

CRACKING IN CONCRETE BRIDGE DECKS

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ABSTRACT

The causes of cracking in concrete bridge decks are investigated, and procedures are recommended to alleviate the problem. Forty continuous steel girder bridges, thirty-seven composite and three noncomposite, from northeast Kansas (KDOT District I) are evaluated. Field surveys conducted to document cracking patterns and to determine the crack density of each bridge are described. Information collected from construction documents, field books, and weather data logs is presented and compared to the observed levels of cracking to identify correlations between cracking and the variables studied. Thirty-one variables are considered. These include material properties, site conditions, construction procedures, and design specifications, as well as age and traffic volume.

Based on the research reported herein, cracking in monolithic bridge decks increases with increasing values of concrete slump, percent volume of water and cement, water content, cement content, and compressive strength, and decreasing values of air content (especially below 6.0%). Bridge deck overlays placed with zero slump concrete exhibit consistently high levels of cracking. Cracking in overlays also increases as placement lengths increase. High maximum air temperatures and large changes in air temperature on the day of casting aggravate cracking in monolithic bridge decks. High average air temperatures and large changes in air temperature similarly aggravate cracking in bridge deck overlays. Both monolithic and two-layer bridges with fixed-ended girders exhibit increased cracking near the abutments compared to those with pin-ended girders.

Keywords

bridge decks, bridge construction, concrete construction, concrete mix design, cracking, durability, overlay, reinforced concrete, shrinkage.

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CHAPTER 1

INTRODUCTION

1.1 General

Cracking in concrete bridge decks has been a problem throughout Kansas and the rest of the country for many years. Cracks can form quite early in the life of a structure, often even before a bridge is open to traffic, and are frequently several times wider than the 0.18 mm (0.007 in.) limit suggested by ACI Committee 224 (1990) for concrete exposed to deicing chemicals. This can accelerate deterioration by allowing water and deicing chemicals to more easily penetrate into the deck. Many of these cracks extend or propagate with time through the full thickness of the deck, which then speeds the degradation of the supporting girders. These items present a maintenance problem and can dramatically reduce the service life of the structure, both of which result in increased costs.

Although there have been many investigations performed in this area (Cheng and Johnston 1985; PCA 1970; Kochanski et al. 1990; Poppe 1981; Perfetti et al. 1985; Wiss, Janney, Elstner Associates, Inc. 1993), the problem of bridge deck cracking is, at this time, not fully understood. Various researchers and professionals have published their findings and opinions, but little consistency as to which factors most significantly influence bridge deck cracking is evident. The reason for this may be due, in part, to the wide variety of bridge types and construction techniques employed throughout the country and the changes in design and construction that have occurred over time. However, regardless of the reasons for this inconsistency, the fact remains that, without a better understanding of what causes the cracking, procedures to alleviate the problem cannot be implemented.

The factors that are generally thought to contribute to the problem can be grouped into the following four categories: 1) environmental or site conditions, 2) construction techniques, 3) design specifications, and 4) material properties. It is agreed by most that bridge deck cracking is the result of the combined effects of factors in several or all of these categories. The large number of variables involved makes it difficult to evaluate the individual contribution of each factor.

This study was undertaken to identify the probable causes of cracking in bridge decks, pinpoint the most significant contributing factors, and recommend alternate design and/or construction procedures that will alleviate the problem.

1.2 Background

As early as the 1960's, with an investigation by the Portland Cement Association into the durability of bridge decks (PCA 1970), efforts have been made to develop methods for reducing the frequency and number of cracks in concrete bridge decks. Since that time, typical design specifications and construction techniques have changed a great deal, yet bridge deck cracking remains a problem. In fact, there are those who believe that the problem is worse now than in past years. Aside from the question of severity, the problem, as it exists today, continues to undermine deck durability and decrease the overall service life of many bridges. It therefore deserves further attention.

Cracks found in bridge decks can be of several different forms and are generally characterized according to their orientation with respect to the longitudinal axis of the bridge. The five major crack types typically associated with bridge decks are as follows: 1) transverse, 2) longitudinal, 3) diagonal, 4) pattern or map, and 5) random. Cracking of each type can appear on the same deck; however, the incidence of each appears to depend on the type of bridge and the section of bridge deck considered. For example, steel or concrete girder bridges usually exhibit more transverse cracking than any other type of cracking, whereas slab bridges are more susceptible to longitudinal cracking. Also, the number of transverse cracks observed in the negative moment regions of concrete girder bridges is often much greater than the number observed in the positive moment regions.

Of the five main types of cracking, transverse cracking is by far the most predominant (PCA 1970). These cracks usually appear soon after the deck is placed and often form directly above or near transverse bars in the top layer of reinforcement. They also tend to run along the top steel in skewed bridges in which the transverse reinforcing steel has been placed parallel to the skew. This provides water and deicing salts direct access to the steel, which increases the rate of corrosion. The exact cause of these cracks is not known, and there are undoubtedly many factors that contribute to their formation. The two factors that appear to be the most significant are 1) the degree of restraint provided by the reinforcing steel and the supporting girders to the early and long-term shrinkage of the concrete, and 2) the presence of transverse reinforcing steel near the surface that acts as a tensile stress raiser (PCA 1970).

Longitudinal cracking occurs primarily in solid and hollow-slab bridges. These cracks usually form above the top longitudinal steel in solid-slab bridges and above void tubes in hollow-slab bridges. The most significant contributing factor to this type of cracking is thought to be the resistance that reinforcing bars and void tubes provide to the subsidence of the concrete just after placement and finishing

(PCA 1970). Shrinkage of the concrete and the buoyancy of the void tubes also contribute.

Diagonal cracking is generally associated with areas of the deck near the ends of skewed bridges and over single-column piers (PCA 1970). The resistance of the structure to deformation, caused by either external loads or concrete shrinkage, is the likely explanation for this type of cracking.

Pattern or map cracking is common on all types of bridges. These cracks are usually very shallow in depth and fine in width. Their occurrence is often attributed to improper curing, which allows surface moisture to evaporate too quickly (ACI Committee 224 1990; PCA 1970). It has been suggested that this type of cracking has little effect on the long-term durability of bridge decks.

Random cracking consists of all those cracks that do not neatly fit into any of the above categories. The causes of these types of cracks are highly variable and are typically considered to be local imperfections or loadings (PCA 1970).

From the most basic point of view, cracks form whenever the tensile stress in a particular region exceeds the tensile strength of the concrete. Since the strength of concrete changes with time, the stress required to cause the formation of a crack is not always the same. There are two types of loads responsible for increases in tensile stress 1) directly applied loads, and 2) loads induced by the restraint of volume changes in the concrete.

For typical bridges, direct loads are further subdivided into dead loads and live loads. Residual tensile stresses can be left in a bridge deck after its completion due to the concrete placing sequence used. As the placing operations continue along the length of a bridge, the dead load of the newly placed concrete causes a change in the deflection or curvature of the supporting girders. This creates tensile stresses in previously placed concrete that has already begun to harden. If these tensile stresses exceed the tensile strength of the concrete (which is likely since the concrete is young), cracks will form. Otherwise these residual stresses remain in the concrete (although they will be reduced by creep) and are additive to the stresses imposed later by other means. The stresses produced by live loads alone are not thought to be of major importance in bridge deck cracking except for possibly in the negative moment regions of certain bridge types.

Loads or stresses are induced in concrete structures whenever and wherever restraint is imposed on concrete volume change. The magnitude of these stresses depends on the amount of the volume change, the degree of the restraint, and the extensibility of the concrete. Sources of restraint in bridge decks are provided by many of the structural elements, including reinforcement, girders, shear studs, and abutments. Internal restraint is also possible. For instance, if the volume of the

surface portion of a slab decreases more rapidly than the inner portion, due to such things as accelerated moisture loss or a temperature drop, the surface is restrained by the inner portion. In this case, tensile stresses develop near the surface and compressive stresses develop in the inner portion. For bridge decks cast in two layers, differential shrinkage between the overlay and the subdeck can have a similar effect.

Volume changes occur 1) while the concrete is still in a plastic state, and 2) after it has hardened. Different problems related to cracking can be associated with each of these stages. Before hardening, plastic shrinkage cracking and settlement cracking can occur. Plastic shrinkage cracks develop when the free moisture on the surface of the deck evaporates more quickly than it can be replaced by bleed water from below. The top layers want to shrink as they dry but are restrained by the lower layer that is losing water less quickly. Tensile stresses are induced in the top layers and, since the concrete has essentially zero strength at this early age, cracks develop in various directions. These cracks are typically very small and shallow, but their size can increase with time as the deck continues to shrink and external loads are applied. This type of cracking can be controlled by preventing moisture loss from the concrete at early ages. The use of proper curing procedures and favorable weather conditions (low wind and high relative humidity) are beneficial in achieving this goal. The use of wind breaks and fog sprays during concrete placement can be particularly effective in reducing plastic shrinkage cracking.

Settlement cracking occurs as concrete continues to settle after placement and finishing. Concrete movement is restrained by the reinforcing steel in the top of the slab, which causes the concrete to sag in between individual bars. This creates a tensile stress directly above each bar, which subsequently produces a crack running along the bar, since the concrete has essentially zero strength at this stage. The extent of this type of cracking is dependent on bar size, slump, and cover thickness, as shown in Fig. 1.1 (Dakhil et al. 1975). Increases in slab depth, poor initial consolidation, and leaking or highly flexible forms can also aggravate the problem.

After concrete has hardened, it can undergo volume changes for various reasons, including drying, temperature changes, and chemical reactions. Volume changes produced by any of these conditions can produce tensile stresses in restrained regions which are additive to the stresses already present. The more slowly that volume changes occur, the lower the induced stresses due to the effects of creep. Therefore, anything that can be done to diminish the magnitude of the volume changes or slow the rate at which they occur is beneficial.

Drying shrinkage occurs as water is lost from the cement paste portion of concrete. Water is stored in both small voids or capillaries in the paste and within the

hardened calcium silicate gel (tobermorite gel) (ACI Committee 224 1990). The gel can absorb a great deal of water and has a very large surface area. It is the moisture loss from this gel that accounts for the majority of the shrinkage. The amount of shrinkage that takes place during drying can be decreased by proper proportioning of the mix. Aggregate in concrete acts to resist the shrinkage of the paste; therefore, mix designs that maximize the aggregate and minimize the paste portions of the concrete result in less overall drying shrinkage. In doing this, the level of compressive strength desired must, of course, be considered. The size and type of aggregate, type of cement, and type of admixtures used in the concrete mix also affect drying shrinkage.

Differential volume changes due to changes in temperature throughout the thickness of a concrete bridge deck are also potential sources of cracking. Here stresses develop in much the same manner as they do for drying shrinkage. Tensile stresses develop in the portions of the structure that are cooling (and thus contracting), while compressive stresses develop in portions that are either warming (expanding) or cooling at a slower rate. The two main sources of temperature change in concrete are the heat produced by hydration and changes in weather conditions. Thermal stresses induced by a build-up of the heat produced by the hydration process are typically a problem in the placement of mass concrete; however, thermal stresses can also cause cracking in bridge decks if precautions are not taken. For example, if protection is removed suddenly from a bridge deck during cold weather, rapid cooling of the concrete surface will produce sizable tensile stresses. Care must be taken to control the rate at which the concrete cools. ACI Committee 306 (1988) recommends that the maximum temperature drop during the first 24 hours following the end of the required protection period not exceed 28 °C (50 °F) for concrete sections with minimum dimensions less than 12 in. (300 mm).

Several different chemical reactions can occur in concrete that cause volume changes. Restraint of these changes will produce tensile stresses in the concrete in a similar fashion to the conditions described above. Volume changes caused by chemical reactions can be avoided by carefully testing each of the individual constituents to be combined in the concrete mix to insure that the possibility of reactions between materials is low.

1.3 Previous Work

A number of studies have been undertaken in the past to determine the main causes of cracking in concrete bridge decks (Cheng and Johnston 1985; PCA 1970; Kochanski et al. 1990; Poppe 1981; Perfetti et al. 1985; Wiss, Janney, Elstner Associates, Inc. 1993). The results of these previous studies are useful in directing

the current research efforts. The following is a summary of the findings of six such studies. The first considers the effects of various factors on bridge deck durability in general. The next four studies concentrate specifically on cracking, and two of these emphasize transverse cracking in particular. The final study summarizes the results of two experimental bridge deck overlays containing silica fume.

In 1961, the Portland Cement Association (PCA) began a cooperative study of concrete bridge deck durability in the United States (PCA 1970). This study was comprised of two main parts, a random survey intended to characterize the various types and the extent of existing durability problems and a detailed investigation intended to identify the causes of bridge deck deterioration. An additional study was performed to investigate the possible effect of superstructure vibration characteristics on bridge deck deterioration.

The random survey included over 1000 bridges from the states of California, Illinois, Michigan, Minnesota, New Jersey, Ohio, Texas, and Virginia. Between 100 and 150 bridges built between 1940 and 1962 were randomly selected for evaluation from each state. Bridges of all structure types were included. Most of the steel girder bridges included in the survey were of noncomposite design. Composite designs did not become prevalent until the late 1970's or early 1980's.

The results of this survey in regard to cracking are as follows. Some form of cracking was readily visible on roughly two-thirds of the spans surveyed. Of all cracking types, transverse cracking was the most predominant. The incidence of this type of cracking seemed to increase with bridge age and span length. Furthermore, transverse cracking was found to be greater on continuous spans than on simply supported spans and greater on decks supported by steel girders than on decks supported by reinforced concrete girders. Random cracking was the second most frequently observed form of cracking, although no correlation could be determined between the incidence of random cracks and structural parameters. Other types of cracking were not present in great quantity.

The detailed investigation included a total of 70 bridges in the states of Kansas, Michigan, California, and Missouri. The bridges were selected in such a way as to obtain a wide range of ages, locations, structure types, and degrees of deterioration. The investigation of each bridge included a field inspection, laboratory analysis of core samples, and a review of construction records.

The results of the detailed investigation are as follows: Transverse cracking was the predominant type of cracking found on bridge decks supported by steel or concrete girders. Laboratory analysis of cores taken over transverse cracks showed that the cracks were typically directly above top reinforcing bars. On one bridge, which employed truss type reinforcing bars, transverse cracks were observed only

over the length of bar that was bent up to provide top reinforcement. Tight cracks were observed in the negative moment regions of decks supported by continuous concrete girders, while few cracks were observed in the positive moment regions. In steel girder bridges (both simple and continuous), transverse cracks were usually found to be spaced at regular intervals over the entire length of the deck. However, in some instances, somewhat more cracking was encountered in the negative moment regions of decks supported by continuous steel girders.

From these observations, the following conclusions were made (PCA 1970): For decks supported by continuous cast-in-place concrete girders, dead and live load tensile stresses in the negative moment regions combine to cause cracking. Fewer cracks are noted in the positive moment regions because significant residual dead load compressive stresses act to offset the tensile stresses produced by live loads and the restraint of volume changes in the hardened concrete. For decks supported by continuous steel girders, live load stresses are not thought to be a major contributor to cracking. The regular spacing of the cracks on most bridge decks suggests that other factors, particularly the restraint imposed by the girders on the shrinkage of the slab, account for the largest portion of the cracking problem in continuous steel girder bridges.

In the study of vibration characteristics, 46 superstructures from the 70 bridges included in the detailed investigation were evaluated. These included most of the bridges from Kansas and Missouri, as well as two simply supported composite spans from one of the California bridges. For each span, the fundamental natural frequency, speed parameter, and impact factor were calculated. These values were compared to the observed levels of deck deterioration. It was concluded that no consistent relationship exists between these variables and the severity of deck deterioration. However, limitations of this study were noted. The bridges included in the study were designed and built between 1940 and 1960, which means most of the designs are conservative when compared to bridge designs since 1960. Taking this into consideration, it was stated that ". . . it would seem reasonable to speculate that there is a level of 'flexibility' (or amplitude of vibration) which would be detrimental to the durability of concrete bridge decks."

Based on the completed study, the PCA (1970) made several recommendations aimed at improving the durability of concrete bridge decks. Three of these specifically addressed the problem of transverse cracking. The three focused on limiting or controlling the amount of shrinkage that takes place in the deck, since the regular spacing of the observed transverse cracks suggested that the restraint of concrete shrinkage was a major contributor to cracking. First, it was recommended that the largest practical maximum size of coarse aggregate be specified to minimize

the water content, and therefore the shrinkage, of the concrete. For similar reasons, the second recommendation was to keep the maximum slump within a range of 2 to 3 in. (51 to 76 mm) and to use the lowest reasonable slump possible. Third, placing the longitudinal steel above, rather than below, the transverse steel was suggested as a means of more effectively controlling the shrinkage of the concrete, since many of the cracks observed in the core samples extended only down to the level of the top transverse reinforcing bars.

In 1981, a study concerning factors affecting the durability of concrete bridge decks was completed by the California Department of Transportation (Poppe 1981). In this study, design, construction, and material parameters were investigated. Several bridges were constructed to determine the effect of each parameter on deck cracking. Individual parameters were varied between different bridges or between different placements on the same bridge. The cracking observed on these modified sections was then compared to the observed cracking on control decks or placements. Most of the experimental bridges were concrete box girders.

Many of the findings of this study are of interest. It was found that strong wind, high ambient temperature, and low humidity have a great effect on cracking. In fact, the effect of these unfavorable weather conditions was greater than any other construction factor studied. It was also noted that inadequate and poorly timed curing procedures increased cracking. Cracking was reduced but not eliminated by using thicker decks, membrane curing compounds when winds or low humidity occurred during concrete placement, and shrinkage compensating cement. Air entrainment, formwork construction, and reinforcing steel placement appeared to have no effect on cracking.

In 1985, the results of a study by North Carolina State University (NCSU) concerning transverse cracking in bridge decks was published (Cheng and Johnston 1985; Perfetti et al. 1985). The study consisted of two volumes. The first investigated the effects of construction and material parameters on transverse cracking. The second investigated the effects of structural parameters on cracking. A total of 72 steel and prestressed concrete girder bridges from the Piedmont area of North Carolina were evaluated. The majority of these bridges were constructed between 1976 and 1981. Of the bridges evaluated, 35 were composed of simple spans only, while 37 were composed of either continuous and simple spans or continuous spans only. Concrete strengths ranged from 3500 to 7500 psi (24 to 52 MPa). Field inspections were made of each bridge to determine the degree of deck deterioration. The extent of the transverse cracking observed was recorded in units of cracks per linear foot of bridge deck (CLF) which were calculated from the formula

$$CLF = (MACR + MICR/4)/LENGTH$$

where,

MACR = the number of major transverse cracks (those cracks which could be followed completely across the deck or which extended from one edge to the roadway centerline).

MICR = the number of minor transverse cracks (those relatively thin cracks which were usually not more than 5 feet long and occurred close to the edge of the deck at parapet joints or intersecting vertical drain pipes).

LENGTH = appropriate span or bridge length inspected.

These CLF values were compared to information obtained from the construction documents and weather bureau databases to identify possible correlations.

The field surveys showed that transverse cracks usually occur directly above or near top reinforcing bars, which is in agreement with the PCA study (1970). Surface crack widths typically measured 0.007 or 0.008 in. (0.18 or 0.20 mm). Measurements made after chiseling down 1/2 in. (12.7 mm) revealed widths on the order of 0.003 in. (0.08 mm). Cracking was more severe on continuous spans than on simple spans and on steel girder bridges than on prestressed concrete girder bridges. This also agrees with the findings of the PCA (1970). Average crack spacings by span/girder type combination were as follows:

continuous steel	10 ft (3.0 m)
continuous prestressed	14 ft (4.3 m)
simple steel	90 ft (27.4 m)
simple prestressed	424 ft (129.2 m)

The main focus of the first volume of the study was to determine the effect that various construction and material parameters had on the incidence of transverse cracking. Several possible contributing factors were considered. The variables, pour length, bridge age, contractor, number of continuous spans, sky cover, wind speed, precipitation, cement type, and coarse aggregate absorption, were found to have no significant effect on cracking. Two of these observations conflict with earlier studies: The PCA study (1970) stated that transverse cracking seemed to increase with increasing bridge age; and the California Department of Transportation study (Poppe 1981) concluded that adverse weather conditions during placement had a greater effect on cracking than any other variable. Variables showing an effect included form

type, pour sequence, air temperature, relative humidity, slump, air content, concrete strength, and yield strength of girder steel. There was a slight but consistent reduction in cracking when metal stay-in-place forms were used instead of removable forms. The decks were divided into placement order and moment region categories to investigate the effect of placing sequence. It was found that sections placed later in the sequence, for a given moment region, exhibited lower CLF values than sections placed earlier in symmetrical positions. Cracking was found to increase on continuous steel girder bridges with decreases in average air temperature and relative humidity on the day the deck is placed. Low slump and air content increased cracking for all bridge types. The California study (Poppe 1981) showed air content to have no effect on cracking. In the NCSU study, a slight tendency toward increased cracking was observed for decks with concrete strengths at the extremes of the strength range [3500-7500 psi (24-52 MPa)]. Also, the average CLF of bridge decks supported by A-588 steel girders was higher than that of decks supported by A-36 steel girders.

The intent of the second volume of the NCSU study was to relate the incidence of transverse cracking to the superstructure type, the deck casting sequence, and the vibration characteristics of the superstructure. This volume was divided into two parts, a vibration study similar to the one performed by the PCA (1970) and a superstructure analysis using a finite element approach. The vibration study, including the continuous units of 10 steel girder bridges, revealed no relationship between the incidence of transverse cracking and the calculated fundamental natural frequency of the bridge, matching the conclusions reached in the PCA study. The finite element analysis was undertaken to determine how stress histories influence transverse cracking. A finite element model was used to calculate, the stresses present in the deck during the concrete placing sequence, the final residual stresses in the deck after all placements have been completed, and the stresses resulting from the combination of all dead and live loads. No consistent relationship was found between the incidence of transverse cracking and the residual maximum dead load placement sequence stresses alone. However, a correlation was found for all bridges analyzed between high values of tensile stress due to dead plus live load and the incidence of cracking. Observable cracking appeared to increase in regions where stresses under dead plus live load exceeded 250 psi (1.7 MPa). In regard to these observations, it was also noted that the placement sequence methods developed by the Wisconsin Department of Transportation (WDOT) were useful in reducing residual dead load tensile stresses and may therefore help decrease cracking. For two of the bridges studied, a comparison was made, using finite element analysis, between residual stresses caused by the actual placing sequences employed at the time of construction and the placement sequences developed by WDOT. For the first bridge, the residual

dead load tensile stresses caused by the Wisconsin method of placement were significantly (about 70%) less than those caused by the actual placement sequence. For the second bridge, the Wisconsin method left most of the deck in residual compression rather than tension.

Based on the results of this study, procedures were recommended to alleviate transverse cracking in continuously supported bridge decks. The number of occasions when concrete is placed at temperatures less than 45 °F (7 °C) should be reduced. Tensile stresses in the deck concrete produced by dead load plus live load should not exceed 250 psi (1.7 MPa). And, alternate placing sequences, such as that proposed by WDOT, to reduce residual dead load tensile stresses should be considered.

In 1990, WDOT published the results of a study of premature cracking in concrete bridge decks (Kochanski et al. 1990). Several procedures were used to collect information, including a literature search and field inspections. Reference was made to an earlier study completed by the Wisconsin Bridge Office (Schuchardt 1982) in which six long-span steel bridges were investigated to determine the factors contributing to deck cracking. A correlation between static live-load deflection and the incidence of transverse cracking could not be identified. This supports the work of the PCA (1970) and NCSU (1985), since it implies that bridge flexibility has no effect on the formation of transverse cracks. However, it was stated in the WDOT report (Kochanski et al. 1990) that vibrations may cause the size of existing cracks to increase. Other references (Englot, year unknown; Kojima and Hawkins 1989) found in the WDOT literature search suggested that thicker bridge decks, particularly those greater than 9 or 10 in. (228 or 254 mm), exhibit less cracking than thinner decks, which agrees with the findings of the California study (Poppe 1981). The reason for this reduction in cracking is thought to be related to the top layer of transverse reinforcing bars. Top bars create stress risers in bridge decks and reduce the cross-sectional area of concrete available to carry tensile stresses. The magnitude of the stress rise and the reduction of cross-sectional area is greater for larger diameter bars than for smaller diameter bars. Therefore, the advantages of thicker decks is that they allow smaller diameter bars to be used and that they provide a greater cross-sectional area over which tensile stresses may be carried. The field inspections performed by WDOT revealed that transverse cracking was more severe on continuous steel girder bridges than on any other type of bridge, the same observation made by the PCA (1970) and NCSU (1985).

The WDOT study made several recommendations to help reduce or prevent premature cracking of bridge decks. The minimum slab thickness for decks supported by girders with effective spacings less than 7.5 ft (2.3 m) should be 8 in. (200 mm). For larger girder spacings, the slab thickness should be increased so that No. 4 or 5

(13 or 16 mm) bars could be used for the transverse reinforcing, since the use of larger diameter bars increases the potential for cracking, as explained above. The mix design for the deck concrete should be modified to reduce drying shrinkage by limiting the water/cement ratio to 0.40 and using larger than 3/4 in. (19 mm) maximum size coarse aggregate, as well as a coarse overall gradation. Larger aggregate reduces the amount of mix water required to obtain a desired slump and is more effective in restraining cement paste shrinkage than smaller aggregate. Deck placements should not be made when the theoretical rate of evaporation exceeds 0.25 lb/ft²/hr (1.22 kg/m²/hr). A placing sequence should be specified when concrete cannot be placed at a rate of 0.6 span lengths per hour [assuming a volume of 70 cubic yards (53.5 m³) of concrete per hour] to prevent cracking caused by disturbing the concrete after it has taken its initial set.

In 1993, a survey of state DOT's and other transportation agencies was completed by Wiss, Janney, Elstner Associates, Inc. (WJE) to determine what factors were perceived as being the causes of concrete bridge deck cracking at early ages. Fifty-two agencies representing over 225,000 bridges in the United States and Canada replied to the survey. The information contained in the survey reflects the experience and engineering judgment of those who responded. The comments received regarding the causes of cracking were grouped into categories of problems involving construction, materials, and design. The construction problem of improper curing was the most noted problem overall. Twenty agencies considered this to contribute to cracking; although, what was considered to be "improper curing" was not specifically stated. The least noted construction problem, noted by only two agencies, was unfavorable ambient conditions during concrete placement, contrasting with observations of the California study (Poppe 1981) that, of all factors, adverse weather had the greatest effect on cracking. In the materials category, seventeen agencies noted concrete shrinkage as a cause of cracking. Deflections were the most noted design problem. This is in conflict with the findings of the WDOT (1990), PCA (1970), and NCSU (1985) studies which concluded that bridge flexibility or deflection has no effect on the formation of cracks. Although, WDOT did state that the vibrations of particularly flexible bridges may cause the size of existing cracks to increase which would make them more readily observable. Placing sequence was the least noted design problem.

WJE also collected information from the responding agencies regarding the effect of various factors relating to bridge design and construction. Two-layer bridge decks (decks with bonded concrete overlays) were not typical, but many of the agencies that did use two-layer decks reported problems with cracking. Thirty-three percent of the responding agencies noted differences in the amount of deck cracking

present in bridges placed at various times of the day. Of this 33 percent, 60 percent agreed that decks placed in the evening or night exhibited the least amount of cracking. Eighty percent believed that the worst cracking occurred on decks placed in the afternoon. Curing techniques (materials, timing of application, and total length of curing) were found to vary significantly. All agencies used wet burlap or fabric. Roughly 50 percent of the agencies employed pigmented curing compounds, fogging, and plastic sheeting. The most noted time of application was "as soon as possible." Total curing times of 5 and 7 days were used by 24 and 53 percent of the agencies, respectively. No other length of curing was used by more than 4 percent.

The use of silica fume in bridge deck overlays is becoming increasingly popular due to its ability to significantly lower the chloride permeability of concrete. However, silica fume concrete displays certain characteristics that may adversely affect bridge deck cracking if not carefully considered. Ozyildirim (1991) presented the results of two projects involving silica fume overlays by the Virginia Department of Transportation. Two bridges, one constructed in 1987 and the other constructed in 1990, contained silica fume in the overlay concrete, added at rates of 7 and 10 percent by the mass of cement, respectively. The most significant finding of the study was that it is important to have good early curing. Silica fume concrete is very susceptible to plastic shrinkage cracking due to its slow rate or lack of bleeding. Immediate application of fog sprays or misting after concrete placement is needed to avoid the formation of plastic shrinkage cracks that will increase in size over time.

The studies summarized above agree on several points. First, all studies that considered the effect of structure type concluded that continuous steel girder bridges exhibit the highest levels of cracking. Second, no study was able to establish a relationship between crack formation and the flexibility or live-load deflection of the superstructure. The major factors generally considered by the studies to contribute to cracking are 1) restraint of concrete shrinkage, 2) improper curing techniques, and 3) dead load tensile stresses induced in the concrete by the placing sequence. A general consensus as to the effects of many other possible contributing factors, such as air content and weather conditions during placement, could not be reached.

1.4 Object and Scope

In this study, cracking patterns in existing bridge decks are documented. The effects of potential contributing factors to cracking are investigated, and efforts are made to identify which factors are most significant. These findings are used to determine and recommend procedures that will alleviate bridge deck cracking.

Forty continuous steel girder bridges in northeast Kansas (KDOT District I)

were selected for evaluation. Thirty-seven of these bridges are of composite design, while the remaining three are of noncomposite design. Bridges were selected to obtain a wide range of ages, traffic volumes, structure types, deck types, and degrees of deck deterioration so that the effect each of the variables under consideration could be evaluated.

Where available, the plans, specifications, and construction diaries were reviewed for each bridge. Information was extracted from these documents and used in the evaluation. Field surveys were performed for each bridge, and detailed sketches were made of the observed cracking patterns. A computer program was created and used to calculate crack densities based on the completed sketches. The information taken from the construction documents is compared to the crack data to identify the principal factors controlling bridge deck cracking.

CHAPTER 2

DATA COLLECTION

2.1 General

To determine the probable causes of cracking in the concrete bridge decks evaluated in this study, design and construction data was collected and compared to the cracking observed on each deck. Previous research (Cheng and Johnston 1985; PCA 1970; Kochanski et al. 1990; Poppe 1981; Perfetti et al. 1985; Wiss, Janney, Elstner Associates, Inc. 1993) has shown that a number of factors contribute to bridge deck cracking; therefore, many variables were considered in this study. Data on material properties, site conditions, construction techniques, and design specifications was collected from project files, field books, as-built plans, and weather data logs. Field surveys were conducted to determine the extent of cracking on each bridge deck.

Most of the data pertinent to this study was readily available; however, information was lacking on certain items that would have been of value. Limited documentation was found on concrete temperatures, placing sequences, and curing methods. Concrete temperatures during placement were occasionally noted in field books, but the amount of information was insufficient to provide a meaningful evaluation of the possible effects of concrete temperature on cracking.

Proposed placing sequences were always presented in the plans, but were seldom used by contractors. Design specifications typically allow contractors to use alternate placing sequences, if they are approved by the engineer. Information on the order and direction in which the sections were actually placed would have been useful, since previous studies (Cheng and Johnston 1985; Kochanski et al. 1990; Perfetti et al. 1985) have shown that the placing sequence has an effect on cracking.

The materials used for curing were usually noted in field books, but details such as the time of application and the date of termination were rarely included. Improper curing is thought to significantly contribute to cracking (PCA 1970; Kochanski et al. 1990; Poppe 1981).

2.2 Selection of Bridges

A total of 40 steel girder bridges in northeast Kansas were selected for evaluation from nine counties: 14 from Wyandotte; 11 from Shawnee; 5 from Osage;

2 each from Atchison, Johnson, Lyon, and Pottawatomie; and 1 each from Douglas and Wabaunsee. The scope of the study was limited to steel girder bridges, since it is generally acknowledged that this type of bridge exhibits the most severe cracking problems and because steel girder bridges account for a large percentage of all bridges built in the state of Kansas. Of the 40 bridges selected, 37 were of composite design. The remaining 3 were noncomposite.

Bridge selection had two objectives. The first was to obtain a sample set of bridges that included a wide range of ages, traffic loads, and degrees of deterioration. This was necessary to evaluate the effect of age and traffic on cracking, and to insure that a variation existed in the crack densities of the bridge decks selected for evaluation. Without this variation, correlations could not have been established between different levels of cracking and the variables under consideration. The final sample included bridges completed between 1966 and 1993. However, emphasis was placed on bridges completed in 1985 or later, since the field books for many of the projects completed prior to 1985 have been discarded. Traffic, expressed in terms of average annual daily traffic (AADT), ranged from a low of 520 to a high of 13,410. The second objective was to match the percentage of sample bridges of each structure type to the percentage of existing bridges throughout the state with the same structure type. From a list of structures provided by KDOT, it was determined that of all the composite steel girder bridges in the state of Kansas under the responsibility of KDOT, 39 percent are of structure type SMCC (steel beam, composite continuous), 31 percent are of structure type SWCC (steel welded plate girder, composite continuous), and 11 percent are of structure type SWCH (steel welded plate girder, composite continuous and haunched). Nine other structure types account for the remaining 19 percent; not one of these types individually makes up more than 4 percent of the total. The proportion of bridges of each of the three main structure types included in the final bridge sample is 40, 37.5, and 15 percent, respectively. Also, within each structure type category, the percentage of sample bridges of each deck type is roughly equal to the percentage of the deck types statewide. In the SMCC category, 44 percent of the sample bridges have monolithic decks and 56 percent have two-layer decks (decks with bonded concrete overlays). Statewide, 52 percent of all SMCC bridges have monolithic decks, and 48 percent have two-layer decks. For SWCC bridges, the sample contains 40 percent monolithic decks and 60 percent two-layer decks compared to 28 and 72 percent, for each deck type respectively, statewide. Similarly, 33 percent of the SWCH bridges in the sample have monolithic decks, and 67 percent have two-layer decks compared to 41 and 59 percent, respectively, statewide.

2.3 Data Sources

Information about each sample bridge was collected from a number of different sources. Most of the bridge data came from as-built plans, project files, and field books obtained from the KDOT District I office in Topeka. Information taken from the plans included deck thickness, top cover thickness, span lengths, and reinforcing bar spacings. The project files contained material test reports that provided information concerning the mix design, strength, air content, and slump of the concrete in the bridge deck. When available, the field books or construction diaries were reviewed. These documents provide information on daily high and low air temperatures, as well as any equipment, material, or weather problems that occurred during placement of the deck. Where field books were unavailable, weekly construction reports in the project files were used as a substitute. Additional weather information, such as average relative humidity and average wind speed, was obtained from publications of the National Environmental Satellite and Information Service and the Weather Data Library at Kansas State University.

2.4 On-Site Field Surveys

On-site field surveys were performed on each bridge in the sample. Traffic control was provided by KDOT maintenance crews during the survey operations. Traffic lanes were completely closed off, one or two lanes at a time, to allow the survey team to make a detailed inspection of the deck surface. The surveys were usually scheduled between 9:00 am and 3:00 pm to avoid rush hour traffic.

A complete field survey consisted of three main parts. First, the survey team, which was typically made up of two or three people, would observe the overall condition of the bridge. All types of deterioration other than cracking, such as scaling or spalling, were noted. Next, a detailed inspection of the surface of the deck was performed, and sketches were made of the observed cracking patterns. Each survey ended with an inspection of the underside of the bridge deck.

Deck inspections were performed and sketches were completed in the following manner. Prior to each field survey, an outline of the bridge deck was drawn on engineering paper at a scale of 1 in. = 10 ft to serve as a guide for sketching the observed cracks. Once at the bridge site, the survey team walked the length of the bridge, covering the closed lane(s), carefully inspecting the deck for cracks. Each visible crack was outlined on the deck with chalk. Spalls, regions of scaling, and small repair areas were noted, but were typically not included in the sketches. After the cracks were marked, they were sketched on the prepared scale drawings. A one hundred foot tape measure placed along the edge of the lane was used to locate the

position of each crack. Crack lengths were measured with a separate tape measure or approximated by comparison to nearby cracks of known length.

The underside of each deck was inspected for signs of cracking and to determine the end condition of the supporting girders. Cracks on the underside of most decks could be readily identified by the presence of white efflorescence along their edges. The number of visible cracks in each span was recorded. This observation could not be made on several spans that extended over rivers or heavily traveled highways. The end condition of the girders was noted as either pinned or fixed.

2.5 Calculation of Crack Densities

To identify the degree of correlation between cracking and the possible contributing factors under investigation, it was necessary to develop a means of numerically quantifying the levels of cracking observed in the field. Crack density in length per unit area [meters per square meter of bridge deck (m/m^2)] was selected as the unit of measure. Crack densities were calculated for entire bridge decks as well as for individual spans and placements. This allowed the effects of different variables to be evaluated. For example, variables which are constant at all points along a bridge deck, such as deck thickness, are compared with crack densities for entire bridge decks. Variables such as air temperature, that can vary from one placement to another, are plotted against crack densities of specific placements, rather than for entire bridge decks.

A Fortran program was written to automate the calculation of crack densities from the cracking pattern sketches made in the field. The program allowed measurements to be made much more rapidly and consistently than could be done by hand and generated crack densities for the entire bridge deck, individual spans, and individual placements. Also, densities could be calculated for cracks occurring at any specified angle, such as zero degrees (transverse cracks) or 90 degrees (longitudinal cracks).

Several steps were necessary to convert the hand-drawn field sketches into a format that could be used by the Fortran program. First, the completed sketches were photocopied onto white paper. The copies were then scanned, creating a digitized image (16-level grayscale) of the sketch using an HP Scanjet scanner and PhotoFinish software. Scanner resolution was set at 100 dots per inch. After the scanning was complete, three modifications to the digitized images were necessary: (1) A line of dark pixels was added from the top boundary of the image to a position on the image representing the upper left-hand corner of the bridge deck. The endpoint of this line,

i.e. the corner of the bridge deck, serves as a point of orientation for the computer program. All other positions required by the program, such as the beginning of each individual span, are located from this initial reference point. (2) All excess information appearing on the image (words, bridge deck outline, span centerline markings, etc.) was removed, leaving only those lines representing cracks. (3) Intersecting and curved cracks were separated into straight segments for proper operation of the computer program. The final step was to convert the digitized image from a graphical .tif file to an ascii file. A program written by John Gauch, Assistant Professor of Electrical Engineering and Computer Science at the University of Kansas, was used to make the conversion.

Qualitatively the Fortran program operates as follows: From the ascii file, the program selects all "dark" pixels and records their coordinates. Adjacent dark pixels are grouped together as cracks. The length of each crack is set equal to the distance between its endpoints. The crack orientation angle equals the angle between the horizontal and the line connecting the endpoints of the crack. Crack densities are calculated by adding the length of all cracks in a given region of bridge deck and dividing that value by the appropriate area. The full program listing is presented in Appendix B.

2.6 Databases

The information taken from the sources described above and the calculated crack densities for each bridge were compiled into three databases. The first database contained variables relative to entire bridge decks. These variables included structure type, deck type, number of spans, traffic volume, bridge length, age, deck thickness, top cover thickness, reinforcing bar size and spacing, and girder end condition. The second database contained variables relative to individual spans, including span length and span type (interior/exterior). The third database contained information relative to individual bridge deck placements. Entries in this database included weather conditions during concrete placement, mix design parameters, material test results, and concrete temperatures.

CHAPTER 3

EVALUATION AND RESULTS

3.1 General

Two methods were employed to evaluate the effect of each of the variables described in Chapter 2 on cracking. First, individual variables were analyzed by plotting the crack density of the appropriate section of bridge deck (entire deck, individual span, individual placement, or end section) versus the value of the variable. This technique allowed general trends to be identified; however, there was typically a large amount of scatter in the data, due to the combined effects of the many factors that contribute to bridge deck cracking, making it difficult to visualize. Further analysis was, therefore, conducted using bar charts, since they more clearly display trends in the data. Most of the bar charts presented in this report follow a standard format. Each bar or category on the chart represents a range of values of the variable under consideration and is identified by the midpoint of that range. The size of the range is equal to the difference between the midpoints of consecutive categories. Deviations from this format are noted in the text.

When generating the charts discussed above, each group of data was divided into smaller sub-groups to eliminate the effect of other design parameters. For example, data obtained from composite bridges was treated separately from that obtained from noncomposite bridges to eliminate the effects of differences in the degree of composite action. Similarly, a distinction was made between monolithic and two-layer bridge deck construction. Also, data for the two bridges in the study with silica fume concrete overlays was separated from the data collected for the other two-layer bridges. The use of silica fume in concrete is a relatively new practice in bridge deck construction, and the crack density of these two bridges was high.

The factors considered in this study were divided into four main categories for evaluation: material properties, site conditions, construction procedures, and design specifications. The effects of traffic volume and bridge age were also investigated. Material properties include admixtures, slump, percent volume of water and cement, water content, cement content, water/cement ratio, air content, and compressive strength. Site conditions include average air temperature, low air temperature, high air temperature, daily temperature range, relative humidity, wind velocity, and evaporation. Construction procedures include concrete placing sequence, length of placement, and curing. Design specifications include structure type, deck type, deck thickness, top cover, transverse reinforcing bar size, transverse reinforcing bar

spacing, girder end condition, span length, bridge length, span type, and bridge skew. Each factor was compared to the crack density of the particular section of bridge deck for which it was applicable. For instance, factors concerning material properties, site conditions, and construction procedures were compared to crack densities of individual placements, since the values of these factors can vary from one placement to another. Design specification factors, with the exception of span length, span type, and girder end condition, were compared to crack densities of entire bridge decks. Span length and span type were compared to crack densities of individual spans, and girder end condition was compared to the crack density of the end section of the bridge deck (see section 3.5.7).

The results of the evaluation of each of these factors, in regard to their effect(s) on bridge deck cracking, appear in the following sections.

3.2 Material Properties

3.2.1 Admixtures

Three admixtures, other than air entraining agent (AEA), were used in the bridge decks selected for evaluation. Set retarder was used in five monolithic bridge decks, and two bridge deck overlays contained silica fume and water reducer. The relationship between these admixture combinations and the mean crack density of individual bridge deck placements is shown in Figs. 3.1 and 3.2.

The mean crack density of monolithic bridge deck placements containing an AEA only is 0.29 m/m^2 (1.07 in./ft^2) versus 0.59 m/m^2 (2.16 in./ft^2) for those containing both an AEA and a set retarder (Fig 3.1). At first, this may seem to suggest that the addition of the retarding agent tends to increase cracking; however, this may not be the case. The crack density for the placements containing set retarder is an average of six values with a large amount of scatter. Two of the six placements come from a single bridge that has a crack density that is substantially higher than average. If these two placements are neglected, the mean crack density of the placements containing set retarder is reduced by 53 percent to 0.28 m/m^2 (1.03 in./ft^2), nearly identical to the 26 placements without a retarder. Since the effect of this one bridge is so large, it cannot be concluded, from this data, that retarding agents increase bridge deck cracking.

A significant increase in crack density can be seen in bridge deck overlays containing silica fume and water reducer, in addition to AEA, over those containing AEA only. The mean crack density of overlays containing only AEA is 0.33 m/m^2 (1.21 in./ft^2) compared to 0.87 m/m^2 (3.18 in./ft^2) for overlays containing AEA, silica fume, and water reducer (Fig. 3.2). In this case, the mean crack density is an average

of four placements, two overlays on each of two bridges. The scatter of these four values is low, and no value is less than 0.65 m/m^2 (2.38 in./ft^2). This, therefore, provides a strong indication that the addition of silica fume and water reducer to overlay concrete increases cracking. The increased cracking is most likely related to reduced bleeding caused by the addition of silica fume. Since silica fume concrete bleeds very slowly or not at all, plastic shrinkage cracks will occur if precautions are not taken to prevent rapid moisture loss from the surface. This is typically accomplished by using a fog spray following placement. No information was found concerning the curing procedures used on these two bridges. Previous research (Ozyildirim 1991) suggests that high quality silica fume overlays can be obtained if appropriate curing procedures are implemented in a timely fashion.

3.2.2 Slump

Concrete slump ranged from 38 mm (1.5 in.) to 76 mm (3.0 in.) for monolithic bridge decks and from 0 mm (0 in.) to 19 mm (0.75 in.) for overlays. The mean crack density of individual placements (all without silica fume) is shown as a function of concrete slump for monolithic decks and bridge deck overlays in Figs. 3.3 and 3.4, respectively.

For monolithic bridge decks (Fig. 3.3), cracking increases with increasing slump. This could be a result of the effect of increased slump on settlement cracking or the effects of a higher water and/or cement content corresponding to the increase in slump. The increase in cracking contradicts the findings of the NCSU study (Cheng and Johnston 1985), which states that cracking decreases slightly with increasing slump, possibly due to easier consolidation. However, virtually all of the slumps in the NCSU study were between 64 mm (2.5 in.) to 76 mm (3.0 in.), making it difficult to draw conclusions. The discrepancy between the two studies may also be attributed to differences in consolidation techniques. The concrete decks included in the NCSU study were consolidated with individual hand-held vibrators. The decks of most of the bridges included in the present study were consolidated using a gang of frame-mounted spud vibrators. Consolidation by this technique is more complete and uniform than can be achieved using a hand-held vibrator.

For bridge deck overlays [all cast with slumps of 19 mm (0.75 in.) or less], those placed at zero slump were found to exhibit consistently high levels of cracking, as shown in Fig 3.4. The average crack density of these overlays was 0.59 m/m^2 (2.15 in./ft^2), with none lower than 0.45 m/m^2 (1.63 in./ft^2), compared to average crack densities of 0.11 to 0.27 m/m^2 (0.40 to 0.99 in./ft^2) for higher slumps. The increased cracking for the zero slump concrete can most likely be attributed to difficulties in

consolidation. Since the crack densities of these overlays are significantly and consistently higher than those with non-zero slumps, they are treated separately in the following sections.

3.2.3 Percent Volume of Water and Cement

The percentage of the volume of fresh concrete occupied by water and cement was calculated for each bridge deck placement. As discussed in Chapter 1, this parameter should give an accurate indication of the effect of shrinkage on cracking, since most concrete shrinkage takes place in the cement paste. Figs. 3.5 and 3.6 show the mean crack density of individual placements as a function of the percent volume of water and cement.

For monolithic bridge decks (Fig 3.5), much higher levels of cracking are observed at water and cement volumes above 27.5 percent than below. The mean crack density of those above 27.5 percent is 0.77 m/m^2 (2.82 in./ft^2) compared to 0.18 m/m^2 (0.66 in./ft^2) for those below. This clear trend strongly suggests that specifying concrete mix designs with paste contents less than 27.5 percent will result in a lower incidence of cracking.

For bridge deck overlays, no clear trend is evident in Fig. 3.6. Considering all overlays, the highest levels of cracking are observed in the lowest category (24.75 to 25.25%) of the percent volume of water and cement. This high incidence of cracking is partially due to the number of overlays with zero slump in that category. When the zero slump overlays are removed from the comparison, there is some indication of slightly higher cracking in the extreme high and low categories of the percent volume of water and cement, although more data would be required to confirm this observation. Increased cracking at high and low paste contents could be caused by differential shrinkage between the overlay and the subdeck. If the total shrinkage or rate of shrinkage of the overlay is greater than that of the subdeck, tensile stresses will be induced in the overlay. However, if the total shrinkage or rate of shrinkage of the overlay is less than that of the subdeck, the portion of the overlay that is bonded to the subdeck will be compressed (shortened) causing tensile stresses to form near the surface of the overlay due to bending.

