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RESEARCH PROGRAMS

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BRIDGE DECK CRACKING EVALUATION

https://www.mdt.mt.gov/research/projects/const/deckcracking.aspx

Introduction

Montana Department of Transportation (MDT) commissioned Wiss, Janney, Elstner Associates (WJE) in 2016 to investigate the cause(s) of transverse cracking on concrete bridge decks in Montana and provide recommendations on mitigation. WJE's investigation and research consisted of a document review, field investigations, laboratory evaluations, and simple analytical modeling of bridge decks.

As reported by WJE on April 21, 2017[1], the most prominent cracking feature observed during WJE's field investigation were closely spaced through-thickness, transverse cracks, which subsequent laboratory testing and analytical studies indicated that they initiated at very early ages primarily due to thermal changes and associated gradients within the bridge deck.

WJE provided recommendations to concrete mix designs, construction practices, and design considerations with the intent of reducing early-age transverse cracking.

Since implementation of the recommendations, MDT personnel reported a notable decrease in early-age transverse cracking due to these changes, but MDT then observed later age development of transverse cracks in some of their bridge decks. Therefore, WJE was further commissioned to perform additional investigations to further assess the benefits of the previous recommendations and to take a focused look at the later-age development of transverse cracking.

WJE implemented a multi-disciplinary approach including literature review, field inspections, bridge deck instrumentation, laboratory evaluations, and finite element modeling.

What We Did

The first step in this research plan was to perform a detailed literature review incorporating the most recent research on transverse bridge deck cracking with a focus on other DOT's research. The literature review was concentrated on the cause(s) and mitigation of transverse bridge deck cracking.

Detailed inspections were performed on a total of 14 recently constructed bridge decks in Montana to quantify the type, amount, location, and extent of transverse cracking on the decks.

Cracking frequency and cracking severity (crack width times crack length per area) were calculated for each deck and analyzed for any trends relative to deck placement time (month), ambient and concrete temperatures, deck thickness, mix designs, bridge bearing type, span length, span bearing type, placement location, and placement length.

One concrete bridge deck was selected (Rarus/Silver Bow Creek Structure, Bridge D, located in Butte) to install instrumentation to monitor internal concrete temperatures, relative humidity, and strains at four separate locations.

At each location, WJE embedded five thermocouples and three relative humidity probes at varying depths of the deck to obtain the temperature and relative humidity profiles. WJE also embedded three vibrating wire strain gages (VWSGs) at each location; one near the top and bottom surfaces and one at mid-depth. Ambient conditions were also monitored including temperature, relative humidity, wind speed, and solar radiation.

After deck concrete placement, data from each gage was collected every 5 minutes with accessing and downloading of the data performed via wireless modem with cloud-based storage. The installed instrumentation system was, and currently still is, powdered by solar panels connected to rechargeable batteries. As of the date of this summary report, all installed gages are still being recorded, and the instrumentation has been in-place for a period of 24 months.

The goal of the instrumentation was to better understand the impact of environmental changes on the internal deck temperatures, relative humidity and strains. The data collected from the instrumentation was also used to validate finite element modeling of this deck replacement.

Nonlinear finite element (FE) simulations were conducted to help gain further insight into the effect of environmental factors and material properties on concrete deck stresses that lead to transverse deck cracking and to further refine previous WJE crack-mitigation recommendations.

To investigate the deck performance, a three-dimensional (3D) finite element model of Rarus/Silver Bow Creek, Bridge D, was constructed and analyzed in the general-purpose FE program Abaqus v2020. The finite element modeling effort was divided into two broad categories: (1) those related to the early-age concrete deck (short-term) performance and (2) those corresponding to aged concrete typically after 90 days of placement (long-term).

The objective of the FE modeling was to identify the factors that have the greatest impact on the maximum tensile stresses within the concrete deck at early or later ages that pose the greatest risk to cause transverse cracking.

