EVALUATION OF CRACKING PERFORMANCE OF BRIDGE DECKS IN MINNESOTA

By

Benjamin Pendergrass

Pankaj Shrestha

Elizabeth Riedel

Grant Polley

David Darwin

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CONSTRUCTION OF CRACK-FREE BRIDGE DECKS
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ABSTRACT

Six bridge decks in Minnesota supported by steel girders were evaluated based on cracking performance. The decks included two constructed in accordance with Minnesota low-cracking specifications and four constructed in accordance with Minnesota standard specifications. Crack surveys were performed on the decks to determine crack densities and location of cracks. The cracking performance of the decks is compared with the performance of decks constructed on steel girders in Kansas in accordance with either the low-cracking high-performance concrete (LC-HPC) or standard Kansas specifications. The decks constructed in accordance with the Minnesota low-cracking specifications have lower crack densities than the decks constructed in accordance with the Minnesota standard specifications. At similar ages, the decks constructed in Minnesota in accordance with either the low-cracking or standard specifications have greater cracking than decks constructed in Kansas in accordance with the LC-HPC specifications and have greater cracking than a majority of decks constructed in Kansas in accordance with the standard specifications. The majority of cracks develop in the transverse direction, parallel to the deck reinforcement. Longitudinal cracks propagate from the abutments. Cracks are generally evenly distributed throughout the decks, although increased cracking is occasionally noted directly above the piers. Additional surveys will be needed to understand the progression of cracking over time.

Key Words: bridge decks, cracking, transverse cracking, high-performance concrete

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OVERVIEW

Crack surveys were completed on six bridge decks in Minnesota by the University of Kansas. The surveys were completed over a span of three days, July 15 through 17, 2013. The surveyed decks included two decks constructed in accordance with Minnesota low-cracking specifications and four decks constructed in accordance with Minnesota standard specifications. The Minnesota low-cracking specifications include aspects of the low-cracking high-performance concrete (LC-HPC) specifications developed at the University of Kansas (Kansas Department of Transportation 2007). Two of the four decks constructed in accordance with the standard specifications were paired with a low-cracking deck to examine the effectiveness of the Minnesota low-cracking specifications. All of the decks were cast on steel girders. Each paired deck was located adjacent to its comparative low-cracking deck, allowing the comparative decks to be subjected to similar traffic and environmental conditions. Two additional decks constructed in accordance with the standard Minnesota specifications were also surveyed.

Crack maps were created for each bridge deck from the survey data, displaying the distribution of cracking on each deck. Crack densities, representing the total length of cracks per unit area of deck (m/m^2), were determined to quantitatively establish the cracking performance of each deck. The cracking performance of the surveyed decks is compared with the performance of decks in Kansas constructed in accordance with either the low-cracking high-performance concrete (LC-HPC) specifications or standard specifications of the Kansas Department of Transportation (KDOT).

BRIDGE DECK INFORMATION

General information regarding the bridge decks surveyed is presented in this section. Characteristics of the Minnesota low-cracking and standard specifications are compared with the LC-HPC and standard KDOT specifications. Information concerning bridge designation, mixture proportioning, plastic concrete properties, environmental conditions during construction, and construction procedures for the bridge decks are shown in Tables 1 through 3. As shown in Tables 1 and 2, no information was available in the construction records for MN Control #1

Table 1 Bridge deck designation, placement type, and mixture proportioning for each surveyed Minnesota bridge deck

Deck Number	Designated Name	Mix Designation	Placement Type	Cementitious Materials (lb/yd^3)			Water (lb/yd^3)	Design *w/cm*
				Cement	Blended Cement w/ 7% Silica Fume	Fly Ash		
9725	MN LC #1	3Y33 LC-HPC	Full Depth	540	0	0	238	0.44
9726	MN Control #1	3Y36	Overlay#	-	-	-	-	-
82805	MN Control #2	3Y33 HP	Full Depth	70	335	135	216	0.40
82806	MN LC #2	3Y33 LC-HPC	Full Depth	535	0	0	225	0.42
82807	MN Control #3	3Y36 HP	Overlay#	70	335	135	216	0.40
82808	MN Control #4	3Y36 HP	Overlay#	70	335	135	216	0.40

- Information not available in construction records # Overlay consists of Concrete Wearing Course (3U17A)

Table 2 Plastic concrete properties and environmental conditions for the surveyed Minnesota bridge decks

Deck Number	Designated Name	Avg. Slump (in.)	Avg. Air Content (%)	Avg. Concrete Temperature (°F)	Avg. Air Temperature (°F)
9725	MN LC #1	3.25	8.0	67	55
9726	MN Control #1	-	-	-	-
82805	MN Control #2	4	7.0	78	77
82806	MN LC #2	3.25	7.8	61	62
82807	MN Control #3	3.75	6.8	78	70
82808	MN Control #4	2.75	7.3	-	60

- Information not available in construction records

Table 3 Construction methods and procedures for the surveyed Minnesota bridge decks

Deck Number	Designated Name	Method of Placement	Time to Burlap Placement (min)	Length of Curing Period (days)
9725	MN LC #1	Pump	20	14
9726	MN Control #1	Pump	15 to 20	7
82805	MN Control #2	Pump	30	8
82806	MN LC #2	Pump	10 to 14	15
82807	MN Control #3	Pump	30	7
82808	MN Control #4	Pump	30	7

regarding mixture proportioning, plastic concrete properties, or environmental conditions during construction. The two decks constructed in accordance with the low-cracking specifications, Bridges 9725 and 82806, are designated as MN LC #1 and #2, respectively, in this report. The four decks constructed in accordance with the standard specifications, Bridges 9726, 82805, 82807, and 82808, are designated as MN Control #1, #2, #3, and #4, respectively. The bridges are designated so that direct comparisons can be made between MN LC #1 and MN Control #1 and also MN LC #2 and MN Control #2.

