Investigation of the Causes of Transverse Bridge Deck Cracking

Final Report
September 2022

BRIDGE ENGINEERING CENTER

IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract

Transverse cracks in concrete bridge decks sometimes initiate in the early stages of the bridge service life, usually just after construction. Cracks in the bridge deck can accelerate the deterioration of the deck concrete, provide a direct pathway for the intrusion of water and chlorides to the deck reinforcement, and detract from the aesthetics. This eventually results in increased maintenance costs and reduced bridge service life.

The goal of this research was to identify factors that consistently lead to the formation of early-age transverse cracks for mitigation in the future. To obtain a comprehensive evaluation and include as many factors as possible in the research, the primary research investigation was conducted in three stages with varying numbers of bridges and factors considered in each stage.

The first stage was carried out on 2,675 bridges constructed in Iowa between 1900 and 2020. The goal of this stage was to identify the correlation between deck cracking and six parameters: deck concrete type (high-performance concrete [HPC] or non-HPC), maximum span length, maximum structure length, Iowa Department of Transportation (DOT) District, year built, and main structure type.

The second stage was conducted to include additional bridge parameters—but with a smaller number of bridges. A group of 20 bridges was selected after reviewing inspection reports for 116 bridges constructed between 2013 and 2018. Various bridge parameters in three main categories, structural, construction, and material, were investigated.

The third stage was carried out based on data collected from six field visits while deck concrete was being placed. The parameters investigated in this stage included evaporation rate (lb/ft^2/h), air temperature (°F), concrete temperature (°F), relative humidity (%), and wind speed (mph).

The results from the three investigation stages were compared with the research results documented in another Iowa DOT report. Based on the research findings from each stage of investigation, the various parameters were classified as having either direct correlation, no correlation, slight positive correlation, or slight negative correlation.

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Final Report
September 2022

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EXECUTIVE SUMMARY

Transverse cracks in concrete bridge decks sometimes initiate in the early stages of the bridge service life, usually just after construction. Cracks in the bridge deck can accelerate the deterioration of the deck concrete, provide a direct pathway for the intrusion of water and chlorides to the deck reinforcement, and detract from the aesthetics. This eventually results in increased maintenance costs and reduced service life.

The goal of this research was to identify factors that consistently lead to the formation of early-age transverse cracks for mitigation in the future. To obtain a comprehensive evaluation and include as many factors as possible in the research, the primary research investigation was conducted in three stages with varying numbers of bridges and factors considered in each stage.

The first stage was carried out on 2,675 bridges constructed in Iowa between 1900 and 2020. The goal of this stage was to identify the correlation between deck cracking and six parameters: deck concrete type (HPC or non-HPC), maximum span length, maximum structure length, Iowa Department of Transportation (DOT) district, year built, and main structure type.

The second stage was conducted to include additional bridge parameters—but with a smaller number of bridges. A group of 20 bridges was selected after reviewing inspection reports for 116 bridges constructed between 2013 and 2018. Various bridge parameters in three main categories, structural, construction, and material, were investigated.

The third stage was carried out based on data collected from six field visits while deck concrete was being placed. The parameters investigated in this stage included evaporation rate (lb/ft^2/h), air temperature (°F), concrete temperature (°F), relative humidity (%), and wind speed (mph).

The results from the three investigation stages were compared with the research results documented in another Iowa DOT report. Based on the research findings from each stage of investigation, the various parameters were classified as having either direct correlation, no correlation, slight positive correlation, or slight negative correlation.

CHAPTER 1. INTRODUCTION

1.1 Background and Problem Statement

Iowa Department of Transportation (DOT) bridge staff have noticed multiple recent occurrences of transverse deck cracks developing shortly after bridge construction. This situation is very problematic because the cracks can provide a direct pathway for the intrusion of water and chlorides. In the worst case, these early-age cracks can speed up corrosion of the reinforcing steel, deteriorate the deck concrete, and eventually lead to increased maintenance costs and a reduced bridge deck service life.

In the past decades, numerous studies have been conducted to determine the factors that induce transverse deck cracks. In general, these factors can be categorized into three groups: structural design factors, construction and environmental factors, and material and mix design factors. Unfortunately, the cause of early-age bridge deck cracking is still not entirely understood. Because of the large number of factors involved, it is difficult to evaluate the contribution of each factor individually. In addition, some research indicates that bridge deck cracking is the result of a combination of factors in different categories, and additional, extensive research is needed to quantitively identify the effect from each factor.

1.2 Research Objective

The goal of this research was to identify factors that consistently lead to the formation of early-age transverse cracks for mitigation in the future. To accomplish this goal, a detailed review of conditions (environmental, structural, material, etc.) was conducted to help identify the factors consistently "in play" when the cracks are formed.

1.3 Research Plan

A four-task research plan was designed to achieve the project objectives:

Task 1: Establish technical advisory committee (TAC)
Task 2: Conduct literature review
Task 3: Investigate factors leading to cracking
Task 4: Prepare draft final report and tech transfer summary

To obtain a comprehensive evaluation and include as many potential factors as possible, the research work in Task 3 was conducted in three stages with a varying number of bridges and factors considered in each stage.

In Stage 1, the data from 2,675 bridges constructed in Iowa between 1900 and 2020 were investigated with the goal of identifying the effect of bridge deck concrete type, maximum span length, maximum structure length, bridge location, bridge age, and main structure type on the formation of bridge deck cracks.

In Stage 2, bridge condition information in terms of structural, construction, and materials for 20 bridges in Iowa was identified and investigated to seek the relationship between these factors and the bridge deck crack rate.

To evaluate the effects of on-site construction factors during deck concrete placement, field visits were conducted in Stage 3 for six bridges during deck concrete placement. This effort enabled the research team to collect bridge construction information (i.e., relative humidity, air and concrete temperature, and so forth). After that, the crack rates of these bridges were calculated and used to study the relationship to bridge construction factors.

In addition, the results from all three investigation stages were compared with the results from previous information collection conducted by the Iowa DOT (Yusuf and Nop 2022). Similarities and differences in the findings between the work conducted by the authors and the previous researchers are also discussed.

CHAPTER 2. INFORMATION COLLECTION

The goal of the information collection phase of this work was to identify the potential factors that may affect bridge deck cracking and to qualify the relation between the factors and the bridge deck cracking situation, if possible. In this chapter, a literature review that was completed early in the project (in 2016) is summarized in Section 2.1 with information on the initiation of early-age transverse bridge deck cracks. The results from a study similar to this research that the Iowa DOT conducted (Yusuf and Nop 2022) was also reviewed and is separately presented in Section 2.2.

2.1 Literature Review

2.1.1 Various Study Findings

Typically, transverse cracks occur in concrete bridge decks at an early age shortly after construction. Transverse cracks usually occur when the concrete is set (Freyermuth et al. 1970, ElSafty et al. 2016) and widen with time (Nelson et al. 2021, Xia et al. 2017, Ramey et al. 1997). These cracks have been observed in bridge decks in most geographic locations and studied for various concrete properties, including modulus of elasticity, creep, drying shrinkage, and coefficient of thermal expansion.

Transverse cracks occur on both simply-supported and continuous bridges, regardless of the girder type. One survey of state DOTs and agencies in the US and Canada estimated that more than 100,000 bridges or about half the bridges monitored by the respondents in the US had developed early transverse cracking (Krauss and Rogalla 1996).

The transverse cracks were typically full depth, located 3 to 10 ft (1 to 3 m) apart along the length of the span and usually observed over the transverse reinforcement (Freyermuth et al. 1970, McKeel 1985, Ramey et al. 1997). The predominant form of deck cracking reported was transverse cracking.

Transverse cracks shorten the service life of the structure and increase maintenance costs. Life span and maintenance costs are of paramount importance in the management of highway activities. (Freyermuth et al. 1970, McKeel 1985, Ramey et al. 1997, Patnaik 2017).

For decades, designers and researchers have been concerned about the development of transverse cracks in bridge decks. However, the effect of contributing factors is still not fully understood. In fact, research findings have shown contradictory results.

National Cooperative Highway Research Program (NCHRP) Report 380 presented the extensive survey of 52 agencies mentioned above with the goal of determining the causes of early-age transverse deck cracking (Krauss and Rogalla 1996, Rogalla et al. 1995). The combination of shrinkage and thermal effects was cited as the main source of early-age deck cracking (i.e., the temperature drop after heat of hydration, drying shrinkage, and plastic shrinkage due to evaporation of the mix water).

Saadeghvaziri and Hadidi (2002) conducted a research study focusing on investigating the relationship between structural design factors and bridge deck cracking. The research team surveyed 24 bridges in New Jersey. The data collected from these bridges included girder type, girder end condition, bridge skew, type of bearing, surface texture, wearing surface, deck thickness, reinforcing steel bar size, and bar spacing. The results indicated that deck cracking was related to concrete volume change and restraint of the deck concrete, which are dependent on the concrete material properties and constitutes, construction environment and techniques, and structural design attributes of the bridge and especially the interaction between the deck and other components.

The research documented by Rogalla et al. (1995) and Krauss and Rogalla (1996) evaluated the effects of different design factors and material factors on early-age transverse deck cracking. The results showed that design factors possibly playing a role in crack development included span type, concrete strength, and girder type, and that material factors included cement content and composition, concrete elastic modulus, creep, aggregate type, heat of hydration, and shrinkage. The researchers concluded that bridge deck cracking can be reduced with appropriate concrete mix design and construction techniques.

For example, bridge decks cast with concretes having higher strength, higher stiffness, less creep, and higher cement content are more likely to crack. Finer cement increases the possibility of cracking, while shrinkage-compensating admixtures and fly ash reduce cracking. Higher aggregate contents reduce cracking, and water reducers decrease water and paste volume and, thus, cracking.

For deck concrete placement, the ideal air temperature is between 40°F and 80°F, and weather conditions that are too cold or too hot cause a rapid temperature change and worsen cracking. Mechanical vibration can consolidate concrete, close plastic cracks, and, thus, reduce cracking. Early finish, early curing, and moist curing for more than 7 days were also cited as reducing the chance of cracking.

Previous reports from the University of Kansas Center for Research documented cracking patterns and density from field surveys and addressed the correlations between cracking and various factors (Schmitt and Darwin 1995, Schmitt and Darwin 1999). For this work, crack densities were described by the length of cracking per unit area of bridge deck. A total of 31 variables were analyzed to investigate the relationship of crack density to the variable magnitudes.

For the deck concrete material, the researchers concluded that concrete slump, percentage volume of water and cement, water content, cement content, and compressive strength are positively correlated (meaning that increasing the value of the studied factor increases the crack rate). High air content (especially >6%) decreases cracking in monolithic bridge decks, and zero slump concrete overlays show more cracks.

For construction conditions, the researchers found that placement lengths are positively correlated with cracking in overlays. A high maximum air temperature or a large change of air temperature during concrete casting increased deck cracking for integral bridges.

For design conditions, bridges with fixed-ended conditions showed more cracking near the abutments in comparison to simply supported conditions.

French et al. (1999) conducted a field inspection study on 72 bridges to investigate the influences of design, material, and construction factors on premature transverse deck cracking. The researchers found that simply supported prestressed concrete girder bridges showed less deck cracking than continuous steel girder bridges due to the reduced end restraint and the creep effects of the prestressed concrete girders.

For steel girder bridges, the researchers found more cracks in the following situations: 1) interior spans (compared to end spans), 2) curved bridges, 3) larger size of top transverse bars, 4) increased restraint due to stud configuration, girder depth, or girder spacing, and 5) stress concentrations near the cross-frame location. The researchers noted that expansion joints help to reduce cracking. In addition, the authors indicated that many material parameters could affect early-age deck cracking including cement content, aggregate type and quality, and air content.

Important construction parameters including ambient air temperature, temperature change due to concrete hydration, curing periods and methods, pour lengths and sequences, finishing procedures, vibration techniques, and weather conditions.

Saadeghvaziri and Hadidi (2005) conducted a finite element (FE) study of deck and girder bridge systems on 24 bridges in New Jersey. The research team tried to understand and evaluate crack patterns and stress histories, as well as the effects of different design factors, on transverse deck cracking. The researchers found that, for the design factors, high concrete strength, unintentional boundary restraints, high ratio of girder/deck stiffness, and non-uniform reinforcement meshes could induce more deck cracks. For mix design factors, low cement content, low w/c ratio, high aggregate content, and type K shrinkage compensating concrete could reduce deck cracking.

Curtis (2007) investigated bridge deck cracking by conducting a series of literature reviews, field surveys, and communications with state DOTs. The researchers investigated crack situations of 63 concrete bridge decks on top of steel girders. The results indicated that 38% of the single span bridges and 67% of the continuous span bridges showed significant cracking.

Based on past experience and collected information, the author concluded that the most influential factors that induce deck cracking included concrete strength, concrete cover above the steel reinforcement, pour temperature, tension stresses due to thermal effects (heat of hydration), live load effects (for continuous bridges), and concrete restraint shrinkage effects.

To reduce deck cracking, the author concluded that required concrete strength should be targeted, controlled, and not too high. The author concluded that thicker concrete cover induces more cracks and larger crack widths, and that warmer pour temperatures decrease the severity of cracking.

Wan et al. (2010) conducted a literature review, on-site inspections, concrete sample testing, and FE simulation to investigate the factors causing transverse deck cracking. The results from the on-site inspection of 16 bridges in Milwaukee, Wisconsin, indicated that more deck cracks were found in continuous bridges. FE analysis results showed that the live loads from ambient traffic had little effect on concrete deck cracking and that these cracks were believed to be induced by the early-stage concrete shrinkage. Results of concrete sample testing indicated that the tensile stresses caused by the rapid development of concrete strength, which were usually higher than the design value, was the reason of the early-age deck cracking.

A transportation research synthesis from the Minnesota DOT (MnDOT 2011) presented the literature review results on the initiation of bridge deck cracking based on 12 research articles or reports published from 1999 to 2011. The synthesis found that volume changes of a restrained concrete deck will cause bridge deck cracking and that volume changes are affected by the material properties and proportions as well as environmental conditions, such as ambient temperature variations and humidity.

Among the contributing factors, including drying shrinkage, autogenous shrinkage, plastic shrinkage, thermal shrinkage, and creep, the synthesis found that drying shrinkage and thermal shrinkage were the main factors that caused deck cracking.

Material conditions influencing deck cracking included cement type and content; the w/c ratio (which is related to the heat of hydration and drying shrinkage); air content (which is positively correlated with drying shrinkage); aggregate type, size, and volume (which are related to shrinkage and water absorption); and the use of fly ash (which decreases hydration and reduces shrinkage).

