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BRIDGE DECK CRACKING

Introduction

Cracking in bridge decks has been a main concern of bridge designers and owners for decades. Various contributing factors have been identified, but their relationships are not fully understood.

The Minnesota Department of Transportation has collected data during construction of bridges between the dates of approximately July 2005 and present. The data includes construction practices and environmental conditions during construction, and bridge inspection results. To prepare for a larger study to analyze this data, this report examines previous studies for the causative factors of bridge deck cracking, a Transportation Research Synthesis (TRS). This TRS has two parts: first to review the causative factors of bridge deck cracking identified by others, and second, a review of completed research projects that used statistical methods to evaluate construction problems. As the basis for the TRS, the Mn/DOT library conducted two literature searches and provided the results to American Engineering Testing, Inc. These results were reviewed and several of the documents chosen for additional review.

Causes of Bridge Deck Cracking

Previous research indicates that the development of cracking in newly constructed bridge decks continues to be a nationwide problem.

The literature search by the Mn/DOT library came back with 53 results of completed research sources. Twelve articles/research reports were chosen that appeared to pertain to the topic and were published within the last 12 years. Many of these reports started with a literature search and used the information gained to follow up with their own data analysis, field studies, finite element simulations, and recommendations for further research.

Bridge deck cracks occur when the concrete deck changes in volume but is restrained from movement. The amount of volume change in the concrete is dependent on the properties and properties and proportions of the cementitious materials, aggregate and admixtures, along with environmental conditions such as ambient temperature changes and humidity. Causative factors of volume change in concrete have been found to be drying shrinking, autogenous shrinkage, plastic shrinkage, thermal shrinking, and creep. Of the factors affecting the volume change, drying shrinking and thermal shrinkage are considered by many studies to be the major cause of concrete deck cracking.

The basic cause of drying shrinkage cracking is a reduction in volume of the concrete due to water loss as the concrete dries. Drying shrinkage cracks are relatively large in scale and will propagate around the coarse aggregate in a sub-vertical orientation. The width of the crack usually will lessen with depth, often penetrating the full depth of the member.

Thermal shrinkage occurs during cooling of the concrete after initial hydration. The peak temperature of curing concrete is usually reached about 12 to 18 hours after pouring the deck. At this time the concrete starts to harden and cools down and shrinks. The longitudinal girders restrain this shrinkage and tensile stresses develop and result in cracking.

Deck restraint by the girder against its volume change provides a condition for cracking. However the relative effect of the different factors on the restraint of the composite system is not fully understood yet. Very little, if any, effort has been made to change the design parameters to reduce the restraint of deck girder systems.

Construction practices, such as curing procedures, pouring sequence, and form type can also affect deck cracking. Although construction methods may increase of decrease the risk of cracking, cracking has been observed on decks built with different construction techniques. Therefore, deck cracking cannot be solely attributed to a certain construction technique.

The following causative factors were identified as relevant to a larger research project:

1. Materials and mix design
    a. Cement type and content, W/C ratio

       The type of cement influences the heat of hydration (thermal shrinkage) and drying shrinkage. Type II cement has been found to reduce thermal stresses therefore, cracking. Type K cement has shrinkage compensating characteristics. Studies also show more cracking with higher amounts of cement in the mix. Reducing the water cement ratio of concrete is believed to reduce shrinkage. As the water content in the concrete increases, shrinkage potential also increases and the greater the volume change. (1 - 5, 6, 8 - 12)

    b. Air content/entrainment

       Increases in air content can decrease the amount of drying shrinkage. Increased air content increases the workability of fresh concrete but must be balanced with the loss of compressive strength. Higher air content has less effect on flexural strength. (1, 4, 6, 8 - 12)

    c. Aggregate type, size, and volume

       The type, size, and content of the aggregates influence shrinkage and absorption (water content). Aggregates with low coefficients of thermal expansion, such as limestone and basalt, can also decrease the amount of cracking. Concrete mixes with good quality, clean, low shrinkage aggregate with high aggregate to past ratio have been observed to perform better. (1, 5 - 12)

d. Admixtures, fly ash, etc.
Fly ash, natural pozzolans, and ground slag can be used to reduce the rate of hydration of the cement past, decreasing early strength, time of set, and temperature rise. The added effects can be lowered permeability and improved resistance to sulfate and chemicals. Water reducers can decrease the amount of drying shrinkage by reducing the amount of water needed for the same workability. Shrinkage reducing admixtures (SRAs) reduce drying shrinkage, but can cause scaling after several freeze-thaw cycles. They have also been found to reduce the efficiency of some air entrainment agents. The use of retarders in the concrete mix delays the hydration process and may be an advantage or disadvantage depending on the ambient temperature at the time of peak hydration temperature. (1, 2, 4 - 6, 8 - 12)