MN LC #1 and MN Control #1 are twin bridges (southbound and northbound, respectively) located on Highway 47 over Trunk Highway (TH) 10 in Coon Rapids, MN. MN LC #1 is a full-depth concrete deck, while MN Control #1 has an overlay (designated as a 3U17A Concrete Wearing Course per Minnesota specifications). MN LC #2 and MN Control #2 are twin bridges (northbound and southbound, respectively) located on I-694 over the Union Pacific Railroad in Oakdale, MN. Both decks were constructed with full-depth concrete. The two additional decks, designated as MN Control #3 and #4, are twin bridges (southbound and northbound, respectively) located on I-694 over TH 5 in Oakdale, MN, approximately one-half mile north of MN LC #2 and MN Control #2. Both decks include a concrete wearing course overlay (3U17A).

The two low-cracking decks, MN LC #1 and #2, respectively, contain 540 and 535 lb/yd^3 (320 and 317 kg/m^3) of portland cement and have water-cement ratios (*w/c*) of 0.44 and 0.42. They contain no supplementary cementitious materials. Current Kansas LC-HPC specifications require a cement content between 500 and 540 lb/yd^3 (297 and 320 kg/m^3) and a water-cement ratio between 0.44 and 0.45. The values of water-cement ratio used in Kansas decks were selected to avoid the placement of concretes with high strengths. Higher-strength concrete can increase cracking by decreasing the mitigation of tensile stresses that occurs as concrete creeps. The three standard decks that had information available on mixture proportions (MN Control #2, #3, and #4) contain 70 lb/yd^3 (42 kg/m^3) of portland cement, 335 lb/yd^3 (199 kg/m^3) of a blended cement with 7 percent silica fume, and 135 lb/yd^3 (80kg/m^3) of fly ash, corresponding to a cementitious-material content of 540 lb/yd^3 (320 kg/m^3). The three standard decks had a water-cementitious material ratio (*w/cm*) of 0.40, considerably lower than the allowable range in the

LC-HPC specifications. These low water-cementitious material ratios have likely increased the potential for cracking in the standard decks. Based on the cementitious material contents and water-cementitious material ratios of the decks, the standard decks appear to contain paste volumes similar to or slightly lower than those of the low-cracking decks (increased paste content contributes to increased drying shrinkage and cracking); however, no data are available regarding the specific gravities of the cementitious materials, and therefore, actual paste contents are unable to be quantified. In addition, it appears that the five MN bridge decks with available mixture design information had paste contents well below 27 percent. Previous studies at the University of Kansas (Schmitt and Darwin 1995, 1999) have found that bridge decks with paste contents below 27 percent exhibit less cracking.

The data available on plastic concrete properties and environmental conditions during construction are shown in Table 2. Both low-cracking decks had concrete with an average slump of 3.25 in. (85 mm). Both the current LC-HPC and Minnesota low-cracking specifications require slumps between 1.5 and 3 in. (40 and 75 mm). The LC-HPC specifications require the Engineer to reject any concrete with a slump greater than 3.5 in. (90 mm). The average slump of 3.25 in. (85 mm) is similar to values for LC-HPC decks constructed in Kansas. The air contents for MN LC #1 and #2 were 8.0 and 7.8 percent, respectively. These values fall within the allowable range of the LC-HPC specifications (6.5 to 9.5 percent). The average concrete temperatures of 67 and 61° F (19 and 16° C) for MN LC #1 and #2, respectively, also fall within the allowable limits of the LC-HPC specifications. The LC-HPC and Minnesota low-cracking specifications require a similar range of concrete temperature [55 to 70° F (13 to 21° C)]. The ambient temperatures of 55 and 62° F (13 and 17° C) for MN LC #1 and #2, respectively, likely did not contribute to high evaporation rates during construction. Information regarding compressive strengths of the Minnesota decks was not available. The Minnesota low-cracking specifications do not require a maximum allowable 28-day compressive strength, while the current LC-HPC specifications require a maximum allowable strength of 5500 psi (37.9 MPa). As discussed previously, higher-strength concrete can increase cracking by reducing the beneficial effects of creep. Although the current LC-HPC specifications require this strength limit, no LC-HPC decks have been constructed since this requirement has been added.

Table 3 shows the method of placement, the time from strike off to burlap placement, and the length of the curing period for the Minnesota bridge decks. All six Minnesota decks were placed by pumping. Pumping was the most common method of placement of the LC-HPC decks in Kansas. Both the LC-HPC and Minnesota low-cracking specifications require the contractor to demonstrate the ability to pump the concrete to be used in a deck prior to construction. Unlike the Minnesota low-cracking specifications, however, the current LC-HPC specifications require the contractor to demonstrate the ability to pump the concrete *using the same pump* as to be used for the deck placement. During construction of LC-HPC decks, different pumps have demonstrated a wide range of abilities, even when pumping similar concrete. Testing the ability of a pump prior to construction provides a good representation of how construction will proceed.

The LC-HPC and Minnesota low-cracking specifications have differing requirements for consolidation. The LC-HPC specifications require the use of internal gang vibrators spaced 1 ft (0.305 m) apart that are vertically mounted to the finishing bridge, while the Minnesota specifications do not require the vibrators to be vertically mounted and allow all consolidation to be completed by hand-held vibrators operated by workers. Vertically-mounted vibrators provide consistent consolidation throughout placement and limit the influence of worker error. Concrete consolidated with hand-held vibrators may be subjected to inconsistent vibration depth, duration, spacing, and angle and speed of insertion and removal. Improper vibration increases the potential for a number of cracking mechanisms. Under-vibrated concrete may continue to consolidate after being finished, increasing the potential for settlement cracking. Over vibration of concrete may force coarse aggregate away from the vibrator and leave excess cement paste at the surface, increasing the potential for plastic shrinkage cracking. Removing vibrators too rapidly may cause divots or indentions in the surface, increasing the potential for voids near the surface and subsequent settlement, which may cause additional settlement cracking.