Construction conditions influencing deck cracking included air temperature, relative humidity, precipitation, solar radiation, and wind speed (which affect water evaporation and thermal stresses), curing (which affects concrete durability and strength), and the deck construction sequence (causing flexural stresses).

The structural conditions included the restraint of the deck from the girders, parapet, and abutment; deck thickness (affecting drying shrinkage and thermal variations due to the surface area to volume ratio); and reinforcing bar alignment.

Ganapuram et al. (2012) conducted a survey on deck cracking for 12 Ohio bridges. This crack survey was conducted according to the protocol developed as part of the Transportation Pooled Fund (TPF-5 (051)) Construction of Crack-Free Concrete Bridge Decks. The results indicated that a slightly higher density of shrinkage cracks was found in slab bridge decks as compared to stringer supported bridge decks. The number of cracks was not affected by the age of the bridge deck. Additionally, large cracks were found near the intermediate supports of continuous bridges.

ElSafty and Abdel-Mohti (2013) performed a parametric study on a validated three-dimensional (3D) FE bridge model to investigate the effect of bridge parameters on the development of early-age deck cracking. The loads under investigation included dead load, temperature change due to hydration, ambient temperature change, shrinkage, creep, and truck loads.

The authors found that shrinkage or temperature induced the initial cracks, while the live load further developed these cracks. Results indicated that concrete compressive strength significantly affected deck cracking and a compressive strength of less than 5 ksi was recommended.

Regarding the stiffness of the bridge, the results indicated that the thicker the deck, the lower the stress developed, resulting in fewer cracks. Deck thickness more than 7 in. was recommended.

Chen (2013) summarized the findings from the investigation conducted by the Ministry of Transportation – Ontario on transverse cracking in bridge decks. A total of 20 precast, prestressed, concrete girder bridges were inspected, and the patterns of cracking in the bridge decks were documented. The study found that two-span bridges showed more cracks than one-span bridges and that the restraint provided by the intermediate support was the main factor causing the transverse cracks in the bridge decks of two-span bridges.

The study found that the number of cracks increased with an increase in bridge stiffness (i.e., in the girder-to-deck cross-section area). The results also stated that the design of the concrete mixture has less of an impact on cracking compared to that of the structural design factor.

A parametric study was performed on the analytical models to understand the correlations between deck cracking and several structural parameters including the deck reinforcement ratio, the concrete strength, and the restraint condition. The results indicated that use of additional longitudinal reinforcing steel was of benefit in reducing the width of transverse cracks; the concrete strength positively correlated with crack width; and the rigidity of the deck end restraint had some influence, such as increasing the number of cracks and their characteristics.

The Bridge Engineering Center at Iowa State University conducted a study that included a developed 3D FE model to evaluate the need for longitudinal expansion joints by assessing the relationship between bridge width (and other factors) and the propensity for deck cracking (Liu et al. 2016, Phares et al. 2015, Liu 2014). The results indicated the commonly observed longitudinal and diagonal cracking in the deck near the abutment on integral abutment bridges is a result of the restraint induced by the integral abutment combined with temperature and shrinkage differences between the abutment and the deck that will occur for bridges of any width and any skew.

The Bridge Engineering Center’s researchers also conducted a study including a full-scale FE model to evaluate the effect of different amounts of longitudinal reinforcement (b2 bars) on resisting the negative moment over the pier on a continuous prestressed concrete girder bridge when subjected to the live load-generated moment and secondary moment (Freeseman et al. 2021, Liu et al. 2020). The results suggested that the transverse cracks induced by the secondary moment occur over the bridge pier within 1/8 of the span length near the pier.

2.1.2 Summary of Literature Review Findings

Based on the findings from the literature review, Table 1 was created to summarize all the possible factors that might lead to early-age transverse bridge deck cracks with the factors categorized into three main groups: structural, construction, and materials.

Table 1. Summary of findings from literature review

Type	Factor	Increased Cracking	Decreased Cracking
Structural Factors	Concrete strength	High strength concrete and higher cement content (especially higher than the design target)	–
	Span type	Continuous span and interior spans compared to end spans; restraint provided by the intermediate supports	–
	Girder type	Curved girder; slab bridge decks compared to slabs on stringer girders	–
	End restraint condition	Fixed-ended conditions; unintentional boundary restraints	Simply-supported condition
	Top transverse reinforcement	Larger size	Additional longitudinal reinforcing steel
	Girder depth/spacing	High relative stiffness of girder to deck	–
	Expansion joints	–	Accommodation of concrete deformation
	Concrete cover	Higher concrete cover causing more cracks and larger crack widths	–
Construction Factors	Air temperature	Too cold or hot weather with a rapid temperature change	–
	Mechanical vibration	Consolidate concrete and close plastic cracks	–
	Concrete finish	–	Early finish reduces crack amount and width
	Curing	–	Early curing and moist curing for more than 7 days affect the concrete durability and strength
	Placement length	Long placement length	–
	Relative humidity	Affects the evaporation rate	–
	Wind speed	Affects water evaporation and thermal stresses	–
	Construction sequences	Sequencing causing flexural stresses	–

Type	Factor	Increased Cracking	Decreased Cracking
Material Factors	Cement type, content, and proportion	Finer cement and more cement content that increase the heat of hydration and shrinkage	Type-K shrinkage compensating cement has less shrinkage; fly ash reduces heat of hydration
	Aggregate content/type	–	Higher aggregate content (related to shrinkage and water absorption)
	Admixture	–	Water reducer decreases water and paste volume results in less drying shrinkage
	Concrete slump/ water content	Higher concrete slump (increases the concrete settlement over steel reinforcing bar)	Low w/c ratio (related to the heat of hydration, thermal shrinkage, and drying shrinkage)
	Air content	–	Higher air content, especially >6% (correlated with drying shrinkage)

The reviews found that using a high concrete strength could increase the chance of bridge deck cracking. In addition, bridges with continuous spans and intermediate support restraints are more susceptible to cracking. Moreover, increasing the top transverse reinforcement size along with a large concrete cover increases the chance of causing the bridge deck to crack. Furthermore, integral abutment bridges can experience a higher rate of cracks than stub abutment bridges due to the absence of expansion joints that could accommodate concrete deformation. Similarly, fixed-ended conditions can increase the chance of cracks along with increasing the bridge stiffness.

Regarding construction factors, high or low air temperature can lead to a high chance of bridge deck cracking due to a rapid jump in temperatures. Also, improper use of mechanical vibration will not consolidate the concrete properly, and, thus, will not enhance the bond with reinforcement steel, which can lead to bridge deck cracking. Moreover, a proper early concrete finish will reduce the crack amounts and size. It was also noted that curing the deck concrete for more than seven days will reduce the chance of cracking since that will affect the concrete durability and strength. Furthermore, high relative humidity and wind speed can increase the chance of bridge deck cracking by increasing the water evaporation and thermal stresses, and, thus, those two factors affect the evaporation rate of concrete.

With respect to the material factors, using finer cement and more cement content will increase the heat of hydration and shrinkage and, thus, will increase the chance of cracking. However, using Type-K shrinkage compensating cement has less shrinkage and that will decrease the cracking chance. Using more fly ash reduces the heat of hydration, and, thus, decreases the cracking chance. Moreover, using higher aggregate contents decreases the cracking rate. Using high concrete slump and water content will increase the chance of cracking due to increased concrete settlement over the steel reinforcement. However, a low w/c ratio will decrease the chance of cracking due to lowering the heat of hydration and, thus, lower thermal and drying shrinkage. Similarly, high air content (i.e., >6%), which correlated with drying shrinkage, will decrease the chance of cracking.

2.2 Iowa DOT Study (Yusuf and Nop 2022)

The Iowa DOT performed a review to study the factors that can lead to transverse cracks in bridge decks. The study considered 136 steel beam and precast, pretensioned concrete beam (PPCB) bridges constructed between 2015 and 2019. In this study, the Iowa DOT researchers calculated the crack rate using equation (1):

$$Crack\ Rate = \frac{1{,}000 \times Crack\ amount}{Bridge\ width \times Bridge\ length} \tag{1}$$

where, *Bridge width* is the out-to-out deck width in feet, and *Crack amount* is the total number of cracks in the deck. The multiplier of 1,000 is to scale the crack rate magnitude to values from 0 to a practical maximum of 30+. The units for crack rate are number of cracks per square foot. Further, the deck crack severity scale factor shown in Table 2 was used.

Table 2. Deck crack severity scale

Description	Crack Rate Range
None	0=no cracks
Low	Greater than 0 to less than 4
Moderate	4 to less than 10
Severe	10 or greater

The primary source of information used in this study was the Structure Inventory and Inspection Management System (SIIMS) maintained by the Iowa DOT. The investigating team reviewed recent inspection sketches, which include a representation of each deck crack identified by the inspector. Then, the team went through each investigated bridge sketch and counted the total number of deck cracks in the entire deck and used it as *Crack amount* in equation (1).

The relationship between the crack rate and each of the bridge factors, including bridge type, type of bridge deck concrete (high-performance concrete [HPC] or non-HPC), the location of the bridge in Iowa (District number), and the length of the bridge, was studied. The results were listed as follows:

- Approximately 41% of the bridges in this investigation had some level of deck cracking, while 19% had moderate to severe cracking.
- PPCB bridges generally had a higher crack rate than steel beam bridges, but the number of steel beam bridges in the pool of data was relatively small.
- A correlation between crack rate and type of deck concrete was not apparent.
- The northwest (District 3), southwest (District 4), and east and southeast (District 6 and 5, respectively) areas of the state had higher concentrations of moderate to severe deck

cracking. This indicated a potential issue related to the concrete mix design (e.g., materials), while other explanations related to geographic location are also possible.

- A correlation between crack rate and bridge length was not apparent.
- A correlation between crack rate and PPCB beam type/span length was not apparent.

CHAPTER 3. STAGE 1: INVESTIGATION OF 2,675 BRIDGES IN IOWA

To keep the sample size large and cover a significant number of brides, the first stage investigation (Stage 1) was conducted on 2,675 bridges constructed in Iowa between 1900 and 2020. The goal of this stage was to study the correlation between deck cracking and six parameters: deck concrete type (high-performance concrete [HPC] or non-HPC), maximum span length, maximum structure length, district, year built, and main structure type.

3.1 Investigation Procedure

The investigation in this stage was conducted on all Iowa state-owned bridges that had data combined into one Excel spreadsheet and sorted into different categories by the Iowa DOT. The bridge information that was available included the following:

- Bridge type: PPCB or steel beam bridges with decks
- Bridge dimensions: width, length, maximum span length, and number of spans
- Year built, year reconstructed
- Bridge ID and location: FHWA bridge identifier, Iowa bridge maintenance number, Iowa county, Iowa DOT district, location, facility carried, feature intersected
- Number of lanes, average daily traffic (ADT), truck ADT, speed limit
- Deck type, wearing surface, membrane, deck protection

The bridge deck crack information used in this stage was obtained primarily from the Iowa DOT Structure Inventory and Inspection Management System (SIIMS) database. A unique ID for each bridge was used to search available sketches, images, and notes in the database. Figure 1 shows a flowchart of the investigation process.

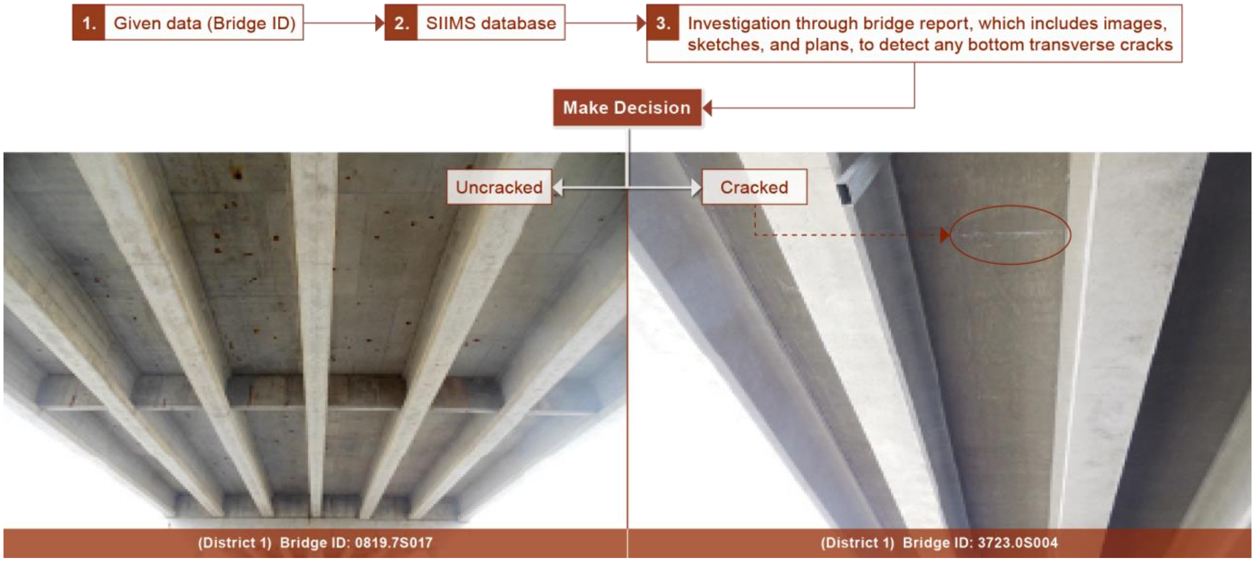


Figure 1. Investigation process used to identify bridges with cracked decks

Based on the information collected from the Iowa DOT databases, each bridge deck was categorized as cracked or uncracked (specifically in relation to the bridge deck and not the entire bridge).

Based on the available bridge data in the Excel sheet, the range of each bridge parameter was determined as presented in Table 3.

Table 3. Stage 1 studied parameters

Deck Concrete Type	Maximum Span Length (ft)	Total Structure Length (ft)	Year Built	District	Main Structure Type
HPC or Non-HPC	Maximum=302 ft Minimum=19 ft	Maximum=4,933 ft Minimum=23 ft	Maximum=2020 Minimum=1900	1, 2, 3, 4, 5, or 6	Steel, Steel continuous, or PPCB

The 2,675 bridges included three primary structure types: steel stringer/multi-beam/girder, continuous steel stringer/multibeam/girder, and PPCB multi-beam stringer or girder.

3.2 Investigation Results

Table 4 shows the number and percentage of bridges with cracked and uncracked decks for the total bridges, HPC deck bridges, and non-HPC deck bridges.

