft (9.1 m) of the south side of the deck was surveyed. The crack map is shown in Figure 3.21.

Bridge 62038 had the highest crack density among the surveyed bridges. The cracks were spread through the entire length of the deck. Most of the cracks were in the transverse direction, parallel to the top deck reinforcement, although longitudinal cracks connected transverse cracks at some locations. The concentration of cracks was observed to be higher closer to the barrier than in the middle of the deck. Longitudinal crack lengths longer than 1 ft (305 mm) were observed mostly near the abutments and the piers. Span 1 had a higher crack density of 2.231 m/m^2, compared to span 2 of 1.600 m/m^2. Ninety-three percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.003 in (0.076 mm) to 0.060 in. (1.524 mm), with an average of 0.015 in. (0.381 mm).



Bridge Number: 62038
Bridge Location: C.S.A.H. 15 over T.H. 51, Ramsey, MN
Construction Date: 6/2/2015*
Crack Survey Date: 7/15/2021

Bridge Length: 181.8 ft (55.4 m)
Bridge Width: 48.0 ft (14.6 m)
Skew: 0
Number of Spans: 2
Span 1: 90.9 ft (27.7 m)
Span 2: 90.9 ft (27.7 m)

Bridge Age: 73.4 months
Crack Density: 1.916 m/m^2
Span 1: 2.231 m/m^2
Span 2: 1.600 m/m^2

* Based on the Mixture Design Approval Date

Figure 3.21: Crack map of bridge 62038

3.15 BRIDGE 62652 (SILICA FUME OVERLAY DECK WITH FIBERS)

Bridge 62652 has a silica fume overlay incorporating fibers constructed in two placements on August 20, 2021, and August 21, 2020. The order of the placements, however, is not known. The bridge carries two-way traffic on Summit Ave over AYD Mill Rd in Ramsey, Minnesota. The concrete supplier and the contractor were Aggregate Industries and PCI Roads, respectively. The bridge has two spans with lengths of 124 ft-9 in. (38.0 m), and 124 ft-9 in. (38.0 m) with a total length of 216 ft-6 in. (65.9 m). The deck has a 54 ft (16.5 m) wide roadway with a median of width 14 ft (4.3 m) in the middle, sidewalks of width 10 ft (3.0) on both sides, and a 1 ft-3 in. (380 mm) wide barrier on both sides, for a total deck width of 76 ft-6 in. (23.3 m). The nominal deck thickness is 9 in. (230 mm) including the 2 in. (50 mm) wearing course. The bridge deck is supported by prestressed concrete girders with a skew of -21º 25’ 12”. The crack survey was performed at an overlay age of 11.9 months and had a crack density of 0.027 m/m^2. The crack map is shown in Figure 3.22.

Bridge 62652 had a low crack density. Eighty percent of the cracks were less than 1 ft (305 mm) long were positioned and distributed throughout the deck, likely due to plastic shrinkage. The north end of the deck had a somewhat higher crack density than the south end. Short transverse cracks of length less than 1 ft (305 mm) originating from the median were also observed throughout the span. Crack widths ranged from 0.003 in (0.076 mm) to 0.016 in. (0.406 mm), with an average of 0.007 in. (0.178 mm).

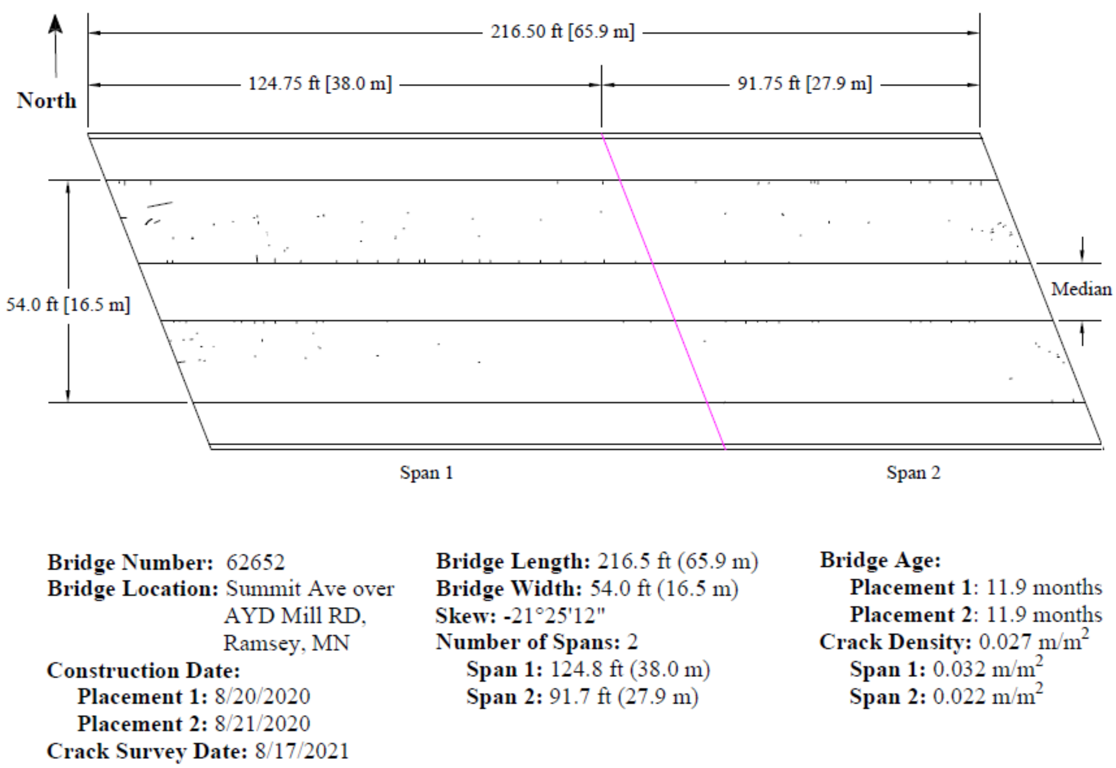


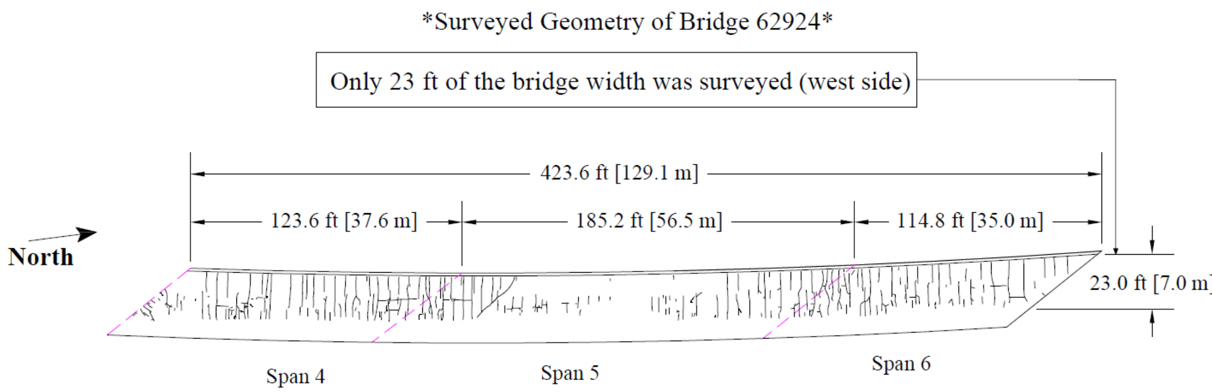
Figure 3.22: Crack map of bridge 62652

3.16 BRIDGE 62924 (CONVENTIONAL OVERLAY DECK WITHOUT FIBERS)

Bridge 62924 is a structural slab constructed in five placements on June 3, 8, 11, 16, and

18, 2015. A conventional overlay was placed in July and early August of the same year. The bridge has a curved and bifurcated steel superstructure connected by steel diaphragms that carries one-way traffic on I-35E NB over BNSF RR in St. Paul, Minnesota. The concrete supplier and the contractor were Aggregate Industries and Lunda Construction Co., respectively. The bridge has six spans with lengths of 68 ft-10 in. (20.9 m), 123 ft-11 in. (37.8 m), 87 ft-2 in. (26.6 m), 123 ft-7 in. (37.6 m), 185 ft-3 in. (56.5 m), and 114 ft-10 in. (35.0 m) with a total length of 703 ft-7 in. (214.4 m). The deck has variable roadway width ranging from 89 ft- 8 in. (27.3 m) to 139 ft- 5 in. (42.5 m), a 1 ft-8 in. (510 mm) and 1 ft-4 in. (405 mm) wide barrier on the east side and west side, respectively, for a maximum total deck width of 107 ft-8 in. (32.8 m). The nominal deck thickness is 9 in. (229 mm) including a 2 in. (50 mm) concrete wearing course. The bridge deck is supported by steel girders and has various skews ranging from -7º 22' 11" to 54º 40' 2.5". The crack survey was performed at an average overlay age of 73.6 months and had a crack density of 0.562 m/m^2. Only 23 ft (7.0 m) of the west end of spans 4 to 6 was surveyed. The crack map is shown in Figure 3.23.

Bridge 62924 had transverse cracks that extended throughout the surveyed portion of the deck width spaced approximately 2 ft (0.6 m) apart in span 4 and span 6. Of the surveyed spans of this slightly curved deck, span 5 had the lowest crack density of 0.427 m/m^2. In span 5, the midspan had cracks that were shorter than at the ends of this span which had cracks that extended throughout the deck width, spaced approximately 2 ft (0.6 m) apart. Although only a portion of the deck width was surveyed, it was observed that most of the transverse cracks extend throughout the deck width. Some longitudinal cracks connecting two or more adjacent transverse cracks were also observed. Ninety-nine percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.009 in (0.229 mm) to 0.060 in. (1.524 mm), with an average of 0.032 in. (0.813 mm).



Bridge Number: 62924
Bridge Location: I-35E NB over BNSF RR, Ramsey, MN
Construction Date: 6/3/2015, 6/8/2015, 6/11/2015, 6/16/2015, 6/18/2015
Crack Survey Date: 7/28/2021

Bridge Length: Only 423.6 ft (129.1 m) was surveyed
Bridge Width: Only 23 ft (7.0 m) was surveyed
Skew: Various
Number of Spans: Only 3 spans were surveyed
Span 4: 123.6 ft (37.6 m)
Span 5: 185.2 ft (56.5 m)
Span 6: 114.8 ft (35.0 m)

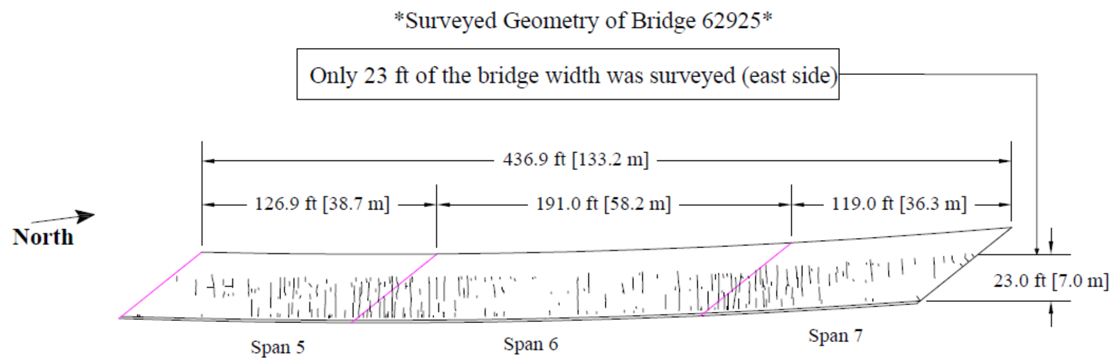
Bridge Age (Avg.): 73.6 months
Crack Density: 0.562 m/m^2
Span 4: 0.720 m/m^2
Span 5: 0.427 m/m^2
Span 6: 0.619 m/m^2

Figure 3.23: Crack map of bridge 62924

3.17 BRIDGE 62925 (CONVENTIONAL OVERLAY DECK WITHOUT FIBERS)

Bridge 62925 has a conventional overlay constructed on a structural slab incorporating 5 lb/yd^3 of macrofibers. The conventional overlay (without fibers) was placed in several passes in late September 2015. The bridge carries one-way traffic on I-35E SB over BNSF RR in St. Paul, Minnesota. The concrete supplier and the contractor were Aggregate Industries and Lunda Construction Co., respectively. The bridge has seven spans with lengths of 68 ft-10 in. (20.9 m), 123 ft-11 in. (37.8 m), 90 ft (27.4 m), 87 ft-11 in. (26.8 m), 126 ft-11 in. (38.7 m), 191 ft (58.2 m), and 119 ft (36.3 m) with a total length of 807 ft-7 in. (246.1 m). The deck has variable roadway width ranging from 90 ft-3 in. (27.5 m) to 120 ft-1 in. (36.6 m), a 1 ft-8 in. (510 mm) and 1 ft-4 in. (405 mm) wide barrier on the west side and east side, respectively, for a maximum total deck width of 123 ft-1 in. (37.5 m). The nominal deck thickness is 9 in. (228.6 mm) including a 2 in. (50 mm) concrete wearing course. The bridge deck is supported by steel girders, and has various skews ranging from -7º 22' 11" to 46º 38' 9". The crack survey was performed at a deck age of 71.1 months and had a crack density of 0.360 m/m^2. Only 23 ft (7.0 m) of the east side of spans 5 to 7 of the bridge width were surveyed. The average crack density of the overlay, 0.360 m/m^2, on this fiber-reinforced structural slab is lower than on the sister bridge, 62924, which did not have fibers in the structural slab, but had an average crack density of 0.562 m/m^2. In both cases, the crack density is high, and it is not clear that the use of fibers in the subdeck on this bridge played a role in its lower crack density, The crack map is shown in Figure 3.24.

The majority of the cracks in this deck were in the transverse direction, with higher cracking located approximately 40 ft (12.2 m) from the piers along the length. Occasionally, the transverse cracks extended throughout the deck width. Cracks were scattered along the deck. The surveyed spans of the deck had crack densities for spans 5, 6, and 7 of 0.351, 0.342, and 0.397 m/m^2, respectively. Ninety-nine percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.003 in (0.076 mm) to 0.060 in. (1.524 mm), with an average of 0.026 in. (0.660 mm).



Bridge Number: 62925
Bridge Location: I-35E SB over BNSF, Ramsey, MN
Construction Date: 8/25/2015*
Crack Survey Date: 7/29/2021

Bridge Length: Only 436.9 ft (133.2 m) was surveyed
Bridge Width: Only 23 ft (7.0 m) was surveyed
Skew: Various
Number of Spans: Only 3 spans were surveyed
Span 5: 126.9 ft (38.7 m)
Span 6: 191.0 ft (58.2 m)
Span 7: 119.0 ft (36.3 m)

Bridge Age: 71.1 months
Crack Density: 0.360 m/m^2
Span 5: 0.351 m/m^2
Span 5: 0.342 m/m^2
Span 6: 0.397 m/m^2

* Based on the Mixture Design Approval Date

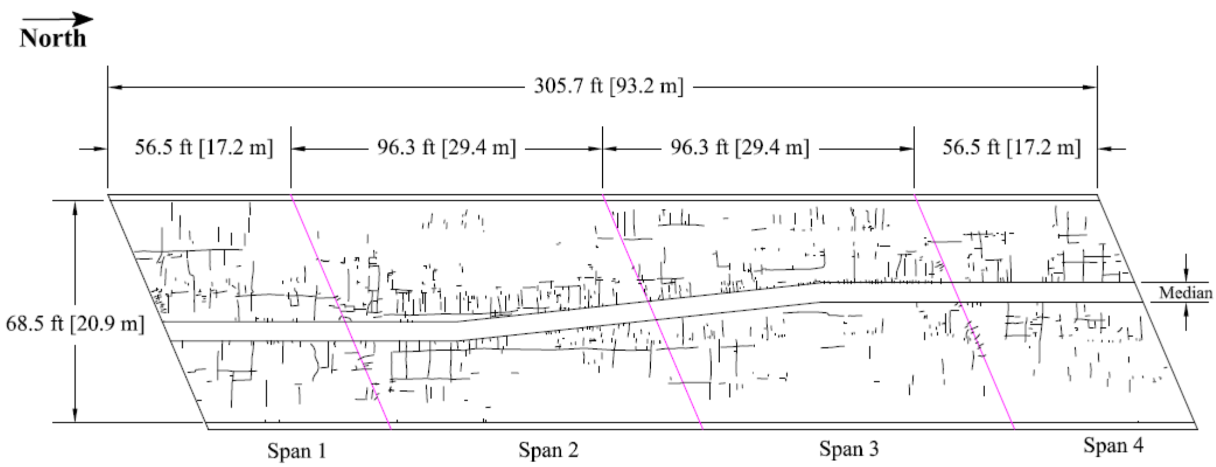
Figure 3.24: Crack map of bridge 62925

3.18 BRIDGE 83026 (CONVENTIONAL OVERLAY DECK WITHOUT FIBERS)

Bridge 83026 has a conventional overlay constructed in three placements on May 2, 3, and 6 of 2019. The order of the placements, however, is not known. The bridge carries two-way traffic on T.H. 4 over MN 60 in St. James, Minnesota. The concrete supplier and the contractor involved in the construction of the deck are not known by MnDOT at the time of the survey. The bridge has four spans with lengths of 56 ft-6 in. (17.2 m), 96 ft-4 in. (29.4 m), 96 ft-4 in. (29.4 m) and 56 ft-6 in. (17.2 m) with a total length of 305 ft-8 in. (93.2 m). The deck has a 68 ft-6 in. (20.9 m) wide roadway with a median of width 6 ft (1.8 m) in the middle, and a 1 ft-11 in. (585 mm) wide barrier on both sides, for a total deck width of 72 ft-4 in. (22.0 m). The minimum nominal deck thickness is 9 in. (230 mm) including the 2 in. (50 mm) wearing course. The bridge deck is supported by prestressed concrete girders with a skew of -23º 11’ 35”. The crack survey was performed at an overlay age of 25.8 months and had a crack density of 0.370 m/m^2. The crack map is shown in

Figure 3.25.