2. Construction practices and ambient conditions

a. Air temperature, relative humidity, precipitation, solar radiation, wind speed
These affect the amount of evaporation, initial hydration temperatures and long term thermal stresses. Thermal stresses developed at an early age in the concrete deck depend greatly on concrete temperature and weather conditions. Plastic shrinkage, which is less often the cause of problems, can be detrimental when there are conditions of low humidity and high wind speed. Plastic shrinkage cracks appear when the surface evaporation rates exceed the rate at which bleeding water rises to the concrete surface. (1, 2, 4 - 12)

b. Curing
Curing has a pronounced effect on the properties of hardened concrete such as durability and strength. Adequate and timely curing is a key factor in reducing shrinkage cracking. The importance of curing is emphasized by most studies. Proper curing is especially important in mixes containing fly ash. One study discusses the feasibility of inclusion of concrete hydration temperature in the specifications as it is measurable and, with certain limitations (cement mill properties), is within the control of the contractor by the concrete mix design and curing. (1 - 4, 6 - 12)

c. Deck construction sequence
Flexural stresses can occur from deflections in the formwork. The Virginia study (2) and New Jersey study (11) recommend a specified pouring sequence.

d. Restraint of the deck is integral to the cracking in concrete decks. Creep reduces the tensile stresses that develop from the restraint of shrinkage and thermal effects and thus reduces the amount of transverse cracking. The rate at which strain is applied has a larger impact on the extent of deck cracking than the ultimate strain from shrinkage and thermal effects because, given time, creep can mitigate the stresses that develop from the restrained forces. (1)

e. Modulus of Elasticity and Poisson's Ratio
The modulus of elasticity is the linear correlation between stress and strain; therefore, the higher the modulus the less strain the concrete can handle before the stresses surpass the rupture strength and cracking occurs. During the first 3 to 5 hours after the fresh concrete begins to harden, the modulus of elasticity increases faster than the concrete strength. At this time, the concrete is more vulnerable to strain/stress increases. The modulus of elasticity of concrete can be lowered by using aggregate with lower modulus of elasticity and lower compressive strength concrete. Poisson's ratio has little effect on thermal shrinkage stresses; however deck stresses generally increase with increasing Poisson's ratio. (1)

3. Design specifications
   a. Restraint
   The most significant design factor is the restraint of the deck in relation to the girders, parapet, abutment, etc. Girder type can have an effect on the restraint and on the amount of cracking observed. The Virginia study (2) says simply supported girders have less incidence of cracking and multi span continuous composite large steel girder bridges are most susceptible to cracking because of additional restraint. Other studies say bridge decks supported on wide flange and composite steel-plate girders exhibit more cracking. A survey of New Jersey bridges showed a higher percentage of cracked decks for those supported by prestressed concrete girders. (1 - 3, 5, 7 - 9, 11)

   b. Deck thickness
   The thinner deck has a higher surface area to volume ratio resulting in higher drying shrinkage and higher thermal changes. A thicker deck has non-uniform stresses from bottom to top. The states of the Central North East Region (Illinois, Minnesota, New York, Pennsylvania, and Wisconsin) generally use 8 or 9 inch thickness for bridge decks. (1, 8, 9, 11)

   c. Reinforcing bar alignment
   A weakened cross section can occur if the top and bottom reinforcing bars are aligned vertically. (1, 8, 9)

<u>Identify Best Practices for Statistical Analysis of Causes of Bridge Deck Cracking</u>

Our review of the literature search did not reveal any statistical analysis practices relevant to a larger study. Several studies used finite element analysis to model the conditions and predict cracking.