The average time between strike off and placement of the burlap was 20 minutes for MN LC #1 and 10 to 14 minutes for MN LC #2. The LC-HPC specifications require a maximum time to burlap placement of 10 minutes, although average burlap-placement times of 20 minutes are common for the LC-HPC decks constructed in Kansas. The Minnesota low-cracking specifications allow for 20 minutes between strike off and burlap placement, 10 minutes longer than the LC-HPC specifications; however, the times to burlap placement for the Minnesota low-cracking decks were similar to many of the LC-HPC decks in Kansas. Unlike the LC-HPC specifications, the Minnesota low-cracking specifications give the Engineer authority to apply a charge of $500 to the contractor for every 5-minute period that the time between strike off and burlap placement exceeds 30 minutes. The risk of this charge provides the contractor with an additional incentive to place the burlap quickly – an incentive that does not exist for LC-HPC decks. The burlap placement for the low-cracking decks in Minnesota was generally faster than for the standard decks. The time from strike off to burlap placement for three of the four standard decks was 30 minutes, while the burlap placement for the other standard deck (MN Control #1) was completed in 15 to 20 minutes. The Minnesota standard specifications require a maximum time to burlap placement of 30 minutes. Similar to the Minnesota low-cracking specifications, the standard specifications include the risk of a $500 charge to the contractor if the time to burlap placement exceeds 30 minutes.

MN LC #1 and #2 were cured for 14 and 15 days, respectively. These curing periods match and exceed, respectively, the 14 days required by the LC-HPC specifications. The standard decks were cured for 7 or 8 days, similar to the 7-day curing period required for decks constructed in accordance with the standard specifications in Kansas. Longer curing periods decrease the potential for cracking by allowing more internal water to become tied up in the cement hydration process during the period that the concrete is protected from drying.

RESULTS

This section presents the results obtained from the crack surveys of the six bridge decks in Minnesota. The crack maps created from the crack surveys are presented in this section, showing the bridge location, dimensions, construction data crack distribution, and crack density. Table 4 shows the crack densities and ages at the time of survey for the six decks. The crack maps for the low-cracking and standard decks in Minnesota are shown in Figures 1 through 6. Descriptions of the crack distributions are presented in this section.

Table 4 Crack density and age at the time of survey for the surveyed Minnesota bridges

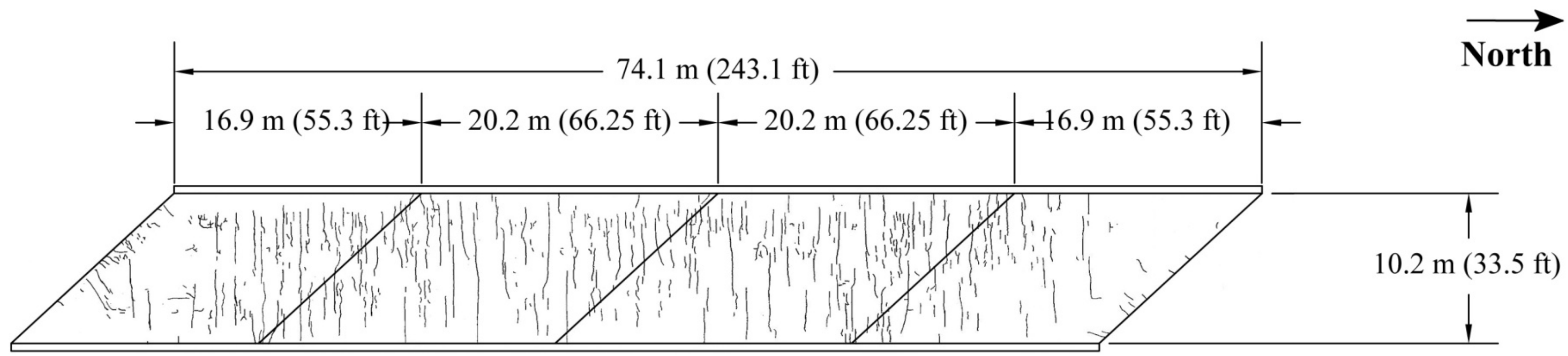
Deck Number	Designated Name	Crack density (m/m^2)	Age (months)
9725	MN LC #1	0.702	48.2
9726	MN Control #1	0.939	62.0
82805	MN Control #2	0.744	35.2
82806	MN LC #2	0.648	37.6
82807	MN Control #3	0.841	35.3
82808	MN Control #4	0.735	37.8

Bridge 9725 (MN LC #1)

The crack map for MN LC #1 is shown in Figure 1. At an age of 48.2 months, the deck had a crack density of 0.702 m/m^2. A majority of the cracks have propagated in the transverse direction, parallel to the deck reinforcement and not parallel to the skew of the bridge and piers. Many of the transverse cracks are long, at times extending across much of the deck width. Smaller cracks have developed throughout the deck between the longer cracks. Cracks have developed relatively evenly throughout the deck, with slight reductions in cracking near the abutments. Small, longitudinal cracks have propagated from the south abutment. These longitudinal cracks at the abutment were likely caused by restraint provided by the abutment.

Bridge 9726 (MN Control #1)

The crack map for MN Control #1, the companion deck for MN LC #1, is shown in Figure 2. At an age of 62.0 months, the deck has a crack density of 0.939 m/m^2, approximately 30 percent greater than the crack density of MN LC #1 at 48.2 months. This deck has the highest crack density of the six decks surveyed. Significant transverse cracking was found throughout the deck. The transverse cracks extend across the entire deck width along the full length of the bridge. As with MN LC #1, the transverse cracking has developed parallel to the deck reinforcement, not parallel to the skew of the bridge and piers. Small, longitudinal cracks have developed from each abutment, likely due to the restraint provided by the abutments. The