What We Found

Bridge Deck Cracking Inspections

- Cracking appears to be less severe in decks with greater deck thicknesses, consistent with WJE's literature review, previous investigation findings, and finite element modeling.
- Differences in cracking condition (severity) between spans and placements within the same bridge were observed; however, the trends were not consistent on every bridge deck.
- The following factors did not yield any consistent trends in the development of transverse cracking severity: bridge bearing type, span length, span bearing type, placement location, and placement length.
- The placement of concrete during the winter months, actively heated from the top, is likely a contributing factor to transverse cracking severity.
- Based on observations from both the deck topside and underside, it appears that the majority of transverse cracks are through the deck thickness.
- GPR surveys at transverse crack locations on the topside of the bridge decks indicate that the transverse cracks were generally in line with the transverse (topmost) deck reinforcement.

Field Instrumentation and Monitoring

- The instrumented bridge deck showed no indication of cracking (sudden change in strain) based on the installed strain gages. This is consistent with the field inspection performed by WJE that showed minimal transverse cracking (or any cracking) on the underside of this deck with no cracking observed to be near any of the installed gages.
- Compressive strains developed in the deck immediately after removal of the winter curing procedures (insulation and underside heating), and the steel girders cooled relative to the deck. For this bridge, this early age compression provided benefits to negate net tensile stresses in the deck that developed during the summer. Over the summer months, the compressive strains dissipated with the warmer temperatures, girder

expansion, deck temperature gradients, concrete moisture gradients, and drying of the deck concrete, but with the top of the deck eventually developing only small tensile strains that were insufficient to cause cracking.

- Large daily ambient temperature changes were observed with associated temperature gradients within the deck, with changes being most pronounced during the summer and early fall months. As an extreme example, daily ambient temperature increases and decreases of 55 to 60°F were observed. More commonly, the ambient temperature variations during the summer and fall months were between 35 to 45°F with diurnal variations in the winter and spring being less.
- Large daily ambient relative humidity changes were also observed, particularly in the spring and summer months, with associated large relative humidity changes and gradients within the deck concrete. For example, in the summer of 2020, the ambient relative humidity increased from approximately 20% to 100% within a 24-hour period, creating a gradient, from top surface to bottom surface of the deck concrete, of approximately 25 to 30%.

Finite Element Modeling

- Stresses in the concrete deck due to restrained thermal gradients, moisture gradients and drying shrinkage are nonlinear across the depth of deck.
- The FE simulations showed that the tensile stresses developed due to restraint of normal drying shrinkage of the concrete deck alone can be as high as 300 psi but manifest over many months.
- At the warmest time of a summer day, there can exist a nonlinear temperature gradient of 50°F (27˚C) between the top and bottom of the concrete deck. Such a thermal gradient can create tensile stress of 200 psi in magnitude near the top surface of the deck.
- The analysis of stresses due to large ambient temperature swings show that with an ambient temperature drop of 55°F (30°C) (the maximum daily ambient temperature change recorded with the field instrumentation) an increase in net tensile stress magnitude was predicted to be 250 to 300 psi in the bottom of the deck.
- The stress analysis of nonuniform moisture gradients suggested that there can exist a significant relative humidity gradient throughout the deck due to large ambient relative humidity changes that can lead to higher relative humidity at the top surface causing elevated tensile stresses at the bottom of the deck. Due to the moisture gradient alone, tensile stresses as high as 250 to 300 psi were predicted to develop at the lower depths of the concrete deck.
- FE analysis of the combined moisture and temperature gradient showed that the effect of these two phenomena can be additive or subtractive, and the interactions and timing are complex and not currently fully understood. Note that concrete tensile strength of the bridge deck concrete is likely higher than the tensile stress caused by any one factor, but that a combination of factors; such as long-term drying and cyclic temperature and relative humidity changes, can cause cracking.
- The early-age simulation results for the summer deck placement showed that application of insulation just after peak hydration temperature (WJE's previous recommendation) can effectively keep the tensile stresses low when compared to the case with no insulation.
- In general, the early-age stress analysis of the winter placements with heating enclosure from the bottom of the deck showed a better performance in terms of limiting the development of tensile stresses.
- On the contrary, in cold-weather placement, the application of a heating source only from the top increases the tensile stresses and risk of cracking.

References

[1]Krauss, P., Nadelman (Wagner), E., and Nelson, T., *Investigation of Bridge Decks*, MDT, 2017.

What The Researchers Recommend

This current research project has improved understanding of the volumetric movement of the concrete decks in Montana and associated superstructures at early- and late-ages; such that, general curing recommendations can be refined for different seasons of construction.

