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“Moving Advancements into Practice”

MAP Brief November 2016

Best practices and promising technologies that can be used now to enhance concrete paving

Causes of Early Cracking in Concrete Bridge Decks

November 2016

ROAD MAP TRACK 6

PROJECT TITLE
Causes of Early Cracking in Concrete Bridge Decks

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The Long-Term Plan for Concrete Pavement Research and Technology (CP Road Map) is a national research plan developed and jointly implemented by the concrete pavement stakeholder community. Publications and other support services are provided by the Operations Support Group and funded by the Federal Highway Administration.

Moving Advancements into Practice (MAP) Briefs describe innovative research and promising technologies that can be used now to enhance concrete paving practices. The March 2016 MAP Brief provides information relevant to Track 6 of the CP Road Map: Concrete Pavement Construction, Reconstruction, and Overlays.

This MAP Brief is available at www.cproadmap.org/publications/MAPbriefNovember2016.pdf.

Introduction

The problem of deck cracking has existed in bridges for many years. The cracks commonly occur after construction but before the bridge is opened to traffic (i.e., days following concrete placement). Figure 1 is an example of such a bridge. In this particular case, the evidence of cracking on both the top and bottom of the deck (commonly observed only on the bottom initially) indicates that this bridge is particularly susceptible to moisture and chloride ingress—the cracks provide a direct pathway for the intrusion of water and chlorides. In the worst case, these early-age cracks could lead to a reduced bridge-deck service life. Interestingly, there have been instances where cracking has occurred in only one of twin, side-by-side bridges. This situation is confusing—the two structures should be the same, yet only one experiences cracking.

It is generally accepted that the occurrence of early-age deck cracking is mainly due to the restraint of concrete volume change by the girders and supports. It is also thought that the major cause of concrete volume change is a combination of shrinkage and thermal effects (including temperature drop after heat of hydration, autogenous shrinkage, drying shrinkage, and plastic shrinkage due to evaporation of the mix water). The amount of concrete volume change and the degree of restraint are dependent upon many factors that can be generally categorized into three broad categories:

- Concrete material properties and proportions
- Structural design attributes of the bridge associated with the structural interaction between the deck and other components
- Construction environment and techniques

Figure 1. Cracking (marked on deck surface) occurred before this newly constructed bridge was opened to traffic.

Because the number of factors is large and the cracking mechanisms related to different factors are complex and highly interactive, it is not easy to conclusively identify the relationships between the factors and the development of deck cracks. In fact, analysis of the causes of deck cracking, taking into account only one or some of these factors, has led to somewhat biased opinions. Any attempt to understand the interaction between factors must include a systematic statistical analysis of the actual correlations between the degree of deck cracking and the magnitudes/characteristics of all the important factors. Only in this way can the interactive effects due to different factors be identified.

Material, Structural, and Construction Conditions

A review of available information reveals the potentially important material, structural, and construction conditions/factors that may either increase or reduce the amount of cracking in bridge decks. The factors are summarized in Tables 1 through 3 with brief descriptions as to how they can positively or negatively affect the degree of deck cracking.

Table 1. Relationships of material properties/proportions and concrete deck cracking

Concrete Deck Material/Mixture Factors	Effects on Concrete Deck Cracking
Cement type, content, and proportion	• Thermal shrinkage (hydration) and dry shrinkage (water loss) are influenced by the type of cement. • Type II cements help reduce thermal stresses and thus cracking. • Type-K shrinkage-compensating cement is associated with less shrinkage cracking. Type-K cement develops expansive characteristics in the concrete that, when properly restrained from expansion, develop compressive stresses. The tensile stresses due to dry shrinkage and other factors have to overcome the compressive stress and tensile strength of the concrete before cracks can form. • Supplementary cementitious materials such as fly ash, slag, and natural pozzolans reduce the rate of hydration of the cement paste, decreasing the set time, temperature rise, and early strength development and thus the potential for thermal cracking.
Aggregate contents/type	• Aggregate content (type, size, volume, and gradation) has an effect on shrinkage and absorption of the concrete. Low shrinkage aggregates with high aggregate-to-paste ratio and low coefficient of thermal expansion can reduce cracking. • Internal curing—the process of replacing approximately 30% of the volume of fine aggregate with water-filled lightweight aggregate—is a relatively new practice that improves concrete's overall performance. The pre-wetted aggregate increases the amount of water available for cement hydration without affecting the water-to-cement ratio and disperses the curing water throughout the depth of the concrete, thus increasing the reaction of the cementitious materials over time. Internal curing will measurably reduce autogenous shrinkage cracking, reduce plastic shrinkage cracking, and by increasing the extent of the hydration reaction reduce fluid transport. Internal curing has primarily been used in bridge decks in Illinois, Indiana (8), Iowa, New York (9), and Utah (10). For detailed information about internal curing, see the December 2015 MAP Brief (Weiss 2015).
Air content	Increasing the air content (especially >6%) decreases dry shrinkage of concrete and thus lowers the potential for cracking.
Other admixtures	• Water reducers reduce the amount of water needed for a workable mix and can thus reduce drying shrinkage. • Shrinkage-reducing admixtures reduce dry shrinkage (but can have the side effect of reducing the efficiency of some air-entraining admixtures and may cause some scaling after several freeze-thaw cycles). • Retarding admixtures delay hydration and thus the potential for dry shrinkage cracks (but may be a disadvantage in cold-weather projects).
Concrete slump/water content	• Higher concrete slump is associated with increased cracking because it is related to increased concrete settlement over steel rebar. • Low water-to-cement ratio is associated with reduced cracking because it helps reduce volume change and concrete shrinkage.

