

Quantification of Cracks in Concrete Bridge Decks in Ohio District 3

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16. Abstract <p>The development of cracks in reinforced bridge decks is a critical problem, not only in Ohio state, but the whole of United States. Many bridge decks constructed within the last 10 years in Ohio have already shown varying levels and patterns of cracking. Bridge deck cracking is a serious issue because cracks allow harmful and corrosive chemicals to penetrate the concrete and deteriorate the reinforcing steel embedded in it, regardless of the bridge design type, length of spans, deck thickness and concrete mixture designs. Proper precautions need to be taken to avoid rapid deterioration of the bridges which can lead to increased maintenance costs and the need for possible replacement. The Ohio Department of Transportation's current procedure for bridge inspection requires periodic surveying of the whole bridge. However, this inspection procedure offers only a qualitative assessment of the bridges inspected. In this study, a quantitative measurement strategy was adopted by measuring the crack densities of twelve bridges in District 3. Two types of bridges were inspected: three structural slab bridge decks and nine stringer supported bridge decks. Crack densities were determined based on crack maps corresponding to the surveys for each bridge deck. The crack densities determined for the twelve bridge decks indicated that structural slab bridge decks have slightly higher shrinkage crack densities compared to the bridge decks constructed with stringer supports. However, the "structural" cracks seem to be wider for structural slabs (greater than 0.007 inch). Particularly on bridge ASD-42-0656, which is a continuous slab bridge, there were several large "structural" cracks that were parallel to the intermediate supports. These cracks very wide (much greater than 0.007 inch). The shrinkage crack densities of the twelve bridge decks determined in this study were considerably lower than the crack densities of similar bridge decks located in other states, demonstrating that Ohio bridge decks in general have lower crack density than those in other states. The shrinkage crack densities of the bridges constructed with QC/QA type of concrete have lower values than the bridges made with other types of concrete.</p>					
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Final Report

State Job No. 134564

**QUANTIFICATION OF CRACKS IN CONCRETE BRIDGE
DECKS IN OHIO DISTRICT 3**

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the U.S. Department of Transportation, Federal Highway Administration*

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CHAPTER I

INTRODUCTION

1.1 Introduction

One serious problem reinforced concrete bridge decks face throughout the United States is the development of several cracks. Concrete bridge decks of all ages and sizes, some even constructed within the last several years, show different levels of cracking. Regardless of the type of superstructure, the number and length of spans, and the type of concrete used, cracks inevitably develop in every reinforced concrete bridge deck. There is a need to study the extent of cracking developed in concrete bridge decks so that the causes of cracking can be identified and counter measures established to minimize cracking in future bridge deck constructions.

Cracks are critical on bridge decks because cracks provide access to harmful, corrosive chemicals that deteriorate the reinforcing steel, which is embedded within the concrete. Once chloride and other deteriorating agents penetrate concrete and make contact with the reinforcing steel, the deteriorating agents will corrode the steel, cause spalling, and eventually cause a loss of cross sectional area for the reinforcing steel. Such deterioration can affect the shear and moment capacity of reinforced concrete bridge decks. Also, the bridge deck cracks allow water and deicing salts to leak down through the bridge deck and damage the substructure and affect the aesthetics of the bridge (Krauss and Rogalla, 1996). Corrosion of the concrete's reinforcing steel, which is accelerated by bridge deck cracking, is an extremely serious issue for State Departments of Transportation. In 2002, it was estimated that the annual direct cost of corrosion in highway bridges was \$8.3 billion, with indirect costs to users due to traffic delays and lost productivity, estimated to be 10 times as much (Yunovich et al., 2002). The replacement costs for bridge decks are a significant portion of that direct cost.

Cracks frequently form relatively early in the life of concrete bridge decks. Cracks may form well in advance of a bridge being open to traffic, and sometimes immediately following construction (Schmitt and Darwin, 1995; Hadidi and Saadeghvaziri, 2005). Concrete bridge deck cracking is influenced by several conditions including construction practices, concrete mix proportions, material properties, structural design, and loading. Early-age deck cracking not only reduces the service life of the bridge deck itself, but it also causes durability issues for the bridge as a whole.

NCHRP Synthesis 333 is one of the only complete resources used to provide details of concrete bridge deck performance for cracking. The report offers strategies and practices to improve reinforced concrete bridge deck cracking performance. Increased clear concrete cover, use of low slump, dense, low permeability concrete, and use of epoxy coated reinforcing bars are several approaches adopted to minimize deck cracking (NCHRP Synthesis 333). Even with significant research and investigations specifically addressing the problem of bridge deck cracking, cracking in reinforced concrete bridge decks is still a widespread concern in old and newly constructed bridges.

When it pertains to bridge inspection, the Ohio Department of Transportation (ODOT) relies on its inspection protocol to assess bridge condition (Manual of Bridge Inspection, 2006). This inspection protocol requires both top and bottom deck inspection periodically. These deck inspections require the engineer to look for cracking, spalling, scaling, leaching, water saturation, delamination, full depth failures, and potholes. Once the engineer has inspected the bridge thoroughly, the engineer gives the bridge a code from 1 to 4, with code 1 representing least severe deterioration to code 4 representing most severe deterioration (Manual of Bridge Inspection, 2006). The Inspection Protocol offers ODOT a qualitative condition assessment of the bridge deck; however, the protocol does not provide a quantitative measurement of the extent and severity of cracking for the bridge deck.

1.2 Objectives

- The primary objective for this project is to determine if there is a higher propensity for cracking to occur on structural slab bridge decks as compared to stringer supported bridge decks.
- Once it is determined which bridge type has a higher propensity for cracking, a secondary objective is to develop insight that will be helpful in understanding the cracking behavior of structural slab bridge decks and stringer supported bridges decks.
- If it is determined that there is a higher tendency for cracking to occur on structural slab bridge decks, then another objective is to identify general areas where future research should be considered.

1.3 Scope of the Project

The results of a recent study aimed at quantifying reinforced concrete bridge deck cracking are presented and discussed. The project focuses primarily on determining if there is a higher tendency for cracking to occur on structural slab bridge decks as opposed to stringer supported bridge decks. Twelve reinforced concrete bridge decks were examined in order to study the cracking behavior and extent of cracking in structural slab and stringer supported bridge decks. The selected bridges for this project consisted of three continuous concrete slab bridges, three simple prestressed concrete beam bridges, one simple steel beam bridge, and five continuous steel beam bridges. In all, three structural slab bridges and nine stringer supported bridges were surveyed. Crack surveys were performed on the bridge decks for these 12 different bridges and crack maps were developed for the corresponding decks. The crack maps were then used to determine crack densities for each bridge. With these crack densities, cracking performances were identified. The details of the study are outlined in this report.

A brief review of literature is presented in Chapter II. The basis for the selection of bridge decks is given in Chapter III along with the list of selected bridges. The crack survey protocol is discussed in Chapter IV. Crack maps of surveyed bridges are presented in Chapter V. Results and discussions for the surveyed bridges are provided in Chapter VI. Lastly, conclusions and recommendations are offered in Chapter VII of the report.

CHAPTER II

REVIEW OF LITERATURE

2.1 Transverse Cracking

Transverse cracks are cracks that are perpendicular to the longitudinal axis of the bridge deck, and they are the main type of cracking found on reinforced concrete bridge decks. These cracks generally form at the surface of the bridge deck under which the transverse reinforcement is placed. Transverse cracks are also typically full depth and located 3-10 feet apart along the length of the concrete bridge deck (Krauss and Rogalla, 1996). Ramey et al. (1997) found in their research that transverse cracks appear very early in the construction process; they typically appear soon after the casting of the concrete. The location and positioning of transverse cracks is critical to the service life and maintenance costs of reinforced concrete bridge decks. Since the transverse cracks generally develop above the transverse reinforcement, deteriorating chemical agents, like deicing chemicals, can easily find access to the reinforcing steel.

2.2 Longitudinal Cracking

Longitudinal cracks are cracks that are parallel to the longitudinal axis of the bridge deck. Similar to transverse cracks, longitudinal cracks form above the longitudinal reinforcing steel on top of the bridge deck. Even though longitudinal cracks can appear on several types of bridges, Schmitt and Darwin (1995) observed that longitudinal cracks occur primarily on solid and hollow slab bridges. Curtis and White (2007) have found that longitudinal cracking generally follows the paths of the steel beams. The researchers discovered that longitudinal cracking is caused by the differential movements along the beams, and they believe the cause of the differential movement is from the rotation of the beams about their longitudinal axis (Curtis and White, 2007). However, based on his research, Frosch (2007) found that longitudinal deck cracking typically occurs above the edge of the girders.

2.3 Diagonal Cracking

Although diagonal cracks can be found in all types of concrete bridge decks, these cracks are commonly associated with bridge decks with a skew. Through their research, Fu et al. (2007) found that decks with a skew have much more of a tendency to have diagonal cracking than their straight counterparts. In bridge decks with a skew, diagonal cracking occurs more in the corner areas as a result of restraint provided by the abutments and piers. These cracks typically start with a right angle to the deck edge that is along the direction of the supports (Fu et al., 2007).

2.4 Map/Pattern Cracking

Pattern or map cracking is a very common form of cracking, and it is prevalent on all types of concrete bridge decks and bridges. One way that this type of cracking occurs is when wet concrete is placed on dry precast concrete beams. The cracks initiate at the bottom of the

concrete deck and propagate their way up through the deck until they reach the surface (Curtis and White, 2007). Map or pattern cracks are often the product of improper curing because the surface moisture on the concrete evaporates too quickly, and the volumetric change of the concrete is restrained (Schmitt and Darwin, 1995). A classification of the different types of cracks is shown in Figure 1.

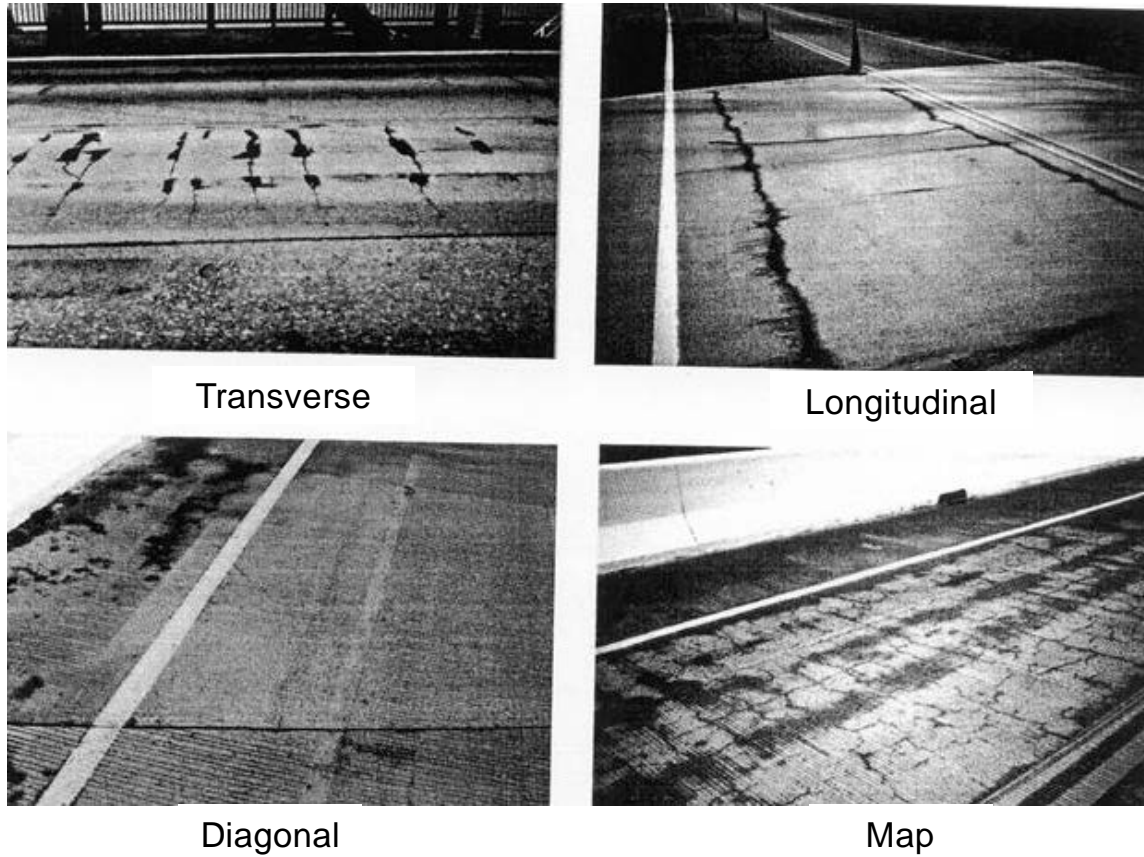


Figure 1 Classification of Cracks (NCHRP Synthesis 333, 2004)

2.5 Causes of Cracking in Concrete Bridge Decks

It is well-known that concrete has relatively low tensile strength, and this characteristic is one of the important causes of cracking. In its early age, concrete cracking occurs due to the restraint of the concrete. The volumetric movement of the concrete is prevented by restraint, which is produced by either internal or external sources. Internal sources of restraint are steel reinforcement in the bridge deck and aggregates in the concrete (Brown et al., 2001). External sources of restraint are produced by the superstructure, friction between the bridge deck and supporting girders, and the sub-base (Brown et al., 2001). Since the bridge deck and superstructure are forced to act compositely, the bridge deck undergoes large amounts of restraint because no relative displacement can occur. Therefore, concrete cracks become visible when the tensile strength of the concrete is exceeded by the tensile stresses produced by restraint. These tensile stresses ultimately turn into cracks that can adversely affect the performance of concrete.

The volumetric movement of concrete can result from drying shrinkage, autogenous shrinkage, plastic shrinkage, and thermal loads (Kosmatka et al., 2002). Different causes of bridge deck cracking are shown in Figure 2. The primary cause of drying shrinkage in concrete is the loss of absorbed water because of relative humidity. Drying shrinkage happens when the volume of the concrete changes due to the change in the water content during the time after placement of the concrete and continues for several days after placement. When the concrete is exposed to the environmental conditions, the atmospheric humidity absorbs the concrete's water, which results in induced tensile forces. As water evaporates, the tensile stresses that are confined to the surface tension of the water are transferred to the capillary walls. This tension in the capillary walls causes the shrinkage of the concrete (Brown et al., 2001).

Plastic shrinkage occurs in early-age, fresh concrete. When the fresh concrete is placed into the forms, plastic shrinkage occurs when the surface water on the plastic concrete evaporates excessively. As the water in the concrete is removed, the voids that are produced begin to pull the cement particles closer together, which increases the internal pressure in the concrete (Cohen et al., 1990). This pressure continues to rise until it reaches a critical value at which plastic shrinkage cracking occurs. Water loss for concrete not only takes place through surface evaporation, but it also happens through the substructure or formwork for the concrete bridge deck.

Another source of tensile stress that causes volumetric changes in concrete is due to autogenous shrinkage in the bridge deck. Autogenous shrinkage is a result of the concrete being dehydrated. When the concrete's volume changes without a change in its water content, autogenous shrinkage occurs (TRC E-C107, 2006). Autogenous shrinkage takes place when no additional water is supplied to the concrete through curing, so the concrete begins to chemically consume its water in order to hydrate and feed its long-term chemical reaction demands of the cementitious materials (Brown et al., 2001). This type of shrinkage is much more prevalent in concrete mixes with low water to cement (w/c) ratios because water demands cannot be met by the external environment. Paillere et al. (1989) stated that autogenous shrinkage is significantly increased by the use of superfine admixtures such as silica fume.

Thermal stresses are also another cause of volumetric change for concrete bridge decks. The first thermal stress on the concrete member is the heat of hydration process. As the concrete gains its initial strength through hydration and chemical reactions, the chemical reactions produce heat in the concrete that forces the concrete to set at high temperatures; well above the temperature of the surrounding steel. The concrete then begins to cool, but the temperature differences between the concrete and steel cause restraint, which induces residual stresses. The second thermal load on concrete is due to the daily temperature cycles on the bridge deck. Once the heat of hydration process is complete, the weather and daily temperature influence the thermal stresses. Temperature gradients, which produce the thermal stresses, develop between the top of the bridge deck and the substructure of the bridge (Curtis and White, 2007).

Several studies have been completed that report some correlation between concrete bridge deck cracking and concrete shrinkage. Krauss and Rogalla (1996) showed that drying shrinkage and temperature changes through the concrete section are responsible for deck cracking. Babaei and Purvis (1994) indicated that concrete mixes with higher drying and

thermal shrinkage values tend to produce more cracking. Ducret et al. (1997) also found that concrete mixes with lower peak hydration temperatures produce less stress in the concrete. Finally, Frosch et al. (2002) proved more conclusively through their field and laboratory tests that drying shrinkage is the most important cause of transverse bridge deck cracking.

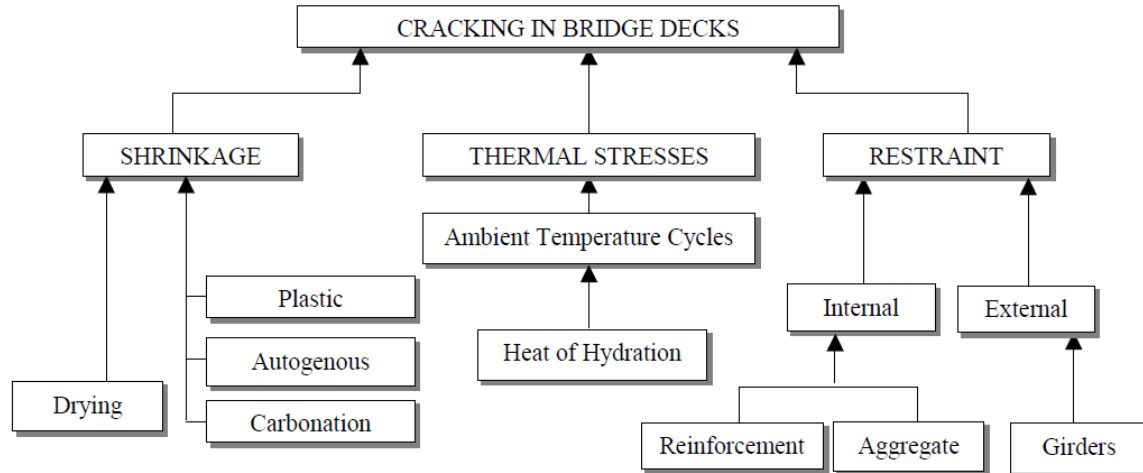


Figure 2 Causes of Bridge Deck Cracking (Brown et al., 2001)

2.5.1 Design Parameters

Design factors are extremely important issues for the cause of concrete bridge deck cracking. Whether it is bridge design type, boundary conditions, deck thickness, or reinforcement type and cover, these factors are directly related to concrete cracking. First and foremost, deck cracking can propagate solely due to bridge design and layout. Several studies have found that concrete bridge decks on steel girders tend to crack more than bridge decks on concrete girders (Krauss and Rogalla, 1996; French et al., 1999). Cheng and Johnston (1985) support this research because they found that continuous steel girder bridges are the type of structures that exhibit the highest incidence of transverse cracking. The researchers believe that since concrete conducts heat slower than steel, thermal stresses are developed slower in concrete girder bridges, which results in less cracking. It has also been found that cast-in-place concrete girders and early age prestressed girders perform the best, while deep steel beams experience the most cracking (Krauss and Rogalla, 1996).

Girder boundary conditions also have a prominent effect on concrete bridge deck cracking. Some researchers believe that the relative stiffness of the bridge deck with respect to the girder is more critical in deck cracking than the bridge design type. Because of this, bridge deck cracking is more prevalent on continuous span bridges than simple span bridges (Meyers, 1982; Cheng and Johnston, 1985). This is believed to be true because in simply supported bridge spans, shrinkage and temperature stresses are relatively equal throughout the length of the span (Brown et al., 2001). Also, simple supported spans allow free rotation against restraint, whereas continuous supported spans restrain the curvature of the deck at the interior supports (Brown et al., 2001).

Concerning bridge deck thickness, thinner bridge decks tend to promote higher stresses and are expected to exhibit increased cracking (Horn et al., 1975). Concrete bridge decks constructed with larger thicknesses experience less shrinkage and thermal stresses, which reduce deck cracking (TRC E-C107, 2006). Theoretically, the thicker concrete deck provides more concrete area to resist tensile forces. However, Brown et al. (2001) discovered that thicker bridge decks are more prone to develop non-uniform shrinkage stresses, which in turn induce bending.

Corrosion of the reinforcing steel ultimately leads to spalling of the bridge deck. Carrier and Cady (1973) concluded in their research that the most serious form of deck deterioration, spalling, is the direct result of inadequate cover of the reinforcing steel with concrete. Dakhil, Cady, and Carrier (1975) reiterated these findings and determined that the tendency for reinforced concrete bridge deck cracking to occur increases with decreasing concrete cover. However, Krauss and Rogalla (1996) found contradicting information. They determined that the concrete cover for the reinforcing steel has an inconsistent effect on cracking. Increased cover depth of the reinforcement reduces the risk of cracking because the reinforcing steel has difficulty distributing the shrinkage stresses. Yet, excessive increases in the cover depth will have a negative effect on the concrete. Reinforcing steel that has excessive clear cover increases the probability of settlement cracks over the reinforcement (Hadidi and Saadeghvaziri, 2005).

Researchers have conflicting views with regard to section stiffness on bridge deck cracking. However, Babaei and Hawkins (1987) are not in agreement with this statement because they suggest increasing the stiffness of the concrete in order to reduce bridge deck cracking. Since restraint of the volume change of the concrete bridge deck is the principal cause of deck cracking, reducing the section stiffness should reduce the amount of deck cracking. In their study, Ducret et al. (1997) confirmed this belief by showing that in an increase in deck stiffness results in an increase in bridge deck cracking. Their findings are in agreement with the findings of French et al. (1999) who also showed that an increase in stiffness results in increased cracking.

2.5.2 Material Parameters

Although factors including environmental conditions, construction techniques, and design specifications all contribute to bridge deck cracking, the selection of materials and material properties may be the most controllable factors influencing bridge deck cracking. Many studies and research work have been completed regarding the correlation between concrete material properties and deck cracking. From cement content and type, compression strength, aggregate size, and water to cement ratio, variations in properties can lead to increased shrinkage and the tendency for cracks to form.

There have been many studies done that show an increase in cement content has a direct connection to an increase in bridge deck cracking (Krauss and Rogalla, 1996; Kosel and Michols, 1985; Schmitt and Darwin, 1995). The adverse effect of using a higher cement content for bridge deck concrete is related to higher drying shrinkage, higher temperature rise during hydration, and higher early modulus of elasticity of concrete (Hadidi and Saadeghvaziri, 2005). All of these consequences for using higher cement content lead to a greater tendency of bridge

deck cracking. Several studies have also analyzed the effects of using different cement types for deck cracking. Ramey et al. (1997) state that as compared to Type II cement, Type I exhibits high heat of hydration, which leads to an increase in thermal expansion; therefore, the corresponding concrete results in more thermal cracking.