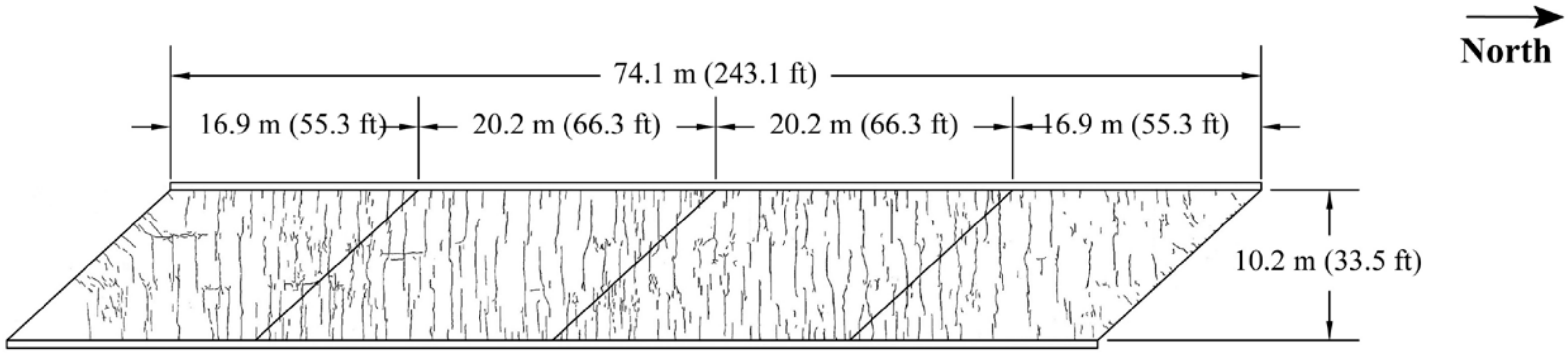
Bridge Number: 9725
Bridge Location: 47 SB over TH 10
Construction Date: 07/11/2009
Crack survey Date: 07/17/2013

Bridge Length: 74.1 m (243.1 ft)
Bridge Width: 10.2 m (33.5 ft)
Skew: -47.4°
Number of Spans: 4
- **Span 1 (South):** 16.9 m (55.3 ft)
- **Span 2 (South):** 20.2 m (66.25 ft)
- **Span 3 (North):** 20.2 m (66.25 ft)
- **Span 4 (North):** 16.9 m (55.3 ft)

Number of Placements: 1

Bridge Age: 48.2 months
Crack density: 0.702 m/m^2
- **Span 1 (South):** 0.712 m/m^2
- **Span 2 (South):** 0.814 m/m^2
- **Span 3 (North):** 0.796 m/m^2
- **Span 4 (North):** 0.449 m/m^2

Figure 1 Crack survey of Bridge 9725 (MN LC #1) at 48.2 months of age



Bridge Number: 9726
Bridge Location: 47 NB over TH 10
Construction Date: 05/16/2008
Crack survey Date: 07/17/2013

Bridge Length: 74.1 m (243.1 ft)
Bridge Width: 11.2 m (33.5 ft)
Skew: -47.4°
Number of Spans: 4
  Span 1 (South): 16.9 m (55.3 ft)
  Span 2 (South): 20.2 m (66.25 ft)
  Span 3 (North): 20.2 m (66.25 ft)
  Span 4 (North): 16.9 m (55.3 ft)
Number of Placements: 1

Bridge Age: 62.0 months
Crack density: 0.939 m/m^2
  Span 1 (South): 0.950 m/m^2
  Span 2 (South): 1.057 m/m^2
  Span 3 (North): 0.995 m/m^2
  Span 4 (North): 0.704 m/m^2

Figure 2 Crack survey of Bridge 9726 (MN Control #1) at 62.0 months of age

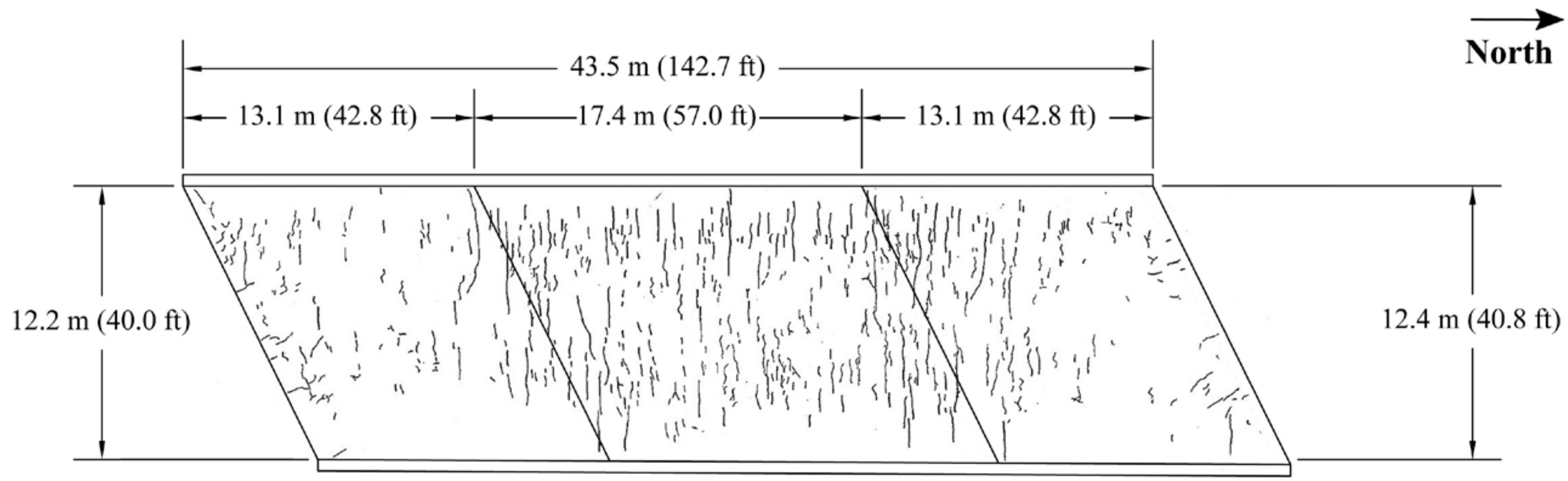
distribution of cracking on MN Control #1 is similar, but more pronounced than the cracking distribution on MN LC #1.

Bridge 82806 (MN LC #2)

The crack map for MN LC #2 is shown in Figure 3. At an age of 37.6 months, the deck had a crack density of 0.648 m/m^2, the lowest of the six decks surveyed. Many small cracks have propagated in the transverse direction throughout the deck. A greater amount of cracking is found in the middle span than in the outer spans. The cracks have generally developed parallel to the deck reinforcement, not parallel to the skew of the bridge or piers. A few small cracks have propagated from each abutment. Smaller cracks, like those found in this deck, are commonly caused by plastic shrinkage. Plastic shrinkage cracking results from the evaporation of water from the surface while the concrete is in the plastic condition. Plastic shrinkage cracking may be increased as the result of slow initiation of wet-curing, over finishing of the surface, or over vibrating during consolidation – the latter two contribute to excess surface paste. The average temperatures of the concrete [61° F (16° C)] and ambient air [62° F (17° C)] recorded during the construction of this deck, however, are not characteristic of a high evaporation rate or plastic shrinkage cracking. In addition, burlap placement was completed quickly during construction, minimizing the potential for plastic shrinkage cracking. These observations suggest that the cracks were likely caused by extra paste worked to the surface as a result of over finishing or by improper vibration techniques, which can lead to increased plastic or settlement cracking, or both.