Table 4. Cracked vs. uncracked HPC and non-HPC deck distribution

Total Bridges				HPC Deck Bridges				Non-HPC Deck Bridges			
Cracked		Uncracked		Cracked		Uncracked		Cracked		Uncracked	
No.	Pct. (%)	No.	Pct. (%)	No.	Pct. (%)	No.	Pct. (%)	No.	Pct. (%)	No.	Pct. (%)
940	35	1,753	65	81	49	86	51	825	34	1,606	66

The results showed that, among the 2,675 bridges, 167 were HPC deck bridges and 2,431 were non-HPC deck bridges. The percentage of bridges with cracked decks among the 2,675 bridges was 35% with 65% of the bridges having uncracked decks. A similar distribution existed in the non-HPC deck bridges with 34% of the bridges having cracked decks and 66% of the bridge decks being uncracked. However, for the 167 HPC deck bridges, the rate of bridges with cracked decks was 49%. This indicated that HPC deck bridge decks had a higher chance of deck cracking than non-HPC deck bridges.

Table 5 shows the cracking rate based on the different maximum bridge span lengths.

Table 5. Percentage of bridges with cracked decks vs. maximum span length

Maximum Span Length (ft)	Number of Bridges	Number of Bridges with Cracked Decks	Percentage of Bridges with Cracked Decks (%)
19–113	2,106	858	41
113–207	530	68	13
207–302	39	6	16

As shown in the previous Table 3 (and inferred in Table 5), the maximum span length of the sampled bridges ranged from 19 to 302 ft. This range was divided into three subranges: 19 to 113 ft, 113 to 207 ft, and 207 to 302 ft. For each subrange, the number of bridges, number of bridges with cracked decks, and the percentage of bridges with uncracked decks was calculated.

The results indicated that most of the bridges (2,106 bridges) had a maximum span length in the range of 19 to 113 ft. The bridges in this subrange showed a higher percentage of cracking (41%) than the other two longer span subranges with 13% and 16%. This indicated that, as the maximum bridge length increased, the rate of the bridges with cracked decks decreased.

Table 6 shows the crack bridge deck rate based on the total bridge length.

Table 6. Percentage of bridges with cracked decks vs. total structure length

Total Bridge Length (ft)	Number of Bridges	Number of Bridges with Cracked Decks	Percentage of Bridges with Cracked Decks (%)
23–273	1,831	834	46
273–523	644	80	13
523–1,023	152	11	8
1,023–2,023	36	5	14
2,023–3,023	8	1	13
3,023–4,023	2	0	0
4,023–4,933	2	0	0

As shown in the previous Table 3 (and inferred in Table 6), the total bridge length of the sampled bridges ranged from 23 to 4,933 ft. In this analysis, the total bridge length was divided into seven subranges as shown in the leftmost column of Table 6. For each subrange, the number of bridges, number of bridges with cracked decks and the percentage of bridges with cracked decks was calculated as presented.

The results indicated that most of the bridges (1,831 bridges) had a bridge length in the range of 23 to 273 ft. And the bridges in this subrange showed a higher percentage of cracking (46%) than the other six subranges. This indicated that, as the maximum bridge length increased, the chances of having a cracked deck decreased.

The bridges considered in this analysis were constructed from 1900 to 2020, as shown in the previous Table 3. To conduct an age-based analysis, these bridges were categorized into 20-year periods as shown in Table 7.

Table 7. Percentage of bridges with cracked decks vs. bridge age

Year Built	Number of Bridges	Number of Bridges with Cracked Decks	Percentage of Bridges with Cracked Decks (%)
1900–<1920	8	0	0
1920–<1940	84	7	9
1940–<1960	227	95	42
1960–<1980	948	532	57
1980–<2000	705	209	30
2000–2020	702	89	13

For each subrange, the researchers calculated the number of bridges, number of bridges with cracked decks, and percentage of bridges with cracked decks.

The results indicated that the majority of the sampled bridges were built after the 1960s. Comparing the bridges in the later three categories (1960–1980, 1980–2000, and 2000–2020), which had relatively similar sample sizes, the researchers found that the bridges constructed from 1960 to 1980 showed a higher crack rate (57%). The second-highest percentage of bridges with cracked decks was 42% for the bridges that were built from 1940 to 1960. For 2000 to 2020, as expected, the percentage of cracked decks decreased significantly to about 13%.

To investigate the effects of the bridge location, the research team studied the district in which the bridges are located. The Iowa DOT divides the state into six districts, as shown in Figure 2.

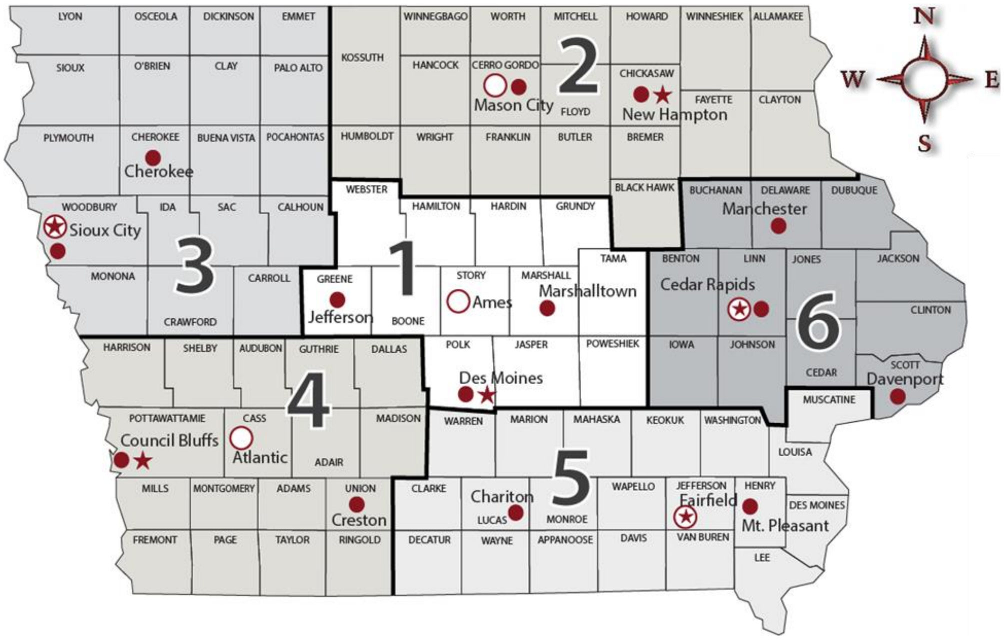


Figure 2. Iowa DOT Districts

Table 8 shows the number of bridges, number of bridges with cracked decks, and percentage of bridges with cracked decks based on the District number.

Table 8. Percentage of bridges with cracked decks vs. District number

District #	Number of Bridges	Number of Bridges with Cracked Decks	Percentage of Bridges with Cracked Decks (%)
1	599	200	34
2	371	99	27
3	297	96	33
4	417	184	45
5	420	94	23
6	570	244	43

District 4 (southwest Iowa) and District 6 (east Iowa) showed a higher percentage of cracked decks with 45% and 43%, respectively. The other districts had cracked deck rates under 40%. This showed agreement with the Iowa DOT study (Yusuf and Nop 2022), which indicated that these districts had the highest percentage of bridges with cracked decks. The differences in the percentages of cracked decks could be due to the different material properties of the concrete aggregates used.

Table 9 shows the cracked deck rate based on the primary structure type: steel, continuous steel, or prestressed concrete.

Table 9. Percentage of bridges with cracked decks vs. structure type

Main Structure Type	Number of Bridges	Number of Bridges with Cracked Decks	Percentage of Bridges with Cracked Decks (%)
Steel	122	8	7
Steel Continuous	718	58	9
PPCB	1,835	847	47

For each structure type, the number of bridges, number of bridges with cracked decks, and percentage of bridges with cracked decks was calculated. The majority of the sampled bridges were PPCB bridges (1,835 bridges), and the crack rate was about 47%, which was higher than the bridges with the other two structure types. This finding showed agreement with the Iowa DOT study findings (Yusuf and Nop 2022), which indicated that PPCB bridges generally have a higher percentage of cracked decks (47.6%) than steel beam bridges.

CHAPTER 4. STAGE 2: INVESTIGATION OF 20 BRIDGES IN IOWA

To incorporate additional bridge parameters into this study, the Stage 2 investigation was conducted on a smaller bridge sample of 20 bridges, but with more detailed information about each bridge considered. The goal of this stage was to investigate the relationship between various bridge parameters and the bridge deck crack rate.

The bridge parameters investigated were divided into three categories: structural, construction, and materials. Then, the Bridge Engineering Center's researchers developed a numerical scale that rates the severity of deck cracking using the average span length, as shown in equation (2), rather than the bridge length as the Iowa DOT researchers (Yusuf and Nop 2022) had done.

$$Crack\ Rate = \frac{1{,}000 \times Crack\ amount}{Bridge\ width \times Average\ span} \tag{2}$$

where the bridge width is the out-to-out deck width in feet; the average span is the summation of one-half the span lengths on each side of the pier in feet; and the crack amount is the total number of deck cracks in the deck region about the pier as defined by the bridge width and average span. The multiplier of 1,000 is to scale the crack rate magnitude to values from 0 to a practical maximum of 30+. The units for crack rate are number of cracks per square foot.

4.1 Investigation Procedure

The sample of bridges considered in Stage 2 consisted of 20 bridges that had transverse cracking and were among 116 bridges constructed between 2013 and 2018. The available data were investigated and sorted into three main categories as shown in Table 10.

Table 10. Bridge parameters investigated in Stage 2

Material Factors	Structural Factors	Construction Factors
Cement type Cement content w/c ratio Concrete strength Slump Air content Fly ash	Structure width and length; span length Girder spacing and depth Span length/girder-spacing ratio Reinforcement ratio Section stiffness (girder/deck stiffness ratio)	Air temperature Concrete temperature Wind speed Relative humidity

The identified information for each bridge is shown in Table 11, Table 12, and Table 13 for structural, construction, and material parameters, respectively. Table 11 includes the structural information for each studied bridge.

Table 11. Structural information for 20 bridges investigated in Stage 2

FHWA No.	Structure Type	Structure Length (ft)	Maximum Span Length (ft)	Girder Spacing (ft)	Girder Depth (ft)	Maximum Span Length/Girder Spacing	*EI* Ratio	Top Transverse (in^2/ft)	Bottom Transverse (in^2/ft)
609965 (NB)	PPCB	162.80	81.50	7.79	3.75	10.46	34.87	0.941	0.551
609970 (SB)	PPCB	162.70	81.50	7.79	3.75	10.46	34.87	0.941	0.551
52211	Steel	459.00	128.00	9.25	7.208	13.84	134.31	0.993	0.654
609955	PPCB	158.20	155.00	7.69	5.25	20.16	120.06	0.31	0.62
609615	PPCB	262.00	116.00	9.041	3.75	12.83	46.21	0.993	0.489
052871 (EB)	PPCB	206.00	116.50	7.42	4.5	15.7	67.63	0.898	0.525
17851	PPCB	179.70	69.00	6.83	3.25	10.1	21.19	0.481	0.528
018501	PPCB	279.00	97.00	8.375	3	11.58	27.87	0.481	0.479
609975	PPCB	255.00	131.00	8.71	4.5	15.04	76.62	0.93	0.464
609585	PPCB	255.00	136.00	8.03	4.5	16.94	83.1	0.896	0.447
053920/053921	PPCB	242.00	126.00	8.7	4.5	14.48	76.7	0.934	0.329
53731	PPCB	259.00	87.00	8.25	3	10.55	28.29	0.645	0.322
700065 (EB)	PPCB	226.30	106.50	7.396	4.5	14.4	67.85	0.893	0.528
700070 (WB)	PPCB	226.30	106.50	7.396	4.5	14.4	67.85	0.893	0.528
609570	PPCB	275.40	136.00	9.17	5.25	14.83	107.63	0.539	0.532
25581	PPCB	247.00	97.00	9.46	3	10.25	24.67	0.985	0.485
45531	Steel	322.00	147.00	9.25	4.3125	15.89	84.63	0.991	0.652
13201	Steel	223.40	88.00	7.42	3	11.86	22.09	0.896	0.527
25611	PPCB	389.00	102.00	6	3.75	17	69.63	0.811	0.405
609980	PPCB	235.00	116.00	9.041	3.75	12.83	46.21	1.01	0.507

Table 12. Construction information for 20 bridges investigated in Stage 2

FHWA No.	**Air Temperature** (°F)	**Concrete Temperature** (°F)	**Average Wind Speed (mph)**	**Relative Humidity (%)**
609965 (NB)	66	N/A	N/A	N/A
609970 (SB)	66	N/A	N/A	N/A
052211	70	N/A	N/A	N/A
609955	73	N/A	N/A	N/A
609615	80.5	87.8	3.9	67.62
052871 (EB)	68	66	1.76	47.44
017851	68.7	71.3	8.2	50.2
018501	60	56.5	N/A	N/A
609975	51	N/A	N/A	N/A
609585	65.5	75.8	1	59.35
053920/053921	71.8	77.3	2.55	74.38
053731	61	N/A	6	N/A
700065 (EB)	72.6	N/A	5.66	40.9
700065 (WB)	72.6	N/A	5.66	40.9
609570	63	N/A	N/A	N/A
025581	64.8	79	N/A	N/A
045531	82.5	77	3.33	79.5
013201	67.3	63.5	N/A	N/A
025611	81.5	N/A	2.18	67.06
609980	54.3	67.2	5.06	54.98

Table 13. Material information for 20 bridges investigated in Stage 2

FHWA No.	Cement Type	Cement Content (pcy)	Fly Ash (pcy)	Coarse Content (pcy)	Fine Content (pcy)	Slump (in.)	w/c Ratio	Air Content (%)	Concrete Strength (psi)
609965 (NB)	1 and 2	474	119	1,531	1,557	3.5	0.468	6.2	5,451
609970 (SB)	1 and 2	474	119	1,572	1,546	2.75	0.428	6	5,451
052211	1 and 2	474	119	1,517	1,553	3.5	0.44	7.5	N/A
609955	1 and 2	474	119	1,534	1,561	3	0.448	7.5	5,476
609615	1 and 2	474	119	1,545	1,560	2.25	0.466	5.8	5,451
052871 (EB)	1 and 2	474	119	1,505	1,532	3.1	0.416	6.8	5,577
017851	1 and 2	474	119	1,506	1,589	3	0.461	6.7	N/A
018501	1 and 2	474	119	1,524	1,550	2.7	0.456	7	N/A
609975	1 and 2	474	119	1,531	1,542	3.25	0.405	5.8	6,619
609585	1 and 2	474	119	1,527	1,546	3	0.424	7.8	5,564
053920/053921	1 and 2	604	89	1,519	1,560	3.25	0.423	8	6,304
053731	1 and 2	474	119	1,502	1,564	2.5	0.407	6.5	5,491
700065 (EB)	1	474	119	1,506	1,534	3.75	0.422	6	6,540
700065 (WB)	1	474	119	1,506	1,534	3.75	0.422	6	6,540
609570	1 and 2	593	0	1,540	1,562	2.5	0.455	6.5	5,451
025581	IP	567	0	938	2,153	3	0.367	7.3	N/A
045531	IP	567	0	942	2,157	3.5	0.426	7.3	N/A
013201	1	474	119	1,532	1,577	3"	0.434	6.75	N/A
025611	1 and 2	593	0	1,522	1,563	3	0.447	7.6	5,880
609980	1	504	89	1,532	1,547	2	0.382	7	5,252

In Table 11, *EI Ratio* represents the girder-to-deck stiffness ratio, which is calculated as follows:

$$EI\ Ratio = \frac{EI_{girder}}{EI_{deck}} \tag{3}$$

where *I* is the moment of inertia, and *E* is the Young's modulus of the deck or girder concrete.