The type, size, relative volume, and properties of aggregates all have a pronounced effect on the cracking characteristics of concrete. The most important reason aggregates are used in concrete is to reduce the amount of cement content used in the mixture design. Decrease in aggregate content will require an increase in cement paste content. Also, the use of aggregates with smaller maximum size requires larger cement content to maintain mixture workability, which increases the potential for stresses and cracking to occur (TRC E-C107, 2006).

Over the past decade, there have been significant increases in concrete compression strength due to newer concretes and better mixture options. Even though increased compressive strength of concrete is linked to larger overall strengths of the structure, an increase in the concrete compression strength is commonly suggested to be a significant cause of deck cracking (Hadidi and Saadeghvaziri, 2005). In order to increase the concrete compression strength, a larger amount of cement paste must be used, which has a negative effect on concrete cracking. Browning and Darwin (2007) suggest that higher compressive strength concretes crack more than lower compressive strength concretes because tensile stresses develop due to restrained drying shrinkage and thermal contraction. Also, an increase in compression strength is accompanied by an early rise in the modulus of elasticity that makes the concrete more susceptible to cracking in its early stages as shrinkage occurs (Wan et al., 2010).

There is a general consensus water to cement ratio for concrete needs to be kept relatively low because increasing the water to cement ratio increases deck cracking (Krauss and Rogalla, 1996; Schmitt and Darwin, 1995). Concrete mix designs with high water to cement ratios tend to have a relatively high porosity and can exhibit substantial drying shrinkage and a higher tendency to crack (TRC E-C107, 2006). Ramey et al. (1997) suggest limiting the water to cement ratio of bridge deck concrete to between 0.40-0.45. However, Krauss and Rogalla (1996) suggest a lower maximum water to cement ratio of 0.4. Yet, Burrows (1998) found that concretes with low water to cement ratios experience less bleeding and are therefore more susceptible to plastic shrinkage cracking.

When it comes to material properties concerning air content and the slump of concrete, researchers have contrasting views on whether they affect cracking in concrete. Schmitt and Darwin (1999) observed in their research an increase in settlement cracking over the top reinforcement with an increase in concrete slump. However, Cheng and Johnston (1985) observed a decrease in transverse cracking in bridge decks when they increased the slump of the concrete. Increase in air content was observed to reduce cracking in bridge decks because an increase in air content increases workability without increasing the tendency of concrete to shrink (Cheng and Johnston, 1985). However, every researcher does not agree with this observation. At least one study points out that no degree of air content has a direct correlation with an increase in bridge deck cracking (Poppe, 1981).

2.5.3 Construction Parameters

Construction procedures and site conditions can also affect the tendency of a reinforced concrete bridge deck to crack. There are several poor construction practices that are directly related to an increase in the likeliness for deck cracking. Looking at the beginning of the construction process, the placement sequence for the concrete onto the bridge deck is very important for the reduction of early-age crack formations. When different sections of concrete are placed on the bridge deck and these sections are made “continuous”, the stresses in each section will redistribute throughout the whole deck (Issa, 1999). Therefore, the sequence is extremely important in the reduction of early-age cracks. Cheng and Johnston (1985) suggest that concrete deck cracking is most likely to occur in the positive moment region of the first span placed for continuous superstructure systems. The researchers stated that this phenomenon occurs because, when concrete is placed onto the second span, this causes the deflection in the first span to reduce, and therefore the first span endures an initial deflection larger than the final deflection.

Following the placing of the concrete onto the bridge deck, the concrete must be cured properly so that the concrete does not lose necessary amounts of water, which ultimately leads to cracking. Curing is one of the most important procedures in the concrete placement process because it has an evident effect on the properties of hardened concrete, including strength and durability. An example of fresh concrete being cured using curing blankets is shown in Figure 3. Hadidi and Saadeghvaziri (2005) believe that adequate and timely curing of concrete is a key factor in order to reduce early-age cracking. One other study specifies that early age deck cracking is the direct result of improper curing techniques (Hussein, 2006). Several studies have indicated that actions such as initial fogging, early curing and extended curing time, sprinkling water on the concrete surface, applying wet burlap, and applying curing compounds to fresh concrete will reduce cracking (Stewart and Gunderson, 1969; Horn et al., 1975; Babaei and Hawkins, 1987). La Fraugh and Perenchio (1989) suggest an extended curing time for concrete and recommend a minimum curing time of 7 to 14 days. However, not all researchers believe that adequate curing of the concrete will ultimately reduce the amount of cracking. Some researchers have indicated that extended moist curing increases the modulus of elasticity and reduces the creep, which makes the concrete more prone to cracking (Burrows, 1998).

Several different types of weather conditions during the placement of concrete can greatly affect concrete deck cracking. Outside air temperature during the placement has a pronounced effect on early-age deck cracking. Numerous studies have shown that hot and cold air temperatures during the placement of concrete increases deck cracking (Cheng and Johnston, 1985; Schmitt and Darwin, 1995). However, one study performed by French et al. (1999) showed a slight trend in which higher air temperature on the day of placement resulted in reduced cracking. High wind speed and low levels of humidity during placement can also influence deck cracking. Plastic shrinkage cracks occur when the evaporation rate exceeds the rate at which the concrete bleeds (Krauss and Rogalla, 1996). If there are high wind speeds, high temperatures, or low humidity during the placement of concrete, the evaporation rate will increase, therefore, increasing the likeliness of plastic shrinkage cracks.

Not only are the weather and site conditions during placement important for bridge deck cracking, but the concrete temperature is also a key factor that must be controlled to reduce deck cracking. Both concrete temperature and weather conditions greatly influence deck cracking because these parameters affect the thermal stresses developed in the concrete. These thermal stresses are created by the temperature difference between the deck and the supporting members (Hadidi and Saadeghvaziri, 2005). Even though weather, site, and concrete conditions are very important during the placement of concrete, it might be argued that the relationships developed between owners, contractors, inspectors, and concrete suppliers are of prime importance. Browning and Darwin (2007) believe that the construction parameter that leads to the most successful placements of bridge decks is a consistent, uninterrupted supply of concrete that meets project specifications.



Figure 3 Curing Blankets on Fresh Concrete (Patnaik, et al., 2010)

2.6 Ways to Reduce Cracks in Concrete Bridge Decks

Cracking on reinforced concrete bridge decks is a very complex problem for Departments of Transportation that is affected by several factors. Cracking is such a problem that, in some situations, a bridge deck will crack regardless of the many precautions taken. Nevertheless, deck cracking can at least be minimized by careful selection of materials, proper construction practices, and appropriate design details. There are steps that can be taken during the design and

construction processes of a bridge deck to help mitigate the severity of any cracks that do develop.

Construction practices by the engineer, contractor, and subcontractor can have a major impact on the likelihood of bridge deck cracking. The careful placement of concrete and strict attention to detail throughout the placement process is very important in order to reduce bridge deck cracking. It is necessary to identify an appropriate deck construction sequence so that every person involved in the bridge deck placement knows the specifications. Ramey et al. (1997) advise to pour the complete concrete deck at one time wherever feasible within the limitation of maximum placement length. Also, special considerations must be made by the contractor and engineer in order to reduce thermal gradients between the concrete deck and supporting girders during placement. Babaei and Purvis (1994) recommend maintaining the concrete deck/girder temperature differential to no greater than 22°F for 24 hours after the placement of the deck. This temperature differential can be accomplished by finding an appropriate time of day to place the bridge deck.

Since shrinkage of fresh concrete is the main cause of bridge deck cracking, control of the evaporation of water from the concrete surface is extremely important. Two construction practices that affect the water in concrete are fogging and curing. Lwin and Russell (2006) suggest that the most effective strategies to control cracking are fogging during placement of the fresh concrete and adequate curing during and soon after the hardening of concrete. Fogging gives concrete an adequate amount of water during placement and curing prevents surface evaporation of water after the concrete has hardened. An example of the fogging process during construction is shown in Figure 4. The Transportation Research Circular E-C107 (2006) states that finishing machines must provide the proper finish on all areas of the concrete and wet burlap mats are placed on the concrete deck soon after finishing is completed.

When designing the concrete mixture design used for a bridge deck, researchers recommend using a concrete with low early strength, low elastic modulus, low heat of hydration, high tensile strength, and high creep in order to mitigate shrinkage (Yun et al., 2007; Frosch et al., 2002). One of the most critical properties in the mixture proportions of bridge deck concrete is the water to cement ratio (w/c). Maintaining the water to cement ratio reasonably low provides the best results for reduced deck cracking (TRC E-C107, 2006). By reducing the water to cement ratio of concrete, the drying shrinkage will be reduced, which in turn, will reduce cracking (Spangler and Tikalsky, 2006). Along with reducing water content, the practice of reducing the volume of cement content can reduce bridge deck cracking. Lwin and Russell (2006) state that reducing cement content has a positive direct effect on controlling cracking by minimizing thermal shrinkage of the concrete.

Researchers' efforts to reduce volume change in concrete involve modifications to material and mixture designs. Wan et al. (2010) recommend avoiding high concrete compression strengths because the increase in cement content leads to increased cracking. Frosch (2007) reinforced this argument through his research where he found that compressive strengths higher than specified by design are not required and exacerbate deck cracking. The use of mineral admixtures in the mixture design has also shown to reduce the amount of bridge deck cracking. Shrinkage reducing admixtures or shrinkage compensating cements can be used to

reduce concrete shrinkage by reducing the surface tension of the pore water and thus lowering plastic shrinkage (Weiss and Berke, 2002). Weiss and Berke (2002) also found that retarding admixtures reduce the rise in temperature of the concrete, which lowers the potential for thermal shrinkage cracking. However, the use of admixtures can have a negative effect on bridge deck cracking. With the use of mineral admixtures like silica fume, concrete's rate of bleeding decreases, which results in an increase in the degree of plastic shrinkage cracking (Ozyildirim, 1991).



Figure 4 Fogging of Fresh Concrete (Patnaik, et al., 2010)

2.7 SD-DOT Report

The basis and premise of this project was derived from the research project entitled, “Evaluation of Crack-Free Bridge Decks” (Patnaik, et al., 2010). The research team in the project worked in conjunction with South Dakota Department of Transportation (SD-DOT) in order to evaluate newly constructed bridges using two different concrete mixture designs. The primary focus of the project was to compare the constructability and cracking behavior of newly constructed bridge decks made with low cracking high performance concrete (LC-HPC) and bridge decks made with SD-DOT’s existing concrete mixture (Patnaik, et al., 2010). Two pairs of bridges were constructed by SD-DOT, with one bridge deck consisting of the LC-HPC, and the companion deck constructed using SD-DOT’s existing mixture design.

Researchers evaluated the bridge decks by performing detailed crack surveys and determined the performance of the LC-HPC bridge decks in terms of the development of cracks over a three year period (Patnaik, et al., 2010). Once a year, for three years, the researchers conducted crack surveys on the bridge decks and produced crack maps of the corresponding bridge decks. These crack maps were then used to determine crack densities of the bridge decks. The performance of the bridge decks was assessed by measuring and comparing the crack densities (Patnaik, et al., 2010). The crack surveys were performed using the protocol developed at the University of Kansas (Pooled Fund TPF-5(051)).

After surveying the bridge decks and determining the crack densities, the researchers concluded that the bridge decks constructed with the current SD-DOT mixture design performed as well as the bridge decks constructed with the LC-HPC (Patnaik, et al., 2010). It was also found that the crack densities calculated by the research team for the two pairs of bridge decks were comparable to crack densities obtained by other South Dakota bridge deck surveys and other crack density values available in the published literature (Patnaik, et al., 2010).

From the literature review, not much information was available in terms of comparison structural slab bridge decks and stringer supported bridge decks.

CHAPTER III

SELECTION OF TYPICAL BRIDGE DECKS

3.1 Bridge Inventory and Selection

For the determination of crack densities for typical structural slab bridge deck and stringer supported bridge decks, several bridge decks built recently by the ODOT department were considered. An inventory of reinforced concrete bridge decks that were built within the last 10 years was compiled by a group of Ohio Department of Transportation (ODOT) Engineers. This list represented bridges of all superstructure types including concrete slab, prestressed concrete beam, prestressed concrete box beam, and steel beam bridges. The listed bridges were classified based on the structural system, location, number of spans, deck widths, age, and type of concrete. In order to select typical and representative reinforced concrete bridge decks for further investigation, the inventory of bridge decks was studied and down-selected to include 12 bridges throughout District 3. The bridges that were selected for further investigation are shown in Table 1.

A selection basis was developed to choose the typical and representative bridge decks for further investigation in this project. Because the length of time between the construction of the oldest bridges and youngest bridges was approximately 10 years, several different types of concrete mixture designs were utilized to produce the concrete for bridge decks. Therefore, it was determined that only bridges constructed after 2007 would be surveyed. This was decided because ODOT began to use Quality Control/Quality Assurance (QC/QA) concrete regularly after 2007. QC/QA concrete is workable concrete designed and produced by concrete manufacturers that have the properties required by the specifications for the work that is to be done. Also, due to safety concerns and traffic control issues, bridges located on Interstate Highways could not be selected for further investigation.

Table 1 List of Surveyed Bridges

	County	Route	SLM	Intersection	Date Built	Rehab Date	Project #
112 - Concrete Slab Continuous							
	Ashland	SR 89	294	Branch Jerome Fork	2009	-	1037(09)
	Lorain	SR 83	1032	Carpenter Ditch	2009	-	1011(09)
	Ashland	US 42	656	Over ASD-060-1647	1955	2009	8022(08)
221 - Prestressed Concrete Beam Simple							
	Huron	US 250	1830	Over Vermilion River	2009	-	449(07)
	Huron	US 250	1841	Over CSX Railroad	2009	-	449(07)
	Medina	SR 18	1403	W. BR of Rocky River	2007	-	437(06)
321 - Steel Beam Simple							
	Lorain	SR 301	2499	Over French Ditch	2008	-	277(07)
322 - Steel Beam Continuous							
	Wayne	US 30	1953	Tracy Bridge Road	2007	-	251(06)
	Ashland	US 42	359	Claremont Ave (RT lane only)	1955	2009	1021(09)
	Ashland	SR 604	296	Over ASD-071-1559	1959	2009	522(08)
	Crawford	SR 602	600	Sandusky River	1960	2008	3000(08)
	Erie	US 250	1138	Huron River	1956	2008	6004(07)

3.2 Bridge Classification

The two superstructure types surveyed were structural slab supported bridges and stringer supported bridges. Structural slab supported bridge decks are bridge decks with uniform deck slab thickness without any stringer beam under the decks. These types of bridges can have a single span or multiple spans. An example of a structural slab supported bridge deck is shown in Figure 5. Bridge decks that are supported by steel beams, prestressed concrete beams, girders, or box beams are classified as stringer supported bridge decks. Stringer supported bridge decks often have several spans, depending upon the length of the bridge. A steel beam bridge, which is an example of a stringer supported bridge deck, is shown in Figure 6.



Figure 5 Structural Slab Supported Bridge



Figure 6 Stringer Supported Bridge

3.3 Documented Properties of Field Concrete

Throughout each project, ODOT engineers perform tests and record properties of the concrete, which include air content, slump, temperature, unit weight, and water to cement ratio. These concrete tests take place at the location of the placement for the bridge decks. During the placement of the concrete, the engineers make several concrete cylinders in order to determine the compressive strength of the field concrete at different time periods.

There were four different types of bridges surveyed during the project, and the concrete mixture designs and concrete properties were compiled for each bridge. Table 2 shows concrete properties for continuous concrete slab bridges. Table 3 gives the concrete properties for simple prestressed concrete beam bridges. Table 4 displays simple steel beam concrete properties. Lastly, Table 5 shows the concrete properties for the continuous steel beam bridges.

3.3.1 Continuous Concrete Slab Bridges

The fresh concrete test results and properties for the continuous concrete slab bridges that were surveyed are summarized in Table 2. Bridge numbers ASD-89-0294 and ASD-42-0359L (Table 5) used the same QC/QA Superstructure 2 mixture design for their bridge deck concrete. Bridge number LOR-83-1032 used a similar but different QC/QA Superstructure 2 concrete mixture design for its bridge deck. The slumps of the concretes used for the bridge decks varied between 6.00 and 7.75 inches, and air contents varied from 5.7 to 6.6% with an average of 6.1%. The w/c ratios for the concretes averaged approximately 0.43, with the compressive strengths averaging 6470 psi.

Table 2 Concrete Properties for Continuous Concrete Slab Bridges

Bridge Number	Project Number	Air Content (%)	Slump (in)	Unit Weight (lb/ft ³)	W/C Ratio	Compressive Strength (psi)
ASD-89-0294	1037(09)	6.6	7.75	138	0.48	6172
LOR-83-1032	1011(09)	5.7	5.69	141	0.42	6541
ASD-42-0656	8022(08)	6.1	6.00	140	0.40	6698

3.3.2 Simple Prestressed Concrete Beam Bridges

The fresh concrete test results and properties for the simple prestressed concrete beam bridges are summarized in Table 3. The reinforced concrete bridge decks for bridge numbers HUR-250-1830 and HUR-250-1841 were placed on the same day, with the same High Performance Mix #4 concrete mixture design (also used for bridge number ASD-42-0656 in Table 2). However, even though the two bridges used the same concrete mixture design, the air contents and the final compressive strengths are widely dissimilar. The percent air calculated in the first bridge was 8 %, whereas the percent air calculated in the second bridge was 5 %. Also, the cylinder compressive strength of the first bridge had an average of 5573 psi, and the compressive strength of the second bridge average was on 7790 psi. The concrete slumps and

unit weights for the bridge decks are relatively similar, ranging from 6.0 to 6.5 inches, and 140 to 141 lb/ft³ respectively. A High Performance #4 Special Concrete Mix design was used in bridge number MED-18-1403.

Table 3 Concrete Properties for Simple Prestressed Concrete Beam Bridges

Bridge Number	Project Number	Air Content (%)	Slump (in)	Unit Weight (lb/ft ³)	W/C Ratio	Compressive Strength (psi)
HUR-250-1830	449(07)	8.0	6.00	140	0.40	5573
HUR-250-1841	449(07)	5.0	6.50	140	0.40	7790
MED-18-1403	437(06)	7.6	6.50	141	0.42	5996

3.3.3 Simple Steel Beam Bridge

The only simple steel beam bridge that was included in the project was bridge number LOR-301-40683. The concrete placement test results and concrete properties for this bridge are shown in Table 4. This bridge used a QC/QA Superstructure 2 concrete mixture design that produced a concrete with 6.7 % air content, average slump of 5.81 inches, water to cement ratio of 0.43, and unit weight of 138 lb/ft³. The average cylinder compressive strength of the QC/QA Superstructure 2 concrete mix was 7143 psi.

Table 4 Concrete Properties for Simple Steel Beam Bridges

Bridge Number	Project Number	Air Content (%)	Slump (in)	Unit Weight (lb/ft ³)	W/C Ratio	Compressive Strength (psi)
LOR-301-40683	277(07)	6.7	5.81	138	0.43	7143

3.3.4 Continuous Steel Beam Bridges

The fresh concrete test results and concrete properties for the continuous steel beam bridges being surveyed are displayed in Table 5. Bridge number WAY-30-1952 utilized a High Performance #4 concrete mixture, and bridge number CRA-602-0600 utilized a Concrete Class S mixture design for its bridge deck. Both bridge numbers ASD-604-0294 and ERI-250-20036 used a QC/QA Superstructure 2 concrete mixture design, but each mixture design was composed of several different elements.

The air content for the different concretes used for the bridge decks ranged from 6.1 to 7.1%. The slumps for the bridge concretes varied excessively from 5.0 to 7.8 inches, with an average of 6.0 inches. Both the unit weights and w/c ratios were relatively consistent throughout, with an average of 139 lb/ft³ and 0.45 respectively. The compressive strengths of the concrete for the five bridge decks ranged from 5450 to 6913 psi. The average compressive strength for the continuous steel beam bridges was 6276 psi.

Table 5 Concrete Properties for Continuous Steel Beam Bridges

Bridge Number	Project Number	Air Content (%)	Slump (in)	Unit Weight (lb/ft ³)	W/C Ratio	Compressive Strength (psi)
WAY-30-1952	251(06)	7.1	5.00	140	0.40	6789
ASD-42-0359L	1021(09)	6.2	7.75	138	0.48	5916
ASD-604-0296	522(08)	6.2	6.90	138	0.48	6313
CRA-602-0600	3000(08)	6.1	5.70	140	0.44	5450
ERI-250-20036	6004(07)	6.1	4.47	137	0.43	6913

The Ohio Department of Transportation Concrete Cylinder Reports and Concrete JMF/Mixture Designs for each bridge surveyed are included in Appendix A.

CHAPTER IV

CRACK SURVEY PROCEDURE

4.1 Crack Survey Protocol

Extensive bridge deck crack surveys are being conducted on the top surface of 12 bridge decks located in District 3 in Ohio. The crack surveys were conducted according to the protocol developed as part of Pooled Fund TPF-5(051) Construction of Crack-Free Concrete Bridge Decks (Pooled Fund). This protocol was developed by the University of Kansas in order to implement the most cost-effective techniques for improving bridge deck life through the reduction of cracking (Pooled Fund). The crack survey protocol calls for researchers to only trace the cracks that can be seen while bending at the waist. An example of a typical crack survey following the crack survey Pooled Fund protocol is shown in Figure 7. The cracks that can be seen while bending at the waist are assumed to be equal or larger than 0.007 inches wide. According to ACI Committee report 224, cracks with widths equal or greater than 0.007 inches can cause deterioration related to durability in conditions similar to those in Ohio (ACI 224R-01). Table 6 shows a summary of the classification of cracks based on crack widths as suggested in ACI 224 report.



