Control of Cracking in Bridge Decks

JoAnn Browning, David Darwin
Will Lindquist, Heather McLeod, Miriam Toledo, Jiqiu Yuan
University of Kansas

NESMEA Conference
October 10, 2006
Newark, Delaware
Research supported by:

- 15 State DOTs: Delaware, Kansas, Idaho, Indiana, Michigan, Minnesota, Mississippi, Missouri, Montana, New Hampshire, North Dakota, Oklahoma, South Dakota, Texas, Wyoming
- FHWA
- Lead state – Kansas
Outline

- Background
- Experiences
- Laboratory work
Background
Project Scope

20 Low-Cracking High Performance Concrete (LC-HPC) Bridges

So far –

13 planned for Kansas
2 planned for South Dakota
1 planned for Missouri
1 planned for Minnesota
Selection of Bridges

Composite steel girder bridges
Full-depth slabs
Removable forms
Matching bridges to serve as a control where possible
Background

Why we use LC-HPC

Specifications for LC-HPC decks
Chloride Content, kg/m³

- Conventional Overlay
- 5% Silica Fume Overlay
- 7% Silica Fume Overlay
- Monolithic

Age, months

76 mm (3 in.)
On cracks 76 mm (3 in.)

Chloride Content, kg/m³

Age, months

Conventional Overlay
5% Silica Fume Overlay
7% Silica Fume Overlay
Monolithic
Linear (20%)
Linear (All)

0 24 48 72 96 120 144 168 192 216 240
Crack Surveys

Composite steel girder bridges
3 deck types
  Monolithic
  Conventional Overlay
  Silica Fume Overlay
3 studies – over 11 years
76 bridges
160 individual concrete placements
139 surveys
Factors

- Age
- Bridge Deck Type
- Material Effects
- Site Conditions - Temperature
- Date of Construction
Age
Bridge Age, months

Crack Density, m/m²

Monolithic
Bridge Deck Type

Monolithic
Conventional Overlay
Silica Fume Overlay

Overlay decks evaluated based on the properties of the subdeck
Crack Density, m/m²

<table>
<thead>
<tr>
<th>Bridge Deck Type</th>
<th>Number of Bridges</th>
<th>Number of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>7% SFO</td>
<td>(9)</td>
<td>(9)</td>
</tr>
<tr>
<td>5% SFO</td>
<td>(18)</td>
<td>(36)</td>
</tr>
<tr>
<td>CO</td>
<td>(30)</td>
<td>(52)</td>
</tr>
<tr>
<td>MONO</td>
<td>(16)</td>
<td>(32)</td>
</tr>
</tbody>
</table>
Material Effects

Concrete Mixture Proportions
  Water content
  Cement content
  Volume of cement paste
Slump
Compressive Strength
Air content
Water content
Crack Density, m/m²

Water Content, kg/m³ (lb/yd³)

Number of Placements

Number of Surveys

Age Corrected

Number of Placements

Number of Surveys

(15)  (13)  (5)

(29)  (26)  (11)

Monolithic
Cement content
Crack Density, m/m²

Cement Content, kg/m³ (lb/yd³)

Number of Bridges

Number of Observations

<table>
<thead>
<tr>
<th></th>
<th>358 (603)</th>
<th>379 (639)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Content</td>
<td>0.18</td>
<td>0.69</td>
</tr>
<tr>
<td>Number of Bridges</td>
<td>(24)</td>
<td>(8)</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>(47)</td>
<td>(16)</td>
</tr>
</tbody>
</table>
Volume of cement paste
Monolithic

![Bar graph showing crack density and percent volume of water and cement.]