The crack rate of each bridge was calculated using equation (2), and the results are presented in Table 14.

Table 14. Calculated deck crack rates for 20 bridges investigated in Stage 2

FHWA No.	Deck Crack Rate
609965 (NB)	0
609970 (SB)	0
52211	0
609955	1
609615	1
052871 (EB)	1
17851	1
018501	2
609975	2
609585	2
053920/053921	2
53731	2
700065 (EB)	3
700070 (WB)	0
609570	5
25581	5
45531	5
13201	5
25611	5
609980	6

Among the 20 sampled bridges, the maximum crack rate was 6, and a 0 crack rate indicates no cracks in the bridge deck. Four bridges had 0 cracks, four bridges had a crack rate of 1, five bridges had a crack rate of 2, one bridge had a crack rate of 3, five bridges had a crack rate of 5, and one bridge had a crack rate of 6.

4.2 Investigation Results

With the calculated bridge deck crack rates and the identified bridge information (structural, construction, and material), the research team investigated the relationship between the deck crack rates and each bridge factor. A scatter plot for each studied factor was created with the crack rate on the vertical axis and the studied factor on the horizontal axis. Then, a best-fit linear regression line with the value of R-squared was generated. The R-squared value was generated to indicate the degree of correlation between the spread data and the regression line. An R-squared value close to 1.0 indicates a good correlation, and a low R-squared value close to 0.0 indicates a poor correlation.

In the results presented in this section, the term, positive correlation, was used to indicate that an increase of the value of the bridge parameter resulted in an increase of the crack rate. Similarly, a negative correlation indicates that an increase of the studied factor resulted in a decrease of the bridge deck crack rate.

4.2.1 Structural Factors

The structural factors studied in this section include structure length, maximum span length, girder spacing and depth, maximum span length/girder spacing, *EI* ratio, and top and bottom transverse reinforcement quantity. For the detailed information on each bridge, see the previous Table 11.

Figure 3 shows the crack rate versus structural bridge length.

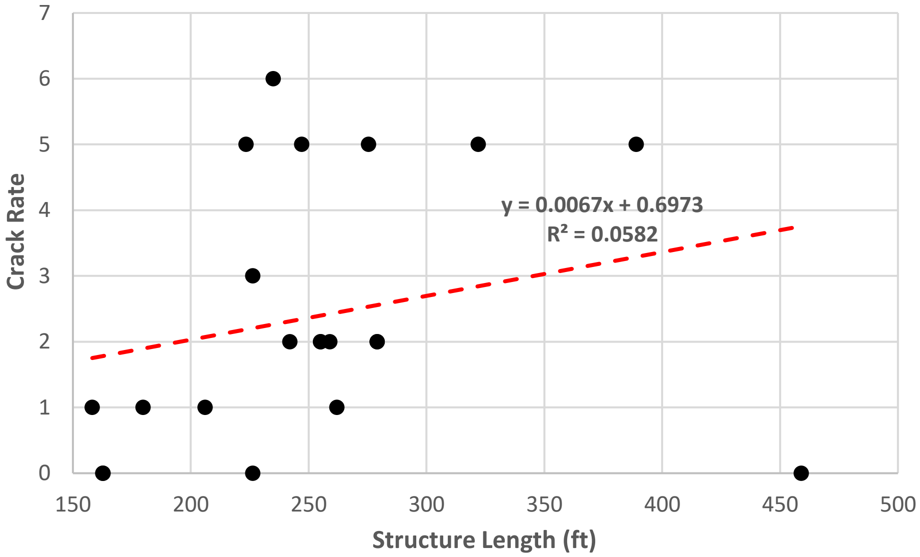


Figure 3. Relationship between crack rate and bridge length (Stage 2 results)

The results showed a positive correlation between the crack rate and structure length, which indicates that increasing the structure length increases the crack rate. However, the R-squared value was 0.0582.

Figure 4 shows the crack rate versus maximum span length.

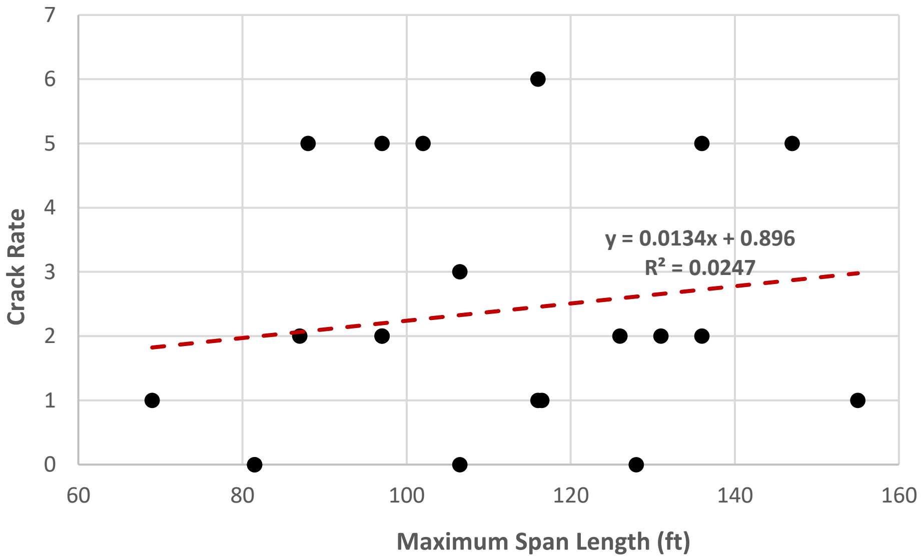


Figure 4. Relationship between crack rate and maximum span length (Stage 2 results)

While the correlation between the crack rate and maximum span length was positive, the R-squared value was 0.0247.

Figure 5 shows the crack rate versus girder spacing.

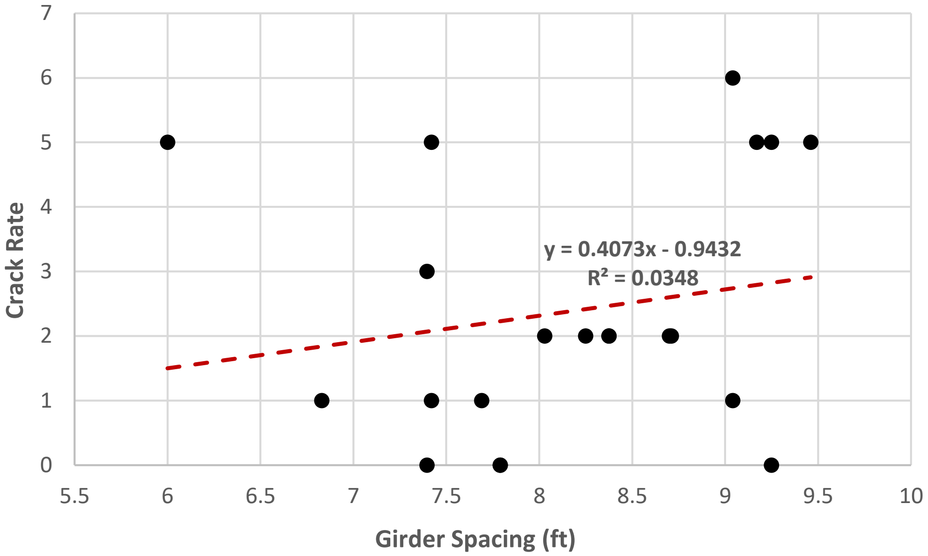


Figure 5. Relationship between crack rate and girder spacing (Stage 2 results)

Even though the correlation between the crack rate and girder spacing was positive, the value of R-squared was 0.0348.

Figure 6 shows the crack rate versus girder depth.

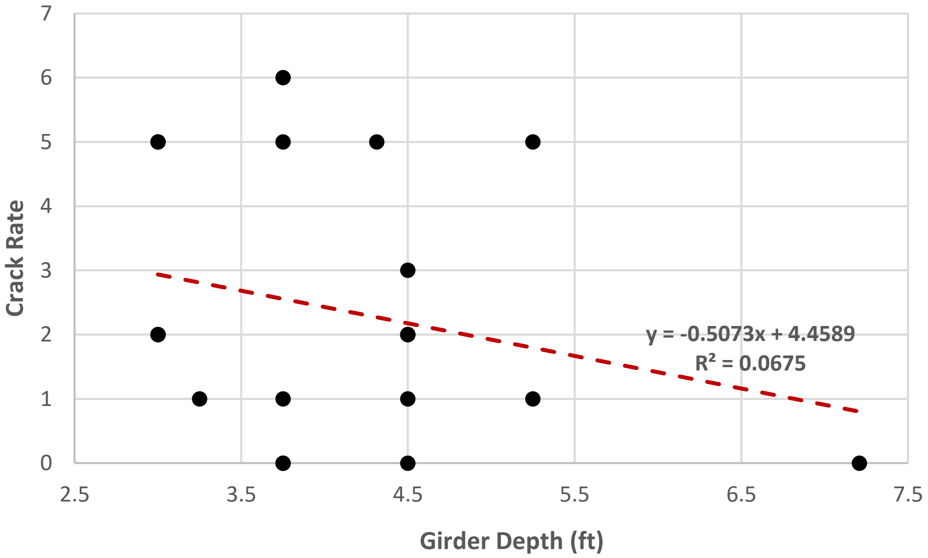


Figure 6. Relationship between crack rate and girder depth (Stage 2 results)

The correlation between the crack rate and girder depth was negative, which means increasing the girder depth decreased the crack rate, while the value of R-squared was 0.0675.

Figure 7 shows the crack rate versus maximum span length-to-girder spacing ratio.

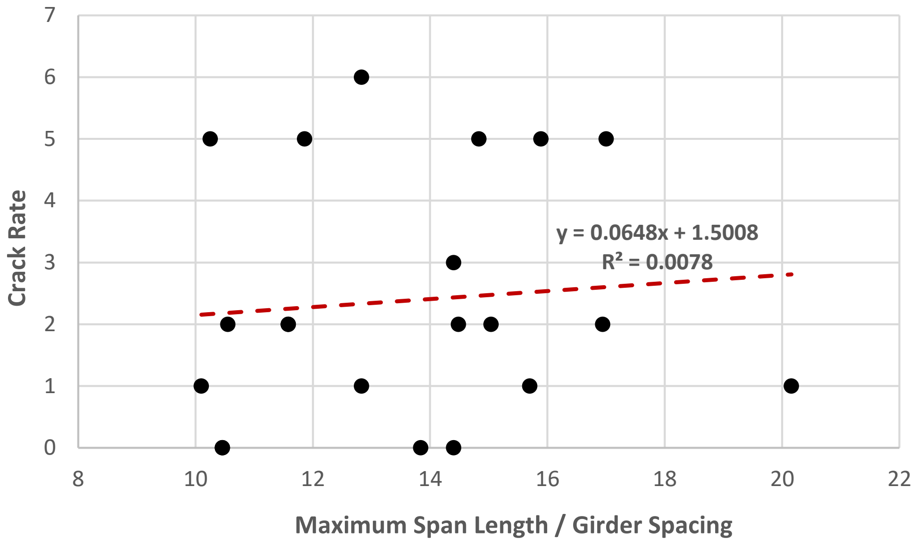


Figure 7. Relationship between crack rate and maximum span length-to-girder spacing ratio (Stage 2 results)

Although, the correlation between the crack rate and the span length-to-girder spacing ratio was positive, the value of R-squared was 0.0078.

Figure 8 shows the crack rate versus top transverse reinforcement area.

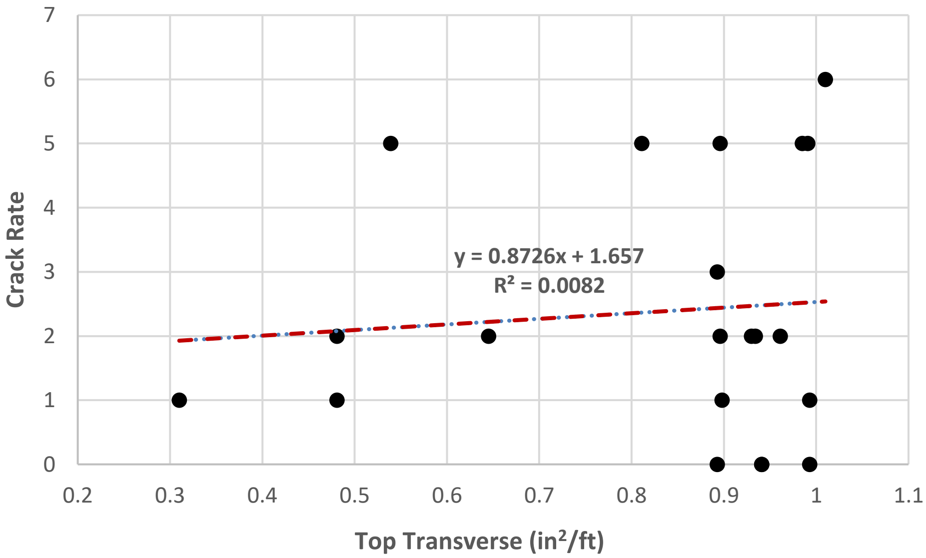


Figure 8. Relationship between crack rate with top transverse reinforcement area (Stage 2 results)

The correlation between the crack rate and top transverse reinforcement area was positive, although the R-squared value was 0.0082.

