Chapter Four  
Field Study: Results

4.1 Introduction

This chapter presents the results of field study and the statistical analysis of based on the data, which were collected during the field study. Results and their limitations are presented under three major categories: structural design, material properties and mix design, and construction. In each part, results are compared to similar studies performed by other researchers. These results are followed by discussions of research findings and some interesting observations that were made during the field study. Areas for detailed analytical and numerical analyses are also outlined. Based on the literature review and field study results, preliminary recommendations are proposed. This chapter concludes with a summary and a general direction of the ongoing work for the second part of this research study. Thus, it is organized in five sections. After this introduction, section 4.2 presents the results of the field survey. Section 4.3 discusses the field observations and results and outlines areas for further study and research. Finally preliminary recommendations are proposed in section 4.4.
4.2 Evaluation of Survey Results

Factors identified relevant to deck cracking are evaluated for all bridges surveyed and are compared with the results of other researchers. Results of literature review were used in the selection of these factors. Of course, availability of data was another criterion in determining the factors considered. In the following sections these results are discussed and summarized using tables and graphs. However, the raw data for all bridges are reported in Appendix A.

4.2.1 Structural Design Factors

The design factors included in the survey are detailed in the Appendix. These factors are as follow:

1. Girder type
2. End Condition
3. Skewness
4. Type of bearing
5. Surface texture
6. Wearing surface
7. Deck thickness
8. Bar size and spacing

Girder Type: Girder type is considered one important factor by various researchers. Some of the pervious works, such as NCHRP Report 380 [9] and Minnesota DOT’s research [15], show that decks supported on steel girders are more likely to crack than those supported on concrete girders. However, results of this study show that 94 percent of decks supported by prestressed concrete girders were cracked whereas only 38 percent of steel girder bridge decks cracked. The bias in this case is more likely due to the fact that a great number of bridges with prestressed concrete girders had more restraint (fixity) at their supports. Nevertheless, the contradiction highlights the fact that there are other factors that play a significant role and complicate the problem. As it will be discussed, it appears that the relative stiffness of the deck with respect to the girder stiffness is more important than the girder type.

End Condition: This study shows a high correlation between the end fixity and the cracking tendency of the bridge decks. As it is shown in Figure 4.1, by increasing the fixity of the end supports the percentage of cracked-decks increases. Note that with reference to this figure the continuous end condition refers to situations where at least one end is continuous. That is, if the
span is an internal one both ends are continuous. If it is an end span, one end is continuous and the other end (i.e., abutment) is simply supported. Fixed condition is when the abutment end is fixed (e.g., the end of the girder is built into the abutment wall or integral abutment). However, integral abutment is not a common practice in the State of New Jersey and was not the case for any of the bridges surveyed. Thus, the term fixed end should be used with some cautions here. Within the context of these data, this end condition refers to a situation as shown in Figure 4.2. This type of construction, where the end diaphragm is cast around the girders and it is quite rigid, is the typical construction on bridges built on Route 133. As long as the diaphragm is uncracked, i.e., under low level of forces, the connection will act like fixed support. Probably for higher level of forces, such as ultimate, the diaphragm will crack and the girders will be more like simply supported condition. It is difficult to determine the actual rotational stiffness provided by this type of diaphragm. However, under shrinkage stresses, which are much smaller than ultimate stresses, the connection quite likely acts like a fixed support. Quantifying the effect of end condition is one of the primary factors that will be the subject of the second phase of this study. Nevertheless, the widespread cracking of bridges with similar end condition, which actually prompted this research investigation, supports the pronounced effect of end condition and rotational rigidity on transverse deck cracking.

![Bar chart showing percent of cracked bridge decks with different end condition](image)

**Figure 4.1 - Percent of cracked bridge decks with different end condition**
Figure 4.2 - End diaphragm cast around the girders

Figure 4.3 - Structural detail of the end diaphragm shown at Figure 4.2
NCHRP report 380 [9], K-Tran [11] and Minnesota DOT report [15] are among research studies that report increased cracking for fixed girders compared to those with pin-ended girders. Since the number of the surveyed bridges is not enough, the effect of the end condition can’t be evaluated for different girder types but comparing the number of the continuous steel and prestressed concrete girder bridges shows that 100 percent of prestressed concrete girder bridges cracked whereas only 25 percent of those continuous bridges with steel girder cracked. However, this result is not reliable due to small number of bridges in the sample.