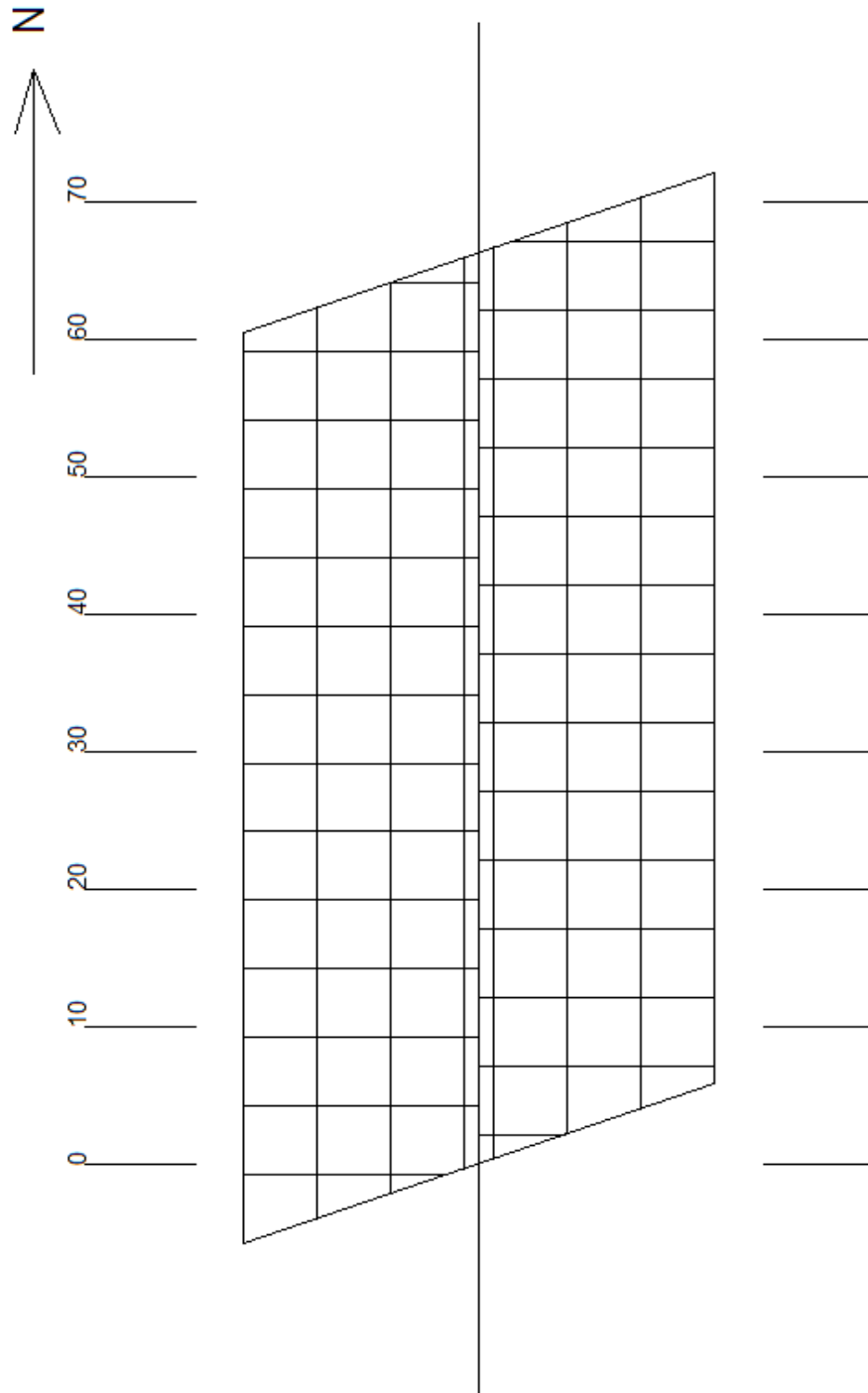
Figure 7 Typical Crack Survey

Table 6 Allowable Crack Widths from ACI 224R-01

Exposure Condition	Maximum Allowable Crack Width
Dry Air	0.016 in.
Humidity, Moist Air, Soil	0.012 in.
Deicing Chemicals	0.007 in.
Sea Water	0.006 in.
Water Retaining Structures	0.004 in.

4.2 Pre-Survey Preparation

Before bridge deck crack surveys could take place, several preliminary items needed to be completed. Bridge plans and bridge details were compiled from the Ohio Department of Transportation for each bridge deck being surveyed. These bridge plans and details were used to study the bridge superstructure type and determine the characteristics of the bridge. The construction documents were also used to produce scaled drawings of the bridge deck with a scale that was 1 inch on paper equals 10 feet on the corresponding bridge deck. The scaled drawing consisted of a 5 foot by 5 foot grid, along with a compass and deck stationing. A similar-sized grid would later be placed on the actual bridge deck during the crack surveys and used to transfer the cracks from the bridge deck to the scaled grid on the paper. An example of a scaled sketch of a typical bridge deck is shown in Figure 8.



ASD - SR 89 - 2.94
 Over Branch Jerome Fork
 Bridge No. ASD-89-0294

Figure 8 Scaled Sketch of a Typical Bridge Deck

4.3 Methodology

In cooperation with District 3 of the Ohio Department of Transportation, county workers controlled traffic so that one lane could be closed on the bridge being surveyed. Once one lane on the bridge deck was closed to traffic, the bridge was cleared as thoroughly as possible using a high-powered, backpack leaf-blower as shown in Figure 9. The bridge deck had to be completely clear of debris and dirt so that the cracks could be seen without difficulty. The bridge decks were also sprayed with water using a backpack water-sprayer as shown in Figure 10. Spraying the bridge decks with water was another strategy used to make the cracks more visible.

Once the bridge deck was cleared and sprayed, the bridge was stationed in the longitudinal direction at 10 foot intervals; as close to the centerline of the bridge as possible. Then, a five foot by five foot grid was marked on the bridge deck. This grid corresponded to the same grid on the scaled sketch of the bridge deck. Both the stationing and the grid were used to locate, position, and dimension the cracks on the bridge deck. Any drains, areas of repair, unusual cracking, spalling, potholes, or any other items of interest were documented and noted so that they were not included in the crack survey.

The crack survey on the bridge deck could begin after these matters were concluded. Starting with one end of the closed portion of the bridge deck, cracks that could be seen while bending at the waist were traced using lumber crayons. Even if a portion of the crack could not initially be seen while bending at the waist, but was seen after the crack was traced, this portion of the crack was included in the crack survey. An example of traced cracks is shown in Figure 11 while Figure 12 shows the example of a crack width measured using crack comparator card. Once half the bridge deck was surveyed for cracks, at least one other researcher checked over the surveyed portion of the deck for any cracks that were missed. The profiles of the traced cracks were then plotted on the scaled grid of the bridge deck. The previous steps were repeated on the other side of the bridge deck, once the traffic was switched over. By using the grid and stationing as references, the crack profiles for the other side of the bridge deck were also plotted on the same scaled sketch. As an additional step towards accurately following the University of Kansas crack survey protocol, crack widths were also determined at select locations throughout the bridge deck. These crack widths were measured using a crack comparator card, which shows lines of varying widths that could be compared to the cracks.

After completing the crack survey on the bridge deck, a crack map was produced by transferring the crack profiles to a scaled AutoCAD drawing. This crack map was needed in order to determine the crack density of each bridge surveyed. The crack density of a bridge deck was calculated by using the following equation,

$$\text{Crack Density} = \frac{\text{Total Length of Cracks}}{\text{Area of Bridge Deck}} \left[\frac{ft}{ft^2} \right] \text{ or } \left[\frac{m}{m^2} \right] \quad (1)$$

The crack maps and the corresponding crack densities for the surveyed bridge decks can be found in Chapter V.



Figure 9 Clearing Bridge Deck of Debris



Figure 10 Spraying Water on Bridge Deck



Figure 11 Traced Cracks on Bridge Deck with Grid



Figure 12 Example of Concrete Crack

CHAPTER V

CRACK MAPS OF BRIDGE DECKS

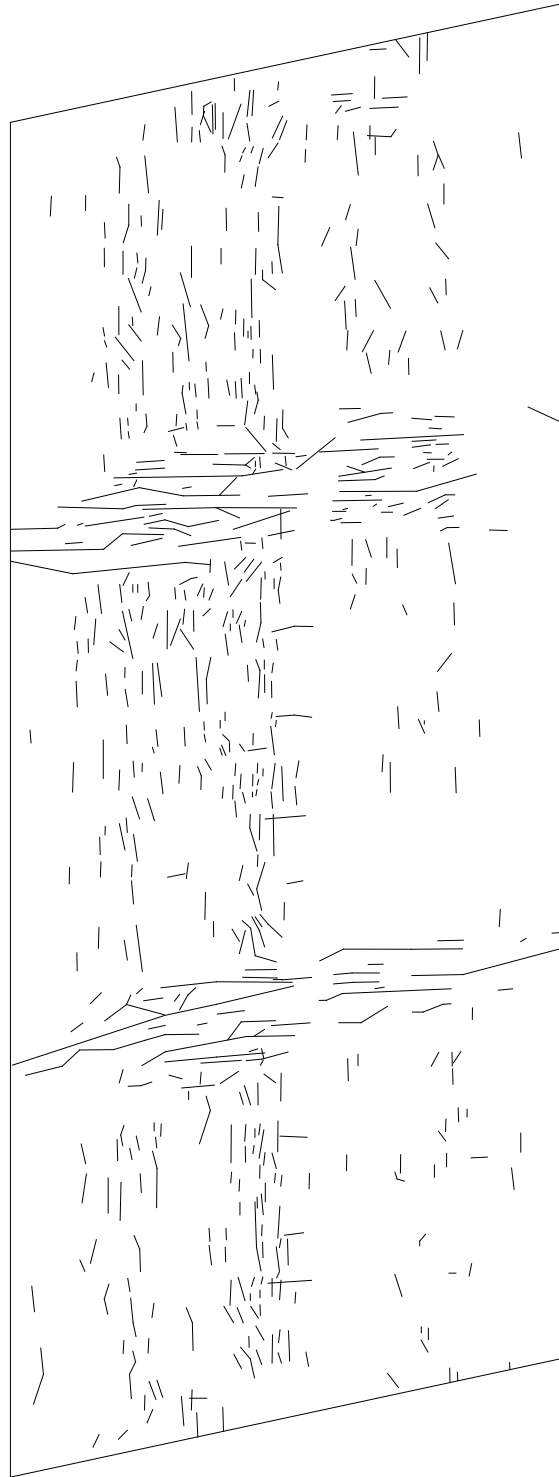
5.1 Crack Maps of Surveyed Bridges

Extensive crack surveys were conducted on twelve bridge decks located in District 3 in order to produce crack maps of the corresponding bridge decks. Used as a tool to directly evaluate the performance of the bridge decks, the crack maps are plotted and shown for the surveyed bridges in Figure 13 to Figure 24. The surveyed bridges consisted of five continuous steel beam bridges, three continuous concrete slab bridges, three prestressed concrete beam bridges, and one simple steel beam bridge. The crack surveys were conducted according to the protocol developed as part of the University of Kansas' Pooled Fund TPF-5(051) Construction of Crack-Free Concrete Bridge Decks and as described in Chapter IV. Also, structural drawings of the bridges are shown from Figure 25 to Figure 36 to find out if there is any correlation between the cracks and the structural layout of the bridge super structure.



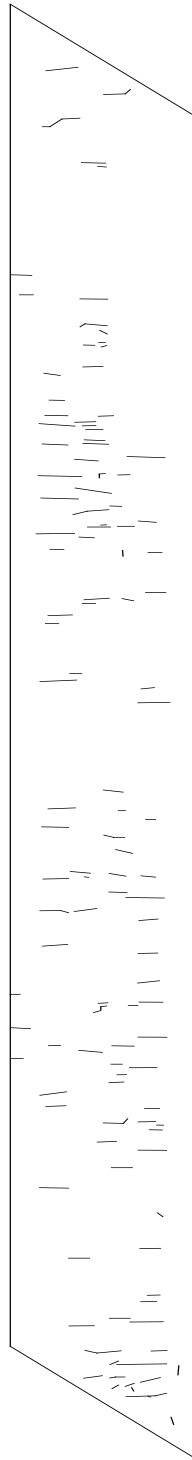
ASD-SR 89-2.94
Over Branch Jerome Fork
Bridge No. ASD-89-0294

Figure 13 Concrete Slab Bridge Number ASD-89-0294 Crack Map



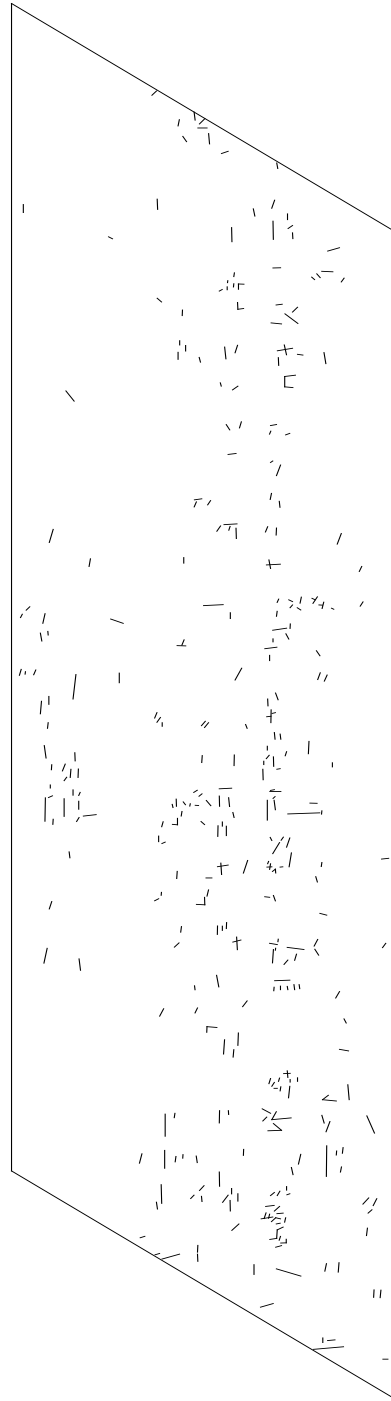
ASD-US 42-6.56
Over SR 60(Center Street)
Bridge No. ASD-42-0656

Figure 14 Concrete Slab Bridge Number ASD-42-0656 Crack Map



ASD-SR604-2.96
Over I71
Bridge No. ASD-604-0296

Figure 15 Steel Beam Bridge Number ASD-604-0296 Crack Map



ASD-US42-3.59
Claremont Avenue (RT Lane Only)
Bridge No. ASD-42-359L

Figure 16 Steel Beam Bridge Number ASD-42-0359 Crack Map

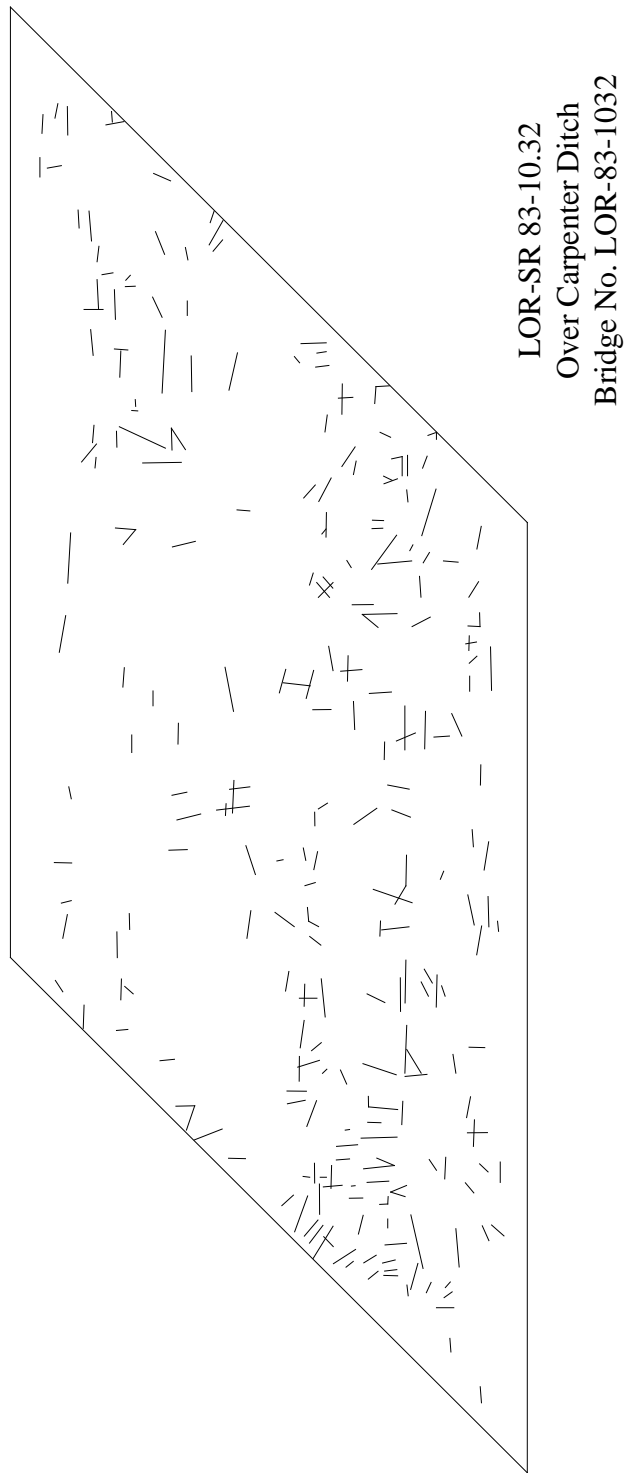
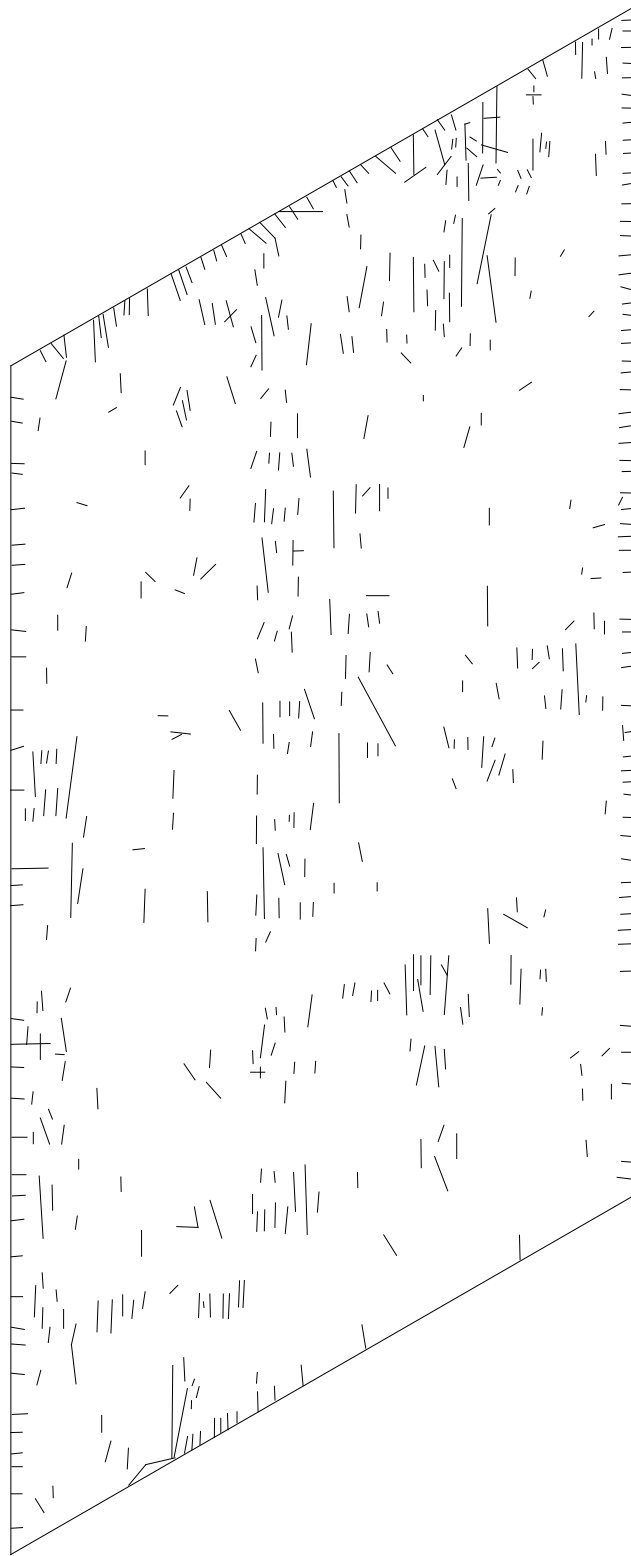
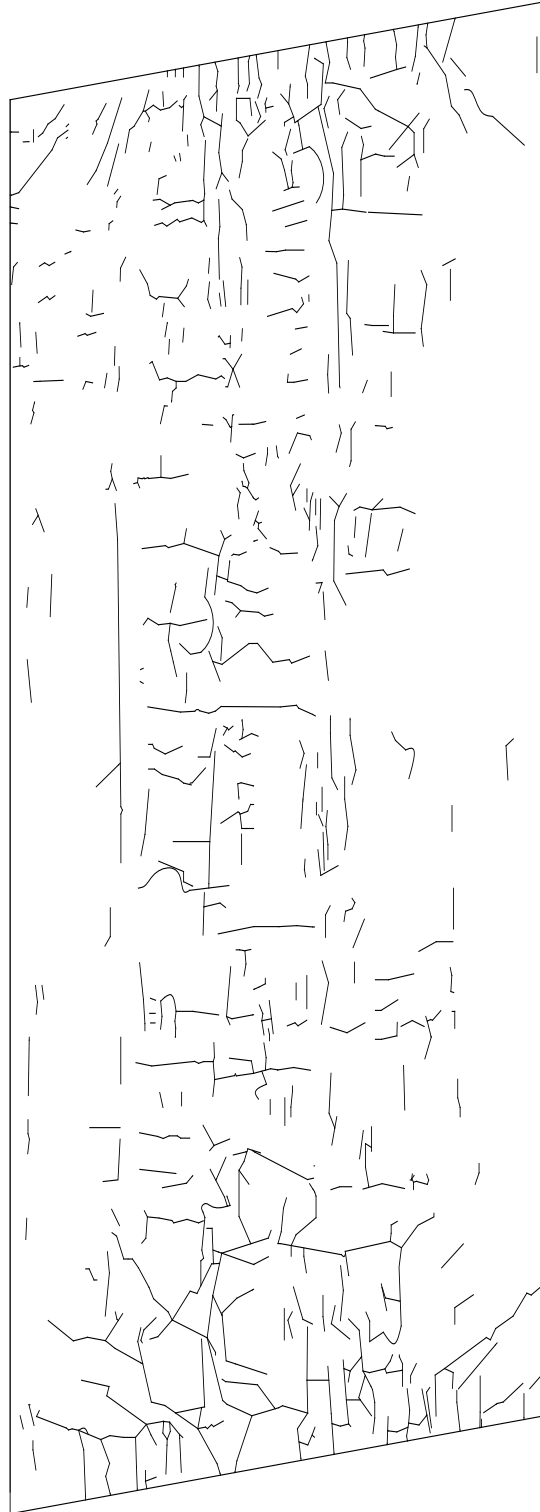


Figure 17 Concrete Slab Bridge Number LOR-83-1032 Crack Map



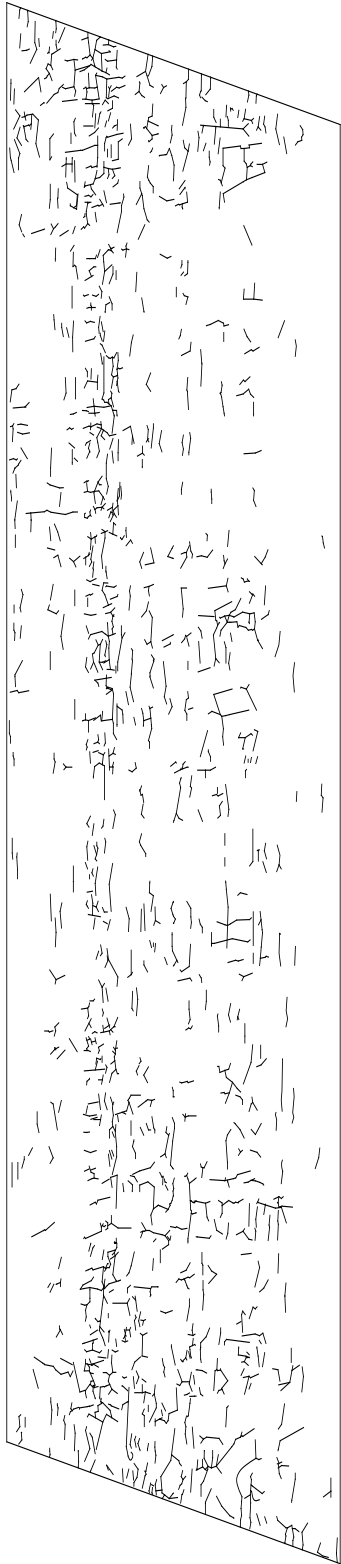
LOR-SR 301-24.99
Over French Ditch
Bridge No. LOR-301-40683