Figure 9 shows the crack rate versus bottom transverse reinforcement area.

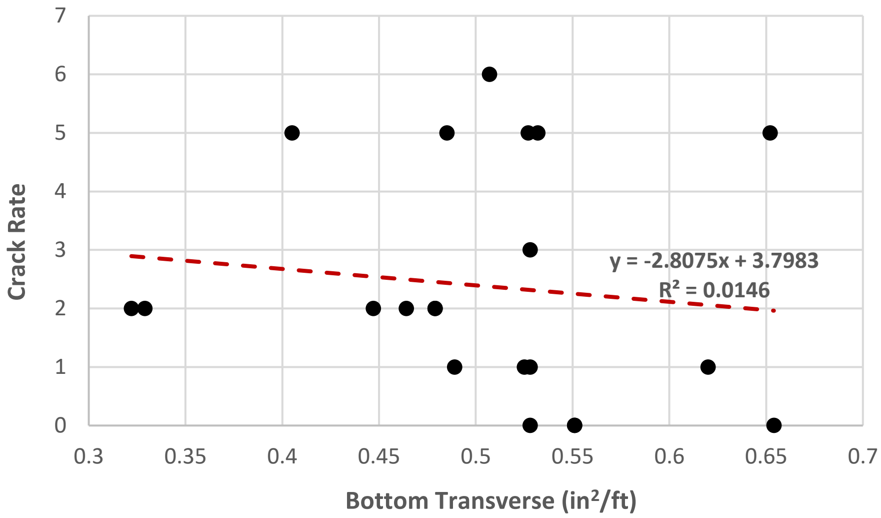


Figure 9. Relationship between crack rate and bottom transverse reinforcement area (Stage 2 results)

Although, the correlation between the crack rate and bottom transverse reinforcement area was negative, the R-squared value was 0.0146.

Figure 10 shows the crack rate versus girder-to-deck stiffness.

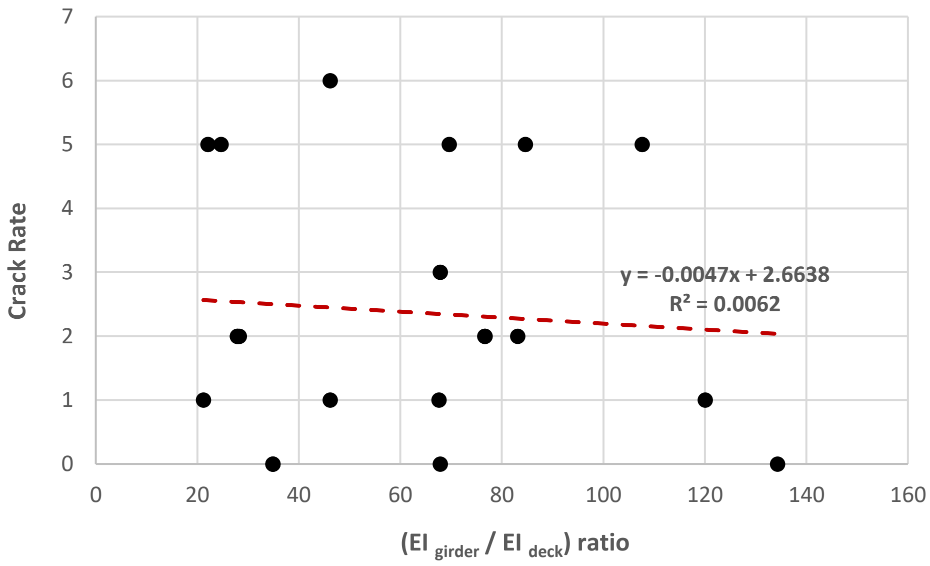


Figure 10. Relationship between crack rate and bridge stiffness (Stage 2 results)

While the correlation between the crack rate and bridge stiffness was negative, the value of R-squared was 0.0062.

4.2.2 Construction Factors

The construction factors studied in this section include air and concrete temperatures, average wind speed, and relative humidity. For the detailed information on each bridge, see the previous Table 12.

Figure 11 shows the crack rate versus air temperature.

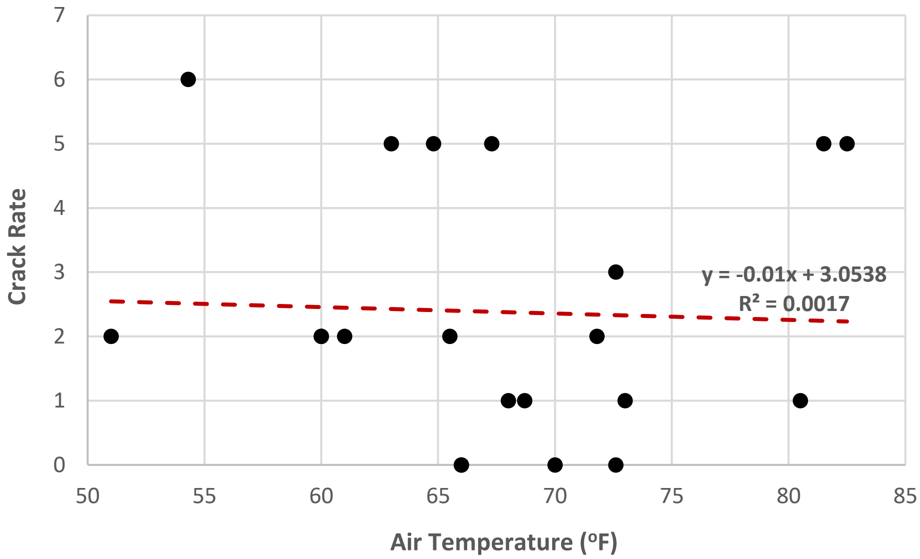


Figure 11. Relationship between crack rate and air temperature (Stage 2 results)

Although the correlation between the crack rate and air temperature was negative, the value of R-squared was 0.0017.

Figure 12 shows the crack rate versus concrete temperature.

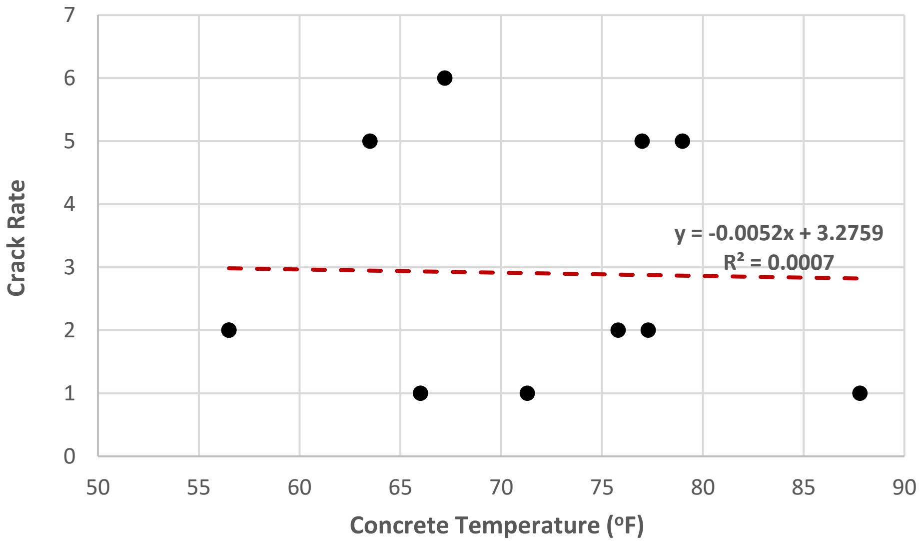


Figure 12. Relationship between crack rate and concrete temperature (Stage 2 results)

Although the correlation between the crack rate and concrete temperature was negative, the value of R-squared was 0.0007.

Figure 13 shows the crack rate versus average wind speed.

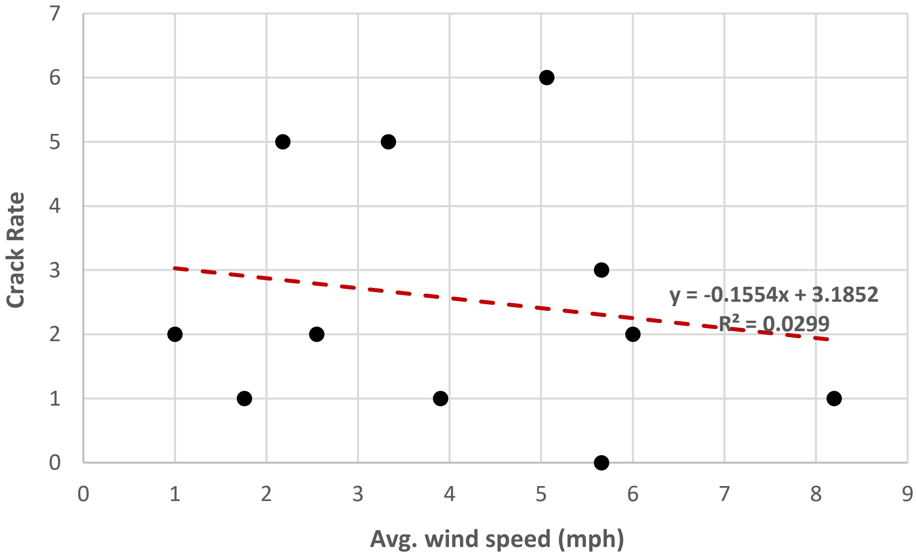


Figure 13. Relationship between crack rate and average wind speed (Stage 2 results)

Even though the correlation between the crack rate and average wind speed was negative, the value of R-squared was 0.0299.

Figure 14 shows the crack rate versus relative humidity.

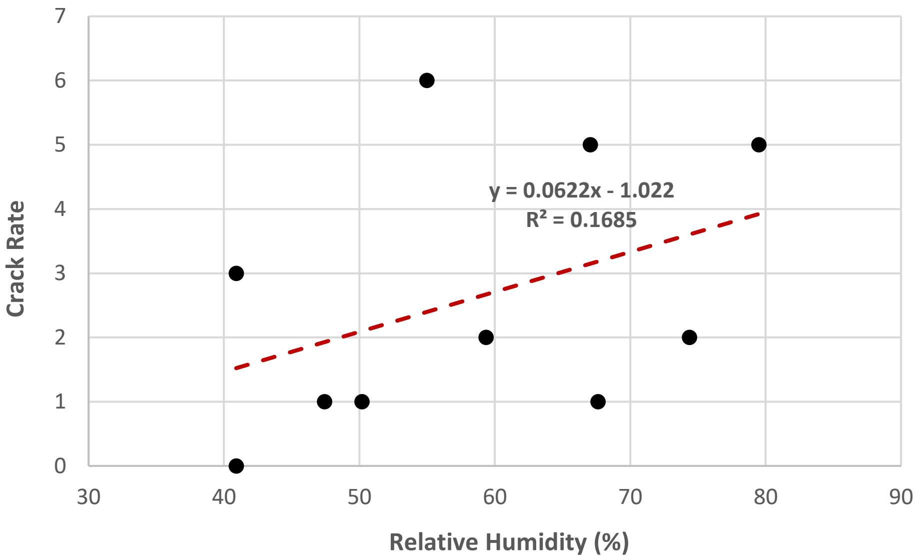


Figure 14. Relationship between crack rate and relative humidity (Stage 2 results)

Despite the positive correlation between the crack rate and relative humidity, the value of R-squared was 0.1685.

4.2.3 Material Factors

The material factors studied in this section include cement content, fly ash, cement type, coarse and fine aggregate, concrete strength, slump, w/c ratio, and air content. For the detailed information on each bridge, see the previous Table 13.

Figure 15 shows the crack rate versus cement content.

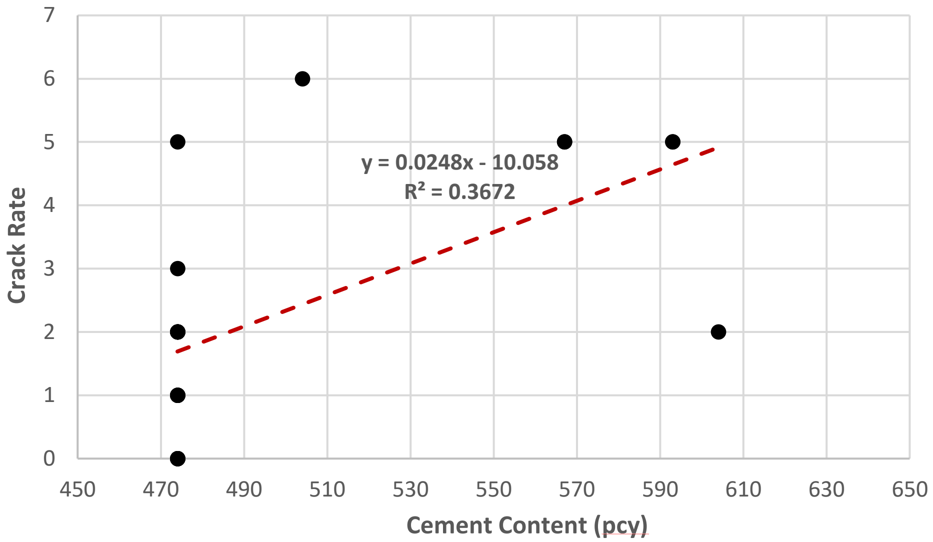


Figure 15. Relationship between crack rate and cement content (Stage 2 results)

Regarding the cement content and its effects on the crack rate, the correlation between the crack rate and cement content positive, and the value of R-squared was 0.3672.

Figure 16 shows the crack rate versus fly ash content.