Summary

Based on our review of the referenced documents, the following recommendations have emerged:

- Use Type II Cement, limit cement content to 470 lb/CY, water cement ratio should range between 0.40 and 0.45 (preferable a ratio of 0.40), the water content should be kept below 300 lb/CY, the water and cement content should not exceed 27 percent of the total volume of concrete, and limit the compressive strength to less than 6000 psi unless special curing provisions are followed.

- Specify air content of 6 percent or higher by volume.

- Coarse aggregate content of 1800 to 1850 lb/CY, and use aggregate size up to 1.5 inches.

- Replace 20 percent of the cement by weight with fly ash to control strength growth, limit silica fume to 6 percent by weight of cement (will increase heat of hydration and promote early age cracking if not moist cured immediately after concrete placement), and add between 1 and 2 percent SRA by weight of cement.

- Place the deck when the temperatures are between 45°F and 80°F and when the daily temperature fluctuation is less that 50°F, maintain the girder/deck differential temperature under 22°F for at least 24 hours after the concrete is placed, avoid placement when the evaporation rate is 0.20 lb./ft^2/hr. for normal concrete and 0.10 lb./ft^2/hr. for concrete with w/c of 0.40 or lower, and avoid placements during high winds.

- Apply mist water or an evaporation retarder film immediately after screeding, apply a white-pigmented curing compound uniformly in 2 directions when bleed water diminishes but before the surface dries, protect concrete with a protective barrier, such as wet burlap, curing membranes, vinyl covers, etc. or use AASHTO "Water Method" for minimum of 7 days.

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

Bibliography

1. **Schmeckpeper, E.R. and Lecoultre, S.T.** "Synthesis into the Causes of Concrete Bridge Deck Cracking and Observation on the Initial Use of the High Performance Concrete in the US 95 Bridge over the South Fork of the Palouse River." Idaho Transportation Department, University of Idaho, 2009.
2. **Sprinkel, M. and McGowan, P.D.** "Transverse Cracking in a Bridge Deck on Rout 15 over the James River in Virginia." 88^{th} Annual Meeting of the Transportation Research Board, 2009.
3. **Fu, G., Feng, J., Dimaria, and Zhuang, Y.** "Bridge Deck Corner Cracking on Skewed Structures." Michigan Department of Transportation: Wayne State University, 2007.
4. **Lucas, D., and Talley, A.** "Successful HPC Brdige Deck Construction: A Contractor's Perspective." 2006 Concrete Bridge Conference: Portland Cement Association, 2006.
5. **Miller, R., Mirmiran, A., Ganesh, P., and Saproo, M.** "Transverse Cracking of High Performance Concrete Bridge Deck after One Season of 6 to 8 Months." Ohio Department of Transportation: University of Cincinnati, 2006.
6. **Kahleghi, B., and Weigel, J.** "High-Performance Concrete Bridge in Washington State." Seventh International Symposium on the Utilization of High Strength/High-Performance Concrete: American Concrete Institute, 2005.
7. **Dekelbah, W., Hendriks, M.A.N., and Witasse, R.** "3-D Finite Element Analysis of Early-Age Bridge Deck Cracking." Seventh International Symposium on the Utilization of High Strength/High-Performance Concrete: American Concrete Institute, 2005.
8. **Hadidi, R. and Saadeghvaziri, M.A.** "Transverse Cracking of Concrete Bridge Decks: State of the Art." *Journal of Bridge Engineering*: American Society of Civic Engineers, 2003.
9. **Hadidi, R., Saadeghvaziri, M.A., and Hsu, C.T.T.** "Practical Tool to Accurately Estimate Tensile Stresses in Concrete Bridge Decks to Control Transverse Cracking." *Practice Periodical on Structural Design and Construction*: American Society of Civil Engineers, 2003.
10. **Aktan Haluk, M., Fu Gongkang, Dekelbab., W. and Attanayaka Upul** "Investigate Causes & Develop Methods to Minimize Early-Age Cracking on Michigan Bridge Decks." Michigan Department of Transportation: Wayne State University, 2003.
11. **Saadeghvaziri, M.A., and Hadidi, R.** "Cause and Control of Transverse Cracking in Concrete Bridge Decks." New Jersey Department of Transportation, Federal Highway Administration: New Jersey Institute of Technology, 2002.
12. **Cope, B.L. and Ramey, G.E.** "Reducing Drying Shrinkage of Bridge-Deck Concrete." *Concrete International*: American Concrete Institute, 2001.