- Crack Density, m/m²
- Percent Volume of Water and Cement, %
- Age Corrected

<table>
<thead>
<tr>
<th>Year</th>
<th>Crack Density</th>
<th>Number of Placements</th>
<th>Number of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>0.19</td>
<td>(8)</td>
<td>(16)</td>
</tr>
<tr>
<td>27</td>
<td>0.16</td>
<td>(16)</td>
<td>(31)</td>
</tr>
<tr>
<td>28</td>
<td>0.68</td>
<td>(4)</td>
<td>(8)</td>
</tr>
<tr>
<td>29</td>
<td>0.73</td>
<td>(5)</td>
<td>(11)</td>
</tr>
</tbody>
</table>
Slump
Crack Density, m/m²

Age Corrected

- Uncorrected
- Adjusted for Water Content

Slump, mm (in.)

<table>
<thead>
<tr>
<th>Slump</th>
<th>Uncorrected</th>
<th>Adjusted for Water Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>38 (1.5)</td>
<td>0.18</td>
<td>0.11</td>
</tr>
<tr>
<td>51 (2.0)</td>
<td>0.31</td>
<td>0.15</td>
</tr>
<tr>
<td>64 (2.5)</td>
<td>0.51</td>
<td>0.19</td>
</tr>
<tr>
<td>76 (3.0)</td>
<td>0.87</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Number of Placements

- (5)
- (20)
- (5)
- (1)

Number of Surveys

- (10)
- (40)
- (11)
- (3)

Monolithic
Compressive Strength
<table>
<thead>
<tr>
<th>Number of Placements</th>
<th>Crack Density, m/m²</th>
<th>Compressive Strength, MPa (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>31 (4500)</td>
</tr>
<tr>
<td></td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>38 (5500)</td>
</tr>
<tr>
<td></td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45 (6500)</td>
</tr>
<tr>
<td></td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>Number of Surveys</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(13)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(12)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(24)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(10)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(23)</td>
<td></td>
</tr>
</tbody>
</table>
Air content
Crack Density, m/m²

<table>
<thead>
<tr>
<th>Air Content, %</th>
<th>Crack Density</th>
<th>Number of Placements</th>
<th>Number of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>0.37</td>
<td>(7)</td>
<td>(14)</td>
</tr>
<tr>
<td>5.5</td>
<td>0.38</td>
<td>(19)</td>
<td>(40)</td>
</tr>
<tr>
<td>6.5</td>
<td>0.13</td>
<td>(5)</td>
<td>(10)</td>
</tr>
</tbody>
</table>

Monolithic
Maximum Air Temperature, C

Crack Density, m/m²

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Crack Density</th>
<th>Number of Placements</th>
<th>Number of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.19</td>
<td>(4)</td>
<td>(8)</td>
</tr>
<tr>
<td>15</td>
<td>0.33</td>
<td>(15)</td>
<td>(31)</td>
</tr>
<tr>
<td>25</td>
<td>0.37</td>
<td>(9)</td>
<td>(17)</td>
</tr>
<tr>
<td>35</td>
<td>0.44</td>
<td>(4)</td>
<td>(9)</td>
</tr>
</tbody>
</table>

Monolithic
Crack Density, m/m²

<table>
<thead>
<tr>
<th>Daily Temperature Range, °C</th>
<th>Number of Placements</th>
<th>Number of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>(2)</td>
<td>(4)</td>
</tr>
<tr>
<td>12</td>
<td>(20)</td>
<td>(42)</td>
</tr>
<tr>
<td>20</td>
<td>(10)</td>
<td>(19)</td>
</tr>
</tbody>
</table>

Monolithic
Date of Construction
Crack Density, m/m²

Date of Construction

1984-1987

Number of Bridges
(6)

Number of Surveys
(12)

1990-1993

Number of Bridges
(7)

Number of Surveys
(16)

Monolithic
Conventional Overlays

Crack Density, m/m²
Age Corrected

Date of Construction

<table>
<thead>
<tr>
<th>Date</th>
<th>Number of Bridges</th>
<th>Number of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985-1987</td>
<td>(6)</td>
<td>(6)</td>
</tr>
<tr>
<td>1990-1992</td>
<td>(17)</td>
<td>(36)</td>
</tr>
<tr>
<td>1993-1995</td>
<td>(3)</td>
<td>(6)</td>
</tr>
</tbody>
</table>