3.2.4 Water Content

Water content was also compared to crack densities as a means of indirectly evaluating the effect of concrete shrinkage on cracking. The mean crack density of individual placements is shown as a function of water content in Figs. 3.7 and 3.8 for

monolithic bridge decks and bridge decks overlays, respectively. Trends in the data for both monolithic bridge decks and bridge deck overlays are similar to those described for percent volume of water and cement. Cracking in monolithic bridge decks increases as the water content increases, and cracking in bridge deck overlays seems to increase slightly at high and low values of water content. For the monolithic decks, however, the percent volume of cement and water appears to be a stronger prediction of bridge deck cracking than water content alone.

3.2.5 Cement Content

Cement contents did not vary greatly for the bridges studied. The cement content for all but one overlay was 371 kg/m^3 (625 lb./cy), preventing the evaluation of the effect of cement content on cracking in bridge deck overlays.

Most monolithic bridge decks were placed at cement contents of 357, 359, or 379 kg/m^3 (602, 605, or 639 lb./cy). The relationship between mean crack density and cement content is shown in Fig. 3.9. The mean crack density of placements with cement contents of 357 and 359 kg/m^3 (602 and 605 lb./cy) is 0.19 m/m^2 (0.68 in./ft²). This is significantly lower than the mean crack density of the placements with cement contents of 379 kg/m^3 (639 lb./cy), which is 0.77 m/m^2 (2.81 in./ft²). One other monolithic deck was placed with a cement content of 390 kg/m^3 (658 lb./cy); its crack density was 0.75 m/m^2 (2.75 in./ft²). From this information, it appears that cracking increases with increases in cement content. Again, since the majority of concrete shrinkage takes place in the cement paste, increasing this portion of the concrete mix, by adding either water or cement, will most likely result in increased cracking.

3.2.6 Water/Cement Ratio

The mean crack density of individual placements is shown as a function of water/cement ratio in Figs. 3.10 and 3.11. The water/cement ratio for most monolithic bridge decks was either 0.42 or 0.44. As shown in Fig. 3.10, the mean crack density of placements with water/cement ratios of 0.44 is slightly higher than those with water/cement ratios of 0.42. This suggests that cracking increases with an increasing water/cement ratio, but it is difficult to draw a conclusion for such a small range. For the bridge deck overlays (Fig. 3.11), trends in the data for water/cement ratio are similar to those observed for water content and percent volume of water and cement, i.e. cracking appears to increase slightly at high and low values.

3.2.7 Air Content

Figs. 3.12 and 3.13 show the mean crack densities of the individual placements as a function of concrete air content for monolithic bridge decks and bridge deck overlays, respectively. The ranges in air contents for the three categories in Fig. 3.12 are 4.50 to 5.24%, 5.25 to 5.99%, and 6.00 to 6.75%, while the ranges in Fig. 3.13 are 4.00 to 4.74%, 4.75 to 5.49%, and 5.50 to 6.25%. All of the bridges studied were constructed under the current KDOT (1990) specification that requires the air content of bridge deck concrete to be $6.0\% \pm 2\%$. For monolithic decks, air contents ranged from 4.5 to 6.5%, with only 17% of the placements containing greater than 6.0% air. As shown in Fig. 3.12, cracking in monolithic decks tends to decrease as air content increases, with a significant decrease for concretes with air contents equal to or greater than 6.0%. The mean crack density of the placements with air contents less than 6.0% is 0.51 m/m^2 (1.87 in./ft^2) compared to 0.18 m/m^2 (0.66 in./ft^2) for those with air contents of 6.0% or greater. This is in agreement with the findings of the NCSU study (Cheng and Johnston 1985), which included air contents between 4.0 and 7.5%. The study performed by Poppe (1981) showed air content to have a neutral effect. For bridge deck overlays (Fig. 3.13), air content appears to have no effect on cracking.

3.2.8 Compressive Strength

The mean crack density of individual placements is presented as a function of concrete compressive strength in Figs. 3.14 and 3.15. For monolithic bridge decks (Fig. 3.14), cracking tends to increase with increasing compressive strength. This relationship may reflect the increase in cracking associated with increases in cement content discussed in section 3.2.5. A separate comparison of cement content and compressive strength reveals a positive correlation; i.e. compressive strength increases as cement content increases. One placement not included in Fig. 3.14 had a compressive strength of 51 MPa (7400 psi) and a crack density of 1.48 m/m^2 (5.43 in./ft^2).

For bridge deck overlays (Fig. 3.15), the relationship between cracking and compressive strength is unclear. If zero slump overlays are neglected, cracking appears to decrease slightly with increasing compressive strength. However, it is difficult to draw conclusions since the majority of the data covers only a small range of compressive strengths.

3.3 Site Conditions

3.3.1 Average Air Temperature

The mean crack density of individual placements is shown as a function of average daily temperature for the date of concrete placement in Figs. 3.16 and 3.17 for monolithic bridge decks and bridge deck overlays, respectively. The NCSU study (Cheng and Johnston 1985) found that, for continuous steel girder bridges, cracking tends to increase with decreasing average temperatures, especially below 45 °F (7 °C). However, the present study revealed no trend between cracking and average temperature for monolithic bridge decks. For the sample bridges, concrete placed during cold weather was usually protected using insulating blankets and/or heated enclosures. For bridge deck overlays (Fig. 3.17), cracking was found to increase with increasing average temperatures, perhaps reflecting the effect of higher temperature on the rate of evaporation and a resulting increased tendency for plastic shrinkage cracking.

3.3.2 Low Air Temperature

The mean crack density of individual placements is shown as a function of minimum daily air temperature in Figs. 3.18 and 3.19 for monolithic bridge decks and bridge deck overlays, respectively. No clear trend can be identified for either monolithic bridge decks or bridge deck overlays.

3.3.3 High Air Temperature

The mean crack density of individual placements is shown as a function of maximum daily air temperature in Figs. 3.20 and 3.21 for monolithic bridge decks and bridge deck overlays, respectively. For monolithic bridge decks, cracking increases significantly as the maximum daily air temperature increases, ranging from 0.20 m/m² (0.73 in./ft²) at 5 °C (41 °F) to 0.58 m/m² (2.12 in./ft²) at 35 °C (95 °F). Cracking in bridge deck overlays appears to follow a similar, but less pronounced, trend.

3.3.4 Daily Temperature Range

The daily air temperature range was calculated by subtracting the minimum air temperature from the maximum air temperature for the date a placement was cast. The relationship between this variable and the mean crack density of individual

placements is presented in Figs. 3.22 and 3.23 for monolithic bridge decks and bridge deck overlays, respectively.

The figures show that cracking tends to increase with increases in daily temperature range for both monolithic bridge decks and bridge deck overlays, increasing from 0.19 m/m^2 (0.69 in./ft^2) to 0.48 m/m^2 (1.76 in./ft^2) for monolithic decks and from 0.31 m/m^2 (1.13 in./ft^2) to 0.49 m/m^2 (1.79 in./ft^2) for deck overlays as the temperature range increases from 4 to $20 \text{ }^\circ\text{C}$ (7 to $35 \text{ }^\circ\text{F}$). The increase in cracking may be caused by thermal expansion of the elements that support the newly placed concrete. The decks of most of the bridges included in this study were placed in the early morning hours and were completed by approximately midday. The supporting girders, and subdeck when considering overlays, are the coolest, and therefore shortest, in the morning hours and expand throughout the day as the ambient temperature increases. If the change in temperature is large, the expansion or elongation of the supporting elements can induce tensile stresses in the young concrete causing small cracks to form. It may be worthy to note that 33% of the agencies responding to the survey conducted by Wiss, Janney, Elstner Associates, Inc. (1993) observed a difference in cracking between morning and evening placements. Of these agencies, 60% noted less cracking on bridge decks placed in the evening, when temperatures were falling.

3.3.5 Relative Humidity

Figs. 3.24 and 3.25 present mean crack density as a function of the average daily relative humidity on the day of casting for monolithic bridge decks and bridge deck overlays, respectively. No relationship can be identified between cracking and relative humidity for either monolithic bridge decks or overlays. This observation fails to support the findings of the NCSU study (Cheng and Johnston 1985), which states that cracking tends to increase at low values of relative humidity. Low relative humidity is generally thought to contribute to bridge deck cracking by increasing the rate at which surface moisture evaporates from fresh concrete. The lack of correlation between relative humidity and cracking in the present study may indicate that the bridge deck concrete of the sample bridges was properly protected from the conditions of the surrounding environment. If curing is begun immediately following finishing, fresh concrete will not be affected by low relative humidity. However, care must be taken not to apply curing compounds before bleeding has ceased, since early application may trap bleed water near the surface, resulting in a decreased resistance to scaling.

3.3.6 Average Wind Velocity

Figs. 3.26 and 3.27 present mean crack density as a function of average wind speed on the day of casting, for monolithic bridge decks and bridge deck overlays, respectively. High winds, like low humidity, are thought to contribute to bridge deck cracking by increasing the rate of evaporation. No relationship between cracking and average wind speed can be identified for monolithic bridge decks. This is in agreement with the findings of the NCSU study (Cheng and Johnston 1985). For bridge deck overlays, cracking appears to decrease with increases in wind speed. Such a relationship is obviously contrary to the expected result, and can most likely be attributed to chance.

3.3.7 Evaporation

The rate of evaporation during bridge deck placements was estimated using Fig. 3.28 (Lerch 1957) and information collected from construction diaries and weather data logs. However, due to a lack of information concerning concrete temperatures during placing, the amount of data collected was insufficient to provide a meaningful evaluation of the effect of evaporation rate on cracking. The study by NCSU (Cheng and Johnston 1985), which suffered from a similar lack of information, found no clear relationship between evaporation and cracking. The fact that no evaluation of evaporation rate was possible in the present study and that no direct link between evaporation and cracking was identified by NCSU does not mean that ambient conditions can be overlooked when scheduling bridge deck placements. Care must still be taken to protect fresh concrete from adverse weather conditions such as high air temperatures, high winds, and low relative humidity.

3.4 Construction Procedures

3.4.1 Placing Sequence

Overall, there was not enough information available to make a meaningful evaluation of the effect of placing sequence on bridge deck cracking. The placing sequences provided in the plans and specifications were seldom used by the contractor, and information concerning the actual placing sequences used were typically unavailable. The study by NCSU (Cheng and Johnston 1985) found that, for sections of the bridge deck that are symmetrically opposite each other, the section that is placed earlier will generally exhibit a higher incidence of cracking.

3.4.2 Length of Placement

Mean crack density is shown as a function of placement length in Figs. 3.29 and 3.30 for monolithic bridge decks and bridge deck overlays, respectively. There is no apparent trend in the data for monolithic bridge decks. For bridge deck overlays, however, cracking clearly increases with an increase in placement length, ranging from 0.09 m/m^2 (0.33 in./ft^2) for average placement lengths of 40 m (131 ft) to 0.50 m/m^2 (1.83 in./ft^2) for average placement lengths of 100 m (328 ft). Overlays placed in shorter segments might exhibit less cracking, since the construction joints between segments act to reduce the magnitude of the tensile stresses caused by restraint of concrete shrinkage. Also, since overlays are thin and contain much less water than concrete used for monolithic decks or subdecks, plastic shrinkage cracking can occur if curing is delayed due to excessive placement lengths.

3.4.3 Curing

An evaluation of the effect of curing procedures was difficult due to the number of different types of materials and combinations of materials used and the fact that details of the curing procedures, such as timing and method of application, were not always included in the construction diaries or project files. Polyethylene, wet burlap, curing compounds, and insulating blankets were used either alone or in various combinations to cure the deck concrete of the bridges studied. From the limited amount of information collected, no relationship could be established between cracking and the type of curing material(s) employed.

3.5 Design Specifications

3.5.1 Structure Type

Four different structure types were investigated in this study, including steel beam, composite continuous (SMCC); steel welded plate girder, composite continuous (SWCC); steel welded plate girder, composite continuous and haunched (SWCH); and noncomposite (NC). Differences in cracking between the four structure types are shown in Fig. 3.31 without distinction of deck type and in Fig. 3.32 with the results presented separately based on deck type. From this information it appears that structure type has little or no effect on cracking.

3.5.2 Deck Type

Fig. 3.33 allows a comparison in mean crack density between monolithic and two-layer decks. All of the two-layer bridges included in this study had a 57 mm (2.25 in.) overlay bonded to a subdeck with a 19 mm (0.75 in.) cover over the top transverse reinforcing bars. The mean crack densities of the two deck types are virtually identical, with the crack density of the two-layer bridges [0.34 m/m^2 (1.24 in./ft²)] slightly higher than that of the monolithic bridges [0.32 m/m^2 (1.17 in./ft²)].

3.5.3 Deck Thickness

Deck thicknesses for the bridges included in this study, range from 180 mm (7.0 in.) to 280 mm (11.0 in.). Since the majority of the sample decks are 215 mm (8.5 in.) thick, the effect of variations in deck thickness could not be evaluated. Poppe (1981) found that cracking tends to decrease with increases in deck thickness. Other studies (Englot, year unknown; Kojima and Hawkins 1989) noted in the literature search of the WDOT study (Kochanski et al. 1990) suggest that bridge decks with thicknesses greater than 9 or 10 in. (230 or 255 mm) exhibit less cracking than thinner decks.

3.5.4 Top Cover

Fig. 3.34 presents mean crack density as a function of top cover for monolithic bridge decks. Since all two-layer decks had a cover of 76 mm (3.0 in.), no evaluation of the effect of cover was possible for those decks.

Monolithic bridge decks with a top cover thickness of 64 mm (2.5 in.) exhibit less cracking [0.25 m/m^2 (0.91 in./ft²)], on average, than decks with a top cover of 51 mm (2.0 in.) [0.87 m/m^2 (3.18 in./ft²)] or decks with a top cover of 76 mm (3.0 in.) [0.36 m/m^2 (1.32 in./ft²)]. Increased cover reduces the possibility of settlement cracking, but it also moves the longitudinal or shrinkage steel farther from the surface, which lessens its ability to control cracking. The transverse or primary steel was placed above the longitudinal steel in all of the bridges included in this study. Research by Poppe (1981) showed that placing longitudinal steel above the transverse steel reduces cracking slightly. These observations, however, are not meant to advocate the use of 64 mm (2.5 in.) cover over 76 mm (3.0 in.) cover.

3.5.5 Transverse Reinforcing Bar Size

Transverse reinforcing bars act as tensile stress raisers in the top portion of bridge decks and effectively reduce the cross-sectional area of the concrete. Fig. 3.35 shows the variation of mean crack density with transverse bar size for composite bridges, and Fig. 3.36 shows the variation of mean crack density with transverse bar size for monolithic and two-layer bridges separately. The mean crack density, considering both deck types, of bridges using No. 6 (19 mm) transverse bars [0.65 m/m^2 (2.38 in./ft^2)] is significantly higher than the mean crack density of those using either No. 5 (16 mm) bars or a combination of No. 4 and No. 5 (13 and 16 mm) bars [0.24 m/m^2 (0.88 in./ft^2)]. This suggests that cracking increases with increasing bar size; although, one bridge using No. 4 (13 mm) transverse bars had a crack density of 0.76 m/m^2 (2.78 in./ft^2). Dividing the comparison by deck type (Fig. 3.36) reveals that only one of the bridges using No. 6 (19 mm) bars is a monolithic bridge. Even though the crack density of this bridge is high, 0.87 m/m^2 (3.18 in./ft^2), it is difficult to conclude, from this data, that cracking in monolithic bridges increases with increasing transverse bar size. However, the data does tend to suggest that cracking in two-layer bridges increases as transverse bar size is increased. The mean crack density of two-layer bridges using No. 6 (19 mm) bars is 0.60 m/m^2 (2.19 in./ft^2) compared to 0.23 m/m^2 (0.84 in./ft^2) and 0.26 m/m^2 (0.95 in./ft^2) for those using No. 5 (16 mm) bars and those using a combination of No. 4 and No. 5 (13 and 16 mm) bars, respectively. The increased mean crack density of bridges using No. 6 (19 mm) bars tends to support the Wisconsin (Kochanski et al. 1990) study which found that transverse cracking increases with increases in transverse reinforcing bar size. Also, Dakhil et al. (1975) found that increases in bar size increases settlement cracking (Fig. 1.1).

3.5.6 Transverse Reinforcing Bar Spacing

Fig. 3.37 presents mean crack density versus spacing of top transverse reinforcing bars for two-layer bridges. Due to a lack of variation in spacings, the effect of transverse reinforcing bar spacing on cracking could not be evaluated for monolithic bridge decks [transverse bars were spaced at 150 mm (6.0 in.) for all monolithic bridge decks, except one in which transverse bars were spaced at 180 mm (7.0 in.)].

For the two-layer decks, there appears to be a clear distinction between bridges with transverse reinforcing bar spacings of less than or equal to 150 mm (6.0 in.) and those with spacings greater than 150 mm (6.0 in.). The mean crack density for spacings less than or equal to 150 mm (6.0 in.) is 0.18 m/m^2 (0.65 in./ft^2), and no

bridge in this category has a crack density greater than 0.36 m/m^2 (1.32 in./ft^2). The mean crack density for spacings greater than 150 mm (6.0 in.) is 0.61 m/m^2 (2.21 in./ft^2), and no bridge in this category has a crack density less than 0.52 m/m^2 (1.88 in./ft^2). Increased cracking at larger spacings might partially reflect the increase in cracking associated with increases in bar size, since spacing typically increases with bar size.

3.5.7 Girder End Condition

During the field surveys, a large number of cracks were noted at the ends of several bridges. These cracks were typically perpendicular to the skew of the bridge and were confined to approximately the first 3 m (10 ft) of the deck. Further inspection revealed that the girders of the bridges exhibiting this type of cracking were cast directly into the abutment rather than resting on rockers. Crack densities were calculated for the end sections, within the first 3 m (10 ft) of the abutment center line, to evaluate the effect of girder end condition on cracking. The results are presented in Figs. 3.38 - 3.41. The two bridges with silica fume overlays and the three noncomposite bridges are excluded in Figs. 3.38 and 3.39. As shown in Fig. 3.38, the mean crack density of the end sections of composite bridges with pinned girders, 0.26 m/m^2 (0.95 in./ft^2), is substantially (57%) lower than the mean crack density of composite bridges with fixed girders, 0.61 m/m^2 (2.23 in./ft^2). For monolithic and two-layer bridges, the mean crack density of bridges with pin-ended girders is 53 and 64% lower than that for bridges with fixed-ended girders, respectively (Fig. 3.39). While these observations are useful, they are biased to some extent in that the crack density of the end section of a bridge is affected, not only by the girder end condition, but by factors that control the crack density of the entire bridge deck as well. The effect that girder end condition has on cracking near the ends of bridges can be more clearly evaluated by comparing the end conditions (pinned and fixed) to the ratio of the crack density in the end section to that of the entire bridge deck. Using this format, bridges with increased cracking in the end sections, presumably due to fixed-ended girders, will have crack density ratios greater than 1.0.

Figs. 3.40 and 3.41 show the relationship between crack density ratio and girder end condition. Silica fume and noncomposite bridges are included in these figures. The mean crack density ratio for fixed-ended girders is substantially higher than that for pin-ended girders for all bridge types combined (Fig. 3.40) and for each bridge type individually (Fig. 3.41). The mean crack density ratio for monolithic, two-layer, and noncomposite bridges with pin-ended girders is 0.20, 0.69, and 0.18

respectively. For monolithic and two-layer bridges with fixed-ended girders, the mean crack density ratio is 1.33 and 3.12 respectively. None of the noncomposite bridges studied had fixed-ended girders. The reason for this is, most likely, the increased restraint of concrete shrinkage provided by the fixed girder design versus a pinned design. When girders are cast into an abutment, the concrete surrounding the ends of the girders is often placed at the same time as the deck concrete. As the concrete cures, the thicker section of concrete at the abutment loses moisture less quickly and restrains the shrinkage of the thinner bridge deck. This causes tensile stresses to develop parallel to the end of the bridge near the abutment. Additional stresses can develop in a similar fashion due to thermal shrinkage and live loads. The combination of these stresses cause cracks to form.

Fig. 3.42 shows the mean crack density ratio for bridges with fixed-ended girders as a function of the length of the bridge deck along the abutment. There appears to be a tendency for the crack density ratio to increase as the length of the bridge deck along the abutment increases, especially at lengths greater than 14 m (45 ft).

3.5.8 Span Length

Fig. 3.43 presents mean crack density as a function of span length for all sample bridges collectively (except those with overlays containing silica fume). The relationship between cracking and span length for each individual bridge type (monolithic, two-layer, and noncomposite) is presented in Fig. 3.44. Mean crack density is nearly constant over the entire range of span lengths for all three bridge types, considering them both individually and collectively. This lack of correlation between span length and cracking is contrary to the results of the study performed by the PCA (1970) that suggested that cracking increases with span length.

3.5.9 Bridge Length

Figs. 3.45 and 3.46 present mean crack density as a function of bridge length for monolithic and two-layer bridges, respectively. For monolithic bridges, cracking appears to increase as bridge length increases; however, this observation may be affected by low amounts of data at high and low values of bridge length. For two-layer bridges, cracking also appears to increase with bridge length. This relationship may reflect the increased cracking associated with increased placement length, as discussed in section 3.4.2., since the overlays on most of the two-layer bridges studied were placed in sections that extended the full length of the bridge.

3.5.10 Span Type

Fig. 3.47 presents mean crack density versus span type (interior or end span) for all sample bridges collectively (except those with overlays containing silica fume). The relationship between cracking and span type for each individual bridge type is presented in Fig. 3.48. For all sample bridges, the mean crack density is 0.31 m/m^2 (1.13 in./ft^2) for both interior spans and end spans. Even when considering monolithic, two-layer, and noncomposite bridges separately, differences in mean crack density between interior and end spans are small. The mean crack density of end spans is 0.20 , 0.39 , and 0.22 m/m^2 (0.73 , 1.43 , and 0.80 in./ft^2) for monolithic, two-layer, and noncomposite bridges, respectively. The mean crack density of interior spans is 0.27 , 0.36 , and 0.29 m/m^2 (0.99 , 1.32 , and 1.06 in./ft^2), respectively.

3.5.11 Skew

Figs. 3.49 and 3.50 present mean crack density as a function of bridge skew for monolithic and two-layer bridges, respectively. Skew is defined as the acute angle between the centerline of the abutment and a line normal to the centerline of the roadway. For monolithic bridges, no relationship between cracking and skew can be identified. For two-layer bridges, some tendency for cracking to increase with increases in skew is possibly discernible. The mean crack density of bridges with skews from 0 to 29 degrees is 0.24 m/m^2 (0.89 in./ft^2) compared to 0.53 m/m^2 (1.93 in./ft^2) for bridges with skews from 30 to 59 degrees.

3.6 Traffic and Age

3.6.1 Traffic

The results of two separate comparisons between traffic and cracking are presented in Figs. 3.51 - 3.54. Figs. 3.51 and 3.52 show the relationship between traffic volume, in terms of the average annual daily traffic (AADT), and mean crack density for monolithic and two-layer bridges, respectively. The comparison indicates some tendency for increased cracking with increases in AADT. Larger average amounts of traffic imposed on a bridge early in its life may increase cracking, since at this stage creep has not yet reduced the magnitude of the residual tensile stresses present in the deck caused by the restraint of concrete shrinkage and the effects of the placing sequence. Figs. 3.53 and 3.54 present crack density as a function of the total number of load cycles that each bridge has been subjected to over its lifetime for monolithic and two-layer bridges, respectively. The data in these figures are divided

by age, since the time of construction appears to have a significant effect on cracking, as discussed in the following section. For monolithic bridges (Fig. 3.53), cracking in the structures built prior to 1988 appears to increase as the number of load cycles increases. Over the total life of a bridge, after the residual tensile stresses have been reduced, additional load cycles may cause the cracks that formed early in the life of the bridge to propagate, thereby increasing the crack density of the bridge deck. The data collected for monolithic bridges built since 1988 cover too small a range to identify a trend. For two-layer bridges (Fig. 3.54), cracking in the bridges built after 1988 appears to increase as the number of load cycles increases. However, cracking in the bridges built prior to 1988 appears to decrease with increasing load cycles, which is contrary to the expected result. In light of this, it should be noted that the two pre-1988 bridges in Fig. 3.54 with unusually high crack densities were built as part of the same project, and the overlay on one of these [the bridge with a crack density of 0.45 m/m^2 (1.64 in./ft^2)] was placed with zero slump concrete.

3.6.2 Age

Figs. 3.55 and 3.56 present mean crack density as a function of bridge age for monolithic and two-layer bridges, respectively. On average, bridges built before 1988 exhibit less cracking than newer bridges for both bridge types. For monolithic bridges, the mean crack density is 0.26 m/m^2 (0.95 in./ft^2) for bridges completed prior to 1988 compared to 0.44 m/m^2 (1.61 in./ft^2) for those completed since that time. Similarly, for two-layer bridges, the mean crack density of those completed prior to 1988 is 0.20 m/m^2 (0.73 in./ft^2) versus 0.48 m/m^2 (1.76 in./ft^2) for newer bridges. The increased cracking of newer bridges most likely reflects changes that have occurred over the years in construction procedures, material properties, and design specifications. For example, in this study, cracking in monolithic bridges was found to increase with increases in concrete slump, compressive strength, and the percent volume of water and cement, as well as decreases in air content. A comparison between the average values of each of these factors for monolithic bridges built before and after 1988 reveals that the newer bridges have higher average values of slump [61 vs. 51 mm (2.4 vs. 2.0 in.)], compressive strength [44 vs. 36 MPa (6300 vs. 5200 psi)], and percent volume of water and cement (28.2 vs. 26.6%) and a lower average value of air content (5.5 vs. 5.7%). This explains why the newer bridges, that should exhibit less cracking, actually have a higher mean crack density than the older bridges. It should also be noted that the average values of AADT for the bridges built before and after 1988 were approximately equal, 2100 for the newer bridges compared to 2000 for the older bridges. This suggests that the difference in mean

crack density between the two groups of bridges cannot be attributed to the effects of traffic volume, since both groups are exposed to a similar amount of traffic annually. However, a further comparison should also be made considering the effects of traffic and age combined. This can be accomplished by multiplying the average age of each group of bridges (in days) by the average value of AADT to obtain a rough estimate of the average number of loadings or load cycles that each bridge has undergone since completion. The resulting value for monolithic bridges built before 1988 is 7.0 million cycles compared to 2.1 million cycles for the newer bridges. From this information, one would reasonably expect cracking to be worse on the older bridges; however, the opposite is true, which gives some indication of the magnitude of the effects of the variables discussed above.

A comparison made between two-layer bridges built before and after 1988 leads to similar results. Cracking in two-layer bridges was found to be adversely affected by increasing placement lengths, zero slump overlay concrete, No. 6 (19 mm) top transverse reinforcing bars, and top transverse reinforcing bar spacings greater than 150 mm (6.0 in.). The average value of each of these variables is worse, in regard to cracking, for the two-layer bridges built since 1988 than for those built prior to that time. The average placement length is greater for the newer bridges than for the older ones, 85 m (280 ft) compared to 64 m (210 ft). Five of the bridges built since 1988 had overlays placed with zero slump concrete compared to only one for those built prior to 1988. All of the two-layer bridges included in the study that used No. 6 (19 mm) transverse bars were built since 1988. And, the average transverse bar spacing of the newer bridges is greater than 150 mm (6.0 in.), averaging 170 mm (6.75 in.) for the newer bridges compared to 140 mm (5.63 in.) for the older bridges. In fact, none of the older bridges have transverse bar spacings greater than 150 mm (6.0 in.). Considering traffic, the average value of AADT is greater for the newer bridges than for the older bridges, 10,100 compared to 4700. The greater traffic volume may account for some of the increase in cracking of the newer bridges along with the effects of the construction, material, and design variables described above; however the combined effect of traffic and age must again be considered. The average number of load cycles for each of the newer bridges is 9.9 million cycles compared to 13.7 million cycles for each of the older bridges.

3.7 Summary

Evaluation of material properties for monolithic bridge decks revealed correlations between cracking and several of the factors under consideration. Cracking was found to increase with increasing values of slump, percent volume of

water and cement, water content, cement content, and compressive strength. Cracking also seemed to increase with increasing values of water/cement ratio; however, it was difficult to draw conclusions, since all but one of the bridges had water/cement ratios of 0.42 or 0.44. These trends indicate that concrete shrinkage, or more precisely restraint of concrete shrinkage, is a major contributor to bridge deck cracking. Decreases in cracking were noted with increases in air content. It was further noted that only 17% of the monolithic bridge deck placements evaluated had air contents greater than the central value of the specified range of $6.0\% \pm 2\%$.

For bridge deck overlays, material properties were found to have the following effects on cracking. Overlays placed with zero slump were found to exhibit consistently high levels of cracking. The crack density of overlays containing silica fume and water reducer, in addition to an air entraining agent (AEA), was significantly higher than that of overlays containing an AEA only. There was some indication of slightly increased cracking for overlays at high and low values of water content, percent volume of water and cement, and water/cement ratio. Air content was found to have no effect on cracking. A clear relationship between cracking and compressive strength could not be identified, because the majority of the data covered only a small range. And finally, no evaluation was made of the effect of cement content on cracking, since all but one of the overlays had cement contents of 371 kg/m^3 (625 lb/cy).

Two site conditions were found to have a significant effect on cracking for monolithic bridge decks. Cracking increased with increases in the maximum daily air temperature and the daily temperature range. No relationship was found between cracking and average air temperature, low air temperature, relative humidity, or average wind speed. Due to an insufficient amount of information, no evaluation was made of the effect of evaporation rate on cracking.

For bridge deck overlays, cracking was found to increase with increases in average air temperature and daily temperature range. Cracking also appeared to increase with increases in maximum daily air temperature, but the trend was not as clear. No relationship was identified between cracking and minimum daily air temperature, or relative humidity. There appeared to be a tendency for cracking to decrease with increased wind speed; however, it is extremely doubtful that such a relationship actually exists. An evaluation of the effect of evaporation rate on cracking was not made due to a lack of information.

Three factors related to construction were considered; placing sequence, length of placement, and curing. Cracking was found to clearly increase as placement length increases for bridge deck overlays; however, no relationship could be identified between placement length and cracking for monolithic bridge decks. Based on the

limited amount of information, no relationship was found between cracking and the type of curing material(s) used for either monolithic bridge deck placements or overlays. The effect of placing sequence on cracking was not evaluated, since the required information was unavailable.

Design specifications were found to have the following effects on bridge deck cracking. For both monolithic and two-layer bridges, fixed-ended girders were found to cause increased cracking in the deck near the abutments. For the bridges with fixed-ended girders, the magnitude of the increase in cracking was found to increase as the length of bridge deck along the abutment increased, especially above 14 m (45 ft). For two-layer bridges, mean crack densities were found to be higher for those containing No. 6 (19 mm) transverse reinforcing bars compared to those containing either No. 5 (16 mm) bars or a combination of No. 4 and No. 5 (13 and 16 mm) bars. Also, two-layer bridges with transverse reinforcing bar spacings of less than 150 mm (6.0 in.) were found to exhibit less cracking than those with bar spacings greater than 150 mm (6.0 in.). Increases in cracking were noted with increases in bridge length for two-layer bridges and possibly for monolithic bridges; there was a low amount of data at high and low values of bridge length for the monolithic bridges. For bridge skew, some tendency for cracking to increase with increased skew was possibly discernible for two-layer bridges, but for monolithic bridges, skew appeared to have no effect on cracking. No significant relationship was found between cracking and structure type, deck type, span type or span length. No evaluation was made of the effect of deck thickness on cracking, since most of the bridge decks were of the same thickness.

Traffic volume and bridge age were found to have an effect on cracking for both monolithic and two-layer bridges, although the effect of age is not what would be expected. The comparison between cracking and AADT indicated some tendency for increased cracking with increases in AADT. Cracking appeared to increase with increases in total load cycles for monolithic bridges built before 1988 and for two-layer bridges built after 1988. Cracking in two-layer bridges built before 1988 appeared to decrease as the number of total load cycles increased; however, this relationship was strongly influenced by two bridges with unusually high crack densities. The range of load cycles covered by monolithic bridges built after 1988 was too small to identify a trend. For bridge age, bridges built since 1988 were found to have higher crack densities, on average, than those built prior to 1988, largely because of differences in the construction, material, and design variables that were found to effect cracking. For monolithic bridges, those built since 1988 had higher average values of concrete slump, percent volume of water and cement, and compressive strength as well as a lower average value of air content than those built prior to 1988. Similarly, for two-layer bridges, the average placement length of those

built since 1988 was greater than the average placement length of older bridges. Five of the bridges built since 1988 had overlays placed with zero slump concrete compared to only one for those built prior to 1988. All of the two-layer bridges included in the study that contained No. 6 (19 mm) transverse bars were built since 1988. And, the average transverse bar spacing of the newer bridges was greater than that of the older bridges.

CHAPTER 4

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.1 Summary

The purpose of this study was to identify the causes of cracking in concrete bridge decks and, based on these findings, to recommend procedures that will alleviate the problem. Forty continuous steel girder bridges, thirty-seven composite and three noncomposite, from northeast Kansas (KDOT District I) were evaluated. Field surveys were conducted to document cracking patterns and to determine the crack density of each bridge. Information for each bridge was collected from construction documents, field books, and weather data logs and compared to the observed levels of cracking to identify correlations between cracking and the factors under investigation. Thirty-one variables were considered. These variables included material properties, site conditions, construction procedures, and design specifications, as well as age and traffic volume.

4.2 Conclusions

The following conclusions are based on the investigation and analysis described in this report:

1. For monolithic bridge decks, cracking increases with increasing values of concrete slump, percent volume of water and cement, water content, cement content, and compressive strength.
2. For monolithic bridge decks, cracking also appears to increase with increasing water/cement ratio, but this trend was only established over a small range of values.
3. Cracking in monolithic bridge decks decreases with increases in air content. Significant decreases occur at air contents greater than 6.0%.
4. Overlays placed with zero slump concrete exhibit consistently high levels of cracking.
5. The use of silica fume in bridge deck overlays significantly increases cracking if precautions are not taken to prevent plastic shrinkage cracking.

6. For monolithic bridge decks, cracking increases with increases in the maximum air temperature and daily air temperature range.
7. For bridge deck overlays, cracking increases with increases in average air temperature and daily temperature range.
8. Cracking in bridge deck overlays also tends to increase with increases in the maximum daily air temperature, but the trend is not as clear as for monolithic decks.
9. Cracking in bridge deck overlays increases as placement length increases.
10. For the monolithic bridges studied, decks with a top cover thickness of 64 mm (2.5 in.) exhibit less cracking than those with top cover thicknesses of either 51 mm (2.0 in.) or 76 mm (3.0 in.). Increased cover reduces the possibility of settlement cracking, but it also moves the shrinkage steel farther from the surface which reduces its ability to control shrinkage cracking. These observations, however, are not meant to advocate the use of 64 mm (2.5 in.) cover over 76 mm (3.0 in.) cover.
11. For the bridges studied, deck type has little influence on cracking. The mean crack densities for the monolithic and two-layer bridges were virtually identical, with the mean crack density of the two-layer bridges being slightly higher.
12. For the two-layer bridges studied, cracking is more severe for those containing No. 6 (19 mm) top transverse reinforcing bars compared to those containing either No. 5 (16 mm) bars or a combination of No. 4 and No. 5 (13 and 16 mm) bars. Cracking is also more severe in two-layer bridges with reinforcing bar spacings greater than 150 mm (6.0 in.). No conclusions can be drawn for monolithic bridges, since only one contained No. 6 (19 mm) bars and all but one had transverse bar spacings of 150 mm (6.0 in.)
13. Bridges with fixed-ended girders exhibit increased cracking near the abutments compared to bridges with pin-ended girders. The magnitude of the increase in cracking is greater for those bridges with longer lengths of attachment along the abutment, especially above 14 m (45 ft).
14. Cracking increases with bridge length for two-layer bridges. This probably reflects the increase in cracking associated with increased placement length, since the overlays on most of the two-layer bridges studied were placed in sections that extended the full length of the bridge.

15. Cracking also seems to increase with bridge length for monolithic bridges, but the trend is not as clear as for two-layer decks.
16. For two-layer bridges, some tendency for cracking to increase with increases in skew is possibly discernible.
17. There appears to be some tendency for cracking to increase with increases in the average annual daily traffic (AADT).
18. Cracking in monolithic bridges built before 1988 and two-layer bridges built after 1988 appears to increase with increases in total load cycles. Conversely, cracking in two-layer bridges built before 1988 seems to decrease with increased load cycles; however, this apparent trend is suspect, as discussed in section 3.6.1. No conclusions can be made for monolithic bridges built after 1988 due to the small range of load cycles covered.
19. For the bridges studied, cracking is worse, on average, for bridges built since 1988 than for those built prior to 1988. The increased cracking of the newer bridges, both monolithic and two-layer, is largely due to the combined effects of several of the variables included in this study that were found to have an effect on cracking (see section 3.6.2).

4.3 Recommendations

Based on the results of this study, the following recommendations are made to reduce cracking in concrete bridge decks:

1. When generating mix designs for monolithic bridge deck placements and the lower course of two-layer decks, the volume of water and cement should not exceed 27.0 percent of the total volume of concrete.
2. The air content of concrete used in monolithic bridge decks should be at least 6.0 percent.
3. Concrete used in bridge deck overlays should not be placed with zero slump.

In addition to these three primary recommendations, there are several other items that should be considered in the design and construction of bridges. First, designers should be aware that the use of fixed-ended girders, as opposed to pin-ended girders, will significantly increase cracking in the end sections of bridge decks

approximately 3 m (10 ft) from each abutment. The advantages provided by using fixed-ended girders should be weighed against the effects of the increased cracking. Second, when scheduling bridge deck placements, the effects of high air temperatures and large changes in air temperature should be considered. High air temperatures increase the evaporation rate of surface moisture from fresh concrete, which increases the potential for plastic shrinkage cracking to occur. High air temperatures also cause concrete to set-up more quickly, which increases the chances that continuing placing operations will cause cracks to form by disturbing the concrete placed early in the sequence after it has taken its initial set. Large increases in air temperature aggravate cracking due to the thermal expansion of the elements supporting the deck as discussed in section 3.3.4. Therefore, if bridge deck placements are scheduled during the morning when air temperatures are low, care should be taken to avoid days in which there is likely to be a large increase in air temperature. As an alternative, placements could be scheduled in the evening when temperatures are falling. In this case, it is important to select a day with moderate high temperatures. Third, for monolithic bridge decks, efforts should be made to limit the concrete slump to approximately 50 mm (2.0 in.). Concrete should be placed at the lowest slump that will reasonably allow for proper placement and consolidation. Furthermore, consideration should be given to using shorter placement lengths, especially for overlays, and to limiting the top transverse reinforcing steel to No. 4 or No. 5 (13 or 16 mm) bars spaced at less than 150 mm (6.0 in.). Finally, when silica fume overlays are placed, the use of fog sprays should be specified to prevent the formation of plastic shrinkage cracks.

As noted throughout the report, information was lacking on several items that may have been of value to this investigation. A great deal of data was taken from construction diaries, but the amount and type of information contained in these documents was inconsistent, varying from one inspector to the next. In order to create a solid base of information from which additional studies can be performed, it is recommended that the following information be recorded in construction diaries for each bridge deck placement: concrete field test results (including concrete temperature), placing sequence details (starting location and time, direction of placement, and ending time), curing details (method and materials used, time of application, and date and time that curing procedures were discontinued), and weather conditions (wind speed, relative humidity, and air temperature at the beginning and end of the placement, in addition to the high and low temperatures for the day).

4.4 Recommendations for Future Study

In this study, the effect of superstructure flexibility was not explicitly considered. Previous research (Kochanski et al 1990; PCA 1970; Perfetti et al. 1985) in this area has revealed no clear relationship between the flexibility of bridge superstructures and the incidence of bridge deck cracking. Despite the lack of correlation, many of those involved in the design and construction of bridges maintain that excessive flexibility in some way adversely affects cracking (Wiss, Janney, Elstner Associates, Inc. 1993). It may be that superstructure flexibility does not have a large effect on the formation of cracks but, rather, causes existing cracks or local defects to increase in size. It would be beneficial to determine the actual effect of flexibility on the formation and propagation of cracks. Assuming a relationship can be established, it would also be of value to determine if a level of flexibility exists below which cracking is unaffected.

All of the two-layer bridges included in this study had a 76 mm (3.0 in.) cover that was made up of a 57 mm (2.25 in.) overlay bonded to a subdeck with a 19 mm (0.75 in.) initial cover. Since settlement cracking has been shown to increase with decreases in cover (Dakhil et al. 1975), it would be useful to investigate the effect of increasing the initial cover provided by the subdeck and decreasing the thickness of the overlay.

The effect of placing sequence on cracking could not be evaluated in this study, due to a lack of information on the actual sequences used during construction. However, previous research (Cheng and Johnston 1985; Perfetti et al. 1985) indicates that placing sequence does have an effect on cracking and suggests that sequences designed to minimize residual dead load tensile stresses, such as those employed by the state of Wisconsin, could be effective in reducing the formation of cracks. In addition to the sequence in which the concrete is placed, the quantity of concrete placed in one continuous placement, the rate at which it is placed, and the time allowed between consecutive placements may affect the amount of bridge deck cracking that occurs. A better understanding of the relative importance of these parameters would be useful.

Further research on the effects of curing and evaporation rate would also be of value, since a sufficient amount of information concerning these variables was not available to reach any conclusions in the present study. Conclusions reached by previous studies concerning the effect of evaporation rate on cracking have differed. The study by NCSU (Cheng and Johnston 1985) was unable to establish a relationship between cracking and evaporation rate; however, Poppe (1981) stated that adverse weather conditions (high ambient temperatures, high winds, and low relative humidity) had a greater effect on cracking than any other factor considered.

Additional research will be necessary to identify the actual relationship. In the 1993 survey of transportation agencies completed by Wiss, Janney, Elstner Associates, Inc., "improper curing" was the most noted cause of cracking in bridge decks. Many different aspects of curing need to be investigated (including type of materials used, time of application, and length of curing period), and it would be beneficial to determine the effect that each of these items has on cracking.

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Table A.1: Crack densities and data for full bridge decks.

Bridge Number	Crack Density (m/m ²)	Structure Type	Deck Type	Bridge Skew (deg.)	Traffic Volume (aadt)	Total Length (ft)	Total Length (m)	Bridge Age (months)
Monolithic Bridges								
3-045	0.19	SWCC	1	45	670	291.5	88.8	112
3-046	0.24	SWCC	1	50	670	323.8	98.7	102
56-142	0.08	SWCH	1	22	4745	404.0	123.1	80
56-148	0.28	SMCC	1	0	575	246.5	75.1	36
70-095	0.07	SMCC	1	0	810	241.7	73.7	106
70-101	0.06	SWCC	1	45	520	263.5	80.3	108
70-103	0.49	SWCC	1	45	3390	263.5	80.3	102
70-104	0.09	SMCC	1	21	710	254.7	77.6	106
70-107	0.34	SMCC	1	0	1900	202.5	61.7	34
75-044	0.19	SMCC	1	0	2500	122.0	37.2	48
75-045	0.51	SMCC	1	0	2500	280.0	85.3	47
89-204	0.75	SMCC	1	0	2535	231.0	70.4	34
99-076	0.76	SWCH	1	0	2585	995.7	303.5	42
105-046	0.87	SWCC	1	35	4582	430.9	131.3	240
105-000	0.27	SWCC	1	0	--	477.8	145.6	12
Two-Layer Bridges								
46-294	0.30	SWCH	2	45	12955	306.5	93.4	20
46-295	0.28	SWCH	2	45	12955	306.5	93.4	24
89-179	0.23	SMCC	2	29	6865	183.4	55.9	45

Table A.1: (continued)

Bridge Number	Crack Density (m/m ²)	Structure Type	Deck Type	Bridge Skew (deg.)	Traffic Volume (aadt)	Total Length (ft)	Total Length (m)	Bridge Age (months)
89-180	0.36	SMCC	2	29	6865	183.4	55.9	51
89-184	0.69	SWCC	2	41	10540	265.8	81.0	39
89-185	0.72	SWCC	2	41	10540	261.3	79.6	41
89-186	0.52	SMCC	2	22	10540	213.3	65.0	42
89-187	1.02	SMCC	2	22	13410	213.2	65.0	41
89-198	0.54	SWCC	2	53	10000	347.5	105.9	33
89-199	0.67	SWCC	2	53	10000	347.5	105.9	35
89-200	0.51	SWCC	2	34	10000	321.0	97.8	33
89-201	0.67	SWCC	2	34	10000	321.0	97.8	34
105-021	0.09	SMCC	2	6	9189	144.3	44.0	74
105-225	0.18	SWCC	2	27	6140	190.3	58.0	94
105-226	0.17	SWCC	2	28	6140	184.4	56.2	94
105-230	0.09	SMCC	2	0	6710	229.0	69.8	98
105-231	0.11	SMCC	2	0	6710	229.0	69.8	98
105-262	0.18	SWCH	2	13	4665	273.1	83.2	108
105-263	0.13	SWCH	2	13	4665	273.1	83.2	128
105-265	0.01	SMCC	2	25	780	132.5	40.4	116
105-268	0.61	SMCC	2	0	1135	192.0	58.5	88
105-269	0.45	SWCC	2	0	1135	245.3	74.8	96

Table A.1: (continued)

Bridge Number	Crack Density (m/m ²)	Structure Type	Deck Type	Bridge Skew (deg.)	Traffic Volume (aadt)	Total Length (ft)	Total Length (m)	Bridge Age (months)
Noncomposite Bridges								
23-022	0.54	NC	1	0	4750	159.0	48.5	336
105-198	0.24	NC	2	3	12640	379.3	115.6	170
105-199	0.18	NC	2	3	12640	379.8	115.8	171

* Bridge has no assigned serial number. Project No. is 105-U-1262-01.

-- Denotes missing data.

Table A.2: Deck properties and crack densities for end sections.