Summaries/synopsis of research results:

TRIS Search Result 1: **Schmeckpeper, E.R. and Lecoultre, S.T.** "Synthesis into the Causes of Concrete Bridge Deck Cracking and Observation on the Initial Use of High Performance Concrete in the US 95 Bridge over the South Fork of the Paulouse River." Idaho Transportation Department, University of Idaho, 2009.

To determine possible reason for the increased cracking, researchers at the University of Idaho performed a literature review of articles, papers, and standard focused on bridge deck cracking. In addition, the deck of a bridge for highway US95 constructed over the South Fork of the Palouse River was instrumented with strain and temperature gauges. This project was the first in the State of Idaho involving the use of High Performance Concrete (HPCO for the bridge deck. The weather and concrete placement procedures were also monitored and material testing was performed on the deck concrete. The deck was placed in two stages; the first stage portion of the deck was constructed using the conventional Idaho mix, while the second state portion was constructed using a high performance concrete mixes.

The results of the monitoring and testing on both stages of the bridge deck were compared to the literature review to determine the cause of cracking in the deck. In addition, the report compares the concrete used in the two bridge decks to determine if the high performance concrete mix provided any improvement with respect to cracking. Finally, the report presents recommendations on how to reduce cracking.

Results from the monitoring and testing of the Stage 1 deck indicated that cracking in the concrete was mostly due to restraint of the deck by the girders and parapet wall. Uplift from skew and high heat of hydration temperatures were the main causes of tensile stress build up in the deck, compounded by the low creep and high modulus of elasticity of the concrete used. Results from the Stage 2 monitoring and testing indicated that cracking in the concrete was also mostly due to restraint of the deck by the girders and parapet wall.

Reducing the cement content, adding fly ash to the mix, decreasing skew, and/or reducing restraint appear to be effective in reducing deck cracking.

TRIS Result 2: **Sprinkel, M., McGowan, P.D., and Modarem, D.** "Transverse Cracking in a Bridge Deck on Route 15 over the James River in Viriginia." 88th Annual Meeting of the Transportation Research Board, 2009.

This paper describes an elevation of the transverse cracking in the deck of a 10-span continuous steel plate girder bridge constructed with two typical Virginia Department of Transportation deck mixtures that contained 19 percent Class F fly ash by weight of cementitious materials. The 1,725.5 ft. long deck was constructed in July 2000, and the cracking was evaluated in May 2006. The evaluation included cracking caused by deck construction sequence, thermal contraction and drying shrinkage of the concrete and live loads.

The study found good agreement between the total width of cracking and the width of cracking caused by AASHTO design live loads. The study concludes that the cracks were caused by the addition of live load induced tensile stress to the stress in the concrete caused by deck construction sequence, thermal contraction, and drying shrinkage. In addition, the crack width caused by the live load was typically maintained and in the earlier placements increased by the presence of stress sin the concrete caused by concrete placement sequence, thermal contraction, and drying shrinkage. The lack of cracks in the vicinity of the joints provides evidence that tensile stress caused by thermal contraction and drying shrinkage was not sufficient to cause cracking. To reduce cracking, the report recommends VDOT should design future continuous steel plate girder composite deck bridges for less than 300 psi live load tensile stress at the surface of the deck and minimize tensile stress in the concrete caused by deck construction sequence, thermal contraction, and drying shrinkage.

TRIS Results 3: **Fu, G., Feng, J., Dimaria, J., and Zhuang, Y.** "Bridge Deck Corner Cracking on Skewed Structures." Michigan Department of Transportation: Wayne State University, 2007.

This study had a focus on corner cracking in cornet decks of skew highway bridges. A survey of state transportation agencies found that deck corner cracking in skew bridges is commonly observed. Deck inspection for bridges in Michigan was also performed in this study. Cracking intensity in these decks was viewed as an effect of several possible causal factors, which was collected form 40 bridge decks, agreeable causal relations. Two skew decks were instrumented using temperature and stain sensors for the concrete and the ambient environment. Concrete deck's temperature and strain response was collected to thermal-, shrinkage-, and truck-wheel-loads. Test results and thereby calibrated finite element analysis results show that the main cause of skew deck corner cracking is cement concrete's thermal and shrinkage load. Based on current Michigan practice of skew deck design and construction, additional reinforcement in the corner areas is therefore recommended to reduce concrete stresses. Further research is also recommended to develop solutions using optimal combinations of ingredients in concrete and to minimize the constraint between the deck and the supporting superstructure.