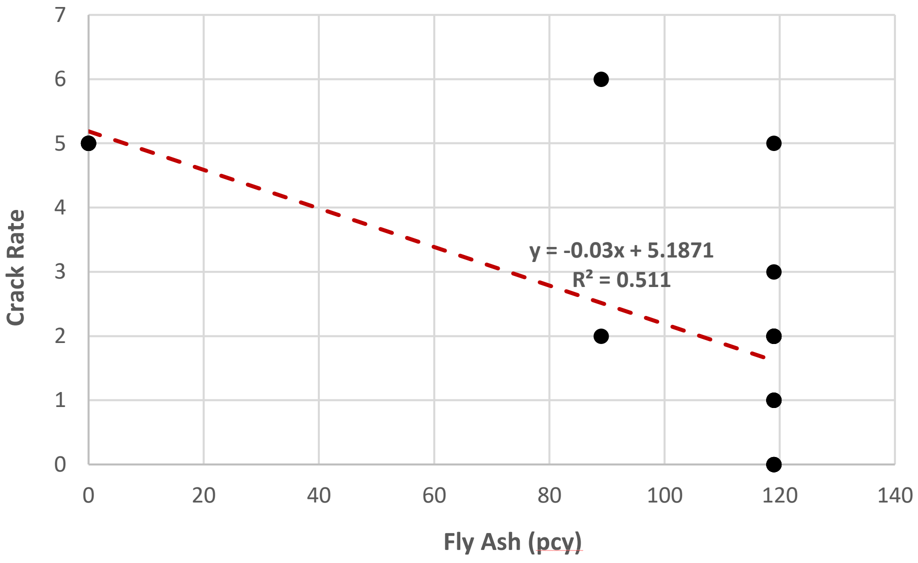


Figure 16. Relationship between crack rate and fly ash content (Stage 2 results)

The results indicated a negative correlation between the crack rate and fly ash content, and the value of R-squared was 0.511.

Figure 17 shows the crack rate versus cement type.

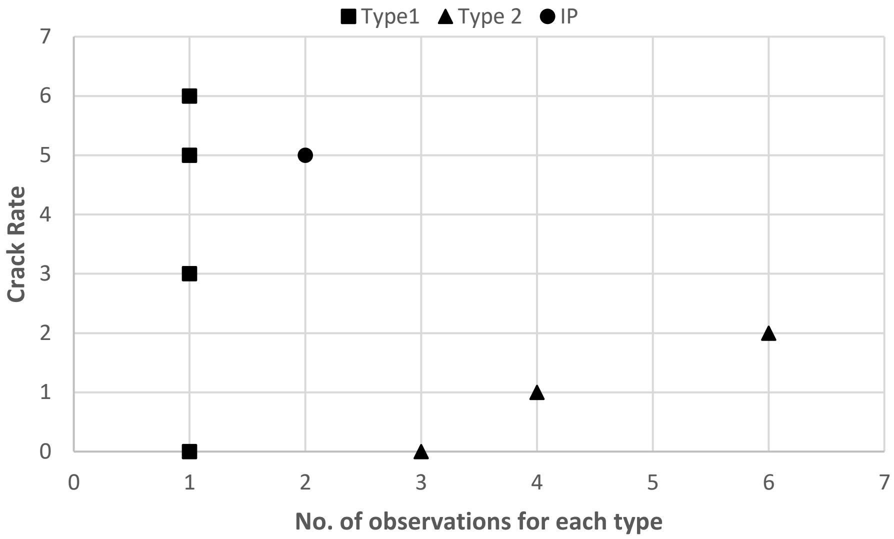


Figure 17. Relationship between crack rate and cement type (Stage 2 results)

In general, the results indicated that a high crack rate (6 and 5) exists when Type 1 and IP cement were used compared to a low crack rate when Type 2 cement was used.

Figure 18 shows the crack rate versus coarse aggregate content.

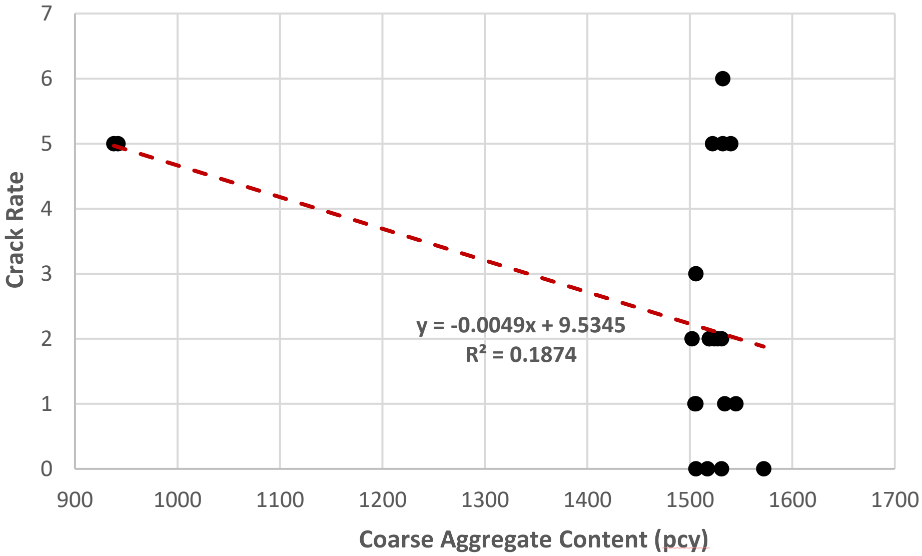


Figure 18. Relationship between crack rate and coarse aggregate content (Stage 2 results)

Thecorrelation between the crack rate and coarse aggregate content was negative, and the value of R-squared was 0.1874.

Figure 19 shows the crack rate versus fine aggregate content.

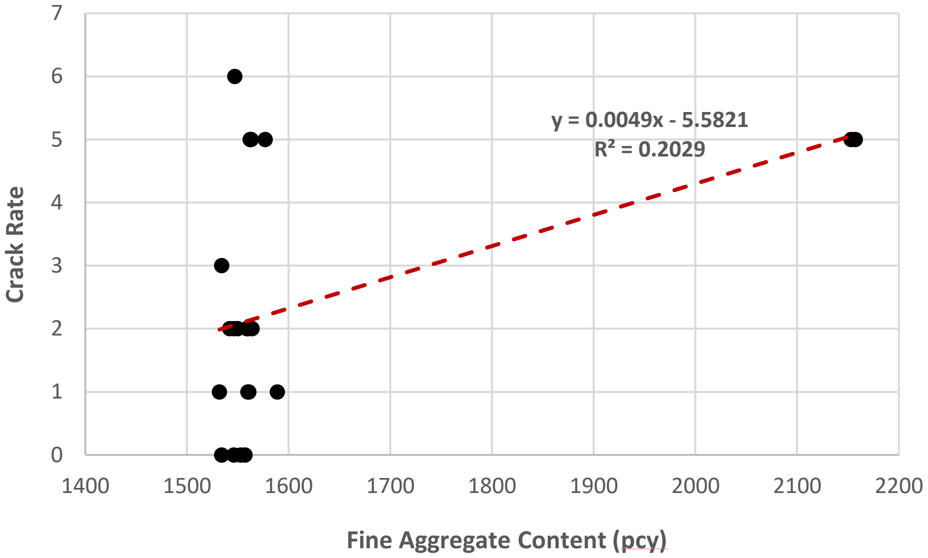


Figure 19. Relationship between crack rate and fine aggregate content (Stage 2 results)

Despite the positive correlation between the crack rate and fine aggregate content, the value of R-squared was 0.2029.

Due to a lack of a good statistical distribution for both coarse and fine aggregate content data in Figure 18 and Figure 19, the results achieved from these graphs were not used for the further investigation in Chapter 6.

Figure 20 shows the crack rate versus concrete strength.

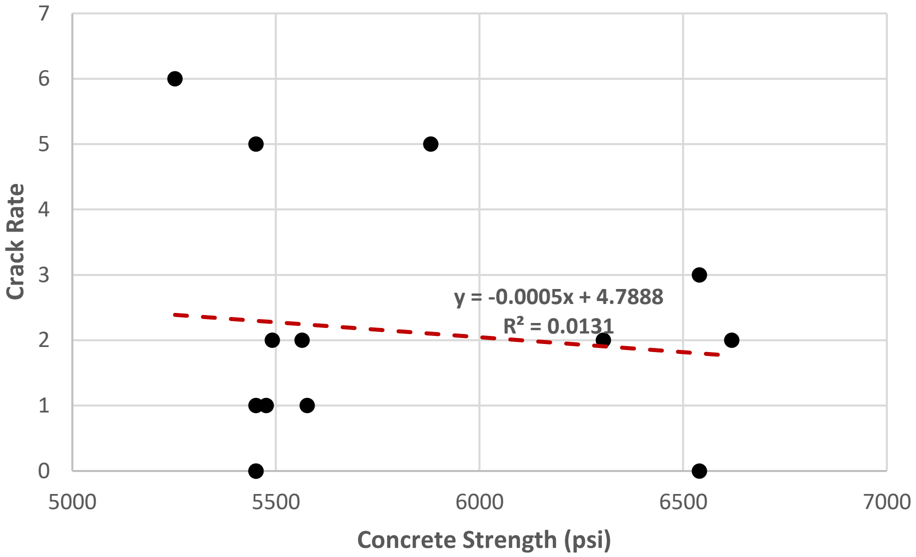


Figure 20. Relationship between crack rate and concrete strength (Stage 2 results)

The correlation between the crack rate and concrete strength negative with a low R-squared value of 0.0131, which indicated that this relation is not significant.

Figure 21 shows the crack rate versus concrete slump.

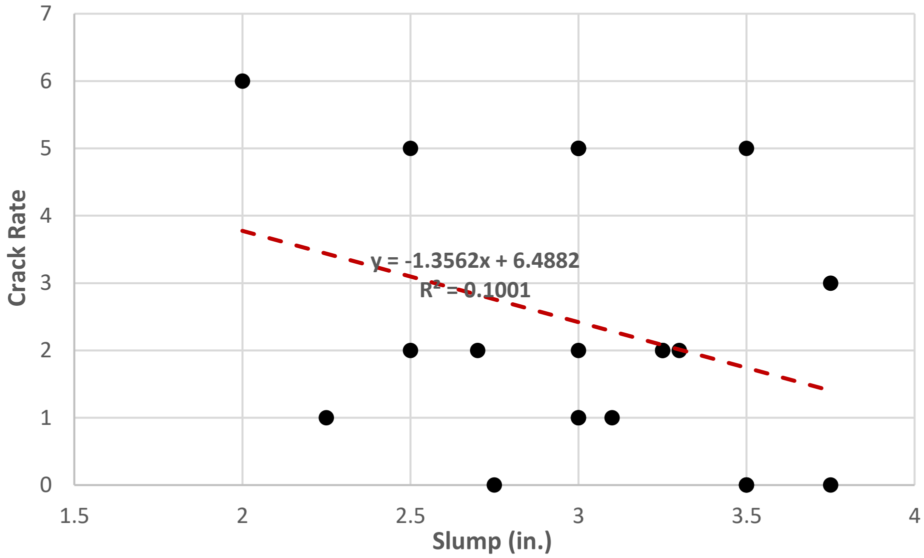


Figure 21. Relationship between crack rate and concrete slump (Stage 2 results)

The results indicated that the value of R-squared was small at 0.1001, which meant the correlation was slight.

Figure 22 shows the crack rate versus w/c ratio.

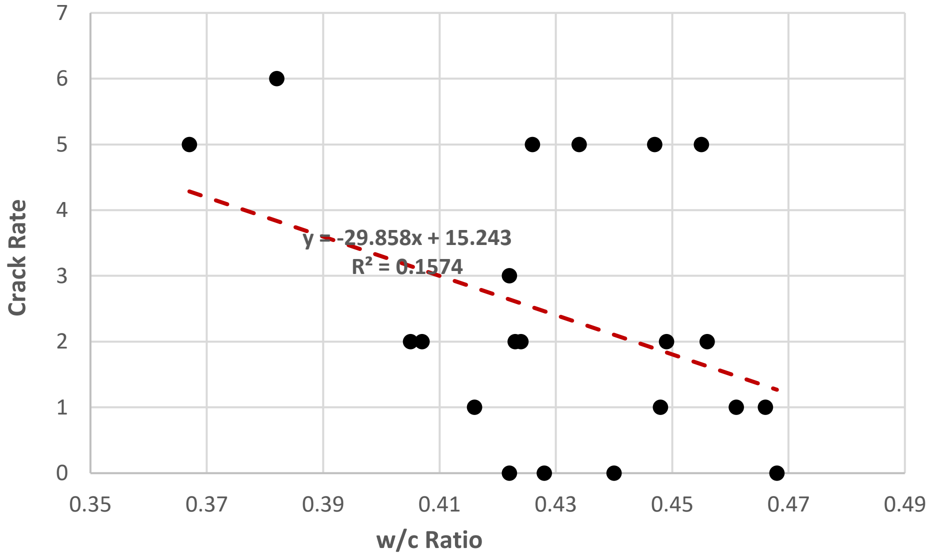


Figure 22. Relationship between crack rate and w/c ratio (Stage 2 results)

The correlation between the crack rate and w/c ratio was negative, and the value of R-squared was 0.1574, which is considered a slight correlation.

Figure 23 shows the crack rate versus air content.

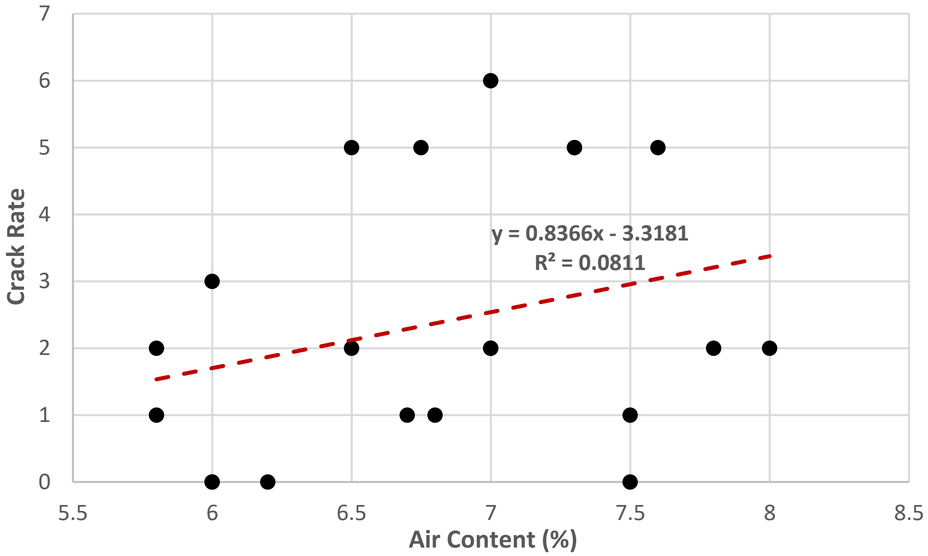


Figure 23. Relationship between crack rate and air content (Stage 2 results)

The correlation between the crack rate and air content was positive with the R-squared value of 0.0811, which is considered a slight correlation.

CHAPTER 5. STAGE 3: INVESTIGATION THROUGH FIELD VISITS

The goal of the Stage 3 investigation was to further study the bridge deck construction factors against the crack rate. In this stage, instead of utilizing data from existing reports, the research team followed the deck concrete placement of six on-going bridge construction projects in the summer of 2019 and collected field information during deck concrete placement.