Bridge 82805 (MN Control #2)

The crack map for MN Control #2, the companion deck for MN LC #2, is shown in Figure 4. At an age of 35.2 months, the deck had a crack density of 0.744 m/m^2, approximately 15 percent greater than the crack density of MN LC #2. As with the other decks, a majority of the cracks have developed in the transverse direction, parallel to the deck reinforcement. A number of long transverse cracks are found in the middle span, occasionally extending across the entire deck width. Transverse cracking is somewhat higher above the north pier (again, not parallel to the pier). Less cracking is found near the south abutment. Similar to other decks, short longitudinal cracks extend from each abutment.

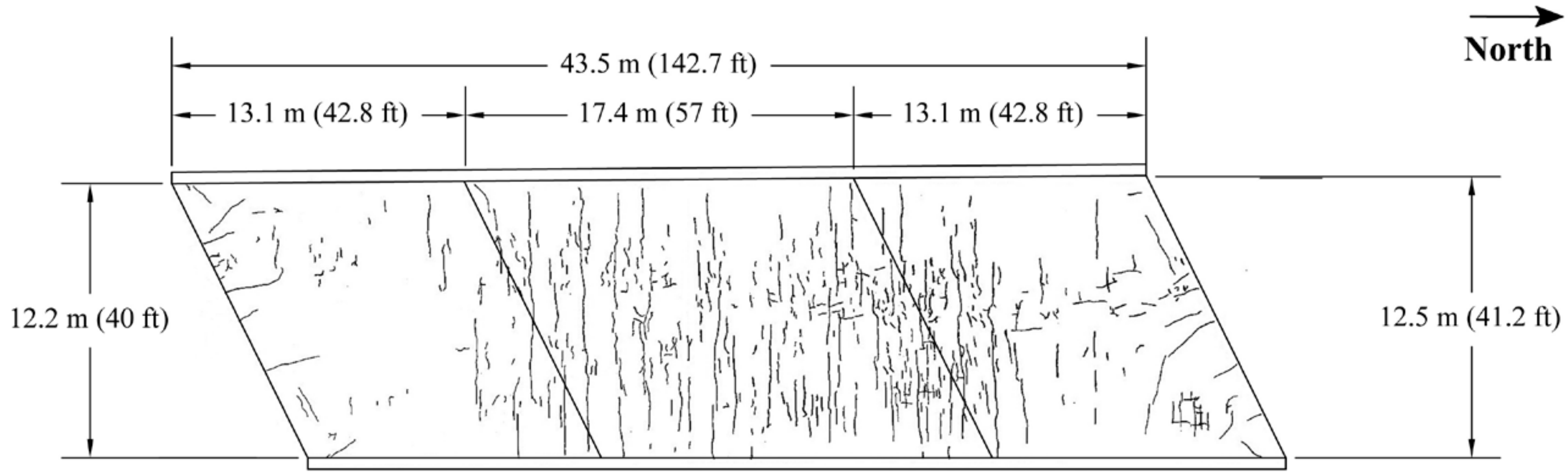


Bridge Number: 82806
Bridge Location: 694 NB over UP RR in Oakdale
Construction Date: 05/28/2010
Crack survey Date: 07/15/2013

Bridge Length: 43.5 m (142.7 ft)
Bridge Width: 12.2 - 12.4 m (40 - 40.8 ft)
Skew: 26.4°
Number of Spans: 3
Span 1 (South): 13.1 m (42.8 ft)
Span 2 (South): 17.4 m (57 ft)
Span 3 (North): 13.1 m (42.8 ft)
Number of Placements: 1

Bridge Age: 37.6 months
Crack density: 0.648 m/m^2
Span 1 (South): 0.422 m/m^2
Span 2 (South): 0.859 m/m^2
Span 3 (North): 0.549 m/m^2

Figure 3 Crack survey of Bridge 82806 (MN LC #2) at 37.6 months of age



Bridge Number: 82805
Bridge Location: 694 SB over UP RR in Oakdale
Construction Date: 08/10/2010
Crack survey Date: 07/15/2013

Bridge Length: 43.5 m (142.7 ft)
Bridge Width: 12.2 - 12.5 m (40 - 41.2 ft)
Skew: 26.4°
Number of Spans: 3
Span 1 (South): 13.1 m (42.8 ft)
Span 2 (South): 17.4 m (57 ft)
Span 3 (North): 13.1 m (42.8 ft)
Number of Placements: 1

Bridge Age: 35.2 months
Crack density: 0.744 m/m^2
Span 1 (South): 0.366 m/m^2
Span 2 (South): 1.04 m/m^2
Span 3 (North): 0.688 m/m^2