TRIS Result 4: **Lucas, D. and Talley, A.** "Successful HPC Bridge Deck Construction: A Contractor's Perspective." 2006 Concrete Bridge Conference: Portland Cement Association, 2006.

High Performance Concrete (HPC) has been implemented in bridge project for several years around the world. However, there is no standard mix design, or a standard way to construct and maintain HPC pavement. The additives and admixtures in HPC cause the concrete to perform differently that a concretes mix of water, cement, and aggregate. As one contractor implemented HPC into steel-reinforced cast-in-place bridge decks, the team faced and met several challenges using the material. Their success using HPC came with several lessons from the perspective of the contractor that can be applied to future implementation of HPC in bridge construction: selecting an appropriate mix, placing and curing the concrete, and maintaining or preparing the concrete.

Based on the experiences described in this paper, the following specific recommendations were made:

- Use the lowest slump possible to maintain workability but minimize uneven curing.
- Place HPC in temperatures as ideal as possible to prevent premature curing.
- Apply curing compound or mats as soon as possible after placement.

HPC presents come opportunities for special handling that might prevent some of the problems unique to the concrete. The contractor learned that it is vital to keep HPC from drying out. Whether this is accomplished by figuring out how to efficiently apply wet curing mats, or by allowing curing compound applications during finishing, the goal is to keep the HPC moist and avoid creating a top layer that cures too quickly.

TRIS Result 5: **Miller, R., Mirmiran, A., Ganesh, P., and Saproo, M.** "Transverse Cracking of High Performance Concrete Bridge Decks after One Season or 6 to 8 Months." Ohio Department of Transportation: University of Cincinnati, 2006.

Cracking is a major problem with newly placed concrete decks. These decks tend to develop full depth, transverse cracks and partial depth longitudinal cracks with a few months of the concrete bring placed. A literature review showed that several other states had experienced similar problems. A review of data from Ohio bridge decks shoed weak correlations between deck cracking and slump, time of year when the deck was placed shrinkage and any of these properties, Data also suggested that using a coarse aggregate with absorption greater than 1% may help mitigate deck cracking but will not always stop it.

As part of this study, three bridge decks were instrumented. One was a standard mix, and the other two were high performance concrete. The standard deck showed only hairline cracking after one year, but transverse cracking is caused by several factors. High heat of hydration caused the plastic concrete to expand. When the concrete sets and cools, tensile stresses develop. Further tensile stresses develop through drying shrinkage, where high heats of hydration cause water evaporation during hydration, and plastic shrinkage may cause more tensile stress.

Recommendations for mitigating cracking included using lower cement contents, addition pozzolans and retarders, using slightly higher water/cement ratios, using larger aggregates, taking steps to limit shrinkage and eliminating restraints.

TRIS Result 6: **Khaleghi, B. and Weigel, J.** "High-Performance Concrete Bridges in Washington State." Seventh International Symposium on the Utilization of High Strength/High[Performance Concrete: American Concrete Institute, 2005.

The durability of concrete is considered the most important factor determining the service life of bridge structures. High performance concrete (HPC) with low permeability is comfortably using HPC as the preferred material in every day prestressed girders and cast-in-place deck slabs. The current use of HPC in prestressed girder results in structurally efficient bridges and greater economy, while improving durability, resistance to cracking, and decreasing the effect of volume changes (due to shrinkage and creep of concrete on prestress losses and camber). HPC is capable of resisting chloride diffusion and other environmental distress that can cause significant deterioration, and costly repairs in bridge decks. HPC's improved mechanical properties make it more resistant to traffic wear and less prone to cracking during construction and under service loads.
A comprehensive review of benefits of using high performance concrete in WSDOT prestressed girders, spliced-girders, and concrete deck slab is presented in the presented in this paper. In regards to concrete deck slabs, the following recommendations are made:

- Reduce cement content to 391 kg/m^3). Consider using fly ash as substitute for cement us to 25% of cement content.
- Consider using lower strength concrete, usually 28MPa (4000 psi), for bridge deck slabs.
- Use Type I and II cement (*in lieu* of Type III) for bridge deck construction to reduce early thermal gradients and shrinkage.
- Limit the water cementitious ration to 0.4. Make use of water reducers to reduce water content.
- Maximize the aggregate content and use the largest possible aggregate size.
- Use 6% air-entrainment to improve the workability of fresh concrete and to increase the freeze-thaw resistance of hardened concrete.
- Specify extended wet curing with two coats of curing compounds and heavy quilted blankets or burlap for 14 days to achieve a superior concrete deck slab.