Bridge Number	Deck Thickness		Top Cover		Transverse Steel			Girder End Condition	End Section Crack Density	
	(in.)	(mm)	(in.)	(mm)	Size (bar no.)	Spacing (in.)	(mm)		(end 1)	(end 2)
Monolithic Bridges										
3-045	9.00	229	3.00	76	5	6.00	152	f	0.24	0.35
3-046	9.00	229	3.00	76	4,5	6.00	152	f	0.54	0.17
56-142	--	--	--	--	--	--	--	p	0.00	0.00
56-148	--	--	--	--	--	--	--	f	0.41	0.09
70-095	8.00	203	2.50	64	5	7.00	178	f	0.00	0.18
70-101	8.50	216	2.50	64	4,5	6.00	152	f	0.11	0.29
70-103	10.00	254	2.50	64	5	6.00	152	f	0.95	0.50
70-104	8.00	203	2.50	64	5	6.00	152	f	0.00	0.03
70-107	8.00	203	2.50	64	4,5	6.00	152	f	0.55	0.20
75-044	8.50	216	2.50	64	5	6.00	152	f	0.36	0.13
75-045	8.50	216	2.50	64	5	6.00	152	f	0.06	0.76
89-204	--	--	--	--	--	--	--	f	0.43	0.41
99-076	8.75	222	3.00	76	4	6.00	152	p	0.45	--
105-046	7.50	191	2.00	51	6	6.00	152	--	--	--
105-000*	8.50	216	3.00	76	5	6.00	152	f	0.61	--
Two-Layer Bridges										
46-294	8.50	216	3.00	76	5	5.00	127	p	0.33	0.16
46-295	8.50	216	3.00	76	5	5.00	127	p	0.20	0.14
89-179	8.25	210	3.00	76	4,5	6.00	152	f	1.01	1.19

Table A.2: (continued)

Bridge Number	Deck Thickness		Top Cover		Transverse Steel			Girder End Condition	End Section Crack Density	
	(in.)	(mm)	(in.)	(mm)	Size (bar no.)	Spacing (in.)	(mm)		(end 1)	(end 2)
89-180	8.25	210	3.00	76	4,5	6.00	152	f	0.64	0.99
89-184	8.50	216	3.00	76	5	7.00	178	f	1.16	1.16
89-185	8.50	216	3.00	76	5	7.00	178	f	1.47	0.68
89-186	8.50	216	3.00	76	4,5	6.50	165	f	0.99	1.04
89-187	8.50	216	3.00	76	4,5	6.50	165	f	1.05	1.66
89-198	8.50	216	3.00	76	6	8.00	203	p	0.38	0.46
89-199	8.50	216	3.00	76	6	8.00	203	p	0.25	0.51
89-200	8.50	216	3.00	76	6	8.00	203	f	1.48	1.52
89-201	8.50	216	3.00	76	6	8.00	203	f	1.92	1.44
105-021	8.50	216	3.00	76	5	6.00	152	--	--	--
105-225	9.00	229	3.00	76	5	5.50	140	f	0.88	0.74
105-226	9.00	229	3.00	76	5	5.50	140	f	1.02	1.07
105-230	9.25	235	3.00	76	4,5	5.75	146	f	0.71	0.88
105-231	9.25	235	3.00	76	4,5	5.75	146	f	0.53	0.63
105-262	9.00	229	3.00	76	5	5.50	140	f	0.37	0.20
105-263	9.00	229	3.00	76	5	5.50	140	f	0.08	0.00
105-265	9.00	229	3.00	76	5	5.50	140	f	0.00	0.12
105-268	8.50	216	3.00	76	--	--	--	f	1.03	0.98
105-269	8.50	216	3.00	76	--	--	--	f	0.51	0.92

Table A.2: (continued)

Bridge Number	Deck Thickness		Top Cover		Transverse Steel			Girder End Condition	End Section Crack Density	
	(in.)	(mm)	(in.)	(mm)	Size (bar no.)	Spacing (in.)	(mm)		(end 1)	(end 2)
Noncomposite Bridges										
23-022	7.00	178	2.00	51	5	7.00	178	p	0.00	0.02
105-198	9.00	229	3.00	76	5	5.50	140	p	0.05	0.20
105-199	11.00	279	3.00	76	6	6.00	152	p	0.00	0.00

* Bridge has no assigned serial number. Project No. is 105-U-1262-01.

-- Denotes missing data.

Table A.3: Site conditions for monolithic bridge deck placements.

Bridge Number	Portion Placed	Date Of Placement	Low		Air Temperature				Average		Average Daily Wind Speed		Average R. H. (%)
			(F)	(C)	High (F)	High (C)	Range (F)	Range (C)	(F)	(C)	(mph)	(km/hr)	
3-045	West Deck	12/21/84	28	-2	46	8	18	10	37	3	14.4	23.2	92.4
	East Deck	12/26/84	33	1	49	9	16	9	41	5	10.1	16.3	79.0
	W. Ctr. Deck	12/27/84	49	9	62	17	13	7	56	13	16.0	25.8	81.7
	Ctr. Deck	3/13/85	35	2	54	12	19	11	45	7	7.0	11.3	66.3
	E. Ctr. Deck	3/14/85	30	-1	61	16	31	17	46	8	7.8	12.6	52.1
3-046	West Deck	12/31/85	28	-2	43	6	15	8	36	2	9.2	14.8	62.5
	East Deck	1/2/86	36	2	52	11	16	9	44	7	11.1	17.9	53.0
	Ctr. Deck	1/10/86	26	-3	50	10	24	13	38	3	4.8	7.7	61.6
56-142	North End	10/1/87	44	7	78	26	34	19	61	16	9.5	15.3	64.6
	N. + Moment	10/1/87	44	7	78	26	34	19	61	16	9.5	15.3	64.6
	S. + Moment	10/1/87	44	7	78	26	34	19	61	16	9.5	15.3	64.6
	South End	10/1/87	44	7	78	26	34	19	61	16	9.5	15.3	64.6
	N. Pier	10/6/87	41	5	65	18	24	13	53	12	4.4	7.1	42.8
	Ctr. Pier	10/6/87	41	5	65	18	24	13	53	12	4.4	7.1	42.8
	S. Pier	10/6/87	41	5	65	18	24	13	53	12	4.4	7.1	42.8
56-148	Deck	7/17-18/91	74	23	97	36	23	13	86	30	8.0	12.9	47.1
70-095	Deck	10/31/85	39	4	57	14	18	10	48	9	6.9	11.1	74.0
70-101	North	--	--	--	--	--	--	--	--	--	--	--	--
	South	--	--	--	--	--	--	--	--	--	--	--	--
70-103	Right	3/14/85	30	-1	61	16	31	17	46	8	7.8	12.6	58.0
	Left	3/19/85	39	4	70	21	31	17	55	13	5.6	9.0	71.0

Table A.3: (Continued)

Bridge Number	Portion Placed	Date Of Placement	Low		Air Temperature				Average		Average Daily Wind Speed		Average R. H. (%)
			(F)	(C)	High (F)	(C)	Range (F)	(C)	(F)	(C)	(mph)	(km/hr)	
70-104	Deck	10/17/85	53	12	73	23	20	11	63	17	9.6	15.5	73.0
70-107	Deck	10/25/91	36	2	57	14	21	12	47	8	7.6	12.2	75.0
75-044	Deck	7/12/90	62	17	66	19	4	2	64	18	13.2	21.3	83.8
75-045	Deck	8/10/90	66	19	88	31	22	12	77	25	6.9	11.1	73.8
89-204	Deck	10/3/91	56	13	77	25	21	12	67	19	10.6	17.1	90.0
99-076	South End	--	--	--	--	--	--	--	--	--	--	--	--
	Placement 2	9/15/89	44	7	82	28	38	21	63	17	0.8	1.3	60.2
	Placement 3	10/13/89	48	9	88	31	40	22	68	20	8.8	14.2	48.7
	Placement 4	11/7/89	28	-2	62	17	34	19	45	7	3.5	5.6	73.3
	Placement 5	11/21/89	28	-2	53	12	25	14	41	5	8.4	13.5	43.3
	North(West Ln.)	1/9/90	37	3	55	13	18	10	46	8	12.9	20.8	65.2
	North(East Ln.)	5/11/90	42	6	60	16	18	10	51	11	11.3	18.2	79.8
105-000*	Deck	6/23/93	66	19	84	29	18	10	75	24	10.9	17.5	66.0

* Bridge has no assigned serial number. Project No. is 105-U-1262-01.

-- Denotes missing data.

Table A.4: Site conditions for overlay placements.

Bridge Number	Portion Placed	Date Of Placement	Low		Air Temperature				Average		Average Daily Wind Speed		Average R. H. (%)
			(F)	(C)	High (F)	High (C)	Range (F)	Range (C)	(F)	(C)	(mph)	(km/hr)	
46-294	Left	7/23/92	68	20	81	27	13	7	75	24	5.5	8.9	83.0
	Right	7/25/92	75	24	91	33	16	9	83	28	13.8	22.2	76.9
46-295	Left	3/6/92	51	11	65	18	14	8	58	14	10.5	16.9	77.5
	Right	3/14/92	32	0	63	17	31	17	48	9	11.7	18.8	42.7
89-179	Right	10/30/90	57	14	82	28	25	14	70	21	12.7	20.4	57.0
	Left	11/1/90	61	16	82	28	21	12	72	22	18.3	29.5	57.0
89-180	Right	4/18/90	43	6	57	14	14	8	50	10	11.3	18.2	47.0
	Left	4/23/90	62	17	85	29	23	13	74	23	13.3	21.4	68.0
89-184	Inside	9/26/90	48	9	96	36	48	27	72	22	3.1	5.0	62.0
	Outside	9/28/90	58	14	82	28	24	13	70	21	7.4	11.9	68.0
89-185	Outside	6/21/90	67	19	89	32	22	12	78	26	8.8	14.2	77.0
	Inside	6/23/90	59	15	84	29	25	14	72	22	8.6	13.8	65.0
89-186	Inside	9/14/90	53	12	83	28	30	17	68	20	10.6	17.1	57.0
	Outside	9/17/90	54	12	71	22	17	9	63	17	12.1	19.5	75.0
89-187	Inside	6/26/90	70	21	93	34	23	13	82	28	8.4	13.5	78.0
	Outside	6/28/90	76	24	93	34	17	9	85	29	18.1	29.1	72.0
89-198	Left	8/24/91	65	18	95	35	30	17	80	27	5.5	8.9	75.0
	Right	8/27/91	66	19	94	34	28	16	80	27	7.2	11.6	67.0
89-199	Left	8/26/91	65	18	95	35	30	17	80	27	5.2	8.4	61.0
	Right	8/28/91	68	20	94	34	26	14	81	27	7.1	11.4	71.0
89-200	Right	8/17/91	62	17	90	32	28	16	76	24	8.1	13.0	63.0

Table A.4: (Continued)

Bridge Number	Portion Placed	Date Of Placement	Low		Air Temperature				Average		Average Daily Wind Speed		Average R. H. (%)
			(F)	(C)	High (F)	High (C)	Range (F)	Range (C)	(F)	(C)	(mph)	(km/hr)	
89-200	Left	8/20/91	51	11	85	29	34	19	68	20	4.6	7.4	67.0
89-201	Right	8/19/91	56	13	85	29	29	16	71	21	6.5	10.5	63.0
	Left	8/21/91	56	13	94	34	38	21	75	24	5.2	8.4	66.0
105-021	East	9/4/87	65	18	91	33	26	14	78	26	7.3	11.8	62.2
	West	9/9/87	53	12	82	28	29	16	68	20	5.1	8.2	66.6
105-225	East	7/22/86	68	20	89	32	21	12	79	26	7.9	12.7	61.2
	Center	7/29/86	75	24	94	34	19	11	85	29	11.6	18.7	66.3
	West	7/26/86	72	22	91	33	19	11	82	28	7.7	12.4	70.6
105-226	West	7/25/86	74	23	89	32	15	8	82	28	9.3	15.0	65.9
	Center	7/28/86	74	23	98	37	24	13	86	30	5.8	9.3	67.6
	East	7/23/86	73	23	93	34	20	11	83	28	10.3	16.6	65.0
105-230	East	--	--	--	--	--	--	--	--	--	--	--	--
	Center	--	--	--	--	--	--	--	--	--	--	--	--
	West	--	--	--	--	--	--	--	--	--	--	--	--
105-231	East	--	--	--	--	--	--	--	--	--	--	--	--
	Center	--	--	--	--	--	--	--	--	--	--	--	--
	West	--	--	--	--	--	--	--	--	--	--	--	--
105-262	Left	--	--	--	--	--	--	--	--	--	--	--	--
	Center	6/12/85	55	13	67	19	12	7	61	16	10.3	16.6	64.6
	Right	6/14/85	63	17	75	24	12	7	69	21	10.9	17.5	70.5
105-263	West	--	--	--	--	--	--	--	--	--	--	--	--

Table A.4: (Continued)

Bridge Number	Portion Placed	Date Of Placement	Low		Air Temperature				Average		Average Daily Wind Speed		Average R. H. (%)
			(F)	(C)	High (F)	High (C)	Range (F)	Range (C)	(F)	(C)	(mph)	(km/hr)	
105-263	Center	10/13/83	38	3	56	13	18	10	47	8	6.9	11.1	125.0
	East	10/18/83	47	8	59	15	12	7	53	12	8.2	13.2	89.5
105-268	Right	6/14/86	68	20	88	31	20	11	78	26	9.3	15.0	66.7
	Left	6/14/86	68	20	88	31	20	11	78	26	9.3	15.0	66.7
105-269	Deck	10/26/85	48	9	54	12	6	3	51	11	9.2	14.8	107.7

-- Denotes missing data.

Table A.5: Site conditions for noncomposite bridge deck placements.

Bridge Number	Portion Placed	Date Of Placement	Low		Air Temperature				Average		Average Daily Wind Speed		Average R. H. (%)
			(F)	(C)	(F)	(C)	Range (F) (C)	(F)	(C)	(mph)	(km/hr)		
23-022	Deck	--	--	--	--	--	--	--	--	--	--	--	--
	West End	--	--	--	--	--	--	--	--	--	--	--	--
105-198	N. Subdeck	6/1/79	49	9	74	23	25	14	62	16	5.6	9.0	61.1
	S. Subdeck	6/6/79	67	19	79	26	12	7	73	23	10.9	17.5	87.3
	Right	7/25/79	69	21	87	31	18	10	78	26	6.2	10.0	76.5
	Center	7/27/79	70	21	90	32	20	11	80	27	7.5	12.1	74.1
	Left	7/31/79	69	21	79	26	10	6	74	23	6.6	10.6	84.4
105-199	S. Subdeck	5/21/79	53	12	67	19	14	8	60	16	11.9	19.2	59.8
	N. Subdeck	5/24/79	46	8	69	21	23	13	58	14	9.9	15.9	56.1
	Ctr. Subdeck	5/29/79	45	7	75	24	30	17	60	16	9.1	14.7	115.2
	Left	6/21/79	69	21	99	37	30	17	84	29	8.6	13.8	53.0
	Center	6/25/79	54	12	79	26	25	14	67	19	7.5	12.1	76.8
	Right	6/27/79	68	20	80	27	12	7	74	23	10.2	16.4	87.4

-- Denotes missing data.

Table A.6: Crack density and mix design information for monolithic bridge deck placements.

Bridge Number	Portion Placed	Crack Density (m/m ²)	Water Content (lb/cy) (kg/m ³)	Cement Content (lb/cy) (kg/m ³)	Water/Cement Ratio	Volume of Water+Cement (%)	Types of Admixtures		
3-045	West Deck	0.12	253	150	602	357	0.42	26.36	None
	East Deck	0.21	253	150	602	357	0.42	26.36	None
	W. Ctr. Deck	0.18	253	150	602	357	0.42	26.36	None
	Ctr. Deck	0.23	253	150	602	357	0.42	26.36	None
	E. Ctr. Deck	0.15	253	150	602	357	0.42	26.36	None
3-046	West Deck	0.33	253	150	602	357	0.42	26.36	None
	East Deck	0.42	253	150	602	357	0.42	26.36	None
	Ctr. Deck	0.15	241	143	602	357	0.40	25.65	Retarder
56-142	North End	0.00	255	151	605	359	0.42	26.54	None
	N. + Moment	0.22	255	151	605	359	0.42	26.54	None
	S. + Moment	0.08	255	151	605	359	0.42	26.54	None
	South End	0.03	255	151	605	359	0.42	26.54	None
	N. Pier	0.02	255	151	605	359	0.42	26.54	None
	Ctr. Pier	0.20	255	151	605	359	0.42	26.54	None
	S. Pier	0.05	255	151	605	359	0.42	26.54	None
56-148	Deck	0.28	266	158	605	359	0.44	27.19	Retarder
70-095	Deck	0.07	266	158	605	359	0.44	27.19	None
70-101	North	0.07	266	158	605	359	0.44	27.19	None
	South	0.04	266	158	605	359	0.44	27.19	None
70-103	Right	0.40	266	158	605	359	0.44	27.19	None
	Left	0.57	266	158	605	359	0.44	27.19	None

Table A.6: (Continued)

Bridge Number	Portion Placed	Crack Density (m/m ²)	Water Content (lb/cy) (kg/m ³)	Cement Content (lb/cy) (kg/m ³)	Water/Cement Ratio	Volume of Water+Cement (%)	Types of Admixtures
70-104	Deck	0.09	266 158	605 359	0.44	27.19	None
70-107	Deck	0.34	266 158	605 359	0.44	27.19	None
75-044	Deck	0.19	268 159	639 379	0.42	27.95	Retarder
75-045	Deck	0.51	268 159	639 379	0.42	27.95	Retarder
89-204	Deck	0.75	276 164	658 390	0.42	28.78	None
99-076	South End	0.46	-- --	-- --	--	--	--
	Placement 2	1.48	268 159	639 379	0.42	27.95	Retarder
	Placement 3	0.95	268 159	639 379	0.42	27.95	Retarder
	Placement 4	0.94	281 167	639 379	0.44	28.72	None
	Placement 5	0.90	281 167	639 379	0.44	28.72	None
	North(West Ln.)	0.77	281 167	639 379	0.44	28.72	None
	North(East Ln.)	0.42	281 167	639 379	0.44	28.72	None
105-000*	Deck	0.27	-- --	-- --	--	--	--

* Bridge has no assigned serial number. Project No. is 105-U-1262-01.

-- Denotes missing data.

Table A.7: Crack density and mix design information for overlay placements.

Bridge Number	Portion Placed	Crack Density (m/m ²)	Water Content (lb/cy) (kg/m ³)	Cement Content (lb/cy) (kg/m ³)	Water/Cement Ratio	Volume of Water + Cement (%)	Types of Admixtures
46-294	Left	0.40	225 133	625 371	0.36	25.13	None
	Right	0.20	225 133	625 371	0.36	25.13	None
46-295	Left	0.43	225 133	625 371	0.36	25.13	None
	Right	0.15	225 133	625 371	0.36	25.13	None
89-179	Right	0.19	250 148	625 371	0.40	26.62	None
	Left	0.28	250 148	625 371	0.40	26.62	None
89-180	Right	0.37	250 148	625 371	0.40	26.62	None
	Left	0.35	250 148	625 371	0.40	26.62	None
89-184	Inside	0.68	225 133	578 343	0.39	24.63	WR/SF(7%)
	Outside	0.70	-- --	-- --	--	--	WR/SF(7%)
89-185	Outside	0.60	225 133	625 371	0.36	25.13	None
	Inside	0.95	-- --	-- --	--	--	--
89-186	Inside	0.56	-- --	-- --	--	--	--
	Outside	0.45	225 133	625 371	0.36	25.13	None
89-187	Inside	1.46	238 141	625 371	0.38	26.16	WR/SF(5%)
	Outside	0.65	-- --	-- --	--	--	WR/SF(5%)
89-198	Left	0.70	225 133	625 371	0.36	25.13	None
	Right	0.40	-- --	-- --	--	--	--
89-199	Left	0.64	225 133	625 371	0.36	25.13	None
	Right	0.71	-- --	-- --	--	--	--
89-200	Right	0.57	225 133	625 371	0.36	25.13	None

Table A.7: (Continued)

Bridge Number	Portion Placed	Crack Density (m/m ²)	Water Content (lb/cy) (kg/m ³)	Cement Content (lb/cy) (kg/m ³)	Water/Cement Ratio	Volume of Water + Cement (%)	Types of Admixtures		
89-200	Left	0.45	--	--	--	--	--		
89-201	Right	0.59	225	133	625	371	0.36	25.13	None
	Left	0.77	--	--	--	--	--	--	--
105-021	East	0.11	238	141	625	371	0.38	25.90	None
	West	0.08	238	141	625	371	0.38	25.90	None
105-225	East	0.21	244	145	625	371	0.39	26.26	None
	Center	0.29	--	--	--	--	--	--	--
	West	0.11	--	--	--	--	--	--	--
105-226	West	0.17	--	--	--	--	--	--	--
	Center	0.27	--	--	--	--	--	--	--
	East	0.12	244	145	625	371	0.39	26.26	None
105-230	East	0.10	--	--	--	--	--	--	--
	Center	0.09	--	--	--	--	--	--	--
	West	0.08	--	--	--	--	--	--	--
105-231	East	0.13	--	--	--	--	--	--	--
	Center	0.12	--	--	--	--	--	--	--
	West	0.09	--	--	--	--	--	--	--
105-262	Left	--	--	--	--	--	--	--	--
	Center	0.15	244	145	625	371	0.39	26.26	None
	Right	0.23	--	--	--	--	--	--	--
105-263	West	--	--	--	--	--	--	--	--

Table A.7: (Continued)

Bridge Number	Portion Placed	Crack Density (m/m ²)	Water Content (lb/cy) (kg/m ³)		Cement Content (lb/cy) (kg/m ³)		Water/Cement Ratio	Volume of Water + Cement (%)	Types of Admixtures
105-263	Center	0.12	234	139	625	371	0.38	25.67	None
	East	0.14	234	139	625	371	0.38	25.67	None
105-268	Right	0.56	--	--	--	--	--	--	--
	Left	0.67	--	--	--	--	--	--	--
105-269	Deck	0.45	238	141	625	371	0.38	25.90	None

-- Denotes missing data.

Table A.8: Crack density and mix design information for noncomposite bridge deck placements.

Bridge Number	Portion Placed	Crack Density (m/m ²)	Water Content (lb/cy) (kg/m ³)	Cement Content (lb/cy) (kg/m ³)	Water/Cement Ratio	Volume of Water + Cement (%)	Types of Admixtures		
23-022	Deck	0.60	--	--	--	--	--		
	West End	0.20	--	--	--	--	--		
105-198	N. Subdeck	0.24	267	158	602	357	0.44	27.19	None
	S. Subdeck	0.23	267	158	602	357	0.44	27.19	None
	Right	0.18	274	162	825	489	0.33	31.81	None
	Center	0.30	--	--	--	--	--	--	--
	Left	0.19	--	--	--	--	--	--	--
105-199	S. Subdeck	0.14	267	158	602	357	0.44	27.19	None
	N. Subdeck	0.18	267	158	602	357	0.44	27.19	None
	Ctr. Subdeck	0.17	267	158	602	357	0.44	27.19	None
	Left	0.19	274	162	825	489	0.33	31.81	None
	Center	0.18	274	162	825	489	0.33	31.81	None
	Right	0.16	274	162	825	489	0.33	31.81	None

-- Denotes missing data.

Table A.9: Field information for monolithic bridge deck placements.

Bridge Number	Portion Placed	Average Slump		Compressive Strength		Air Content (%)	Curing Materials ⁺
		(in.)	(mm)	(psi)	(MPa)		
3-045	West Deck	2.00	51	4790	33	5.00	--
	East Deck	2.25	57	6190	43	4.50	--
	W. Ctr. Deck	2.00	51	5640	39	5.00	--
	Ctr. Deck	2.25	57	6140	42	5.50	--
	E. Ctr. Deck	1.75	44	6270	43	6.00	--
3-046	West Deck	2.00	51	5260	36	6.00	--
	East Deck	2.25	57	5760	40	6.00	--
	Ctr. Deck	1.50	38	5630	39	6.00	--
56-142	North End	2.00	51	4760	33	6.10	White Poly.
	N. + Moment	2.00	51	4760	33	6.10	White Poly.
	S. + Moment	2.00	51	4760	33	6.10	White Poly.
	South End	2.00	51	4760	33	6.10	White Poly.
	N. Pier	2.25	57	5130	35	6.00	White Poly.
	Ctr. Pier	2.25	57	5130	35	6.00	White Poly.
	S. Pier	2.25	57	5130	35	6.00	White Poly.
56-148	Deck	2.58	66	6170	43	6.50	--
70-095	Deck	1.75	44	5510	38	5.93	Burlap/Poly.
70-101	North	--	--	--	--	--	Burlap/Poly.
	South	--	--	--	--	--	Burlap/Poly.
70-103	Right	1.88	48	5110	35	5.85	Burlap/Poly.
	Left	1.75	44	4750	33	5.40	Burlap/Poly.

Table A.9: (Continued)

Bridge Number	Portion Placed	Average Slump		Compressive Strength		Air Content (%)	Curing Materials ⁺
		(in.)	(mm)	(psi)	(MPa)		
70-104	Deck	1.75	44	4170	29	5.00	Burlap/Poly.
70-107	Deck	2.15	55	6820	47	5.40	Burlap/Poly.
75-044	Deck	2.54	65	6430	44	5.63	CC/Poly.
75-045	Deck	2.41	61	5640	39	5.76	Poly.
89-204	Deck	3.00	76	6370	44	5.20	--
99-076	South End	--	--	--	--	--	--
	Placement 2	1.96	50	7400	51	5.00	CC/Poly.
	Placement 3	2.25	57	6700	46	5.25	CC/Poly.
	Placement 4	2.38	60	6100	42	5.75	Poly.
	Placement 5	2.25	57	6250	43	4.75	Poly./Blankets
	North(West Ln.)	2.50	64	5380	37	5.50	Poly./Blankets
	North(East Ln.)	2.25	57	5750	40	6.00	--
105-000*	Deck	--	--	--	--	--	--

* Bridge has no assigned serial number. Project No. is 105-U-1262-01.

-- Denotes missing data.

+ Curing Materials:

White Poly. = white polyethylene (plastic).

Burlap/Poly. = wet burlap covered w/ plastic.

CC/Poly. = curing compound covered w/ plastic.

Poly. = plastic (assumed clear).

Poly./Blankets = plastic covered w/ insulating blankets.

Table A.10: Field information for overlay placements.

Bridge Number	Portion Placed	Average Slump		Compressive Strength		Air Content (%)	Curing Materials ⁺
		(in.)	(mm)	(psi)	(MPa)		
46-294	Left	0.75	19	6300	43	4.60	White Poly.
	Right	0.75	19	6250	43	5.20	White Poly.
46-295	Left	0.25	6	6960	48	--	CC/Poly.
	Right	0.25	6	8230	57	5.20	CC/Poly.
89-179	Right	0.25	6	5360	37	6.13	CC/Burlap/Poly.
	Left	0.25	6	5620	39	5.00	CC/Burlap/Poly.
89-180	Right	0.25	6	5960	41	5.15	CC/Burlap/Poly.
	Left	0.25	6	5380	37	5.25	CC/Burlap/Poly.
89-184	Inside	1.50	38	7060	49	6.40	--
	Outside	--	--	--	--	--	--
89-185	Outside	0.00	0	6670	46	6.00	--
	Inside	--	--	--	--	--	--
89-186	Inside	--	--	--	--	--	--
	Outside	0.25	6	6410	44	5.70	--
89-187	Inside	2.25	57	6240	43	6.00	--
	Outside	--	--	--	--	--	--
89-198	Left	0.00	0	7140	49	5.00	--
	Right	--	--	--	--	--	--
89-199	Left	0.00	0	6920	48	4.80	--
	Right	--	--	--	--	--	--
89-200	Right	0.00	0	6570	45	4.80	--

Table A.10: (Continued)

Bridge Number	Portion Placed	Average Slump		Compressive Strength		Air Content (%)	Curing Materials ⁺
		(in.)	(mm)	(psi)	(MPa)		
89-200	Left	--	--	--	--	--	--
89-201	Right	0.00	0	6820	47	--	--
	Left	--	--	--	--	--	--
105-021	East	0.50	13	6080	42	5.00	Burlap/Poly.
	West	0.25	6	6700	46	4.00	--
105-225	East	0.13	3	7180	49	5.00	--
	Center	--	--	--	--	--	--
	West	--	--	--	--	--	--
105-226	West	--	--	--	--	--	--
	Center	--	--	--	--	--	--
	East	0.25	6	6630	46	5.50	--
105-230	East	--	--	--	--	--	--
	Center	--	--	--	--	--	--
	West	--	--	--	--	--	--
105-231	East	--	--	--	--	--	--
	Center	--	--	--	--	--	--
	West	--	--	--	--	--	--
105-262	Left	--	--	--	--	--	--
	Center	0.13	3	6530	45	4.50	--
	Right	--	--	--	--	--	--
105-263	West	--	--	--	--	--	--

Table A.10: (Continued)

Bridge Number	Portion Placed	Average Slump		Compressive Strength		Air Content (%)	Curing Materials ⁺
		(in.)	(mm)	(psi)	(MPa)		
105-263	Center	0.75	19	6410	44	5.90	--
	East	0.75	19	5880	41	5.40	--
105-268	Right	--	--	--	--	--	--
	Left	--	--	--	--	--	--
105-269	Deck	0.00	0	6490	45	5.50	Burlap/Poly.

-- Denotes missing data.

+ Curing Materials:

White Poly. = white polyethylene (plastic).

Burlap/Poly. = wet burlap covered w/ plastic.

CC/Poly. = curing compound covered w/ plastic.

CC/Burlap/Poly. = curing compound covered w/ wet burlap & plastic.

Table A.11: Field information for noncomposite bridge deck placements.

Bridge Number	Portion Placed	Average Slump		Compressive Strength		Air Content	Curing Materials ⁺
		(in.)	(mm)	(psi)	(MPa)	(%)	
23-022	Deck	--	--	--	--	--	--
	West End	--	--	--	--	--	--
105-198	N. Subdeck	2.50	64	5600	39	5.00	Poly.
	S. Subdeck	2.00	51	5320	37	4.00	Poly.
	Right	0.38	10	6770	47	6.50	Burlap
	Center	--	--	--	--	--	Burlap
	Left	--	--	--	--	--	Burlap/Poly.
105-199	S. Subdeck	2.50	64	5160	36	5.00	Poly.
	N. Subdeck	1.75	44	4870	34	4.50	Poly.
	Ctr. Subdeck	2.25	57	4310	30	5.00	Poly.
	Left	0.50	13	6550	45	6.50	Burlap
	Center	0.50	13	--	--	7.20	Burlap
	Right	0.50	13	--	--	7.50	Burlap

-- Denotes missing data.

+ Curing Materials:

Poly. = plastic (assumed clear).

Burlap = wet burlap.

Burlap/Poly. = wet burlap covered w/ plastic.

Table A.12: Crack densities and data for individual spans.

Bridge Number	Span Type	Span Location	Crack Density (m/m ²)	Span Length (ft)	Span Length (m)
Monolithic Bridges					
3-045	End	West	0.09	64	19.5
	Interior	W. Ctr.	0.18	80	24.4
	Interior	E. Ctr.	0.26	80	24.4
3-046	End	East	0.18	64	19.5
	End	West	0.25	100	30.5
	Interior	Ctr.	0.15	120	36.6
56-142	End	East	0.32	100	30.5
	End	North	0.01	88	26.8
	Interior	N. Ctr.	0.16	112	34.1
56-148	Interior	S. Ctr.	0.12	112	34.1
	End	South	0.03	88	26.8
	End	West	0.33	72	21.9
70-095	Interior	Ctr.	0.32	100	30.5
	End	East	0.19	72	21.9
	End	--	0.01	74	22.6
70-101	Interior	--	0.12	90	27.4
	End	--	0.07	74	22.6
	End	West	0.02	80	24.4
70-103	Interior	Ctr.	0.06	100	30.5
	End	East	0.08	80	24.4
	End	South	0.54	80	24.4
70-104	Interior	Ctr.	0.54	100	30.5
	End	North	0.36	80	24.4
	End	South	0.17	56	17.1
70-107	Interior	S. Ctr.	0.08	70	21.3
	Interior	N. Ctr.	0.06	70	21.3
	End	North	0.04	56	17.1
75-044	End	South	0.45	60	18.3
	Interior	Ctr.	0.36	80	24.4
	End	North	0.19	60	18.3
75-044	End	North	0.27	37	11.3
	Interior	Ctr.	0.16	46	14.0

Table A.12: (Continued)

Bridge Number	Span Type	Span Location	Crack Density (m/m ²)	Span Length	
				(ft)	(m)
75-044	End	South	0.12	37	11.3
75-045	End	South	0.26	62	18.9
	Interior	S. Ctr.	0.77	77	23.5
	Interior	N. Ctr.	0.58	77	23.5
	End	North	0.34	62	18.9
89-204	End	North	--	--	--
	Interior	Ctr.	--	--	--
	End	South	--	--	--
99-076	End	South	--	75	22.9
	Interior	--	--	100	30.5
	Interior	--	--	128	39.0
	Interior	--	--	128	39.0
	Interior	--	--	128	39.0
	Interior	--	--	128	39.0
	Interior	--	--	128	39.0
	Interior	--	--	100	30.5
	Interior	--	--	75	22.9
105-000*	Interior	--	0.33	86.5	26.4
	Interior	--	0.42	74	22.6
	Interior	--	0.12	74	22.6
	End	North	0.17	47.625	14.5
Two-Layer Bridges					
46-294	End	North	0.32	150	45.7
	End	South	0.27	150	45.7
46-295	End	South	0.25	150	45.7
	End	North	0.31	150	45.7
89-179	End	East	0.25	55	16.8
	Interior	Ctr.	0.14	70	21.3
	End	West	0.32	55	16.8
89-180	End	West	0.28	55	16.8
	Interior	Ctr.	0.33	70	21.3
	End	East	0.50	55	16.8
89-184	End	N. W.	0.77	48	14.6

Table A.12: (Continued)

Bridge Number	Span Type	Span Location	Crack Density (m/m ²)	Span Length	
				(ft)	(m)
89-184	Interior	N. W. Ctr.	0.58	93	28.3
	Interior	S. E. Ctr.	0.73	70	21.3
	End	S. E.	0.78	51	15.5
89-185	End	S. E.	0.90	49	14.9
	Interior	S. E. Ctr.	0.93	85	25.9
	Interior	N. W. Ctr.	0.53	71.5	21.8
89-186	End	N. W.	0.47	52	15.8
	End	N. W.	0.56	45	13.7
	Interior	N. W. Ctr.	0.59	60	18.3
89-187	Interior	S. E. Ctr.	0.39	60	18.3
	End	S. E.	0.54	45	13.7
	End	S. E.	1.00	45	13.7
89-189	Interior	S. E. Ctr.	0.97	60	18.3
	Interior	N. W. Ctr.	1.12	60	18.3
	End	N. W.	0.94	45	13.7
89-198	End	N. W.	0.51	66	20.1
	Interior	N. W. Ctr.	0.52	97	29.6
	Interior	S. E. Ctr.	0.68	97	29.6
89-199	End	S. E.	0.40	80	24.4
	End	N. W.	0.52	66	20.1
	Interior	N. W. Ctr.	0.67	97	29.6
89-200	Interior	S. E. Ctr.	0.83	97	29.6
	End	S. E.	0.63	80	24.4
	End	N. W.	0.60	84	25.6
89-201	Interior	Ctr.	0.45	150	45.7
	End	S. E.	0.55	84	25.6
	End	S. E.	0.99	84	25.6
105-021	Interior	Ctr.	0.44	150	45.7
	End	N. W.	0.76	84	25.6
	End	North	0.06	67	20.4
105-225	End	South	0.14	74	22.6
	End	North	0.23	60	18.3
105-226	Interior	Ctr.	0.10	76	23.2
	End	South	0.25	51	15.5
	End	South	0.26	60	18.3

Table A.12: (Continued)

Bridge Number	Span Type	Span Location	Crack Density (m/m ²)	Span Length	
				(ft)	(m)
105-226	Interior	Ctr.	0.05	76	23.2
	End	North	0.27	45	13.7
105-230	End	North	0.16	47	14.3
	Interior	N. Ctr.	0.00	66	20.1
	Interior	S. Ctr.	0.04	66	20.1
105-231	End	South	0.22	47	14.3
	End	North	0.17	47	14.3
	Interior	N. Ctr.	0.05	66	20.1
	Interior	S. Ctr.	0.04	66	20.1
105-262	End	South	0.25	47	14.3
	End	South	0.14	67	20.4
	Interior	Ctr.	0.18	135	41.1
105-263	End	North	0.20	67	20.4
	End	South	0.17	67	20.4
	Interior	Ctr.	0.17	135	41.1
105-265	End	North	0.00	67	20.4
	End	North	0.01	43	13.1
	Interior	Ctr.	0.00	57	17.4
105-268	End	South	0.04	43	13.1
	End	West	0.60	57	17.4
	Interior	Ctr.	0.72	57	17.4
105-269	End	East	0.54	75	22.9
	End	West	0.45	122	37.2
	End	East	0.45	122	37.2
Noncomposite Bridges					
23-022	End	East	0.44	37	11.3
	Interior	Ctr.	0.69	82	25.0
105-198	End	West	0.29	37	11.3
	End	South	0.10	58	17.7
	Interior	S. Int.	0.21	70	21.3
	Interior	S. Ctr.	0.31	72	21.9
	Interior	N. Ctr.	0.25	70	21.3
	Interior	N. Int.	0.27	62	18.9

Table A.12: (Continued)

Bridge Number	Span Type	Span Location	Crack Density (m/m ²)	Span Length	
				(ft)	(m)
105-198	End	North	0.27	44	13.4
105-199	End	South	0.12	58	17.7
	Interior	S. Int.	0.18	70	21.3
	Interior	S. Ctr.	0.18	72	21.9
	Interior	N. Ctr.	0.19	70	21.3
	Interior	N. Int.	0.31	62	18.9
	End	North	0.07	44	13.4

* Bridge has no assigned serial number. Project No. is 105-U-1262-01.

-- Denotes missing data.

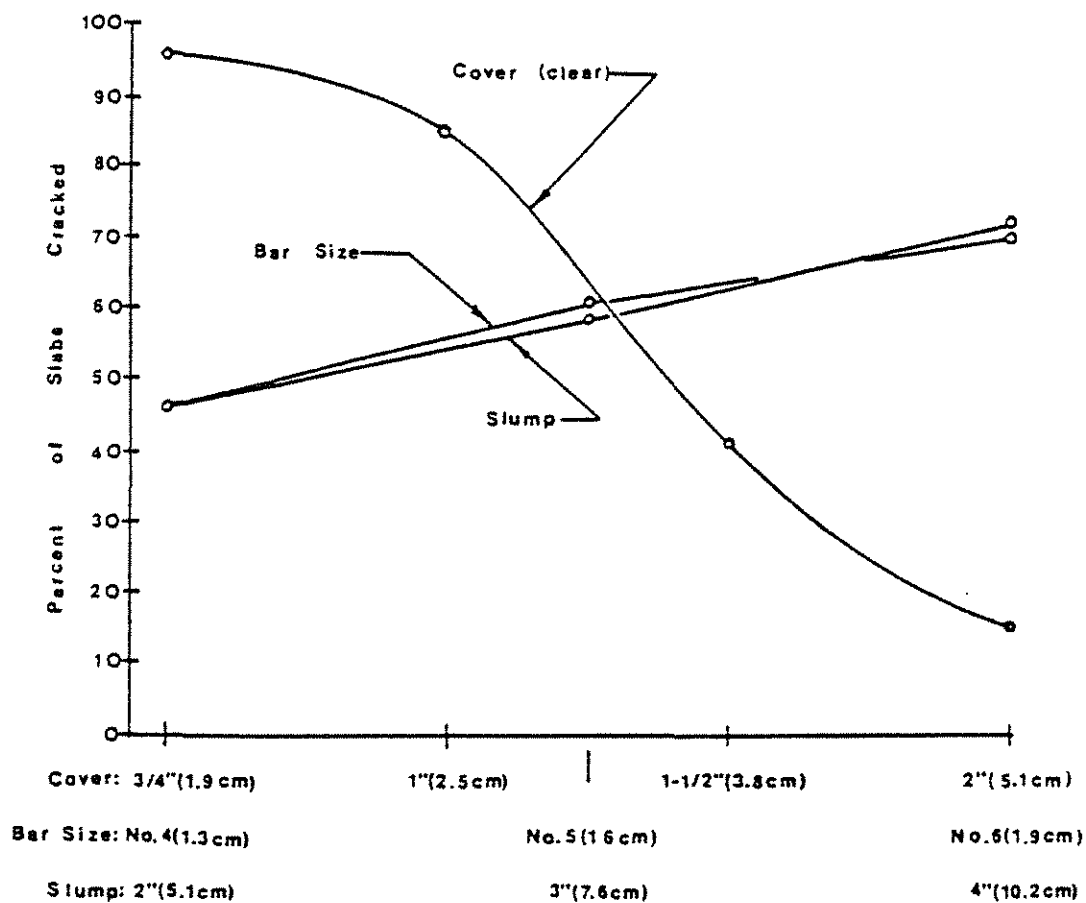


Fig. 1.1: Cracking as a function of bar size, slump, and cover.
(Dakhil et al. 1975)

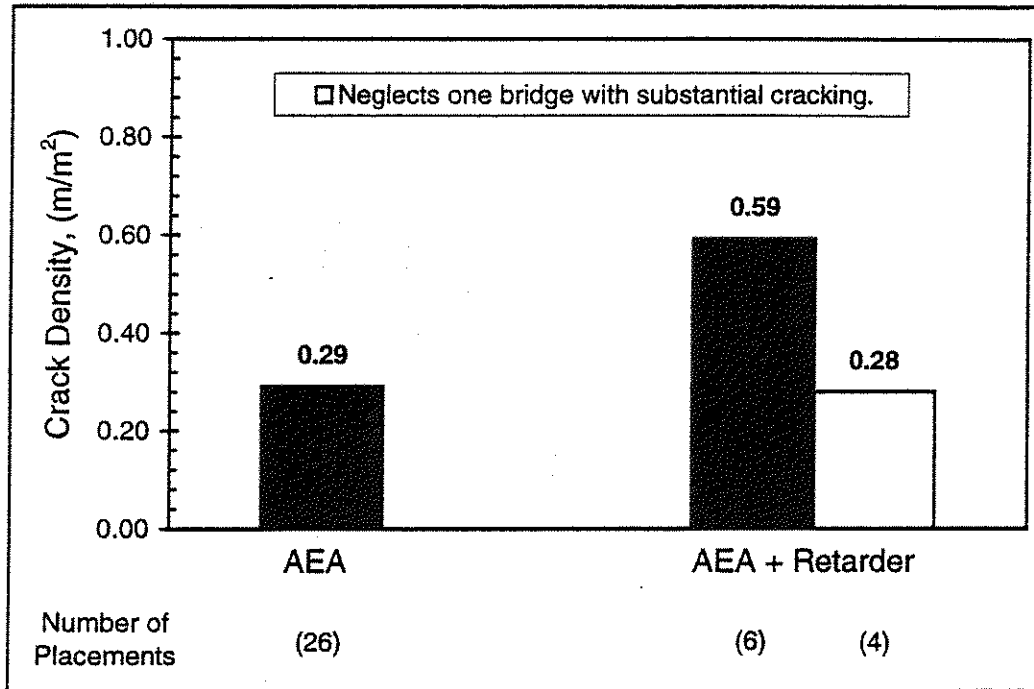


Fig. 3.1: Mean crack density of individual placements versus admixture combinations for monolithic bridge decks.

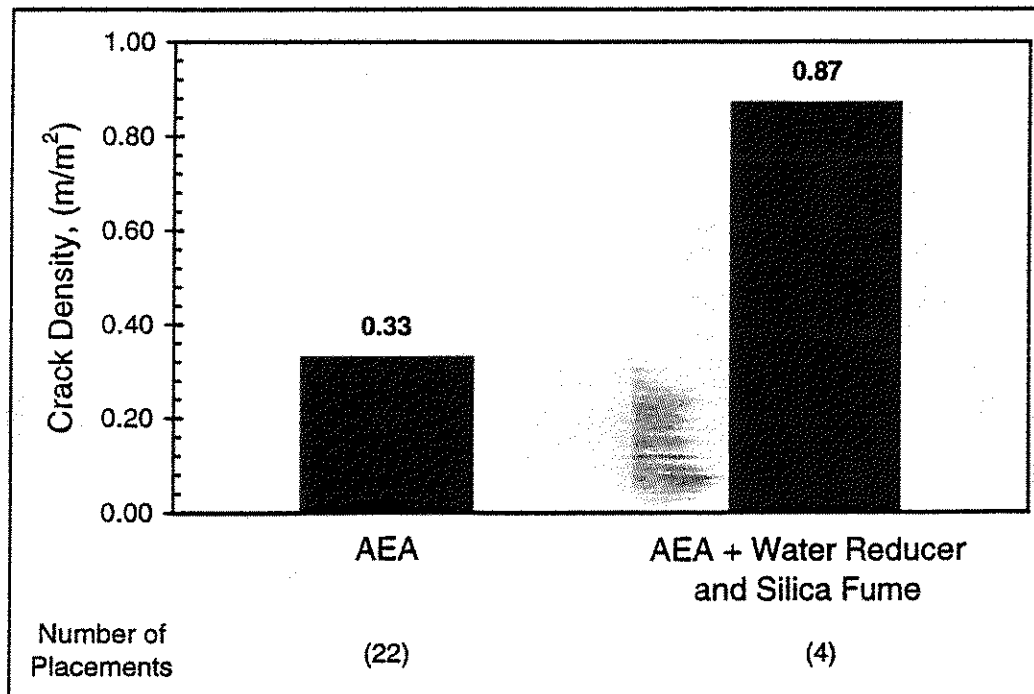


Fig. 3.2: Mean crack density of individual placements versus admixture combinations for bridge deck overlays.

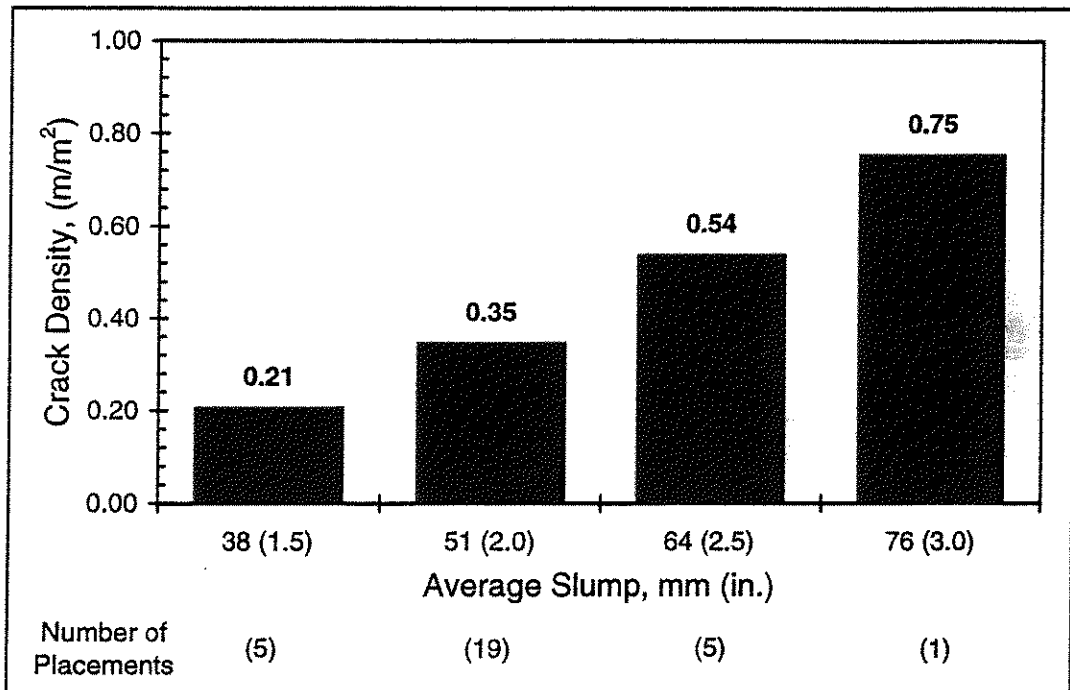


Fig. 3.3: Mean crack density of individual placements versus concrete slump for monolithic bridge decks.