Table 2. Relationships of structural design attributes with concrete deck cracking

Structural Factors	Effects on Concrete Deck Cracking
Concrete strength	• High strength concrete has an increased stiffness, which promotes crack development. Concrete strengths should not be allowed to be excessively high. • Modulus of elasticity (Ec) increases faster than strength for the first 3 to 5 hrs after initial set, potentially leading to cracking. The modulus can be lowered using lower Ec aggregate with reasonable compressed strength.
Span type	Interior spans are associated with increased restraint, and thus increased cracking, compared to end spans, due to the restraint provided by the intermediate supports.
Girder type	• Curved girders and slab bridge decks are related to increased cracking compared to slabs on stringer girders. • Simply supported girders impose less restraint on the deck than multi-span continuous composite large steel girders.
End restraint condition	• Fixed-ended conditions (e.g., integral abutments) and unintended boundary restraints are associated with increased cracking. • Simply-supported conditions are associated with reduced cracking.
Top transverse bars	Large size bars are associated with increased cracking due to the bars' higher relative stiffness.
Girder depth/spacing	• High relative girder-to-deck stiffness is associated with increased cracking • Wide flanges and composite steel plate girders may be associated with restraint-induced cracking.
Cross-frame location	Stress concentrations between cross-frames and steel girders are associated with increased deck cracking.
Expansion joints	Expansion joints accomodate concrete movement, reducing the potential for cracking.
Reinforcement mesh	Non-uniform distribution of reinforcement and improper reinforcing bar sizes and spacing are associated with increased cracking due to changing stiffnesses.
Concrete cover	Higher concrete cover causes more cracks and larger crack widths for reasons that aren't fully understood.

Table 3. Relationships of construction environment/techniques with concrete deck cracking

Construction Factors	Effects on Concrete Deck Cracking
Ambient conditions	The rate of evaporation, initial hydration temperatures, and long-term thermal stresses developed at early age in the deck are affected by weather conditions. Ambient conditions for the duration of concrete placement should be such that drastic temperature variations are not permitted; follow specifications.
Mechanical vibration	Mechanically vibrating the concrete consolidates it and closes plastic cracks.
Concrete finish	Early finishing reduces the amount and widths of cracks.
Curing	Early curing and moist curing for more than seven days enhance concrete's durability and strength and help maintain proper moisture content in early-age concrete, which helps control dry shrinkage cracking.
Placement time period	Increased placement time period can result in more cracks due to differential development of strength and stiffness.
Wind speed	Influences water evaporation and thermal stresses.
Construction sequence	Where feasible the deck should be poured at one time. If the deck is too big to allow for timely placement of the entire deck, the deck should be placed in stages with proper consideration to flexural stresses resulting from non-uniform dead loads.

With the above factors in mind and with the goal of understanding the degree and characteristics causing deck cracking, a study was initiated by the authors, during which 22 bridges constructed in the past five years were inspected and the deck cracks of those bridges mapped and analyzed. A typical crack distribution in a bridge with cracks and leaching is shown in Figures 2 and 3. Commonly observed crack characteristics can be best summarized as follows:

- Cracks are mostly perpendicular to the girders irrespective of the bridge skew. However, diagonal cracks are also sometimes present but tend to be restricted to the bridge ends.
- Cracks exist in both steel girder bridges and prestressed concrete girder bridges.
- Cracks are most commonly found near the pier location.
- Cracks are commonly spaced at 3-8 ft.
- Crack leaching indicates the cracks are full depth.