As with the Stage 2 investigation covered in the last chapter (Chapter 4), the crack rate of each bridge was calculated using the Bridge Engineering Center's crack rate formula as shown in the previous equation (2) (using the average span length rather than the bridge length). Then, the relationships between the construction factors and the crack rates were established.

5.1 Investigation Procedure

The construction data collected in the third stage investigation included evaporation rate (lb/ft^2/h), air temperature (°F), concrete temperature (°F), relative humidity (%), and wind speed (mph). The researchers conducted field visits to six bridges located in various Iowa DOT districts in the state in the summer of 2019 to obtain a better understanding of the impacts from the construction environment. Figure 24 shows the locations of the six bridges studied through field visits in Stage 3 of the investigation.

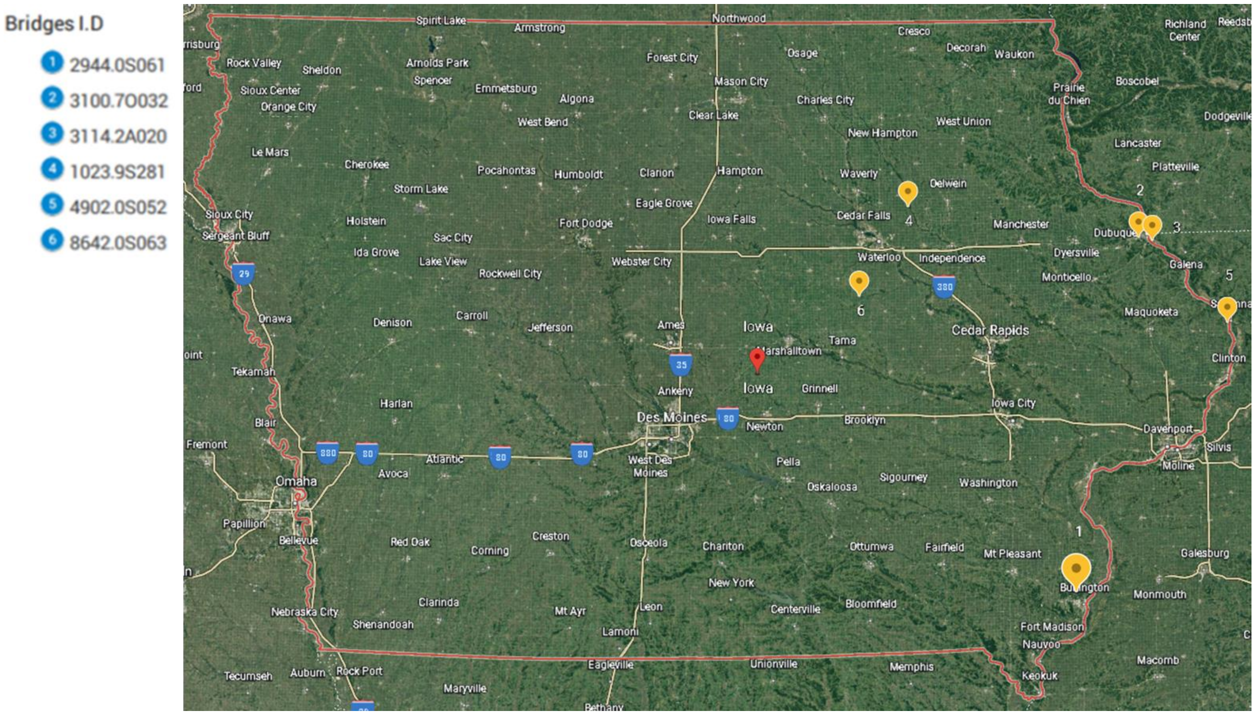
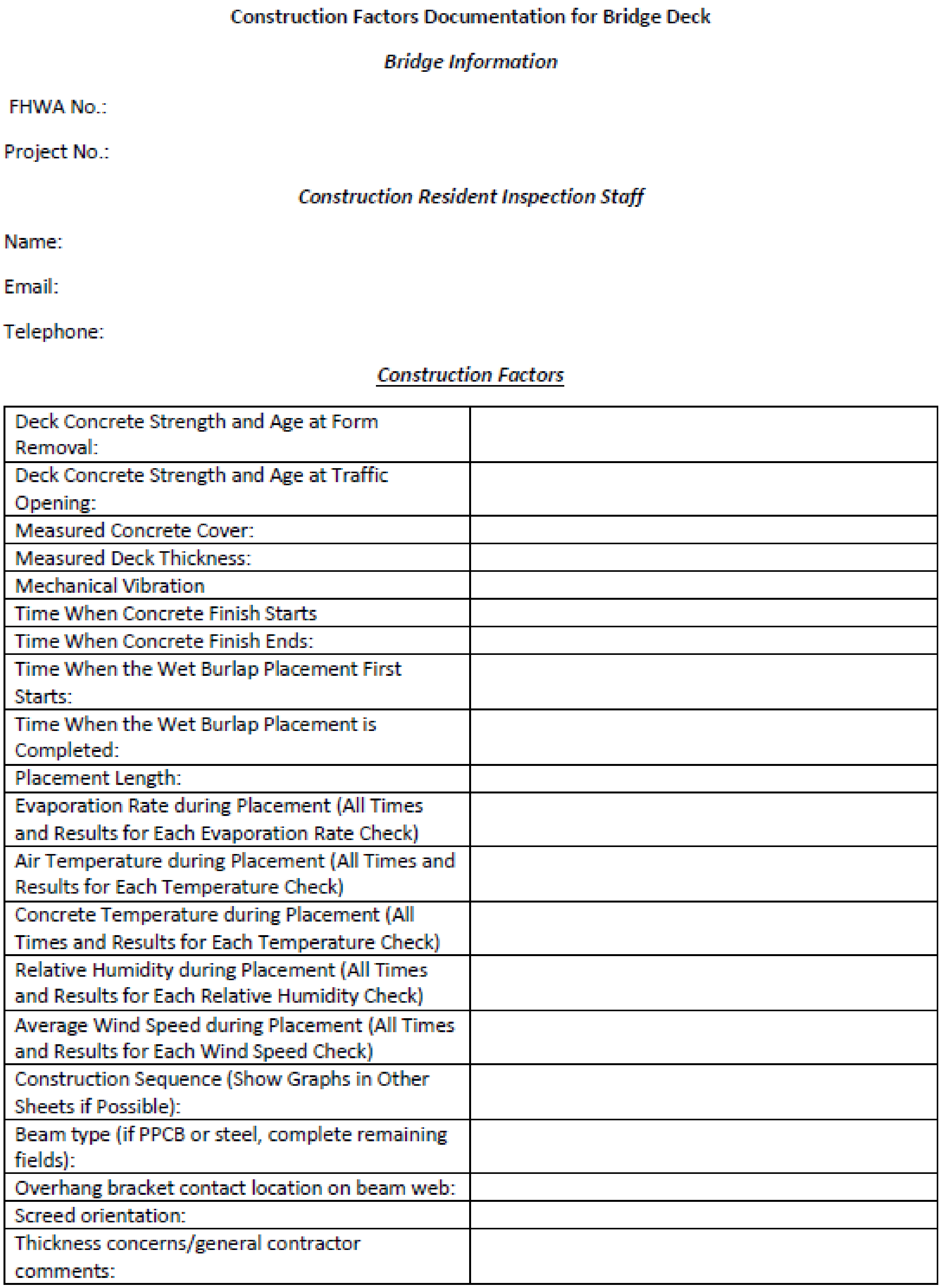


Figure 24. Locations of the six field visits in Iowa

The form shown in Figure 25 was used for each bridge studied in Stage 3 of the investigation.



Construction Factors Documentation for Bridge Deck

Bridge Information

FHWA No.:

Project No.:

Construction Resident Inspection Staff

Name:

Email:

Telephone:

Construction Factors

Deck Concrete Strength and Age at Form Removal:	
Deck Concrete Strength and Age at Traffic Opening:	
Measured Concrete Cover:	
Measured Deck Thickness:	
Mechanical Vibration	
Time When Concrete Finish Starts	
Time When Concrete Finish Ends:	
Time When the Wet Burlap Placement First Starts:	
Time When the Wet Burlap Placement is Completed:	
Placement Length:	
Evaporation Rate during Placement (All Times and Results for Each Evaporation Rate Check)	
Air Temperature during Placement (All Times and Results for Each Temperature Check)	
Concrete Temperature during Placement (All Times and Results for Each Temperature Check)	
Relative Humidity during Placement (All Times and Results for Each Relative Humidity Check)	
Average Wind Speed during Placement (All Times and Results for Each Wind Speed Check)	
Construction Sequence (Show Graphs in Other Sheets if Possible):	
Beam type (if PPCB or steel, complete remaining fields):	
Overhang bracket contact location on beam web:	
Screed orientation:	
Thickness concerns/general contractor comments:	

Figure 25. Field-visited bridge form

Each bridge visit was conducted on the day of bridge deck placement to collect the pertinent construction data. Basic bridge information was collected including data for each construction factor every hour during concrete placement. The data collection started immediately after concrete placement started and continued until completion of the concrete finishing process. The whole deck concrete placement usually took 4 to 8 hours.

Table 15 shows the Iowa DOT district, a summary of the field-collected data, and the calculated crack rate for each of the six field-visited bridges.

Table 15. Field-collected data from six bridges in Stage 3 investigation

Bridge ID	Iowa DOT District	Evaporation Rate (lb/ft^2/h)	Air Temperature (°F)	Concrete Temperature (°F)	Relative Humidity (%)	Wind Speed (mph)	Crack Rate*
2944.0S061	5	0.04–0.13	53–74	78–85	38–99	0–5	3
3100.7O032	6	0.06–0.08	75–76	83.5	81–89	5–7	4
3114.2A020	6	0.03–0.13	54–58	68–72	58–77	2–10	0
1023.9S281	6	0.21–0.27	62–65	77–80	66–73	15–17	16
4902.0S052	6	0.04–0.09	24–32	51–75.5	63–72.4	2.3–4.7	2
8642.0S063	1	0.04	61.5	77–79	73.3–88	1.0–1.5	0

* Number of cracks on the deck of each bridge was counted utilizing available inspection reports in the SIIMS database later, in 2022

As mentioned, the data were collected at each one-hour interval; thus, the range of data for each factor shows the minimum and maximum values during concrete placement. However, some data were reported as a single value, which means the variation between the two values during construction was not significant.

As mentioned, the six field visits were conducted in the summer of 2019, and the number of cracks on the deck of each bridge was counted utilizing available inspection reports in the SIIMS database in 2022. Then, the crack rate was calculated utilizing the Bridge Engineering Center's crack rate formula in the previous equation (2). The results are listed in the rightmost column of Table 15. While the maximum crack rate of the six field-visited bridges was 16, two bridges showed no cracks in 2022.

5.2 Investigation Results

With the calculated bridge deck crack rate and field-collected data for each construction parameter, the research team used scatter plots to show the relationship between the deck crack rate and each construction factor. The scatter plot for each studied factor was created with the crack rate on the vertical axis and the studied factor on the horizontal axis.

Then, a best-fit linear regression line with the R-squared value was generated. The R-squared value indicated the degree of correlation between the spread data and the regression line. An R-squared value close to 1.0 indicated a good/positive correlation, and a low R-squared value close to 0.0 indicated a poor/negative correlation.

Figure 26 shows the crack rate versus the evaporation rate.

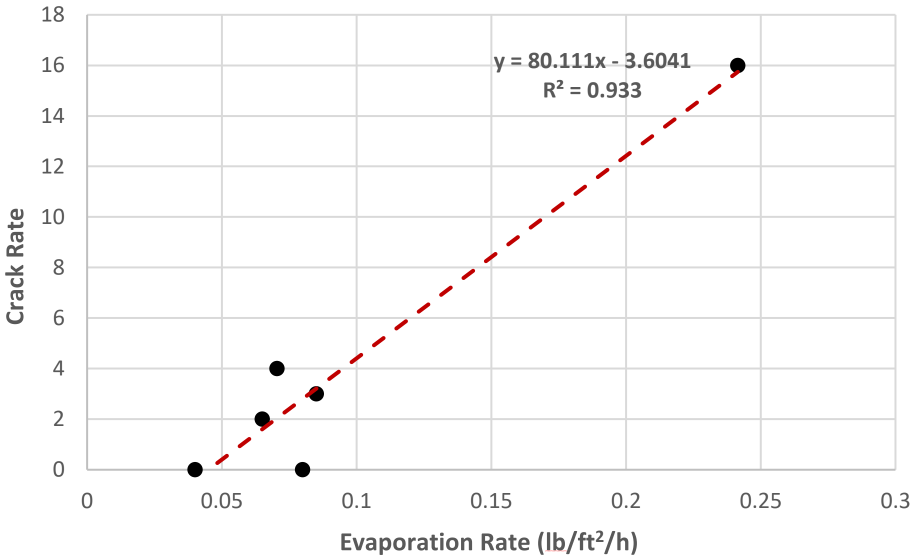


Figure 26. Relationship between crack rate and evaporation rate (Stage 3 results)

The results indicated a positive correlation between the crack rate and evaporation rate. Moreover, the R-squared value was 0.933 This indicated a significant correlation between crack rate and evaporation rate.

Figure 27 shows the crack rate versus wind speed.

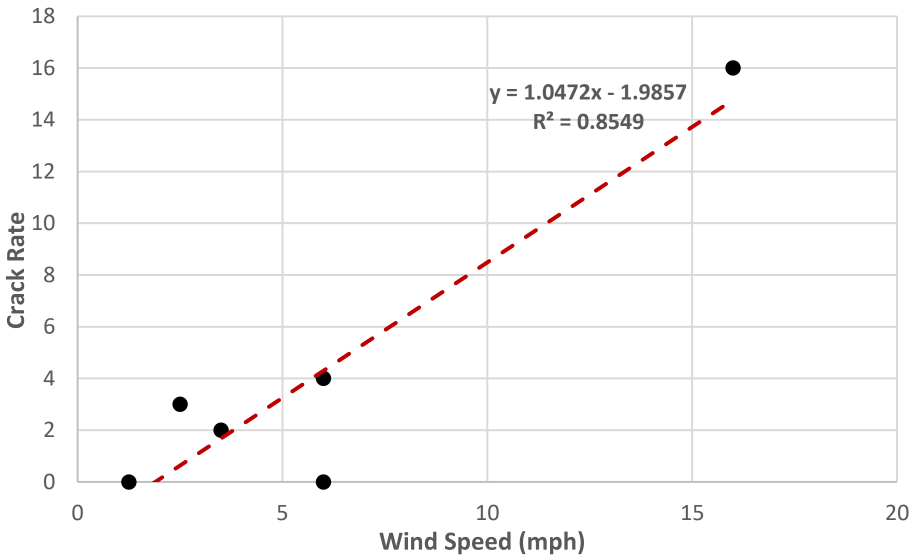


Figure 27. Relationship between crack rate and wind speed (Stage 3 results)

The results indicated a positive correlation between the crack rate and wind speed. Furthermore, the R-squared value was 0.8549. This indicated a significant correlation between the crack rate and wind speed.