Figure 18 Steel Beam Bridge Number LOR-301-40683 Crack Map



HUR-US250-18.41
Over CSX Railroad
Bridge No. HUR-250-1841

Figure 19 Prestressed Concrete Beam Bridge Number HUR-250-1841 Crack Map



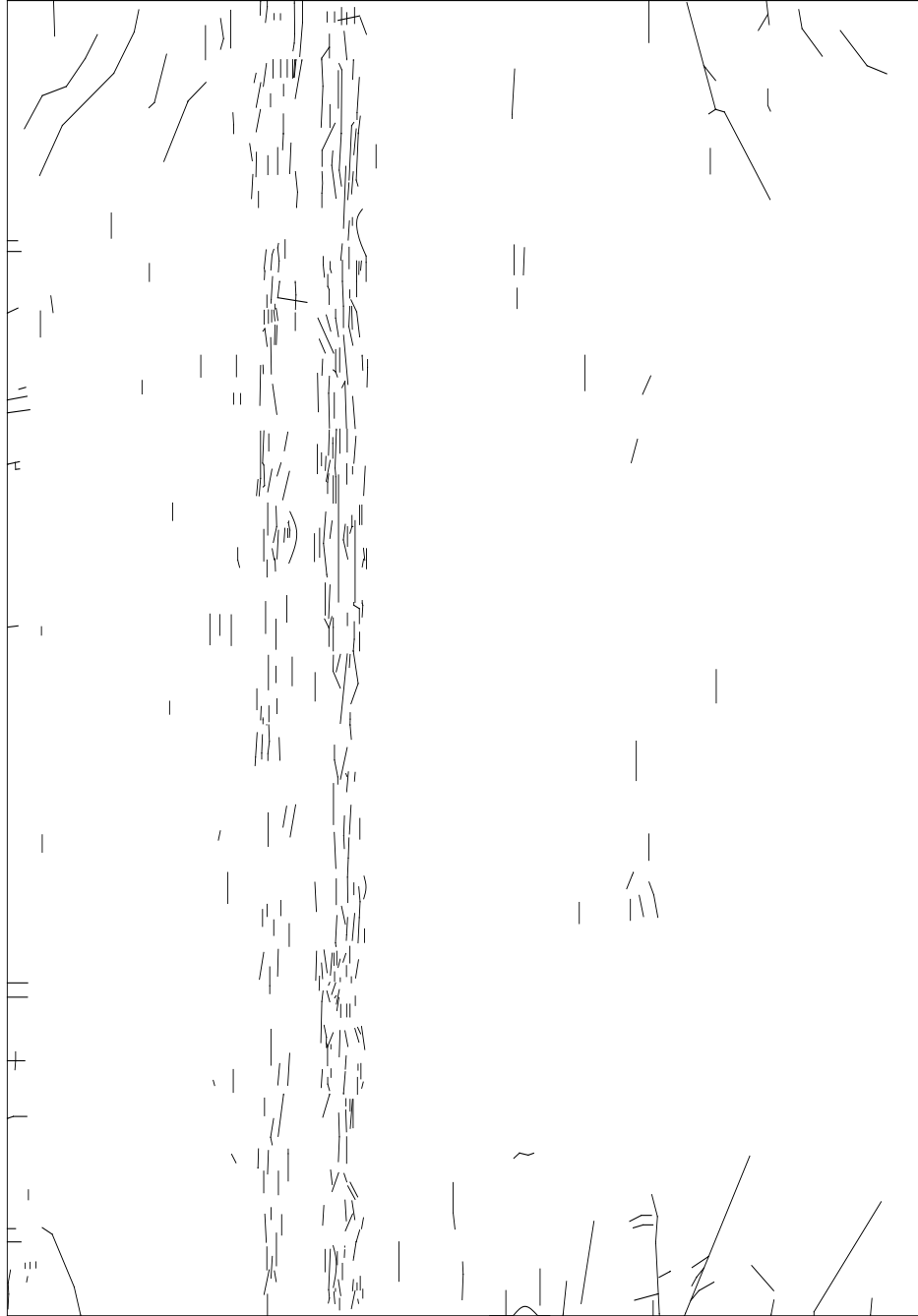
HUR-US 250-18.30
Over Vermilion River
Bridge No. HUR-250-1830

Figure 20 Prestressed Concrete Beam Bridge Number HUR-250-1830 Crack Map



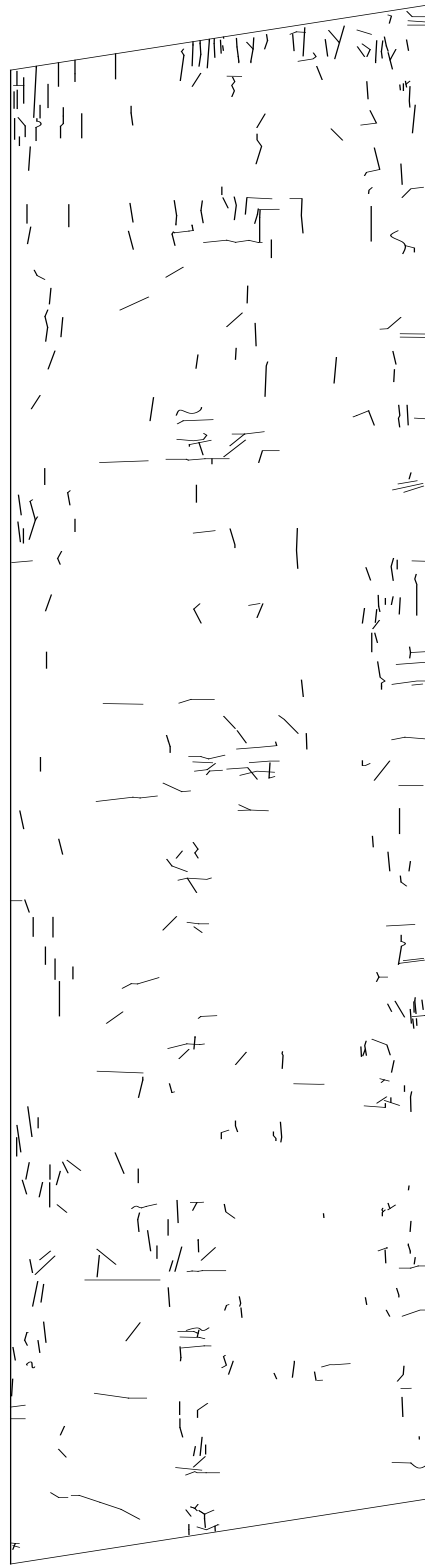
CRA-SR602-6.00
Over Sandusky River
Bridge No. CRA-602-0600

Figure 21 Steel Beam Bridge Number CRA-602-600 Crack Map



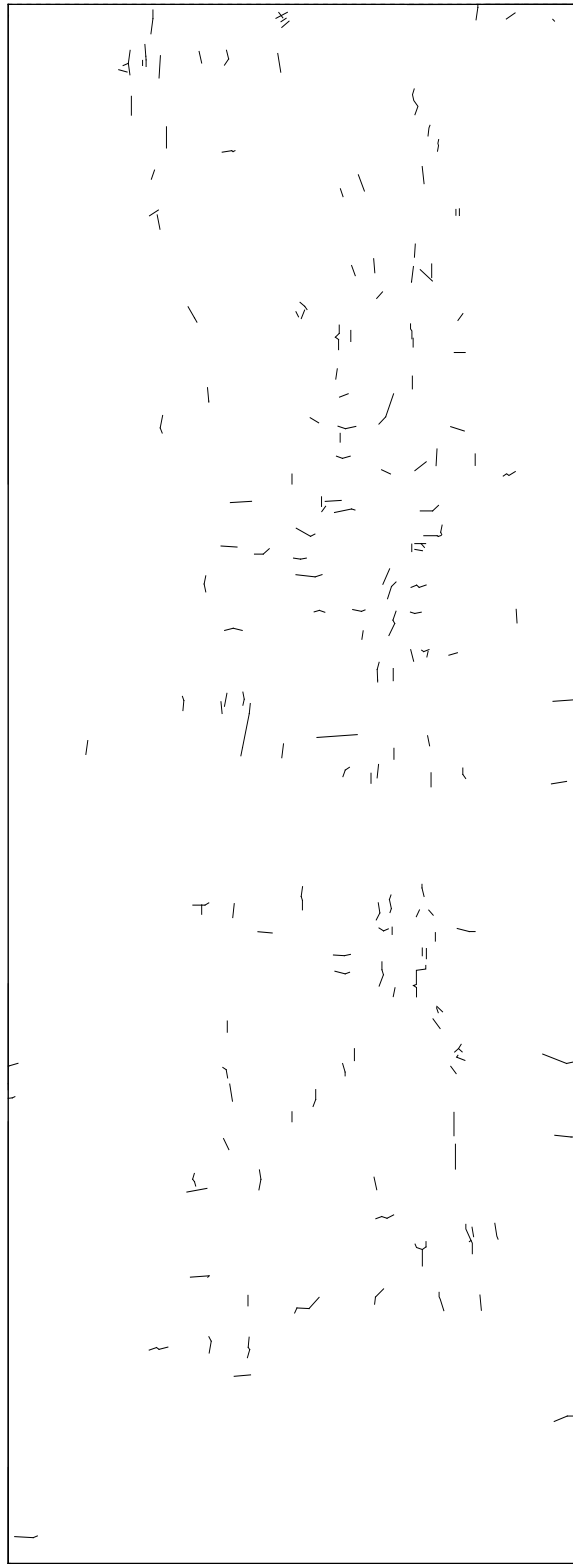
MED-SR 18-14.03
Over West Branch of Rocky River
Bridge No. MED-18-1403

Figure 22 Prestressed Concrete Beam Bridge Number MED-18-1403 Crack Map



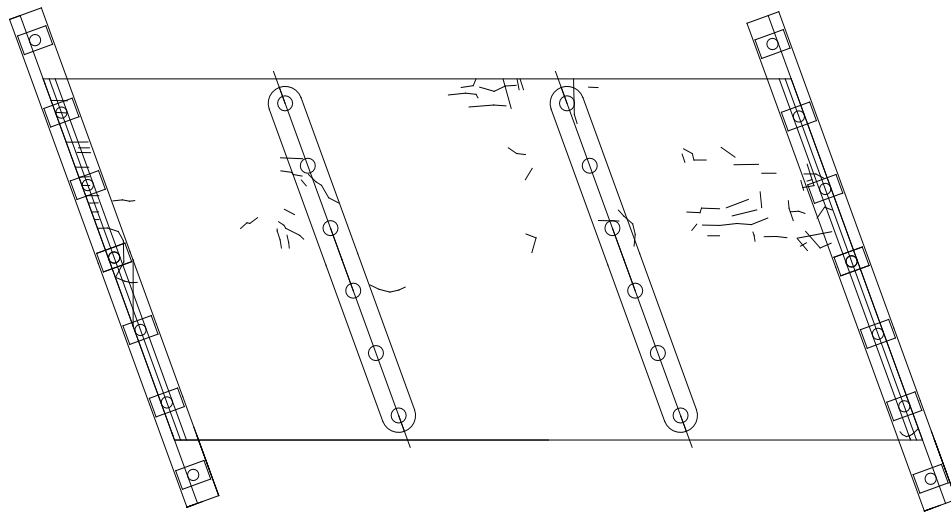
WAY-US 30-19.52
Tracy Bridge Road
Bridge No. WAY-30-1952

Figure 23 Steel Beam Bridge Number WAY-30-1953 Crack Map



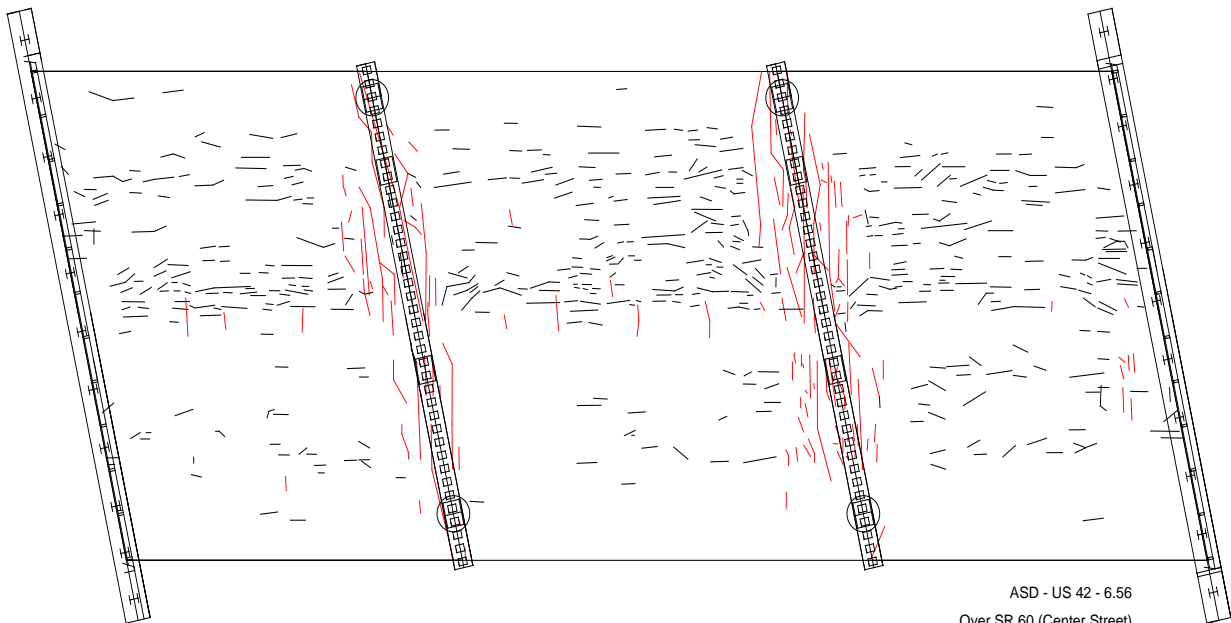
ERI-US 250-11.38
Over Huron River
Bridge No. ERI-250-20036

Figure 24 Steel Beam Bridge Number ERI-250-1138 Crack Map



ASD - SR 89 - 2.94
 Over Branch Jerome Fork
 Bridge No. ASD-89-0294

Figure 25 Crack map interposed with structural layout for Bridge Number ASD-89-0294



ASD - US 42 - 6.56
 Over SR 60 (Center Street)
 Bridge No. ASD-42-0656

Figure 26 Crack map interposed with structural layout for Bridge Number ASD-42-0656

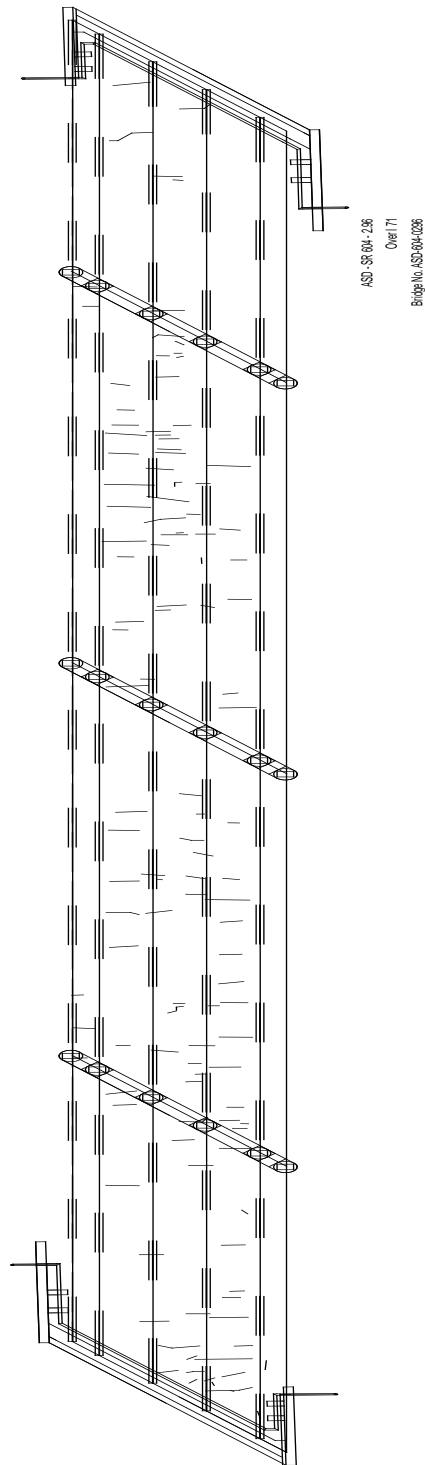


Figure 27 Crack map interposed with structural layout for Bridge Number ASD-604-0296

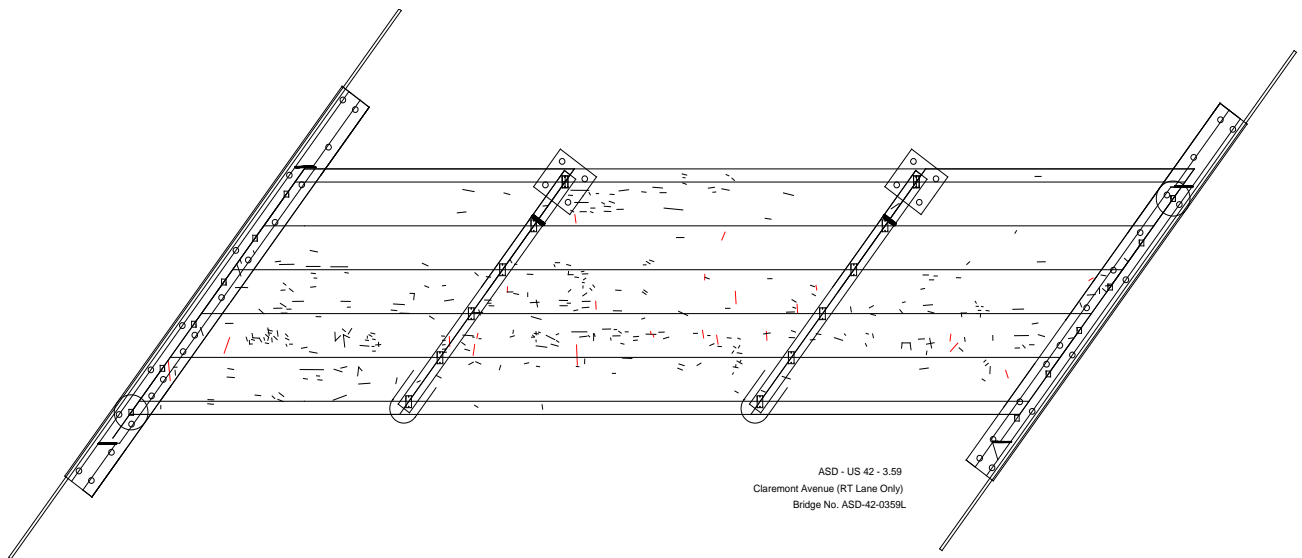


Figure 28 Crack map interposed with structural layout for Bridge Number ASD-42-0359

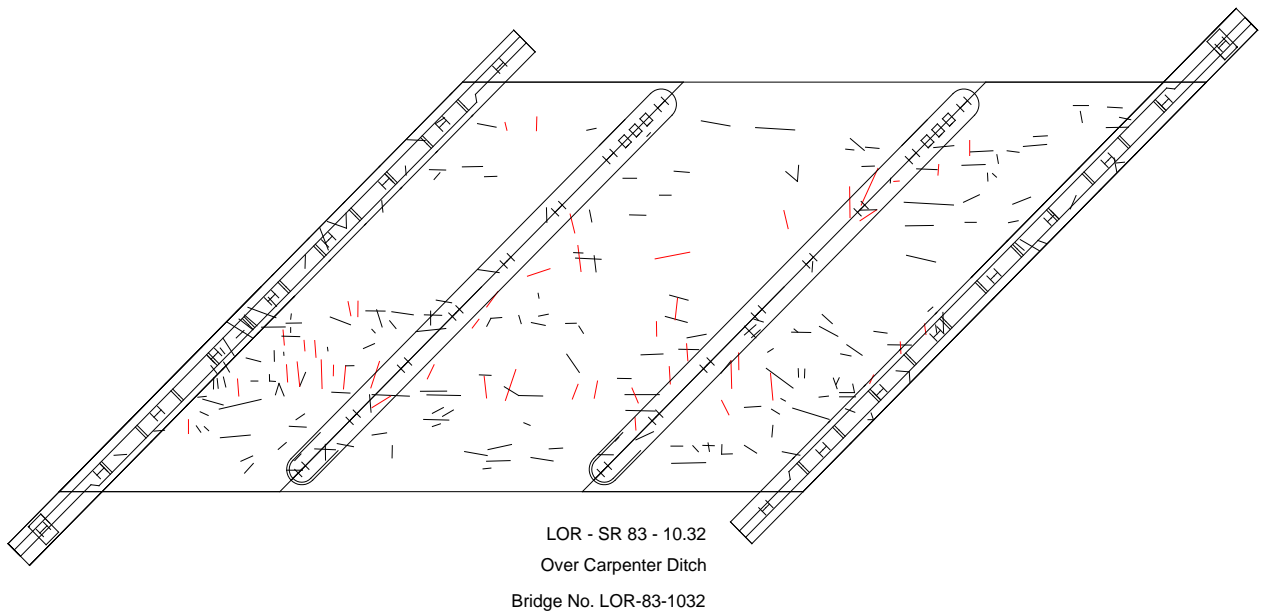


Figure 29 Crack map interposed with structural layout for Bridge Number LOR-83-1032

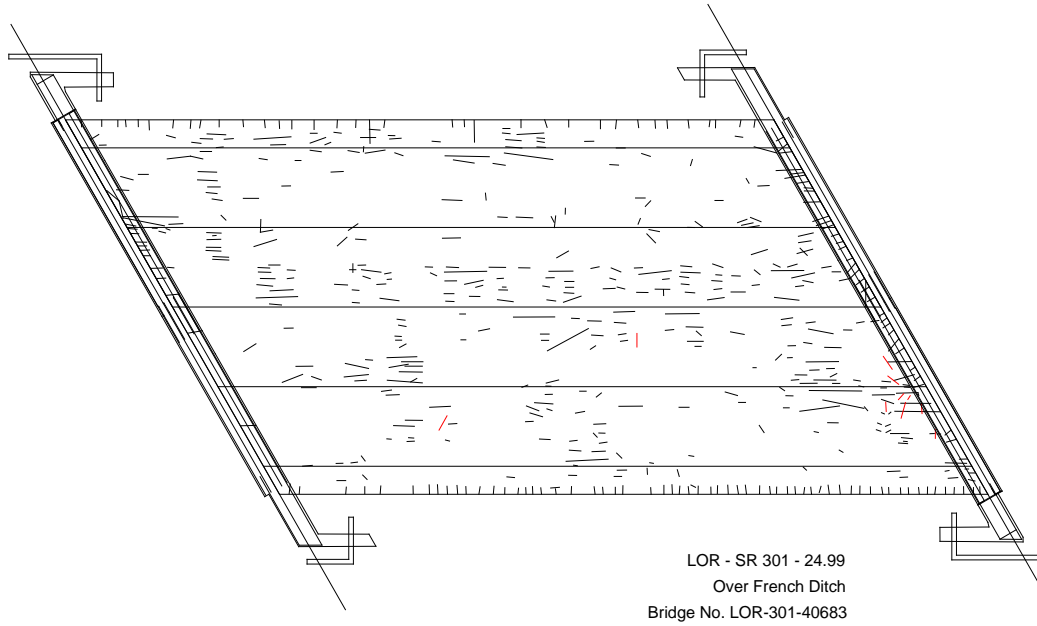


Figure 30 Crack map interposed with structural layout for Bridge Number LOR-301-40683