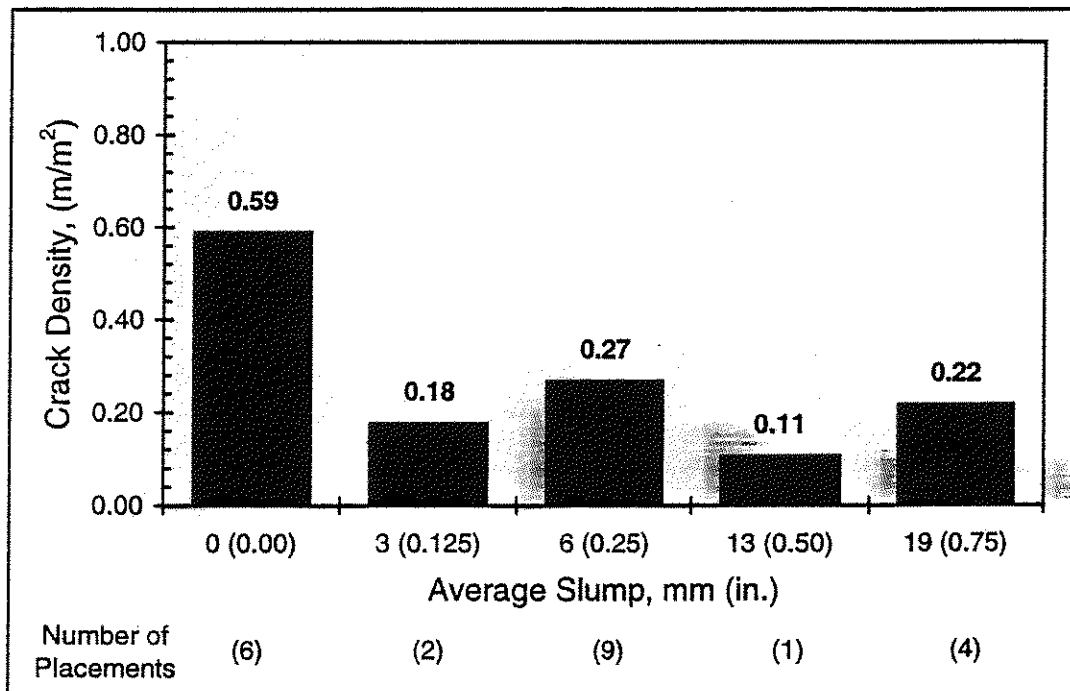


Fig. 3.4: Mean crack density of individual placements versus concrete slump for bridge deck overlays.

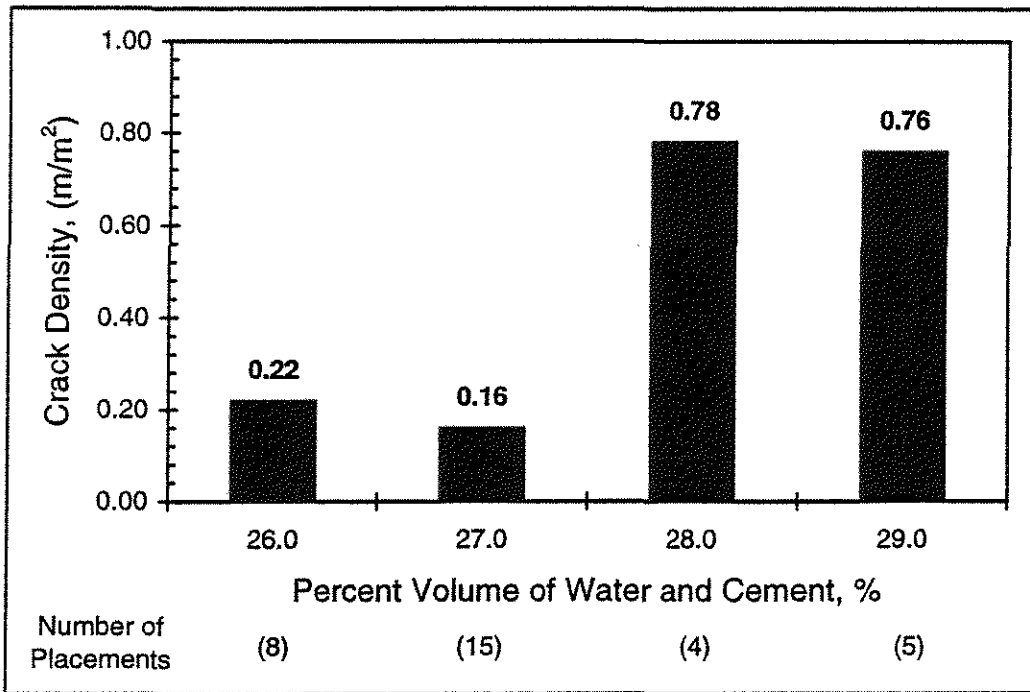


Fig. 3.5: Mean crack density of individual placements versus the percent volume of water and cement for monolithic bridge decks.

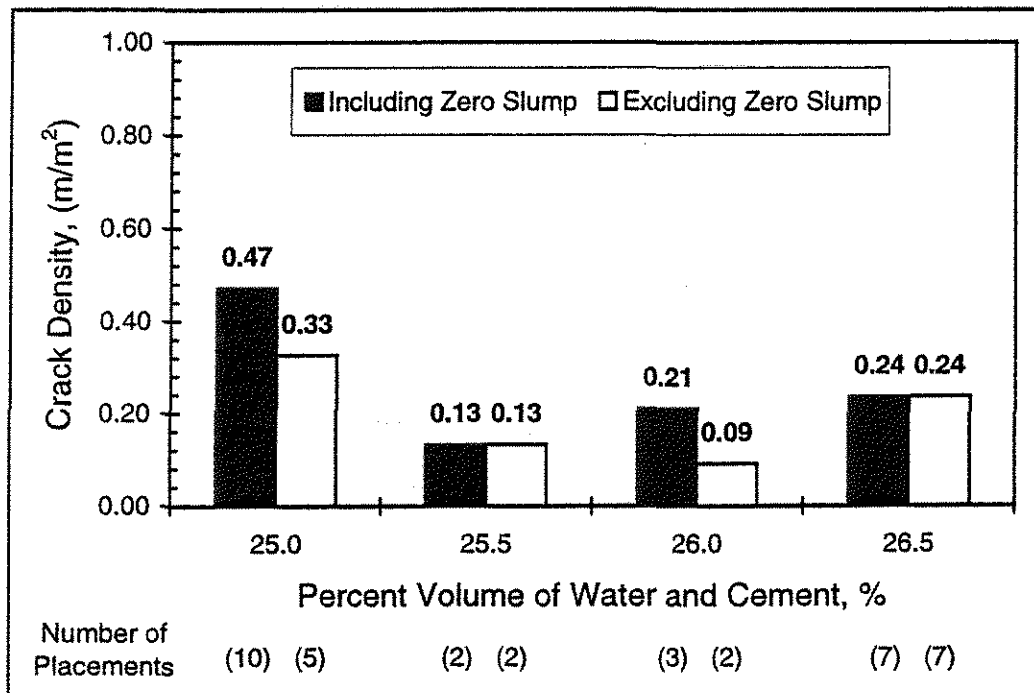


Fig. 3.6: Mean crack density of individual placements versus the percent volume of water and cement for bridge deck overlays.

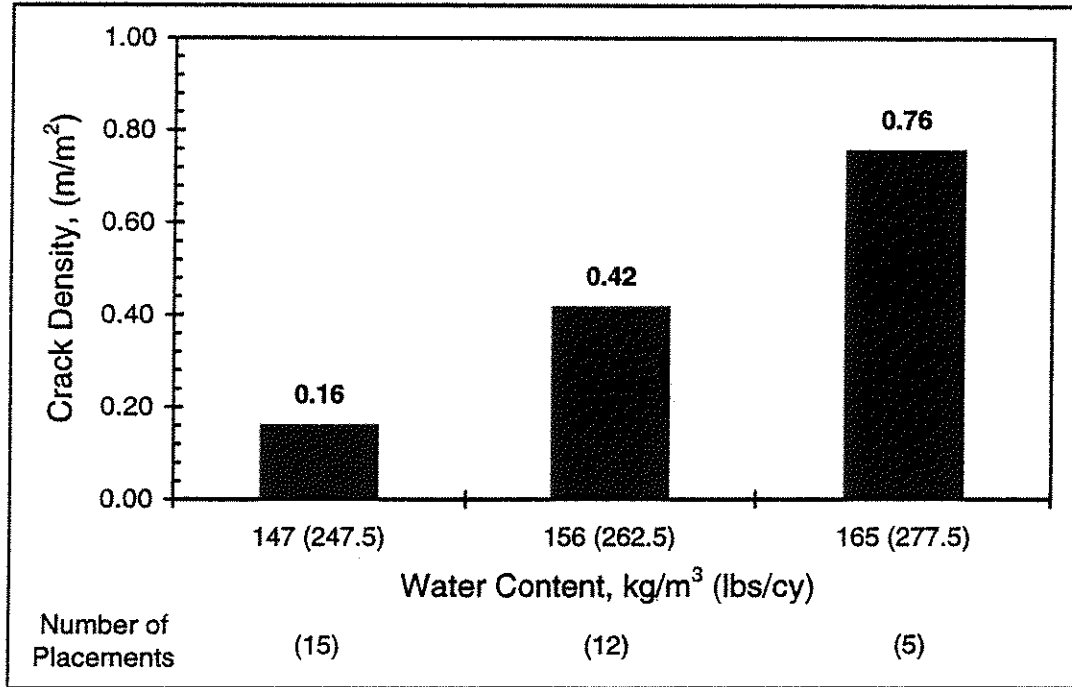


Fig. 3.7: Mean crack density of individual placements versus water content for monolithic bridge decks.

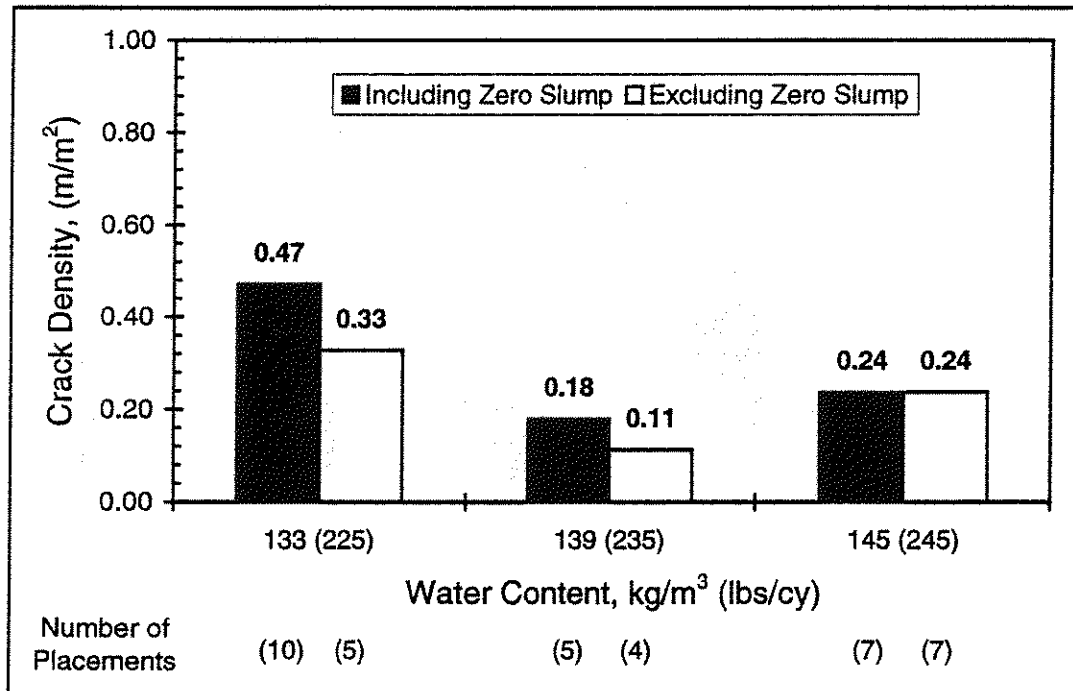


Fig. 3.8: Mean crack density of individual placements versus water content for bridge deck overlays.

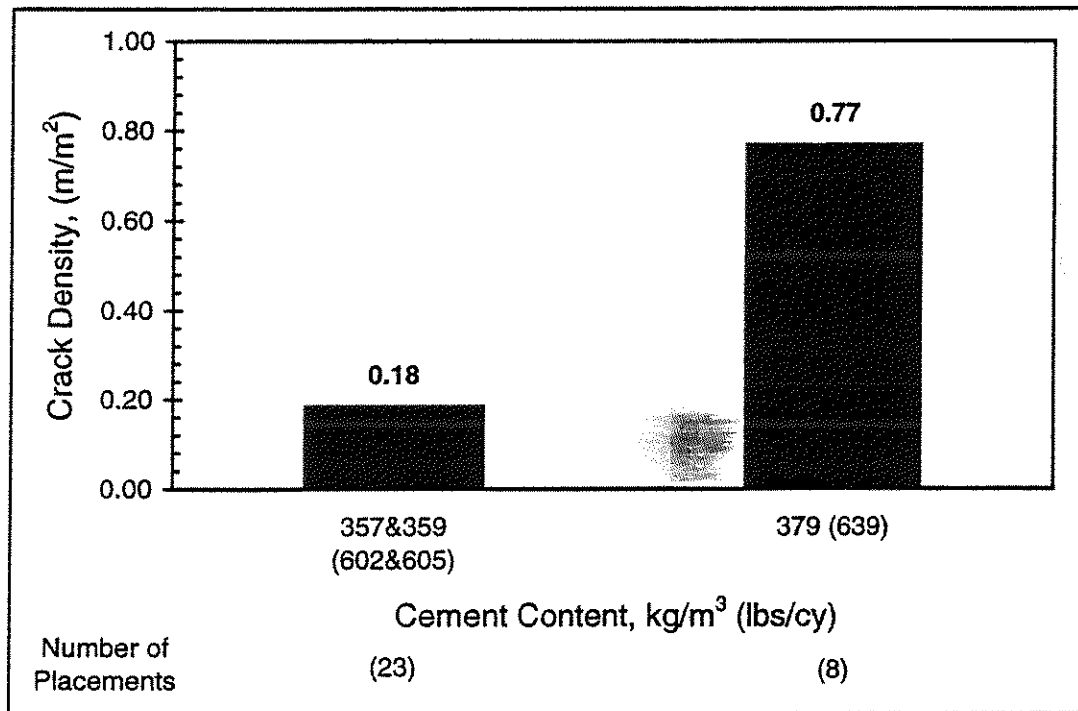


Fig. 3.9: Mean crack density of individual placements versus cement content for monolithic bridge decks.

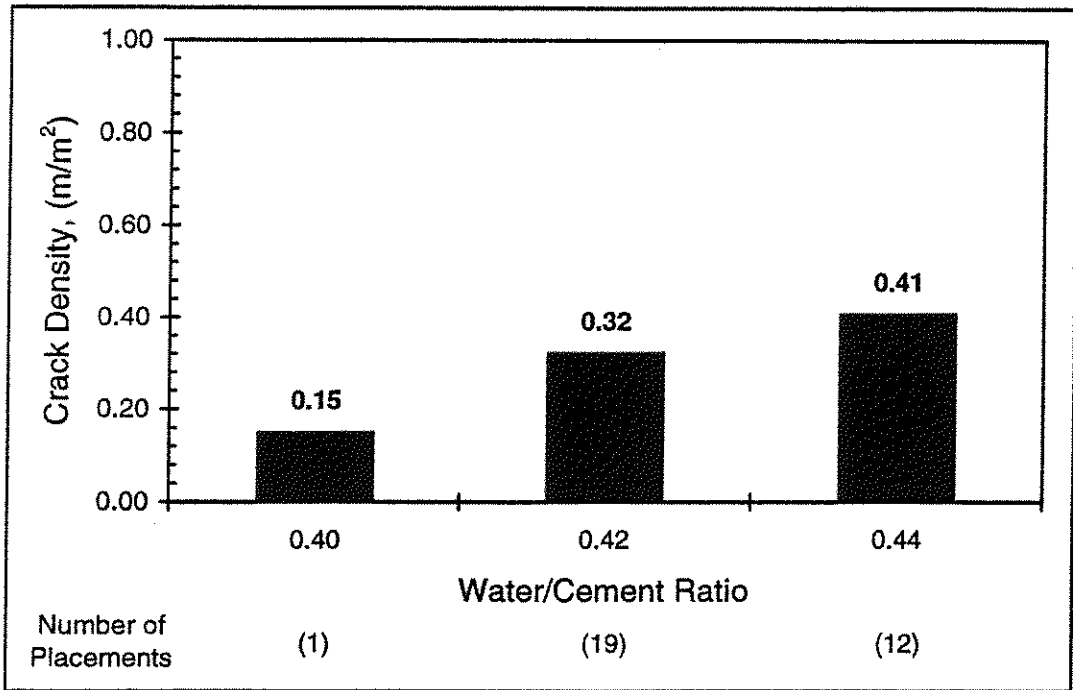


Fig 3.10: Mean crack density of individual placements versus water/cement ratio for monolithic bridge decks.

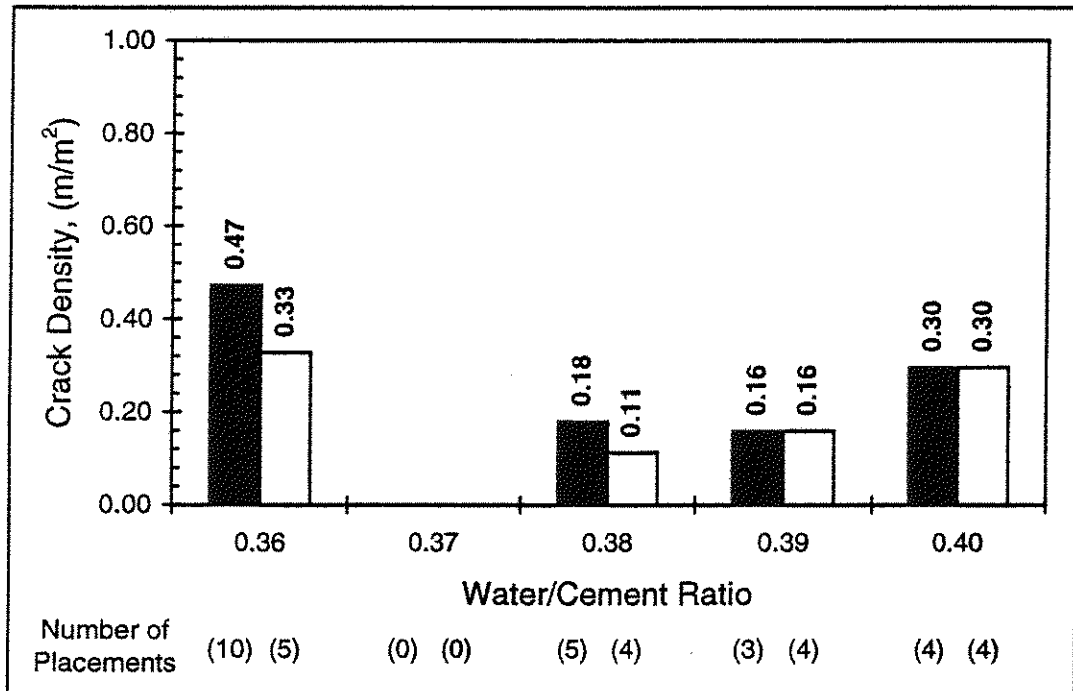


Fig. 3.11: Mean crack density of individual placements versus water/cement ratio for bridge deck overlays.

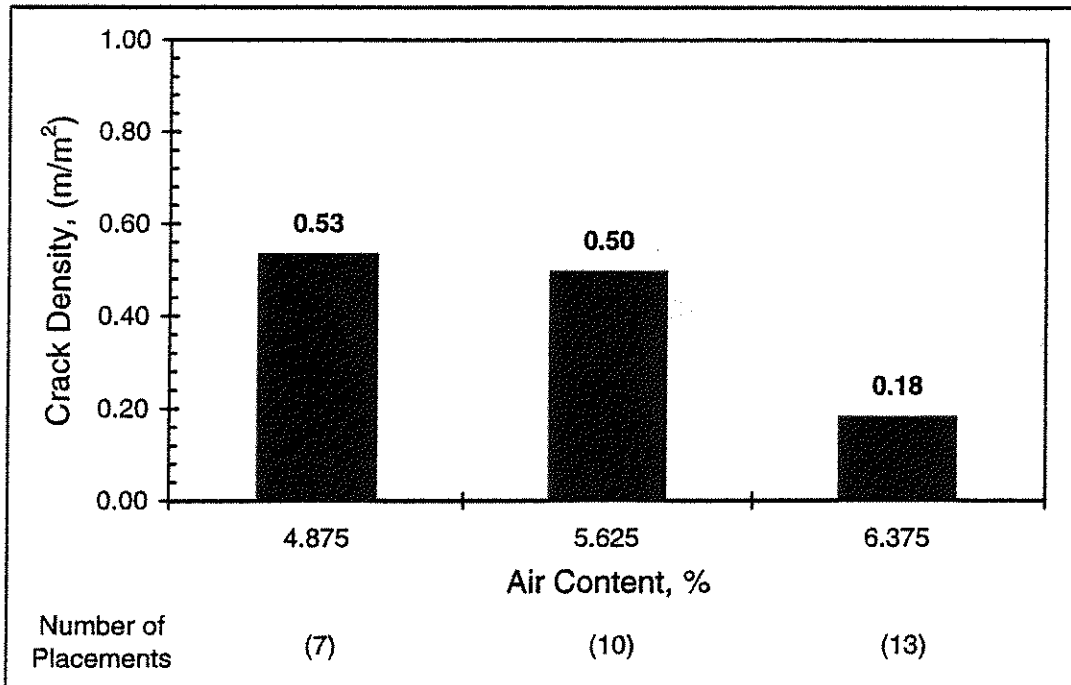


Fig. 3.12: Mean crack density of individual placements versus air content for monolithic bridge decks.

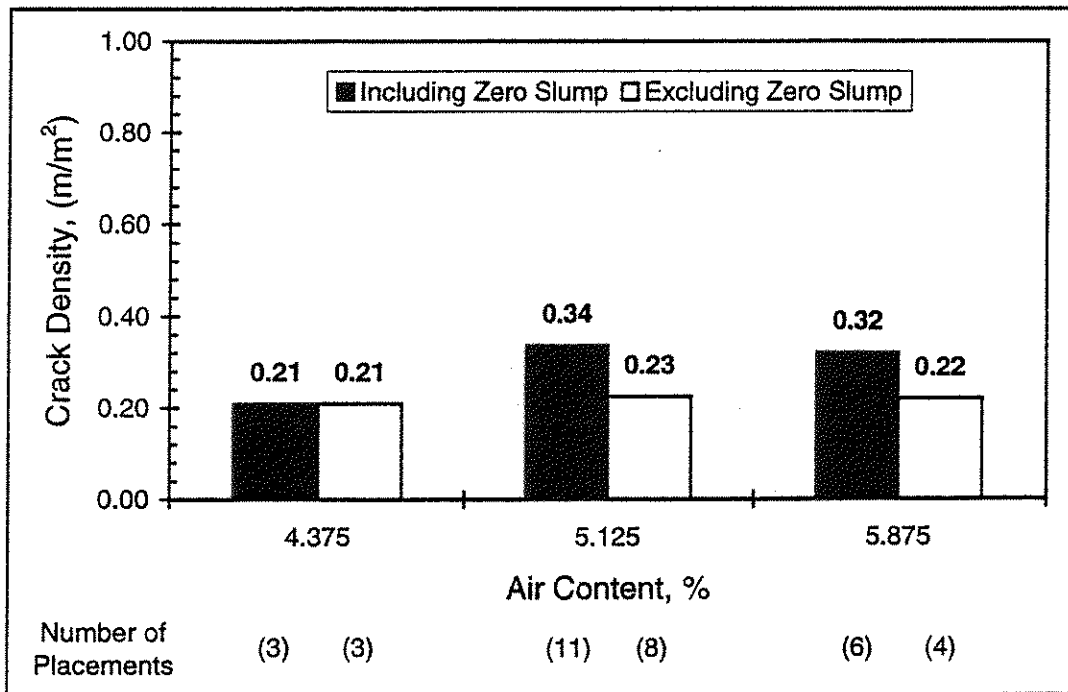


Fig. 3.13: Mean crack density of individual placements versus air content for bridge deck overlays.

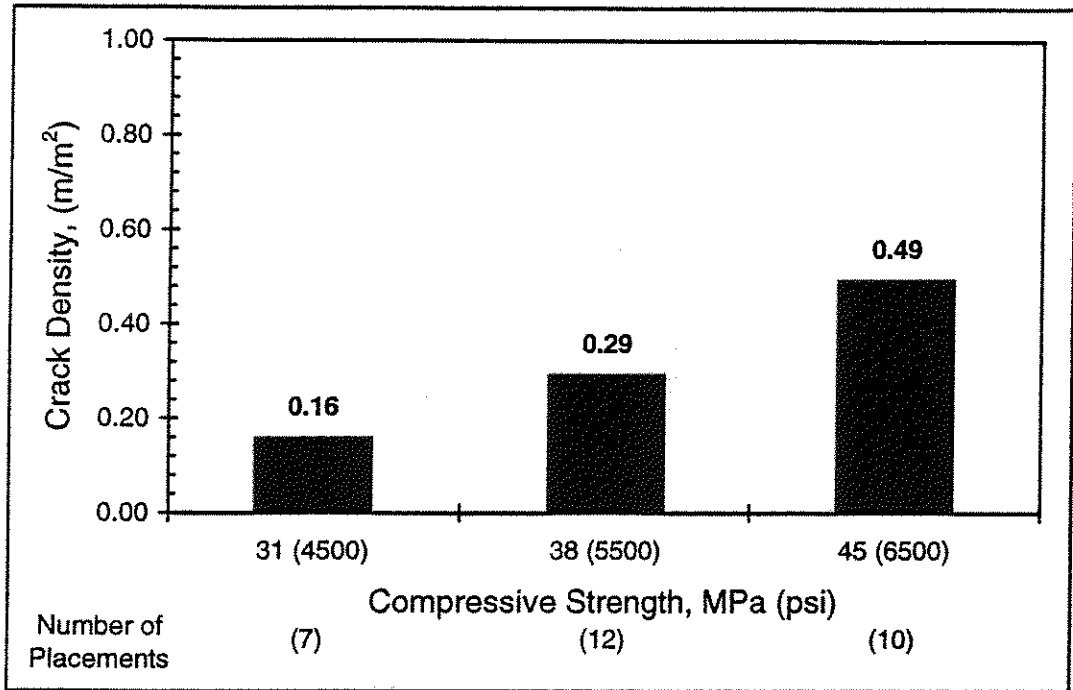


Fig. 3.14: Mean crack density of individual placements versus compressive strength for monolithic bridge decks.

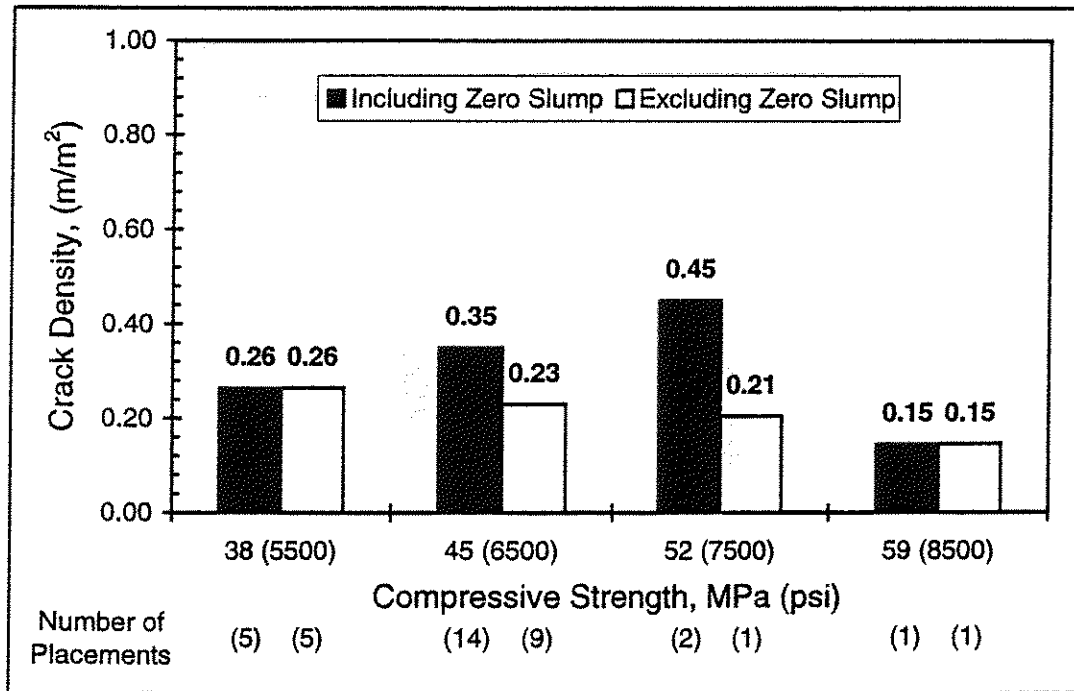


Fig. 3.15: Mean crack density of individual placements versus compressive strength for bridge deck overlays.

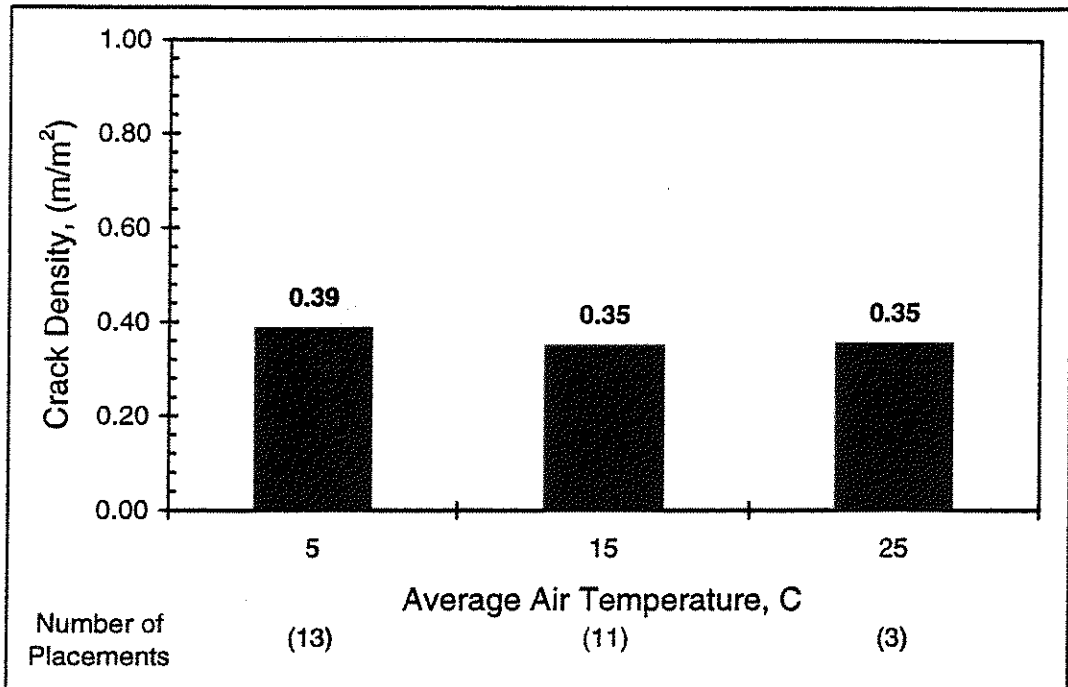


Fig. 3.16: Mean crack density of individual placements versus average air temperature for monolithic bridge decks.

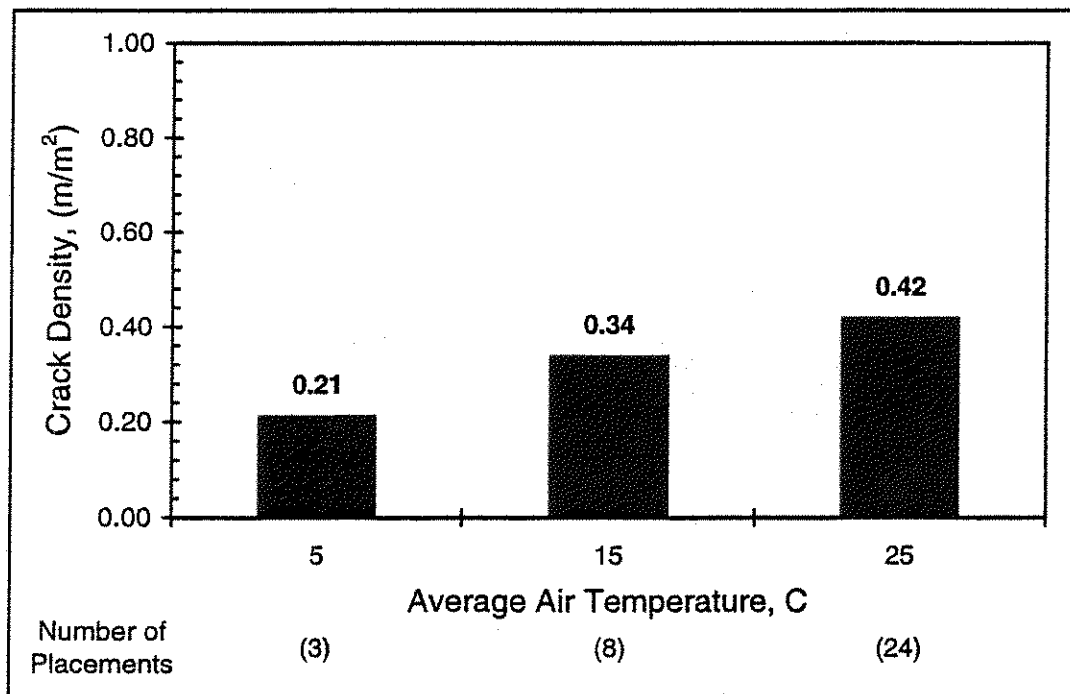


Fig. 3.17: Mean crack density of individual placements versus average air temperature for bridge deck overlays.

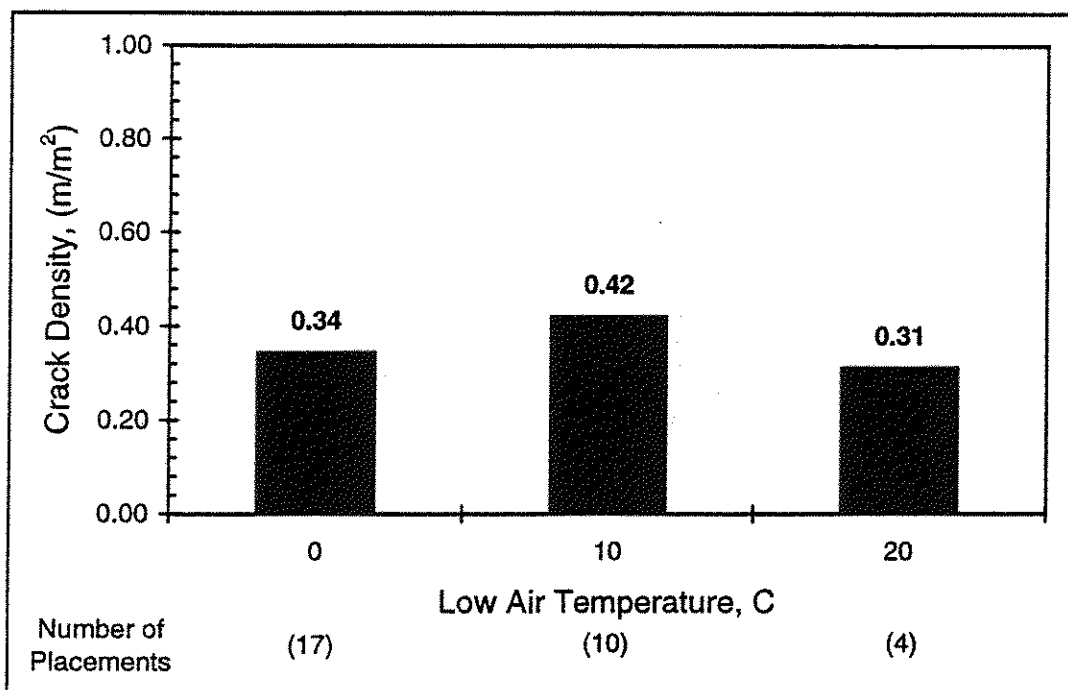


Fig. 3.18: Mean crack density of individual placements versus low air temperature for monolithic bridge decks.

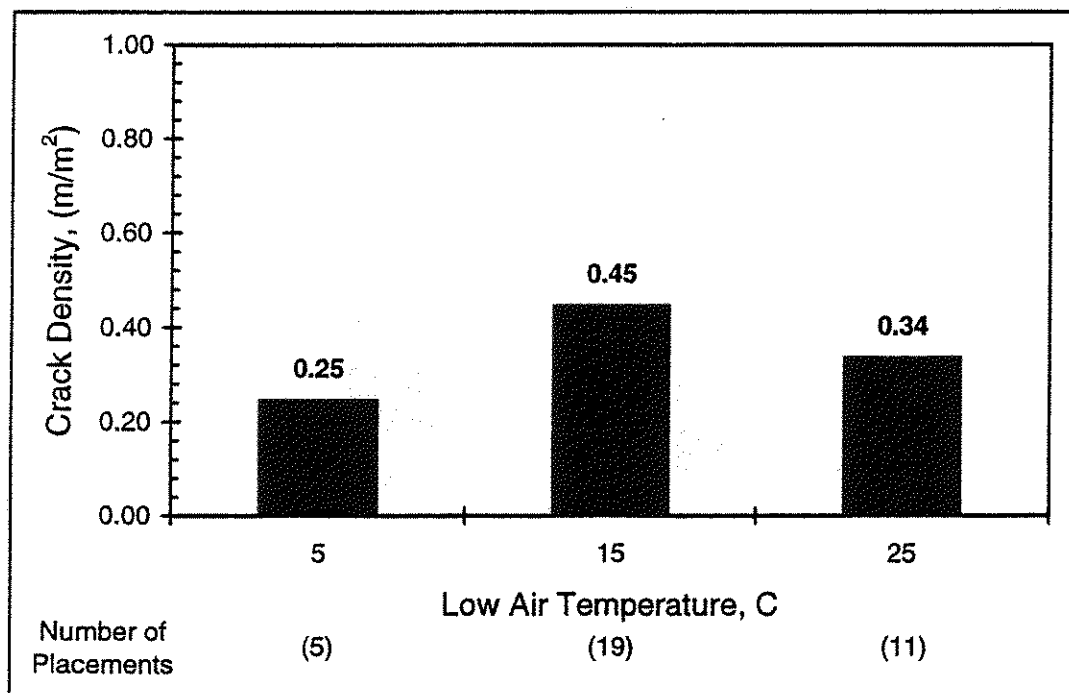


Fig. 3.19: Mean crack density of individual placements versus low air temperature for bridge deck overlays.

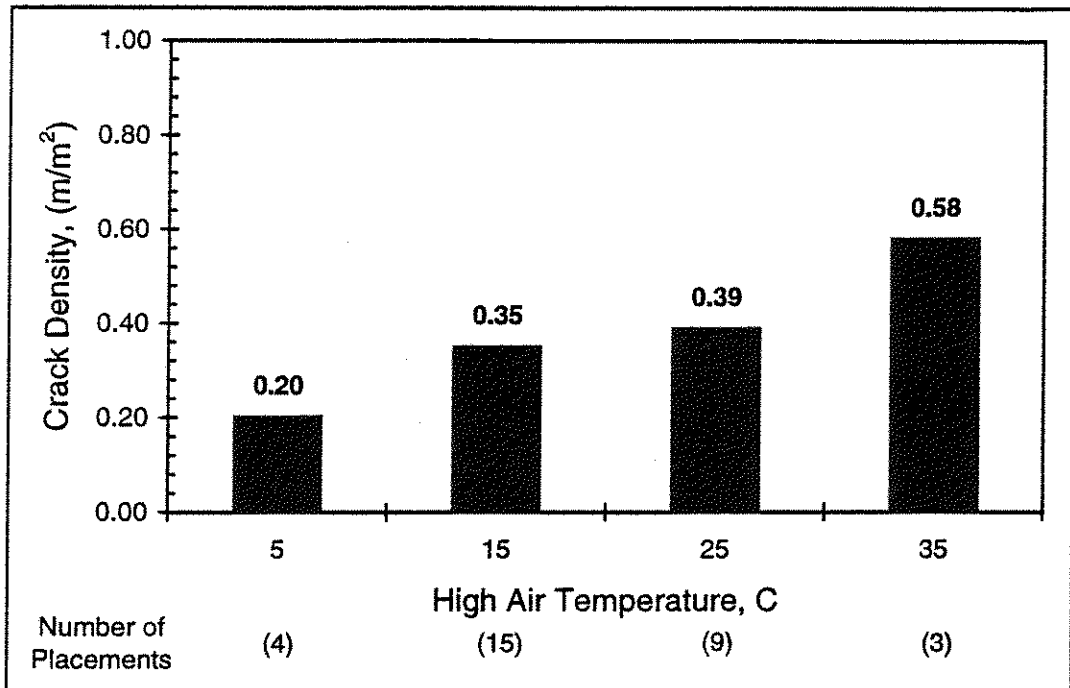


Fig. 3.20: Mean crack density of individual placements versus high air temperature for monolithic bridge decks.

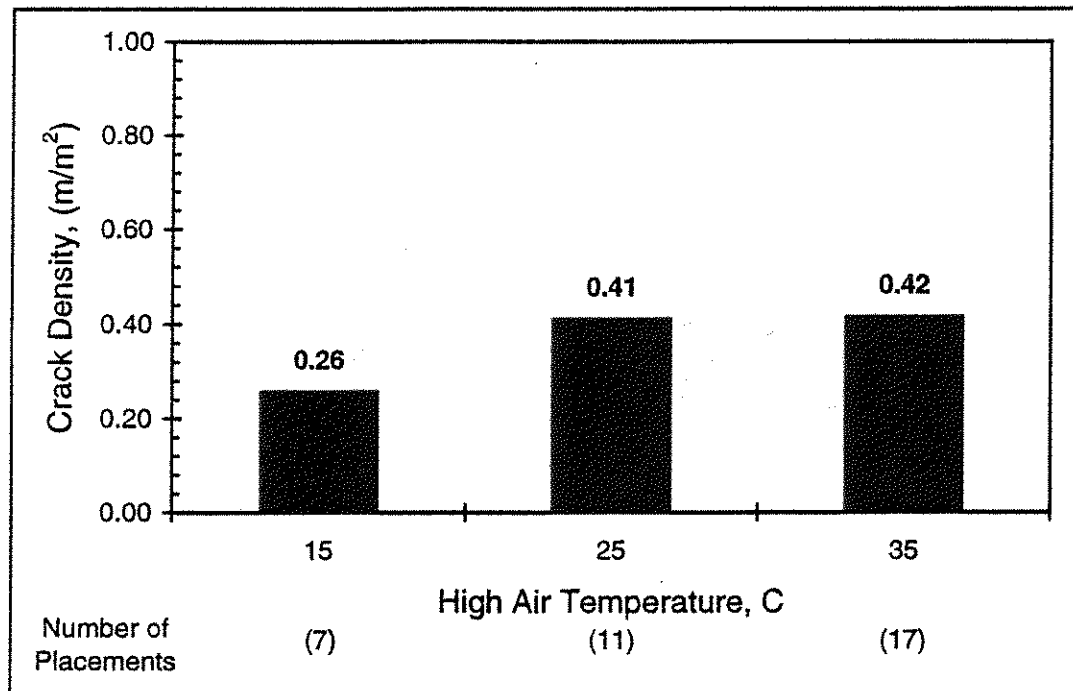


Fig. 3.21: Mean crack density of individual placements versus high air temperature for bridge deck overlays.

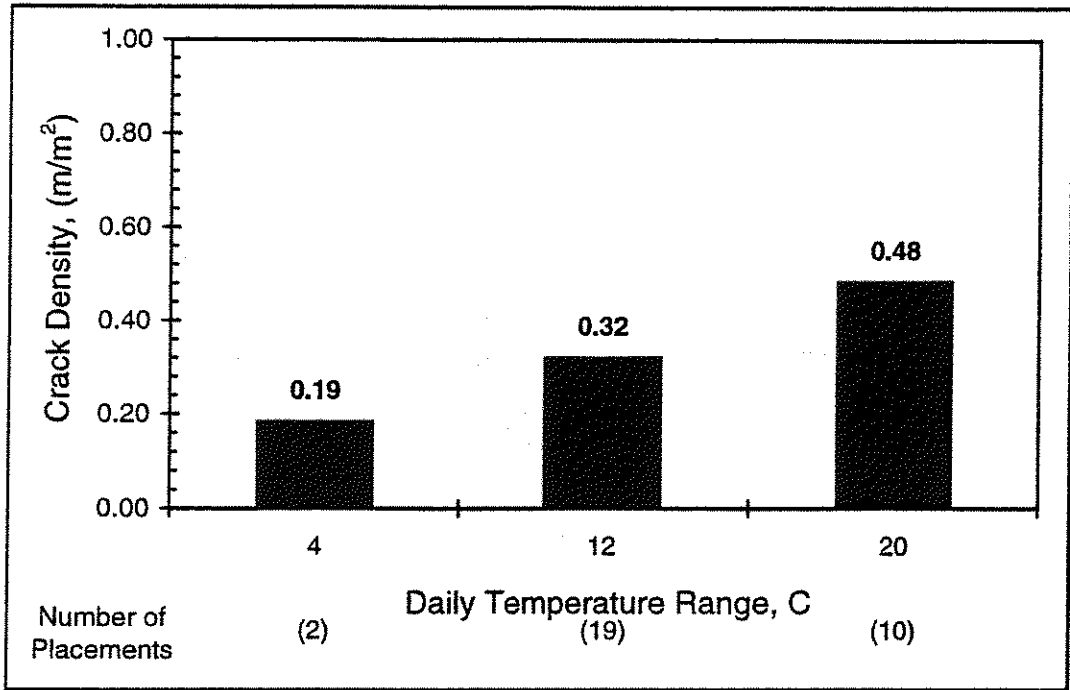


Fig. 3.22: Mean crack density of individual placements versus daily temperature range for monolithic bridge decks.