Transverse and longitudinal cracks of various lengths ranging from 6 in. (0.2 m) to 80 ft (24.4 m) were observed throughout the deck. Cracks were located throughout the span, with higher cracking closer to the median. A longitudinal crack, with a length of almost 80 ft (24.4 m) formed in span 2. Cracks shorter than 1 ft (305 mm) were observed originating from the edge of the median throughout the span length. Ninety percent of the cracks were longer than 1 ft (305 mm). Crack widths ranged from 0.009 in (0.229 mm) to 0.040 in. (1.016 mm), with an average of 0.021 in. (0.533 mm).



Bridge Number: 83026
Bridge Location: T.H. 4 over MN 60, Watonwan, MN
Construction Date:
Placement 1: 5/2/2019
Placement 2: 5/3/2019
Placement 3: 5/6/2019
Crack Survey Date: 6/29/2021

Bridge Length: 305.7 ft (93.2 m)
Bridge Width: 68.5 ft (20.9 m)
Skew: -23°11'35"
Number of Spans: 4
Span 1: 56.5 ft (17.2m)
Span 2: 96.3 ft (29.4 m)
Span 3: 96.3 ft (29.4 m)
Span 4: 56.5 ft (17.2 m)

Bridge Age (Avg.): 25.8 months
Crack Density: 0.370 m/m^2
Span 1: 0.415 m/m^2
Span 2: 0.399 m/m^2
Span 3: 0.325 m/m^2
Span 4: 0.351 m/m^2

Figure 3.25: Crack map of bridge 83026

3.19 BRIDGE 83027 (CONVENTIONAL OVERLAY DECK WITHOUT FIBERS)

Bridge 83027 has a conventional overlay constructed in two placements on August 3 and 6, 2018. The order of the placements, however, is not known. The bridge carries two-way traffic on C.S.A.H. 12 over MN 60 in St. James, Minnesota. The concrete supplier and the contractor were not provided by MnDOT. The bridge has four spans with lengths of 66 ft (20.1 m), 112 ft (34.1 m), 112 ft (34.1 m), and 66 ft (20.1 m) with a total length of 356 ft (108.4 m). The deck has a 70 ft-6 in. (21.5 m) wide roadway with a median of width 6 ft (1.8 m) in the middle, and a 1 ft-11 in. (585 mm) wide barrier on both sides, for a total deck width of 74 ft-4 in. (22.7 m). The minimum nominal deck thickness is 9 in. (230 mm) including the 2 in. (50 mm) wearing course. The bridge deck is supported by prestressed concrete girders with a skew of 55^{o} 22' 39". The crack survey was performed at an overlay age of 34.8 months with a crack density of 0.157 m/m^2. The crack map is shown in Figure 3.26.

Transverse and longitudinal cracks of various lengths ranging from 6 in. (0.1 m) to 36 ft (11.0 m) were observed throughout the deck. The cracks were randomly positioned throughout the span length. The highest crack density occurred in span 4 with a crack density of 0.300 m/m^2. The lowest cracking was observed in span 1 with a crack density of 0.066 m/m^2. A 60 ft (18.3 m) long longitudinal crack was observed in span 3. Cracks shorter than 1 ft (305 mm) were also observed originating from the edge of the median. Crack widths ranged from 0.007 in (0.178 mm) to 0.030 in. (0.762 mm), with an average of 0.017 in. (0.432 mm).

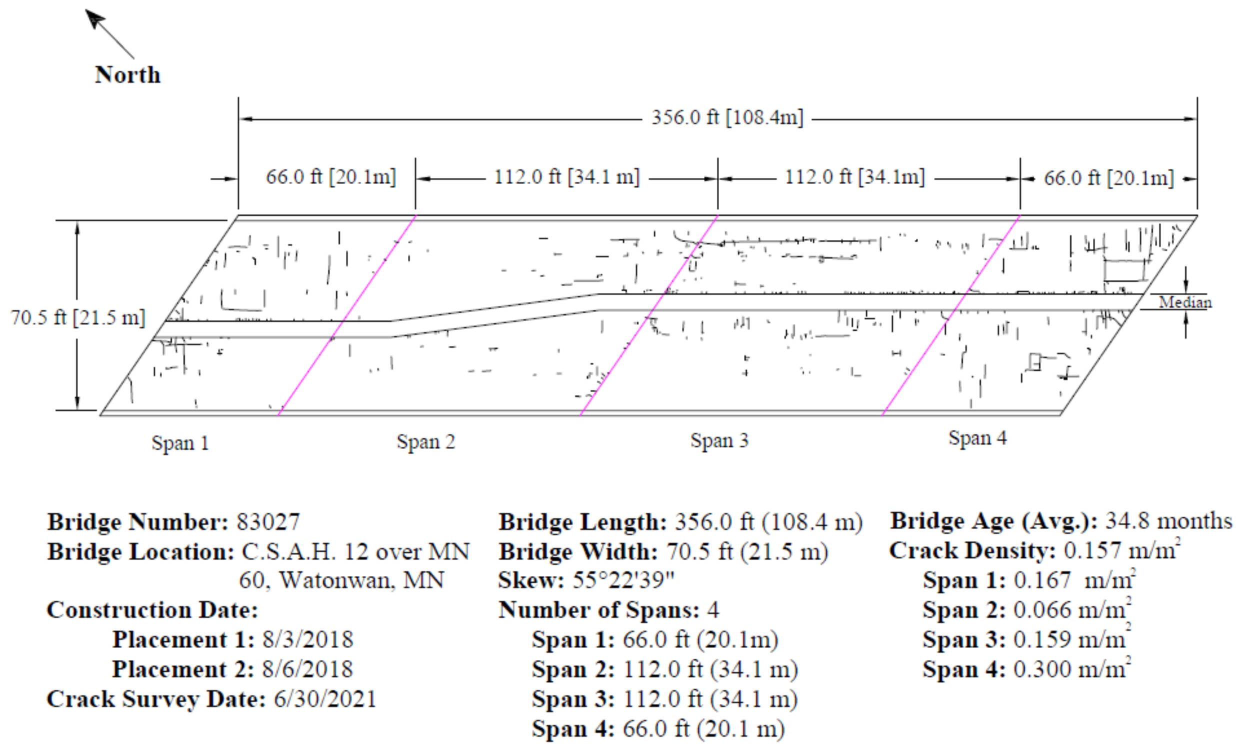


Figure 3.26: Crack map of bridge 83027

3.20 CRACK DENSITIES AND CRACK WIDTH RESULTS

Table 3.2 summarizes the crack survey results, crack densities, and average crack widths of 19 decks (26 placements) covered in this study. Individual crack width measurements are provided in Appendix B.

Table 3.2: Crack Survey Results

Bridge No.	Technology	Fibers	Type of Girder	Deck/ Overlay Age (months)	Crack Density (m/m^2)	Crack Width Range (in.)	Avg. Crack Width (10^{-3} in.)
9071	Conventional	No Fibers	Steel	47.7	1.147	0.003 to 0.060	21
62924			Steel	73.6	0.562	0.009 to 0.060	32
19004 NB			Post-Tensioned Slab	95.9	0.787	0.003 to 0.010	5
19004-SB			Post-Tensioned Slab	95.9	1.065	0.003 to 0.013	5
62038			Prestressed	73.4	1.916	0.003 to 0.060	15
83026			Prestressed	25.8	0.370	0.009 to 0.040	21
83027			Prestressed	34.8	0.157	0.007 to 0.030	17
62925			Steel	71.1	0.360	0.003 to 0.060	26
22801	Silica fume	Fibers	Steel	14.2	0.159	0.009 to 0.040	18
22802			Steel	23.5	0.047	0.009 to 0.025	15
46824			Prestressed	23.6	0.005	0.007 to 0.020	11
46831			Prestressed	23.6	0.016	0.004 to 0.018	11
46835			Prestressed	23.6	0.006	0.016 to 0.025	20
46836			Prestressed	12.7	0.016	0.002 to 0.020	13
62652			Prestressed	11.9	0.027	0.003 to 0.016	7
9689			Prestressed	46.5	0.622	0.005 to 0.030	14
7268	Monolithic	No Fibers	Steel	95.2	0.547	0.003 to 0.060	25
10004-U4			Prestressed	70.4	0.093	0.006 to 0.025	18
10004-U7			Prestressed	71.9	0.110	0.009 to 0.013	10
10004-U8			Prestressed	71.7	0.105	0.009 to 0.025	15
10004-U10			Prestressed	71.3	0.085	0.003 to 0.013	9
7263		Fibers	Steel	26.6	0.144	0.003 to 0.030	12
27133-P1			Steel	22.9	0.450	0.007 to 0.060	29
27133-P2			Steel	22.4	0.364		
10004-U5			Prestressed	70.4	0.028	0.009 to 0.016	12
10004-U9			Prestressed	71.5	0.132	0.003 to 0.020	12

3.21 CRACK DENSITIES AS A FUNCTION OF CRACK LENGTH

Figures 3.27 and 3.28 compare the crack densities based on (1) total cracking, (2) cracks with lengths ≥ 1 ft (305 mm), and (3) cracks with lengths ≥ 6 in. (150 mm), for decks with and without fibers, respectively. The figures also compare the crack densities with varying crack lengths among conventional overlay, silica fume overlay, and monolithic decks. The figures show that the vast majority of the cracks had lengths greater than 1 ft (305 mm) for all types of decks, regardless of the presence of fibers.

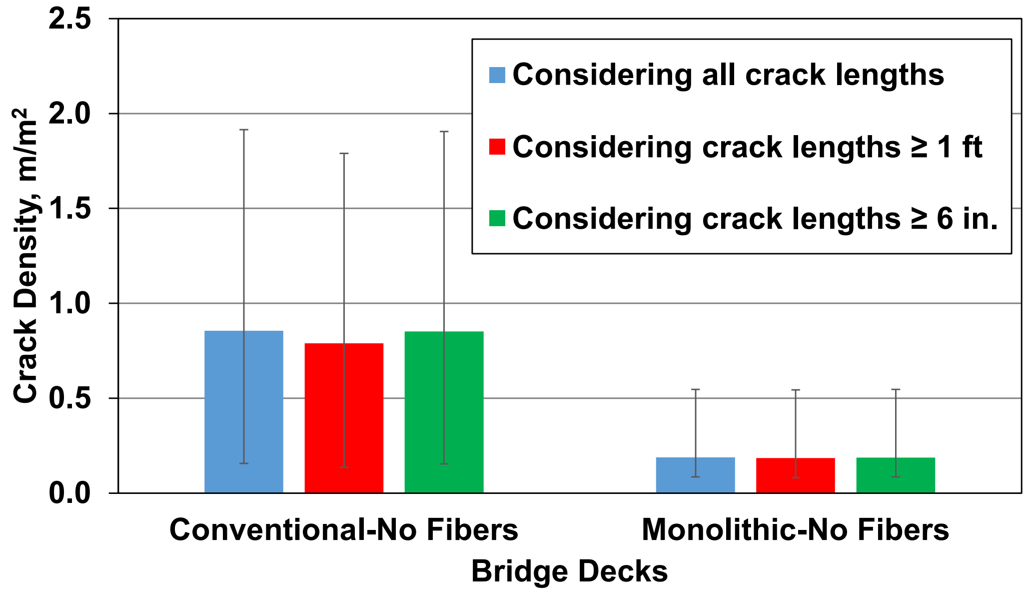


Figure 3.27: Comparison of crack densities, total, cracks with lengths ≥ 1 ft (305 mm), and cracks with lengths ≥ 6 in. (150 mm) for decks with conventional overlays and monolithic decks without fibers

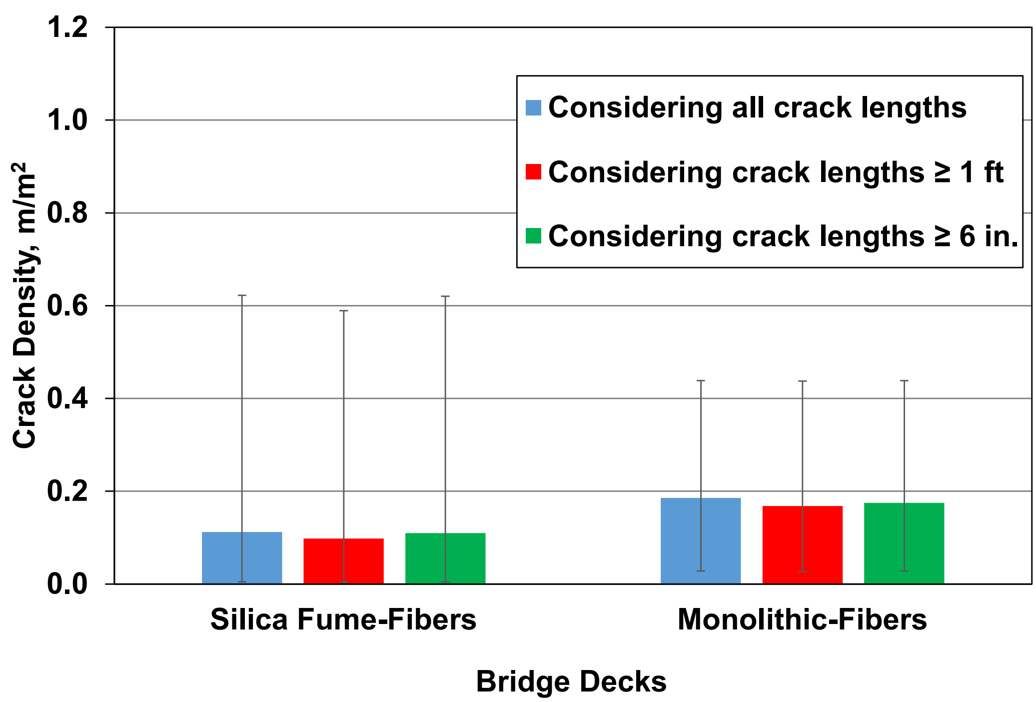


Figure 3.28: Comparison of crack densities, total, cracks with lengths ≥ 1 ft (305 mm), and cracks with lengths ≥ 6 in. (150 mm), for decks with silica fume decks with fibers, and monolithic decks with fibers.

CHAPTER 4: CRACK DENSITY ESTIMATION AT 36 MONTHS

The crack density of bridge decks increases over time. Since the bridge decks in this study had different ages at the time of the crack survey, ranging from 12 to 96 months, a fair comparison is not possible unless the crack densities are compared at the same deck age. For surveys that are performed on the same deck over many years, estimating the crack density for a given bridge deck at a given age usually involves simple interpolation. In the present study, however, another approach is necessary, which is based on rates of change in crack density observed for multiple bridge decks from previous studies. In this report, the cracking rate of the overlay decks are examined for two time intervals: 0 to 48 months and after 48 months. To justify this approach, the crack densities of decks the served as controls in Kansas, all of which had overlays, are shown in Figure 4.1. For the most part, the crack densities of the decks increased linearly up to an age of 48 months, as shown within the blue rectangle. After 48 months, the crack densities largely stabilized, remaining almost constant, as shown within the green rectangle, except for Control 12, which exhibited increases in crack density after 48 months (Pendergrass and Darwin 2014).