TRIS Result 7: **Dekelbab, W., Hendricks, M.A.N., and Witasse, R.** "3-D Finite Element Analysis of Early-Age Bridge Deck Cracking." Seventh International Symposium on the Utilization of High Strength/High-Performance Concrete: American Concrete Institute, 2005.

Early age deck cracking is the single most prevalent distress on bridges reported by all of the state DOTs. Although there have been many studies performed with regard to the cause of early-age deck cracking, the problem still exists. The early-age deck cracking due to restraint thermal stresses can be predicted using the 3-D finite element program DIANA. It simulates hydration of young concrete, shrinkage, and cracks due to the environmental conditions during the construction period and the restraint of the girders and adjacent structural elements. The analysis covers two stages. The first stag covers the construction period before the bridge is opened to traffic. The second stage starts after removing the formwork including just the bridge self-weight. Simulation results including time and crack initiation enable the understanding of cracking mechanisms in young concrete as a first step to avid early-age bridge deck cracking.

TRIS Result 8: **Hadidi, R. and Saadeghvaziri, M.A.** "Transverse Cracking of Concrete Bridge Decks: State of the Art." *Journal of Bridge Engineering*: American Society of Civil Engineer, 2005.

This state-of-the-art paper presents the results of a comprehensive literature review of the cause of transverse deck cracking. It includes compilation of experimental and analytical research results as well as survey studies on the effects of different factors on concrete deck cracking. Consistent with the past work on the subject, causes of transverse deck cracking are classified under three categories, namely: 1) material and mix design, 2) construction practices and ambient condition factors, and 3) structural design factors. The literature review revealed that the first two items have been studied extensively over the past several decades, while literature is limited on the effect of structural design factors on deck cracking. This paper evaluates the existing work in depth and presents recommendations on mix design and construction procedures to reduce the potential for transverse deck cracking. Furthermore, areas for additional research are identified.

TRIS Result 9: **Hadidi, R., Saadeghvaziri, M.A., and Hsu, C.T.T.** "Practical Tool to Accurately Estimate Tensile Stresses in Concrete Bridge Decks to Control Transverse Cracking." Practice Periodical on Structural Design and Construction: American Society of Civil Engineers, 2003.

This paper describes a simple method to estimate tensile stresses due to early age time dependent loadings in concrete bridge decks with full composite action between the deck and girder. These stresses can cause transverse deck cracking if they exceed the modulus of rupture for concrete, and need to be checked. A system of equations for a pin-roller supported composite girder is developed to estimate the deck stresses due to the volume change in concrete caused by shrinkage and/or other effects. These equations are further extended to consider different boundary conditions. The results of this method agree very well with the results of finite-element analyses. It is proposed that this practical method be used as a tool during bridge design to examine concrete bridge deck stresses against the possibility of transverse cracking. A Microsoft Windows application that is easy to use is developed and presented. Furthermore, an overview of factors causing the volume change in bridge deck concrete and their typical magnitude is presented herein to further simplify the use of the use of this practical method.