A factor termed the “crack rate”—defined as ten times the cracking divided by the bridge width—was established following the 22 bridge inspections mentioned above to conduct a statistical analysis of the factors most likely to result in cracking. After the information on the structural, construction, and material factors were collected for the different bridges, correlations between the various factors and crack rates were studied. Although very preliminary (and the scope of the study has been since expanded as a result), it has been observed that, independent of other variables, the cement content is positively correlated with the crack rate while the fly ash content is negatively correlated with the crack rate, as shown in Figure 4.

As a part of the same study, a pre-stressed concrete bridge recently constructed in Louisa County, Iowa, used a bond breaker in the south span of the bridge in an attempt to minimize crack development in that region. Only one span of the bridge had the bond breaker to allow for the influence of this detail to be directly compared to areas within the same bridge that did not have the bond breaker. In this trial, an 8-in. smooth finish region was created at the edges of the top flanges, as shown in Figure 5, where a bond breaker substance is applied. The bond breaker material can either be something similar to tar paper or a painted-on substance.

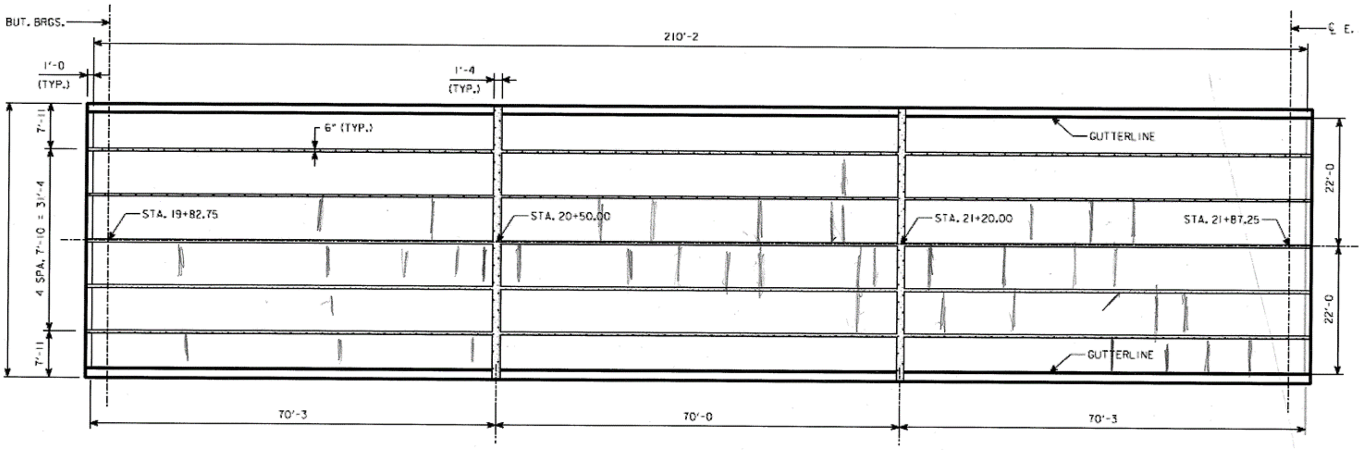

Figure 2. Sketch of typical crack locations and numbers

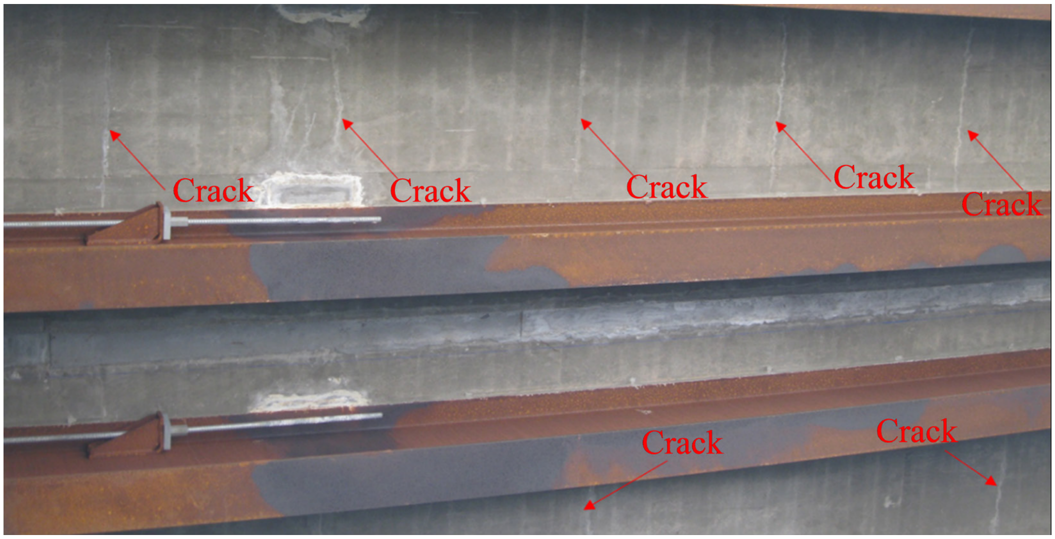

Figure 3. Bottom of deck cracking

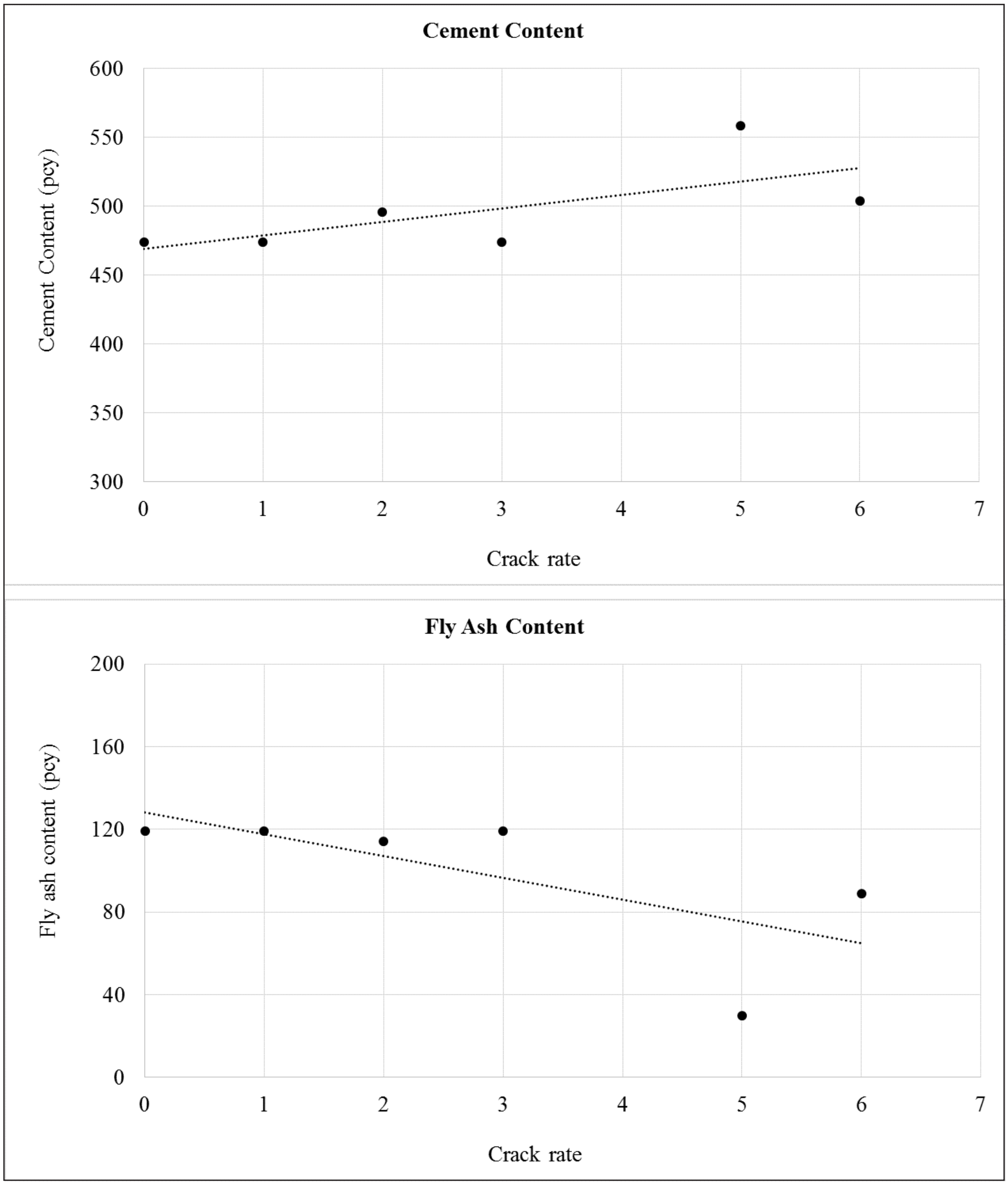

Figure 4. Relationship between cement content and crack rate (top) and relationship between fly ash content and crack rate (bottom)

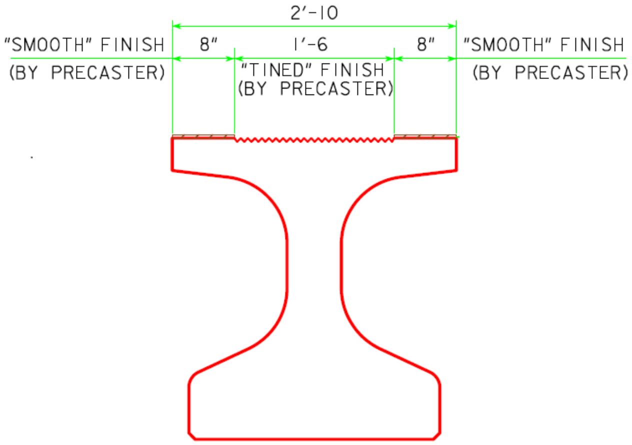

Figure 5. Bond breaker region

As shown in the crack map sketch (Figure 6) more cracks were found in the deck near the pier location without bond breaker (i.e., north span and mid-span) in comparison with