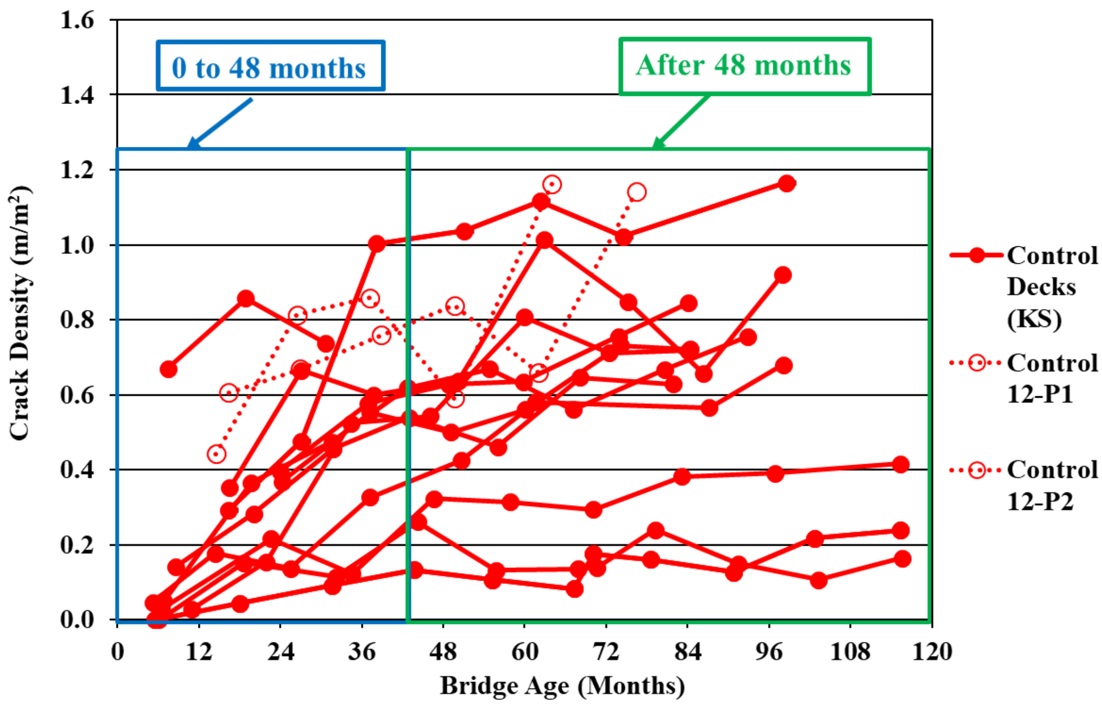


Figure 4.1: Crack densities for control decks in Kansas (All with Overlays)

The procedure described in Appendix C is used to estimate the crack densities of the bridges in this study at an age of 36 months, shown in Table 4.1, for the decks with an overlay. For the monolithic decks, the procedure used to estimate the crack densities of the bridges in this study at an age of 36 months is presented by Bahadori et al. (2022) and in Appendix C.2. It is worth noting that, as shown in Figure 4.1, crack densities can increase significantly between 24 and 36 months (Khajehdehi and Darwin 2018) with the result that crack densities based on crack surveys taken before 36 months may underestimate the extent of the cracking at 36 months.

The bridge decks in this study are divided into two groups: bridge decks supported by steel girders, identified with a leading indicator of S and bridge decks supported by precast concrete girders or a post-tensioned slab, identified with a leading indicator of PS or PT, respectively. The decks surveyed in this study also have a trailing indicator of MN. The bridge decks supported by steel girders are categorized into four groups: bridge decks with conventional overlays without fibers, S-CONVO-MN; bridge decks with silica fume overlays incorporating fibers, S-SFO-F-MN;

monolithic bridge decks without fibers, S-MONO-MN; and monolithic bridge decks incorporating fibers, S-MONO-F-MN. The bridge decks supported by precast concrete girders or a post-tensioned slab are categorized into five groups: precast concrete girder bridge decks with conventional overlays without fibers, PS-CONVO-MN; post-tensioned slab bridge decks with conventional overlays without fibers, PT-CONVO-MN; precast concrete girder bridge decks with silica fume overlays incorporating fibers, PS-SFO-F-MN; precast concrete girder monolithic bridge decks without fibers, PS-MONO-MN; and precast concrete girder monolithic bridge decks incorporating fibers, PS-MONO-F-MN. There are no silica fume overlay decks without fibers in this study. As shown in Table 4.1, the paste content of the overlays is used for the analysis of the decks with conventional and silica fume overlays, and the paste content of the decks is used for the analysis of the monolithic decks. The category, deck/overlay age, measured and the 36-month estimated crack densities are also shown.

Table 4.1: Estimated crack densities at an age of 36-month for the placements surveyed in this study

Bridge Number	**Category**	**Deck / Overlay Age (Months)**	**Paste Content Overlay/Deck (%)**	**Measured Crack Density (m/m^2)**	**36-Month Estimated Crack Density(m/m^2)**
9071	S-CONVO-MN	47.7	31.8	1.147	0.937
62924	S-CONVO-MN	73.6	31.8	0.562	0.457
62925	S-CONVO-MN	71.1	31.8	0.360	0.293
22801	S-SFO-F-MN	14.2	26.9	0.159	0.272
22802	S-SFO-F-MN	23.5	26.9	0.047	0.062
7268	S-MONO-MN	95.2	22.7	0.547	0.338
7263	S-MONO-F-MN	26.6	27.1	0.144	0.167
27133-P1	S-MONO-F-MN	22.9	26.0	0.450	0.511
27133-P2	S-MONO-F-MN	22.4	26.0	0.364	0.419
62038	PS-CONVO-MN	73.4	31.8	1.916	1.559
83026	PS-CONVO-MN	25.8	31.8	0.370	0.460
83027	PS-CONVO-MN	34.8	31.8	0.157	0.161

P = Placement

Table 4.1 (con't): Estimated crack densities at an age of 36-month for the placements surveyed in this study

Bridge Number	Category	Deck / Overlay Age (Months)	Paste Content Deck / Overlay (%)	Measured Crack Density (m/m^2)	36-Month Estimated Crack Density(m/m^2)
46824	PS-SFO-F-MN	23.6	26.9	0.005	0.007
46831	PS-SFO-F-MN	23.6	26.9	0.016	0.021
46835	PS-SFO-F-MN	23.6	26.9	0.006	0.008
46836	PS-SFO-F-MN	12.7	26.9	0.016	0.029
62652	PS-SFO-F-MN	11.9	28.0	0.027	0.050
9689	PS-SFO-F-MN	46.5	29.9	0.622	0.518
10004-U4	PS-MONO-MN	70.4	24.8	0.093	0.039
10004-U7	PS-MONO-MN	71.9	24.8	0.110	0.051
10004-U8	PS-MONO-MN	71.7	24.8	0.105	0.047
10004-U10	PS-MONO-MN	71.3	24.8	0.085	0.032
10004-U5	PS-MONO-F-MN	70.4	24.8	0.028	0.028
10004-U9	PS-MONO-F-MN	71.5	24.8	0.132	0.070
19004 NB	PT-CONVO-MN	95.9	31.8	0.787	0.640
19004-SB	PT-CONVO-MN	95.9	31.8	1.065	0.866

P = Placement; U = Unit; NB = Northbound; SB = Southbound

Figure 4.2 shows the average 36-month crack densities for the bridge decks (nine placements) supported by steel girders. An increase in cracking has been correlated with poor construction procedures (Khajehdehi and Darwin 2018, 2021, Feng and Darwin 2020, Lafikes et al. 2020). This may be the case for the decks on bridges 7268, 27133 Placement 1, and 27133 Placement 2, which are monolithic decks supported by steel girders. These decks have 36-month crack densities above 0.3 m/m^2, and suspected to have had poor construction procedures, as described in Section 5.2.2. The small number of decks in each category precludes a statistical comparison of the crack densities.

Figure 4.3 shows the average 36-month crack densities of the bridge decks (17 placements) supported by prestressed concrete girders or a post-tensioned slab. The placements with a conventional overlay supported by a post-tensioned slab have the highest average 36-month crack density, 0.753 m/m^2. The monolithic decks have the lowest crack densities, 0.042 and 0.049 m/m^2, for decks with and without fibers, respectively. The low crack density exhibited by the decks with silica fume overlays may be tied to the fact that all of these decks were surveyed less than 36 months after construction.

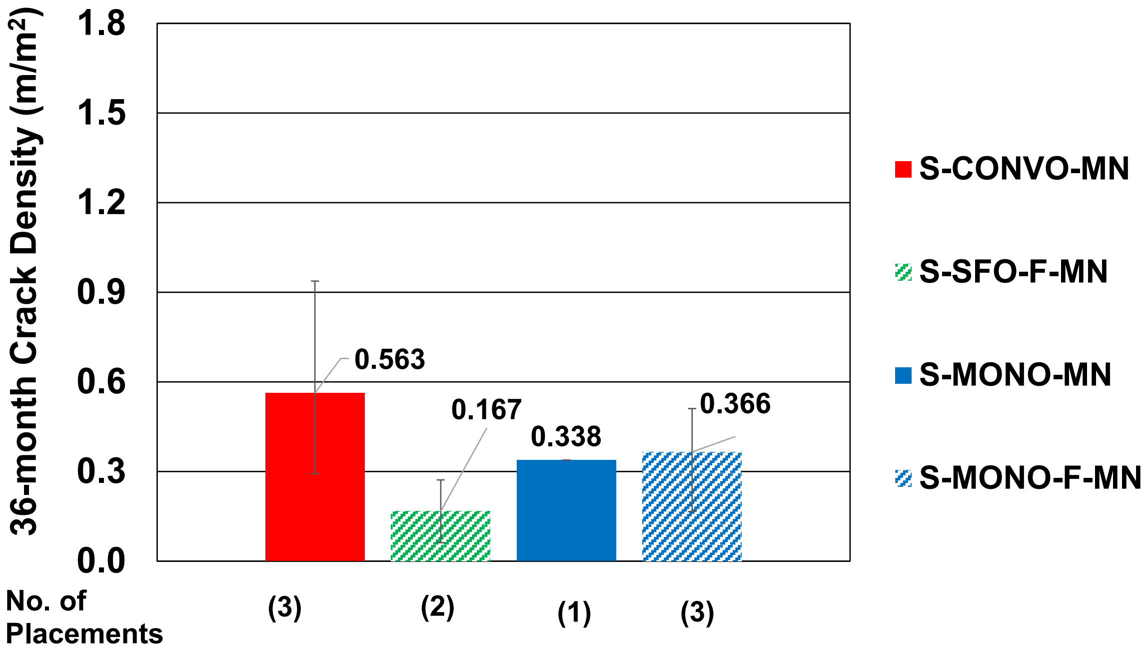


Figure 4.2: Average crack densities at 36 months for bridge decks supported by steel girders

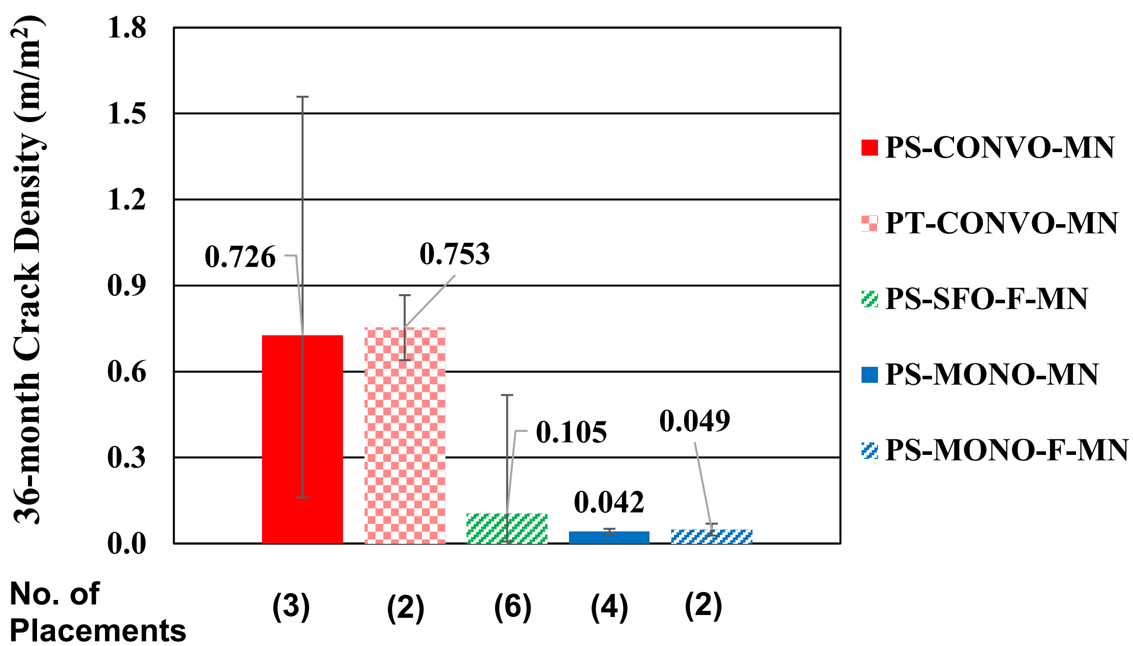


Figure 4.3: Average crack densities at 36 months for bridge decks supported by prestressed concrete girders or a post-tensioned slab

As shown in Tables 4.2 and 4.3, the difference in the average 36-month estimated crack densities of the conventional overlay decks supported by a post-tensioned slab and the monolithic decks supported by prestressed concrete girders is statistically significant (with a *p*-value of 0.001), with monolithic decks having lower crack densities, indicating that the use of overlays to improve bridge deck cracking performance is not supported by the data obtained in this study, as has been demonstrated before (Lindquist et al. 2005).

Table 4.2: *p*-values obtained in Student's t-test comparing the 36-month estimated crack density of decks without fibers supported by prestressed concrete girders or a post-tensioned slab

Bridges (No. of Placements)	**Group**	**PS-CONVO-MN (3)**	**PT-CONVO-MN (2)**	**PS-MONO-MN (4)**
Group	**Average**	**0.726**	**0.753**	**0.042**
PS-CONVO-MN (3)	**0.726**		0.964	0.113
PT-CONVO-MN (2)	**0.753**			**0.001**

Table 4.3: *p*-values obtained in Student's t-test comparing the 36-month estimated crack density of decks with fibers supported by prestressed concrete girders

Bridges (No. of Placements)	**Group**	**PS-SFO-F-MN (6)**	**PS-MONO-F-MN (2)**
Group	**Average**	**0.105**	**0.049**
PS-SFO-F-MN (6)	**0.105**		0.721

CHAPTER 5: BRIDGE DECKS USED FOR COMPARISON WITH SURVEYED DECKS

Crack survey results from 50 bridge deck placements with overlays in Kansas and Minnesota and 74 monolithic (one-course) bridge deck placements in Kansas, Virginia, and Indiana are used to evaluate the 16 bridge deck placements with overlays and the 10 monolithic bridge deck placements surveyed in this study. The earlier survey results are based on research at the University of Kansas (KU) dating back to the early 1990s. Over that period, KU surveyors have performed more than 665 field surveys on over 225 bridge deck placements. Previous studies have shown that although many factors are involved in bridge deck cracking, the primary factors are functions of the concrete material properties and construction procedures.

The primary variables in the current study are the type of deck (conventional overlay, silica fume overlay, or monolithic), fiber reinforcement (FRC), girder type (steel, prestressed concrete, or box girders), and construction procedures of monolithic decks.

The 50 bridge decks with overlays from previous studies are described in Section 5.1. The 74 monolithic (single-coarse) bridge deck placements are described in Section 5.2.

5.1 BRIDGE DECKS WITH OVERLAYS

The 50 bridge decks with overlays from previous studies are categorized into seven groups. Each group includes decks that were surveyed at least twice. The decks in each group have the same type of overlay, girders, and crack reducing technologies.

Group 1 includes 12 control decks in Kansas with silica fume overlays without fibers supported by steel girders, as shown in Table 5.1. Surveys on these decks are reported by Schmitt and Darwin (1995), Miller and Darwin (2000), Lindquist et al. (2005), Gruman et al. (2009), McLeod et al. (2009), Yuan et al. (2011), Pendergrass et al. (2011), Kaul et al. (2012), Bohaty et al. (2013), Pendergrass and Darwin (2014), Alhmood, et al. (2015), and Darwin et al. (2016). The bridge deck placements in Group 1 are labeled S-SFO and overlays contain a 7% mass replacement of portland cement with silica fume.

Table 5.1: Bridge decks in Group 1

Bridge Deck Placement[a]	Bridge Deck Placement[a]
Control 1/2-P1 (S-SFO)	Control 7-P2 (S-SFO)
Control 1/2-P2 (S-SFO)	Control 9-P1 (S-SFO)
Control 3 (S-SFO)	Control 9-P2 (S-SFO)
Control 4 (S-SFO)	Control 12-P1 (S-SFO)
Control 6 (S-SFO)	Control 12-P2 (S-SFO)
Control 7-P1 (S-SFO)	Control 13 (S-SFO)

[a]P = Placement; S = Steel girder; SFO = Silica Fume Overlay

Group 2 includes 23 decks in Kansas with silica fume overlays without fibers supported by steel girders, as shown in Table 5.2. Surveys of these decks are reported by Schmitt and Darwin (1995), Miller and Darwin (2000), and Lindquist et al. (2005). The bridge deck placements in Group 2 are labeled as S-SFO and the overlays contain 5% mass replacement of portland cement with silica fume.