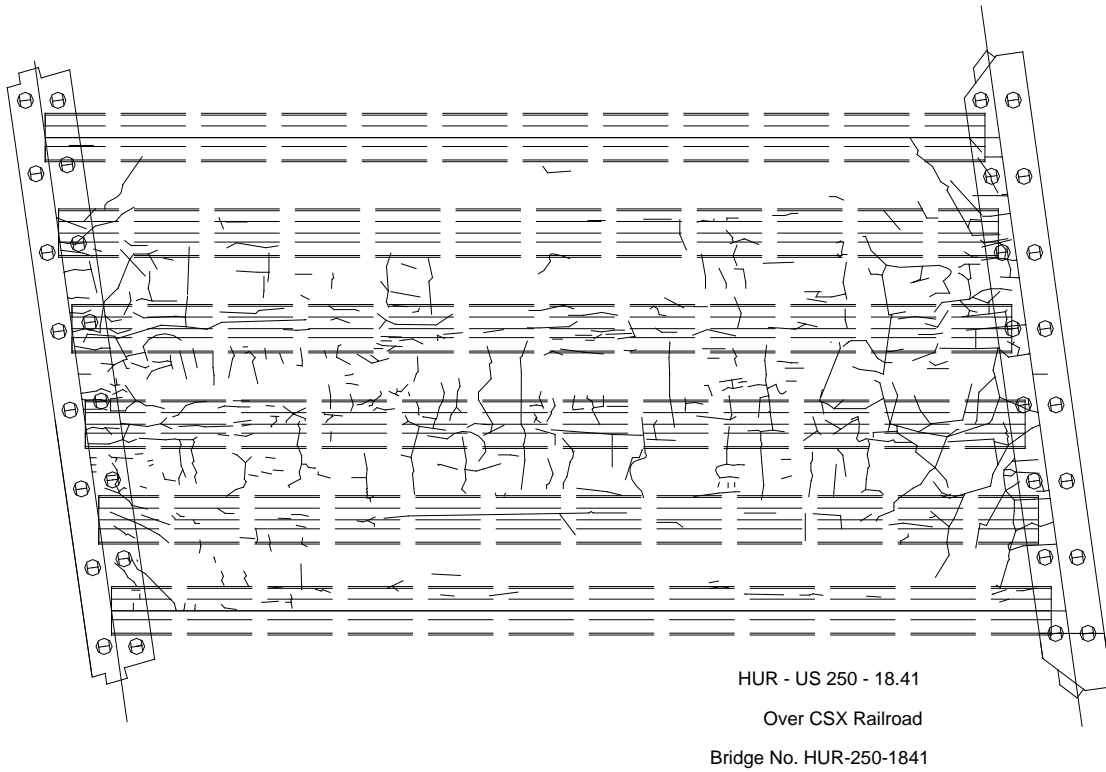


Figure 31 Crack map interposed with structural layout for Bridge Number HUR-250-1841

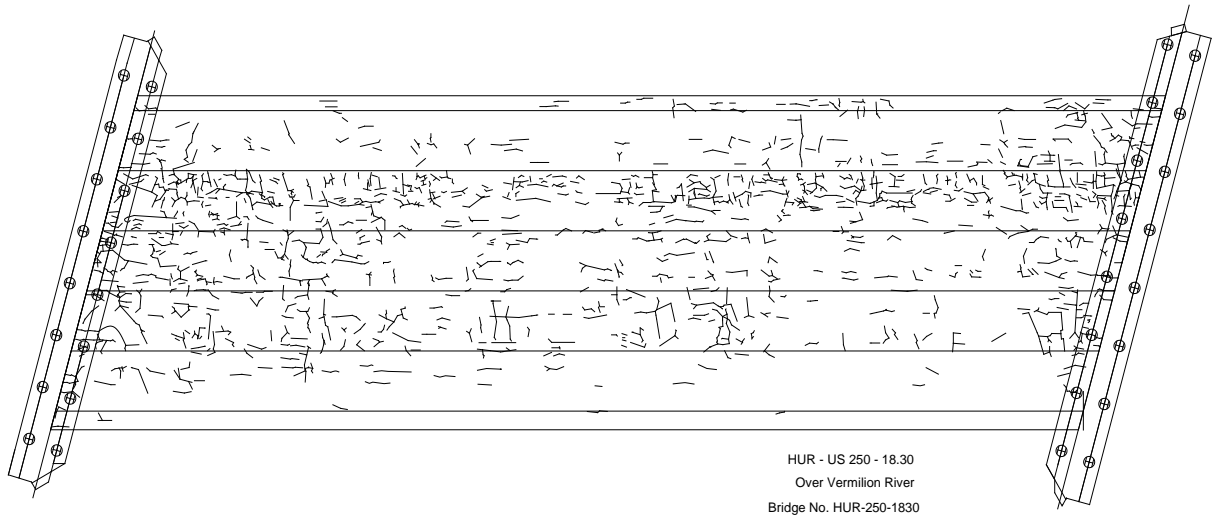


Figure 32 Crack map interposed with structural layout for Bridge Number HUR-250-1830

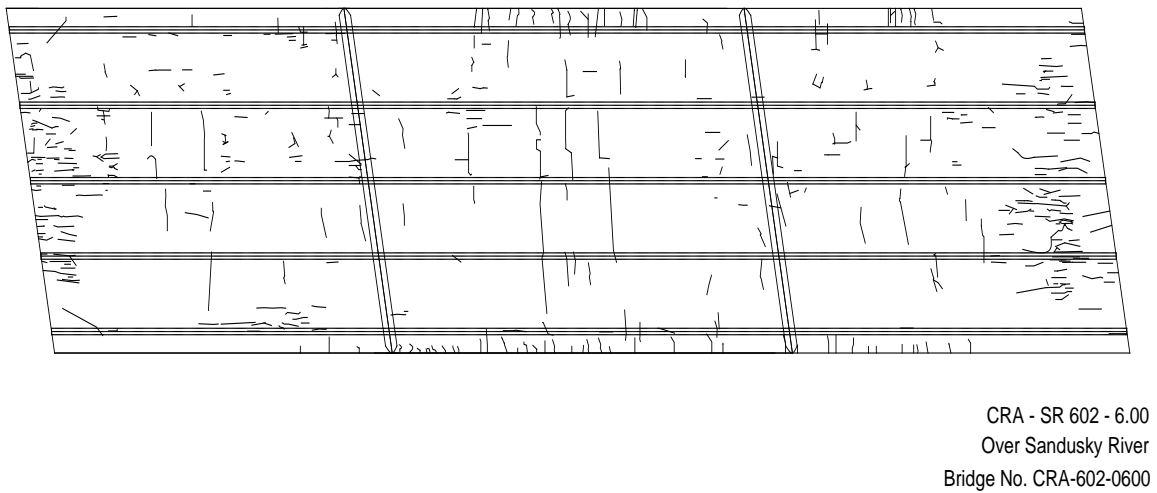


Figure 33 Crack map interposed with structural layout for Bridge Number CRA-602-600

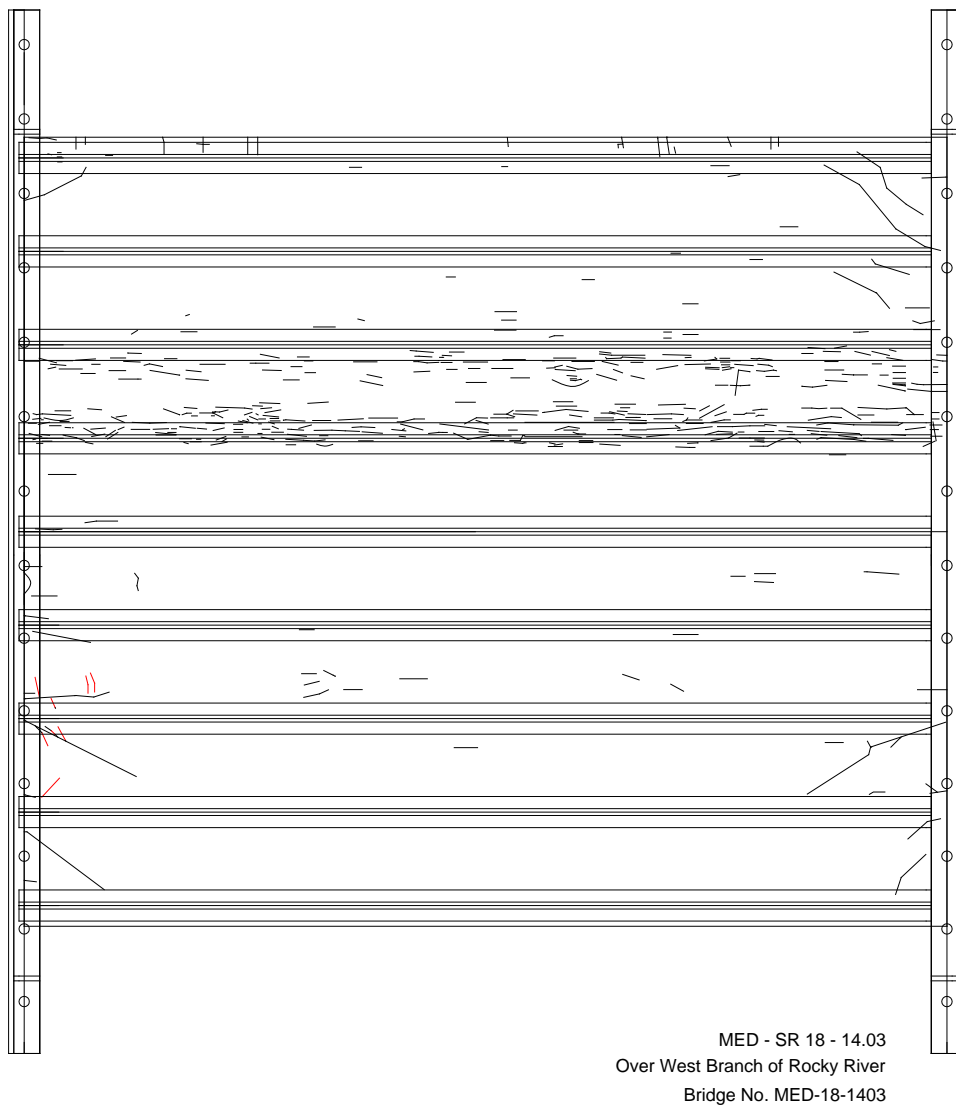


Figure 34 Crack map interposed with structural layout for Bridge Number MED-18-1403

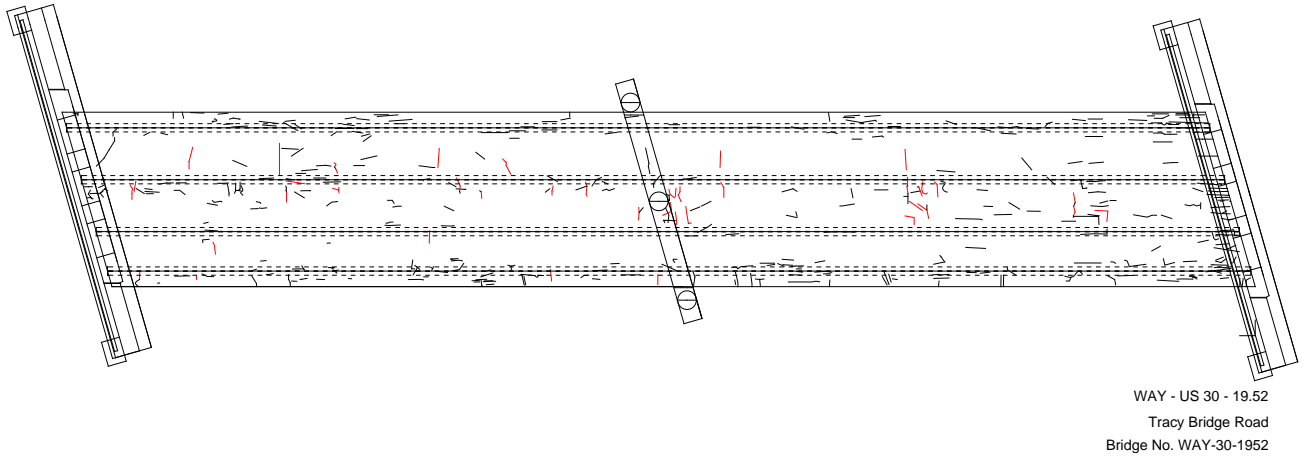


Figure 35 Crack map interposed with structural layout for Bridge Number WAY-30-1953

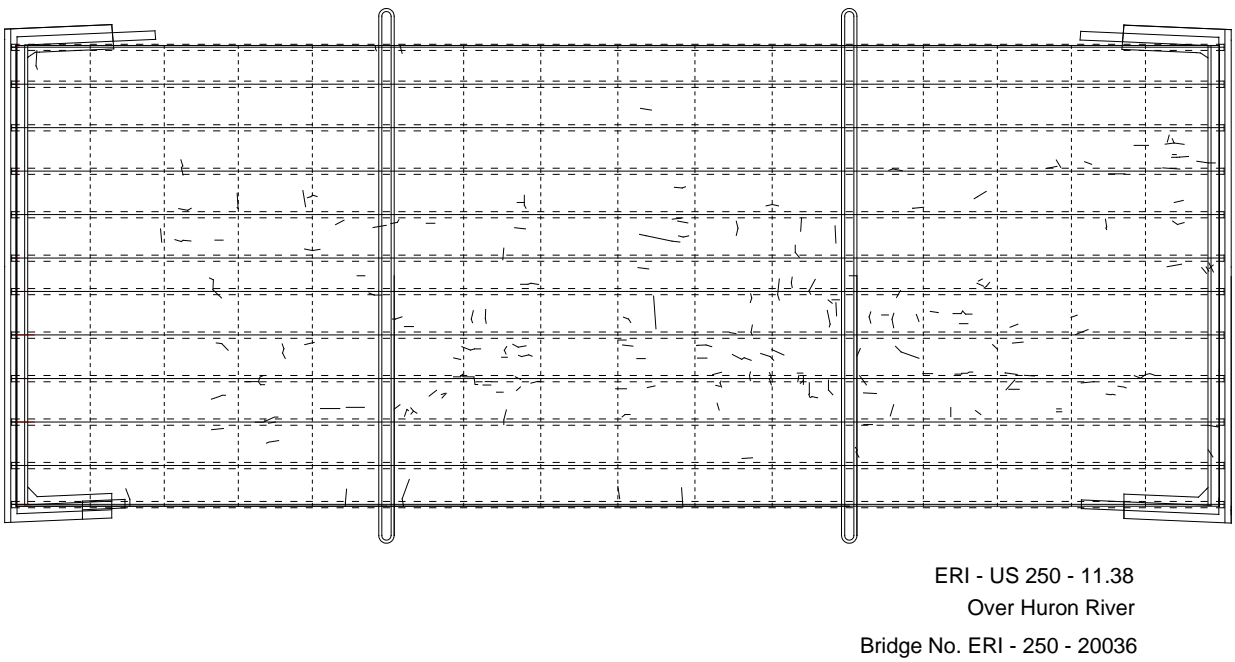


Figure 36 Crack map interposed with structural layout for Bridge Number ERI-250-20036

CHAPTER VI

RESULTS AND DISCUSSION

6.1 Results

Crack surveys were performed following the University of Kansas crack survey protocol for six of the 12 bridge decks. Three of the bridges surveyed were structural slab supported bridge decks, and the other three bridges surveyed were stringer supported bridge decks. After completing the crack survey, crack maps were produced, and the crack densities were calculated for the completed bridge decks. A summary of the crack densities for the surveyed bridge decks is shown in Table 7.

Most cracks recorded in the crack maps seem to be shrinkage cracks. However upon closer review of crack maps, some of the bridge decks exhibit cracking pattern which is a characteristic of that of structural cracks. Using judgment, the apparent structural cracks were separated from the shrinkage cracks. Table 7 shows structural crack densities and shrinkage crack densities after such separation for the twelve bridges.

The overall objective was to compare the crack densities for the structural slab supported bridge decks with the crack densities for the stringer supported bridge decks and determine which bridge superstructure type has a higher propensity for cracking. A comparison of the total crack densities between structural slab supported bridge decks and stringer supported bridge decks is shown in Figure 37, while Figure 39 shows the comparison of shrinkage crack densities of different type of bridges. Also, Figure 38 includes crack density values determined from previous studies and the current research along with the calculated shrinkage crack densities. Typically, the structural slab supported bridge decks experienced more cracking than the stringer supported bridge decks. All but one of the structural slab bridges produced a higher crack density than the stringer supported bridge decks.

For the structural slab supported bridge decks, cracks were located throughout the bridge decks, with some cracking concentrated over the supports. The cracking located over the supports is characterized as structural cracks, whereas all other cracks are considered shrinkage cracks. Most of the cracking over the supports was parallel to the support. This cracking is believed to be due to the continuous of the bridge; meaning, the bridge deck concrete was placed integral with the internal supports.

The stringer supported bridge decks experienced cracking different than the structural supported bridge decks. Transverse cracks were located continuously along the axis of the bridges at roughly 5-10 feet intervals, with some cracking concentrated over the supports in the negative moment regions. This transverse cracking is believed to be caused by the restraint of the supporting beams under the deck.

Table 7 Summary of Crack Densities of Surveyed Bridges

Bridge Number	Date Placed	Date of Crack Survey	Age (Mon.)	Concrete Type	Deck Length (ft)	Deck Width (ft)	Deck Area (ft ²)	Crack Density		
								Total Cracks (ft/ft ²)	Structural Cracks (ft/ft ²)	Shrinkage Cracks (ft/ft ²)
Concrete Slab Continuous										
ASD-89-0294	10/1/09	3/8/11	17	QC/QA 4500	66.3	30.5	2023	0.061	0	0.061
LOR-83-1032	8/24/09	4/21/11	20	QC/QA 4500	73.8	40.0	2952	0.141	0.018	0.123
ASD-42-0656	9/23/09	3/22/11	18	HP Mix 4	131.9	52.5	6925	0.193	0.074	0.119
Average								0.13	0.03	0.10
Prestressed Concrete Beam Simple Span										
HUR-250-1830	9/26/09	9/15/11	24	HP Mix 4	139.1	45.5	6331	0.284	0	0.284
HUR-250-1841	9/26/09	9/13/11	24	HP Mix 4	89	44.5	3960	0.287	0	0.287
MED-18-1403	5/5/08	9/29/11	40	HP Mix 4 Modified	89	76	6765	0.114	0	0.114
Average								0.23	0.0	0.23
Simply Supported Steel Beam										
LOR-301-40683	4/30/08	4/28/11	36	QC/QA 4500	75.2	39.4	2963	0.205	0	0.205

Table 7 Summary of Crack Densities of Surveyed Bridges (Continued)

Bridge Number	Date Placed	Date of Crack Survey	Age (Mon.)	Concrete Type	Deck Length (ft)	Deck Width (ft)	Deck Area (ft ²)	Crack Density		
								Total Cracks (ft/ft ²)	Structural Cracks (ft/ft ²)	Shrinkage Cracks (ft/ft ²)
Steel Beam Continuous										
WAY-30-1953	10/10/07	10/6/11	48	HP Mix 4	184.1	29.1	5357	0.135	0.017	0.118
ASD-42-0359	10/21/09	4/7/11	17	QC/QA 4500	158.3	40.5	6413	0.053	0.005	0.048
ASD-604-0296	7/27/09	4/5/11	21	QC/QA 4500	405.3	32.0	12971	0.032	0	0.032
CRA-602-600	10/15/08	9/20/11	35	Class S	141.1	36.6	5165	0.155	0.032	0.123
ERI-250-1138	5/30/08	11/1/11	42	QC/QA 4500	195	74	14430	0.024	0	0.024
Average								0.08	0.01	0.07