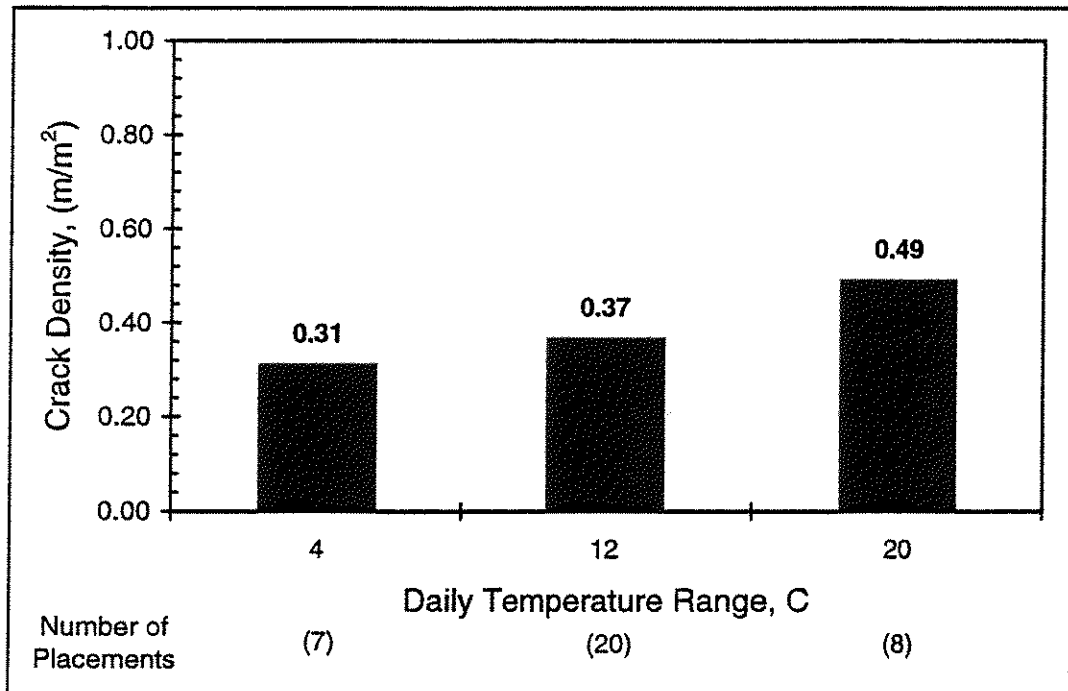


Fig. 3.23: Mean crack density of individual placements versus daily temperature range for bridge deck overlays.

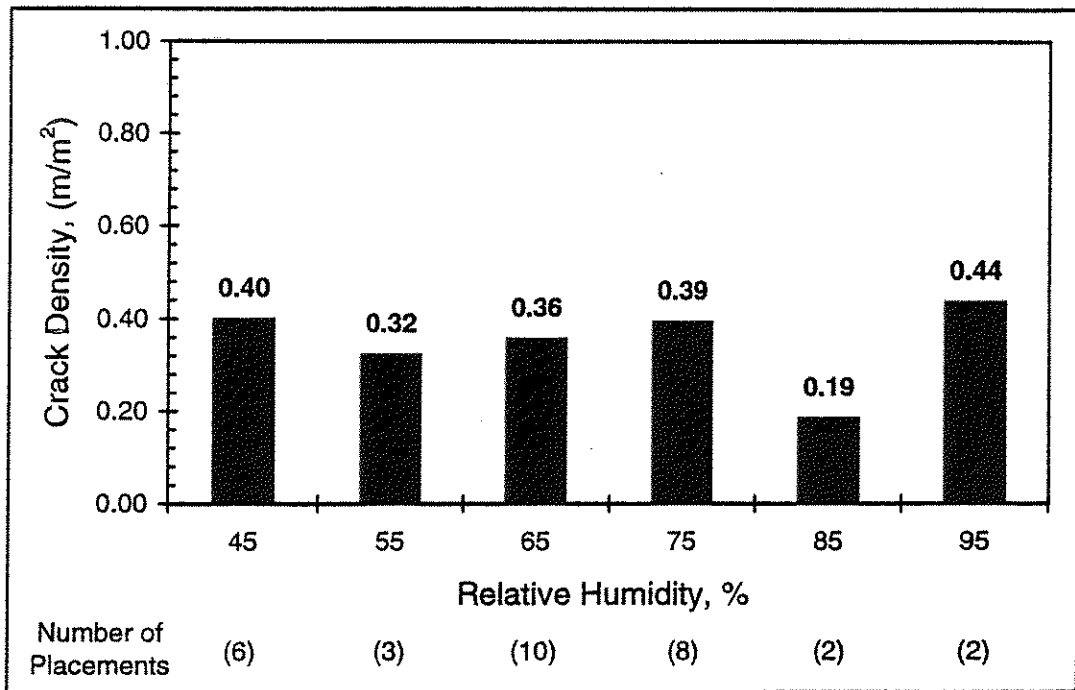


Fig. 3.24: Mean crack density of individual placements versus relative humidity for monolithic bridge decks.

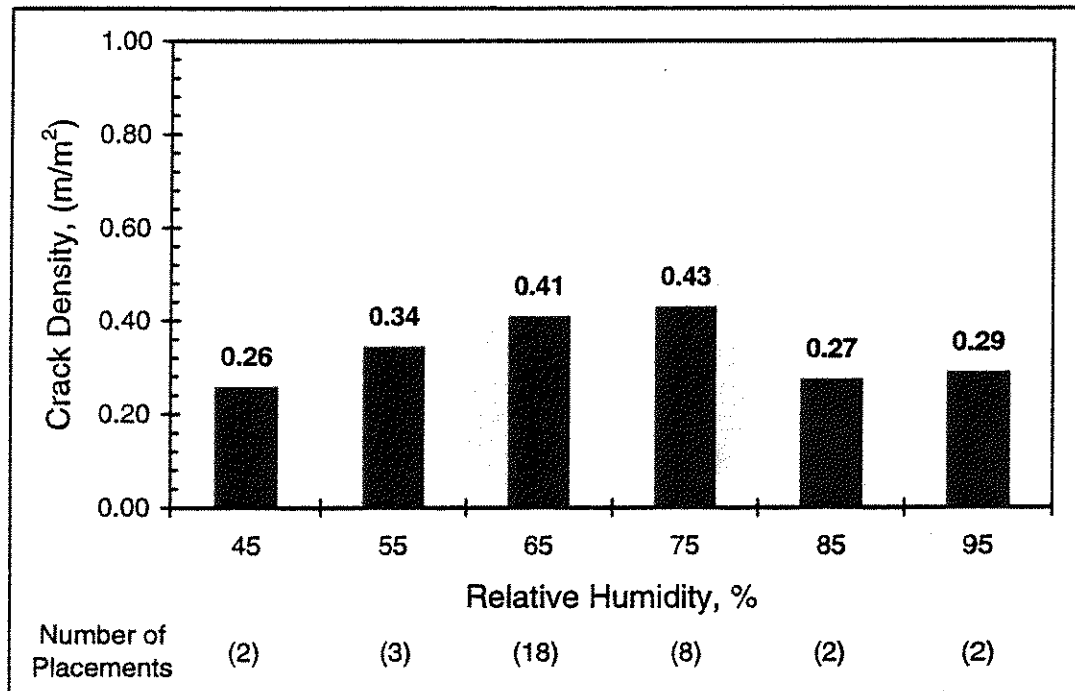


Fig. 3.25: Mean crack density of individual placements versus relative humidity for bridge deck overlays.

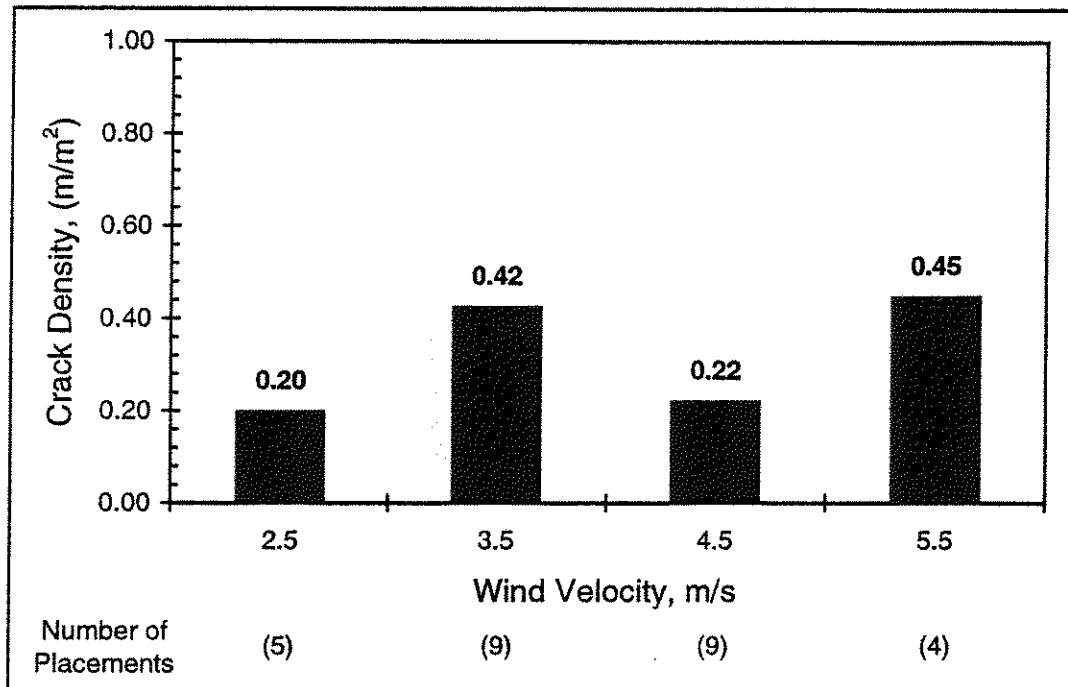


Fig. 3.26: Mean crack density of individual placements versus wind velocity for monolithic bridge decks.

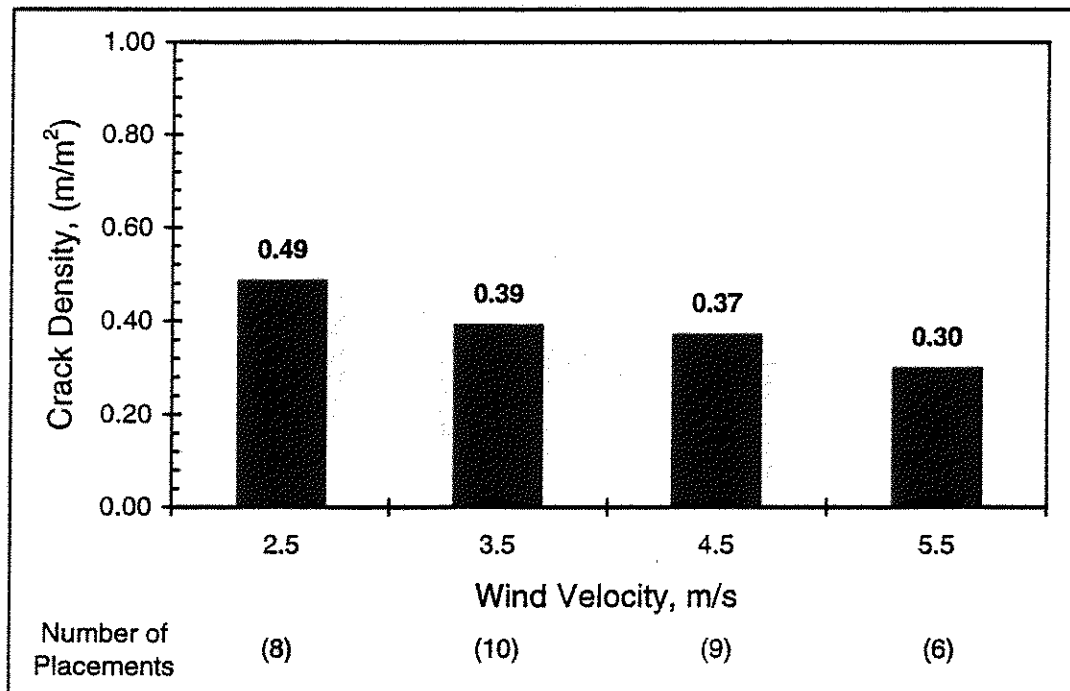


Fig. 3.27: Mean crack density of individual placements versus wind velocity for bridge deck overlays.

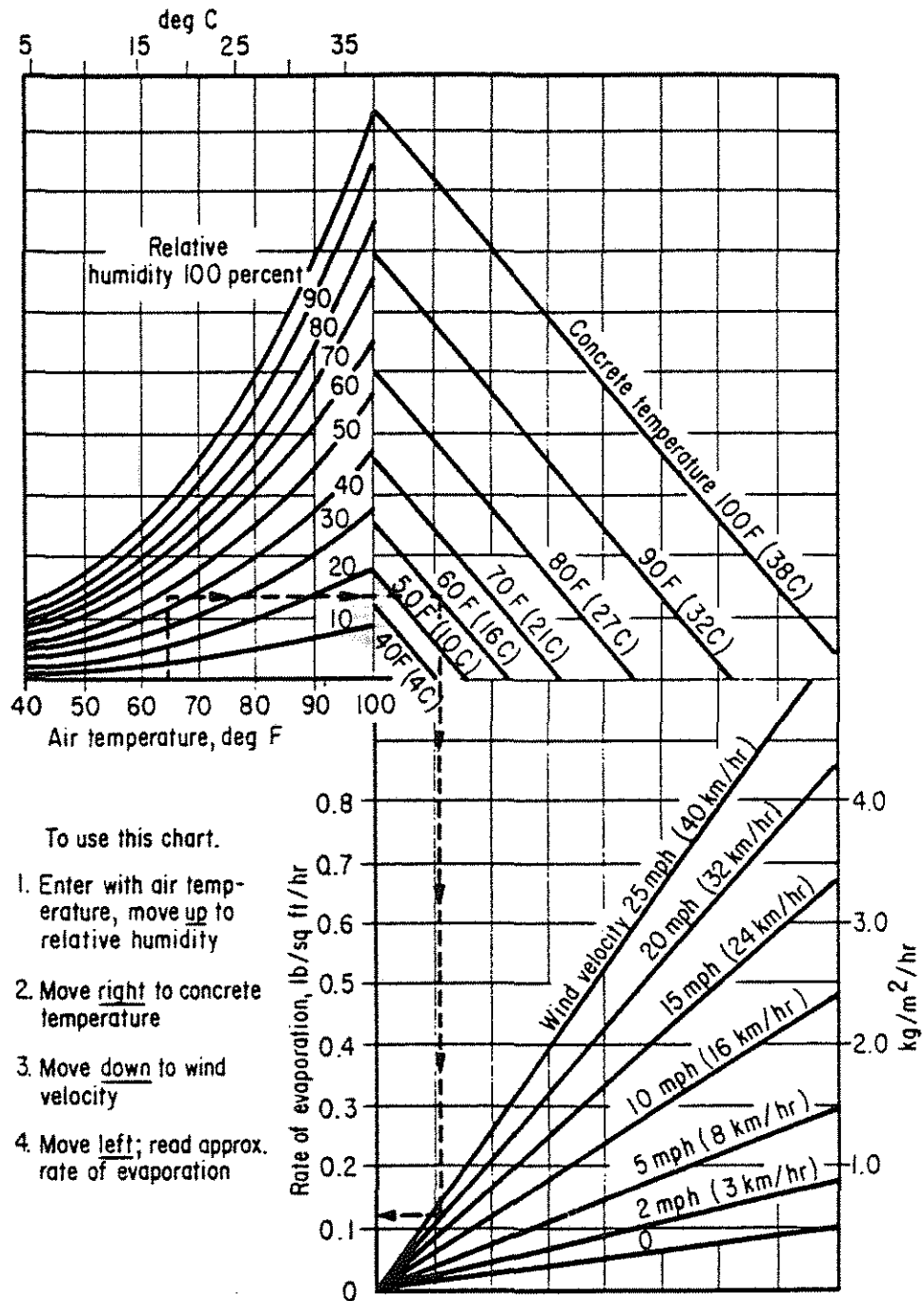


Fig. 3.28: Graphic representation of the relationship between air temperature, relative humidity, concrete temperature, wind velocity, and rate of evaporation of free surface moisture. (Lerch 1957)

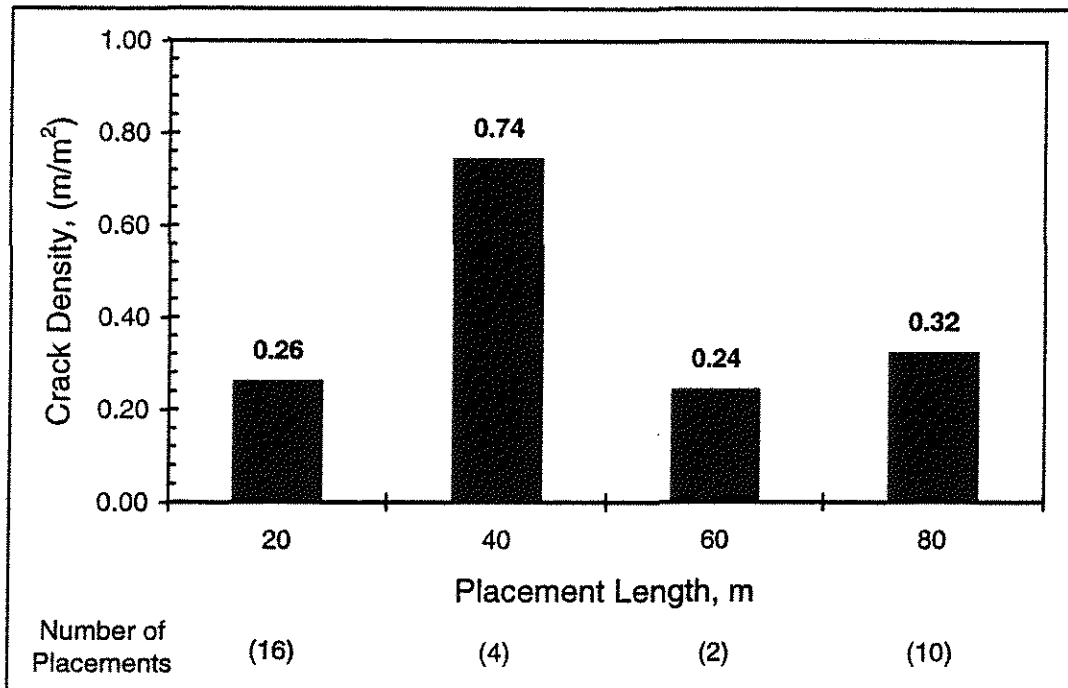


Fig. 3.29: Mean crack density of individual placements versus placement length for monolithic bridge decks.

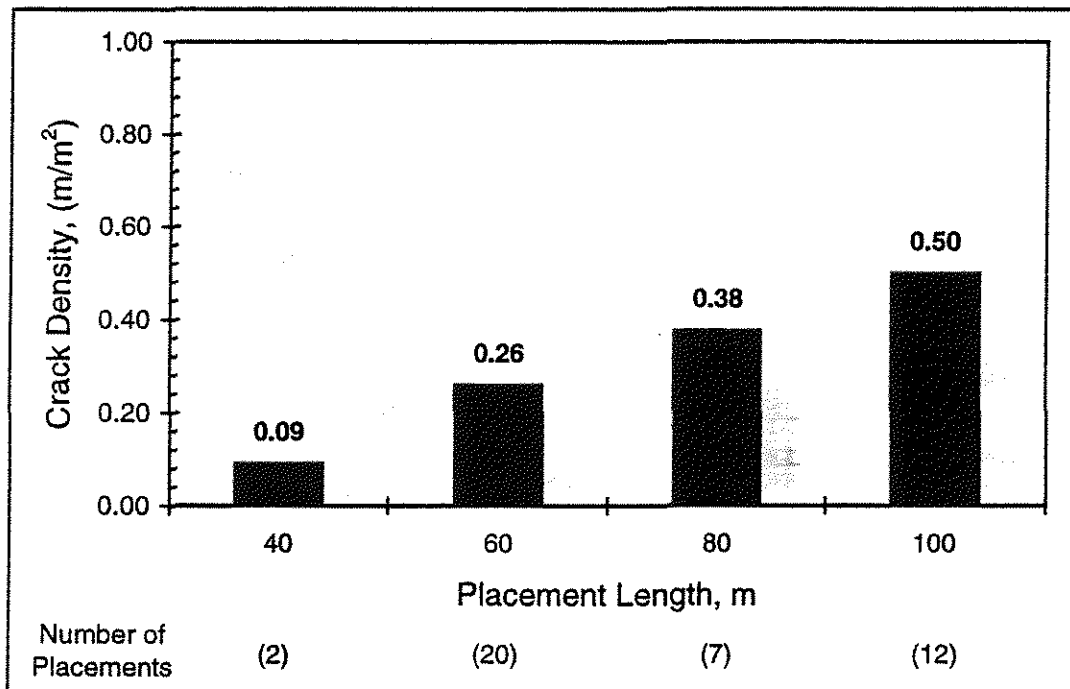


Fig. 3.30: Mean crack density of individual placements versus placement length for bridge deck overlays.

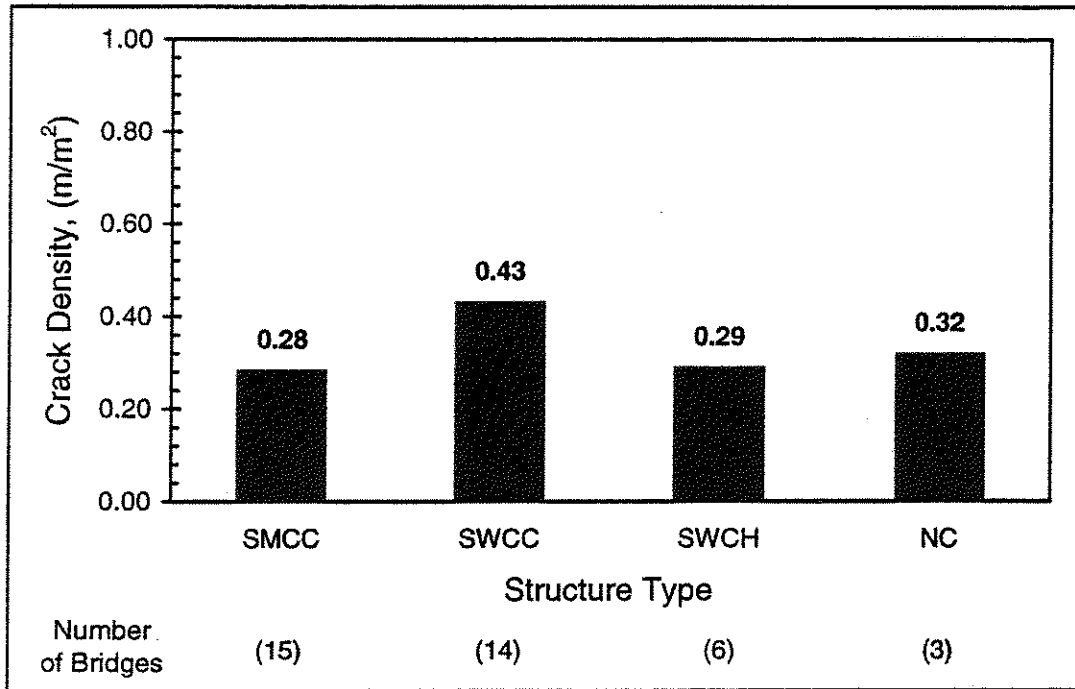


Fig. 3.31: Mean crack density of entire bridge decks versus structure type for all bridges.

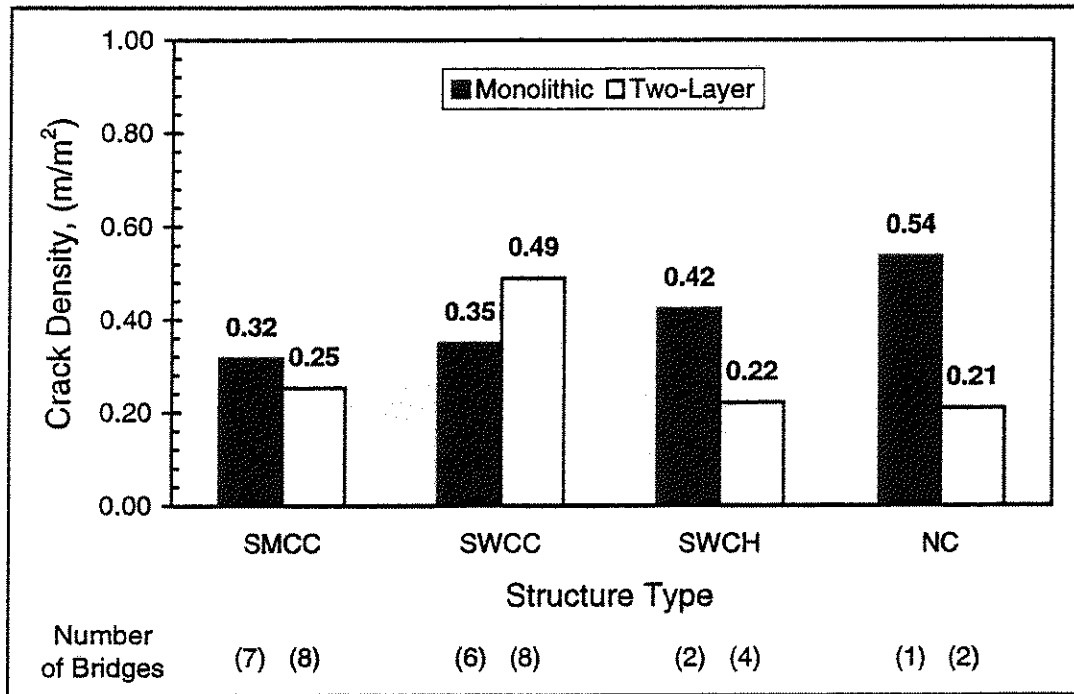


Fig. 3.32: Mean crack density of entire bridge decks versus structure type, based on deck type, for all bridges.

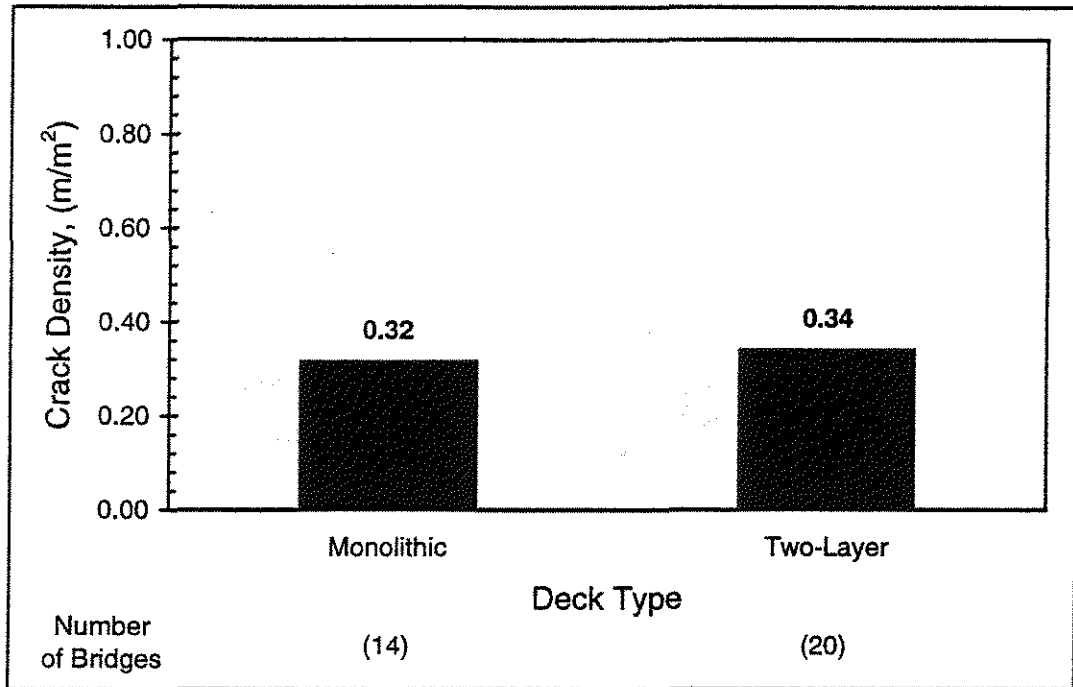


Fig. 3.33: Mean crack density of entire bridge decks versus deck type for composite bridges.

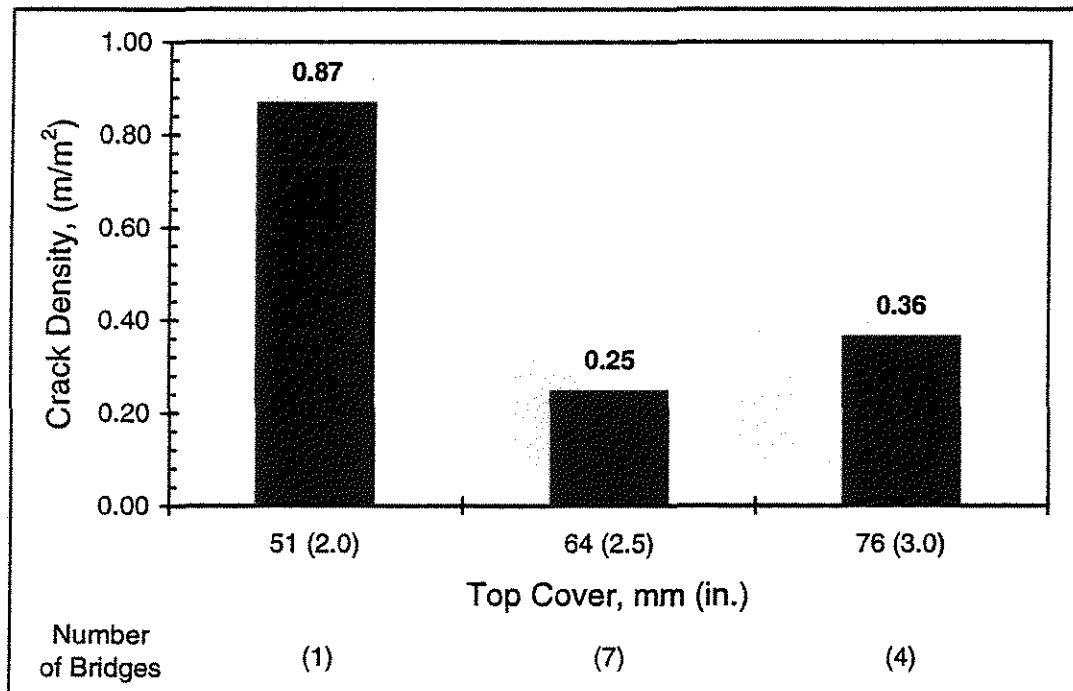


Fig. 3.34: Mean crack density of entire bridge decks versus top cover thickness for monolithic composite bridges.

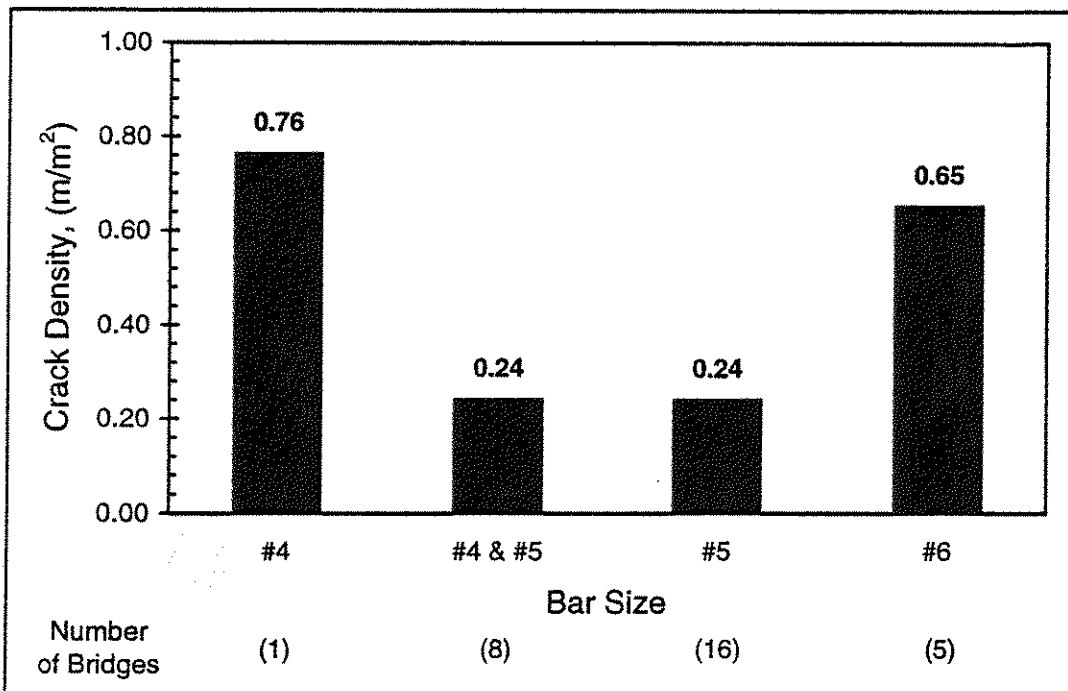


Fig. 3.35: Mean crack density of entire bridge decks versus top transverse reinforcing bar size for composite bridges.

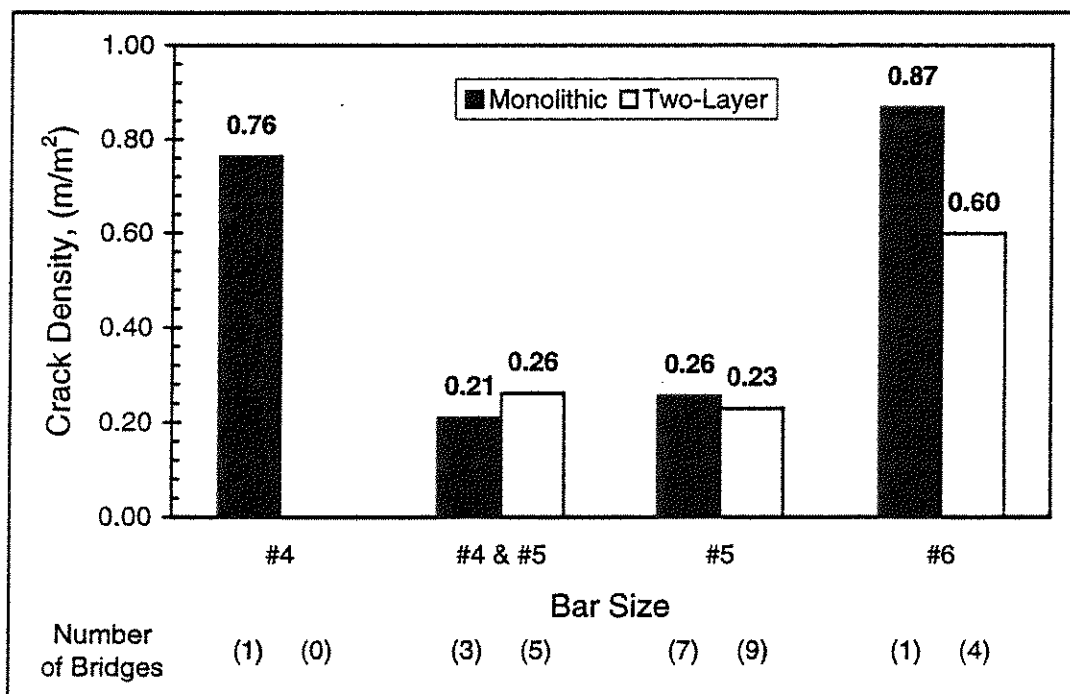


Fig. 3.36: Mean crack density of entire bridge decks versus top transverse reinforcing bar size, based on deck type, for composite bridges.

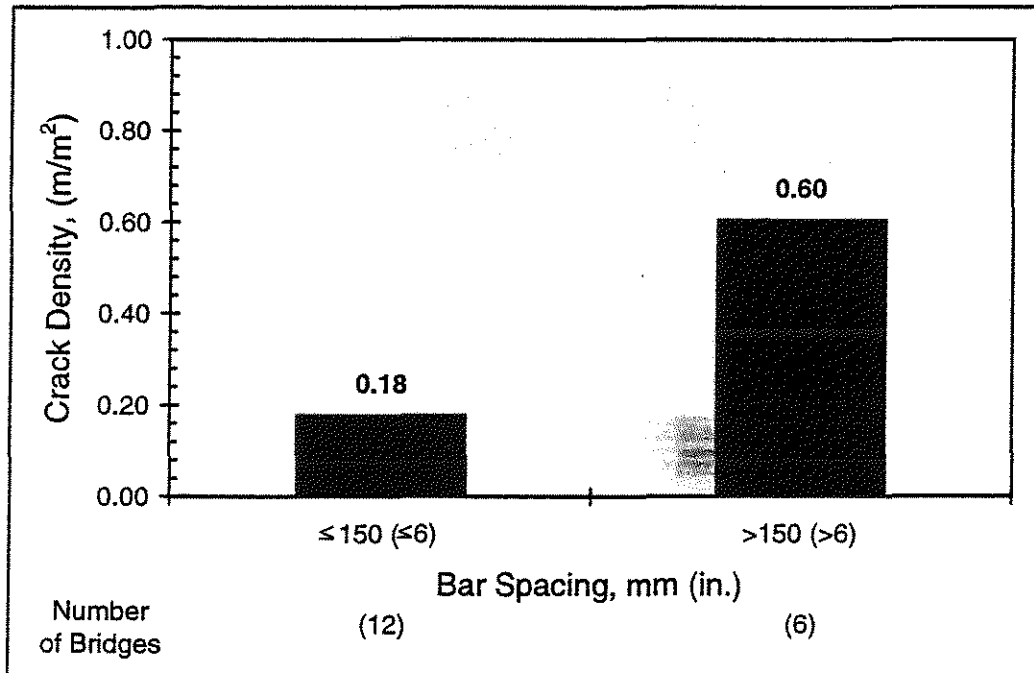


Fig. 3.37: Mean crack density of entire bridge decks versus top transverse bar spacing for two-layer composite bridges.

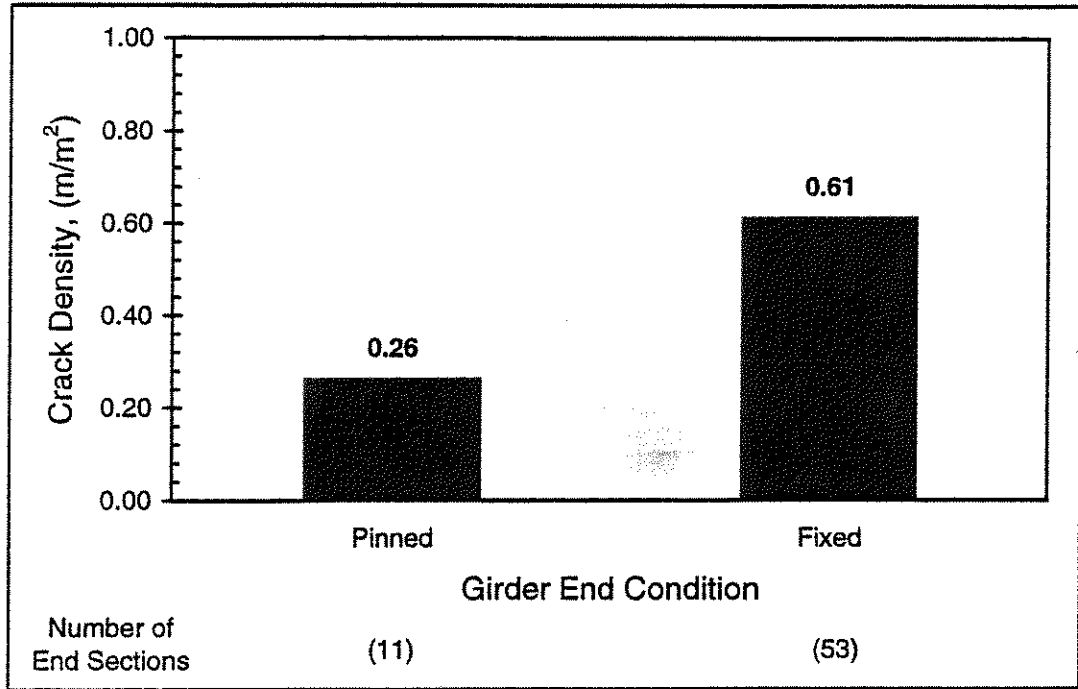


Fig. 3.38: Mean crack density of end sections versus girder end condition for composite bridges.

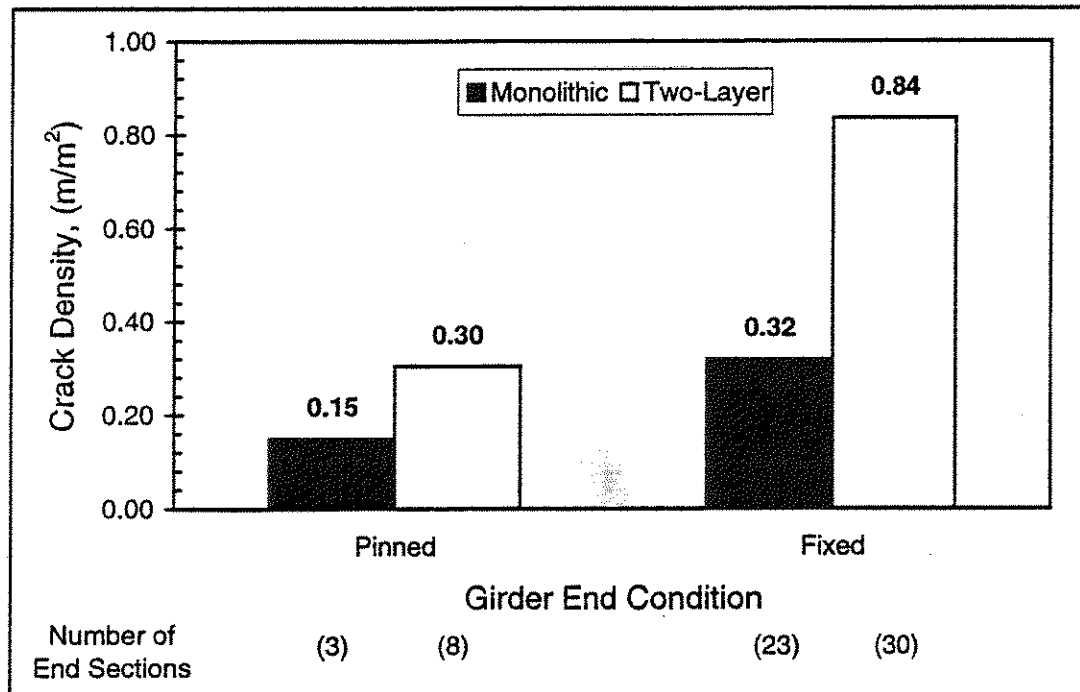


Fig. 3.39: Mean crack density of end sections versus girder end condition, based on deck type, for composite bridges.

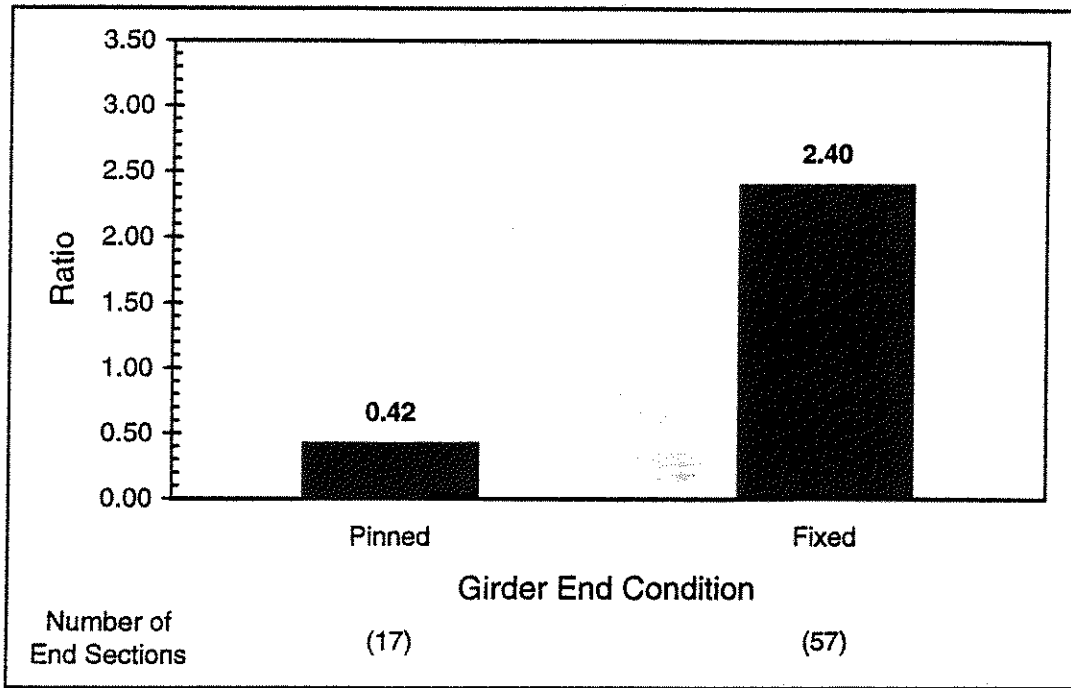


Fig. 3.40: Ratio of end section crack density to the crack density of the entire deck versus girder end condition for all bridges, including decks with overlays containing silica fume and noncomposite bridges.

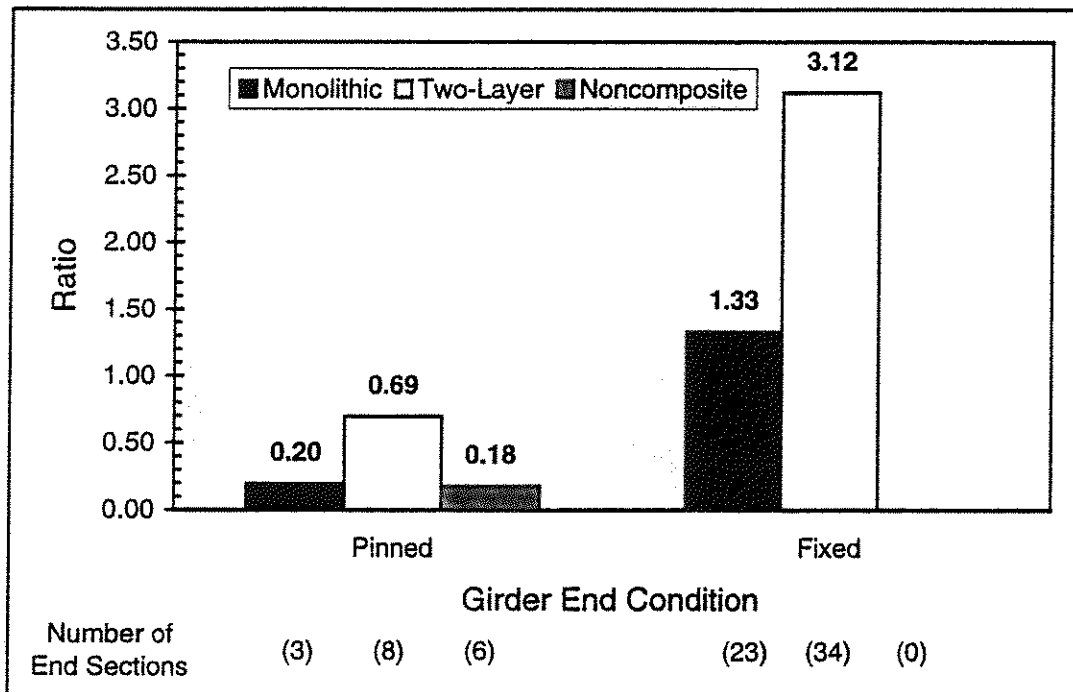


Fig. 3.41: Ratio of end section crack density to the crack density of the entire deck versus girder end condition, based on bridge type, for all bridges.