Table 5.2: Bridge decks in Group 2

Bridge Deck Placement[a]	Bridge Deck Placement[a]
46-317-SFO 12’ (S-SFO)	87-454-Lt (S-SFO)
81-50-Lt (S-SFO)	46-309-Lt (S-SFO)
46-302-Lt (S-SFO)	89-206-Lt (S-SFO)
46-302-Rt (S-SFO)	89-210-Rt (S-SFO)
87-454-Rt (S-SFO)	46-309-Rt (S-SFO)
89-234-Center (S-SFO)	89-207-Lt (S-SFO)
23-85-West (S-SFO)	23-85-East (S-SFO)
46-317-SFO 16’ (S-SFO)	89-210-Lt (S-SFO)
89-234-North (S-SFO)	89-184-In (S-SFO)
81-50-Rt (S-SFO)	89-184-Out (S-SFO)
89-207-Rt (S-SFO)	89-187-Out (S-SFO)
89-234-SFO South (S-SFO)	

[a]Lt = Left Placement; Rt = Right Placement; In = Inside Placement; Out = Outside Placement; S = Steel girder; SFO = Silica Fume Overlay

Groups 3, 4 and 5 include a total of three decks with silica fume overlays. The deck in Group 3 has a silica fume overlay with fibers and is supported by steel girders; the deck in Group 4 has a silica fume overlay without fibers and is supported by steel girders; and the deck in Group 5 has a silica fume overlay with fibers and is supported by prestressed concrete girder. Surveys on these decks are reported by Harley et al. (2011), and Shrestha et al. (2013). These bridges are located on highway US-59 south of Lawrence, Kansas. US-59-5 (Group 3) is labeled as S-SFO-F and contains a 3.9% mass replacement of portland cement with silica fume and 5 lb/yd^3 of macro fibers in the overlay. US-59-6 (Group 4) is labeled as S-SFO and contains 3.9% mass replacement of portland cement with silica fume and no fibers in the overlay. US-59-11 (Group 5) is labeled as PS-SFO and contains 7.8% mass replacement of portland cement with silica fume and no fibers in the overlay.

Table 5.3: Bridge deck in Group 3

Bridge Deck Placement[a]	Bridge Deck Placement[a]
US-59-5 (S-SFO-F)	

[a]S = Steel girder; SFO = Silica Fume Overlay; F = With Fibers

Table 5.4: Bridge deck in Group 4

Bridge Deck Placement[a]	Bridge Deck Placement[a]
US-59-6 (S-SFO)	

[a]S = Steel girder; SFO = Silica Fume Overlay

Table 5.5: Bridge deck in Group 5

Bridge Deck Placement[a]	Bridge Deck Placement[a]
US-59-11 (PS-SFO)	

[a]PS = Prestressed Concrete girder; SFO = Silica Fume Overlay

Group 6 includes nine decks in Kansas with conventional overlays supported by steel girders. Surveys on these decks are reported by Schmitt and Darwin (1995), Miller and Darwin (2000), and Lindquist et al. (2005). The bridge deck placements in Group 6 are labeled as S-CONVO and contain 100% portland cement in the overlay.

Table 5.6: Bridge decks in Group 6

Bridge Deck Placement[a]	Bridge Deck Placement[a]
89-186-Out (S-CONVO)	46-301-Lt (S-CONVO)
89-186-In (S-CONVO)	89-198-Rt (S-CONVO)
89-201-Rt (S-CONVO)	89-199-Lt (S-CONVO)
89-200-Rt (S-CONVO)	46-300-Lt (S-CONVO)
89-185-Out (S-CONVO)	

[a]Lt = Left Placement; Rt = Right Placement; In = Inside Placement; Out = Outside Placement; S = Steel girder; CONVO = Conventional Overlay

Group 7 includes three decks in Minnesota with conventional overlays without fibers supported by steel girders. Surveys on these decks are reported by Bahadori et al. (2023). The bridge deck placements in Group 7 are labeled as PS-CONVO and contains 100% portland cement in the overlay.

Table 5.7: Bridge decks in Group 7

Bridge Deck Placement[a]	Bridge Deck Placement[a]
IC-LC-HPC-2 (PS-CONVO)	MN-Control-2 (PS-CONVO)
IC-LC-HPC-3 (PS-CONVO)	

[a]PS = Prestressed concrete girder; CONVO = Conventional Overlay

5.2 MONOLITHIC BRIDGE DECKS

The monolithic decks in this study are evaluated using the crack survey results from 74 monolithic (one-course) bridge deck placements in Kansas, Virginia, and Indiana, as presented in by Bahadori et al (2022). The primary variables include paste content, ranging from 22.8 to 29.4%, a crack-reducing technology; low-cracking high-performance concrete (LC-HPC), internal curing (IC), fiber reinforcement (FRC), shrinkage-reducing admixtures (SRA); girder type (steel, prestressed concrete, or box girders); and construction procedures (of the 74 decks, 62 were constructed with good construction procedures and 12 with poor construction procedures). Each placement is treated as a different deck and analyzed individually. The procedure described by Bahadori et al. (2022) is used to calculate the crack densities of the 74 monolithic bridge decks at an age of 36 months. The labeling used for the bridge deck placements has been modified from that used by Bahadori et al. (2022) to keep the identifiers consistent within this report. The bridge decks are categorized into eight groups, as described in the following sections.

5.2.1 Monolithic Bridge Decks with Good Construction Procedures

The 62 monolithic bridge deck placements with no construction issues are organized into seven groups. The decks in each group have the same type of deck, girders, and crack-reducing technologies.

Group 1 includes 43 monolithic bridge deck placements with the decks supported by steel girders without the use of a crack-reducing technology with the exception that some decks were constructed following low-cracking high-performance concrete (LC-HPC) specifications. Surveys of 24 of the placements are reported by Schmitt and Darwin (1995), Miller and Darwin (2000), and Lindquist et al. (2005) on decks constructed following Standard Kansas Department of Transportation (KDOT) specifications. Surveys on 12 of the placements are reported by Lindquist et al. (2008), McLeod et al. (2009), Yuan et al. (2011), Pendergrass and Darwin (2014), Bohaty et al. (2013), and Alhmood et al. (2015) on the decks constructed in Kansas as part of a 13-year two-phase Pooled-Fund study at KU following low-cracking high-performance concrete specifications. Surveys of two of the decks are reported by Harley et al. (2011) and Shrestha et al. (2013). These bridges are located on highway US-59 south of Lawrence, Kansas and are referred to as the US-59 decks. Surveys of three of the decks, referred to as Control, are reported by Feng and Darwin (2020). These bridges are located on highway K-10 south of Lawrence, Kansas. Surveys of one deck, referred to as VA Control, constructed near Fredericksburg, Virginia, are reported by Polley et al. (2015) and Feng and Darwin (2020), and surveys of one deck, referred to as Extra Control, constructed in 2005 in Kansas, are described by Khajehdehi and Darwin (2018). The bridge deck placements in Group 1 are labeled S-MONO. The decks in this group had paste contents ranging from 23.4 to 29.4% of the concrete volume, as shown in Table 5.8.

Table 5.8: Paste contents of the bridge decks in Group 1, (S)

Bridge Deck Placement	**Paste Content (%)**	**Bridge Deck Placement**	**Paste Content (%)**
Conv*. 3-046 Ctr. Deck (S-MONO)	25.7	Conv. 99-076 North (West Ln.) (S-MONO)	28.7
Conv. 3-045 E. Ctr. Deck (S-MONO)	26.4	Conv. 99-076 p4 (S-MONO)	28.7
Conv. 70-095 Deck (S-MONO)	27.2	LC-HPC 1 p1 (S-MONO)	24.6
Conv. 70-104 Deck (S-MONO)	27.2	LC-HPC 1 p2 (S-MONO)	24.6

Table 5.8 (con't): Paste contents of the bridge decks in Group 1, (S)

<table>
<tr><th>Bridge Deck Placement</th><th>Paste Content (%)</th><th>Bridge Deck Placement</th><th>Paste Content (%)</th></tr>
<tr><td>Conv. 70-103 Left (S-MONO)</td><td>27.2</td><td>LC-HPC 2 (S-MONO)</td><td>24.6</td></tr>
<tr><td>Conv. 70-103 Right (S-MONO)</td><td>27.2</td><td>LC-HPC 4 p2 (S-MONO)</td><td>23.4</td></tr>
<tr><td>Conv. 3-045 East Deck (S-MONO)</td><td>26.4</td><td>LC-HPC 5 (S-MONO)</td><td>23.9</td></tr>
<tr><td>Conv. 3-045 Ctr. Deck (S-MONO)</td><td>26.4</td><td>LC-HPC 6 (S-MONO)</td><td>24.4</td></tr>
<tr><td>Conv. 3-046 East Deck (S-MONO)</td><td>26.4</td><td>LC-HPC 7 (S-MONO)</td><td>24.6</td></tr>
<tr><td>Conv. 99-076 North (East Ln.) (S-MONO)</td><td>28.7</td><td>LC-HPC 9 (S-MONO)</td><td>24.2</td></tr>
<tr><td>Conv. 56-148 Deck (S-MONO)</td><td>27.2</td><td>LC-HPC 11 (North Ln.) (S-MONO)</td><td>23.4</td></tr>
<tr><td>Conv. 75-044 Deck (S-MONO)</td><td>27.9</td><td>LC-HPC 15 (S-MONO)</td><td>22.8</td></tr>
<tr><td>Conv. 3-045 West Deck (S-MONO)</td><td>26.4</td><td>LC-HPC 16 (S-MONO)</td><td>22.8</td></tr>
<tr><td>Conv. 3-045 W. Ctr. Deck (S-MONO)</td><td>26.4</td><td>LC-HPC 17 (S-MONO)</td><td>24.6</td></tr>
<tr><td>Conv. 3-046 West Deck (S-MONO)</td><td>26.4</td><td>US 59 1 (S-MONO)</td><td>24.0</td></tr>
<tr><td>Conv. 70-107 Deck (S-MONO)</td><td>27.2</td><td>US 59 2 (S-MONO)</td><td>24.0</td></tr>
<tr><td>Conv. 56-142 N. Pier (S-MONO)</td><td>26.5</td><td>Control 5 (Eastbound) (S-MONO)</td><td>24.7</td></tr>
<tr><td>Conv. 56-142 + Moment (S-MONO)</td><td>26.5</td><td>Control 6 (Eastbound) (S-MONO)</td><td>24.6</td></tr>
<tr><td>Conv. 89-208 Deck (S-MONO)</td><td>27.1</td><td>Control 7 (Eastbound) (S-MONO)</td><td>24.6</td></tr>
<tr><td>Conv. 89-204 Deck (S-MONO)</td><td>28.8</td><td>VA Control (S-MONO)</td><td>29.4</td></tr>
<tr><td>Conv. 99-076 p3** (S-MONO)</td><td>27.9</td><td rowspan="2">Extra Control (S-MONO)</td><td rowspan="2">25.7</td></tr>
<tr><td>Conv. 99-076 p5 (S-MONO)</td><td>28.7</td></tr>
</table>

* Conv. = Conventional deck
** p = placement

Group 2 consists of six monolithic bridge deck placements incorporating fibers supported by steel girders (Feng and Darwin 2020). The bridges are located in Wyandotte, Shawnee, and Douglas Counties in Kansas. The paste contents of these decks ranged from just 23.8 to 24.7% of the concrete volume. The bridge deck placements in Group 2 are labeled S-MONO-F. The paste contents of the bridge decks in Group 2 are shown in Table 5.9.

Table 5.9: Paste contents of the bridge decks in Group 2, (S-F)

Bridge Deck Placement	Paste Content (%)
Fiber 1 NB p1* (S-MONO-F)	23.8
Fiber 1 NB p2 (S-MONO-F)	23.8
Fiber 2 SB p1 (S-MONO-F)	23.8
Fiber 5 WB (S-MONO-F)	24.7
Fiber 6 WB (S-MONO-F)	24.6
Fiber 7 WB (S-MONO-F)	24.6

* p = placement

Group 3 consists of four monolithic bridge deck placements incorporating internal curing (IC) water supported by steel girders. The bridge deck placements (identified as IN-HPC-IC) are located in two districts, Seymour and Vincennes, in Indiana (Lafikes et al. 2020). Bridge deck placements in Group 3 are labeled S-MONO-IC. The paste contents of these decks ranged from 25.3 to 26.0% of the concrete volume, as shown in Table 5.10.

Table 5.10: Paste contents of the bridge decks in Group 3, (S-IC)

Bridge Deck Placement	Paste Content (%)
IN-HPC-IC-2 (S-MONO-IC)	25.3
IN-HPC-IC-3 (S-MONO-IC)	25.9
IN-HPC-IC-4 p1* (S-MONO-IC)	25.7
IN-HPC-IC-4 p2 (S-MONO-IC)	26.0

* p = placement

Group 4 consists of two monolithic bridge deck placements incorporating shrinkage-reducing admixtures (SRAs) supported by steel girders. The bridge decks (VA-SRA) are located in Staunton and Fredericksburg, Virginia (Polley et al. 2015, Feng and Darwin 2020). Bridge deck placements included in Group 4 are labeled S-MONO-SRA. The paste contents of these decks were 27.0 or 27.3%, as shown in Table 5.11.

Table 5.11: Paste contents of the bridge decks in Group 4, (S-SRA)

Bridge Deck Placement	Paste Content (%)
VA-SRA 4 (S-MONO-SRA)	27.0
VA-SRA 8 (S-MONO-SRA)	27.3

Group 5 consists of three monolithic bridge deck placements without crack-reducing technology supported by prestressed concrete girders. The decks were constructed as part of a 13-year Pooled-Fund program at KU, two following (LC-HPC) specifications and one deck (Control 8/10) constructed following KDOT specifications (Lindquist et al. 2008, McLeod et al. 2009, Yuan et al. 2011, Pendergrass and Darwin 2014, Bohaty et al. 2013, Alhmood et al. 2015). Bridge decks included in Group 5 are labeled PS-MONO. The paste contents of these decks ranged from 23.4 to 26.0%, as shown in Table 5.12.

Table 5.12: Paste contents of the bridge decks in Group 5, (PS)

Bridge Deck Placement	Paste Content (%)
LC-HPC 8 (PS-MONO)	23.4
LC-HPC 10 (PS-MONO)	23.4
Control 8/10 (PS-MONO)	26.0

Group 6 consists of two monolithic bridge deck placements incorporating fibers supported by prestressed concrete girders located on US-59 south of Lawrence, Kansas (Harley et al. 2011, Shrestha et al. 2013). Bridge decks included in Group 6 are labeled as PS-MONO-F. Both decks had a paste content of 26.4% by volume of concrete, as shown in Table 5.13.

Table 5.13: Paste contents of the bridge decks in Group 5, (PS-MONO-F)

Bridge Deck Placement	Paste Content (%)
US-59 10 (PS-MONO-F)	26.4
US-59 12 (PS-MONO-F)	26.4

Group 7 consists of two monolithic bridge deck placements supported by prestressed box girders. The bridges are located near Seymour, Indiana. One deck (IN-Control) incorporated no crack-reducing technology and the other (IN-IC) incorporated internal curing (Lafikes et al. 2020). The bridge decks included in Group are labeled as PS Box-MONO and PS Box-MONO-IC, respectively. Both decks had a paste content of 27.6% by volume of concrete (Table 5.14).

Table 5.14: Paste contents of the bridge decks in Group 7, (PS-Box/PS-Box-IC)

Bridge Deck Placement	Paste Content (%)
IN-Control (PS Box-MONO)	27.6
IN-IC (PS Box-MONO-IC)	27.6

Summary: The 36-month crack densities of the bridge decks used for comparison in this study are shown in Table 5.15. The procedures used to calculate these values are presented by Bahadori et al. (2022) in Section C.2 of Appendix C. The detailed crack survey results are documented by Lindquist et al. (2006) and Khajehdehi and Darwin (2018) for the Conventional decks and the extra control deck constructed in Kansas; by Darwin et al. (2016) for the LC-HPC decks constructed in Kansas; by Shrestha et al. (2013) for the south of Lawrence bridge decks; by Polley et al. (2015) for the decks in Virginia containing SRAs, Feng and Darwin (2020) for the decks in Kansas containing fiber reinforcement and by Lafikes et al. (2020) for the Indiana decks with and without IC technology.