**Skewness:** There seems to be no direct relationship between the degree of skewness and the potential for transverse deck cracking. Figure 4.4 shows that the percentage of cracked bridge decks do not follow a consistent trend with respect to skewness. Considering the overall percentage of cracked bridge decks in this study which is equal to 75 percent, it seems that the data on the graph is just some variation with respect to this number which exists in any statistical analysis. Similar result is reported in NCHRP Report 380 [9].

![Figure 4.4 - Percent of cracked bridge decks with different skewness](image)

**Type of Bearing:** There were two types of bearings in surveyed bridges. Steel bearing and elastomeric pads. Elastomeric pads where only used with girders on route 133 bridges, where, as discussed, the end diaphragm where cast around the girders (see Figure 4.2). The survey shows that all bridges with elastomeric pads are cracked but for steel bearings the percent of cracked bridge decks is 56. This could be due to the fact that probably steel bearings allow rotation more freely. Thus, it seems that the type of bearing may have an affect on transverse deck cracking.
However, the result should be viewed with cautions because the elastomeric pads were only used in bridges that also had a different end diaphragm as discussed under end condition.

**Surface Texture:** Since the dominant texture for bridges surveyed is saw-cut texture and there is only one bridge decks with other type of surface texture, comparison between different textures is not possible.

**Wearing Surface:** 80 percent of the surveyed bridges had concrete wearing surface whereas latex concrete was the wearing surface for the remaining bridge decks. 84 percent of the bridge decks with the concrete wearing surface were cracked while only 20 percent of the bridge decks with the latex concrete surface developed cracking. Thus, there is an indication that latex concrete can reduce the cracking but due to the small number of bridges in the latex sample (5 bridges), this result should be treated carefully and one cannot draw a general conclusion.

**Deck Thickness:** The average thickness of the cracked deck was about 8.75 in while this average for the un-cracked bridge decks is around 9 in. This shows that an increase in the deck thickness reduces cracking. Similar results are also reported by other researchers (e.g., NCHRP 380 [9]).

**Bar Size and spacing:** All of the surveyed bridges use a mesh of #5 or #6 bars spaced 5 to 7 in as the top mesh (except in the negative moment areas). This study can’t identify any significant relationship between the bar size and bar spacing and transverse deck cracking in the range of available data. It is generally accepted that smaller bar size and closer spacing can reduce cracking.

### 4.2.2 Material Properties and Mix Design Factors

Based on the NJDOT Inspection/Testing datasheets that contain the information about mix design and construction practice several material properties are extracted and used in the development of the database. The material properties that are recorded in the NJDOT Inspection/Testing datasheets and are used in this study are:

- Cement Content
- Water Content
- Water cement ratio
- Air content
- Cement Type
- Slump
Note that the range of data for these factors is quite narrow and this fact should be considered in interpreting the results. However, this may be a good thing and supportive of the research thrust on design factors. That is, the data are within a narrow band and most of them well within the recommended range made by other research. Still majority of the bridges have cracked supporting the fact that design factors play a significant role in causing and/or controlling transverse deck cracking.

**Cement Content:** The cement content in the deck concrete for bridges surveyed is in the range of 611 to 735 lb/yd³ with most of the bridge decks built with cement content of 700 lb/yd³ (19 bridges). This study shows that the cracking occurs on both decks with high cement content and low cement content, albeit within that narrow range. 80 percent of decks with cement content of 700 lb/yd³ and more cracked, whereas 50 percent of decks with lower cement content cracked. As for those 19 bridges with exactly 700 lb/yd³ cement content 73 percent are cracked. This, there is an indication that lower level of cement content reduces cracking but considering the distribution of data (i.e., narrow range and the fact that majority had one cement content) this result cannot be emphasized. Other researchers also reported increased cracking with an increase in cement content. (such as NCHRP Report 380 [9], Minnesota DOT [15], Penn DOT [10], K-Tran [11])

**Water Content:** The water content for the deck concretes is between 31.5 lb/yd³ and 35 lb/yd³, where 19 bridge decks have water content of 31.8 lb/yd³ and water content for 23 decks is in the range of 31.5 lb/yd³ to 32.6 lb/yd³. The ratio of cracked bridges is 77 percent. Previous studies reported that cracking increase with an increase in water content (NCHRP [9], K-Tran [11], Minnesota [15], Penn DOT [10]), but due to the narrow range of data in this part no conclusion can be made.

**Water Cement Ratio:** The w/c ratio for the surveyed bridges is between 0.44 and 0.36, where 19 bridges have w/c of 0.38. Again, due to the narrow range of data and their distribution this part is also inconclusive. But it should be noted that the range of the w/c ration in bridges surveyed more or less is in the range recommended by other researchers.