that near the pier location with the bond breaker (i.e., south span and mid-span). While not completely conclusive, this case study appears to point to the fact that structural details resulting in increased deck restraint may increase the amount of deck cracking.

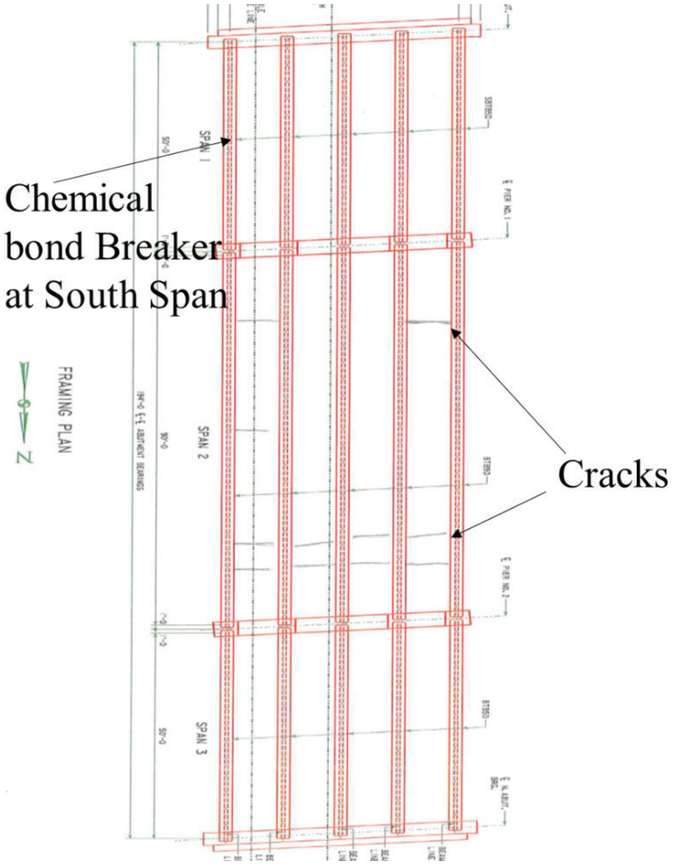

Figure 6. Cracks in bridge partially with bond breaker

Concluding Remarks

There is no industry consensus on the cause of bridge deck cracking. As a result, there are numerous on-going studies being conducted—including one by the authors—to more completely study the phenomenology of crack development. It is expected that in mid-2017 a wealth of knowledge on the subject will be generated from these numerous sources. In the absence of that information, the importance of proper concrete mix proportioning, observance of environmental conditions at the time of deck placement, and proper structural detailing cannot be understated.

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