Table 5.15: Crack density of bridge decks used for comparison at 36 months of age

Bridge Deck Placement	Crack Density (m/m^2)	Bridge Deck Placement	Crack Density (m/m^2)
*Conv. 3-046 Ctr. Deck (S-MONO)	0.042	LC-HPC 8 (S-MONO)	0.358
Conv. 3-045 E. Ctr. Deck (S-MONO)	0.043	LC-HPC 9 (S-MONO)	0.325
Conv. 70-095 Deck (S-MONO)	0.025	LC-HPC 10 (PS-MONO)	0.029
Conv. 70-104 Deck (S-MONO)	0.069	LC-HPC 11 (North Ln.) (S-MONO)	0.163
Conv. 70-103 Left (S-MONO)	0.391	LC-HPC 15 (S-MONO)	0.227
Conv. 70-103 Right (S-MONO)	0.253	LC-HPC 16 (S-MONO)	0.250
Conv. 3-045 East Deck (S-MONO)	0.078	LC-HPC 17 (S-MONO)	0.283
Conv. 3-045 Ctr. Deck (S-MONO)	0.174	US 59 1 (S-MONO)	0.391
Conv. 3-046 East Deck (S-MONO)	0.392	US 59 2 (S-MONO)	0.242
Conv. 99-076 North (East Ln.) (S-MONO)	0.412	US 59 10 (PS-F)	0.178
Conv. 56-148 Deck (S-MONO)	0.259	US 59 12 (PS-MONO-F)	0.047
Conv. 75-044 Deck (S-MONO)	0.165	Fiber 1 NB p1 (S-MONO-F)	0.112
Conv. 3-045 West Deck (S-MONO)	0.074	Fiber 1 NB p2 (S-MONO-F)	0.220
Conv. 3-045 W. Ctr. Deck (S-MONO)	0.178	Fiber 2 SB p1 (S-MONO-F)	0.127
Conv. 3-046 West Deck (S-MONO)	0.254	Fiber 5 WB (S-MONO-F)	0.061
Conv. 70-107 Deck (S-MONO)	0.322	Fiber 6 WB (S-MONO-F)	0.011
Conv. 56-142 N. Pier (S-MONO)	0.064	Fiber 7 WB (S-MONO-F)	0.004
Conv. 56-142 + Moment (S-MONO)	0.071	Control 5 (Eastbound) (S-MONO)	0.052
Conv. 89-208 Deck (S-MONO)	0.009	Control 6 (Eastbound) (S-MONO)	0.011
Conv. 89-204 Deck (S-MONO)	0.736	Control 7 (Eastbound) (S-MONO)	0.033
Conv. 99-076 p3 (S-MONO)	0.739	Control 8/10 (PS-MONO)	0.136
Conv. 99-076 p5 (S-MONO)	0.861	VA Control (S-MONO)	0.232
Conv. 99-076 North (West Ln.) (S-MONO)	0.801	VA-SRA 4 (S-MONO-SRA)	0.083
Conv. 99-076 p4 (S-MONO)	0.872	VA-SRA 8 (S-MONO-SRA)	0.056
LC-HPC 1 p1** (S-MONO)	0.049	IN-IC (PS Box-MONO-IC)	0.181
LC-HPC 1 p2 (S-MONO)	0.024	IN-Control (PS Box-MONO)	0.236
LC-HPC 2 (S-MONO)	0.048	IN-HPC-IC-2 (S-MONO-IC)	0.003
LC-HPC 4 p2 (S-MONO)	0.090	IN-HPC-IC-3 (S-MONO-IC)	0.061
LC-HPC 5 (S-MONO)	0.154	IN-HPC-IC-4 p1 (S-MONO-IC)	0.214
LC-HPC 6 (S-MONO)	0.271	IN-HPC-IC-4 p2 (S-MONO-IC)	0.032
LC-HPC 7 (S-MONO)	0.012	Extra Control (S-MONO)	0.215

* Conv. = Conventional deck
** p = placement

5.2.2 Bridge Decks With Poor Construction Procedures

The 12 bridge deck placements from previous studies (identified as Group 8) constructed with documented poor construction procedures were supported by steel girders. No prestressed girder bridges are in this group because very few decks supported by prestressed concrete girders were surveyed earlier in the studies based on earlier observation that cracking was higher on steel girder bridges (*Durability* 1970). Eight placements had no crack-reducing technology (S-MONO) and four contained fibers (S-MONO-F). Comparing the cracking in the Group 8 decks with that of the decks surveyed in this study is done to help identify the effects of construction procedures. The 36-month crack densities and concrete properties of the 12 bridge decks with poor construction procedures are provided in Table 5.16.

With reference to Table 5.16, the main issue associated with the construction of LC-HPC 12 p1 and p2, LC-HPC 13, Topeka Control p1 and p2, Topeka Fiber 1, and Topeka Fiber 2 p1 and p2 was the loss of consolidation caused by workers walking through freshly consolidated concrete. The contractor failed to re-consolidate the holes left in the concrete by the workers and merely relied on the finishing machine to cover them, which left the concrete susceptible to settlement cracking.

Poor practices were also observed during the construction of LC-HPC-14 and Fiber 2 SB p2. A variety of issues were observed in the construction of LC-HPC 14, including insufficient consolidation, overfinishing of the deck, and late delivery of concrete. As a result, the three placements on LC-HPC 14 exhibited the highest crack density of decks constructed under LC-HPC specifications, largely because the specifications were not followed. Additional details associated with the construction of LC-HPC-12, LC-HPC-13, and LC-HPC-14 are provided by McLeod et al. (2009), Pendergrass and Darwin (2014), and Khajehdehi and Darwin (2018). In addition, based on on-site observations, the contractor of Fiber 2 SB p2 did not follow many aspects of the specifications, resulting in a highly cracked bridge deck.

Table 5.16: 36-month crack density and concrete properties of decks with construction issues

Bridge Deck Placement	Crack Density (m/m^2)	Cement Paste (%)	Air Content (%)	Slump (in.)	28-day Strength (psi)
LC-HPC 12 p1 (S-MONO)	0.301	24.3	7.4	2¾	4600
LC-HPC 12 p2 (S-MONO)	0.332	24.2	7.8	4¼	4380
LC-HPC 13 (S-MONO)	0.344	24.1	8.1	3	4280
LC-HPC 14 p1 (S-MONO)	0.543	24.4	8.7	3¾	4440
LC-HPC 14 p2 (S-MONO)	1.223	24.4	9.8	4¼	3710
LC-HPC 14 p3 (S-MONO)	0.695	24.4	9.9	5¼	3830
Topeka Control p1 (S-MONO)	0.766	22.2	5.5	3¼	-[a]
Topeka Control p2 (S-MONO)	0.393	22.2	5.7	3¼	5700
Topeka Fiber 1 (S-MONO-F)	0.284	22.2	6.5	3¼	5230
Topeka Fiber 2 p1 (S-MONO-F)	0.709	22.2	6.5	3	5330
Topeka Fiber 2 p2 (S-MONO-F)	0.431	22.2	6.7	3¼	5530
Fiber 2 SB p2 (S-MONO-F)	0.456	23.8	5.3	5	5950

[a] Data not available

CHAPTER 6: COMPARISONS AND DISCUSSION

The effect of overlays (silica fume and fibers), crack reducing technology (fibers), and construction procedures on cracking of the 16 bridge deck placements with an overlay and the 10 monolithic bridge deck placements surveyed in this study are evaluated using the 50 bridge decks with overlays and the 74 monolithic bridge deck placements summarized in Chapter 5.

6.1 EFFECTS OF OVERLAYS

Overlays are used on bridge decks because the low permeability of the concrete used in the overlays is thought to reduce access of deicing chemicals to the concrete below (Schmitt and Darwin 1995). Curing is believed to be especially important. Ozyildirim (1991) observed that when silica fume overlays are not provided with good early curing, plastic shrinkage cracks form and increase in size over time. Lindquist et al. (2005) observed that cracking in silica fume overlay decks was greater than in conventional monolithic decks and decks with conventional overlays. As discussed in Chapter 4, decks with overlays increase in crack density until the overlay age reaches 48 months, with the crack density leveling off at later ages.

Lindquist et al. (2005) observed a significantly lower crack density for monolithic decks than for both silica fume overlays and conventional overlays. The higher crack density occurs due to the added restraint provided by the concrete deck to the overlay (Pendergrass and Darwin 2014). Increased plastic shrinkage can occur because bleed water is limited in concrete with silica fume (Krauss and Rogalla 1996). The silica fume overlays in the current study had a 3.9 to 7.8% mass replacement of portland cement with silica fume. Lindquist et al. (2005) observed no statistically significant differences in cracking between silica fume overlays with 5% and 7% mass replacements of portland cement with silica fume. Although the range of values used for silica fume replacement was greater in the current study, the number of decks with silica fume are considered a single deck type.

Miller and Darwin (2000) observed that the older conventional overlay decks (60 to 120 months old) exhibited crack densities that were almost equal to those of younger silica fume overlay decks (20 to 40 months old). They predicted (with some uncertainty) that the silica fume overlay deck will exhibit similar cracking performance as conventional overlays. In the current study, the decks with silica fume overlays were surveyed at an average age of 22 months, while the conventional overlays were surveyed at an average age of 64 months.

Due to the limited number of decks surveyed in this study, additional decks with similar girder types (steel, prestressed concrete, or box girders), type of deck (conventional overlay, silica fume overlay, or monolithic) and fiber content (FRC), as described in Chapter 5, are also included in this comparison. Because they now include additional decks for comparison purposes, the deck types are labeled with a trailing indicator of "ALL" in this chapter. For the monolithic decks, only the decks with good construction procedures, described in Section 5.2, are included; the three monolithic bridges with suspected construction issues in this study are analyzed separately in Section 6.3.

Figure 6.1 shows the average 36-month crack densities of the bridge decks without and with fibers (designated by F) for decks supported by steel girders (S). Error bars show the ranges of the crack densities for each deck type. The decks with a conventional overlay, labeled as CONVO, include 12 placements without fibers. The decks with a silica fume overlay, labeled as SFO, include 36 placements without fibers and 3 placements with fibers. The monolithic decks, labeled as S-MONO, include 43 placements without fibers and 7 placements with fibers (F). The conventional overlay decks without fibers, S-CONVO, have the highest average 36-month crack density, 0.566 m/m^2, followed by the decks with silica fume overlay decks, S-SFO, with a crack density of 0.450 m/m^2. The monolithic decks with fibers, S-MONO-F, have the lowest average 36-month crack density, 0.100 m/m^2. The other deck types exhibit average values of cracking between 0.206 and 0.241 m/m^2.

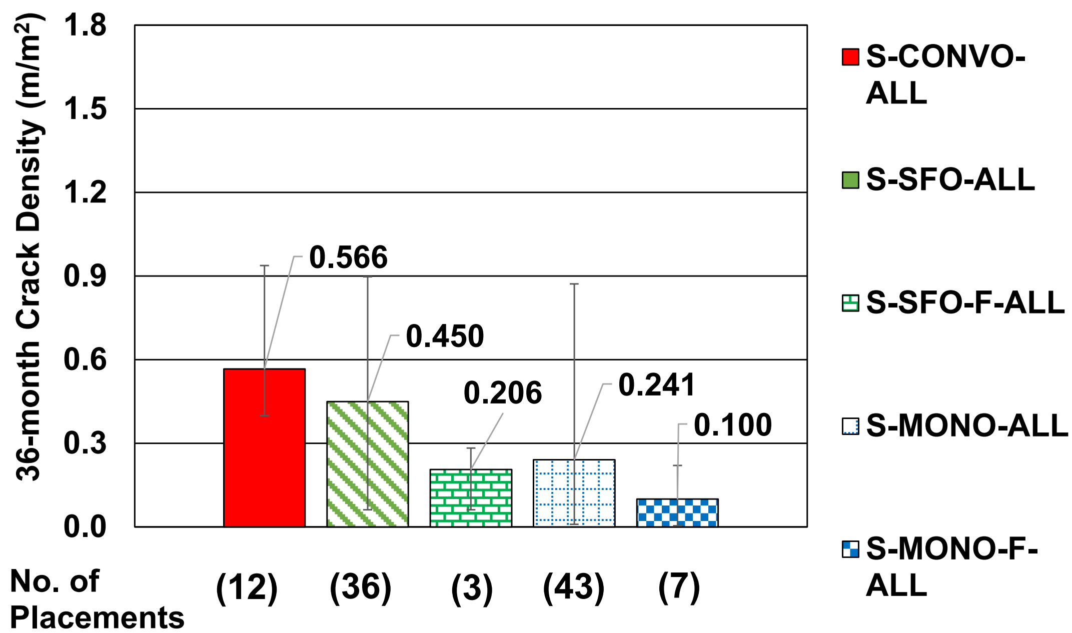


Figure 6.1: Average crack densities at 36 months for bridge decks supported by steel girders

Figure 6.2 shows the average 36-month crack density of the bridge decks without and with fibers (F) supported by prestressed concrete girders, box girders, or a post-tensioned slab (PS, PB, or PT, respectively). Error bars show the ranges of the crack densities for each deck type. The decks with a conventional overlay and supported by prestressed concrete girders, labeled as PS-CONVO-ALL, include 6 placements without fibers and no placements with fibers. The decks with a conventional overlay and supported by a post-tensioned slab, labeled as PT-CONVO-ALL, include 2 placements without fibers. The decks with a silica fume overlay supported by prestressed concrete girders, labeled as PS-SFO, include no placements without fibers and 7 placements with fibers. The monolithic decks supported by prestressed concrete girders, labeled as PS-MONO, include 7 placements without fibers and 4 placements with fibers. One monolithic deck supported by box girders is labeled as PS BOX-MONO-ALL and has no fibers. The decks with a conventional overlay and supported by post-tensioned slabs had the highest average 36-month crack density, 0.753 m/m^2. The monolithic decks with fibers have the lowest average 36-month crack density, 0.081 m/m^2.

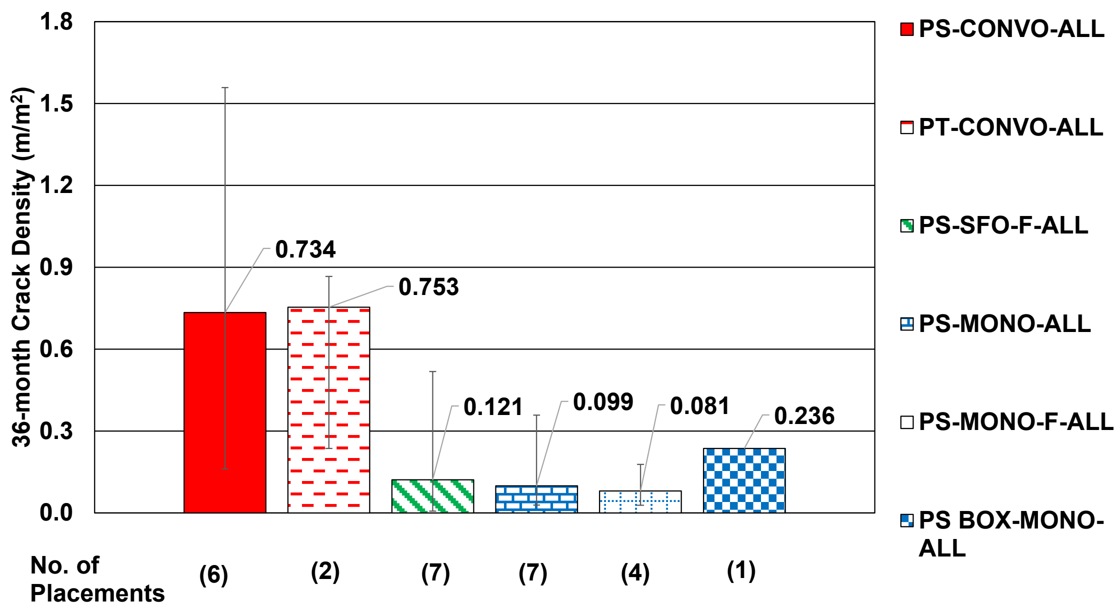


Figure 6.2: Average crack densities at 36 months for bridge decks supported by prestressed concrete or box girders or post-tensioned slabs

6.2 EFFECT OF PASTE CONTENT ON MONOLITHIC DECKS

Numerous studies have shown that concrete material properties play a crucial role in the durability and cracking of monolithic bridge decks. Cement paste content is the most dominant factor in concrete shrinkage and, consequently, cracking in bridge decks. The effects of paste content on the cracking performance of bridge decks have been addressed in numerous studies (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005, Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2020, Khajehdehi et al. 2021). In a study performed on 32 monolithic bridge decks, Schmitt and Darwin (1995, 1999) observed that concrete decks with a cement paste content greater than 27% (by concrete volume) showed significantly greater cracking than decks with lower paste contents. Based on an evaluation of the cracking performance of 40 monolithic bridge deck placements supported by steel girders at the age of 96 months, Khajehdehi and Darwin (2018) and Khajehdehi et al. (2021) showed that cracking of bridge decks with a paste content greater than 27.2% paste content was significantly higher than that of decks with a paste content of 26.4% or less.

In the current study, to evaluate the effect of paste content on the 10 monolithic deck placements, the decks have been categorized into two group: decks without construction issues (7 decks); and the decks potentially involving poor construction practices (3 decks [7268, 27133 Placement 1, and 27133 Placement 2]).[1] The reason for classifying the four decks separately is that they had paste contents below 26% but had crack densities above 0.3 m/m^2. In other decks, this has occurred only in cases involving poor construction practices. As a result, these decks are analyzed separately in Section 6.3.

Figure 6.3 shows the 36-month crack density of the seven Minnesota bridge decks (with good construction procedures) surveyed in this study and those used for comparison with good construction procedures (Section 5.2.1), as a function of the paste content. In Figure 6.3, the Minnesota decks surveyed in this study (a trailing indicator of "MN" in the legend IDs) have paste contents ranging from 24.8 to 27.1%. As shown in the figure, the decks with paste contents below 27.6% exhibited crack densities below 0.4 m/m^2 at 36 months. Once the paste content exceeds 27.6%, cracking tends to increase. Of the nine decks with a paste content greater than or equal to 27.9%, five decks have crack densities above 0.4 m/m^2 at 36 months. Among the seven Minnesota

[1] The designation of poor construction practice for the bridges in the current study is not based on direct observation or direct reporting, but based on cracking survey experience from earlier studies for bridge decks that should otherwise exhibit low cracking.

decks included in Figure 6.3, all the decks with a paste content below 27.1% had crack densities below 0.167 m/m^2.