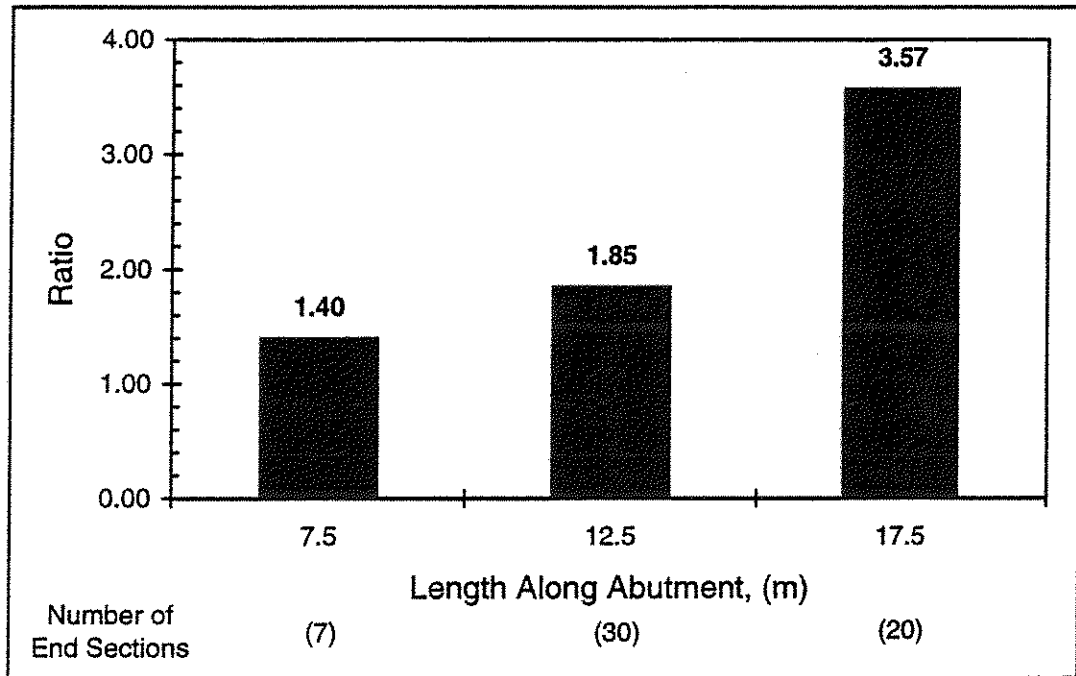


Fig. 3.42: Ratio of end section crack density to the crack density of the entire deck versus length of bridge deck along the abutment for composite bridges with fixed-ended girders.

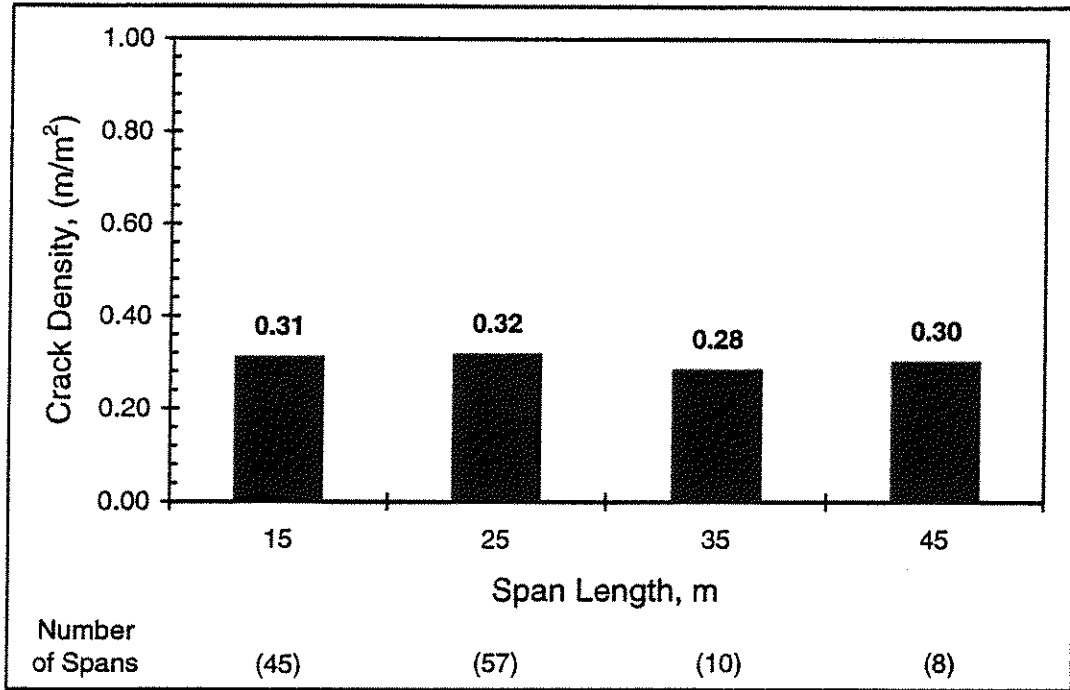


Fig. 3.43: Mean crack density of individual spans versus span length for all bridges including noncomposite bridges.

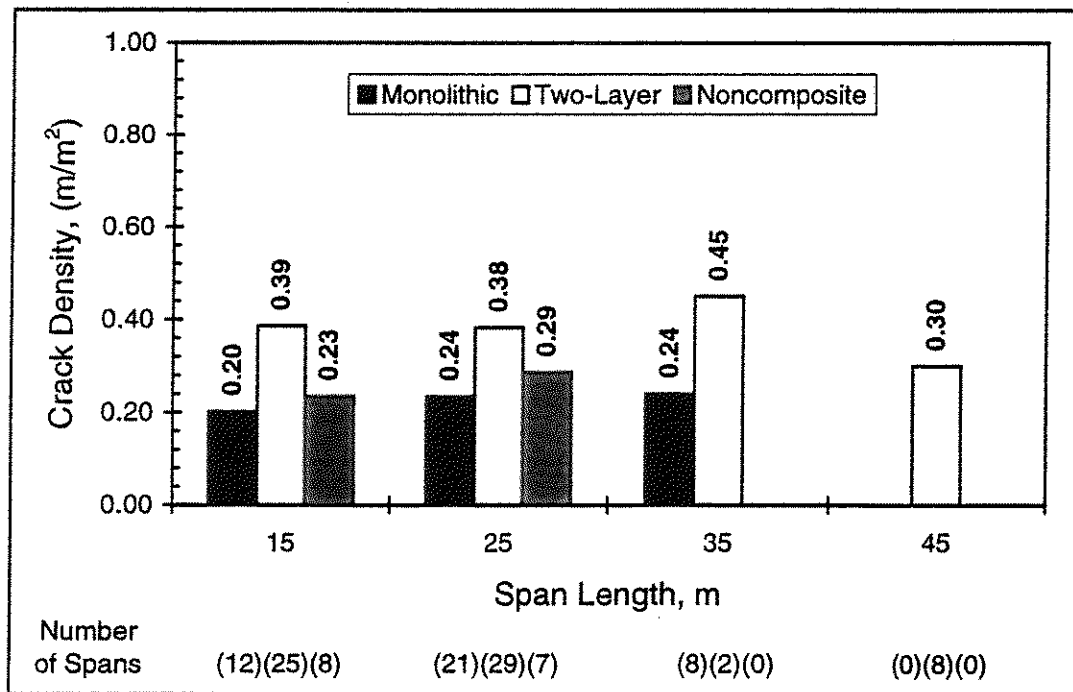


Fig. 3.44: Mean crack density of individual spans versus span length, based on bridge type, for all bridges.

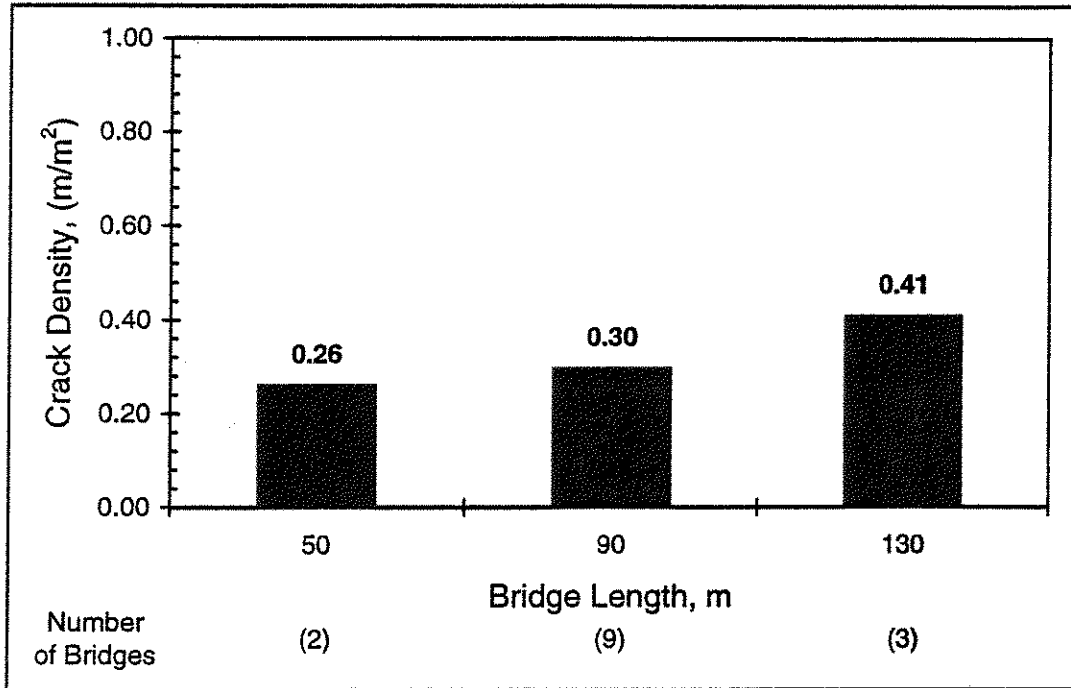


Fig. 3.45: Mean crack density of entire bridge decks versus bridge length for monolithic composite bridges.

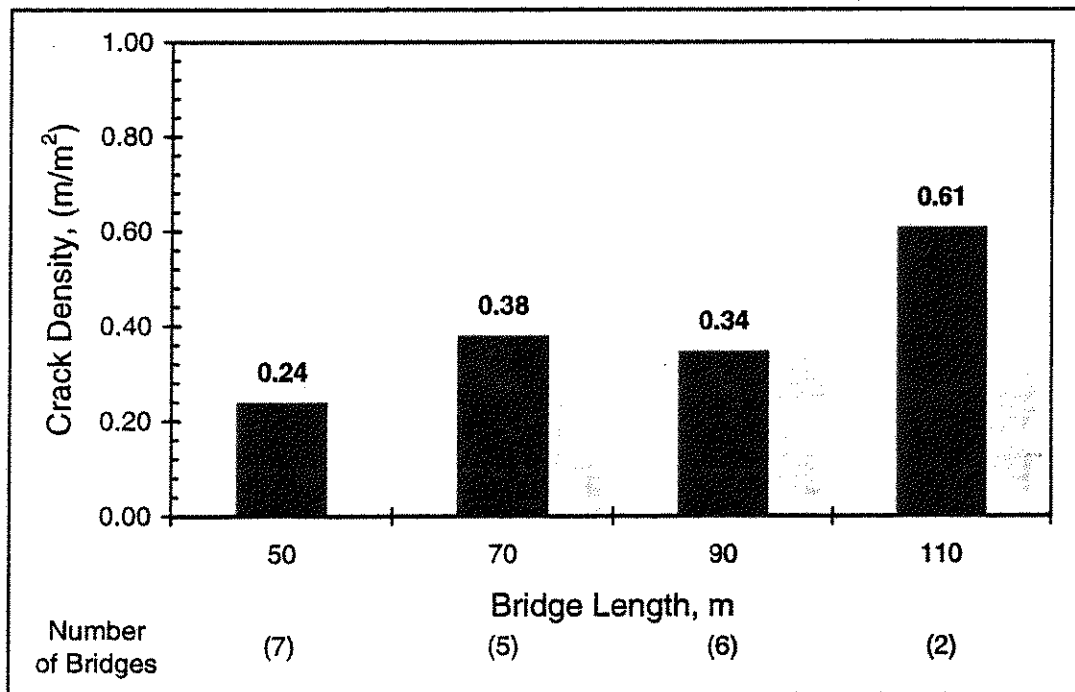


Fig. 3.46: Mean crack density of entire bridge decks versus bridge length for two-layer composite bridges.

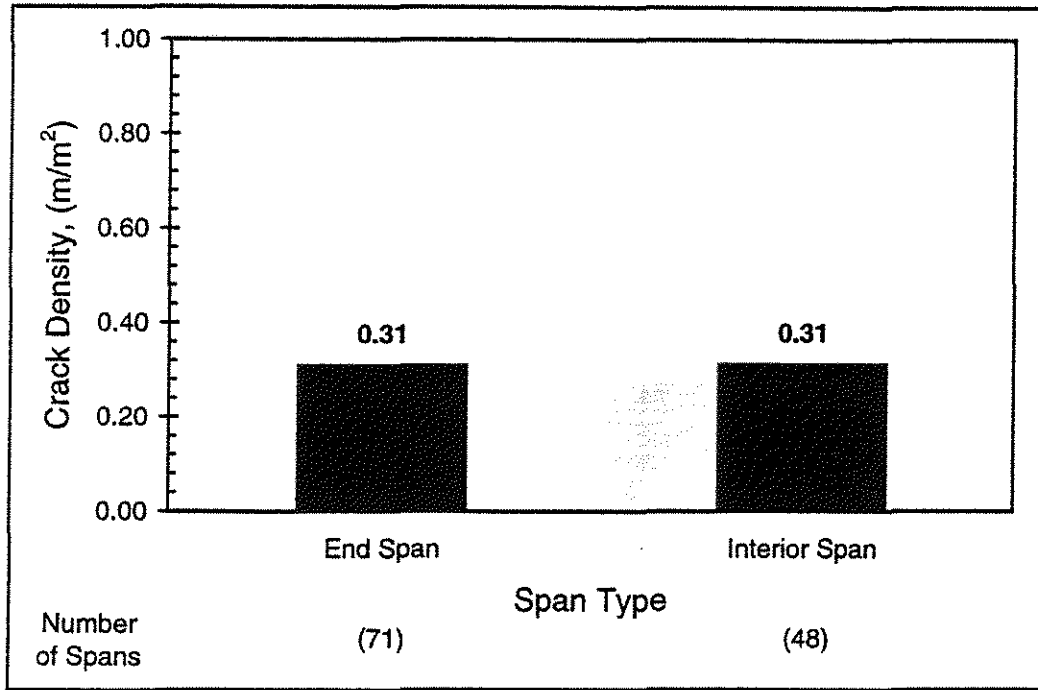


Fig. 3.47: Mean crack density of individual spans versus span type for all bridges, including noncomposite bridges.

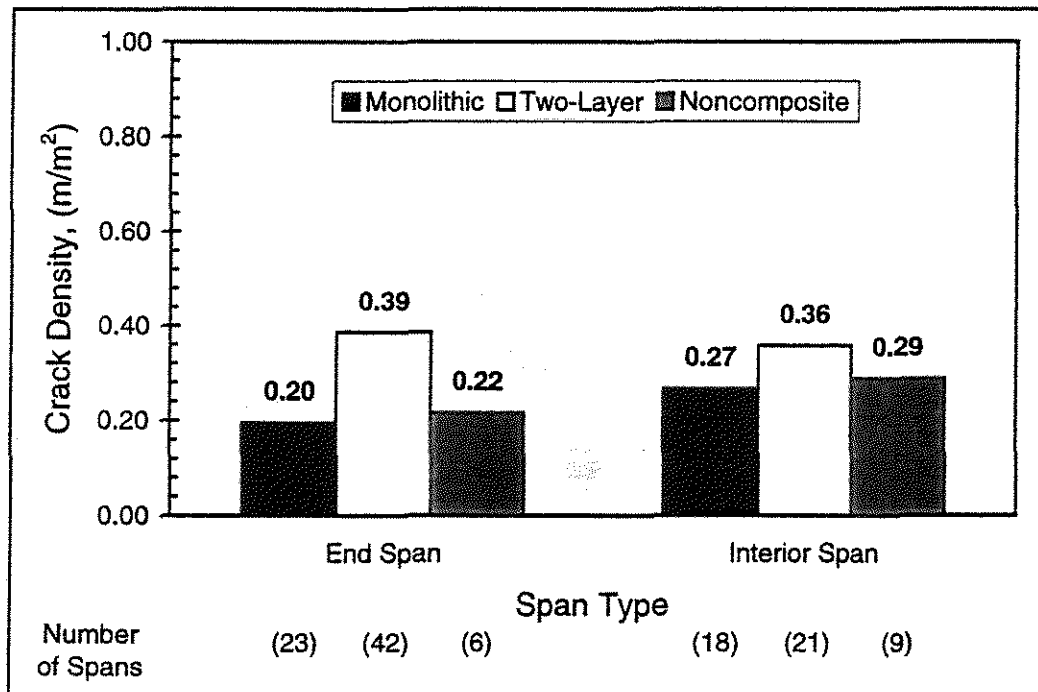


Fig. 3.48: Mean crack density of individual spans versus span type, based on bridge type, for all bridges.

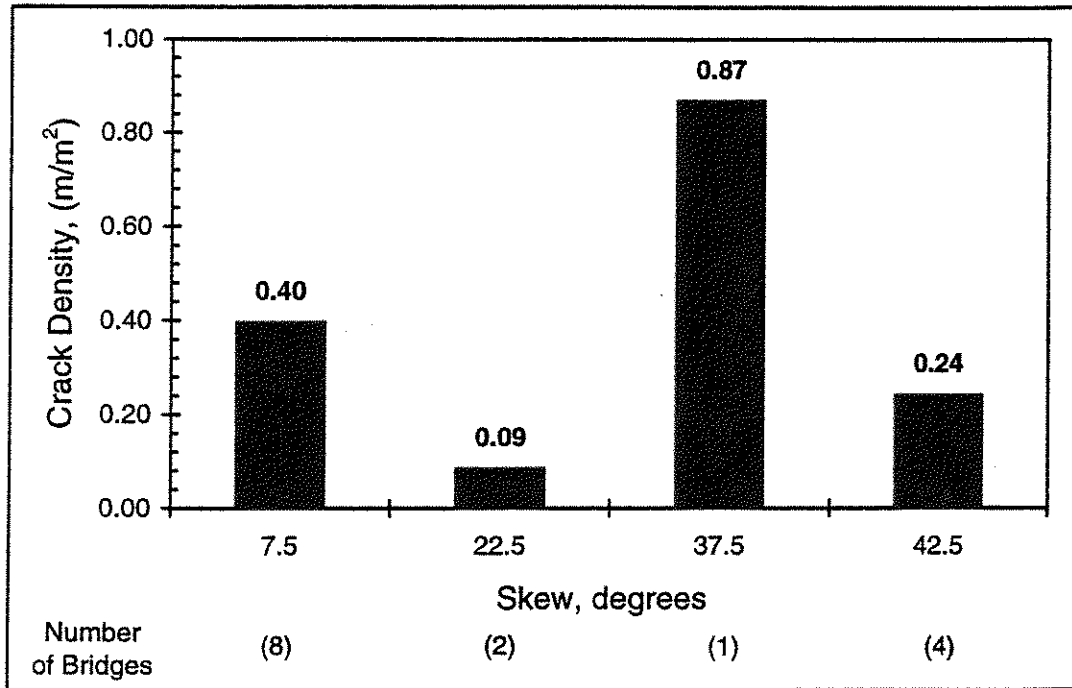


Fig. 3.49: Mean crack density of entire bridge decks versus skew for monolithic composite bridges.

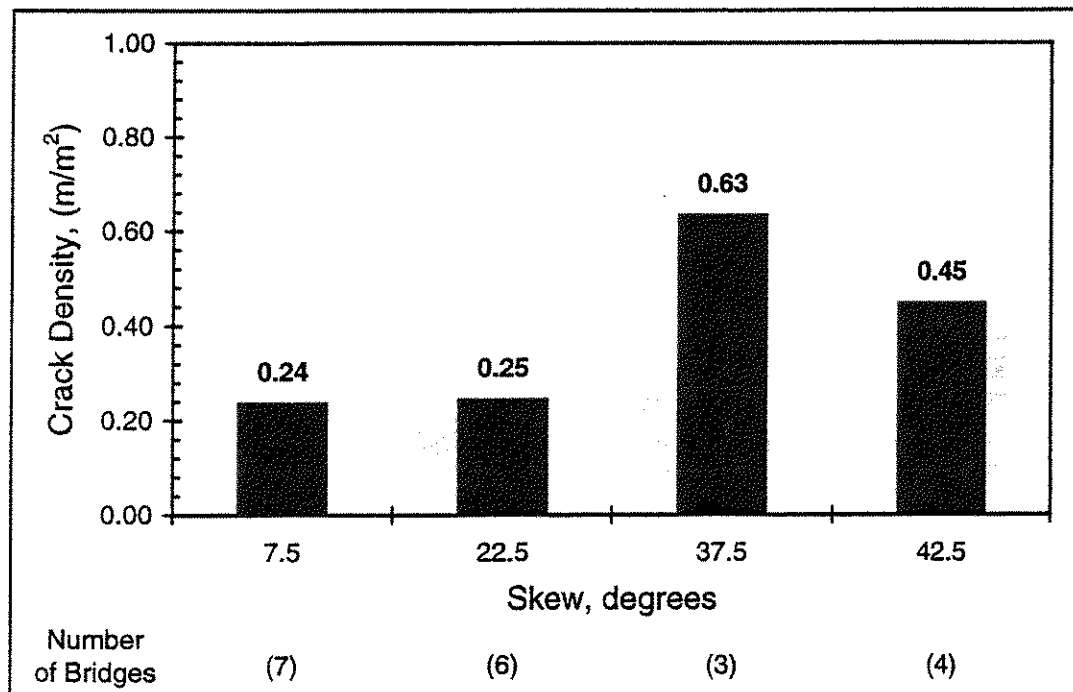


Fig. 3.50: Mean crack density of entire bridge decks versus skew for two-layer composite bridges.

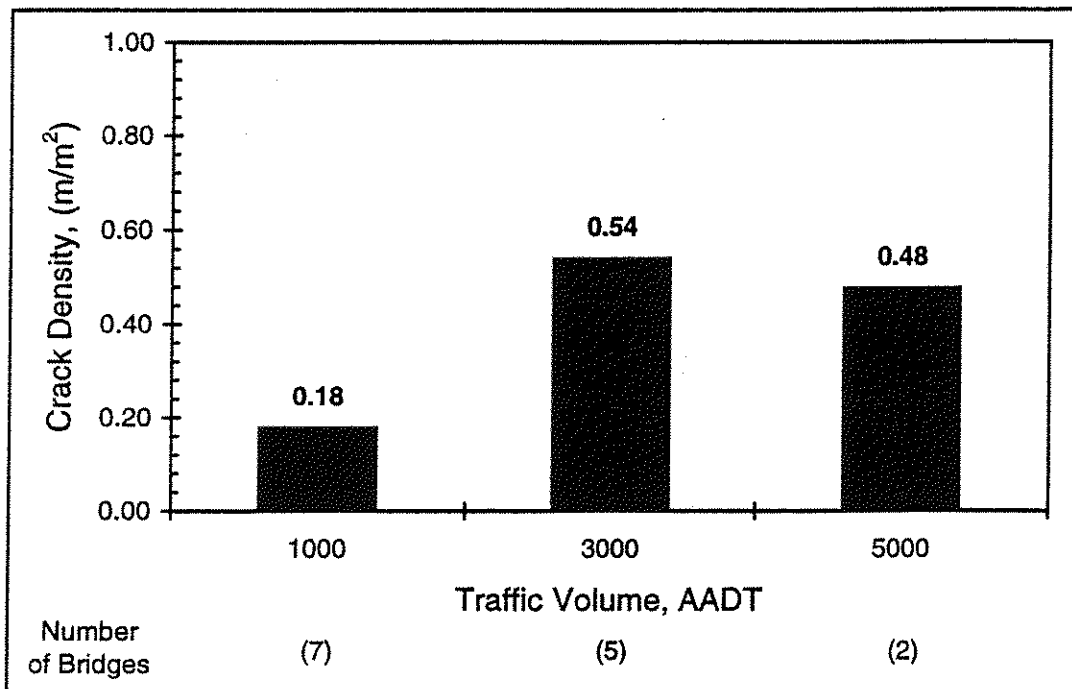


Fig. 3.51: Mean crack density of entire bridge decks versus traffic volume for monolithic composite bridges.

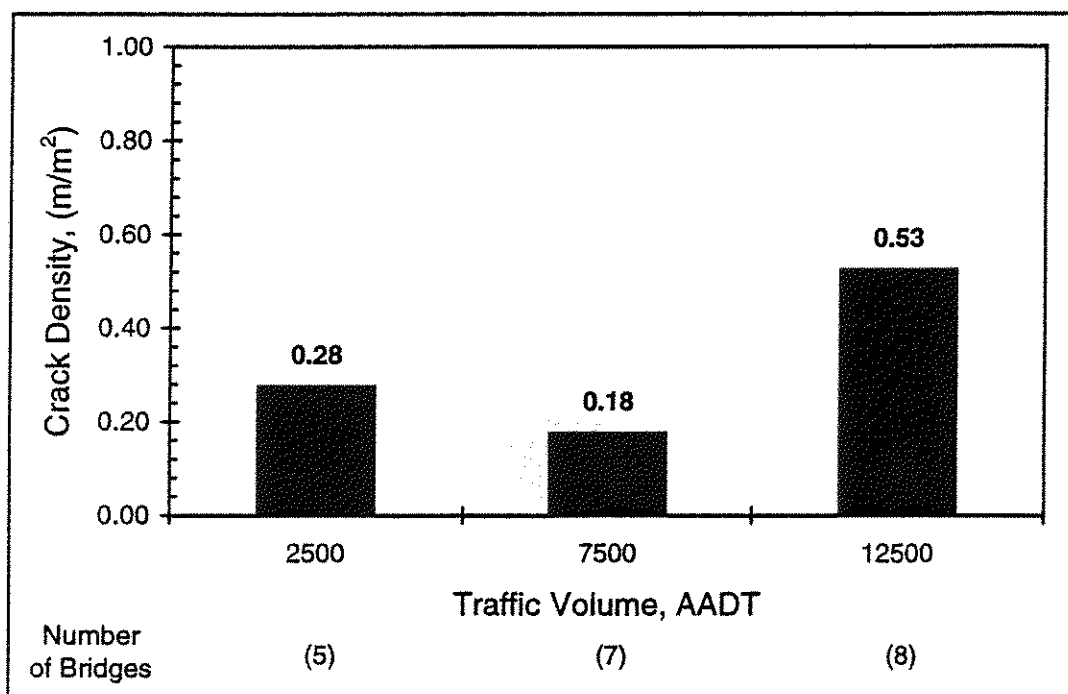


Fig. 3.52: Mean crack density of entire bridge decks versus traffic volume for two-layer composite bridges.

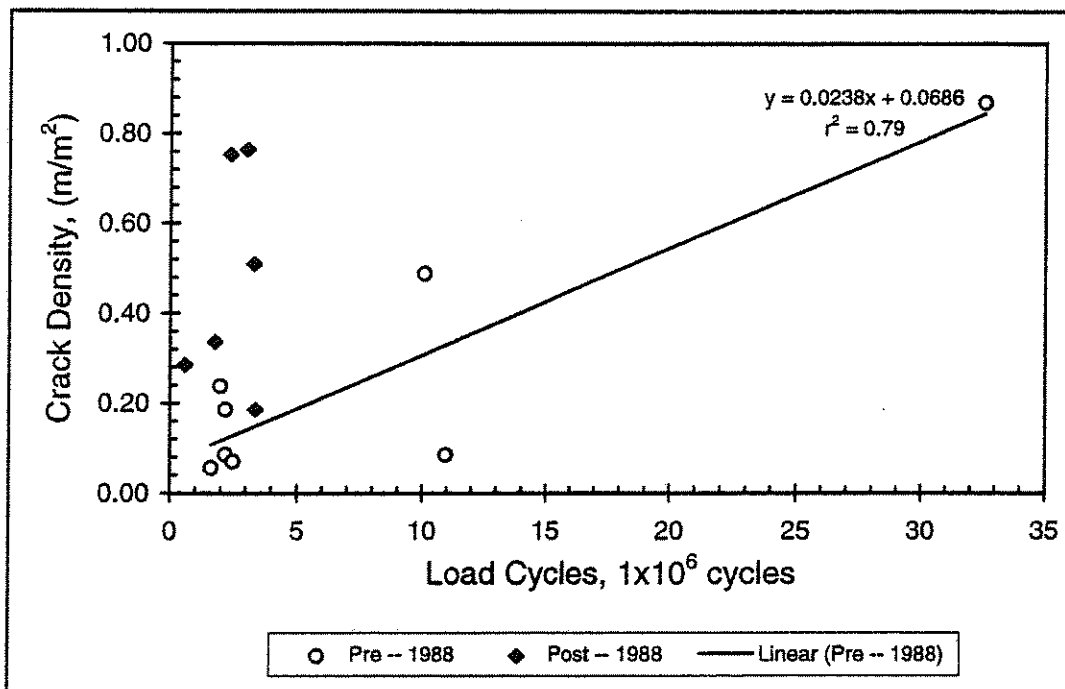


Fig. 3.53: Crack density of entire bridge decks versus total number of load cycles for monolithic composite bridges.

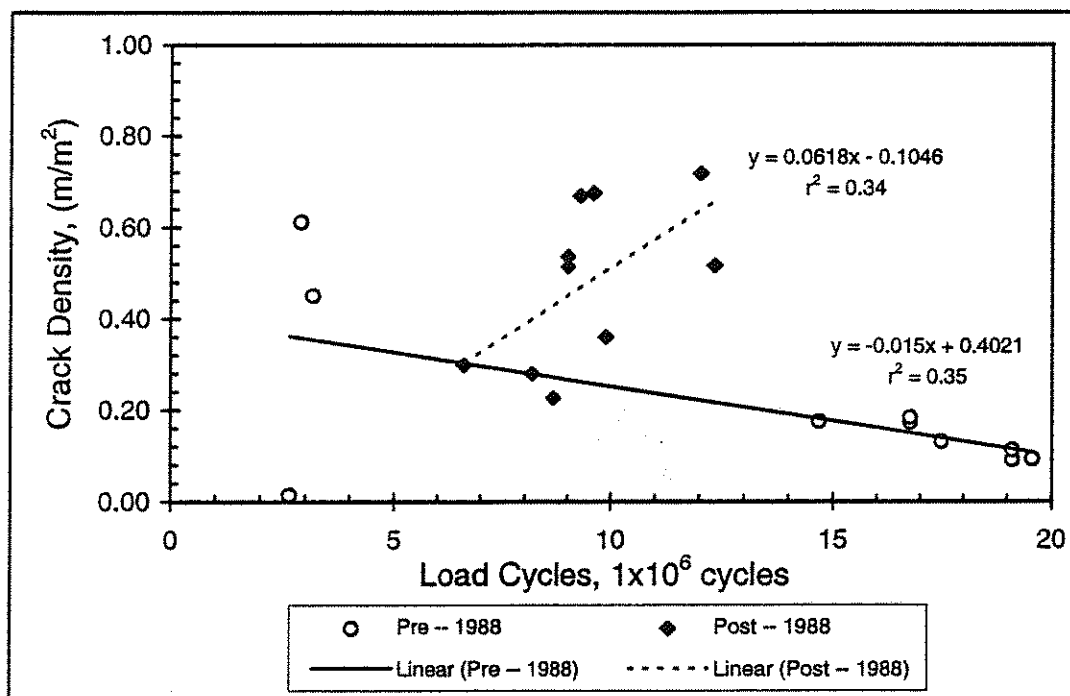


Fig. 3.54: Crack density of entire bridge decks versus total number of load cycles for two-layer composite bridges.

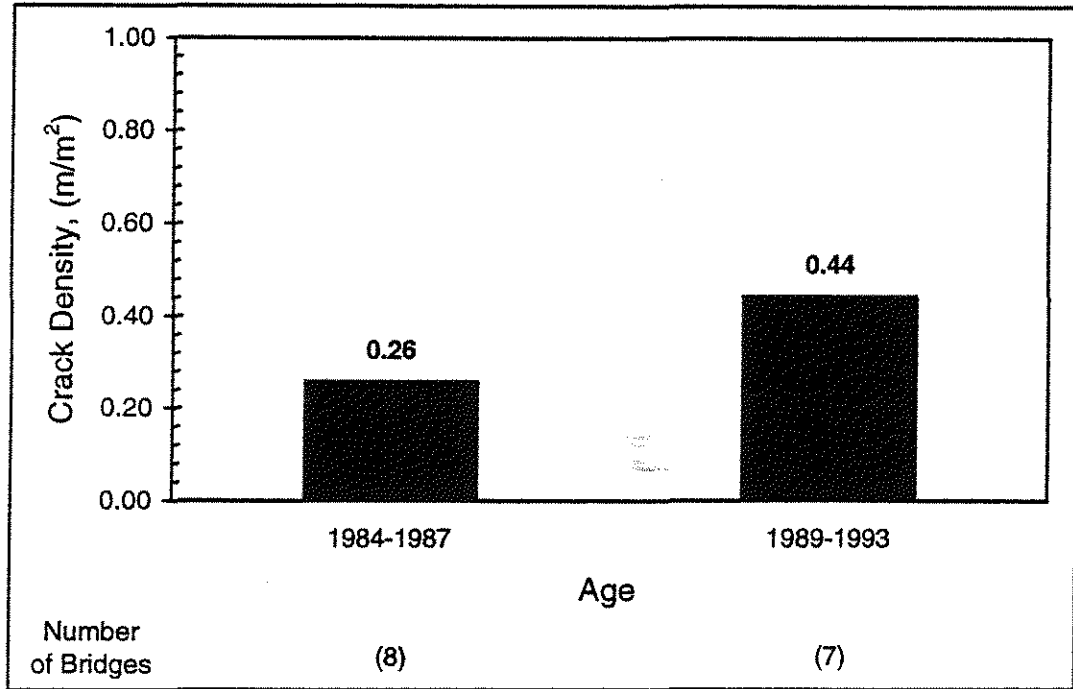


Fig. 3.55: Mean crack density of entire bridge decks versus bridge age for monolithic composite bridges.

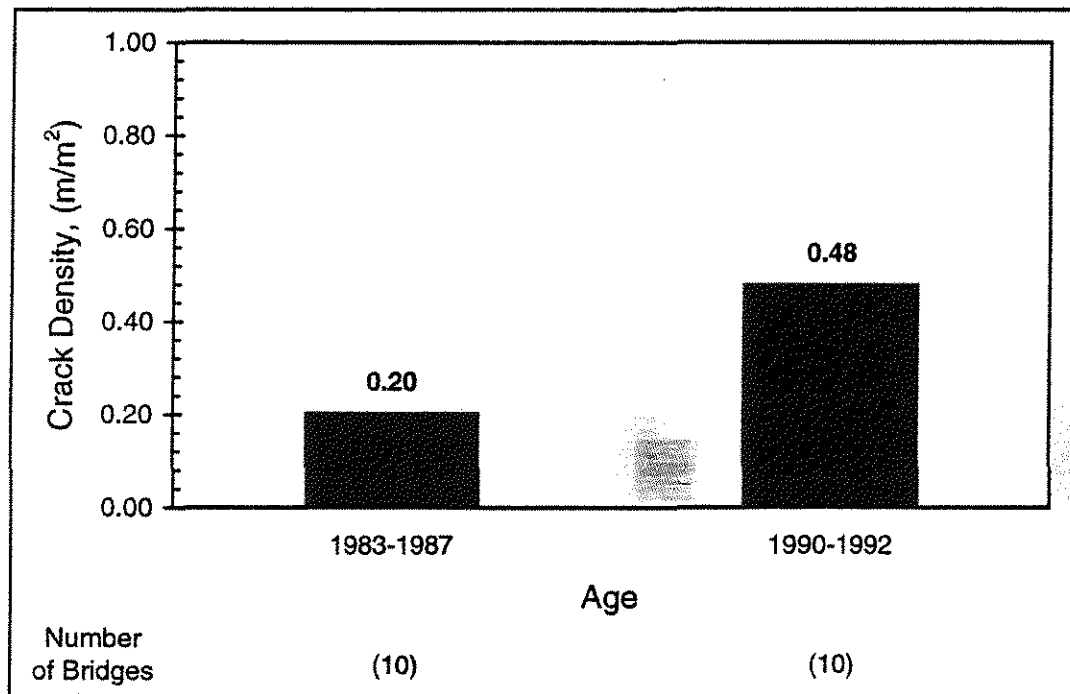



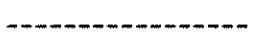



Fig. 3.56: Mean crack density of entire bridge decks versus bridge age for two-layer composite bridges.

APPENDIX A
BRIDGE DECK CRACKING PATTERNS

A.1 Legend

	Edge of Roadway
	Abutment/Pier Centerline
	Construction Joint
	Survey Boundary
	Crack

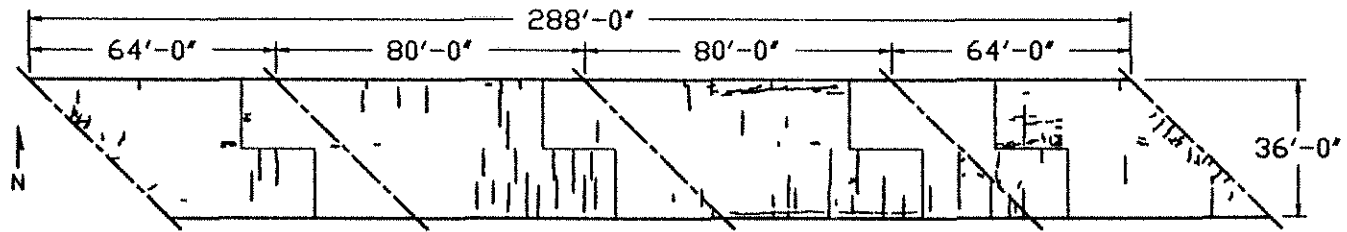


Fig. A.1 Bridge number 3-045 (Monolithic). Scale: 1" = 50'-0".

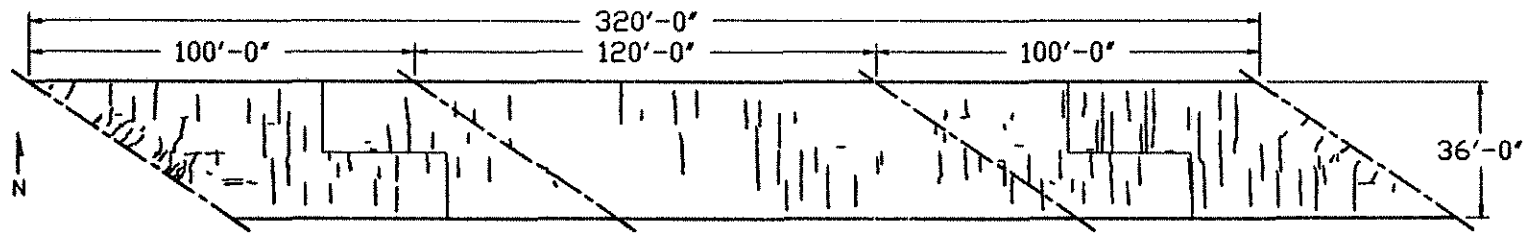


Fig. A.2 Bridge number 3-046 (Monolithic). Scale: 1" = 50'-0".

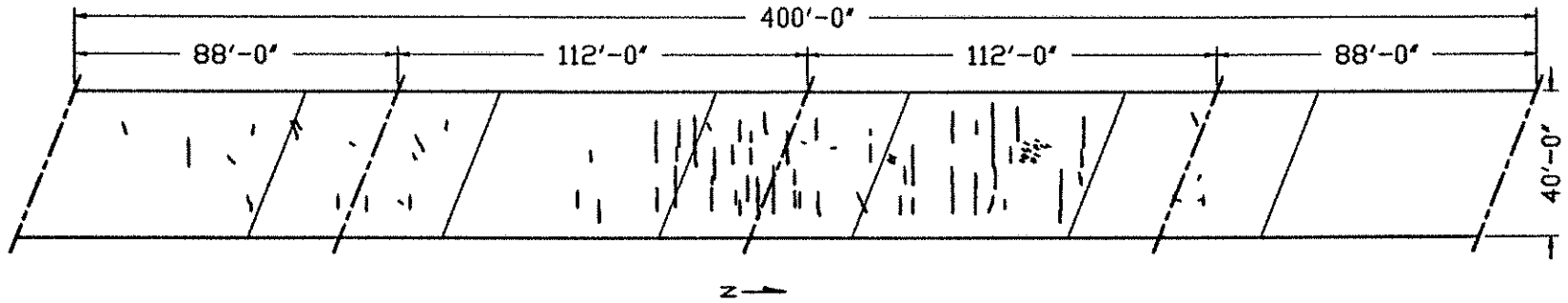


Fig. A.3 Bridge number 56-142 (Monolithic). Scale: 1" = 50'-0".

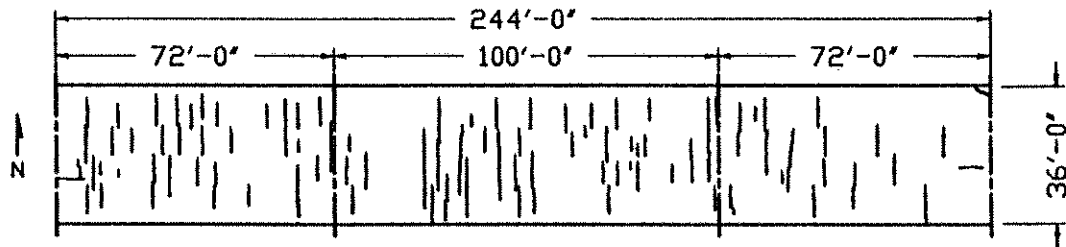


Fig. A.4 Bridge number 56-148 (Monolithic). Scale: 1" = 50'-0".

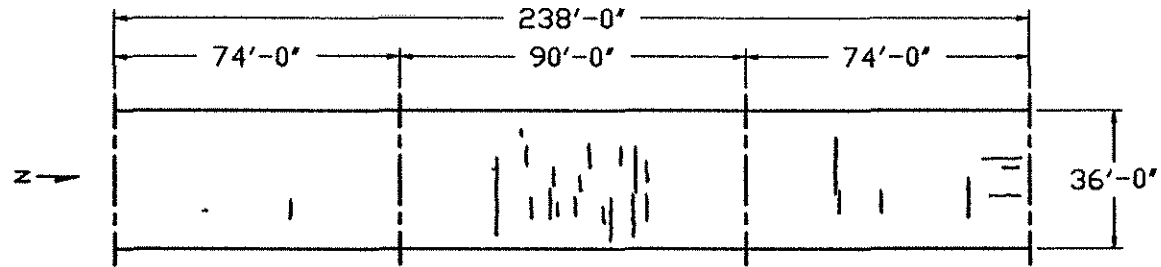


Fig. A.5 Bridge number 70-095 (Monolithic). Scale: 1" = 50'-0".

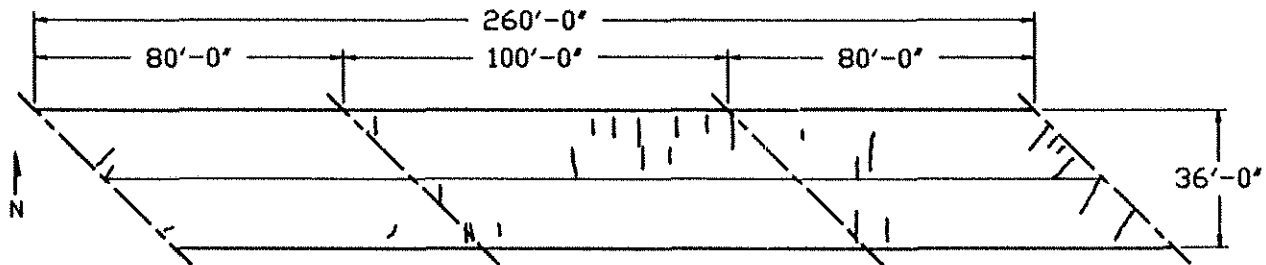


Fig. A.6 Bridge number 70-101 (Monolithic). Scale: 1" = 50'-0".

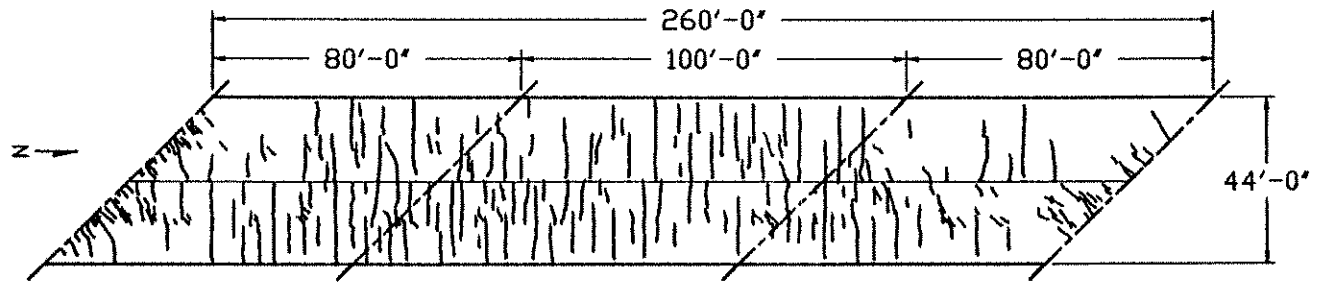


Fig. A.7 Bridge number 70-103 (Monolithic). Scale: 1" = 50'-0".

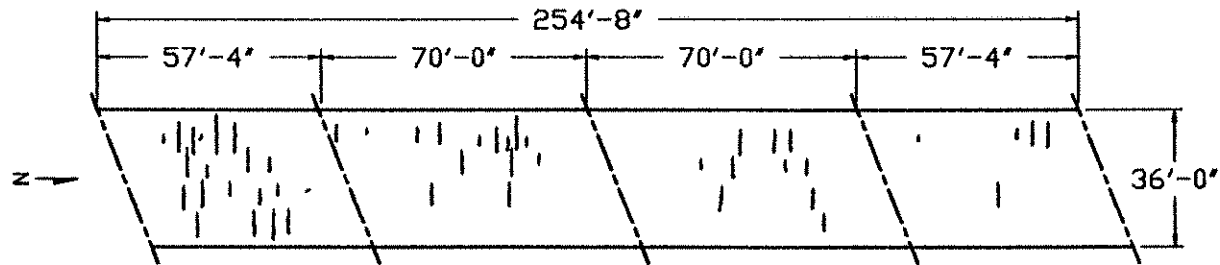


Fig. A.8 Bridge number 70-104 (Monolithic). Scale: 1" = 50'-0".