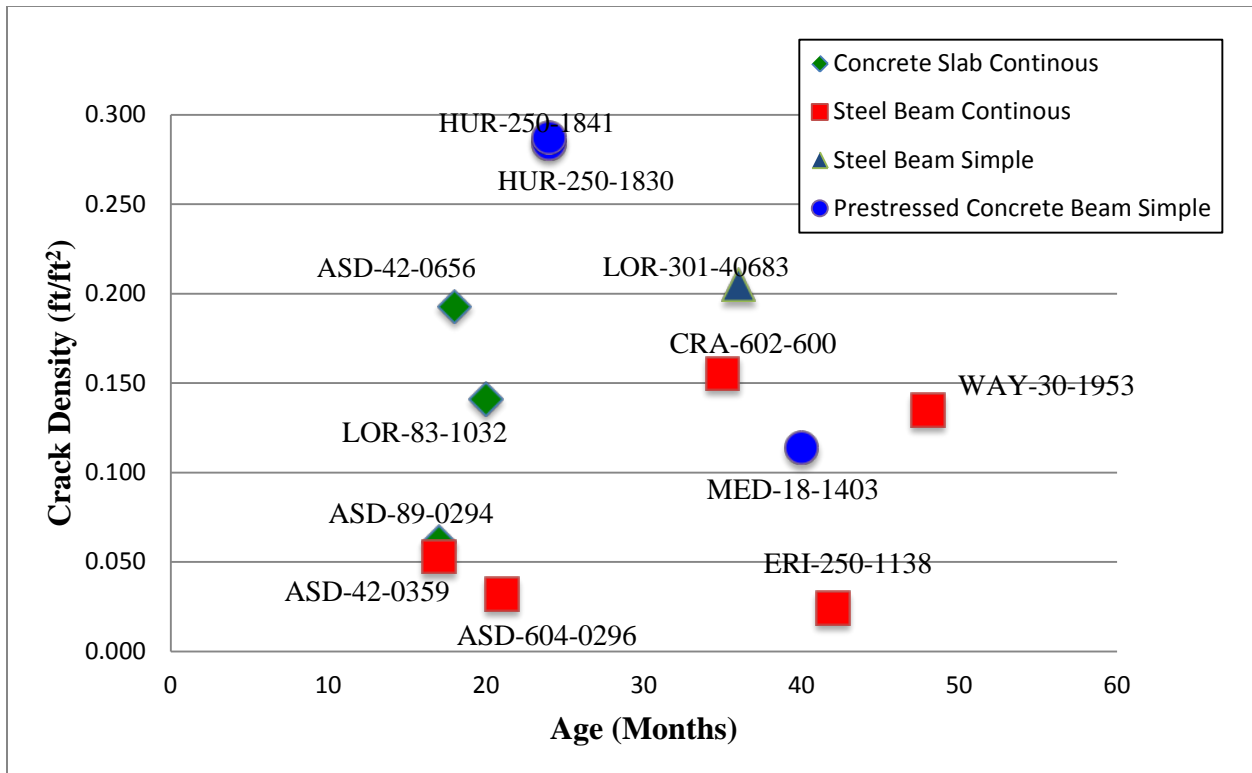


Figure 37 Plot of Total Crack Densities with Age

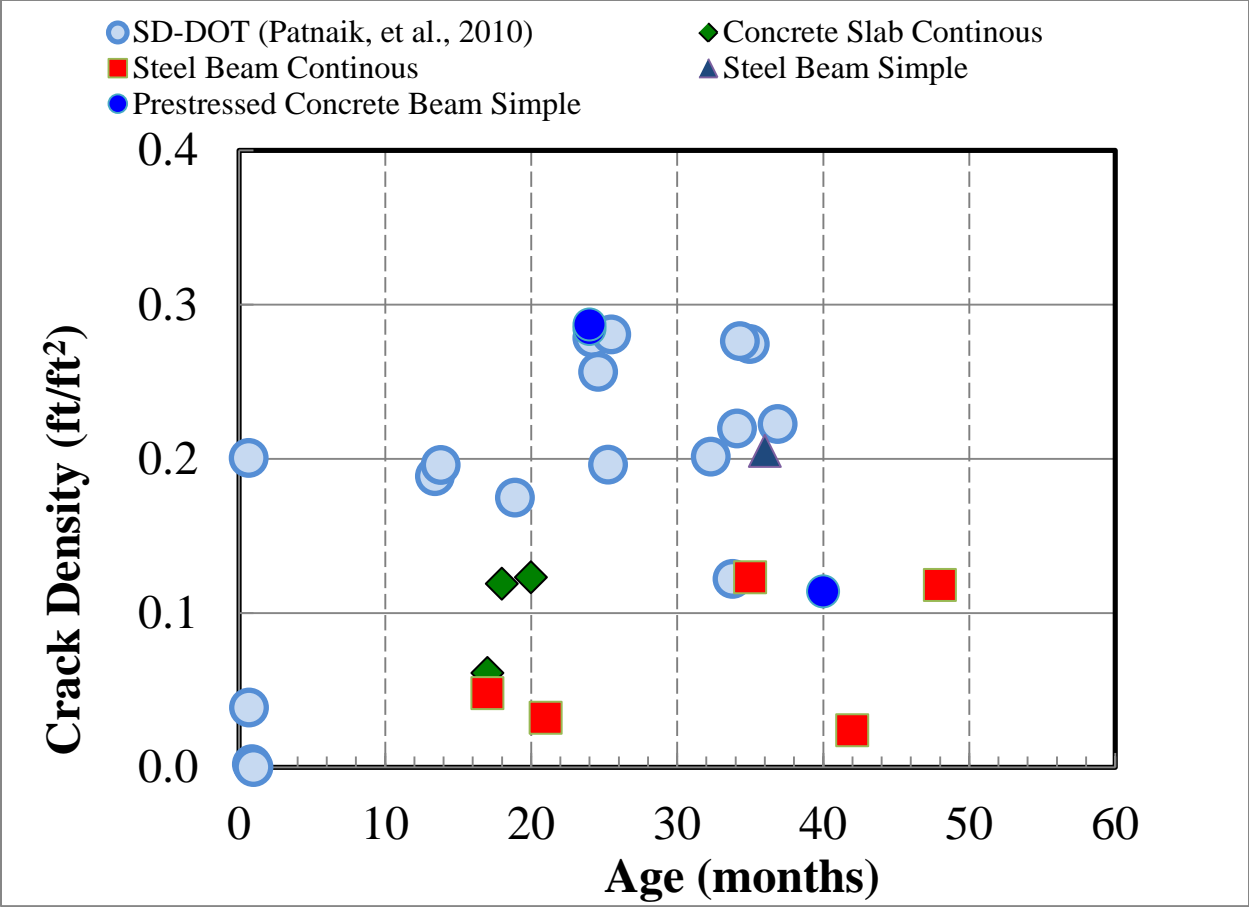


Figure 38 Comparison of Shrinkage Crack Densities with Those from Previous Studies

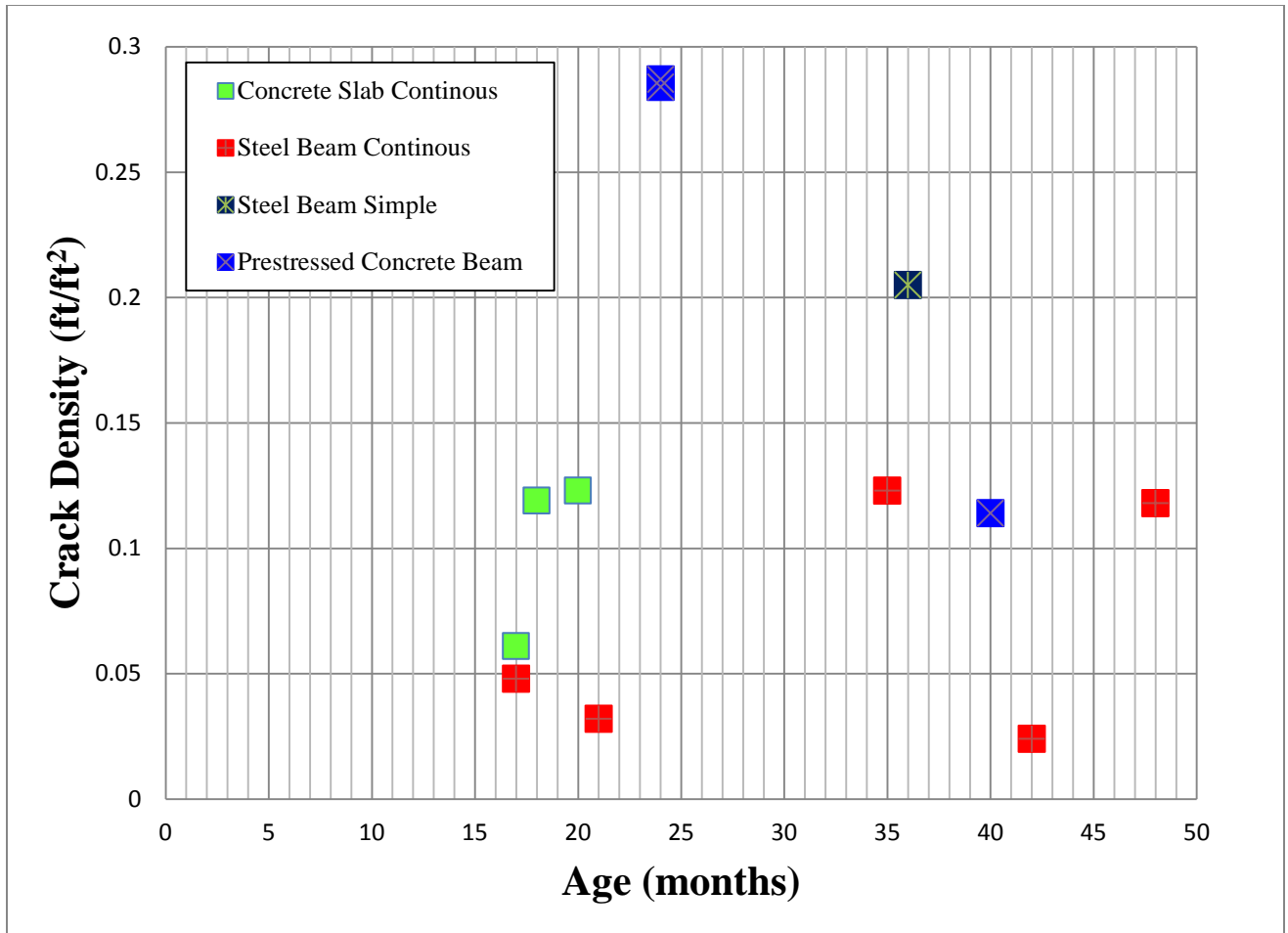


Figure 39 Shrinkage Crack Densities vs. Age for Different Types of Bridges

6.2 Bridge ASD-89-0294

The first bridge surveyed was bridge number ASD-89-0294. This bridge was constructed as a concrete slab bridge with continuous supports. The type of concrete used was QC/QA 4500. The crack map for bridge number ASD-89-0294 is shown in Figure 13 and the crack map interposed with structural layout is shown in Figure 25. Very few cracks were marked on this bridge deck, with most of the cracks located on the West side. Since this was a relatively small bridge with a deck surface area of approximately 2023 ft², the crack density was 0.062 ft/ft² (0.204 m/m²). This means the average length of visible cracks from waist height of a person with normal height is 0.062 feet of crack length over an area of one square foot of bridge deck surface. Crack width measurements at select crack locations indicated that the surveyed cracks were as large as or greater than 0.007 inches wide.

6.3 Bridge ASD-42-0656

Following ASD-89-0294, another continuous concrete slab bridge was surveyed, namely bridge number ASD-42-0656. This bridge deck had a surface area of 6925 ft², approximately three times the size of the previous bridge deck. The type of concrete used was high performance mix # 4. The crack map for bridge number ASD-42-0656 is shown in Figure 14 and the crack map interposed on structural layout is shown in Figure 26. As seen in the crack map, there was a large amount of small cracks throughout the bridge deck. These cracks were not large as compared to some of the structural cracks, and most of the cracks were very fine, hairline cracks. From crack width measurements at select locations, some of the cracks were as wide as 0.0625 inches, while others were 0.0468 inches. Still, some of the structural cracks were even larger at 0.125 inches wide. Typical structural cracks from the bridge deck are shown in Figure 40 and Figure 41. Many cracks that were measured were larger than the ACI 224 maximum required crack widths of 0.007 inches. The calculated crack density for bridge number ASD-42-0656 was 0.195 ft/ft² (0.640 m/m²).

6.4 Bridge ASD-604-0296

The next bridge crack surveyed was bridge number ASD-604-0296. This bridge was the first stringer supported (continuous steel beam) bridge surveyed, and its length was roughly three times as long as ASD-42-0656. The type of concrete used was QC/QA 4500. The surface area of bridge number ASD-604-0296 was about 12,971 ft², and the crack map for this bridge is shown in Figure 15 and the crack map overlaid on structural drawing is shown in Figure 27. Most of the cracks located on this bridge were transverse cracks that were perpendicular to the longitudinal axis of the bridge. These cracks were relatively evenly spaced, about 7-10 feet apart. However, since the bridge deck was placed about 21 months ago, several of the transverse cracks were difficult to locate and add to the crack map. Also, the crack surveys for this bridge deck were conducted on days when the temperature was low, which made it difficult to locate cracks on the deck.

6.5 Bridge ASD-42-0359

The next crack survey took place on bridge number ASD-42-0359L. Along with the previous bridge, this bridge was also supported by steel beams; therefore, it was classified as a stringer supported bridge. The type of concrete used was QC/QA 4500. The crack map for bridge number ASD-42-0359L is shown in Figure 16 and the crack map overlaid on structural layout is shown in Figure 28. This bridge deck had a total surface area of 6413 ft², which was relatively similar to bridge number ASD-42-0656. The calculated crack density for bridge number ASD-42-0359L was 0.053 ft/ft² (0.174 m/m²), which was a comparable value to the other stringer supported deck; bridge number ASD-604-0296. Once again, due to the early-age of the bridge, about 17 months, there were numerous small cracks located throughout the bridge deck that were difficult to locate. If another crack survey was performed on this bridge in one to two more years, then these small cracks may open up to be wider and more visible.

6.6 Bridge LOR-83-1032

Following ASD-42-0359, bridge number LOR-83-1032 was crack surveyed in order to determine the crack density. This bridge deck was the third and final structural slab bridge deck, and it was relatively similar in size compared to the first structural slab bridge deck that was surveyed. The type of concrete used was QC/QA 4500. LOR-83-1032 had a deck surface area of about 2950 ft², and the crack map for this bridge deck is shown in Figure 17 and crack map interposed on structural layout in is shown in Figure 29. Cracks were located frequently during the crack survey, but most of these cracks were extremely small cracks with negligible lengths. The calculated crack density of the bridge deck was 0.141 ft/ft² (0.461 m/m²), which was the second largest calculated crack density for structural slab bridge decks. Crack width measurements were taken at select locations throughout the bridge deck, and the measurements ranged from 0.01 to 0.05 inches. These crack width measurements were all larger than the required crack width of 0.007 inches.

6.7 Bridge LOR-301-40683

The next bridge deck crack survey occurred on bridge number LOR-301-40683. This bridge was not a continuous steel beam bridge; rather, it was constructed as a simple steel beam bridge. LOR-301-40683 was the only simple steel beam bridge that was surveyed, and it was classified as a stringer supported bridge deck. The type of concrete used was QC/QA 4500. The crack map for the bridge is shown in Figure 18 and crack map interposed on structural layout is shown in Figure 30. With almost the exact surface area of the other bridge constructed in Lorain County, bridge number LOR-301-40683 had a deck surface area of about 2965 ft². Cracks were widespread throughout the bridge deck, with most cracking occurring close to the centerline of the bridge and the edge of the bridge decks where the deck meets the approach slab. This cracking close to the approach slab is believed to be caused by restraint due to integral abutments. The crack density of the bridge deck was 0.205 ft/ft² (0.671 m/m²), which was by far the highest crack density for stringer supported bridge decks. This bridge deck was three years old at the time of the survey, about twice the age of the five other bridges, which may explain the higher value for the crack density. Since this survey was completed three years into the life of the bridge, the cracks were able to develop and were much more defined than the cracks on more recent bridges surveyed.

6.8 Bridge HUR-250-1841

The next bridge deck surveyed was bridge number HUR-250-1841. This bridge was the first prestressed concrete beam bridge surveyed and is classified as stringer supported bridge deck. The crack map for this bridge is shown in Figure 19 and crack map interposed on structural layout is shown in Figure 31. This bridge deck has a total surface area of 3960 ft², and the type of concrete used here is high performance mix # 4. This bridge is 24 months old. The crack density for this bridge is 0.287 ft/ft² (0.942m/m²), which is the highest crack density of all the twelve surveyed bridges. From the crack maps, it can be observed that this bridge deck has a lot of transverse cracks that are long and are relatively evenly spaced.

6.9 Bridge HUR-250-1830

The next crack survey took place on bridge number HUR-250-1830. This bridge is also a prestressed concrete beam bridge similar to bridge number HUR-250-1841, and both are located adjacent to each other. The crack map for this bridge is shown in Figure 20 and the structural drawing with cracks is shown in Figure 32. This bridge deck has a total surface area of 6330 ft². The type of concrete used here is high performance mix # 4. This bridge is 24 months old. The crack density for this bridge is 0.284 ft/ft²(0.932m/m²). The lengths of the individual cracks measured for this bridge were relatively smaller compared to the other bridges. However, it depicted higher density of cracking.

6.10 Bridge CRA-602-600

Following bridge HUR-250-1830, bridge number CRA-602-600 was surveyed. This bridge is a continuous steel beam bridge and is classified as stringer supported bridge deck. The crack map for this bridge is shown in Figure 21 and crack map interposed on structural layout is shown in Figure 33. This bridge deck has a total surface area of 5150 ft², and the type of concrete used here is Class S. This bridge is 35 months old. The crack density for this bridge is 0.155 ft/ft² (0.508 m/m²). From the crack maps it can be observed that this bridge deck has higher crack density at the joints, than the remaining area. The cracks in this bridge are mostly narrow.

6.11 Bridge MED-18-1403

The next bridge surveyed was bridge number MED-18-1403. This bridge is a prestressed concrete beam bridge and is classified as stringer supported bridge deck. The crack map for this bridge is shown in Figure 22 and crack map interposed on structural layout is shown in Figure 34. This bridge deck has a total surface area of 6765 ft², and the type of concrete used here is high performance mix # 4 MOD. This bridge is 40 months old. The crack density for this bridge is 0.114 ft/ft² (0.374m/m²). From the crack maps it can be observed that the entire cracks are concentrated in one section of the bridge. Also, it was observed that there are a lot of parallel cracks on parapet walls (not considered part of bridge deck cracks).

6.12 Bridge WAY-30-1953

This bridge is a continuous steel beam bridge with 2 spans and is classified as stringer supported bridge deck. The crack map for this bridge is shown in Figure 23 and crack map interposed on structural layout is shown in Figure 35. This bridge deck has a total surface area of 5365 ft², and the type of concrete used here is high performance mix # 4. This bridge is the oldest of the twelve bridges surveyed, being 48 months old. The crack density for this bridge is 0.135 ft/ft² (0.443 m/m²). From the crack maps, it was observed that the crack density was even throughout the bridge deck. Also, it was observed that there are a lot of parallel cracks on parapet walls (not considered part of bridge deck cracks).

6.13 Bridge ERI-250-1138

This bridge ERI-250-1138 was the last surveyed bridge of all the bridges. This bridge is a continuous steel beam bridge with 3 spans and is classified as stringer supported bridge deck. The crack map for this bridge is shown in Figure 24 and the structural drawing is shown in Figure 36. This bridge deck has a largest total surface area of 14430 ft² compared to other bridges surveyed, and the type of concrete used here is High Performance QC/QA 4500. This bridge is 42 months old. The crack density for this bridge is 0.024 ft/ft² (0.078 m/m²), which is the lowest crack density of all the twelve surveyed bridges. At the ends of this bridge deck, some railings were provided to separate the deck from the approach slabs. There are very few cracks at the ends (near the abutments) compared to the other bridge decks.



Figure 40 Structural Crack on Bridge Number ASD-42-0656



Figure 41 Structural Crack on Bridge Deck

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions:

Extensive crack surveys on twelve Ohio Department of Transportation bridge decks located in District 3 were completed. Crack maps were created showing the crack profiles for the twelve bridges. These crack maps resulted in the calculation of crack densities for the bridge decks. The following conclusions are drawn after comparing the crack densities for the structural slab bridges and the crack densities for the stringer supported bridges:

- (a) Crack densities determined for the twelve bridge decks indicated that structural slab bridge decks have slightly higher shrinkage crack densities compared to the bridge decks constructed with stringer supports. However, the “structural” cracks seem to be wider for structural slabs (greater than 0.007 inch).
- (b) There appears to be no direct correlation between the age of the bridge deck and the amount of cracking. However, since the bridges are relatively early-aged, it was not expected that there would be such a correlation.
- (c) On bridge ASD-42-0656, which is a continuous slab bridge, there were several large “structural” cracks that were parallel to the intermediate supports. These cracks were very wide and much greater than 0.007 inch giving a reason for concern.
- (d) The average shrinkage crack density of bridge decks that are supported on prestressed concrete beams over simple spans was about the same as that of the bridge deck supported on steel beams with simply supported end conditions.
- (e) The shrinkage crack densities of the twelve bridge decks determined in this study were considerably lower than the crack densities of similar bridge decks located in other States, demonstrating that Ohio bridge decks in general have lower shrinkage crack density than those of other States.
- (f) The shrinkage crack densities of the bridges constructed with QC/QA type of concrete were lower than the bridges made with other types of concrete.

7.2 Recommendations:

- (a) The results from this project demonstrate that shrinkage crack densities of the twelve bridge decks surveyed were considerably lower than the crack densities of similar bridge decks located in other States. Therefore, Ohio bridge decks in general have lower shrinkage crack density than those of other States. Bridge decks made from QC/QA 4500 concrete seem to be performing better than other concretes used in the State. It is recommended that QC/QA 4500 concrete continue to be used to minimize shrinkage cracking.

- (b) Continuous structural slab bridges showed cracks much wider than 0.007 inch near the intermediate continuous supports. These cracks were very wide (as much as 0.075 inch at some locations which is more than 10 times the limit recommended in ACI 224 report). The research team classified these cracks at the moment as “non-shrinkage cracks”. The frequencies, magnitudes, and widths of these cracks however, were alarming. The possible reasons for the non-shrinkage cracks in structural slab bridges are being thought to be due to one or a combination of the following (1) negative moment due to loading (2) reinforcement details (3) overloading (4) fatigue (5) foundation movements (6) concrete properties (7) construction issues and sequence (8) traffic conditions (9) Other. A thorough investigation of the source, severity and consequences of these “non-shrinkage” cracks in structural slab bridges is needed to develop further insight into the problem of cracking in structural slab bridge decks.
- (c) Most of the crack surveys were completed on bridges that were constructed as recently as 2009; meaning, these bridges were in service for a little over one year at the time of the crack surveys. During the crack surveys, several small, hairline cracks were found throughout the decks, and in some cases, cracks were very difficult to locate. The cracks are believed to begin to form on these bridge decks. Therefore, if a second crack survey were to be completed later in two to five years from now, the majority of these fine, hairline cracks is expected to become wider and would be much more visible. Also, several of the cracks that were very difficult to locate would be much more defined if another crack survey took place in a few years.
- (d) Before the crack surveys could take place, the bridge decks must be blown off to remove loose debris and also sprayed with water to make it easier to see the cracks. A backpack air blower was used to remove the debris from the bridge decks, and a backpack water sprayer was used to spray water on the decks. After completing several crack surveys, it was hastily determined that our means of removing the debris worked to remove the loose debris, but struggled to remove the heavy, packed-down debris located within the grooves and near the parapet walls. The use of a brush vehicle to quickly sweep the decks, immediately followed by cleaning the decks with an air compressor, would have assisted in completely clearing off the bridge decks and allowed the crack surveys to be completed faster. Also, our water sprayer was limited to the sections immediately in line to be surveyed and required a single person to continuously spray. If the bridge decks were sprayed with a water truck sprayer directly after the bridge being cleared of debris, then the bridge deck could have been sufficiently sprayed and at least one more person could have assisted in the crack surveys.
- (e) The crack surveys were completed on the bridge decks in the early part of the year, during the cold, rainy season. However, the cracks on the bridge decks were easiest to locate and trace when the weather was sunny and warm. Therefore, an ideal setting for a crack survey would include mild, sunny weather so that the cracks could be found with more ease. If the crack surveys were limited to ideal weather days, then the surveys would be completed in less time and cracks would be more visible.