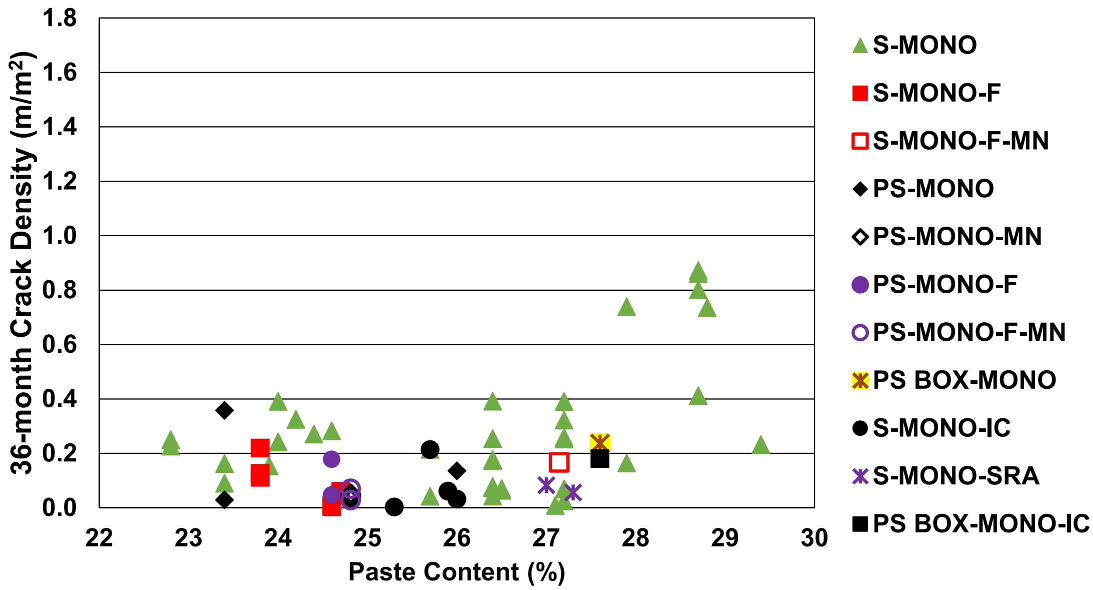


Figure 6.3: Paste content versus 36-month crack density for decks with good construction procedures

Based on the results shown in Tables 4.1 and 5.15, the average 36-month crack densities of bridge decks without and with fibers (F) for decks supported by steel (S) and prestressed concrete (PS) girders are compared in Figures 6.4 and 6.5, respectively. A comparison is also made as a function of paste content, such that decks with a paste content of 27.2% and lower are categorized as "Low Paste," and decks with paste contents of 27.9% and greater are categorized as "High Paste." Error bars show the ranges of the crack densities for each deck type. The decks supported by steel girders, designated as "S-MONO" with "Low Paste" contents include 35 placements, with paste contents ranging from 22.8 to 27.2%; decks designated as "S-MONO" with "High Paste" contents include eight placements, with paste contents ranging from 27.9 to 29.4%; decks designated as "S-MONO-F" with "Low Paste" contents include six placements with paste contents ranging from 23.8 to 24.7%; and a single deck designated as "S-MONO-F-MN" with

"Low Paste" content includes one placement with a paste content of 27.1%. Similarly, decks supported by prestressed concrete girders, designated as "PS-MONO" with "Low Paste" contents include three placements, with paste contents ranging from 23.4 to 26.0%; decks designated as "PS-MONO-MN," with "Low Paste" contents include four placements, with paste contents of 24.8%; decks designated as "PS-MONO-F" with "Low Paste" contents include two placements, each with a paste content of 24.6%; decks designated as "PS-MONO-F-MN" with "Low Paste" contents include two placements, with paste contents of 24.8%.

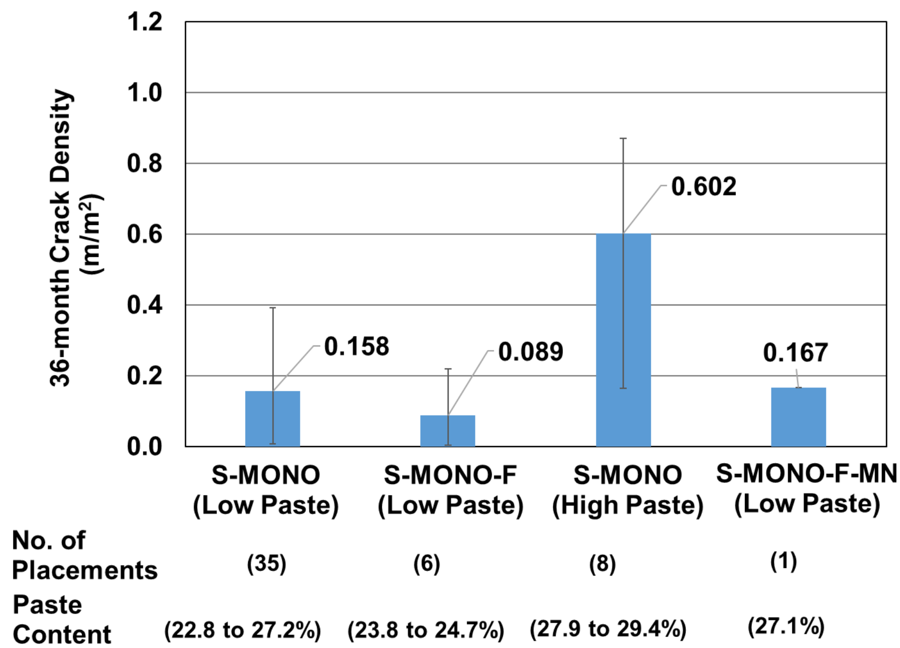


Figure 6.4: 36-month crack densities of decks supported by steel girders with and without fibers

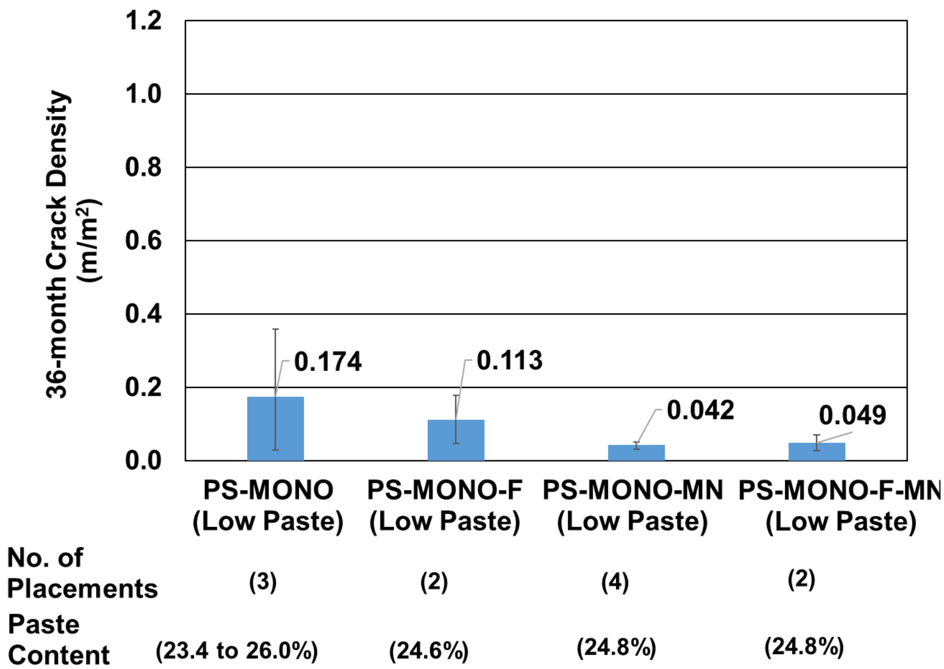


Figure 6.5: 36-month crack densities of decks supported by prestressed concrete girders with and without fibers

Figure 6.4 shows that the bridge decks with high paste contents (≥27.9%) supported by steel girders exhibited noticeably higher crack densities at 36 months than those with paste contents ≤ 27.2%. For the decks supported by prestressed concrete girders (Figure 6.5), all with paste contents less than 26.0%, the 36-month crack densities were all less than or equal to 0.174 m/m^2. Tables 6.1 and 6.2 show the Student's t-test results comparing cracking of the decks supported by steel and prestressed girders, respectively. To perform such an analysis, at least two data points are needed for each data set. Thus, single deck placements with S-MONO-F-MN with "Low Paste" are excluded from the tables.

Table 6.1: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported by steel girders with and without fibers

Bridges (No. of Placements)	**Group**	**S-MONO-F (Low Paste) (6)**	**S-MONO (High Paste) (8)**
Group	**Average**	**0.089**	**0.602**
S-MONO (Low Paste) (35)	**0.158**	0.197	**2.15×10^{-8}**
S-MONO-F (Low Paste) (6)	**0.089**		**0.001**

Table 6.2: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported by prestressed concrete girders with and without fibers

Bridges (No. of Placements)	**Group**	**PS-MONO-F (Low Paste) (2)**	**PS-MONO-MN (Low Paste) (4)**	**PS-MONO-F-MN (Low Paste) (2)**
Group	**Average**	**0.113**	**0.042**	**0.049**
PS-MONO (Low Paste)	**0.174**	0.677	0.165	0.393
PS-MONO-F (Low Paste)	**0.113**		0.159	0.450
PS-MONO-MN (Low Paste)	**0.042**			0.680

As stated in Section 1.2.3, a *p*-value of 0.05 or less is an indication that the differences between average values are statistically significant. Tables 6.1 and 6.2 show that paste content is the dominant factor in the cracking of monolithic bridge decks. In decks supported by steel girders, the difference between the crack density of the decks with high paste contents (average of 0.602 m/m^2) and that of the decks with low paste contents, without fibers (0.158 m/m^2) or with low paste and with fibers (0.089 m/m^2), is statistically significant ($p = 2.1 \times 10^{-8}$ and 0.001, respectively). In decks supported by prestressed concrete girders, the differences between deck types are not statistically significant because all the decks had low paste contents. Additionally, the difference in crack densities of the monolithic decks with and without fibers is not statistically significant.

6.3 EFFECT OF POOR CONSTRUCTION PROCEDURES ON MONOLITHIC DECKS

Section 5.2.2 describes monolithic Kansas decks with construction issues that were used for comparison with monolithic MnDOT decks. The Kansas decks all have low paste contents and, as such, would be expected to have low crack densities. Studies of Kansas decks have shown that construction issues have caused high crack densities. MnDOT monolithic decks (refer to Figure 6.6) also utilize low paste contents and should have low crack densities, approximately 0.2 m/m^2 or less. However, the crack densities in the three MnDOT decks discussed in this section range between 0.338 and 0.511. Kansas experience shows that crack densities of this magnitude, at a deck age of three years, are caused by poor construction practices. Note that the decks compared within this section (the Kansas decks in Section 5.2.2 and the three MnDOT decks in Figure 6.6) were supported by steel girders. While there is an industry-wide perception that steel girder-supported decks exhibit more cracking relative to their prestressed beam supported counterparts, the importance of construction practice is also shown within this section.

Three monolithic MnDOT bridge decks (7268, 27133-P1, and 27133-P2, with respective crack densities of 0.338, 0.511, and 0.419 m/m^2) are suspected to have had issues during construction. To investigate this hypothesis, Figure 6.6 compares the crack densities of these three decks with those with low paste contents in earlier studies that are known to have poor construction procedures (Section 5.2.2). As shown in Figure 6.6, the average 36-month crack densities of the three monolithic decks surveyed in this study are similar to the Kansas monolithic decks that had poor construction procedures. As shown in the figure, the average 36-month crack density of decks with construction issues was 0.338 m/m^2 or more, even when low paste content concretes were used. The average 36-month crack density of the two Minnesota decks with fibers shown in Figure 6.6 is 0.465 m/m^2, while that of the one deck without fibers is 0.338 m/m^2. The results of Student's t-test provided in Table 6.3 show that the differences in crack density of the poorly constructed decks documented in Section 5.2.2, (averages of 0.470 and 0.577 m/m^2 for decks with and without fibers), and the two Minnesota decks constructed with fibers (27133-P1 and 27133-P2, average crack density of 0.465 m/m^2) are not statistically significant (p = 0.970 and 0.641, respectively). The single monolithic deck without fibers [S-MONO-MN or 7268] is excluded from the student's t-test analysis. The paste contents ranged from 22.2 to 26.0%. The results strongly suggest that the high crack densities of decks 7268, 27133-P1, and 27133-P2 resulted from poor construction practices, and thus, resulted in higher crack densities than the other bridge decks surveyed in this study. Experience shows that it is unlikely for decks with low paste contents to have crack densities as high as those shown in Figure 6.6 without a significant problem during construction (Khajehdehi and Darwin 2018, Khajedehi, Darwin, D., and Feng, 2021). In the case of Bridge 27133, the superstructure design, with the need for counterweights to prevent uplift at the south end of bridge, may have also contributed to higher cracking.

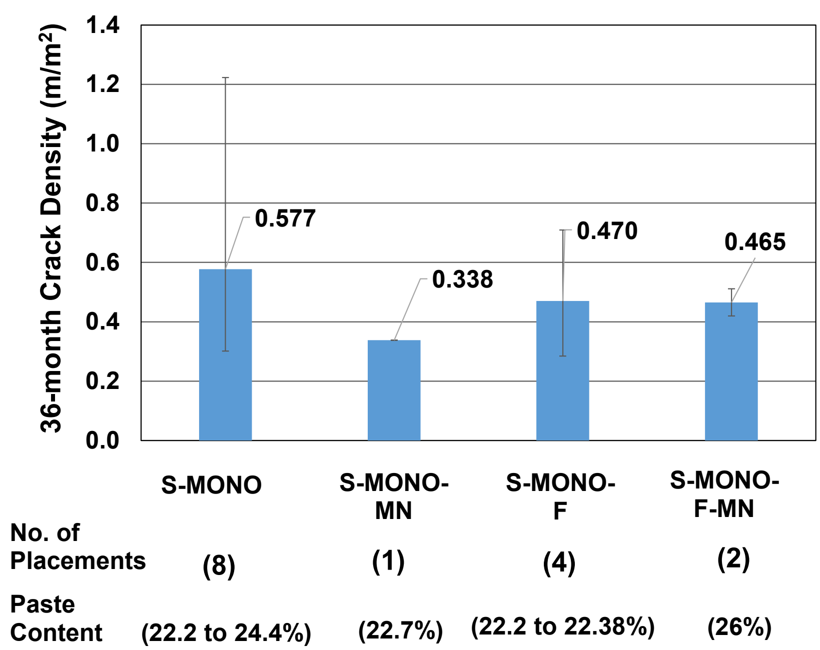


Figure 6.6: Comparison of 36-month crack densities of monolithic decks with construction issues

Table 6.3: *p* values obtained from Student's t-test for the differences in cracking performance of decks with overlays or monolithic decks supported by steel girders, poorly constructed, with and without fibers

Bridges	Group	S-MONO-F (4)	S-MONO-F-MN (2)
Group	**Avg. of 36-month crack density (m/m^2)**	**0.470**	**0.465**
S-MONO (8)	**0.577**	0.543	0.641
S-MONO-F (4)	**0.470**		0.970

CHAPTER 7: SUMMARY AND CONCLUSIONS

7.1 SUMMARY

Ninety-three spans on 19 bridges, constructed between 2013 and 2020, were surveyed for cracks. The decks were constructed on either steel or prestressed concrete girders. The spans were constructed with or without overlays, some of which used silica fume as a partial replacement for portland cement, with or without nonmetallic fibers, or with monolithic decks with or without nonmetallic fibers. Of the six bridges with conventional overlays (without silica fume), four contained fibers. All nine of the bridges with silica fume overlays had fibers. Of the four monolithic decks, two had spans with fibers, one did not have fibers, and one had two surveyed units (each with three spans) with fibers and four surveyed units without fibers. The decks had from two to seven spans with lengths ranging from 147 to 808 ft (44.9 to 246. m), and roadways with widths ranging from 32 to 70.5 ft (9.8 to 21.5 m). The cracking performance of the decks is expressed in terms of crack density in m/m^2.

7.2 CONCLUSIONS

The following conclusions are based on the crack surveys and analyses presented in this report:

1. Decks with overlays crack more than monolithic decks.

2. In the current study, with its small samples, there was no tendency toward less cracking in decks supported by prestressed concrete girders than for those supported on steel girders, as has been observed in some earlier studies.

3. Decks with cement paste contents less than 27% of the concrete volume cracked less that decks with a higher volumes of cement paste.

4. More generally, good construction practices are needed for low-cracking decks, and

with poor construction practices, even decks with low paste content, with or without fibers, can exhibit high cracking.

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APPENDIX A: BRIDGE DECK SURVEY SPECIFICATIONS

A.1 DESCRIPTION.

This specification covers the procedures and requirements to perform bridge deck surveys of reinforced concrete bridge decks.

A.2 SURVEY REQUIREMENTS.

A.2.1 Pre-Survey Preparation.

(1) Prior to performing the crack survey, related construction documents need to be gathered to produce a scaled drawing of the bridge deck. The scale must be exactly 1 in. = 10 ft (for use with the scanning software), and the drawing only needs to include the boundaries of the deck surface.

NOTE 1 – In the event that it is not possible to produce a scaled drawing prior to arriving at the bridge deck, a hand-drawn crack map (1 in.= 10 ft) created on engineering paper using measurements taken in the field is acceptable.