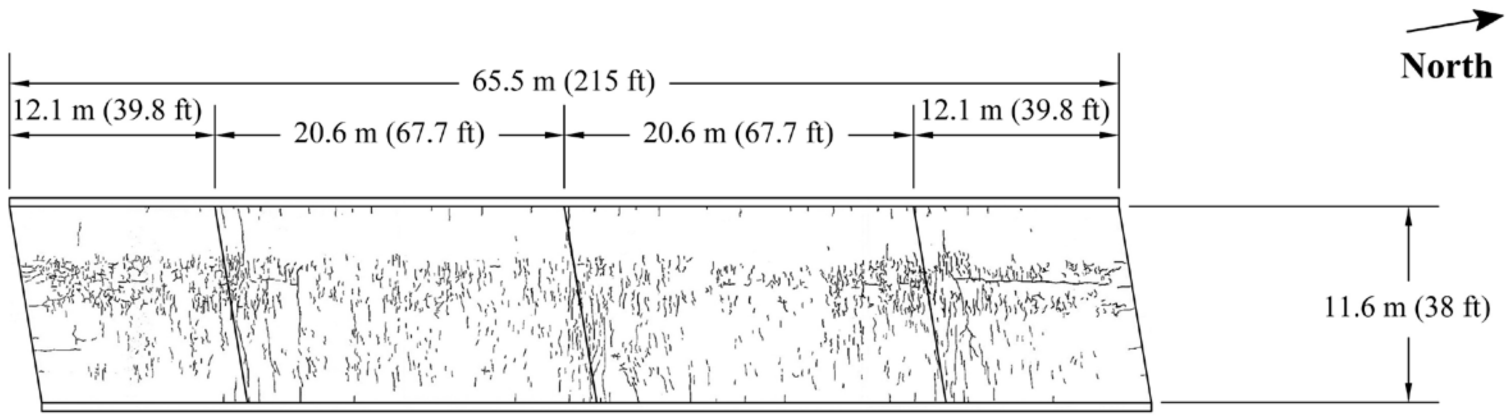
Figure 4 Crack survey of Bridge 82805 (MN Control #2) at 35.2 months of age

Bridge 82807 (MN Control #3)

The crack map for MN Control #3 is shown in Figure 5. At an age of 35.3 months, the deck had a crack density of 0.841 m/m^2. The cracks on this deck are significantly smaller than on the other decks. The small cracks are observed throughout the deck, increasing in density near the piers. The greatest cracking occurs along the outer edge of the driving lane. Little cracking is found outside of the lane line, in the shoulder area (west side of deck). The small cracks are typical to those caused by plastic shrinkage cracking. The construction data indicates that the average concrete temperature was 78° F (26° C), above the limit of 70° F (21° C) allowed in the LC-HPC specifications. The construction records also show that burlap placement was slow (average of 30 minutes between strike off and burlap placement). Increasing concrete temperatures and decreasing rates of burlap placement both can increase evaporation and the potential for plastic shrinkage cracking. As with MN LC #2, over vibration may have also contributed to plastic shrinkage cracking. A few long, transverse cracks have formed above and parallel to the south pier, in the negative moment region of the deck, a region in which the upper surface of the deck is in tension, increasing the potential for cracking. Although flexural stresses are significantly lower than shrinkage and thermal stresses induced in bridge decks, the combination of the different mechanisms increases the potential for cracking. A single, longitudinal crack, extending approximately 30 ft (9.1 m), has formed along the outer lane line in the north span. A few longitudinal cracks propagate from the abutments.

Bridge 82808 (MN Control #4)

The crack map for MN Control #4 is shown in Figure 6. At an age of 37.8 months, the deck had a crack density of 0.735 m/m^2. A greater number of longitudinal cracks have formed on this deck than on the other decks. A number of longitudinal cracks, located approximately 15 ft (4.6 m) from the west edge of the deck, extend along most of the bridge length. Another group of longitudinal cracks have formed approximately 15 ft (4.6 m) from the east edge of the deck, extending along portions of the bridge length. Many transverse cracks have propagated from the west edge of the deck. As with MN Control #3, minimal cracking is noted in the shoulder area of the deck. A number of long, transverse cracks extend across most of the deck width, directly above and parallel to the piers in the negative moment region.

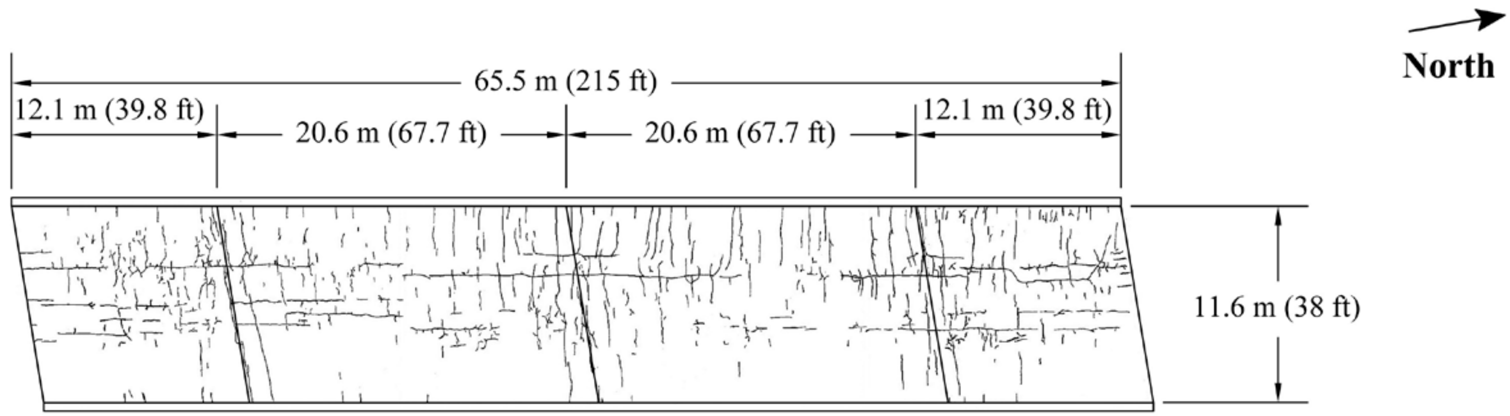


Bridge Number: 82807
Bridge Location: 694 SB over TH 5 in Oakdale
Construction Date: 08/06/2010
Crack survey Date: 07/15/2013

Bridge Length: 65.5 m (215 ft)
Bridge Width: 11.6 m (38 ft)
Skew: 9.4°
Number of Spans: 4
Span 1 (South): 12.1 m (39.8 ft)
Span 2 (South): 20.6 m (67.7 ft)
Span 3 (North): 20.6 m (67.7 ft)
Span 4 (North): 12.1 m (39.8 ft)
Number of Placements: 1

Bridge Age: 35.3 months
Crack density: 0.841 m/m^2
Span 1 (South): 0.882 m/m^2
Span 2 (South): 0.850 m/m^2
Span 3 (North): 0.801 m/m^2
Span 4 (North): 0.848 m/m^2