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APPENDICES

APPENDIX A

ODOT CONCRETE CYLINDER REPORTS AND JMF/MIXTURE DESIGNS

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PCJMF
Act: I
JMF: C27012C Matl Cd: 215QSC2 QC/QA SUPERSTRUCT 2 D03MB2 CMTAS039
      Prod/Supp Cd: 2701Q 01 MORITZ-QC/QA W/C Max: 0.48
      Class Concrete: QSC2 4500 Design Cf: 27 % Air: 7.8
      Design Slump: 6.00 Eff Date: 09/30/09 Term Date:
W/
Matl Code Name C P/S Code Name Spgr Abs Yd Lbs Qty Cu
021SD2 SAND, NATURAL /02 04212 01 MAR-ZANE#14-MELCO 2.60 2.11 1110
0250080 8 CR STONE 8SS/02 4205C 01 LEHIGH HANSON-CASTAL 2.62 2.55 415
0250570 57 CR STONE 57SS/02 4205D 01 LEHIGH HANSON-CASTAL 2.65 1.52 1360
37504 CEM TYPE 1 701.04 Y 06579 01 LAFARGE/ALPENA MI 3.15 0.01 395
37604 GRAN SLAG GR 120 Y 06799 01 LAFARGE SLAG/CHICAGO 2.84 0.01 170

001014 WATER Source: 499.02 272
Matl Code Name P/S Code Name Amt(Oz/Cy)
Admx1 42106 ADMIXTURE TYPE F 06502 01 AXIM CONCRETE TECH 128.00
Admx2
Aea 42001 ADMIXTURE AEA 06502 01 AXIM CONCRETE TECH 30.00
Tot Weight/Cubic Yard: 3722 Weight/Cubic Foot Fresh Concrete Design: 137.85
REMARKS
F4 LIST F9 RMKS
    
```

Figure 42 Concrete Mixture Design for Bridge Number ASD-89-0294 and Bridge Number ASD-42-0359

Requested for: Project: 09-1021 County: ASD Route: US 42 Section: 003.59 PE/PS: VAN HOR CI District: 03
 Prod/Supp: QC/QA SUPERSTRUCT 2
 Material Code: 215QSC2
 Cement Prod/Supp: Ending Date: 10/22/09

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	% AIR	Slump	Compressive Strength		AVG	Initials
						Cyl 1	Cyl 2		
00985780-03	10/21/09	27010-01	C27012C	6.0	7.50	6670	6710	6690	
				7.0	7.50	5180	5340	5260	
				6.6	8.50	5830	5690	5760	
				5.2	7.50	5930	5980	5955	

MEAN: 5916.3
 Standard Deviation: 552
 Minimum: 5260.0
 Maximum: 6690.0
 Coefficient of Variation: 9.3

 -E
 ***** END OF REPORT *****

Figure 43 Concrete Cylinder Report for Bridge Number ASD-89-0294

Requested for: County: ASD Route: US 42 Section: 003.59 PE/PS: VAN HOR CI District: 03
 Project: 09-1021
 Prod/Supp: QC/QA SUPERSTRUCT 2
 Material Code: 215QSC2
 Cement Prod/Supp: Ending Date: 10/22/09
 Beginning Date: 10/20/09

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	% AIR	Slump	Compressive Strength		AVG	Initials
						Cyl 1	Cyl 2		
00985780-03	10/21/09	2701Q-01	C27012C	6.0	7.50	6670	6710	6690	
				7.0	7.50	5180	5340	5260	
				6.6	8.50	5830	5690	5760	
				5.2	7.50	5930	5980	5955	

MEAN: 5916.3
 Standard Deviation: 552
 Minimum: 5260.0
 Maximum: 6690.0
 Coefficient of Variation: 9.3

 ~E
 ***** END OF REPORT *****

Figure 44 Concrete Cylinder Report for Bridge Number ASD-42-0359

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PCJMF                                PC CONCRETE JMF
Act: I
JMF: C27162A  Matl Cd: 215QSC2      QC/QA SUPERSTRUCT 2      D03MB2  CMTAS039
          Prod/Supp Cd: 2716Q 01    GRAFTON-QC/QA          W/C Max: 0.42
          Class Concrete: DECK 4500  Design Cf: 27           % Air: 8.1
          Design Slump: 3.75        Eff Date: 06/15/09    Term Date:
                                W/
Matl Code Name                      C P/S Code Name                      Spgr Abs Yd Lbs
021SD2  SAND, NATURAL /02           04210 01 BAKER SD-BURBANK          2.64 1.20 1180
0250080 8 CR STONE 8SS/02           4204A 01 HANSON/WAGNER-SANDUS    2.61 3.00 500
0250570 57 CR STONE 57SS/02          4204A 01 HANSON/WAGNER-SANDUS    2.63 2.20 1180
37504   CEM TYPE 1 701.04           Y 06579 01 LAFARGE/ALPENA MI    3.15 0.01 465
37604   GRAN SLAG GR 120            Y 06799 01 LAFARGE SLAG/CHICAGO  2.89 0.01 200

001014  WATER                      Source: 499.02                      279
          Matl Code Name                      P/S Code Name                      Amt (Oz/Cy)
Admx1 42109  ADMIXTURE TYPE A,D      06511 01 EUCLID CHEMICAL CO      26.60
Admx2 42110  ADMIXTURE TYPE A,F      06511 01 EUCLID CHEMICAL CO      99.75
Aea 42001   ADMIXTURE AEA            06511 01 EUCLID CHEMICAL CO       5.32
Tot Weight/Cubic Yard: 3804 Weight/Cubic Foot Fresh Concrete Design: 140.89
REMARKS
F4 LIST F9 RMKS

```

Figure 45 Concrete Mixture Design for Bridge Number LOR-83-1032

Requested for:
 Project: 09-1011 County: LOR Route: SR 83 Section: 010.30 PE/PS: BLAZEK A1 District: 03
 Prod/Supp: QC/OA SUPERSTRUCT 2
 Material Code: 215QSC2
 Cement Prod/Supp: Ending Date: 09/01/09
 Beginning Date: 08/01/09

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	AIR %	Slump	Compressive Strength		AVG	Initials
						Cyl 1	Cyl 2		
00974749-03	08/24/09	27160-01	C27162A	6.1	5.75	6410	6350	6380	
				5.5	5.50	6420	6350	6385	
				6.2	6.50	6430	6230	6330	
				5.0	5.00	7230	6910	7070	

MEAN: 6541.3
 Standard Deviation: 343
 Minimum: 6330.0
 Maximum: 7070.0
 Coefficient of Variation: 5.3

 -E
 ***** END OF REPORT *****

Figure 46 Concrete Cylinder Report for Bridge Number LOR-83-1032


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PCJMF                               PC CONCRETE JMF
Act: 1                               D03MB2   CMTAS039
JMF: C273207  Matl Cd: 21527        HI PERFORMANCE MIX 4   W/C Max: 0.40
      Prod/Supp Cd:
      Class Concrete: HI PER #4      Design Cf: 27           % Air: 7.0
      Design Slump: 8.00             Eff Date: 01/10/05    Term Date:
                                   W/
Matl Code Name                      C P/S Code Name                Spgr Abs  Yd Lbs
021SD2  SAND, NATURAL /02           04212 01 MAR-ZANE#14-MELCO    2.62  0.01  1370
0250080  8 CR STONE 8SS/02          4205C 01 LEHIGH HANSON-CASTAL 2.65  0.01  1490
37504    CEM TYPE 1 701.04         Y 04302 01 INPUT ACTUAL P/S CD 3.15  0.01  440
37601    MICRO-SILICA POWDER       Y 04302 01 INPUT ACTUAL P/S CD 2.20  0.01   30
37603    GRAN SLAG GR 100          Y 04302 01 INPUT ACTUAL P/S CD 2.90  0.01  190

001014  WATER                      Source: 499.02                264
      Matl Code Name                P/S Code Name                Amt (Oz/Cy)

Admx1
Admx2
Aea
Tot Weight/Cubic Yard: 3784  Weight/Cubic Foot Fresh Concrete Design: 140.15

F4 LIST  F9 RMKS

```

Figure 47 Concrete Mixture Design for Bridge Number ASD-42-0656, Bridge Number HUR-250-1830, and Bridge Number HUR-250-1841

ODOT CONSTRUCTION MANAGEMENT SYSTEM
PC CONCRETE CYLINDER REPORT

CMTAR011

Requested for: County: ASD Route: US 42 Section: 006.38 PE/PS: LABAKI J1 District: 03
 Project: 08-8022
 Prod/Supp: HI PERFORMANCE MIX 4
 Material Code: 21527
 Cement Prod/Supp: Ending Date: 01/01/10
 Beginning Date: 06/01/09

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	% AIR	Slump	Compressive Strength Cyl 1	Compressive Strength Cyl 2	AVG	Initials
00983308-01	09/23/09	02701-01	C273207	5.0	5.00	7450	7750	7600	JAD
00983311-01	09/23/09	02701-01	C273207	5.5	5.00	6510	6530	6520	JAD
00982552-01	09/16/09	02701-01	C273207	5.5	6.50	6490	6390	6440	PHC
00982556-01	09/16/09	02701-01	C273207	5.0	6.00	6740	6650	6695	PHC
00981437-01	09/10/09	02701-01	C273207	7.0	6.75	7070	6970	7020	JAD
				6.5	7.00	6520	6820	6670	JAD
				7.0	8.00	7030	6760	6895	JAD
00969976-01	06/24/09	02701-01	C273207	6.4	4.00	6500	7210	6855	PHC
00969095-01	06/17/09	02701-01	C273207	6.0	5.00	7260	7530	7395	PHC
00967971-01	06/10/09	02701-01	C273207	6.5	7.00	4910	4470	4690	JAD
				7.5	26.73	7090	6800	6945	JAD
				7.5	26.90	6570	6730	6650	JAD

MEAN: 6697.9
 Standard Deviation: 719
 Minimum: 4690.0
 Maximum: 7600.0
 Coefficient of Variation: 10.7

 END OF REPORT *****

Figure 48

Concrete Cylinder Report for Bridge Number ASD-42-0656

Requested for: Project: 07-0449 County: HUR Route: US 250 Section: 018.39 PE/PS: PATTI R1 District: 03
 Prod/Supp: HI PERFORMANCE MIX 4
 Material Code: 21527
 Cement Prod/Supp: Ending Date: 07/30/09

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	% AIR	Slump	Compressive Strength		AVG	Initials
						Cyl 1	Cyl 2		
00974782-01	07/29/09	02701-01	C273207	6.5	3.00	7600	7270	7435	JAD
00974586-01	07/27/09	02701-01	C273207	7.0	3.00	6460	6410	6435	PHC
00973733-01	07/21/09	02701-01	C273207	5.0	0.50	7770	8550	8160	JAD
00972249-01	07/10/09	02701-01	C273207	8.5	6.00	4900	5360	5130	PHC
				7.4	6.00	5950	6080	6015	PHC
				5.0	6.50	7780	7800	7790	PHC

MEAN: 6827.5
 Standard Deviation: 1128
 Minimum: 5130.0
 Maximum: 8160.0
 Coefficient of Variation: 16.5

 -E

 END OF REPORT *****

Figure 49 Concrete Cylinder Report for Bridge Number HUR-250-1830 and Bridge Number HUR-250-1841

```

PCJMF                                PC CONCRETE JMF
Act: I                                D03MB2  CMTAS039
JMF: C200324  Matl Cd: 21523          CONCRETE SPECIAL MIX  W/C Max: 0.42
      Prod/Supp Cd: 02713 01          MEDINA-BRUNSWICK
      Class Concrete: HP4 MOD          Design Cf: 27          % Air: 7.0
      Design Slump: 8.00              Eff Date: 07/09/07    Term Date: 11/18/08
                                      W/                                Qty Cu
Matl Code Name                        C P/S Code Name                Spgr Abs  Yd Lbs
021SD2  SAND, NATURAL /02             04303 01 AMER S&G#4-MASSILLON 2.65  1.20  1245
0250080 8 CR STONE 8SS/02             04024 01 NATIONAL-CAREY"WEST" 2.69  1.61   365
0250570 57 CR STONE 57SS/02          04024 01 NATIONAL-CAREY"WEST" 2.68  1.48  1335
37504   CEM TYPE 1 701.04            Y 06665 01 ST.MARYS/BOWMANVILLE 3.15  0.01   400
37601   MICRO-SILICA POWDER          Y 06511 01 EUCLID CHEMICAL CO   2.20  0.01    30
37604   GRAN SLAG GR 120             Y 06799 01 LAFARGE SLAG/CHICAGO 2.89  0.01   170

001014  WATER                        Source: 499.02                252
      Matl Code Name                  P/S Code Name                Amt (Oz/Cy)
Admx1 42110  ADMIXTURE TYPE A,F      06511 01 EUCLID CHEMICAL CO    76.00
Admx2 42112  ADMIXTURE TYPE B,D      06511 01 EUCLID CHEMICAL CO    18.00
Aea 42001  ADMIXTURE AEA              06511 01 EUCLID CHEMICAL CO     6.60
Tot Weight/Cubic Yard: 3797 Weight/Cubic Foot Fresh Concrete Design: 140.63
                                                                    REMARKS
F4 LIST  F9 RMKS

```

Figure 50 Concrete Mixture Design for Bridge Number MED-18-1403

Requested for: County: MED Route: SR 18 Section: 013.45 PE/PS: BLAZEK A1 District: 03
 Project: 06-0437
 Prod/Supp: CONCRETE SPECIAL MIX
 Material Code: 21523
 Cement Prod/Supp: Ending Date: 07/20/07

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	% AIR	Slump	Compressive Strength		AVG	Initials
						Cyl 1	Cyl 2		
00895085-01	07/17/07	02722-01	C200324	8.0	7.00	6300	6750	6525	PHC
						5710	5690	5700	PHC
						4960	5590	5275	PHC

Phase 1

MEAN: 5833.3
 Standard Deviation: 619
 Minimum: 5275.0
 Maximum: 6525.0
 Coefficient of Variation: 10.6

 -E
 ***** END OF REPORT *****

Figure 51 Concrete Cylinder Report for Bridge Number MED-18-1403, Phase 1

Requested for: Project: 06-0437 County: MED Route: SR 18 Section: 013.45 PE/PS: BLAZEK A1 District: 03
 Prod/Supp: Material Code: 21523 CONCRETE SPECIAL MIX
 Cement Prod/Supp: Beginning Date: 10/20/07 Ending Date: 11/01/07

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	AIR %	Slump	Compressive Strength Cyl 1	Compressive Strength Cyl 2	AVG	Initials
00911270-01	10/30/07	02722-01	C200324	7.0	5.00	6180	6790	6485	JAD
						MEAN:	6485.0		
						Standard Deviation:	431		
						Minimum:	6485.0		
						Maximum:	6485.0		
						Coefficient of Variation:	6.7		

Phase 2

 -E
 ***** END OF REPORT *****

Figure 52 Concrete Cylinder Report for Bridge Number MED-18-1403, Phase 2

```

PCJMF                               PC CONCRETE JMF
Act: 1                                D03MB2  CMTAS039
JMF: C27072E  Matl Cd: 215QSC2  QC/QA SUPERSTRUCT 2  W/C Max: 0.43
      Prod/Supp Cd: 2707Q 01  DAUCH-QC/QA
      Class Concrete: QC/QA 4500  Design Cf: 27  % Air: 7.6
      Design Slump: 6.75  Eff Date: 04/14/08  Term Date:
      W/
      Qty Cu
Matl Code Name  C P/S Code Name  Spgr Abs  Yd Lbs
021SD2  SAND, NATURAL /02  04210 01 BAKER SD-BURBANK  2.63  1.58  1248
0250080  8 CR STONE 8SS/02  4204A 01 HANSON/WAGNER-SANDUS  2.62  2.83  276
0250570  57 CR STONE 57SS/02  4204A 01 HANSON/WAGNER-SANDUS  2.63  2.14  1249
37504  CEM TYPE 1 701.04  Y 06573 01 HOLCIM/DUNDEE MI  3.15  0.01  475
37603  GRAN SLAG GR 100  Y 06725 01 HOLCIM SLAG/CHICAGO  2.92  0.01  190

001014  WATER  Source: 499.02  288
      Matl Code Name  P/S Code Name  Amt (Oz/Cy)
Admx1 42101  ADMIXTURE TYPE A  06502 01 AXIM CONCRETE TECH  33.25
Admx2 42106  ADMIXTURE TYPE F  06502 01 AXIM CONCRETE TECH  133.00
Aea 42001  ADMIXTURE AEA  06502 01 AXIM CONCRETE TECH  7.98
Tot Weight/Cubic Yard: 3726  Weight/Cubic Foot Fresh Concrete Design: 138.00
REMARKS
F4 LIST  F9 RMKS

```

Figure 53 Concrete Mixture Design for Bridge Number LOR-301-40683

Requested for: County: LOR Route: SR 301 Section: 40.673 PE/PS: RAWLING B1 District: 03
 Project: 07-0277
 Prod/Supp: QC/QA SUPERSTRUCT 2
 Material Code: 215QSC2
 Cement Prod/Supp: Ending Date: 05/01/08

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	% AIR	Slump	Compressive Strength Cyl 1	Compressive Strength Cyl 2	AVG	Initials
00923351-02	04/30/08	2707Q-01	C27072B	6.7	5.71	7160	7180	7170	
00923351-03	04/30/08	2707Q-01	C27072B	6.4	3.54	7670	7320	7495	
00923351-04	04/30/08	2707Q-01	C27072B	7.5	8.27	6990	6800	6895	
00923351-05	04/30/08	2707Q-01	C27072B	6.3	5.71	6990	7030	7010	

MEAN: 7142.5
 Standard Deviation: 264
 Minimum: 6895.0
 Maximum: 7495.0
 Coefficient of Variation: 3.7

***** END OF REPORT *****
 -E

Figure 54 Concrete Cylinder Report for Bridge Number LOR-301-40683


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PCJMF                                PC CONCRETE JMF
Act: I                                D03MB2  CMTAS039
JMF: C273248  Matl Cd: 21527          HI PERFORMANCE MIX 4  W/C Max: 0.40
      Prod/Supp Cd:
      Class Concrete: HI PER #4      Design Cf: 27          % Air: 7.0
      Design Slump: 8.00             Eff Date: 08/14/06  Term Date:
                                      W/
Matl Code Name                        C P/S Code Name                Spgr Abs  Yd Lbs
021SD2  SAND, NATURAL /02            04215 01 OLEN CORP-WOOSTER      2.62  0.01  1370
0250080  8 CR STONE 8SS/02           04202 01 NATIONAL-BUCYRUS       2.65  0.01  1490
37504    CEM TYPE 1 701.04          Y 04302 01 INPUT ACTUAL P/S CD   3.15  0.01   440
37601    MICRO-SILICA POWDER        Y 04302 01 INPUT ACTUAL P/S CD   2.20  0.01   30
37603    GRAN SLAG GR 100           Y 04302 01 INPUT ACTUAL P/S CD   2.90  0.01   190

001014  WATER                        Source: 499.02                    264
      Matl Code Name                P/S Code Name                    Amt (Oz/Cy)

Admx1
Admx2
Aea
Tot Weight/Cubic Yard: 3784  Weight/Cubic Foot Fresh Concrete Design: 140.15

F4 LIST  F9 RMKS

```

Figure 55 Concrete Mixture Design for Bridge Number WAY-30-1952

ODOT CONSTRUCTION MANAGEMENT SYSTEM
PC CONCRETE CYLINDER REPORT

CMTAR011

Requested for: Project: 06-0251 County: WAY Route: US 30 Section: 019.52 PE/PS: RAWLING B1 District: 03
 Prod/Supp: HI PERFORMANCE MIX 4
 Material Code: 21527
 Cement Prod/Supp: Ending Date: 04/26/07
 Beginning Date: 04/24/07

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	AIR	%	Slump	Compressive Strength		AVG	Initials
							Cyl 1	Cyl 2		
00885348-01	04/24/07	02730-01	C273248	6.5	5.00	5660	7740	6700	JAD	
				6.5	5.00	6370	6470	6420	JAD	
				8.0	5.00	6770	6720	6745	JAD	
				7.5	5.00	8010	6570	7290	JAD	

MEAN: 6788.8
 Standard Deviation: 756
 Minimum: 6420.0
 Maximum: 7290.0
 Coefficient of Variation: 11.1