(2) The scaled drawing should also include compass and traffic directions in addition to deck stationing. A scaled 5 ft by 5 ft grid is also required to aid in transferring the cracks observed on the bridge deck to the scaled drawing. The grid shall be drawn separately and attached to the underside of the crack map such that the grid can easily be seen through the crack map.

NOTE 2 – Maps created in the field on engineering paper need not include an additional grid.

(3) For curved bridges, the scaled drawing need not be curved, i.e., the curve may be approximated using straight lines.

(4) Coordinate with traffic control so that at least one side (or one lane) of the bridge can be closed during the time that the crack survey is being performed.

A.2.2 Preparation of Surface.

(1) After traffic has been closed, station the bridge in the longitudinal direction at ten feet intervals. The stationing shall be done as close to the centerline as possible. For curved bridges, the stationing shall follow the curve.

(2) Prior to beginning the crack survey, mark a 5 ft by 5 ft grid using lumber crayons or chalk on the portion of the bridge closed to traffic corresponding to the grid on the scaled drawing. Measure and document any drains, repaired areas, unusual cracking, or any other items of interest.

(3) Starting with one end of the closed portion of the deck, using a lumber crayon or chalk, begin tracing cracks that can be seen while bending at the waist. After beginning to trace cracks, continue to the end of the crack, even if this includes portions of the crack that were not initially seen while bending at the waist. Cracks not attached to the crack being traced must not be marked unless they can be seen from waist height. Surveyors must return to the location where they started tracing a crack and continue the survey. Areas covered by sand or other debris need not be surveyed. Trace the cracks using a different color crayon than was used to mark the grid and stationing.

(4) At least one person shall recheck the marked portion of the deck for any additional cracks. The goal is not to mark every crack on the deck, only those cracks that can initially be seen

while bending at the waist.

NOTE 3 – An adequate supply of lumber crayons or chalk should be on hand for the survey. Crayon or chalk colors should be selected to be readily visible when used to mark the concrete.

A.2.3 Weather Limitations.

(1) Surveys are limited to days when the expected temperature during the survey will not be below 60 °F.

(2) Surveys are further limited to days that are forecasted to be at least mostly sunny for a majority of the day.

(3) Regardless of the weather conditions, the bridge deck must be completely dry before the survey can begin.

A.3 BRIDGE SURVEY.

A.3.1 Crack Surveys.

Using the grid as a guide, transfer the cracks from the deck to the scaled drawing. Areas that are not surveyed should be marked on the scaled drawing. Spalls, regions of scaling, and other areas of special interest need not be included on the scale drawings but should be noted.

A.3.2 Delamination Survey.

At any time during or after the crack survey, bridge decks shall be checked for delamination. Any areas of delamination shall be noted and drawn on a separate drawing of the bridge. This second drawing need not be to scale.

A.3.3 Under Deck Survey.

Following the crack and delamination survey, the underside of the deck shall be examined and any unusual or excessive cracking noted.

APPENDIX B: CRACK WIDTH RESULTS

Table B.1: Individual crack-width measurements for decks surveyed in this study ($\times 10^{-3}$ in.)

	9071		62924	19004NB	19004SB		62038		83026	
1	13	40	10	10	5	13	25	9	20	20
2	3	25	20	5	5	5	25	16	30	16
3	13	5	40	3	3	9	60	9	30	30
4	3	30	50	7	3	7	60	7	13	30
5	30	3	60	5	5	5	13	5	9	16
6	13	40	60	5	3	7	7	5	25	30
7	7	40	60	7	7	9	13	20	13	30
8	25	16	40	5	7	7	40	16	20	
9	20	13	50	5	7	9	30	20	16	
10	16	20	16	5	7	7	16	25	13	
11	20	40	60	7	3		4	13	16	
12	10	5	40	7	9		13		13	
13	13	13	25	3	2		9		13	
14	16	40	13	3	2		16		30	
15	25	60	16	3	3		10		25	
16	16	3	25	5	3		30		16	
17	20	25	20	7	3		25		16	
18	25	25	20	5	5		25		20	
19	13	25	40	3	2		16		16	
20	20	30	9	3	7		5		20	
21	20	20	25	5	7		7		40	
22	30	5	60	3	9		3		13	
23	30	30	40		5		3		40	
24	10	30	25		5		20		20	
25	20	13	40		2		20		12	
26	25	10	40		5		3		40	
27	25	16	20		7		16		30	
28	20		20		2		16		16	
29	20		30		5		3		13	
30	20		40		3		13		40	
31	16		60		5		7		13	
32	25		13		7		13		20	
33	40		30		3		7		20	
34	30		20		2		7		20	
35	40		60		2		9		20	
36	20		25		5		10		13	
37	50		16		5		5		16	
38	13		16		5		5		30	
39	13		10		3		13		20	
40	13				5		3		20	

Table B.1(Con't): Individual crack-width measurements for decks surveyed in this study ($\times 10^{-3}$ in.)

	83027		62925		22801	22802	46824	46831	46835	46836	62652
1	20	30	20	13	16	13	10	16	3	16	13
2	13	30	13	60	10	16	9	13	3	20	13
3	30	9	7	40	9	9	16	18	16	25	16
4	20	30	10	16	9	9	5	9	7		20
5	7	9	10	60	25	13	7	7	9		9
6	9	13	16	13	13	20	7	13	3		20
7	9	30	9	40	13	13	20	10	16		9
8	30	9	3	30	16	13		13	3		16
9	20	20	25	10	20	13		16	5		2
10	9	30	50	30	30	10		4	3		
11	9	20	16	50	13	10		4	10		
12	9	25	30	9	30	25		13	16		
13	13	13	13		16	20			3		
14	3	20	16		40	20			3		
15	13	20	60		30	20					
16	9	16	20		16						
17	13		30		10						
18	16		10		20						
19	20		50		40						
20	25		40		16						
21	9		16		16						
22	9		9		16						
23	20		10		16						
24	20		13		9						
25	20		5		13						
26	9		13		16						
27	9		60		10						
28	20		60								
29	20		30								
30	20		25								
31	9		25								
32	30		40								
33	20		13								
34	13		16								
35	13		5								
36	13		25								
37	25		60								
38	7		40								
39	20		16								
40	30		30								

Table B.1(Con't): Individual crack-width measurements for decks surveyed in this study (×10^{-3} in.)

	9689		10004-U4	10004-U7	10004-U8	10004-U10	10004-U5	10004-U9	19004NB	19004SB	
1	16	13	25	9	13	3	10	10	10	5	13
2	13	9	13	9	16	9	13	16	5	5	5
3	9	13	16	9	13	10	16	13	3	3	9
4	16	9	16	13	20	10	10	10	7	3	7
5	16	9	30	10	10	13	10	20	5	5	5
6	16	16	20	9	13		10	16	5	3	7
7	16	20	25	9	25		16	6	7	7	9
8	16	13	16	10	16		10	9	5	7	7
9	30	9	13		13		9	13	5	7	9
10	20	10	6		16			20	5	7	7
11	16	13	16		13			13	7	3	
12	10	13			9			13	7	9	
13	9	9			16			10	3	2	
14	9	9			20			3	3	2	
15	9	25			10			9	3	3	
16	25	10						9	5	3	
17	20	9						13	7	3	
18	30	10						9	5	5	
19	10	9							3	2	
20	16	13							3	7	
21	13	20							5	7	
22	9	9							3	9	
23	9	13								5	
24	9	13								5	
25	13									2	
26	5									5	
27	20									7	
28	9									2	
29	9									5	
30	25									3	
31	13									5	
32	9									7	
33	20									3	
34	9									2	
35	9									2	
36	13									5	
37	9									5	
38	30									5	
39	15									3	
40	9									5	

APPENDIX C: PROCEDURE FOR ESTIMATING 36-MONTH CRACK DENSITY

C.1 ESTIMATED 36-MONTH CRACK DENSITY OF OVERLAY DECKS

This appendix describes the procedure for estimating the 36-month crack density of the bridge decks with overlays surveyed in this study.

C.1.1 BRIDGE DECK SELECTION

The University of Kansas has been involved in cracking surveys since the 1990s. To estimate the 36-month cracking density of the bridge decks with overlays surveyed in this study, 50 bridge deck placements with characteristics (such as overlay type and crack-reducing technologies) similar to those surveyed bridge decks in Minnesota were chosen. As described in Section 5.1, the decks included different types of overlays (conventional overlay, and silica fume overlay) and different types of girders (steel, prestressed concrete, and box concrete girders) and had been surveyed at least twice. The conventional overlay decks had only portland cement as the cementitious material, whereas the silica fume overlays had 3.9 to 7.8% mass replacement of portland cement with silica fume. As discussed in Section 6.1, all silica fume overlays are considered a single deck type. All of the bridge decks had been surveyed at least once at an overlay age between 24 and 48 months. The crack density of all decks increased over time. If no data is available at dates between 24 and 48 months, the decks were not selected for analysis. The bridge decks are divided into three cases. For Case 1, the deck has only one survey between 24 and 36 months; in this case, the 36-month crack density is determined by extrapolating between that survey and the closest survey before 24 months. For Case 2, the bridge deck has at least two surveys available at dates between 24 and 48 months; in this case, the 36-month crack density is determined by linearly interpolating between the two data points. For Case 3, the deck has only one survey between 36 and 48 months; in this case the 36-month crack density is determined by extrapolating between that data and the closest data after 48 months.

C.1.2 CRACKING RATE AND 36-MONTH CRACK DENSITY

The change in crack density as a function of time is referred to as the cracking rate. The process of calculating cracking rates and the associated 36-month crack density of the decks is as follows:

- The bridge deck is categorized as one of the three cases as defined above. The crack density between the applicable time in months is plotted.
- A line connecting the two crack densities at applicable times is drawn. The cracking rate is determined as the slope of the line.
- Using the slope of the line, the 36-month crack density is calculated for each deck.
- The cracking rate and the 36-month crack density are assigned to each bridge deck for further analysis.

The crack density of Control 4 serves as an example:

1. Plot the applicable data points that falls in the cases defined above disregarding other data points. Control 4 falls under Case 2.

2. Draw the line using only applicable data points, as shown in Figure C.1.

3. The cracking rate and crack density corresponding to 36 months of age is found using the equation of the line, where the slope of the line is the cracking rate, as shown in Figure C.1.

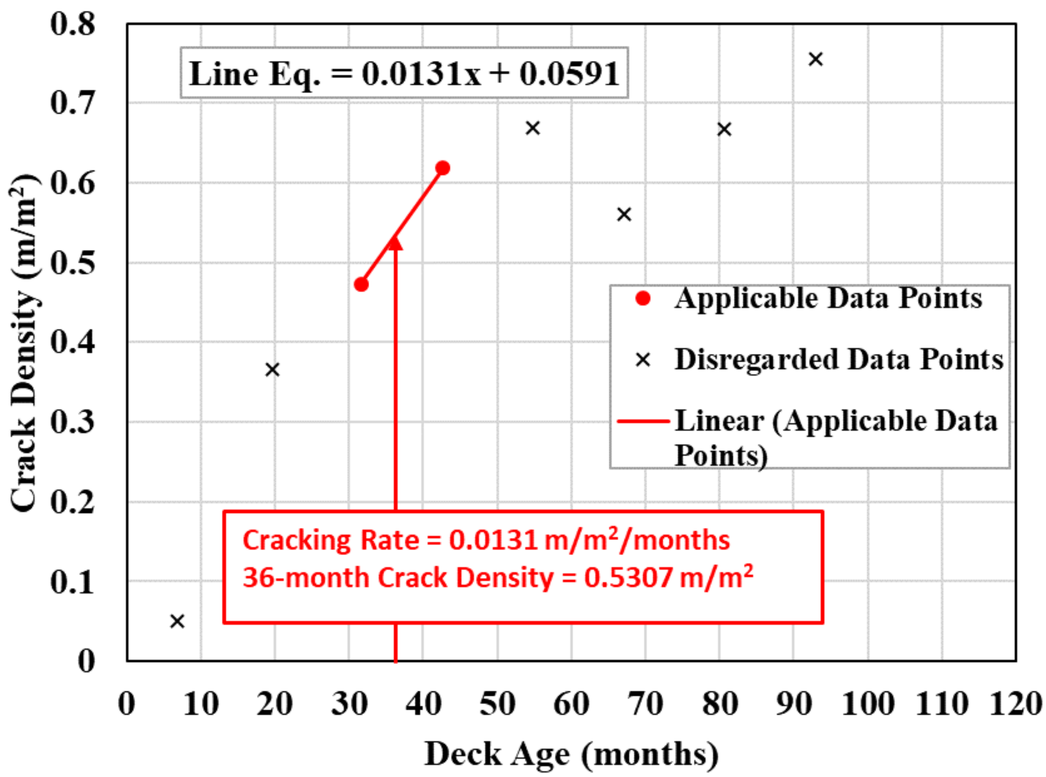

Figure C.1: Cracking rate and 36-month crack density of Control 4

The best-fit line, cracking rate, technology, cracking rate, and 36-month crack density assigned to each bridge deck are calculated using this procedure and shown in Table C.1.

Table C.1: Best-fit line equation, technology, cracking rate, and 36-month crack density of decks

Bridge Deck Placement	Technology	Best-fit line Equation	Cracking Rate (m/m^2/month)	36-month Crack Density (m/m^2)
Control 1/2-P1	S-SFO	y = 0.0123x - 0.2811	0.0123	0.162
Control 1/2-P2	S-SFO	y = 0.0035 x - 0.0194	0.0035	0.107
Control 3	S-SFO	y = 0.0167 x - 0.4537	0.0167	0.148
Control 4	S-SFO	y = 0.0131 x + 0.0591	0.0131	0.531
Control 6	S-SFO	y = 0.0074 x + 0.2197	0.0074	0.486
Control 7-P1	S-SFO	y = 0.0473 x - 0.805	0.0473	0.898
Control 7-P2	S-SFO	y = 0.0064 x + 0.0693	0.0064	0.300
Control 9-P1	S-SFO	y = 0. 0142x + 0.0237	0.0142	0.535
Control 9-P2	S-SFO	y = 0.014 x + 0.06	0.014	0.564

Table C.1 (con't): Best-fit line equation, technology, cracking rate, and 36-month crack density of decks

Bridge Deck Placement	Technology	Best-fit line Equation	Cracking Rate (m/m^2/month)	36-month Crack Density (m/m^2)
Control 12-P1	S-SFO	y = 0.0075 x + 0.4671	0.0075	0.737
Control 12-P2	S-SFO	y = 0.0042 x + 0.7021	0.0042	0.853
Control 13	S-SFO	y = 0.0016 x + 0.4685	0.0016	0.526
46-317-SFO 12	S-SFO	y = 0.0026 x + 0.0036	0.0026	0.097
81-50-Lt	S-SFO	y = 0.0126 x + 0.2965	0.0126	0.750
46-302-Lt	S-SFO	y = 0.006 x + 0.2632	0.006	0.479
46-302-Rt	S-SFO	y = 0.0062 x + 0.3872	0.0062	0.610
87-454-Rt	S-SFO	y = 0.0024 x + 0.7626	0.0024	0.849
89-234-Center	S-SFO	y = 0.001 x + 0.4871	0.001	0.523
23-85-West	S-SFO	y = 0.0046 x + 0.2417	0.0046	0.407
46-317-SFO 16	S-SFO	y = 0.0067 x - 0.0952	0.0067	0.146
89-234-North	S-SFO	y = 0.0002 x + 0.2262	0.0002	0.233
81-50-Rt	S-SFO	y = 0.0051 x + 0.5013	0.0051	0.685
89-207-Rt	S-SFO	y = 0.001 x + 0.3625	0.001	0.399
89-234-SFO South	S-SFO	y = 0.0002 x + 0.166	0.0002	0.173
87-454-Lt	S-SFO	y = 0.003 x + 0.5839	0.003	0.692
46-309-Lt	S-SFO	y = 0.0038 x + 0.2563	0.0038	0.393
89-206-Lt	S-SFO	y = 0.0036 x + 0.1505	0.0036	0.280
89-210-Rt	S-SFO	y = 0.0118 x - 0.2089	0.0118	0.216
46-309-Rt	S-SFO	y = 0.0038 x + 0.1898	0.0038	0.327
89-207-Lt	S-SFO	y = 0.0012 x + 0.2902	0.0012	0.333
23-85-East	S-SFO	y = 0.0036 x + 0.2651	0.0036	0.395
89-210-Lt	S-SFO	y = 0.0105 x - 0.1868	0.0105	0.191
89-184-In	S-SFO	y = 0.0047 x + 0.4956	0.0047	0.665
89-184-Out	S-SFO	y = 0.0065 x + 0.4447	0.0065	0.679
89-187-Out	S-SFO	y = 0.0025 x + 0.5475	0.0025	0.638
US-59-5	S-SFO	y = 0.0106 x - 0.0439	0.0106	0.338
US-59-6	S-SFO	y = 0.0038 x + 0.0498	0.0038	0.187
US-59-11	PS-SFO	y = 0.0009 x + 0.1825	0.0009	0.215
89-186-Out	S-CONVO	y = 0.0058 x + 0.2051	0.0058	0.414
89-186-In	S-CONVO	y = 0.0024 x + 0.4574	0.0024	0.544
89-201-Rt	S-CONVO	y = 0.0014 x + 0.5427	0.0014	0.593
89-200-Rt	S-CONVO	y = 0.002 x + 0.5035	0.002	0.576
89-185-Out	S-CONVO	y = 0.0037 x + 0.4497	0.0037	0.583
46-301-Lt	S-CONVO	y = 0.0042 x + 0.716	0.0042	0.867
89-198-Rt	S-CONVO	y = 0.0002 x + 0.3921	0.0002	0.399
89-199-Lt	S-CONVO	y = 0.0023 x + 0.5605	0.0023	0.643
46-300-Lt	S-CONVO	y = 0.0038 x + 0.353	0.0038	0.490
IC-LC-HPC-2	PS-CONVO	y = 0.0076 x - 1.3054	0.076	1.431
IC-LC-HPC-3	PS-CONVO	y = 0.0088 x - 0.1409	0.0088	0.176
MN-Control-2	PS-CONVO	y = 0.0357 x - 0.6674	0.0357	0.618

C.1.2.1 Estimated Cracking Rate at 36 months

As the final step for estimating the 36-month crack density of the bridge decks surveyed in this study, the cracking rates and 36-month crack densities of the decks (shown in Table C.1) are plotted in Figure C.2.