The findings of this current study suggest that diurnal and seasonal changes in ambient temperature and humidity in the alpine regions of Montana may be unique and provide sufficient strain within decks to cause transverse cracking at later ages. This finding may be applicable nationally but is especially significant to alpine decks in Montana, since daily fluctuations in temperature and humidity are some of the highest in the nation (see Figure 1 and Figure 2).

Based on these findings, WJE's recommendations focused on the reduction in drying shrinkage potential and the reduction of thermal and moisture gradients:

Concrete Proportioning Recommendations

1. Maintain total cementitious content below 600 pounds per cubic yard (lb/yd³) and ideally below 550 lb/yd³ with water to cementitious ratios (w/cm) between 0.40 to 0.45. Limit silica fume to a 5% maximum replacement rate. The use of supplementary cementitious materials (SCMs) is recommended, with fly ash and slag cement being the preferrable SCMs.
2. Consider the use, practicality, and cost benefit of shrinkage reducing admixtures (SRAs) in concrete bridge decks mixes.

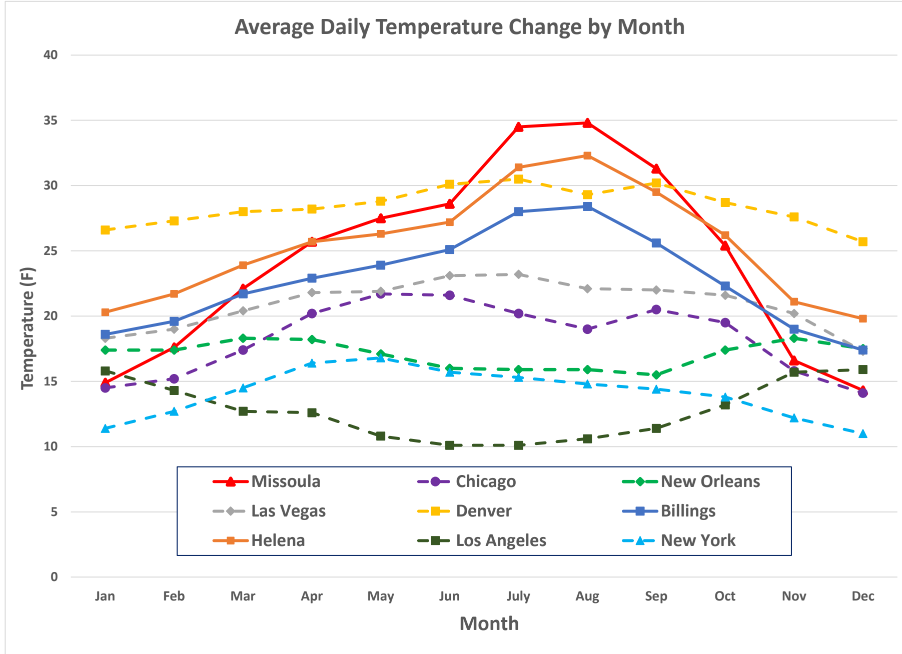

Figure 1: Average daily changes in ambient relative humidity by month for cities in the US.