 -E
 ***** END OF REPORT *****

Figure 56 Concrete Cylinder Report for Bridge Number WAY-30-1952

```

PCJMF                               PC CONCRETE JMF
Act: I                               D03MB2  CMTAS039
JMF: C27012E  Matl Cd: 215QSC2      QC/QA SUPERSTRUCT 2      W/C Max: 0.48
      Prod/Supp Cd: 2701Q 01        MORITZ-QC/QA
      Class Concrete: QSC2 4500      Design Cf: 27              % Air: 7.8
      Design Slump: 6.00             Eff Date: 02/27/09        Term Date: 07/06/10
                                   W/
                                   Qty Cu
Matl Code Name                      C P/S Code Name                      Spgr Abs  Yd Lbs
021SD2  SAND, NATURAL /02            04212 01 MAR-ZANE#14-MELCO          2.60  2.11  1110
0250080  8 CR STONE 8SS/02           4205C 01 LEHIGH HANSON-CASTAL       2.62  2.55   415
0250570  57 CR STONE 57SS/02          4205C 01 LEHIGH HANSON-CASTAL       2.65  1.52  1360
37504    CEM TYPE 1 701.04           Y 06579 01 LAFARGE/ALPENA MI          3.15  0.01   395
37604    GRAN SLAG GR 120            Y 06799 01 LAFARGE SLAG/CHICAGO      2.84  0.01   170

001014  WATER                        Source: 499.02                      272
      Matl Code Name                      P/S Code Name                      Amt(Oz/Cy)
Admx1 42106  ADMIXTURE TYPE F          06502 01 AXIM CONCRETE TECH          128.00
Admx2
Aea 42001  ADMIXTURE AEA                06502 01 AXIM CONCRETE TECH          30.00
Tot Weight/Cubic Yard: 3722  Weight/Cubic Foot Fresh Concrete Design: 137.85
                                                                    REMARKS
F4 LIST  F9 RMKS

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Figure 57 Concrete Mixture Design for Bridge Number ASD-604-0296

Requested for: County: ASD Route: SR 604 Section: 002.94 PE/PS: YETZER E1 District: 03
 Project: 08-0522 QC/QA SUPERSTRUCT 2
 Prod/Supp: Material Code: 215QSC2
 Cement Prod/Supp: Ending Date: 07/30/09
 Beginning Date: 07/26/09

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	AIR	Slump	Compressive Strength		AVG	Initials
						Cyl 1	Cyl 2		
00970335-03	07/27/09	2701Q-01	C27012B	5.3	6.75	6620	6530	6575	
				6.4	7.00	5740	5850	5795	
				6.0	7.75	6190	6260	6225	
				6.4	7.25	6190	6110	6150	
				6.1	8.00	6380	6320	6350	
				7.6	7.50	6060	6230	6145	
				6.4	7.75	6640	6590	6615	
				6.2	5.00	6740	6470	6605	
				5.7	5.00	6440	6250	6345	
				6.2	7.00	6330	6320	6325	

MEAN: 6313.0
 Standard Deviation: 256
 Minimum: 5795.0
 Maximum: 6615.0
 Coefficient of Variation: 4.1

***** END OF REPORT *****

Figure 58 Concrete Cylinder Report for Bridge Number ASD-604-0296

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PCJMF
Act: I
JMF: C033916 Matl Cd: 21503 CONC CLASS S D03MB2 CMTAS039
Prod/Supp Cd: W/C Max: 0.44
Class Concrete: CLASS S Design Cf: 27 % Air: 6.0
Design Slump: 4.00 Eff Date: 05/01/08 Term Date:
W/
Matl Code Name C P/S Code Name Spgr Abs Yd Lbs Qty Cu
021SD2 SAND, NATURAL /02 04019 01 NATIONAL-U.SANDUSKY 2.62 0.01 1240
0250570 57 CR STONE 57SS/02 04202 01 NATIONAL-BUCYRUS 2.65 0.01 1510
37504 CEM TYPE 1 701.04 Y 04302 01 INPUT ACTUAL P/S CD 3.15 0.01 715

001014 WATER Source: 499.02 315
Matl Code Name P/S Code Name Amt (Oz/Cy)

Admx1
Admx2
Aea
Tot Weight/Cubic Yard: 3780 Weight/Cubic Foot Fresh Concrete Design: 140.00

F4 LIST F9 RMKS

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Figure 59 Concrete Mixture Design for Bridge Number CRA-602-0600

PCJMF		PC CONCRETE JMF			
Act:	I			D03MB2	CMTAS039
JMF:	C27072L	Matl Cd: 215QSC2	QC/QA SUPERSTRUCT 2	W/C Max: 0.43	
		Prod/Supp Cd: 2707Q 01	DAUCH-QC/QA		
		Class Concrete: QC/QA 4500	Design Cf: 27	% Air: 7.6	
		Design Slump: 6.75	Eff Date: 06/09/08	Term Date: 05/11/09	
		W/			Qty Cu
Matl Code Name		C P/S Code Name		Spgr Abs	Yd Lbs
021SD2	SAND, NATURAL /02	05060 01	BARTLEY&BOLIN@LAKEVI	2.60 1.90	1253
0250080	8 CR STONE 8SS/02	4204A 01	HANSON/WAGNER-SANDUS	2.62 2.88	276
0250570	57 CR STONE 57SS/02	4204A 01	HANSON/WAGNER-SANDUS	2.63 2.20	1229
37504	CEM TYPE 1 701.04	Y 06573 01	HOLCIM/DUNDEE MI	3.15 0.01	475
37603	GRAN SLAG GR 100	Y 06725 01	HOLCIM SLAG/CHICAGO	2.92 0.01	190
001014	WATER	Source: 499.02			288
	Matl Code Name	P/S Code Name		Amt (Oz/Cy)	
Admx1	42101	ADMIXTURE TYPE A	06511 01	EUCLID CHEMICAL CO	20.00
Admx2	42106	ADMIXTURE TYPE F	06511 01	EUCLID CHEMICAL CO	93.10
Aea	42001	ADMIXTURE AEA	06511 01	EUCLID CHEMICAL CO	12.60
Tot Weight/Cubic Yard: 3711 Weight/Cubic Foot Fresh Concrete Design:					137.44
					REMARKS
F4 LIST F9 RMKS					

Figure 61 Concrete Mixture Design for Bridge Number ERI-250-20036

Requested for: Project: 07-6004 County: ERI Route: US 250 Section: 19.742 PE/PS: DONOFRI MI District: 03
 Prod/Supp: 27070-01
 Material Code: 215QSCZ QC/QA SUPERSTRUCT 2
 Cement Prod/Supp: 27070-01
 Beginning Date: 06/24/08 Ending Date: 10/06/08

Sample ID	DATE MADE	Concrete Prod/Supp	JMF	% AIR	Slump	Compressive Strength Cyl 1	Compressive Strength Cyl 2	AVG	Initials
00935695-07	10/04/08	27070-01	C27072D	5.2	3.90	7310	7250	7280	
00935695-08	10/04/08	27070-01	C27072D	5.0	7.99	6720	6560	6640	
00935695-09	10/04/08	27070-01	C27072D	5.0	6.50	7350	7350	7350	
00935695-10	10/04/08	27070-01	C27072D	6.7	6.50	5080	5020	5050	
00935695-11	10/04/08	27070-01	C27072D	6.6	5.24	6290	6440	6365	
00935695-06	07/03/08	27070-01	C27072D	5.0	0.51	7720	7420	7570	
00935695-01	06/25/08	27070-01	C27072D	7.6	5.00	6770	6500	6635	
00935695-02	06/25/08	27070-01	C27072D	6.2	4.49	7560	7400	7480	
00935695-03	06/25/08	27070-01	C27072D	7.2	5.47	6500	6840	6670	
00935695-04	06/25/08	27070-01	C27072D	5.8	4.92	7450	7340	7395	
00935695-05	06/25/08	27070-01	C27072D	6.2	4.92	7580	7640	7610	

MEAN: 6913.2
 Standard Deviation: 748
 Minimum: 5050.0
 Maximum: 7610.0
 Coefficient of Variation: 10.8

***** END OF REPORT *****

Figure 62 Concrete Cylinder Report for Bridge Number ERI-250-20036

APPENDIX B

ODOT PROJECT PLANS FOR SURVEYED BRIDGES

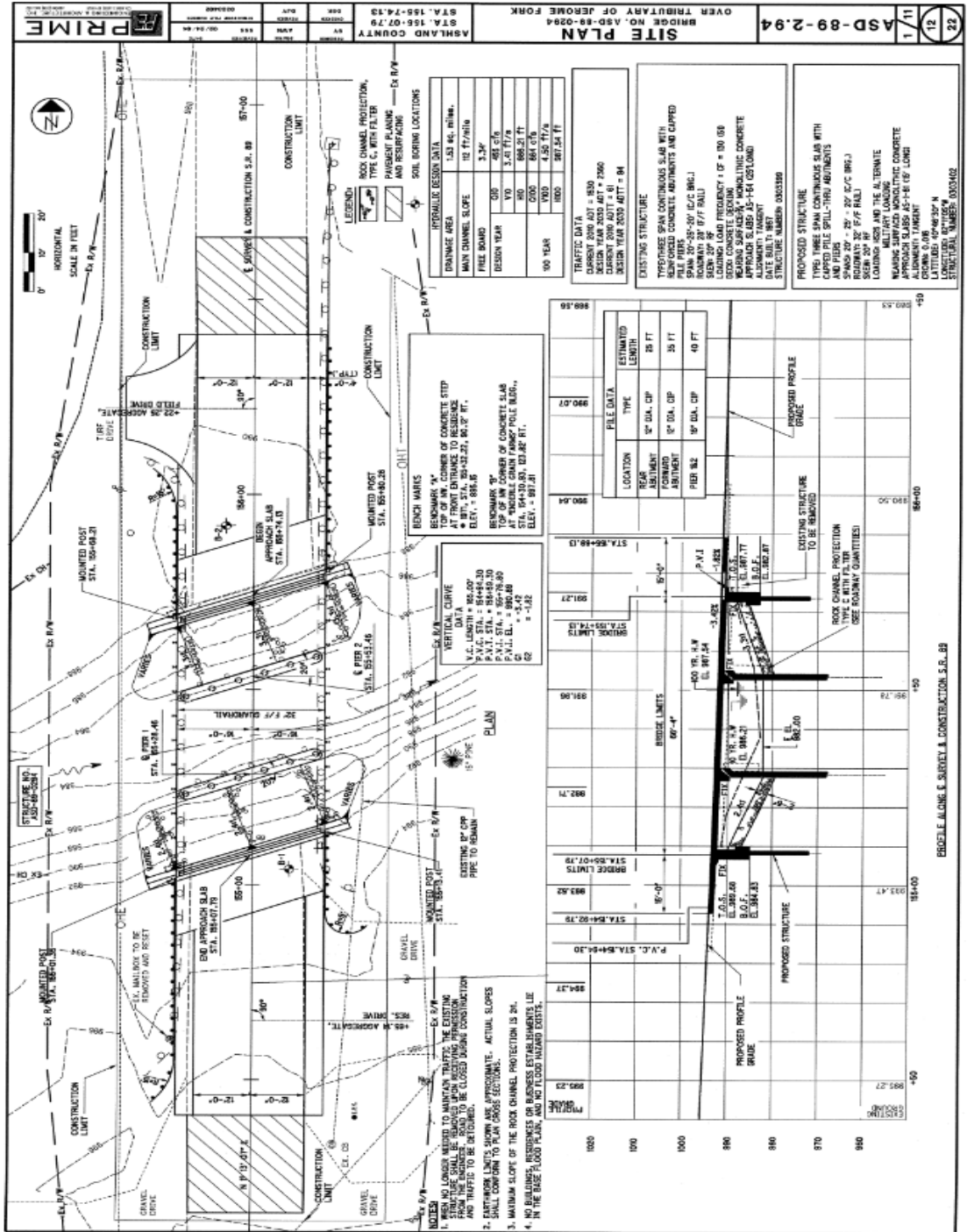


Figure 63 Plans for Bridge Number ASD-89-0294

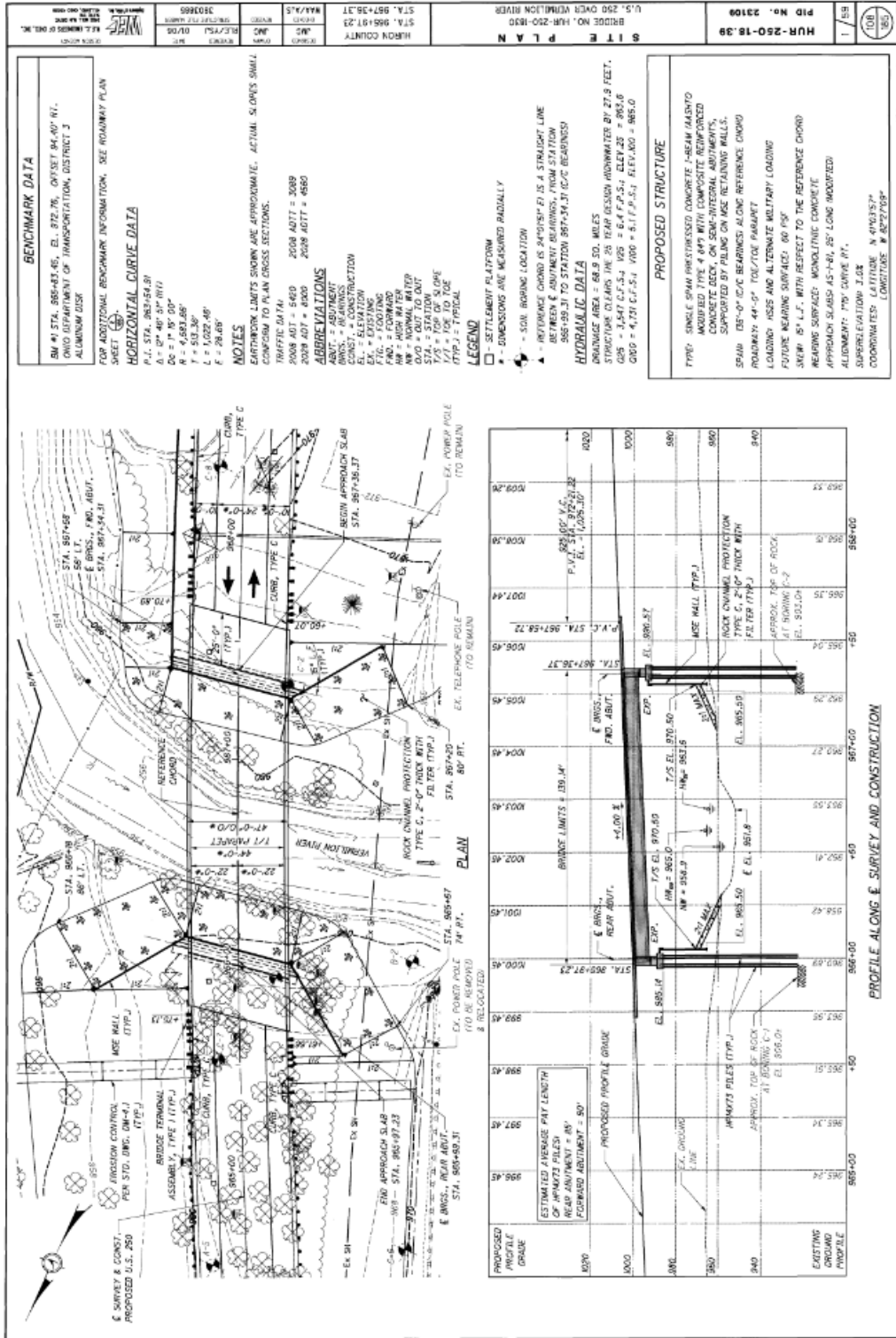


Figure 66 Plans for Bridge Number HUR-250-1830

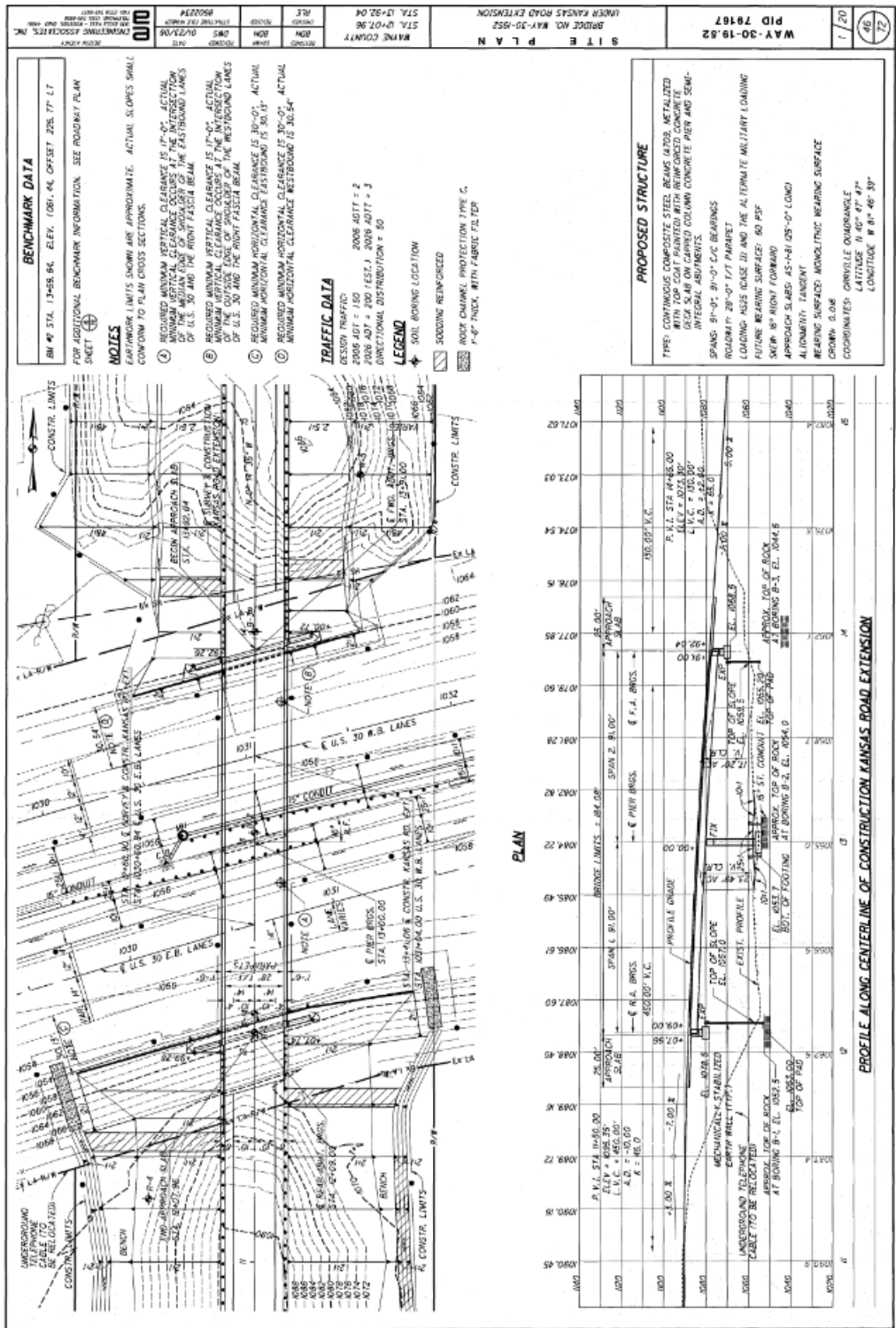


Figure 70 Plans for Bridge Number WAY-30-1952

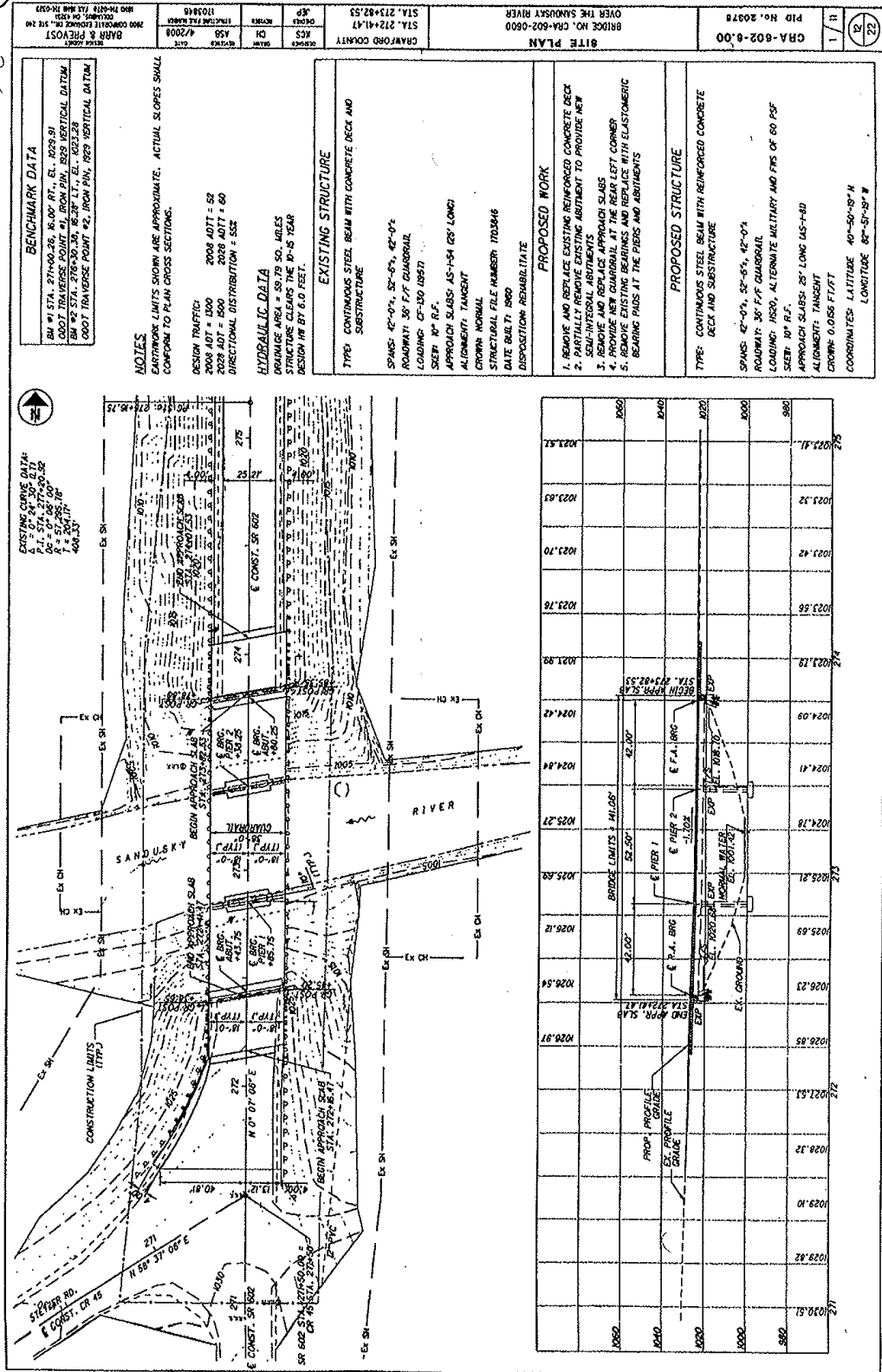


Figure 73 Plans for Bridge Number CRA-602-0600

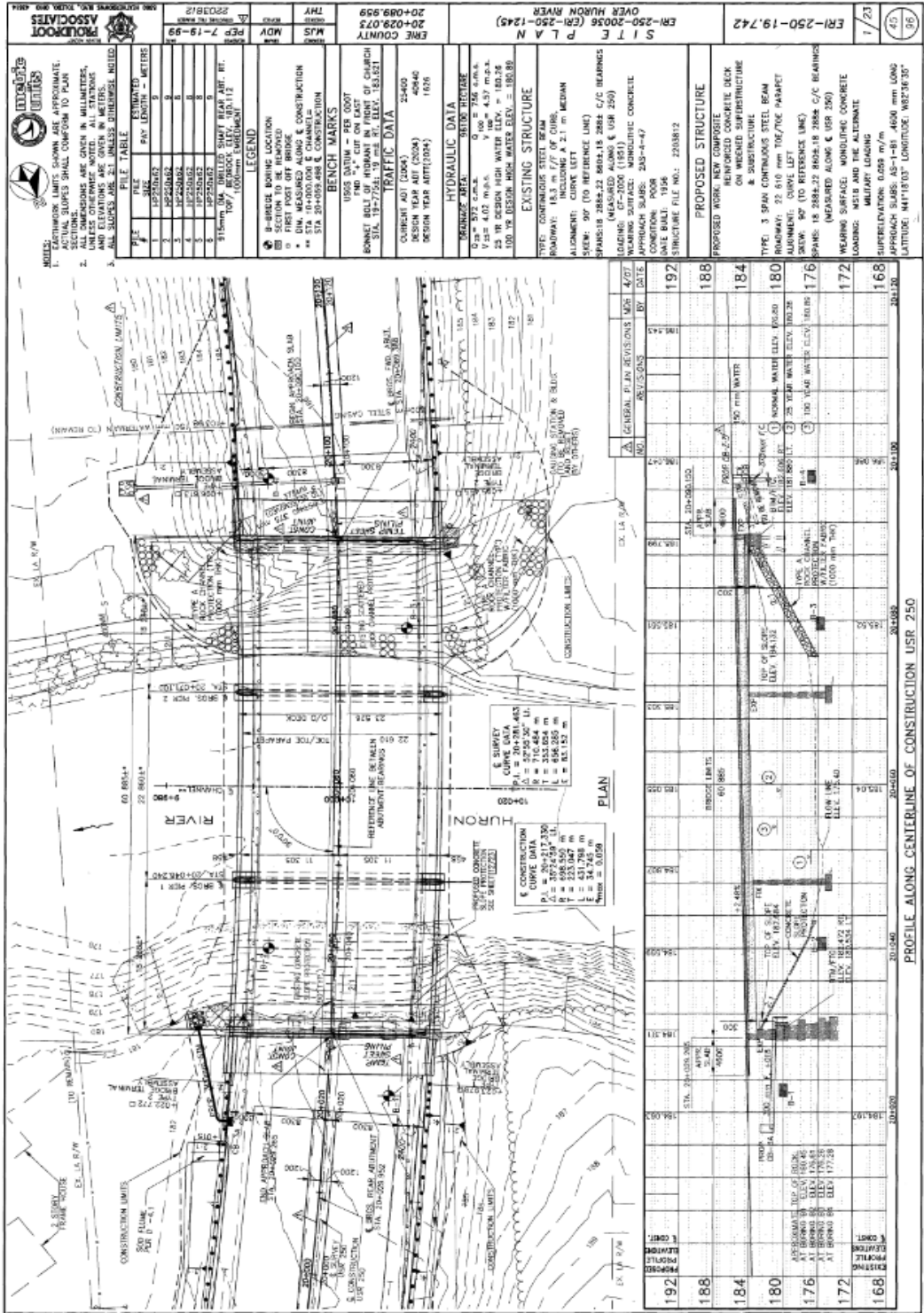


Figure 74 Plans for Bridge Number ERI-250-20036