**Air Content:** The average air content for the bridge decks is in the range of 5.1 to 6.7. There is no indication of the effect of higher or lower air content on deck cracking in the bridges surveyed based on the results.
Cement Type: Type II cement is used in all decks for bridges surveyed. The cement manufacturer is also one company for 92 percent of bridges. Literature also recommends the use of type II cement to minimize transverse deck cracking.

Slump: The average slump of the concrete used in these bridge decks is in the range of 3 to 4 inches. Cracking is observed in decks with both high slump (4 inches) and low slump (3 inches). It seems that for the range of slump observed in these bridges, it has no effect on the transverse deck cracking.

Compressive Strength: The compressive strength of the bridge decks is in the range of 4500 to 6623 psi, which is a broad range. The average compressive strength of un-cracked bridge decks is 5640 psi, whereas this average for cracked bridges is 5730 psi. This shows that cracked bridges have slightly higher compressive strength, which is in agreement with previous studies (e.g., NCHRP [9]). In fact comparing these strengths with the 4500 psi, which is the required strength for design, it is observed that the average compressive strength is about 1200 psi more than that specified in design. Reducing this margin, which partly means reducing cement content, may reduce the potential for deck cracking.

Admixture: Water reducer and air entraining agent is used in all bridges surveyed. Also, 79 percent of the deck bridges have retarder agent in their mix. There is no indication of increase or decrease in cracking because of the use of these admixtures.

4.2.3 Construction Practice Design Factors

All the data that are available and used in the development of the database are those provided on the Inspection/Testing sheets. Unfortunately no documented data is available about curing method and time of curing, which are among the most important factors with regard to transverse deck cracking. Therefore, it may be a good practice to include more data on construction methods in the inspection and quality control forms. Among data that may be included are: wind velocity, humidity, curing method, curing period, and placement length. Note that measurement of humidity is required based on the NJDOT Specs [4].

Thus, based on the available data, in this study the effect of the following factors are considered:
1. Air and concrete temperature
2. Month of placement

**Air and Concrete Temperature:** The study shows that the cracked bridge decks were cast in slightly higher temperatures and with slightly higher concrete temperatures. The average air temperature in the time of casting for cracked bridges is 64°F while this number is 60°F for un-cracked bridges. Also, the average concrete temperature in the time of casting for un-cracked bridges is 76°F, while this number is 73°F for un-cracked bridges. Literature indicates [e.g., 10] that placement of bridge decks in very high and very cold weather increases the possibility of cracking. However, the data show that none of these 24 bridges surveyed were cast in very hot or very cold weather.

**Month of placement:** As it was just mentioned, literature indicates that deck placement in very hot and very cold weather increases transverse cracking. The month of placement can be a good indicator of this situation. The decks for none of the bridges surveyed were cast in the winter. Construction season for the surveyed bridges are as follows: 37.5 percent in the spring, 33.3 percent in the summer and 29.2 percent in the fall. 43 percent of bridge decks cast in the fall developed cracking, while this number is 75 and 89 for the bridges cast in the months of summer and spring, respectively. This indicates that casting the decks in mild weathers can reduce the potential for deck cracking.

### 4.3 Remarks and Further Research

Review of the collected data and comparison with the literature and with the 1998 NJDOT Specs [4] show that many material and mix design recommendations are already satisfied. Due to the limitation of the data such a conclusion cannot be made with regard to construction factors. For example, it could not be determined if 7 day wet curing is employed. However, consistent with the literature recommendation, NJDOT Specs [4] does require 7 day wet curing. This is a very important factor in controlling transverse deck cracking and every effort must be made to adhere to the Specifications. In summary, NJDOT Specs [4] contains many of the recommendations made as results of prior research. Additional recommendations to be considered for possible implementation and inclusion in future revisions to the specifications are proposed in the next section. There are also some factors that probably coincidently are consistent with research recommendation. For example, none of the bridges surveyed were cast in the winter and all surveyed bridge decks had relatively low w/c ratio.
With regard to design and material property factors, higher compressive strength of the tested specimens compared to design value shows that the structural design requirement on the compressive strength could have been satisfied by use of lower cement in the mix. Reducing the cement content in turn can reduce drying shrinkage, thermal shrinkage and temperature differentials during casting, which are believed to be the dominant causes of transverse cracking. Therefore, it is highly recommended to reduce the cement content. Considering the design compressive strength of 4500 psi for bridge decks, this recommendation can still be satisfied quite easily. If the current guideline provides any incentive for higher than design compressive strength it should be revoked. It is also noticeable that except for high amount of cement content, other parameters included in the study satisfies recommendations made in the literature. Use of type II cement, adequate air content (>5%), satisfactory w/c ratio (<4.5) and use of the water reducer and retarder agents are indications of good mix design as required by literature to reduce transverse cracking.