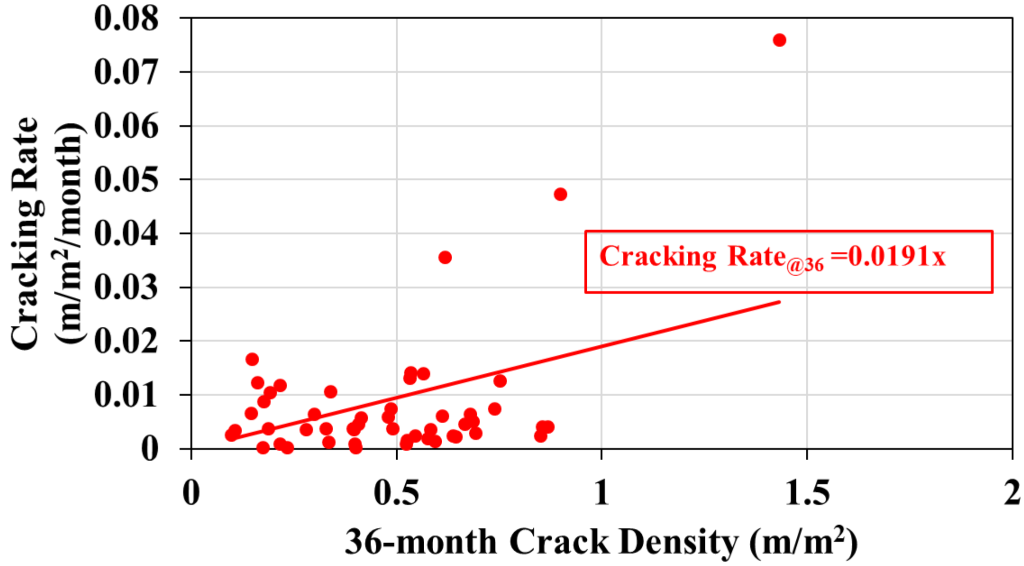

Figure C.2: Cracking rate as a function of 36-month crack density of 50 deck placements with overlays

As shown in Figure C.2, the cracking rate for the deck increases as the 36-month crack density increases. Cracking rate is a function of the crack density at 36 months $CD_{@36months}$ obtained using a trendline fitted to the cracking rate data for the 50 deck placements. The cracking rate is calculated using Eq. (C.1).

$$\text{Cracking Rate}_{@36months} = 0.0191 \times (CD_{@36months}) \qquad \text{(C.1)}$$

where the crack density $CD_{@36months}$ is expressed in m/m^2.

C.1.2.2 Estimated 36-month Crack Density for 16 overlay deck placements surveyed in this study

For the decks with an overlay, based on the process described above, an expression for estimating the 36-month crack density $CD_{@36months}$ of the decks surveyed in this study is shown in Eq. (C.3)

$$CD_{Actual} = CD_{@36\ months} + (\text{Cracking Rate}_{@36months}) \times (\text{Age-36}) \qquad (C.2)$$

where CD_{Actual} is the measured crack density at the deck age at which the deck was surveyed.

The estimated 36-month crack density ($CD_{@36months}$) is provided in Eq. (C.3).

$$CD_{@36\ months} = CD_{Actual} - (\text{Cracking Rate}_{@36months}) \times (\text{Age-36}) \qquad (C.3)$$

If the deck age is greater than 48 months, the deck age is reduced to 48 months, and Eq. (C.3) is used to estimate the 36-month crack density ($CD_{@36months}$). As shown in Chapter 4, for decks with an overlay, the crack density remains almost constant after the deck age of 48 months for the most part.

The estimated 36-month crack densities of the decks with overlay based in Eq. (C.3) is shown in Table C.2.

Table C.2: Estimated crack densities at an age of 36-month for the placements with conventional or silica fume overlays surveyed in this study

Bridge Number	Category	Overlay Age (Months)	Reduced Overlay Age (Months)	Actual Crack Density	Estimated 36-month Crack Density(m/m^2)
9071	S-CONVO-MN	47.7		1.147	0.937
62924	S-CONVO-MN	73.6	48	0.562	0.457
19004-NB	PT-CONVO-MN	95.9	48	0.787	0.640
19004-SB	PT-CONVO-MN	95.9		1.065	0.866
62038	PS-CONVO-MN	73.4		1.916	1.559
83026	PS-CONVO-MN	25.8	48	0.370	0.460
83027	PS-CONVO-MN	34.8		0.157	0.161
62925	S-CONVO-MN	71.1		0.360	0.293
22801	S-SFO-F-MN	14.2		0.159	0.272
22802	S-SFO-F-MN	23.5	48	0.047	0.062
46824	PS-SFO-F-MN	23.6		0.005	0.007

Table C.2 (con't): Estimated crack densities at an age of 36-month for the placements conventional or silica fume overlays surveyed in this study

Bridge Number	Category	Overlay Age (Months)	Reduced Overlay Age (Months)	Actual Crack Density	Estimated 36-month Crack Density(m/m^2)
46831	PS-SFO-F-MN	23.6		0.016	0.021
46835	PS-SFO-F-MN	23.6		0.006	0.008
46836	PS-SFO-F-MN	12.7		0.016	0.029
62652	PS-SFO-F-MN	11.9		0.027	0.050
9689	PS-SFO-F-MN	46.5		0.622	0.518

C.2 ESTIMATED 36-MONTH CRACK DENSITY OF MONOLITHIC DECKS

For estimating the 36-month crack density of the monolithic bridge decks surveyed in this study, reference from Bahadori et al. (2022) is taken, where 62 decks with good construction procedures are used for generating Eq. (C.4).

C.2.1 Estimated 36-month Crack Density for 10 monolithic deck placements surveyed in this study

Two categories were defined, based on the 36-month crack density. Category 1 consisted of deck placements with 36-month crack densities greater than 0.7 m/m^2. Category 2 consisted of all other decks. In this study, no placements have crack density greater than 0.7 m/m^2. Thus, equation for Category 2 is used for estimating the 36-month crack density of the monolithic decks surveyed in this study. The equation is presented in Eq. (C.4).

$$CD_{@36\ months} = CD_{Actual} - (0.0066 \times \text{Cracking Rate}_{@36months} + 0.0013) \times (\text{Age}-36) \quad (C.4)$$

The estimated 36-month crack densities of the monolithic decks based in Eq. (C.4) is shown in Table C.3.

Table C.3: Estimated crack densities at an age of 36-month for the monolithic decks surveyed in this study

Bridge Number	**Category**	**Deck Age (Months)**	**Actual Crack Density**	**Estimated 36-month Crack Density(m/m^2)**
7268	S-MONO-MN	95.2	0.547	0.338
10004-U4	PS-MONO-MN	70.4	0.093	0.039
10004-U7	PS-MONO -MN	71.9	0.110	0.051
10004-U8	PS-MONO-MN	71.7	0.105	0.047
10004-U10	PS-MONO-MN	71.3	0.085	0.032
7263	S-MONO-F-MN	26.6	0.144	0.167
27133-P1	S-MONO-F-MN	22.9	0.450	0.511
27133-P2	S-MONO-F-MN	22.4	0.364	0.419
10004-U5	PS-MONO-F-MN	70.4	0.028	0.028
10004-U9	S-MONO-F-MN	71.5	0.132	0.070

APPENDIX D: CRACK SURVEY RESULTS FOR CHAPTER 5

D.1 Crack Densities at 36 Months

The crack density of bridge decks increases over time (Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2019). To eliminate the variable of age and compare bridge deck cracking on an equal-age basis, the crack density at 36 months after construction is chosen for the analyses in this study. An age of 36 months is selected because the tendency to exhibit cracking over the long term becomes apparent at this age (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014).

To eliminate bias in the estimation of 36-month crack density, in this study, all of the bridge decks had been surveyed at least once at an overlay age between 24 and 48 months. The rate of cracking is highest within the first 36 months (Pendergrass and Darwin 2014), and remains almost constant after the age of 48 months as discussed in Chapter 4. If no data are available at dates between 24 and 48 months, the decks were not selected. If the deck has only one survey data point between 24 and 36 months, the 36-month crack density is determined by extrapolating between that data and the closest data point before 24 months. For bridge decks with two survey data points available at dates between 24 and 48 months, the 36-month crack density is determined by linearly interpolating between the two data points. If the deck has only one survey data point between 36 and 48 months, the 36-month crack density is determined by extrapolating between that data and the closest data after 48 months. The crack density of all decks increased over time.

The crack survey results of the applicable consecutive survey data points, used in calculation of 36-month crack densities of the 50 deck placements described in Chapter 5 are presented in Tables D.1 through D.7.

Table D.1: Crack Densities Used for Analysis and Eq. (C.2) of Control Decks (7% SFO) in Kansas

Placements[a]	Survey A		Survey B		36-month Crack Density (m/m^2)
	Overlay Age (month)	Crack Density (m/m^2)	Overlay Age (month)	Crack Density (m/m^2)	
Control 1/2-P1 (S-SFO)	32.2	0.114	44.2	0.261	0.162
Control 1/2-P2 (S-SFO)	31.6	0.091	43.6	0.133	0.107
Control 3 (S-SFO)	34.6	0.123	46.6	0.323	0.148
Control 4 (S-SFO)	31.6	0.473	42.7	0.618	0.531
Control 6 (S-SFO)	31.8	0.456	43.0	0.539	0.486
Control 7-P1 (S-SFO)	27.1	0.476	38.2	1.003	0.898
Control 7-P2 (S-SFO)	32.6	0.277	45.5	0.359	0.300
Control 9-P1 (S-SFO)	24.2	0.368	37.2	0.553	0.535
Control 9-P2 (S-SFO)	24.0	0.395	37.0	0.577	0.564
Control 12-P1 (S-SFO)	26.9	0.669	38.9	0.759	0.737
Control 12-P2 (S-SFO)	26.5	0.813	37.2	0.858	0.853
Control 13 (S-SFO)	34.4	0.524	46.1	0.543	0.526

[a]P = Placement; S = Steel girder; SFO = Silica Fume Overlay

Table D.2: Crack Densities Used for Analysis and Eq. (C.2) of Silica Fume Overlay Decks (5% Silica) in Kansas

Placements[a]	Survey A		Survey B		36-month Crack Density (m/m^2)
	Overlay Age (month)	Crack Density (m/m^2)	Overlay Age (month)	Crack Density (m/m^2)	
46-317-SFO 12’ (S-SFO)	26.0	0.070	73.0	0.190	0.097
81-50-Lt (S-SFO)	32.0	0.700	78.0	1.280	0.750
46-302-Lt (S-SFO)	28.0	0.430	75.0	0.710	0.479
46-302-Rt (S-SFO)	28.0	0.560	75.0	0.850	0.610
87-454-Rt (S-SFO)	24.0	0.820	70.0	0.930	0.849
89-234-Center (S-SFO)	24.0	0.510	87.0	0.570	0.523
23-85-West (S-SFO)	28.0	0.370	76.0	0.590	0.407
46-317-SFO 16’ (S-SFO)	26.0	0.080	72.0	0.390	0.146
89-234-North (S-SFO)	24.0	0.230	87.0	0.240	0.233
81-50-Rt (S-SFO)	33.0	0.670	78.0	0.900	0.685
89-207-Rt (S-SFO)	27.0	0.390	86.0	0.450	0.399
89-234-SFO South (S-SFO)	25.0	0.170	88.0	0.180	0.173
87-454-Lt (S-SFO)	25.0	0.660	71.0	0.800	0.692
46-309-Lt (S-SFO)	33.0	0.380	81.0	0.560	0.393
89-206-Lt (S-SFO)	33.0	0.270	91.0	0.480	0.280
89-210-Rt (S-SFO)	32.0	0.170	70.0	0.620	0.216
46-309-Rt (S-SFO)	34.0	0.320	81.0	0.500	0.327
89-207-Lt (S-SFO)	33.0	0.330	91.0	0.400	0.333
23-85-East (S-SFO)	29.0	0.370	76.0	0.540	0.395

Table D.2 (con't): Crack Densities Used for Analysis and Eq. (C.2) of Silica Fume Overlay Decks (5% Silica) in Kansas

Placements[a]	Survey A		Survey B		36-month Crack Density (m/m^2)
	Overlay Age (month)	Crack Density (m/m^2)	Overlay Age (month)	Crack Density (m/m^2)	
89-210-Lt (S-SFO)	32.0	0.150	70.0	0.550	0.191
89-184-In (S-SFO)	39.0	0.680	94.0	0.940	0.665
89-184-Out (S-SFO)	39.0	0.700	94.0	1.060	0.679
89-187-Out (S-SFO)	41.0	0.650	97.0	0.790	0.638

[a]Lt = Left Placement; Rt = Right Placement; In = Inside Placement; Out = Outside Placement; S = Steel girder; SFO = Silica Fume Overlay

Table D.3: Crack Densities Used for Analysis and Eq. (C.2) of US-59 Decks with silica fume overlay with fibers in Kansas

Placements[a]	Survey A		Survey B		36-month Crack Density (m/m^2)
	Overlay Age (month)	Crack Density (m/m^2)	Overlay Age (month)	Crack Density (m/m^2)	
US-59-5 (S-SFO-F)	38.0	0.320	46.0	0.465	0.283

[a]S = Steel girder; SFO = Silica Fume Overlay; F = With Fibers

Table D.4: Crack Densities Used for Analysis and Eq. (C.2) of US-59 Decks with silica fume overlay in Kansas

Placements[a]	Survey A		Survey B		36-month Crack Density (m/m^2)
	Overlay Age (month)	Crack Density (m/m^2)	Overlay Age (month)	Crack Density (m/m^2)	
US-59-6 (S-SFO)	29.0	0.160	39.0	0.198	0.187

[a]S = Steel girder; SFO = Silica Fume Overlay

Table D.5: Crack Densities Used for Analysis and Eq. (C.2) of US-59 Decks with silica fume overlay in Kansas

Placements	Survey A		Survey B		36-month Crack Density (m/m^2)
	Overlay Age (month)	Crack Density (m/m^2)	Overlay Age (month)	Crack Density (m/m^2)	
US-59-11(PS-SFO)	33.0	0.213	46.0	0.225	0.215

[a]PS = Prestressed concrete girder; SFO = Silica Fume Overlay

Table D.6: Crack Densities Used for Analysis and Eq. (C.2) of Decks with conventional overlay in Kansas

Placements	Survey A		Survey B		36-month Crack Density (m/m^2)
	Overlay Age (month)	Crack Density (m/m^2)	Overlay Age (month)	Crack Density (m/m^2)	
89-186-Out (S-CONVO)	42.0	0.450	94.3	0.755	0.414
89-186-In (S-CONVO)	42.0	0.560	94.4	0.688	0.544
89-201-Rt (S-CONVO)	34.0	0.590	83.6	0.659	0.593
89-200-Rt (S-CONVO)	33.0	0.570	83.6	0.672	0.576
89-185-Out (S-CONVO)	41.0	0.600	97.2	0.806	0.583
46-301-Lt (S-CONVO)	48.0	0.922	95.0	1.117	0.867
89-198-Rt (S-CONVO)	33.0	0.400	83.3	0.412	0.399
89-199-Lt (S-CONVO)	35.0	0.640	83.4	0.750	0.643
46-300-Lt (S-CONVO)	36.0	0.491	72.0	0.629	0.490

[a]Lt = Left Placement; Rt = Right Placement; In = Inside Placement; Out = Outside Placement; S = Steel girder; CONVO = Conventional Overlay

Table D.7: Crack Densities Used for Analysis and Eq. (C.2) of Decks with conventional overlay in Minnesota

Placements	Survey A		Survey B		36-month Crack Density (m/m^2)
	Overlay Age (month)	Crack Density (m/m^2)	Overlay Age (month)	Crack Density (m/m^2)	
IC-LC-HPC-2 (PS-CONVO)	22.4	0.396	36.0	1.429	1.431
IC-LC-HPC-3 (PS-CONVO)	20.9	0.042	34.5	0.161	0.176
MN-Control-2 (PS-CONVO)	20.1	0.05	33.8	0.539	0.618

[a]PS = Prestressed concrete girder; CONVO = Conventional Overlay