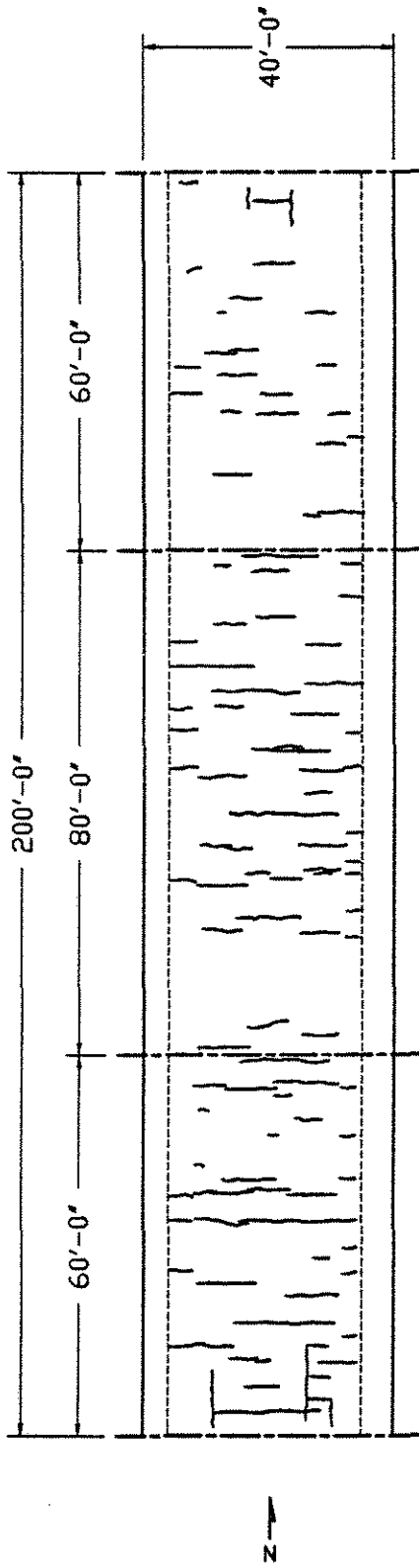


Fig. A.9 Bridge number 70-107 (Monolithic). Scale: 1" = 30'-0".

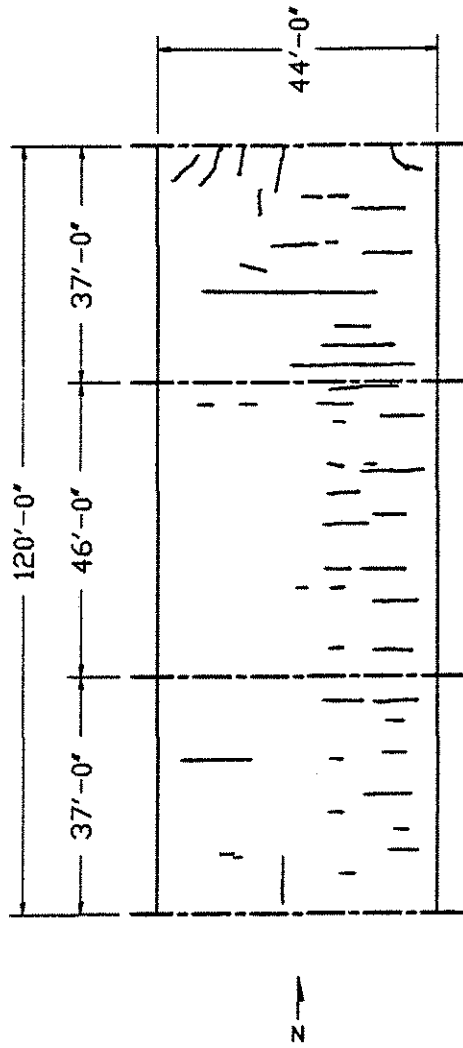


Fig. A.10 Bridge number 75-044 (Monolithic). Scale: 1" = 30'-0".

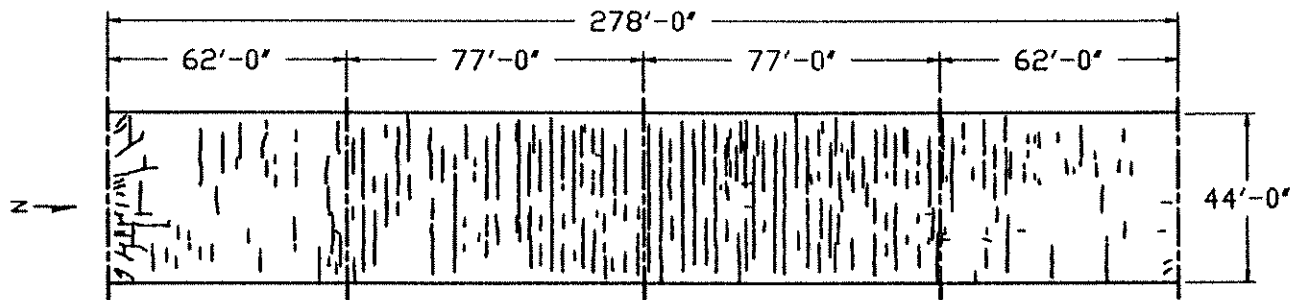


Fig. A.11 Bridge number 75-045 (Monolithic). Scale: 1" = 50'-0".

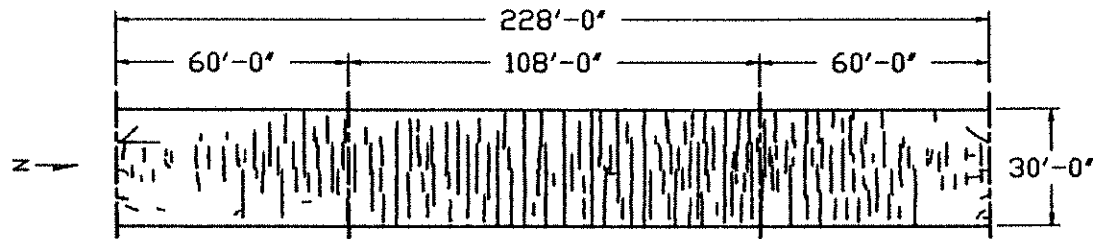


Fig. A.12 Bridge number 89-204 (Monolithic). Scale: 1" = 50'-0".

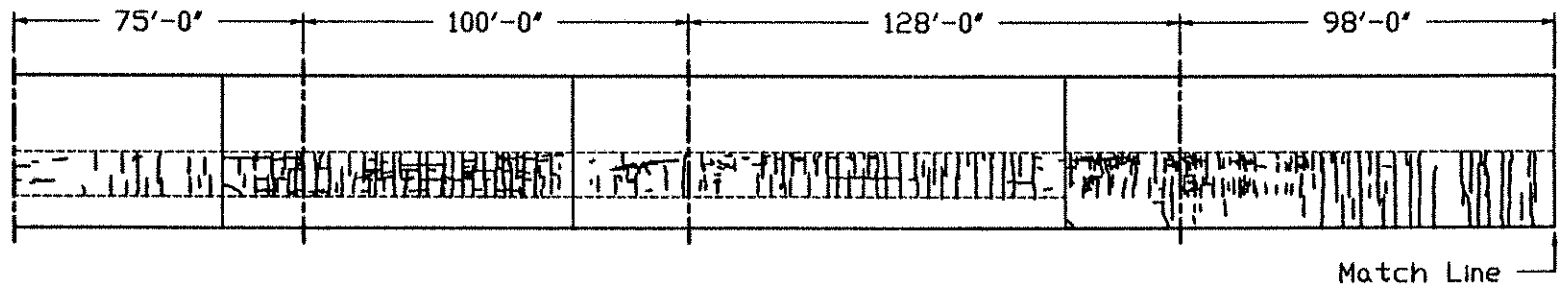


Fig. A.13a Bridge number 99-076 (Monolithic). Scale: 1" = 50'-0".

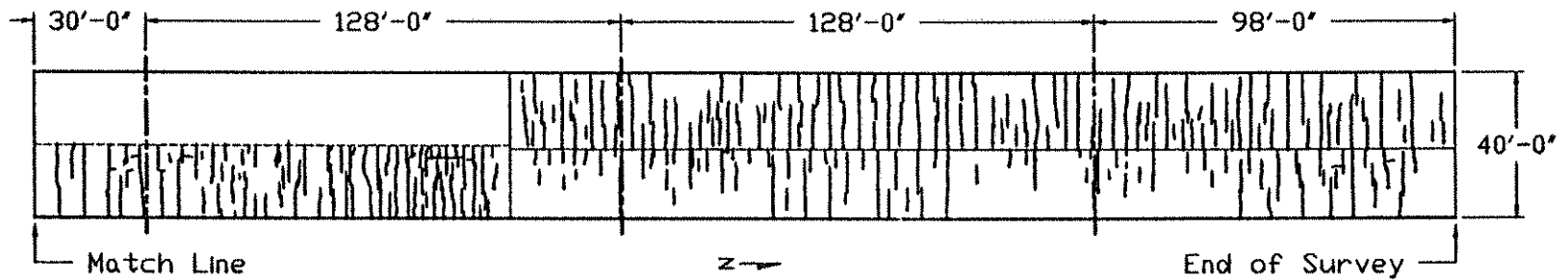


Fig. A.13b Bridge number 99-076 (Monolithic). Scale: 1" = 50'-0".

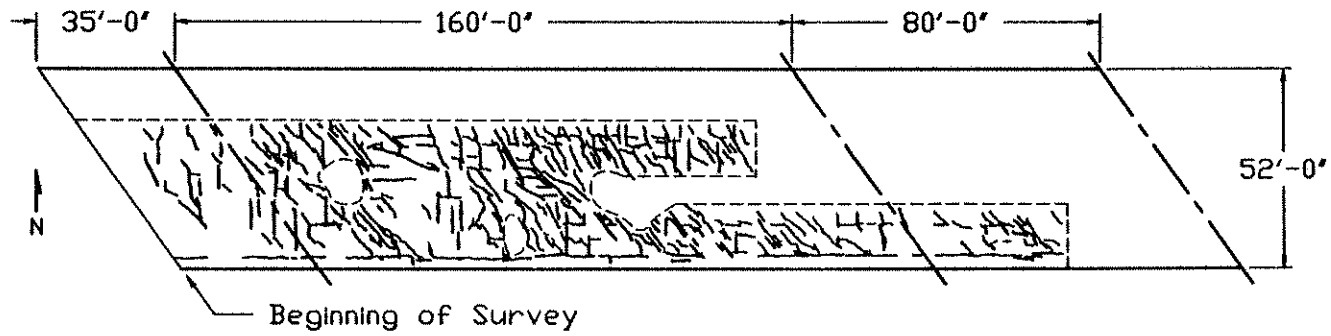


Fig. A.14 Bridge number 105-046 (Monolithic). Scale: 1" = 50'-0".

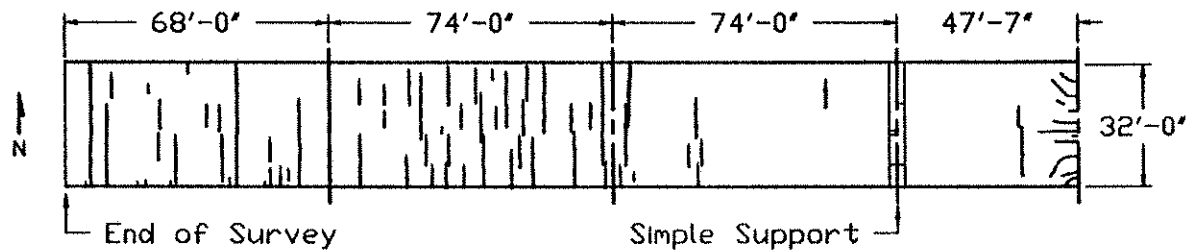


Fig. A.15 Bridge number 105-000 (Monolithic). Scale: 1" = 50'-0".

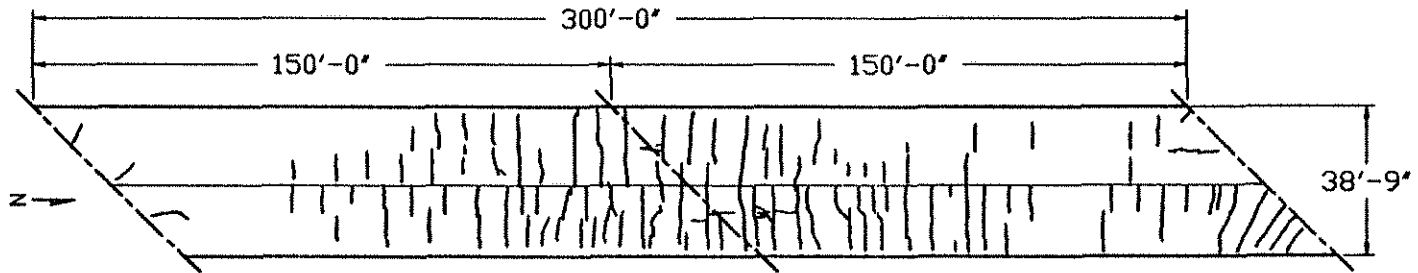


Fig. A.16 Bridge number 46-294 (Two-Layer). Scale: 1" = 50'-0".

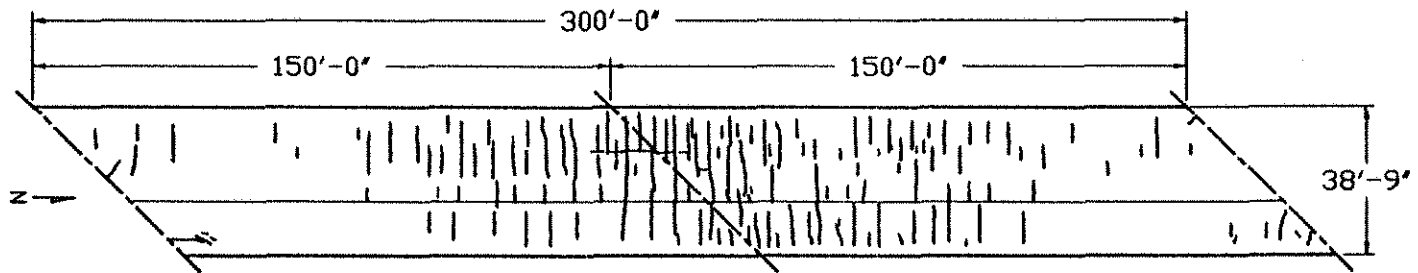


Fig. A.17 Bridge number 46-295 (Two-Layer). Scale: 1" = 50'-0".

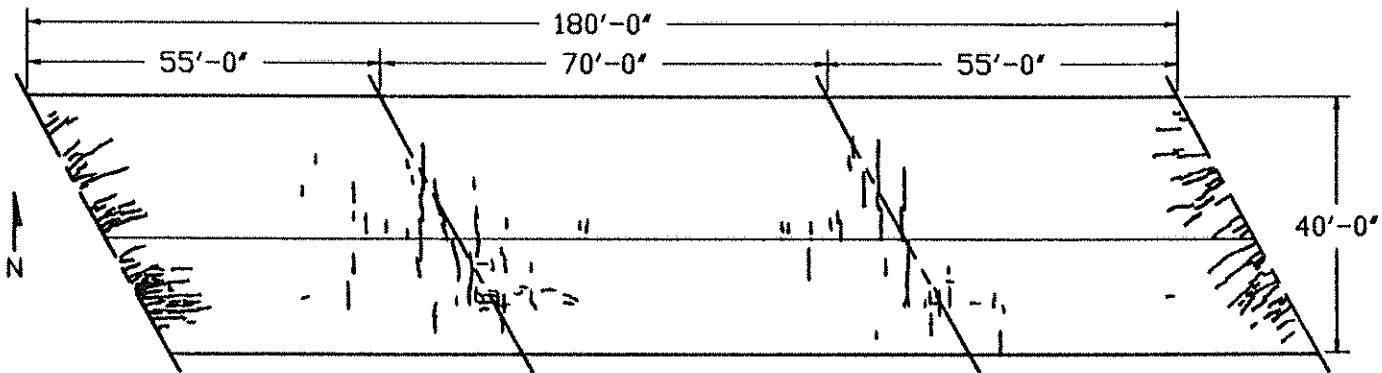


Fig. A.18 Bridge number 89-179 (Two-Layer). Scale: 1" = 30'-0".

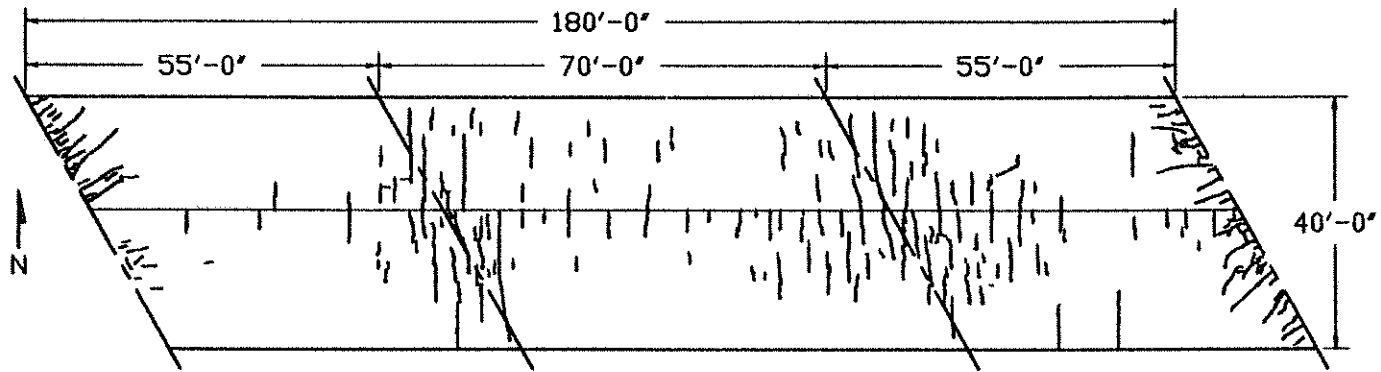


Fig. A.19 Bridge number 89-180 (Two-Layer). Scale: 1" = 30'-0".

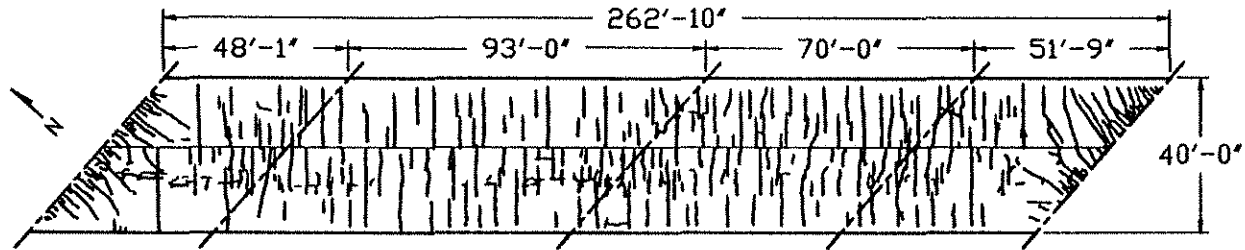


Fig. A.20 Bridge number 89-184 (Two-Layer). Scale: 1" = 50'-0".

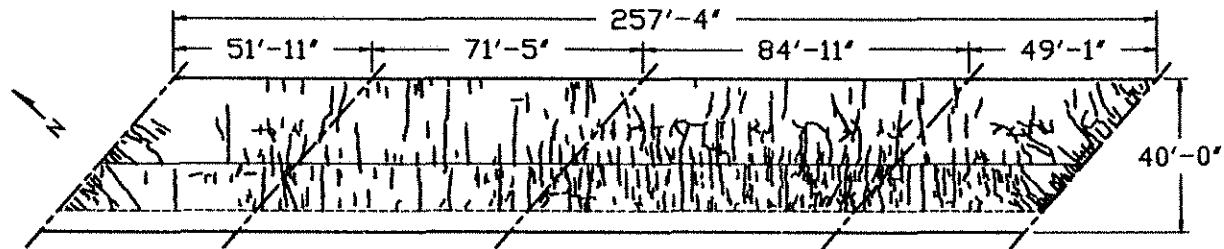


Fig. A.21 Bridge number 89-185 (Two-Layer). Scale: 1" = 50'-0".

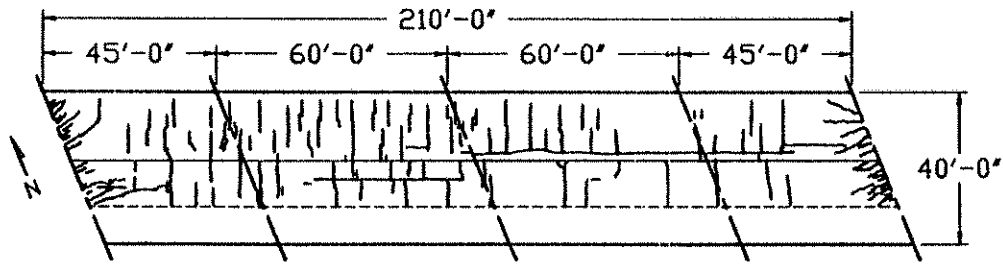


Fig. A.22 Bridge number 89-186 (Two-Layer). Scale: 1" = 50'-0".

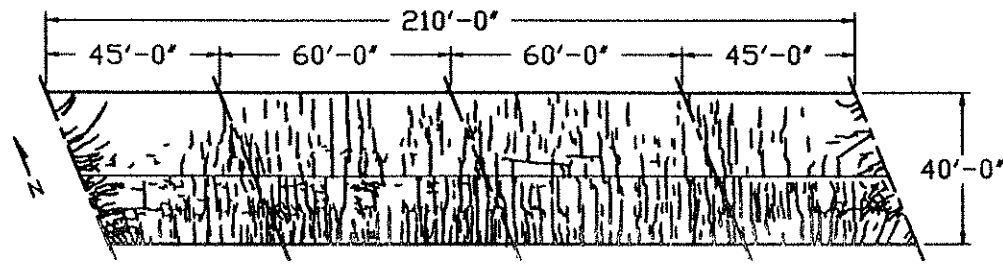


Fig. A.23 Bridge number 89-187 (Two-Layer). Scale: 1" = 50'-0".

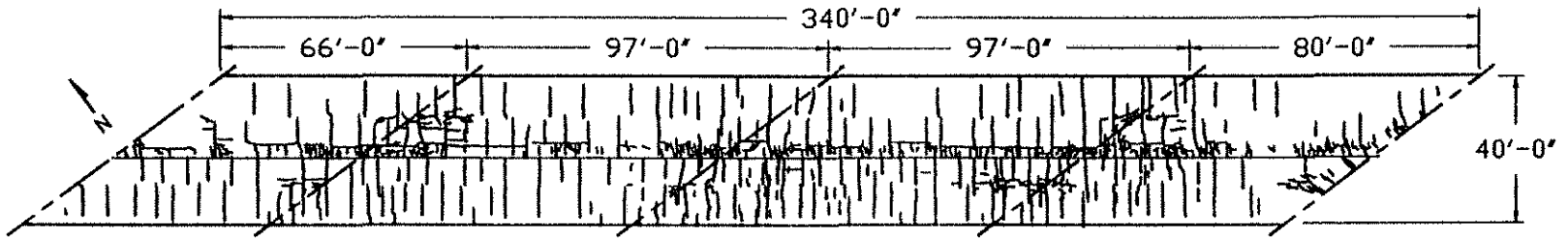


Fig. A.24 Bridge number 89-198 (Two-Layer). Scale: 1" = 50'-0".

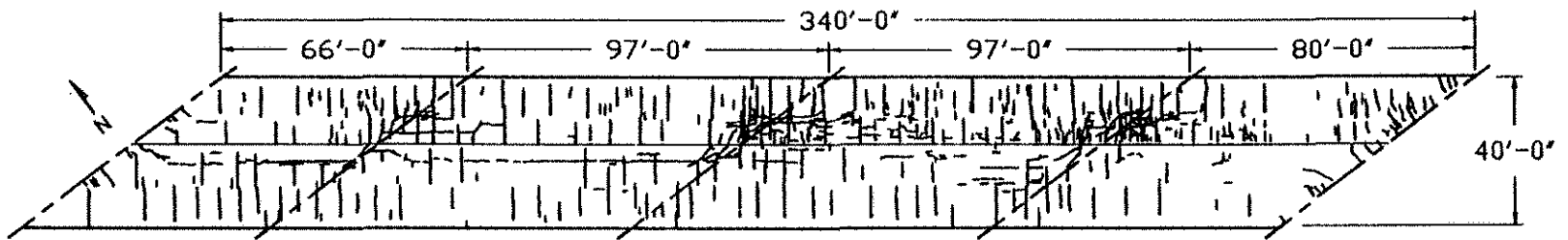


Fig. A.25 Bridge number 89-199 (Two-Layer). Scale: 1" = 50'-0".

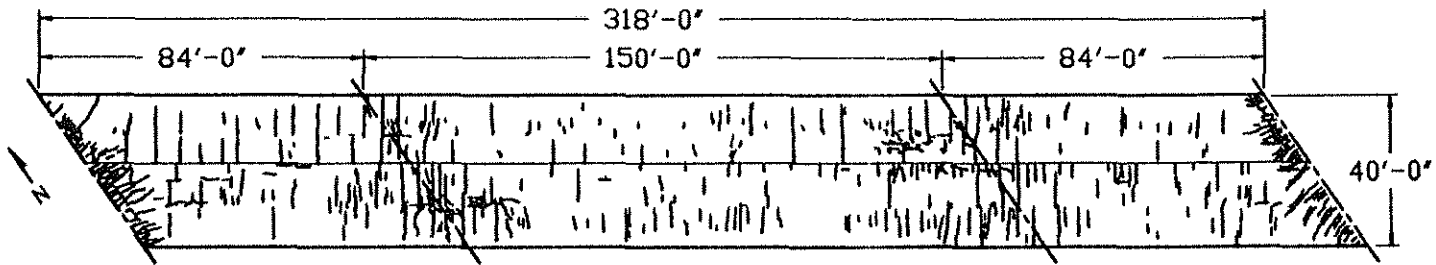


Fig. A.26 Bridge number 89-200 (Two-Layer). Scale: 1" = 50'-0".

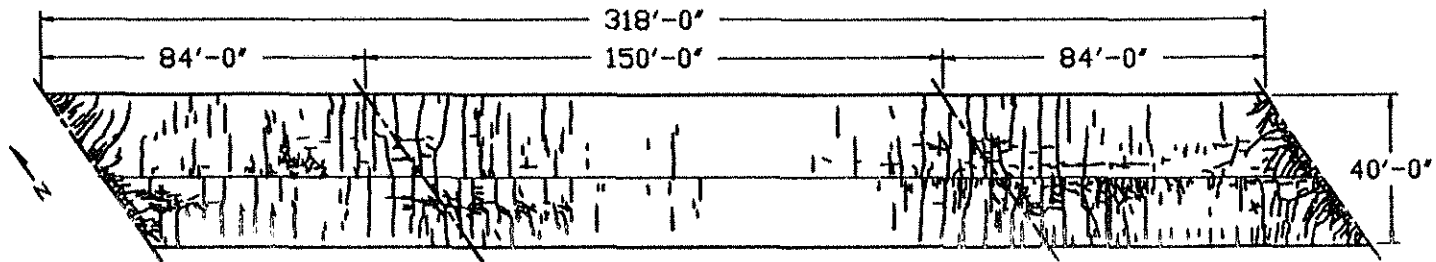


Fig. A.27 Bridge number 89-201 (Two-Layer). Scale: 1" = 50'-0".

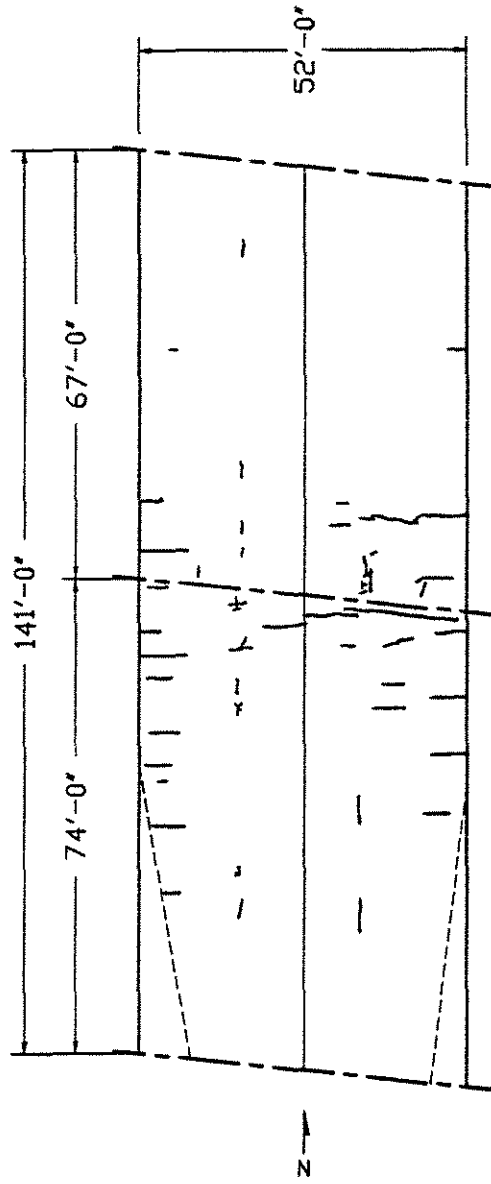


Fig. A.28 Bridge number 105-021 (Two-Layer). Scale: 1" = 30'-0".

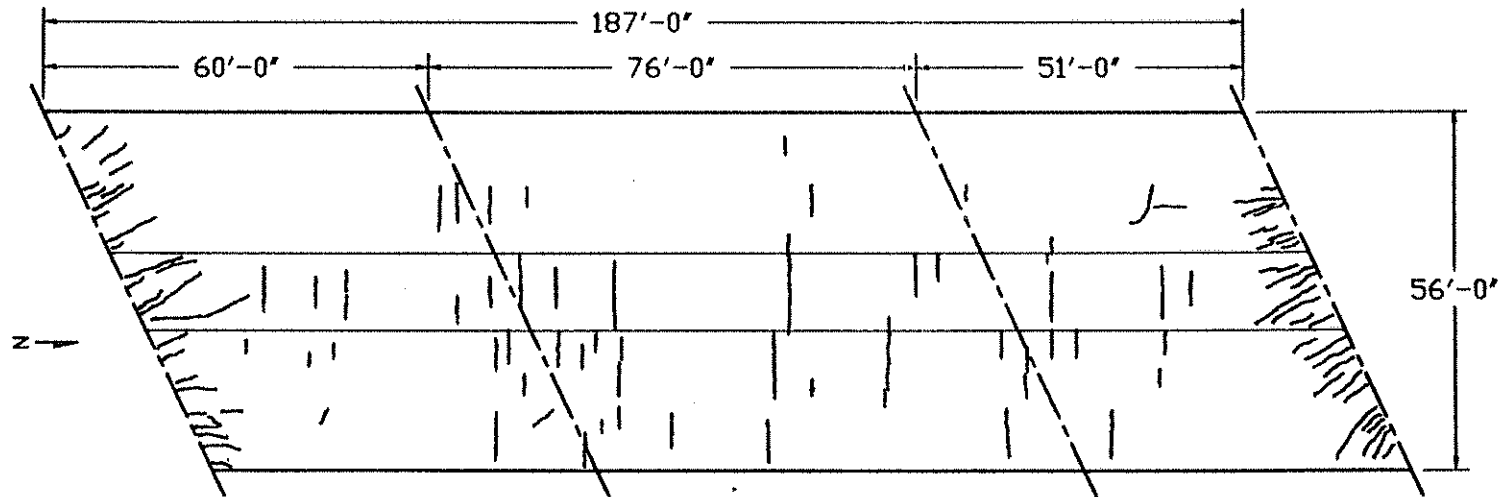


Fig. A.29 Bridge number 105-225 (Two-Layer). Scale: 1" = 30'-0".

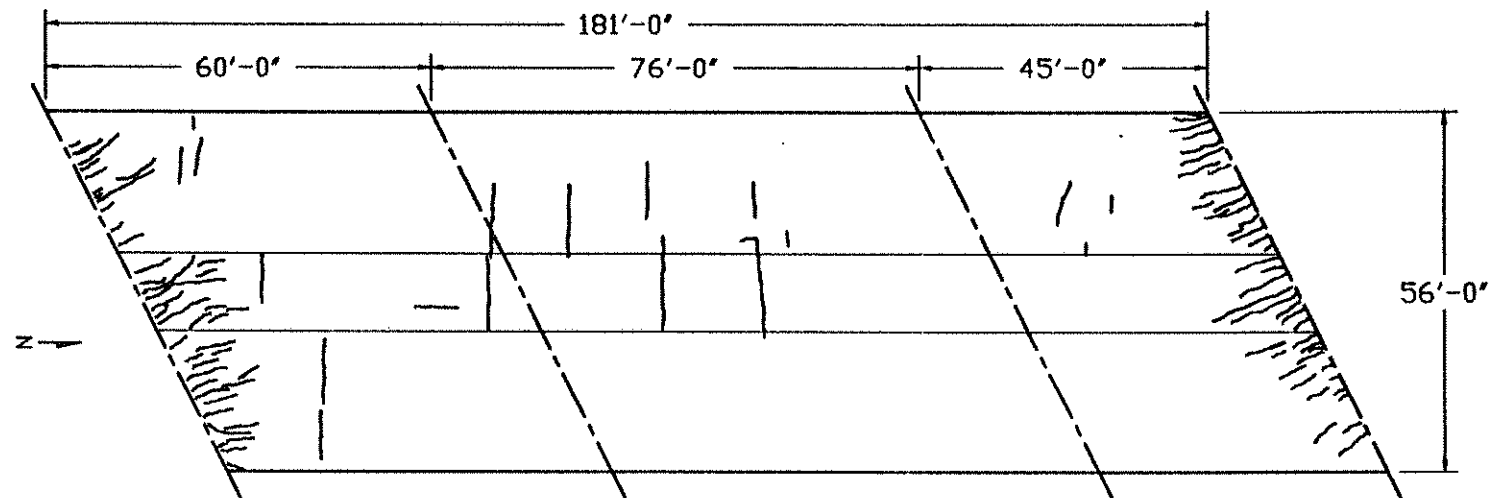


Fig. A.30 Bridge number 105-226 (Two-Layer). Scale: 1" = 30'-0".

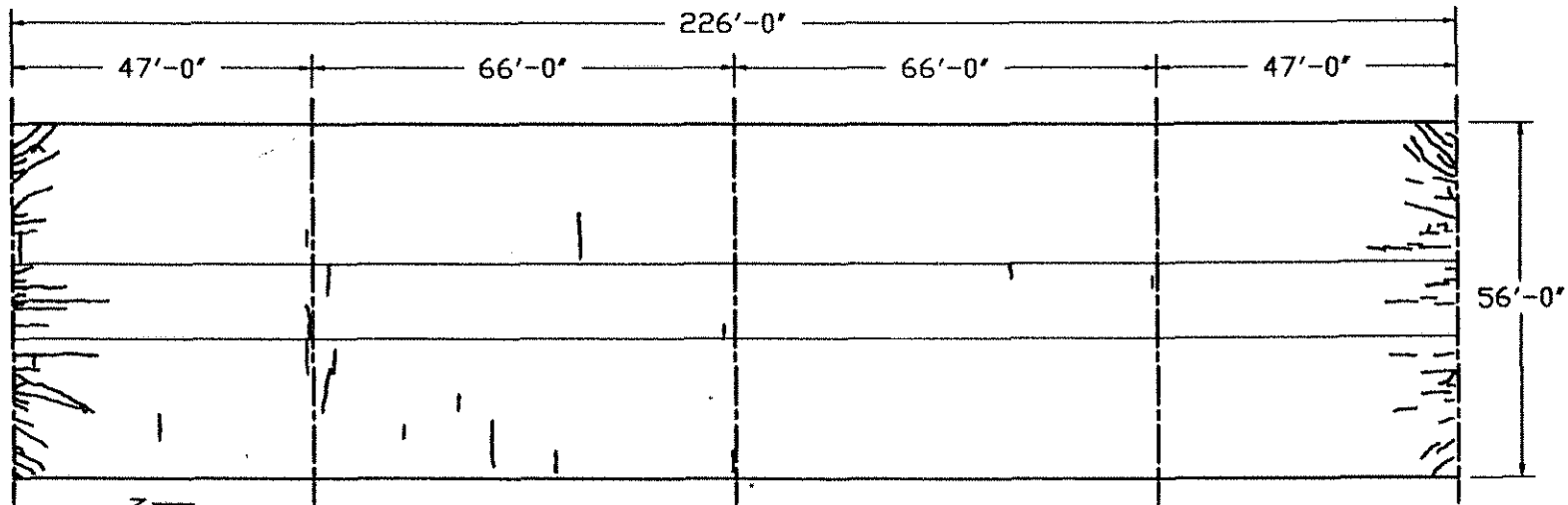


Fig. A.31 Bridge number 105-230 (Two-Layer). Scale: 1" = 30'-0".

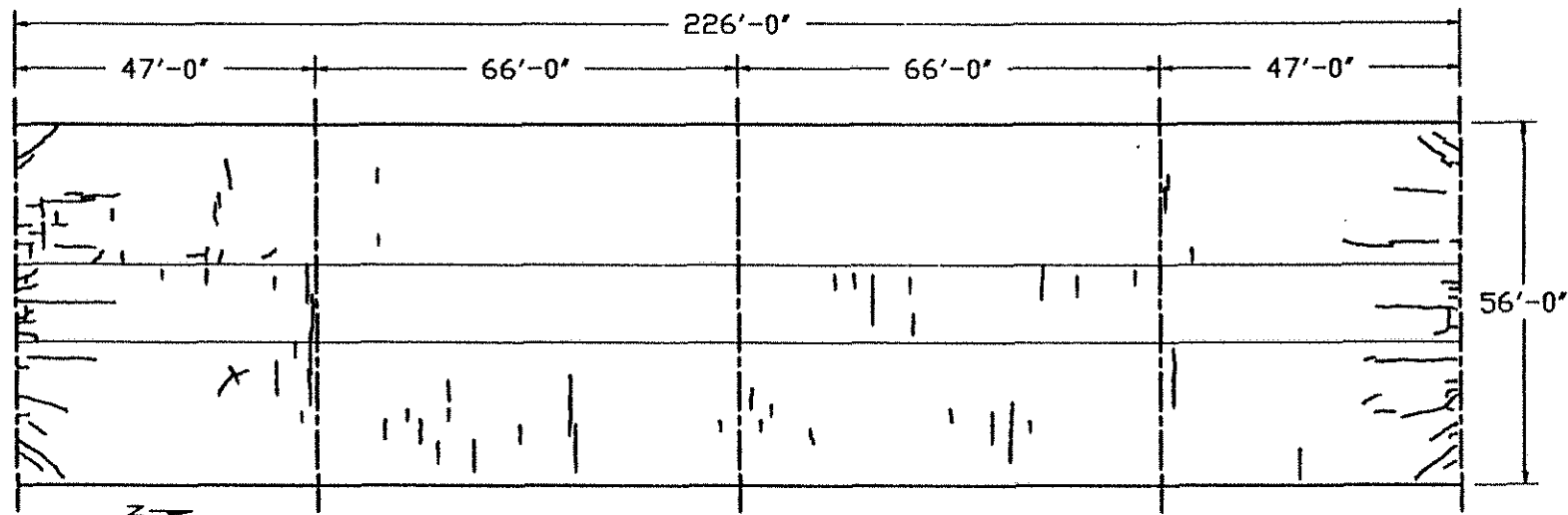


Fig. A.32 Bridge number 105-231 (Two-Layer). Scale: 1" = 30'-0".

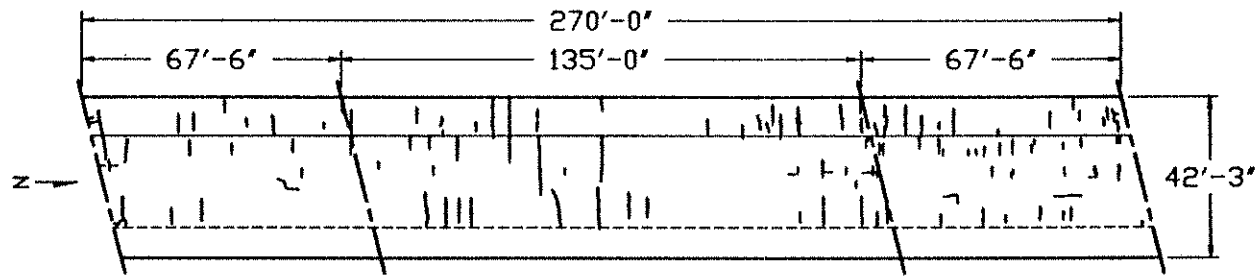


Fig. A.33 Bridge number 105-262 (Two-Layer). Scale: 1" = 50'-0".

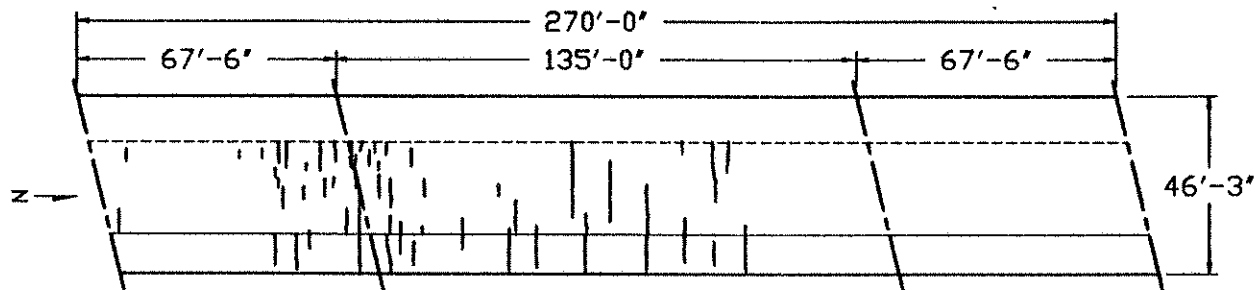


Fig. A.34 Bridge number 105-263 (Two-Layer). Scale: 1" = 50'-0".

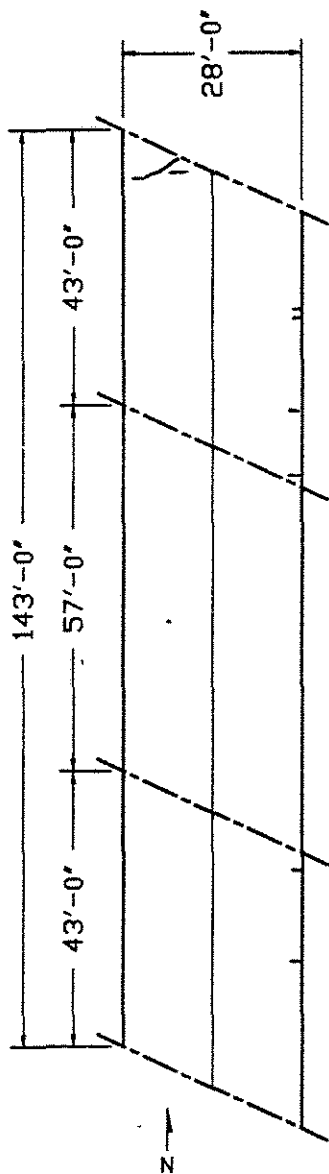


Fig. A.35 Bridge number 105-265 (Two-Layer). Scale: 1" = 30'-0".

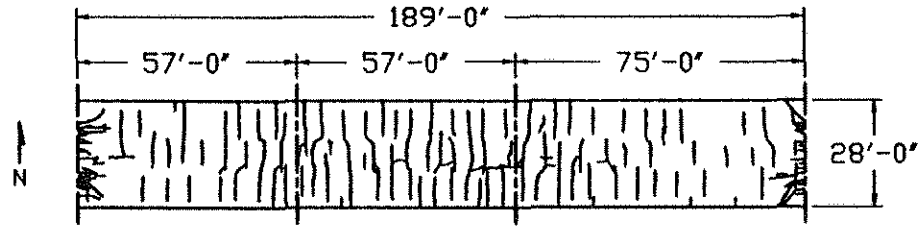


Fig. A.36 Bridge number 105-268 (Two-Layer). Scale: 1" = 50'-0".

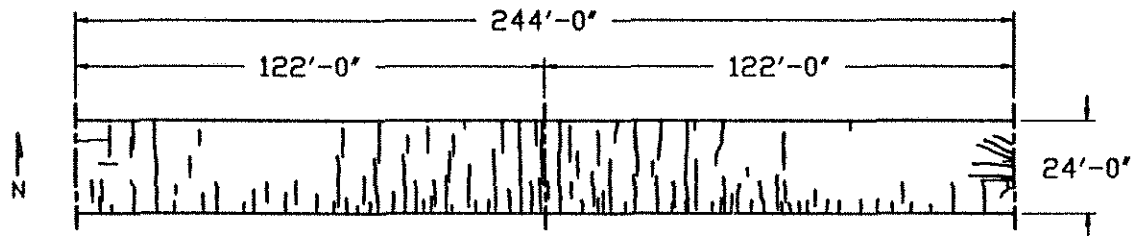


Fig. A.37 Bridge number 105-269 (Two-Layer). Scale: 1" = 50'-0".

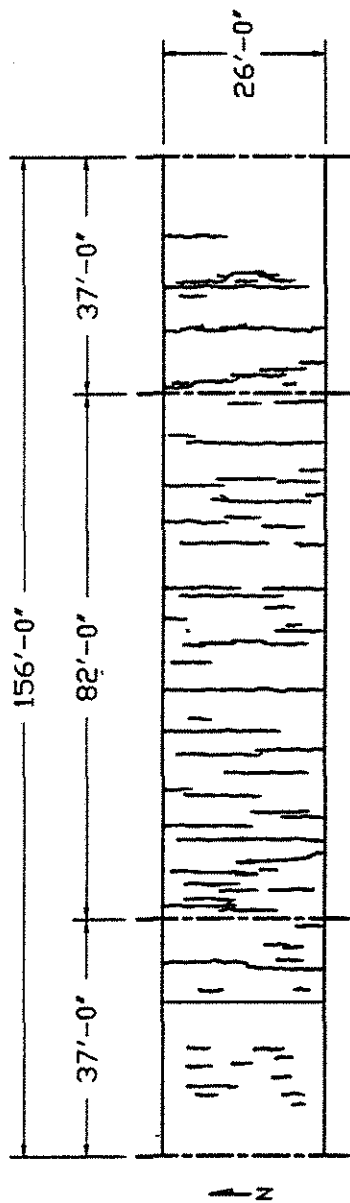


Fig. A.38 Bridge number 23-022 (Noncomposite). Scale: 1" = 30'-0".

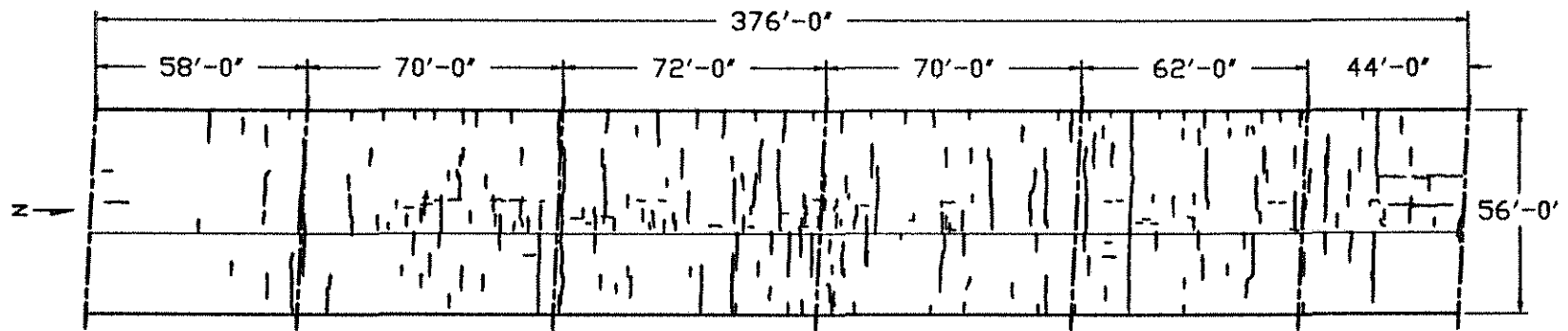


Fig. A.39 Bridge number 105-198 (Noncomposite). Scale: 1" = 50'-0".