Despite significant research work and enhanced knowledge of the two previous categories (i.e., mix design and construction practices), the current knowledge on the effects of structural design factors on deck cracking is limited. The design recommendations proposed in the literature are mostly based on engineering judgment and have not been quantified in details through analytical and/or experimental studies. For example, it is accepted that reducing deck restraint or increasing deck thickness can reduce the possibility of deck cracking, however, no specific guidelines and/or values have been recommended. The observations of bridges on route 133 (see Figure 4.2, and 4.3), as mentioned in section 4.2, suggest that the design factors can be important in deck cracking. Note that the end diaphragms on all of these bridges are cast around the girders. As shown in Figure 4.4, the cracks in these bridges are parallel to the bridge axis and become normal to the axis as they propagate towards the center of the span. Considering the not so common design of the end diaphragms and its high rigidity compared to a pinned case, the question arises about the possible contribution of design factors to significantly increase transverse deck cracking. On the other hand the same factors can be employed in a balanced design to provide remedies. This is currently under study and the approach and preliminary results are discussed in the next chapter.
The observations made from the field survey of two parallel bridges crossing the Watson Creek (EB and WB) further support the need for more knowledge on the effects of the structural design factors. These two bridges are almost identical and built on EB and WB side of route I-195. The structural design, and the mix design for these two bridges are very similar to each other (see appendix A). During the surveys transverse cracks were observed on the eastbound side but the westbound side had no transverse deck cracking. The examination of the joint continuity for these two bridges showed that the joints on the westbound side were cracked, while the continuity joints on eastbound side were intact (see Figure 4.5 and 4.6). That is, the bridge with cracked joint (less rigidity/constraint) did not develop any cracking in the deck, while the one with uncracked joint (more rigid/restraint) did develop transverse deck cracking. These observations point to the role of structural design factors in deck cracking and further research to enhance or knowledge about these factors.
Figure 4.6 – Cracked continuity joints on westbound side (bridge No.1130-152)

Figure 4.7 – Cracked continuity joints on eastbound side (bridge No.1130-153)
4.4 Preliminary Recommendations

Based on results of this part of the study and review of the NJDOT Specs [4], the following recommendations, which are agreed upon by most researchers, can be made. These recommendations are divided into two categories: material properties and mix design, and construction practices. Some important factors, which are already considered in NJDOT Specs [4], are also included to emphasize their importance on transverse deck cracking.

4.4.1 Construction Practice

Placement sequence:
- Pour complete deck at one time whenever feasible within the limitation of the maximum placement length based on drying shrinkage consideration.
- If multiple placements must be made and the bridge is composed of simple spans, then place each span in one placement.
- If bridge is simple span, but cannot be placed in a single placement, divide the deck longitudinally and make two placements.
- If the bridge is simple span and single placement cannot be made over full span length, then place the center of span segment first and make this placement as large as possible.
- If multiple placements must be made and the bridge is continuous span, then place concrete in the center of positive moment region first and observe a 72-h delay between placements.
- When deck construction joints are created, require priming existing interfaced surfaces with a Primer/Bonding agent prior to placement of new concrete.

Wind, Weather and Concrete Temperature (Already included in the NJDOT Specs): Follow procedures in sections 501.12 and 501.17. Make use of evaporation rate chart proposed by ACI. Cast the deck in mild temperatures. (It is also recommended that wind and humidity levels be recorded on the Inspection/Testing datasheets)

Protection and curing (Already included in NJDOT Specs): Follow procedures in section 501.17. Start curing immediately after finishing and cure at least 7 consecutive calendar days.
4.4.2 Mix Design

**Cement Content:** Reduce cement content to 650-660 lb/yd$^3$. Consider using fly ash.

**Cement Type:** Use AASHTO specification Type II cement for bridge deck construction.

**Water Cement Ratio:** Limit the w/c ratio to 0.4-0.45. Make use of water reducers to reduce water content. Consider w/c<0.4 with use of water reducers.

**Aggregate Size and Shape:**
- Use largest possible grain size as specified in ACI–318.
- Use crushed stone for coarse aggregate.
- Maximize aggregate content.

**Shrinkage Compensating Concrete:** Consider using type K when available.