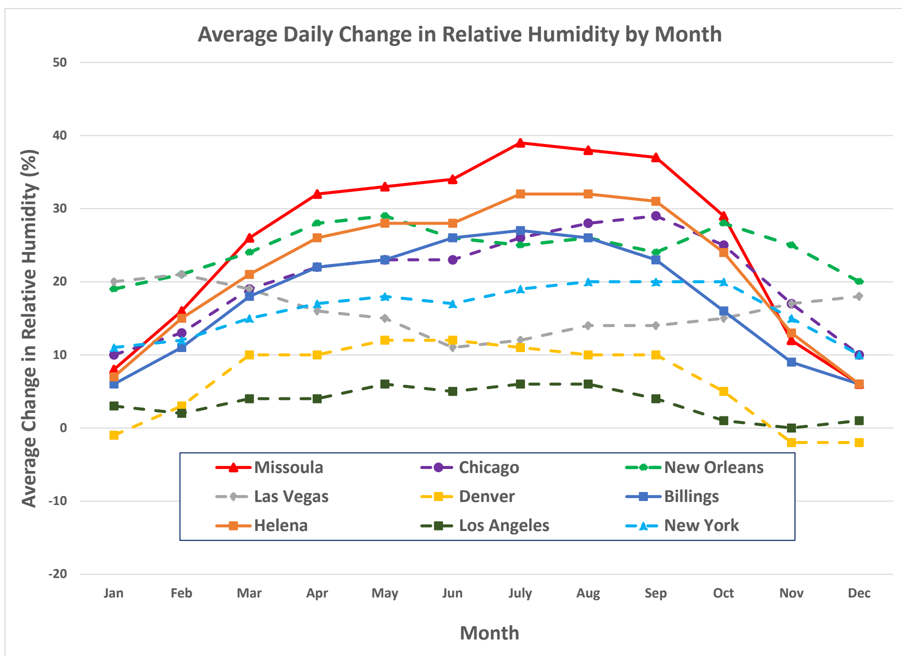

Figure 2: Average daily changes in ambient relative humidity by month for cities in the US.

3. Optimized aggregate gradations are recommended to ensure that the mixes maintain cohesiveness, workability, and constructability with the recommended paste reductions.
4. The use of lightweight aggregates (LWAs), as a replacement of a percentage of the fine aggregate, may provide benefit in reducing deck cracking but more research is needed to assess applicability to Montana and long-term durability.

Design Recommendations

5. Top Side of the Deck: Application of polymer overlays on the top side of the deck, preferably prior to the first mid-summer heat, may be beneficial to reduce the risk of cracking. Polymer overlays have a low moisture permeability to both moisture vapor and liquid transport, which will reduce the daily impact of the ambient relative humidity fluctuations and the rain events.
6. Bottom Side of Deck: The largest variations in humidity and resultant stress can occur along the bottom of the deck. Recommended options that seal the bottom surface of the deck and mitigate the moisture changes from the bottom of the deck should reduce cracking risk. These might include sealing of the bottom side with a barrier coating or using stay-in-place forms.
7. A minimum deck thickness of 8 inches is recommended.

Curing Recommendations

Summer Curing

8. WJE's previous recommendations (WJE Report from 2017) of early age curing are still recommended. WJE also recommends removal of insulation blankets late afternoon or early evening (not in the morning) to provide added benefit of deck compression during nighttime cooling of the girders. If concrete mixtures contain slag cement, fly ash, and/or silica fume continued wet curing for 14 days.

Winter Curing

9. Heating from the bottom of the bridge deck is recommended as opposed to heating from the top as bottom side heating ultimately reduces tensile stresses in the deck while top side heating increases deck tensile stresses.
10. If top side heating is the only option for winter placements, recommend a maximum temperature gradient of the deck of 25°F, which should be monitored by the contractor during curing and during curing material removal.
11. At the end of the wet-curing period, it is also recommended that the heat and insulation be slowly removed instead of complete removal all at once.

Recommendations on Future Research

12. Further research is needed to optimize curing recommendations based on actual deck designs, early- and late-age concrete properties, and anticipated construction and environmental conditions for a particular project. Generalized recommendations or guidelines or specific calculators might be developed.
13. Concrete mix and curing optimization using Montana aggregates; commonly available cements and cementitious material combinations; the use of SRAs; and varying moist cure times would be recommended as part of future research. The goal is to determine optimized mixture proportions, including aggregate gradations, SCM replacement rates, chemical admixtures, and curing durations to reduce cracking tendencies of concrete mix designs. Also, evaluate feasibility of lightweight aggregate substitution.
14. Evaluate options to reduce differential thermal movements of bridge superstructures by modeling. Examples included alternate steel compositions, increased thermal coefficient of the concrete, or girder insulation.
15. Evaluate options to reduce the effect of alpine humidity fluctuations on deck cracking by laboratory testing and modeling. Consider effects of sealing the top and bottom surfaces or installation of stay-in-place forms.
16. Research innovative means to add precompression into the deck. For example, heating the steel girders during concrete placement may be effective.

For More Details . . .

The research is documented in Report FHWA/MT-21-005/9696-700, https://www.mdt.mt.gov/research/projects/const/deckcracking.aspx.

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MDT Implementation Status: January 2022

Implementation will be documented in the Implementation Planning and documentation form for this project as per the implementation report, which can be found at the above URL.