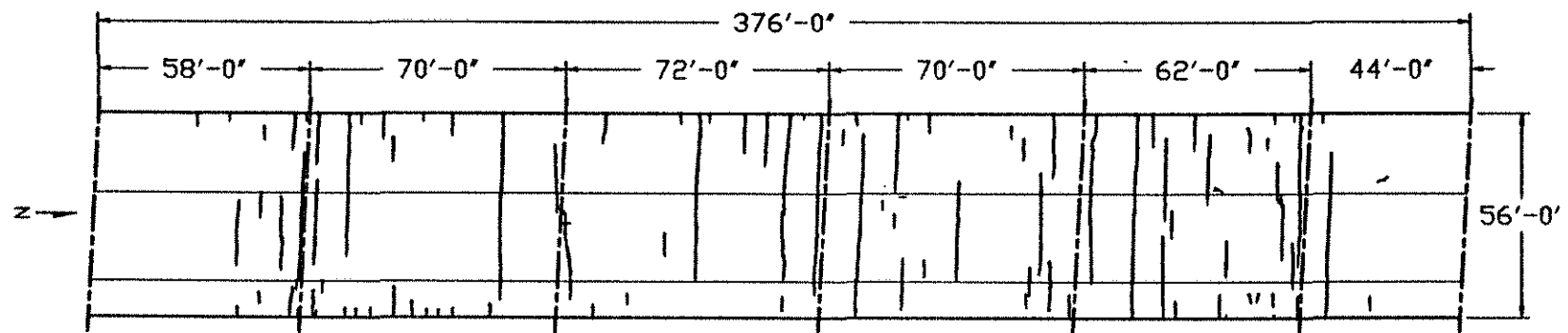


Fig. A.40 Bridge number 105-199 (Noncomposite). Scale: 1" = 50'-0".

APPENDIX B
CRACK DENSITY CALCULATION PROGRAM LISTING

```

*****
*
* PROGRAM NAME: AngLen
*
* VERSION: 2.0
*
* CREATED BY: Tony R. Schmitt
* University of Kansas
* Department of Civil Engineering
*
* FUNCTION: Takes an ascii file created from a .tif file,
* locates pixels that are within a user specified
* graylevel range, groups pixels that are adjacent to
* one another (these groups represent cracks), and
* then calculates the length and angle of each crack.
*
*****
*
* VARIABLE DEFINITIONS
*
* REAL VARIABLES:
*
* ANGLE Angle of crack. Horizontal = 0 degrees.
* Cracks increasing from left to right are positive.
* AREA Bridge deck area in square feet.
* AREA1 Bridge deck area in square meters.
* AREAPLAC Area of an individual concrete placement.
* D Distance between two pixels. This is used to
* establish the length of a given crack.
* DENS Crack density of a given deck area.
* DIVTOTD Total crack density of a bridge division.
* DIVTOTL Total length of all cracks in a division.
* DIVTRD Transverse crack density of a bridge division.
* DIVTRL Total length of all transverse cracks in a division.
* LENBRG Length of bridge in feet.
* LENDIV Length of each bridge division.
* LENGTH Length of an individual crack. This is calculated
* as the greatest distance between any two pixels
* in a given crack.
* LENPLACE Length of an individual concrete placement.
* RDIVS Number of bridge divisions. (real number format)
* RDWY Width of roadway in feet.
* RHIGH Real number variation of integer variable HIGH.
* RLOW Real number variation of integer variable LOW.
* RTEMP Real number variation of integer variable ITEMP.
* SCALE Drawing scale in ft./in. Note that many conversion
* factors are built into the program and must be
* modified if the scale of the input image is altered.
*
* SKEW Skew of the end of the bridge in degrees.
* SPANAREA Area of an individual span.
* SPANG Special angle, in degrees, defined by user to

```

```

*          investigate angles other than the default angles.
*  SPANLEN  Length of a span.
*  SPDENS   Density of cracks at defined special angle.
*  SPTL     Total length of cracks at defined special angle.
*  TLPG     Total length of cracks in a given angle group.
*  TOL      Tolerance, in degrees, for the special angle.
*  TOTDENS  Total crack density.
*  TOTLEN   Total length of all cracks.
*  WIDPLACE Width of concrete placement.
*  X1       X coordinate of a pixel.
*  X2       X coordinate of a pixel.
*  Y1       Y coordinate of a pixel.
*  Y2       Y coordinate of a pixel.
*
*  INTEGER VARIABLES:
*
*  BOTBND   Bottom bound of bridge section being considered.
*  CHECK    Used in subroutine GROUP to determine when the
*           last of the pixels have been collected into crack
*           groups.
*  CHOICE   Represents "main menu" option.
*  CX       X coordinate of a pixel within graylevel range.
*  CY       Y coordinate of a pixel within graylevel range.
*  DIVTOTC  Total number of cracks in a division.
*  DIVTRC   Total number of transverse cracks in a division.
*  HIGH     Used to define angle groups.
*  ITEMP    Used to increment YLOCATOR in division analysis.
*  JUMP     The number of rows in the ascii file that represent
*           one row of pixels in the .tif file.
*  LDPIX    Length of division in units of pixels.
*  LENPIX   Length of an individual placement in units of pixels.
*  LEVEL    Graylevel of a pixel. Takes on a value of 0 (black)
*           to 255 (white).
*  LOW      Used to define angle groups.
*  LOWER    Lower graylevel bound.
*  LTBND    Left bound. Used to define the section of bridge
*           being analyzed.
*  N        Total number of pixels in input file.
*  NCL      Limit on number of cracks program will handle.
*  NCPG     Number of cracks per angle group.
*  NUM      Number of additional specified angles (sub. SPECANG).
*  NUMCRCKS Number of cracks.
*  NUMDIVS  Number of divisions.
*  NUMPIX   Number of pixels.
*  NUMPLACE Number of placements.
*  NUMSPANS Number of spans.
*  PCL      Limit on maximum number of pixels allowed in a crack.
*  RDWYPIX  Width of roadway in units of pixels.
*  RES      Resolution in DPI (dots per inch).
*  RTBND    Right bound. Used to define the section of bridge
*           being analyzed.

```

```

*      SLPIX      Span Length in units of pixels.
*      SPNC       Number of cracks at the specified angle.
*      TCHECK     Total number of cracks in all angle groups.
*      TOPBND     Top bound. Used in defining a span.
*      TPL        Total pixel limit.
*      UPPER      Upper graylevel bound.
*      WIDPIX     Width of a placement in units of pixels.
*      X           X coordinate of a pixel.
*      XCOUNT    Counter used to assign proper X coordinate to a
*                selected pixel.
*      XEDGE      X coordinate of line used to locate starting pixel.
*      XLOCATOR   Used to define section of bridge being analyzed.
*      XPERM      Permanent list of X coordinates of pixels within
*                defined graylevel range.
*      XPT2       Used to define section of bridge being analyzed.
*      XSIZE      Number of pixels along X axis in input image.
*      XSTART     X coordinate of starting point pixel.
*      Y           Y coordinate of a pixel.
*      YBOTPT     Used to define section of bridge being analyzed.
*      YCOUNT    Counter used to assign proper Y coordinate to a
*                selected pixel.
*      YLOCATOR   Used to define section of bridge being analyzed.
*      YPERM      Permanent list of Y coordinates of pixels within
*                defined graylevel range.
*      YPT2       Used to define section of bridge being analyzed.
*      YSIZE      Number of pixels along Y axis in input image.
*      YSTART     Y coordinate of starting point pixel.
*      YTOPPT     Used to define section of bridge being analyzed.

```

```

*      CHARACTER VARIABLES:

```

```

*      INFILE*14   Name of input ascii file.
*      OUTFILE*18  Name of output file.
*      YESNO       See subroutine SPECANG.

```

```

*      BEGIN

```

```

      PROGRAM MAIN

```

```

      REAL LENGTH, ANGLE, AREA, DENS, TLPG, SCALE, TOTLEN,
+      TODENS, SPANG, SPTL, SPDENS, AREAL, SPANLEN, SKEW, RDWY,
+      SPANAREA, LENBRG, WIDPLACE, AREAPLAC, LENPLACE, RTEMP,
+      RDIVS, LENDIV, DIVTRL, DIVTRD, DIVTOTL, DIVTOTD
      INTEGER X, Y, NUMCRCKS, NUMPIX, CX, CY, NCPG, RES, SPNC,
+      TCHECK, LOWER, UPPER, N, TPL, PCL, NCL, XPERM, YPERM, CHOICE,
+      NUMSPANS, XLOCATOR, YLOCATOR, LTBND, RTBND, BOTBND, TOPBND,
+      XPT2, YPT2, RDWYPIX, SLPIX, YTOPPT, YBOTPT, NUMPLACE, WIDPIX,
+      LENPIX, ITEMP, LDPIX, NUMDIVS, XSTART, YSTART, DIVTRC,
+      DIVTOTC, JOUT
      CHARACTER INFILE*14, OUTFILE*18
      DIMENSION X(300000), Y(300000), NUMPIX(1000), CX(3000, 1000),
+      CY(3000, 1000), LENGTH(1000), ANGLE(1000),
+      NCPG(20), TLPG(20), DENS(20), SPANG(10), SPNC(10),

```

```

+          SPTL(10),SPDENS(10),XPERM(300000),YPERM(300000),
+          SPANLEN(12),SLPIX(12),SPANAREA(12),WIDPLACE(8),
+          WIDPIX(8),AREAPLAC(8),LENPLACE(8),LENPIX(8),
+          DIVTRC(50),DIVTRL(50),DIVTRD(50),DIVTOTC(50),
+          DIVTOTL(50),DIVTOD(50)

```

```
*****
```

```
* INPUT INFORMATION SECTION
```

```
*
```

```

RES = 100
SCALE = 10.0
TPL = 300000
PCL = 3000
NCL = 1000
WRITE(6,1009)
1009  FORMAT (//,'CURRENT SETTINGS:')
WRITE(6,*) ' '
WRITE(6,*) ' Resolution (DPI) . . . . . ',RES
WRITE(6,*) ' Drawing Scale (ft./in.) . . . . . ',SCALE
WRITE(6,*) ' Total Pixel Limit . . . . . ',TPL
WRITE(6,*) ' Pixels per Crack Limit. . . . . ',PCL
WRITE(6,*) ' Number of Cracks Limit. . . . . ',NCL
WRITE(6,*) ' Lower Graylevel Bound (suggested) . . 0'
WRITE(6,*) ' Upper Graylevel Bound (suggested) . . 200'
WRITE(6,*) ' '
WRITE(6,*) 'ENTER INPUT FILE NAME.'
READ(5,1010) INFILE
1010  FORMAT(A)
WRITE(6,*) 'ENTER LOWER GRAYLEVEL BOUND.'
READ(5,*) LOWER
WRITE(6,*) 'ENTER UPPER GRAYLEVEL BOUND.'
READ(5,*) UPPER
WRITE(6,*) ' '

```

```
*****
```

```
* MAIN SECTION
```

```
*
```

```

CCC=>The following subroutine scans the ascii file, records the coordin-
C   ates of each pixel within the specified graylevel range, and identifies
C   the starting point pixel from which all distances are measured (span
C   length, placement width, etc.).

```

```
*
```

```
CALL COORDS (INFILE,XPERM,YPERM,LOWER,UPPER,N,XSTART,YSTART)
```

```
*
```

```

CCC=>The following lines represent the program's "main menu". The IF
C   statement 17 lines below this comment line divides the main program
C   into sections containing the commands for each menu option.

```

```

701  WRITE(6,*) ' '
WRITE(6,*) 'CRACK DENSITY CALCULATION OPTIONS.'
WRITE(6,*) ' (1) ENTIRE BRIDGE'
WRITE(6,*) ' (2) SPANS'
WRITE(6,*) ' (3) PLACEMENTS'
WRITE(6,*) ' (4) DIVISIONS'

```

```

WRITE(6,*)' (5) QUIT'
WRITE(6,*)' '
WRITE(6,*)'ENTER CHOICE.'
700 READ(5,*) CHOICE
IF ((CHOICE.LT.1) .OR. (CHOICE.GT.5)) THEN
    WRITE(6,*)'ENTER 1, 2, 3, 4, OR 5.'
    GO TO 700
ENDIF
CCC=>Option 1 -- Entire Bridge.
C This section taken alone is essentially the same as version 1.0 of
C this program.
*
IF (CHOICE .EQ. 1) THEN
    DO 702 I = 1,N
        X(I) = XPERM(I)
        Y(I) = YPERM(I)
702 CONTINUE
    WRITE (6, '(//,A)') 'ENTER OUTPUT FILE NAME.'
    READ (5,1010) OUTFILE
    OPEN(13, FILE=OUTFILE, STATUS='UNKNOWN')
    WRITE (6, '(//,A)') 'ENTER BRIDGE DECK AREA (ft.^2).'
    READ (5,*) AREA
    AREA1 = AREA
    AREA = AREA*(0.09290304)
    CALL GROUP (N,X,Y,NUMCRCKS,NUMPIX,CX,CY)
    CALL CALCS (NUMCRCKS,NUMPIX,ANGLE,LENGTH,CX,CY)
    CALL OUTINFO (NUMCRCKS,ANGLE,LENGTH,AREA,NCPG,TLPG,TOTLEN,
+             TOTDENS,TCHECK,DENS)
    CALL PRINT (NCPG,TLPG,DENS,TCHECK,AREA,AREA1,NUMCRCKS,
+             TOTLEN,TOTDENS,OUTFILE)
    CALL SPECANG (AREA,NUMCRCKS,ANGLE,LENGTH,SPANG,SPNC,
+             SPTL,SPDENS)
    CLOSE(13)
    GO TO 700
CCC=>Option 2 -- Spans.
*
ELSEIF (CHOICE .EQ. 2) THEN
    WRITE(6,*)'ENTER OUTPUT FILE NAME.'
    READ(5,1010)OUTFILE
    OPEN(13, FILE=OUTFILE, STATUS='UNKNOWN')
    WRITE(6, '(//,A)')'ENTER WIDTH OF ROADWAY. (ft.)'
    READ(5,*) RDWY
    RDWYPIX = NINT(RDWY*10)
    WRITE(6, '(//,A)')'ENTER NUMBER OF SPANS.'
    READ(5,*)NUMSPANS
    DO 710 I = 1,NUMSPANS
        WRITE(6,*)'ENTER LENGTH OF SPAN',I,'. (ft.)'
        WRITE(6,*)'(NOTE: Span 1 is at top of TIFF image.)'
        READ(5,*)SPANLEN(I)
        SLPIX(I) = NINT(SPANLEN(I)*10)
        SPANAREA(I) = SPANLEN(I)*RDWY

```

```

SPANAREA(I) = SPANAREA(I)*(0.09290304,
710 CONTINUE
WRITE(6,'(//,A)')'ENTER SKEW. [(+) OR (-) DEGREES]'
READ(5,*) SKEW
XLOCATOR = XSTART
YLOCATOR = YSTART
LTBND = XSTART
RTBND = LTBND + RDWYPIX
DO 712 I = 1,NUMSPANS
AREA = SPANAREA(I)
AREA1 = AREA/0.09290304
IF (SKEW .EQ. 0) THEN
BOTBND = YLOCATOR + SLPIX(I)
TOPBND = YLOCATOR
DO 714 J = 1,N
IF ((XPERM(J).LT.LTBND) .OR. (XPERM(J).GT.RTBND)) THEN
X(J) = 0
Y(J) = 0
ELSEIF((YPERM(J).LT.TOPBND) .OR. (YPERM(J).GT.BOTBND)) THEN
X(J) = 0
Y(J) = 0
ELSE
X(J) = XPERM(J)
Y(J) = YPERM(J)
ENDIF
714 CONTINUE
ELSE
YPT2 = YLOCATOR - NINT(TAND(SKEW)*RDWY*10)
XPT2 = RTBND
DO 716 J = 1,N
IF ((XPERM(J).LT.LTBND) .OR. (XPERM(J).GT.RTBND)) THEN
X(J) = 0
Y(J) = 0
ELSE
YTOPPT = YLOCATOR+((-XPERM(J)+XLOCATOR)*
(YLOCATOR-YPT2))/RDWYPIX
YBOTPT = YTOPPT + SLPIX(I)
IF((YPERM(J).LT.YTOPPT) .OR. (YPERM(J).GT.YBOTPT)) THEN
X(J) = 0
Y(J) = 0
ELSE
X(J) = XPERM(J)
Y(J) = YPERM(J)
ENDIF
ENDIF
716 CONTINUE
ENDIF
CALL GROUP (N,X,Y,NUMCRCKS,NUMPIX,CX,CY)
CALL CALCS (NUMCRCKS,NUMPIX,ANGLE,LENGTH,CX,CY)
CALL OUTINFO (NUMCRCKS,ANGLE,LENGTH,AREA,NCPG,TLPG,TOTLEN,
TODENS,TCHECK,DENS)

```

```

      CALL PRINT (NCPG, TLPG, DENS, TCHECK, AREA, AREA1, NUMCRCKS,
+           TOTLEN, TOTDENS, OUTFILE)
      CALL SPECANG (AREA, NUMCRCKS, ANGLE, LENGTH, SPANG, SPNC,
+           SPTL, SPDENS)
      YLOCATOR = YLOCATOR + SLPIX(I)
712  CONTINUE
      CLOSE(13)
      GO TO 701
CCC=>Option 3 -- Placements.
*
      ELSEIF (CHOICE .EQ. 3) THEN
        WRITE(6,*) 'ENTER OUTPUT FILE NAME.'
        READ(5,1010)OUTFILE
        OPEN(13,FILE=OUTFILE,STATUS='UNKNOWN')
        WRITE(6,'(//,A)') 'ENTER SKEW. [(+) OR (-) DEGREES]'
        READ(5,*) SKEW
        WRITE(6,'(//,A)') 'PLACEMENTS ARE . . .'
        WRITE(6,*) '    (1) FULL LENGTH/PARTIAL WIDTH'
        WRITE(6,*) '    (2) PARTIAL LENGTH/FULL WIDTH'
        WRITE(6,*) '    '
        WRITE(6,*) 'ENTER CHOICE.'
720  READ(5,*) CHOICE
        IF ((CHOICE.NE.1) .AND. (CHOICE.NE.2)) THEN
          WRITE(6,*) 'ENTER 1 OR 2.'
          GO TO 720
        ENDIF
        IF (CHOICE .EQ. 1) THEN
          WRITE(6,'(//,A)') 'ENTER LENGTH OF BRIDGE. (ft.)'
          READ(5,*) LENBRG
          WRITE(6,'(//,A)') 'ENTER NUMBER OF PLACEMENTS.'
          READ(5,*) NUMPLACE
          DO 722 I = 1,NUMPLACE
            WRITE(6,*) 'ENTER WIDTH OF PLACEMENT',I,'. (ft.)'
            READ(5,*) WIDPLACE(I)
            WIDPIX(I) = NINT(WIDPLACE(I)*10)
            AREAPLAC(I) = LENBRG*WIDPLACE(I)*0.09290304
722  CONTINUE
            XLOCATOR = XSTART
            DO 724 I = 1,NUMPLACE
              LTBND = XLOCATOR
              RTBND = LTBND + WIDPIX(I)
              AREA = AREAPLAC(I)
              AREA1 = AREA/0.09290304
              DO 726 J = 1,N
                IF ((XPERM(J).LT.LTBND) .OR. (XPERM(J).GT.RTBND)) THEN
                  X(J) = 0
                  Y(J) = 0
                ELSE
                  X(J) = XPERM(J)
                  Y(J) = YPERM(J)
                ENDIF
              ENDIF
            ENDIF
          ENDIF
        ENDIF
      ENDIF

```



```

726      CONTINUE
          CALL GROUP (N,X,Y,NUMCRCKS,NUMPIX,CX,CY)
          CALL CALCS (NUMCRCKS,NUMPIX,ANGLE,LENGTH,CX,CY)
          CALL OUTINFO (NUMCRCKS,ANGLE,LENGTH,AREA,NCPG,TLPG,TOTLEN,
+             TOTDENS,TCHECK,DENS)
          CALL PRINT (NCPG,TLPG,DENS,TCHECK,AREA,AREA1,NUMCRCKS,
+             TOTLEN,TOTDENS,OUTFILE)
          CALL SPECANG (AREA,NUMCRCKS,ANGLE,LENGTH,SPANG,SPNC,
+             SPTL,SPDENS)
          XLOCATOR = RTBND
724      CONTINUE
      ELSE
          WRITE(6,*)'ENTER NUMBER OF PLACEMENTS.'
          READ(5,*) NUMPLACE
          WRITE(6,*)'ENTER WIDTH OF ROADWAY. '(ft.^2)'
          READ(5,*) RDWY
          RDWYPIX = NINT(RDWY*10)
          DO 730 I = 1,NUMPLACE
              WRITE(6,*)'ENTER LENGTH OF PLACEMENT',I,' '(ft.^2)'
              READ(5,*) LENPLACE(I)
              LENPIX(I) = NINT(LENPLACE(I)*10)
              AREAPLAC(I) = RDWY*LENPLACE(I)*0.09290304
730      CONTINUE
          XLOCATOR = XSTART
          YLOCATOR = YSTART
          LTBND = XSTART
          RTBND = LTBND + RDWYPIX
          DO 732 I = 1,NUMPLACE
              AREA = AREAPLAC(I)
              AREA1 = AREA/0.09290304
              IF (SKEW.EQ. 0) THEN
                  BOTBND = YLOCATOR + LENPIX(I)
                  TOPBND = YLOCATOR
                  DO 734 J = 1,N
                      IF ((XPERM(J).LT.LTBND) .OR. (XPERM(J).GT.RTBND)) THEN
                          X(J) = 0
                          Y(J) = 0
                      ELSEIF((YPERM(J).LT.TOPBND) .OR. (YPERM(J).GT.BOTBND))
+             THEN
                          X(J) = 0
                          Y(J) = 0
                      ELSE
                          X(J) = XPERM(J)
                          Y(J) = YPERM(J)
                      ENDIF
734      CONTINUE
          ELSE
              YPT2 = YLOCATOR - NINT(TAND(SKEW)*RDWY*10)
              XPT2 = RTBND
              DO 736 J = 1,N
                  IF ((XPERM(J).LT.LTBND) .OR. (XPERM(J).GT.RTBND)) THEN

```

```

      X(J) = 0
      Y(J) = 0
    ELSE
      YTOPPT = YLOCATOR + ((-XPERM(J) + XLOCATOR) *
+         (YLOCATOR - YPT2)) / RDWYPIX
      YBOTPT = YTOPPT + LENPIX(I)
      IF (YPERM(J) .LT. YTOPPT) .OR. (YPERM(J) .GT. YBOTPT) THEN
        X(J) = 0
        Y(J) = 0
      ELSE
        X(J) = XPERM(J)
        Y(J) = YPERM(J)
      ENDIF
    ENDIF
736    CONTINUE
      ENDIF
      CALL GROUP (N, X, Y, NUMCRCKS, NUMPIX, CX, CY)
      CALL CALCS (NUMCRCKS, NUMPIX, ANGLE, LENGTH, CX, CY)
      CALL OUTINFO (NUMCRCKS, ANGLE, LENGTH, AREA, NCPG, TLPG, TOTLEN,
+         TOTDENS, TCHECK, DENS)
      CALL PRINT (NCPG, TLPG, DENS, TCHECK, AREA, AREA1, NUMCRCKS,
+         TOTLEN, TOTDENS, OUTFILE,
+         CALL SPECANG (AREA, NUMCRCKS, ANGLE, LENGTH, SPANG, SPNC,
+         SPTL, SPDENS)
      YLOCATOR = YLOCATOR + LENPIX(I)
732    CONTINUE
      ENDIF
      CLOSE(13)
      GO TO 701

```

CCC=>Option 4 -- Divisions.

*

```

ELSEIF (CHOICE .EQ. 4) THEN
  WRITE(6,*) 'ENTER OUTPUT FILE NAME.'
  READ(5,1010) OUTFILE
  OPEN(13, FILE=OUTFILE, STATUS='UNKNOWN')
  WRITE(6,*) 'ENTER WIDTH OF ROADWAY. (ft.)'
  READ(5,*) RDWY
  RDWYPIX = NINT(RDWY*10)
  WRITE(6,*) 'ENTER LENGTH OF BRIDGE. (ft.)'
  READ(5,*) LENBRG
  WRITE(6,*) 'ENTER NUMBER OF DIVISIONS.'
  READ(5,*) NUMDIVS
  RDIVS = REAL(NUMDIVS)
  LENDIV = LENBRG/RDIVS
  LDPIX = NINT(LENDIV*10)
  AREA = LENDIV*RDWY*0.09290304
  AREA1 = AREA/0.09290304
  WRITE(6,*) 'ENTER SKEW. [(+) OR (-) DEGREES]'
  READ(5,*) SKEW
  XLOCATOR = XSTART
  YLOCATOR = YSTART

```

```

LTBND = XLOCATOR
RTBND = LTBND + RDWYPIX
DO 742 I = 1, NUMDIVS
  IF (SKEW .EQ. 0) THEN
    BOTBND = YLOCATOR + LDPIX
    TOPBND = YLOCATOR
    DO 744 J = 1, N
      IF ((XPERM(J) .LT. LTBND) .OR. (XPERM(J) .GT. RTBND)) THEN
        X(J) = 0
        Y(J) = 0
      ELSEIF ((YPERM(J) .LT. TOPBND) .OR. (YPERM(J) .GT. BOTBND)) THEN
        X(J) = 0
        Y(J) = 0
      ELSE
        X(J) = XPERM(J)
        Y(J) = YPERM(J)
      ENDIF
    CONTINUE
  ELSE
    YPT2 = YLOCATOR - NINT(TAND(SKEW)*RDWY*10)
    XPT2 = RTBND
    DO 746 J = 1, N
      IF ((XPERM(J) .LT. LTBND) .OR. (XPERM(J) .GT. RTBND)) THEN
        X(J) = 0
        Y(J) = 0
      ELSE
        YTOPPT = YLOCATOR + ((-XPERM(J) + XLOCATOR) *
          (YLOCATOR - YPT2)) / RDWYPIX
        YBOTPT = YTOPPT + LDPIX
        IF ((YPERM(J) .LT. YTOPPT) .OR. (YPERM(J) .GT. YBOTPT)) THEN
          X(J) = 0
          Y(J) = 0
        ELSE
          X(J) = XPERM(J)
          Y(J) = YPERM(J)
        ENDIF
      ENDIF
    CONTINUE
  ENDIF
  CALL GROUP (N, X, Y, NUMCRCKS, NUMPIX, CX, CY)
  CALL CALCS (NUMCRCKS, NUMPIX, ANGLE, LENGTH, CX, CY)
  CALL OUTINFO (NUMCRCKS, ANGLE, LENGTH, AREA, NCPG, TLPG, TOTLEN,
    TOTDENS, TCHECK, DENS)
  DIVTRC(I) = NCPG(1)
  DIVTRL(I) = TLPG(1)
  DIVTRD(I) = DENS(1)
  DIVTOTC(I) = TCHECK
  DIVTOTL(I) = TOTLEN
  DIVTOTD(I) = TOTDENS
  RTEMP = I*LENDIV*10
  ITEMP = NINT(RTEMP)

```

```

      YLOCATOR = YSTART + ITEMP
742  CONTINUE
      DO 747 J = 1,2
        IF (J .EQ. 1) THEN
          JOUT = 6
        ELSE
          JOUT = 13
        ENDIF
        WRITE(JOUT,*) OUTFILE
        WRITE(JOUT,*) 'DIVISION LENGTH =',LENDIV,' (ft.)'
        WRITE(JOUT,*) '          =',LENDIV*.3048,' (m)'
        WRITE(JOUT,*) 'DIVISION AREA =',AREAL,' (ft.^2)'
        WRITE(JOUT,*) '          =',AREA,' (m^2)'
        WRITE(JOUT,*) ' '
        WRITE(JOUT,*) '          -----TRANSVERSE-----',
+         '          -----TOTAL-----'
        WRITE(JOUT,*) 'DIV.  #CRACKS  LENGTH  DENSITY',
+         '          #CRACKS  LENGTH  DENSITY'
        WRITE(JOUT,*) '          (m)      (m/m^2)',
+         '          (m)      (m/m^2)'
        WRITE(JOUT,*) '-----'
        WRITE(JOUT,*) '-----'
        DO 745 I = 1,NUMDIVS
          WRITE(JOUT,1745) I, DIVTRC(I), DIVTRL(I), DIVTRD(I),
-          DIVTOTC(I), DIVTOTL(I), DIVTOTD(I)
745  CONTINUE
747  CONTINUE
1745  FORMAT(2X, I2, 5X, I3, 4X, F6.2, 3X, F5.3, 5X, I3, 4X, F6.2, 3X, F5.3)
      CLOSE(13)
      GO TO 701
CCC=>Option 5 -- Quit.
*
      ELSE
        WRITE(6,*) 'END!'
      ENDIF
    END
*****
*  SUBROUTINE GROUP
*****
*  DIVIDES PIXELS INTO CRACK GROUPS
*  NUMCRCKS = TOTAL NUMBER OF CRACKS IN SECTION CONSIDERED
*  NUMPIX(K) = TOTAL NUMBER OF PIXELS IN A GIVEN CRACK K
*  N = TOTAL NUMBER OF PIXELS IN THE INPUT FILE
*
  SUBROUTINE GROUP (N,X,Y,NUMCRCKS,NUMPIX,CX,CY)
    INTEGER N,X,Y,NUMCRCKS,NUMPIX,CX,CY,CHECK
    DIMENSION X(300000),Y(300000),NUMPIX(1000),CX(3000,1000),
+     CY(3000,1000)
*
*
    DO 24 I = 1,1000

```

```

DO 23 J = 1,3000
  CX(J,I) = 0
  CY(J,I) = 0
23  CONTINUE
24  CONTINUE
  NUMCRCKS = 0
DO 50 K = 1,1000
  write(6,*)'K = ',K
  CHECK = 0
  DO 25 M = 1,N
    CHECK = CHECK + X(M)
25  CONTINUE
  write(6,*)'check = ',CHECK
  IF (CHECK .EQ. 0) THEN
    GO TO 60
  ELSE
    NUMPIX(K) = 1
    DO 5 L = 1,N
      IF (X(L) .NE. 0) THEN
        CX(1,K) = X(L)
        CY(1,K) = Y(L)
        X(L) = 0
        Y(L) = 0
        GO TO 8
      ENDIF
    CONTINUE
5    DO 40 J = 1,3000
8    IF (CX(J,K) .NE. 0) THEN
      DO 30 I = 1,N
        IF (X(I) .NE. 0) THEN
          IF (((X(I).EQ.CX(J,K)).OR.(X(I).EQ.(CX(J,K)+1)).OR.
+           (X(I).EQ.(CX(J,K)-1))))
+           .AND.
+           ((Y(I).EQ.CY(J,K)).OR.(Y(I).EQ.(CY(J,K)+1)).OR.
+           (Y(I).EQ.(CY(J,K)-1)))) THEN
            NUMPIX(K) = NUMPIX(K) + 1
            CX(NUMPIX(K),K) = X(I)
            CY(NUMPIX(K),K) = Y(I)
            X(I) = 0
            Y(I) = 0
          ENDIF
        ENDIF
30      CONTINUE
      ELSE
        GO TO 45
      ENDIF
40    CONTINUE
45    CONTINUE
    NUMCRCKS = NUMCRCKS + 1
  ENDIF
50  CONTINUE

```

```

60      CONTINUE
        write(6,*)'numcrcks = ',NUMCRCKS
        RETURN
      END
*****
*   SUBROUTINE CALCS
*****
*   CALCULATES LENGTH AND ANGLE OF EVERY CRACK
*   K = CRACK NUMBER
*   J = FIXED (BASE) PIXEL FROM WHICH DISTANCES ARE MEASURED
*   I = VARIABLE (ENDPOINT) PIXEL
*
      SUBROUTINE CALCS (NUMCRCKS,NUMPIX,ANGLE,LENGTH,CX,CY)
      REAL ANGLE,LENGTH,D,X1,Y1,X2,Y2
      INTEGER NUMCRCKS,NUMPIX,CX,CY
      DIMENSION ANGLE(1000),LENGTH(1000),NUMPIX(1000),CX(3000,1000),
+           CY(3000,1000),D(1000)
*
*
      DO 78 I = 1,1000
        ANGLE(I) = 0
78      CONTINUE
        DO 90 K = 1,NUMCRCKS
          LENGTH(K) = 0
          DO 80 J = 1,NUMPIX(K)
            X1 = REAL(CX(J,K))
            Y1 = REAL(CY(J,K))
            DO 70 I = 1,NUMPIX(K)
              X2 = REAL(CX(I,K))
              Y2 = REAL(CY(I,K))
              D(K)=SQRT(((X1-X2)**2)+((Y1-Y2)**2))
              IF (D(K) .GT. LENGTH(K)) THEN
                LENGTH(K) = D(K)
                IF (X1 .EQ. X2) THEN
                  ANGLE(K) = 0
                ELSEIF (Y1 .EQ. Y2) THEN
                  ANGLE(K) = 90
                ELSE
                  ANGLE(K)=(ATAN((Y1-Y2)/(X1-X2)))*(-180/3.14159265)
                ENDIF
              ENDIF
            ENDIF
          ENDIF
        ENDIF
      DO 70 I = 1,NUMPIX(K)
      CONTINUE
70      CONTINUE
80      CONTINUE
90      CONTINUE
CCC=> THE FOLLOWING LINES CONVERT THE LENGTHS FROM PIXELS TO METERS.
CCC=> IF THE RESOLUTION OR DRAWING SCALE CHANGES, THE CONVERSION FACTOR
CCC=> MUST CHANGE ACCORDINGLY.
      DO 95 K = 1,NUMCRCKS
        LENGTH(K) = LENGTH(K) * (0.03048)
95      CONTINUE
      RETURN

```

```

END
*****
* SUBROUTINE OUTINFO
*****
* CREATES INFORMATION FOR OUTPUT
*   NCPG = NUMBER OF CRACKS PER GROUP
*   TLPG = TOTAL LENGTH PER GROUP
*   DENS = CRACK DENSITY PER GROUP (LIN. M/M^2)
*
*
SUBROUTINE OUTINFO (NUMCRCKS, ANGLE, LENGTH, AREA, NCPG, TLPG, TOTLEN,
+                 TOTDENS, TCHECK, DENS)
REAL ANGLE, LENGTH, AREA, TLPG, TOTLEN, TOTDENS, DENS
INTEGER NUMCRCKS, NCPG, TCHECK, LOW, HIGH
DIMENSION ANGLE(1000), LENGTH(1000), NCPG(20), TLPG(20), DENS(20)
*
*
DO 110 L = 1, 19
  NCPG(L) = 0
  TLPG(L) = 0
  DENS(L) = 0
110 CONTINUE
DO 130 K = 1, NUMCRCKS
  LOW = -5
  HIGH = 5
  DO 120 L = 1, 9
    IF ((ANGLE(K) .GE. LOW) .AND. (ANGLE(K) .LT. HIGH)) THEN
      NCPG(L) = NCPG(L) + 1
      TLPG(L) = TLPG(L) + LENGTH(K)
      GO TO 130
    ENDIF
    LOW = LOW + 10
    HIGH = HIGH + 10
120 CONTINUE
  IF ((ANGLE(K) .GE. 85) .AND. (ANGLE(K) .LE. 90)) .OR.
  + ((ANGLE(K) .LT. -85) .AND. (ANGLE(K) .GT. -90)) THEN
    NCPG(10) = NCPG(10) + 1
    TLPG(10) = TLPG(10) + LENGTH(K)
  ENDIF
  LOW = -15
  HIGH = -5
  DO 125 L = 11, 18
    IF ((ANGLE(K) .GE. LOW) .AND. (ANGLE(K) .LT. HIGH)) THEN
      NCPG(L) = NCPG(L) + 1
      TLPG(L) = TLPG(L) + LENGTH(K)
      GO TO 130
    ENDIF
    LOW = LOW - 10
    HIGH = HIGH - 10
125 CONTINUE
130 CONTINUE

```

```

DO 140 L = 1,18
  DENS(L) = TLPG(L)/AREA
140 CONTINUE
  TOTLEN = 0
  DO 145 K = 1,NUMCRCKS
    TOTLEN = TOTLEN + LENGTH(K)
145 CONTINUE
  TOTDENS = TOTLEN/AREA
  TCHECK = 0
  DO 147 I = 1,18
    TCHECK = TCHECK + NCPG(I)
147 CONTINUE
  RETURN
END
*****
* SUBROUTINE PRINT
*****
* WRITES RESULTS TO THE SCREEN AND TO AN OUTPUT FILE
*
SUBROUTINE PRINT (NCPG,TLPG,DENS,TCHECK,AREA,AREA1,NUMCRCKS,
+ TOTLEN,TOTDENS,OUTFILE)
  REAL TLPG,DENS,AREA,AREA1,TOTLEN,TOTDENS
  INTEGER NCPG,TCHECK,NUMCRCKS,LOW,HIGH
  CHARACTER OUTFILE*18
  DIMENSION NCPG(20),TLPG(20),DENS(20)
*
*
  WRITE(6,*)'          # OF    TOTAL    CRACK'
  WRITE(6,*)'  ANGLE    CRACKS  LENGTH  DENSITY'
  WRITE(6,*)'  (deg)                (m)    (lin.m/m^2)'
  WRITE(6,*)'-----'
  LOW = -5
  HIGH = 5
1020 FORMAT(1X,'(',I3,')-(',I3,')',4X,I3,3X,F6.2,3X,F9.7)
  DO 150 I = 1,10
    WRITE(6,1020)LOW,HIGH,NCPG(I),TLPG(I),DENS(I)
    LOW = LOW + 10
    HIGH = HIGH + 10
150 CONTINUE
  LOW = -5
  HIGH = -15
  DO 160 I = 11,18
    WRITE(6,1020)LOW,HIGH,NCPG(I),TLPG(I),DENS(I)
    LOW = LOW - 10
    HIGH = HIGH - 10
160 CONTINUE
  WRITE(6,1030)'TOTAL',NUMCRCKS,TOTLEN,TOTDENS
  WRITE(6,1037)'CHECK',TCHECK
1030 FORMAT(4X,A5,7X,I3,3X,F6.2,3X,F9.7)
  WRITE(13,*) OUTFILE
  WRITE(13,*)'AREA = ',AREA1,' (ft.^2)'

```



```

WRITE(13,*)'AREA = ',AREA,' (m^2)'
WRITE(13,*)' '
WRITE(13,*)'          # OF TOTAL      CRACK'
WRITE(13,*)'    ANGLE   CRACKS  LENGTH  DENSITY'
WRITE(13,*)'    (deg)                (m)   (lin.m/m^2)'
WRITE(13,*)'-----'
LOW = -5
HIGH = 5
DO 170 I = 1,10
    WRITE(13,1020)LOW,HIGH,NCPG(I),TLPG(I),DENS(I)
    LOW = LOW + 10
    HIGH = HIGH + 10
170 CONTINUE
LOW = -5
HIGH = -15
DO 180 I = 11,18
    WRITE(13,1020)LOW,HIGH,NCPG(I),TLPG(I),DENS(I)
    LOW = LOW - 10
    HIGH = HIGH - 10
180 CONTINUE
WRITE(13,1030)'TOTAL',NUMCRCKS,TOTLEN,TOTDENS
WRITE(13,1037)'CHECK',TCHECK
1037 FORMAT (4X,A5,7X,I3)
RETURN
END
*****
* SUBROUTINE SPECANG
*****
* SPECIFIED ANGLE SECTION
*
SUBROUTINE SPECANG (AREA,NUMCRCKS,ANGLE,LENGTH,SPANG,SPNC,
+                   SPTL,SPDENS)
REAL AREA,ANGLE,LENGTH,SPANG,SPTL,SPDENS,LOW,RHIGH,TOL
INTEGER NUMCRCKS,SPNC,NUM
CHARACTER YESNO
DIMENSION ANGLE(20),LENGTH(20),SPANG(10),SPNC(10),SPTL(10),
+         SPDENS(10)
*
*
WRITE(6,1050)
1050 FORMAT(///,///,' DO YOU WISH TO SEE INFORMATION FOR ANGLES OTHER')
WRITE(6,*)'THAN THOSE LISTED?'
1051 FORMAT (A1)
READ(5,1051) YESNO
IF (YESNO .EQ. 'Y' .OR. YESNO .EQ. 'y') THEN
    WRITE(6,*)'ENTER THE NO. OF ADDITIONAL ANGLES DESIRED.'
    READ(5,*)NUM
    WRITE(6,*)'ENTER TOLERANCE FOR EACH ANGLE (+/- ___ deg.).'
    READ(5,*) TOL
    DO 190 I = 1,NUM
        WRITE(6,*)'ENTER ANGLE',I,' (deg.).'

```

```

      READ(5,*) SPANG(I)
190  CONTINUE
      DO 195 I = 1,10
          SPNC(I) = 0
          SPTL(I) = 0
          SPDENS(I) = 0
195  CONTINUE
      DO 200 K = 1,NUMCRCKS
          DO 198 I = 1,NUM
              IF((ANGLE(K).GT.(SPANG(I)-TOL)) .AND.
+              (ANGLE(K).LT.(SPANG(I)+TOL))) THEN
                  SPNC(I) = SPNC(I) + 1
                  SPTL(I) = SPTL(I) + LENGTH(K)
              ENDIF
198  CONTINUE
200  CONTINUE
      DO 210 I = 1,NUM
          SPDENS(I) = SPTL(I)/AREA
210  CONTINUE
      WRITE(6,1052)
1052  FORMAT(//,'SPECIFIED ANGLES:')
      WRITE(6,*)' '
      WRITE(6,*)'          # OF TOTAL      CRACK'
      WRITE(6,*)'          ANGLE      CRACKS  LENGTH  DENSITY'
      WRITE(6,*)'          (deg)                (m)      (lin.m/m^2)'
      WRITE(6,*)'-----'
      WRITE(13,1052)
      WRITE(13,*)' '
      WRITE(13,*)'          # OF TOTAL      CRACK'
      WRITE(13,*)'          ANGLE      CRACKS  LENGTH  DENSITY'
      WRITE(13,*)'          (deg)                (m)      (lin.m/m^2)'
      WRITE(13,*)'-----'
1060  FORMAT(1X,'(',F6.2,')-(',F6.2,')',4X,I3,3X,F6.2,3X,F9.7)
      DO 220 I = 1,NUM
          RLOW = SPANG(I) - TOL
          RHIGH = SPANG(I) + TOL
          WRITE(6,1060)RLOW,RHIGH,SPNC(I),SPTL(I),SPDENS(I)
          WRITE(13,1060)RLOW,RHIGH,SPNC(I),SPTL(I),SPDENS(I)
220  CONTINUE
      ENDIF
      RETURN
      END
*****
*   SUBROUTINE COORDS
*****
*   SELECTS ALL "DARK" PIXELS FROM ASCII FILE AND WRITES THEIR COORDINATES
*   TO FILE coords.dat
*
      SUBROUTINE COORDS (INFILE,XPERM,YPERM,LOWER,UPPER,N,XSTART,YSTART)
      INTEGER LEVEL,XCOUNT,YCOUNT,XPERM,YPERM,LOWER,UPPER,N,
+      XSIZE,YSIZE,CHOICE,JUMP,XEDGE,XSTART,YSTART

```

```

CHARACTER INFILE*14
DIMENSION LEVEL(16),XPERM(300000),YPERM(300000)
*
*
XSIZE = 592
YSIZE = 4208
WRITE(6,*)'DEFAULT IMAGE SIZE: ',XSIZE,' x',YSIZE
WRITE(6,*)' (1) USE DEFAULT'
WRITE(6,*)' (2) SPECIFY NEW SIZE'
WRITE(6,*)' '
WRITE(6,*)'ENTER CHOICE'
600 READ(5,*)CHOICE
IF ((CHOICE .NE. 1) .AND. (CHOICE .NE. 2)) THEN
WRITE(6,*)'ENTER 1 OR 2.'
GO TO 600
ENDIF
IF (CHOICE .EQ. 2) THEN
601 WRITE(6,*)'ENTER X-DIMENSION.'
READ(5,*)XSIZE
WRITE(6,*)'ENTER Y-DIMENSION.'
READ(5,*)YSIZE
WRITE(6,*)'NEW IMAGE SIZE: ',XSIZE,' x',YSIZE
WRITE(6,*)' (1) ACCEPT'
WRITE(6,*)' (2) MODIFY'
WRITE(6,*)' '
WRITE(6,*)'ENTER CHOICE:'
602 READ(5,*)CHOICE
IF ((CHOICE .NE. 1) .AND. (CHOICE .NE. 2)) THEN
WRITE(6,*)'ENTER 1 OR 2.'
GO TO 602
ENDIF
IF (CHOICE .EQ. 2) THEN
GO TO 601
ENDIF
ENDIF
JUMP = XSIZE/16
WRITE(6,*)'SCANNING ASCII FILE . . .'
1002 FORMAT (16(I3,1X))
OPEN (11,FILE=INFILE,STATUS='OLD')
N = 0
YCOUNT = 0
DO 3 K = 1,YSIZE
YCOUNT = YCOUNT + 1
XCOUNT = 0
DO 2 J = 1,JUMP
READ (11,1002) (LEVEL(I), I=1,16)
DO 1 I = 1,16
XCOUNT = XCOUNT + 1
IF ((LEVEL(I).GE.LOWER) .AND. (LEVEL(I).LE.UPPER)) THEN
N = N + 1
XPERM(N) = XCOUNT

```

```

        YPERM(N) = YCOUNT
        ENDIF
1       CONTINUE
2       CONTINUE
3       CONTINUE
        CLOSE(11)
CCC=>The following lines locate the starting point pixel.
        IF (YPERM(1) .NE. 1) THEN
            WRITE(6,*)'ERROR!! CHECK TIFF FILE.'
            STOP
        ENDIF
        XEDGE = XPERM(1)
        J = 1
        DO 610 I = 1,N
            IF ((XPERM(I).EQ.XEDGE) .AND. (YPERM(I).EQ.J)) THEN
                XSTART = XPERM(I)
                YSTART = YPERM(I)
                J = J + 1
                XPERM(I) = 0
                YPERM(I) = 0
            ENDIF
510     CONTINUE
CCC=>
1003    OPEN (12,FILE='coords.dat',STATUS='UNKNOWN')
        FORMAT (3X,I3,4X,I4)
        DO 4 I = 1,N
            IF (XPERM(I) .NE. 0) THEN
                WRITE (12,1003) XPERM(I),YPERM(I)
            ENDIF
4       CONTINUE
        CLOSE(12)
        WRITE(6,*)'TOTAL NUMBER OF "DARK" PIXELS =',N,'.'
        RETURN
END

```