Figure 5 Crack survey of Bridge 82807 (MN Control #3) at 35.3 months of age



Bridge Number: 82808
Bridge Location: 694 NB over TH 5 in Oakdale
Construction Date: 05/22/2010
Crack survey Date: 07/15/2013

Bridge Length: 65.5 m (215 ft)
Bridge Width: 11.6 m (38 ft)
Skew: 9.4°
Number of Spans: 4
- **Span 1 (South):** 12.1 m (39.8 ft)
- **Span 2 (South):** 20.6 m (67.7 ft)
- **Span 3 (North):** 20.6 m (67.7 ft)
- **Span 4 (North):** 12.1 m (39.8 ft)

Number of Placements: 1

Bridge Age: 37.8 months
Crack density: 0.735 m/m^2
- **Span 1 (South):** 0.729 m/m^2
- **Span 2 (South):** 0.705 m/m^2
- **Span 3 (North):** 0.674 m/m^2
- **Span 4 (North):** 0.879 m/m^2

Figure 6 Crack survey of Bridge 82808 (MN Control #4) at 37.8 months of age

COMPARISON OF CRACKING PERFORMANCE

This section compares the cracking performance of the six bridge decks surveyed in Minnesota with similar decks constructed in Kansas in accordance with either the LC-HPC or standard Kansas Department of Transportation (KDOT) specifications. All decks were constructed on steel girders. The decks constructed in Kansas in accordance with the LC-HPC specifications are full-depth placements. The Kansas decks constructed in accordance with the standard KDOT specifications, designated as KS Control, each have a silica fume overlay. Fifteen LC-HPC and fourteen KS Control placements are analyzed in this section. The crack densities of the Minnesota LC and Control decks are compared with those of the LC-HPC and KS Control decks in Figures 7 and 8, respectively.

The figures show that the two Minnesota low-cracking (MN LC) decks have lower crack densities than all four of the Minnesota Control (MN Control) decks. As described earlier, the crack density of MN Control #1 is approximately 30 percent greater than the crack density of MN LC #1 (0.939 vs. 0.702 m/m^2). Similarly, the crack density of MN Control #2 is approximately 15 percent greater than the crack density of MN LC #2 (0.744 vs. 0.648 m/m^2). The other two MN Control decks also had higher crack densities than the two MN LC decks.

The comparison of the Minnesota decks with the Kansas LC-HPC decks in Figure 7 shows that all six Minnesota decks have significantly more cracking than the Kansas LC-HPC decks at similar ages. No Kansas LC-HPC deck has a crack density greater than 0.400 m/m^2, while all six Minnesota decks have crack densities above 0.600 m/m^2.

Figure 8 compares the cracking performance of the Minnesota decks with the decks constructed in Kansas in accordance with the standard KDOT specifications (KS Control). The figure shows that the Minnesota decks yielded higher crack densities than a majority of the KS Control decks. Four of the fourteen KS Control decks have equal or greater cracking than the Minnesota decks at similar ages. Previous studies at the University of Kansas observed greater cracking in decks with silica fume overlays, such as the KS Control decks and three of the Minnesota standard decks (MN Control #1, #3, and #4) (Lindquist et al. 2005). Additional surveys of the Minnesota decks would provide a better understanding of the progression of cracking performance over time.