Figure 28 shows the crack rate versus concrete temperature.

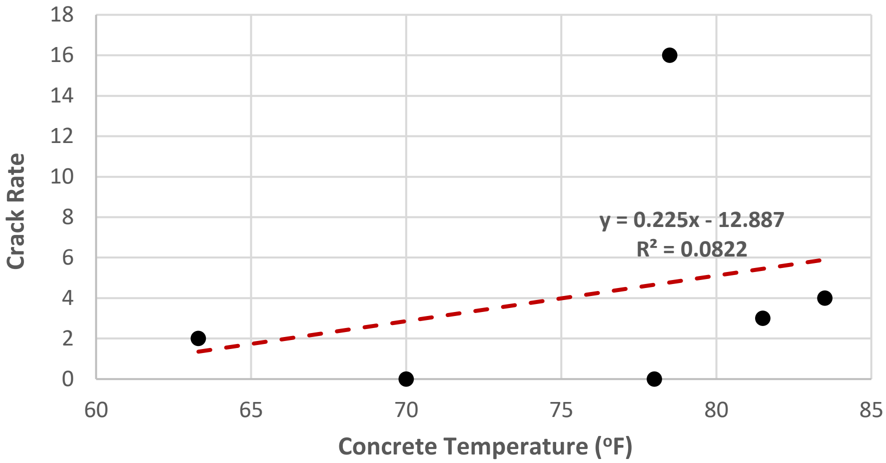


Figure 28. Relationship between crack rate and concrete temperature (Stage 3 results)

The results indicated a positive correlation between the crack rate and concrete temperature. However, the R-squared value was 0.0822. This indicated a slight correlation between the crack rate and concrete temperature.

Figure 29 shows the crack rate versus relative humidity.

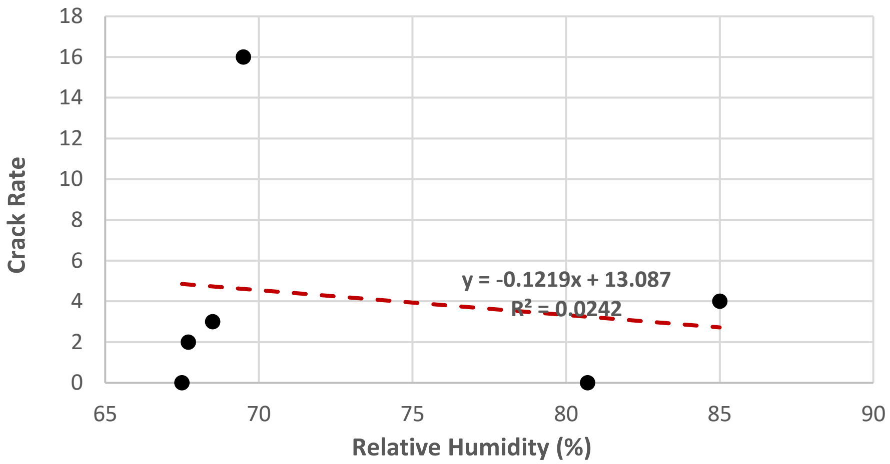


Figure 29. Relationship between crack rate and relative humidity (Stage 3 results)

The correlation between the crack rate and relative humidity was negative with an R-squared value of 0.0242. This indicated a slight correlation between the crack rate and relative humidity.

Figure 30 shows the crack rate versus air temperature.

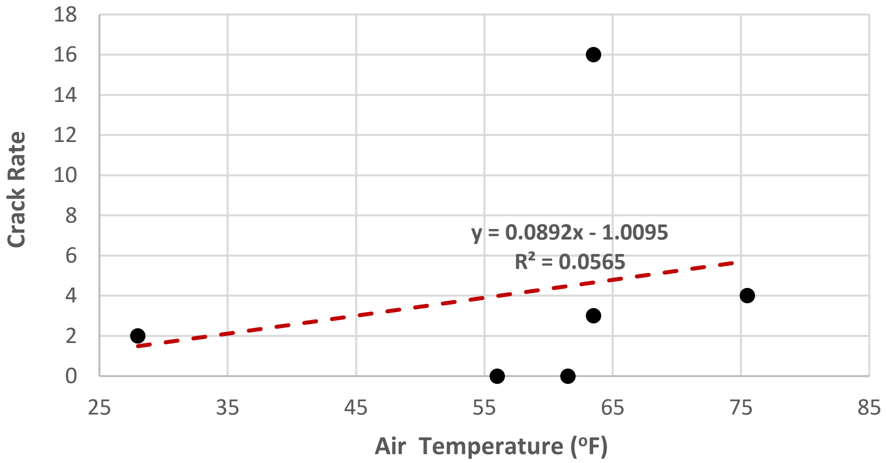


Figure 30. Relationship between crack rate and air temperature (Stage 3 results)

The results indicated a positive correlation between the crack rate and air temperature with an R-squared value of 0.565. This indicated a slight correlation between the crack rate and air temperature.

CHAPTER 6. RESULTS DISCUSSION

In this chapter, the research findings obtained from the Stage 1, Stage 2, and Stage 3 investigations are summarized and compared to evaluate the significance of each parameter and to identify parameters that may be related to the development of bridge deck cracks. In addition, related research results documented in the Iowa DOT report (Yusuf and Nop 2022) were used as a reference. The results from the Iowa DOT report were used given that the research work was recently conducted in 2022 and the bridge data used were from Iowa.

Table 16 shows the results of the comparison between the three investigation stages and the Iowa DOT report (Yusuf and Nop 2022).

In this table, the factors were divided into three categories: structural, construction, and materials. The term positive indicates the crack rate increased as the magnitude of the studied factor increased, and negative indicates the crack rate increased as the magnitude of the studied factor decreased. The values shown in parentheses are the R-squared values as determined during the investigation.

Based on the research findings through the three stages of investigation and the results from Iowa DOT report (Yusuf and Nop 2022), a final designation about the relationship between each bridge parameter and deck cracking was developed. The rightmost column in Table 16 shows the designation for each parameter studied. The final designation was made based on three approaches:

- Direct correlation between the crack rate and studied factor and the research team clearly reported the type, name, or value of the studied factor, such as district, structure age, structure type, cement type, or type of deck concrete.

- No correlation or agreement between the crack rate and the studied factor. As such, with contradicting findings in two different stages, the research team decided to exclude that factor from the final decision stage and label that as NR, which means no significant relationship or no agreement between the findings.

- Positive or negative correlation between the crack rate and the studied factor. The research team decided if the considered factor had been studied in at least one stage, they would report the correlation including positive or negative even if the R-squared value was small (i.e., less than 0.5).

Table 16. Summary of findings and correlation final decisions

Factor		Stage 1	Stage 2 (R^2)	Stage 3 (R^2)	Iowa DOT Study	Final Decision
Structural	**District**	4, 6	NS	NS	SW (4) SE (6 and 5)	**4 and 6**
	Structure Age	1960–1980	NS	NS	NS	**1960–1980**
	Structure Type	PPCB	NS	NS	PPCB	**PPCB**
	Structure Length (ft)	Negative	Positive (0.058)	NS	NS	**NR**
	Max. Span Length (ft)	Negative	Positive (0.025)	NS	NS	**NR**
	Girder Spacing (ft)	NS	Positive (0.035)	NS	NS	**Positive**
	Girder Depth (ft)	NS	Negative (0.068)	NS	NS	**Negative**
	Span Length/Girder Spacing	NS	Positive (0.008)	NS	NS	**Positive**
	EI Ratio	NS	Negative (0.0062)	NS	NS	**Negative**
	Top Transverse (in^2/ft)	NS	Positive (0.008)	NS	NS	**Positive**
	Bottom Transverse (in^2/ft)	NS	Negative (0.015)	NS	NS	**Negative**
Construction	**Air Temperature**	NS	Negative (0.002)	Positive (0.06)	NS	**NR**
	Concrete Temperature	NS	Negative (0.0007)	Positive (0.082)	NS	**NR**
	Average Wind Speed (mph)	NS	Negative (0.03)	Positive (0.85)	NS	**NR**
	Relative Humidity	NS	Positive (0.17)	Negative (0.024)	NS	**NR**
	Evaporation Rate	NS	NS	Positive (0.93)	NS	**Positive**
Material	**Cement Type**	NS	Type 1 and IP	NS	NS	**Type 1 and IP**
	Type of Deck Concrete (HPC and Non-HPC)	HPC	NS	NS	NS	**HPC**
	Cement Content (pcy)	NS	Positive (0.37)	NS	NS	**Positive**
	Concrete Strength	NS	Negative (0.013)	NS	NS	**Negative**
	Fly Ash (pcy)	NS	Negative (0.51)	NS	NS	**Negative**
	Coarse Content (pcy)	NS	NR (0.19)	NS	NS	**NR**
	Fine Content (pcy)	NS	NR (0.2)	NS	NS	**NR**
	Slump (in.)	NS	Negative (0.1)	NS	NS	**Negative**
	w/c Ratio	NS	Negative (0.16)	NS	NS	**Negative**
	Air Content (%)	NS	Positive (0.08)	NS	NS	**Positive**

NS = not studied in that stage due to a lack of available data, NR = no significant relationship or no agreement on the final decision between the crack rate and the studied factor

Table 17 summarizes the results of this comparison.

Table 17. Final correlation findings between crack rate and the studied factors

Correlation with Deck Crack	Studied Factors
Direct Correlation	• Districts 4 and 6 • PPCB bridges • Type 1 and IP cements • 1960–1980 construction period • Evaporation rate • HPC deck concrete
No Correlation	• Structure length • Maximum span length • Air temperature • Concrete temperature • Relative humidity • Structure age • Coarse and fine aggregate contents
Slight Positive Correlation	• Girder spacing • Span length-to-girder spacing ratio • Top transverse reinforcement • Cement content • Air content • Average wind speed
Slight Negative Correlation	• Girder depth • EI ratio • Bottom transverse reinforcement • Concrete strength • Fly ash • Slump • w/c ratio

The final correlation findings were divided into four categories: direct correlation, no correlation, slight positive correlation, and slight negative correlation.

The results indicated that the deck cracking could be directly related to six bridge parameters including location, girder type, cement type, concrete type (HPC), bridge age, and evaporation rate during construction.

No correlation could be established between the crack rate and structure length, maximum span length, air temperature, concrete temperature, relative humidity, structure age, coarse aggregate content, or fine aggregate content.

A slight positive correlation with a low confidence level could be established between the crack rate and girder spacing, span length-to-girder spacing ratio, top transverse reinforcement, cement content, air content, and average wind speed.

Moreover, a slight negative correlation with a low confidence level could be configured between the crack rate and girder depth, EI ratio, bottom transverse reinforcement, concrete strength, fly ash, concrete slump, and w/c ratio.

CHAPTER 7. SUMMARY AND CONCLUSIONS

Transverse cracks in concrete bridge decks sometimes initiate in the early stages of the bridge service life, usually just after its construction. The cracks in the bridge deck can accelerate deterioration of the deck concrete, provide a direct pathway for the intrusion of water and chlorides, and detract from the aesthetics. This eventually results in increased maintenance costs and reduced service life.

Over the past several decades, numerous studies have been conducted on the causes of transverse bridge deck cracking. Unfortunately, the causes of transverse deck cracking remain unclear, and the problem persists. Sometimes, the results from different research studies contradict each other, indicating that further research is needed.

The goal of this research was to identify factors that consistently lead to the formation of early-age transverse cracks so that they can be mitigated in the future. To obtain an evaluation and include as many potential factors as possible while still keeping the research manageable, the primary research investigation was conducted in three stages with varying numbers of bridges and factors studied in each stage.

The first stage of the investigation was carried out based on the use of a ready-made database provided by the Iowa DOT. These data, which were combined in the form of an Excel sheet, included information on 2,675 bridges across the entire state. The bridge deck crack information used in this stage was obtained primarily from the SIIMS database, and each bridge deck was categorized as either cracked or uncracked based on inspection notes and images. The parameters studied in this stage included deck concrete type, maximum span length, maximum structure length, bridge location, bridge age, and main structure type.

The second stage of the investigation was conducted to include additional bridge parameters into this study. A smaller group of 20 bridges was selected after reviewing inspection reports for 116 bridges constructed between 2013 and 2018. After that, the bridge data were collected and sorted into three main categories, structural, construction, or material, and the Bridge Engineering Center’s crack rate equation (2) was utilized to calculate the crack rate for each bridge. Furthermore, the research team analyzed the results to establish the relationship between the crack rate and each studied factor.

The third stage of the investigation was carried out based on data collected starting with deck concrete placement from six field visits. The parameters investigated in this stage include evaporation rate (lb/ft^2/h), air temperature (°F), concrete temperature (°F), relative humidity (%), and wind speed (mph). During each field trip, a form was used to record the basic bridge information and the on-site construction data. The crack rate for each bridge was later calculated utilizing the Bridge Engineering Center’s crack rate equation (2) and used to characterize the relationship to each studied factor.

The results from all three stages of the investigation were compared with the research results achieved from the Iowa DOT report by Yusuf and Nop (2022). Based on the research findings from each stage of this investigation, a final designation on the relationship between each bridge parameter and deck cracking was made as either direct correlation, no correlation, slight positive correlation, or slight negative correlation. The key findings from this research were as follows:

- HPC bridge decks showed a higher chance of cracking compared to non-HPC bridge decks
- Iowa DOT Districts 4 and 6 in southwest and east Iowa, respectively, had a higher propensity for having cracked bridge decks
- PPCB bridges showed a higher chance of deck cracking than steel beam bridges
- Type 1 and IP (portland-pozzolan) cement showed a higher chance of deck cracking compared to that for Type 2 cement
- Bridges constructed between 1960 and 1980 showed a higher chance of deck cracking
- Based on the data recorded from six concrete bridge deck placements, a high evaporation rate resulted in a higher chance of deck cracking

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