TRIS Result 10: **Aktan Haluk, M. Fu Gongkang, Dekelbag, W., and Attanyaka, Upul** "Investigate Cause & Develop Methods to minimize Early-Age Cracking on Michigan Bridge Decks." Michigan Department of Transportation: Wayne State University, 2003.
The research identified the major parameters influencing the concrete transverse deck cracking and made recommendations to modify these parameters in order to minimize deck cracking. The synthesis of the date collected revealed that the tensile stress due to early-age thermal load along could cause deck cracking. Volume change of concrete due to temperature and shrinkage occurs simultaneously. An increase in drying shrinkage arising from delays in concrete placement and wet curing also affect the deck cracking. Additionally, drying shrinkage beyond the very early ages increases the crack widths that have previously formed due to thermal loads. Concrete parameters influencing the thermal load levels are; cement type, content, and fineness, ambient temperature at the time of concrete placement, and the time of inception of curing. An important recommendation of this study is the implementation of measures to control and manage thermal and shrinkage stresses in reinforced concrete decks. The first conclusion is related to current practice. If the curing related stipulations of the Michigan Department of Transportation – Standard Specifications for Construction is strictly adhere to, the density of transverse deck cracks will be reduce. This research established that approximately a 12˚C (20˚F) of thermal load initiates deck cracking. Second, in order to reduce transverse cracking, the primary recommendation is to develop and optimize project specific mix design for the minimization of thermal load. Additional recommendations include the reduction and/or substitution of cement with mineral admixtures and use or current and forecast weather data in optimizing the mix design and placement time in order to minimize the thermal loads.

TRIS Result 11: **Saadeghvaziri, M.A. and Hadidi, R.** “Cause and Control of Transverse Cracking in Concrete Bridge Decks.” New Jersey Department of Transportation, Federal Highway Administration: New Jersey Institute of Technology, 2002.

Many concrete bridge decks develop transverse racking and most of these cracks develop at early ages, some right after construction, and some after the bridge has been opened to traffic for a period of time. Transverse cracks usually occur when concrete is set and widen with time. These cracks have been observed in most geographical locations, and on many superstructure types. It is estimated that more than 1,000,000 bridges in the United States develop early transverse cracks. These cracks are typically full depth location 1 to 3 m (4 to 12 ft.) apart along the length of the span and are usually observed over transverse reinforcement. It has been reported that predominate form of deck cracking is transverse cracking. These cracks reduce the services life of the structure and increase maintenance costs, which is of paramount importance in highway maintenance activities. Transverse cracks accelerate reinforcement corrosion, especially in regions where deicing chemical are applied. Corrosion damage has been observed eve on epoxy coated reinforcing bars. Freeze-thaw cycles of water in cracks and leakage of water to supporting structures may also reduce service life of structures.

Cracks in concrete occur when a restraint mass of concrete tends to change volume. Volume change in concrete depends on the properties of its constituents and their proportions as well as environmental conditions such as ambient temperature changes and humidity. Restraint, which is basically due to composite action of deck and girder, depends on design characteristics of bridge (i.e., structural design factors). Construction techniques also contribute to volume change and/or degree of restraint of concrete mass.

Factors associated with mix design/material and construction procedures have been the subject of a significant number of research studies over the past several decades. Structural design factors, however, have not been the subject of much research in the past and they were the main thrust of this research study. Using 2-D and 3-D linear and nonlinear finite element models many design factors such as girder stiffness, deck thickness, girder spacing, and relative stiffness of deck to existing literature as well as survey of 24 bridges in the state of New Jersey. Results of each research task are presented and discussed in detail. Furthermore, based on analytical results and literature review effect of various factors are quantified and specific recommendations for possible consideration in design are made. These are classified under the three major categories, namely: 1) materials and mix design, 2) construction practice and ambient condition factors, and 3) structural design. A simple Window application program to more accurately estimate deck stresses during design is also developed under this study. Future research needs are also identified.

TRIS Result 12: Cope, B.L. and Ramey, G.E. “Reducing Drying Shrinkage of Bridge-Deck Concrete.” *Concrete International*: American Concrete Institute, 2001.

Because shrinkage-compensating concrete (SCC) has been found to substantially reduced shrinkage and thus shrinkage cracking, Alabama Department of Transportation supported a study using SCC and shrinkage reducing admixtures (SRA). Laboratory tests of fresh and hardened concrete were performed for four mixtures. ALDOT was particularly interested in the long-term strength, shrinkage cracking and durability properties of the mixtures for use in bridge decks. The study compares ALDOT Standard mix to a mix using type-K cement (SCC-K), with a mix using SSC-K and microsilica, and with the Standard mix with 1.5% shrinkage-reducing admixture. The results of the study indicated the SCC-K mixture proved to be effective in reducing drying shrinkage when exposed to wet curing conditions. The study recommended that further study be done on full-scale bridge decks.