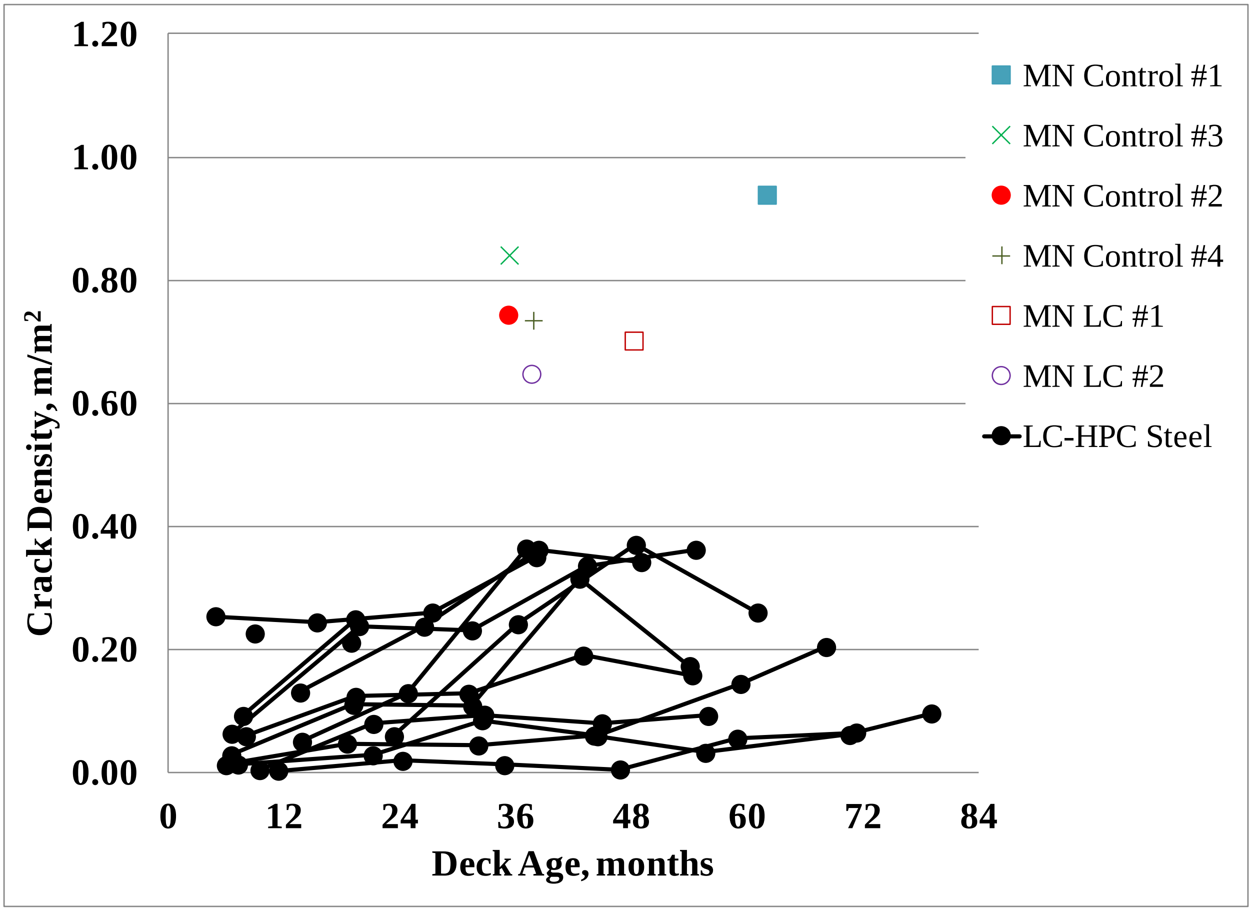


Figure 7 Crack density versus deck age for the standard Minnesota decks (MN Control), low-cracking Minnesota decks (MN LC), and low-cracking high-performance concrete decks constructed in Kansas on steel girders (LC-HPC Steel)

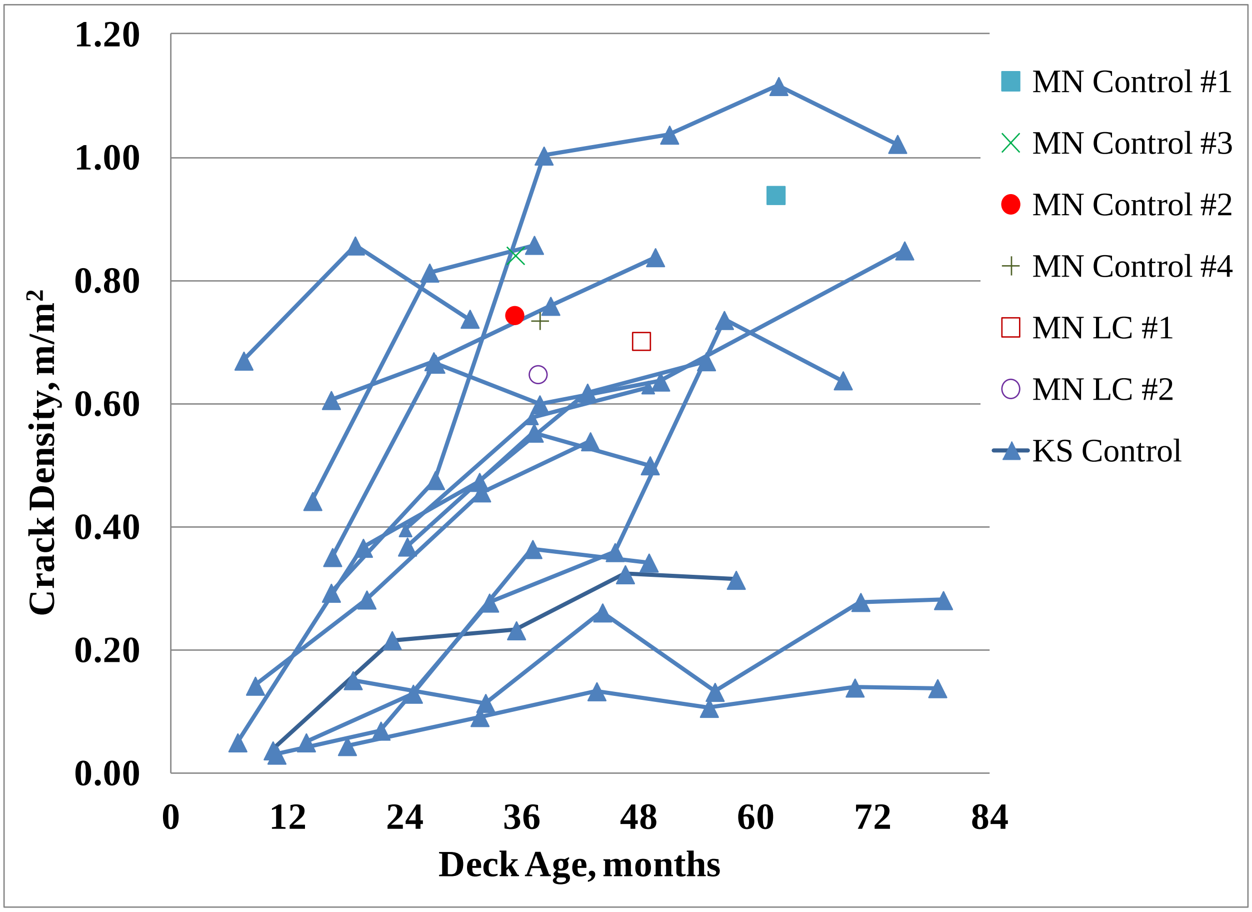


Figure 8 Crack density versus deck age for the standard Minnesota decks (MN Control), low-cracking Minnesota decks (MN LC), and decks constructed in Kansas on steel girders in accordance with the standard Kansas Department of Transportation (KDOT) specifications (KS Control)

CONCLUSIONS

The following conclusions are based on the results and analysis of the completed surveys:

1. The bridge decks in Minnesota constructed in accordance with the Minnesota low-cracking specifications have lower cracking than the bridge decks constructed in accordance with the standard Minnesota specifications.
2. The bridge decks in Minnesota constructed in accordance with either the low-cracking or standard specifications have greater cracking at similar ages than the bridge decks constructed on steel girders in Kansas in accordance with the low-cracking high-performance concrete (LC-HPC) specifications.
3. The bridge decks in Minnesota constructed in accordance with either the low-cracking or standard specifications have greater cracking at similar ages than a majority of the bridge decks constructed on steel girders in Kansas in accordance with the standard Kansas Department of Transportation (KDOT) specifications.
4. Cracks in the bridge decks commonly occur in the transverse direction, parallel to the deck reinforcement. Longitudinal cracks are commonly found propagating from the abutments. Cracking was generally observed to be evenly distributed throughout the decks, although increased cracking was noted occasionally directly above the piers.
5. Additional surveys are needed on the Minnesota bridge decks to understand the progression of cracking performance over time.

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