- 0.24
- 0.53
- 0.81
Silica Fume Overlays

Crack Density, m/m²

<table>
<thead>
<tr>
<th>Date of Construction</th>
<th>Number of Bridges</th>
<th>Number of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990-1991</td>
<td>(2)</td>
<td>(6)</td>
</tr>
<tr>
<td>1995-1996</td>
<td>(10)</td>
<td>(20)</td>
</tr>
<tr>
<td>1997-1998</td>
<td>(8)</td>
<td>(16)</td>
</tr>
<tr>
<td>2000-2002</td>
<td>(10)</td>
<td>(10)</td>
</tr>
</tbody>
</table>
Control of Early Evaporation
Silica Fume Overlays

Crack Density, m/m²

<table>
<thead>
<tr>
<th>Special Provision, (R#)</th>
<th>Number of Bridges</th>
<th>Number of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>NONE</td>
<td>(2)</td>
<td>(6)</td>
</tr>
<tr>
<td>R1, R2</td>
<td>(4)</td>
<td>(8)</td>
</tr>
<tr>
<td>R3</td>
<td>(5)</td>
<td>(10)</td>
</tr>
<tr>
<td>R4, R5, R6</td>
<td>(9)</td>
<td>(18)</td>
</tr>
<tr>
<td>R8, R9</td>
<td>(10)</td>
<td>(10)</td>
</tr>
</tbody>
</table>
Overall Approach

- Low cement & water contents
- Low slump
- High strength is not always good
- Low evaporation rate
- Construction methods and materials matter
- More early cracking means more total cracking
LC-HPC

- 1 inch Max Size Aggregate
- Optimized Aggregate Gradation
- Cement Content < 535 lb/yd³
- Air Content of 8 ±1%
- Max w/c ratio of 0.42
- Improved curing
- Controlled temperature
Thermal Cracking

**Rule of Thumb:** Cracking will result when the temperature of the concrete deck exceeds the temperature of the girders by more than 20° C (36° F).
Thermal Cracking

PennDOT\(^1\) 15° C (27° F)

KDOT 14° C (25° F)

Alternatives to Pumping

- Concrete Buckets
- Conveyor Belts
Consolidation Requirements

Vertically mounted internal gang vibrators
Machine Fogging
Machine Fogging
Supplemented by Hand Fogging
Early Wet Burlap Cure
Curing

- 14 days wet cure with burlap, soaker hoses, and plastic
- Followed by curing compound to slow the rate of evaporation
Qualification Slab

To demonstrate implementation of the specialized process and address problems before bridge deck casting.

- Process
- Contractor
- Ready Mix Plant
- Inspectors

NO SURPRISES
Selection of Contractors

Prequalified
Multiple bridge contracts (to gain from experience)
Experiences
Unless specifically noted, all control bridges are in the same county as LC-HPC bridge.
<table>
<thead>
<tr>
<th>Bridge Groups</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1-2control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3control</td>
<td>4</td>
<td>4control</td>
<td>5control</td>
</tr>
<tr>
<td>6control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7control</td>
<td>8*</td>
<td>8-10control*</td>
<td>9control</td>
</tr>
<tr>
<td>10*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>11control</td>
<td>12</td>
<td>12control</td>
<td>13control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LET Date</strong></td>
<td><strong>Pre-Construction Meeting</strong></td>
<td><strong>Qualification Slab</strong></td>
<td><strong>Cast Deck</strong></td>
<td><strong>1st Crack Survey</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* Prestressed-Girder Bridge</td>
<td></td>
</tr>
</tbody>
</table>
Construction experiences
Qualification slabs

- Contractor learned:
  - Could pump mix
  - Need two bridges to place burlap, pre-fold
  - Fogging could not be used as finishing aid (especially in front of roller)
  - Proper use of gang vibrators
Burlap placement within 10 min and 10 ft of strike off
KsDOT Project Manager: “This proves the value of the trial slab. You can see how much the contractor learned from the beginning to the end of the slab.”
Bridge Placements

- Temperature controlled with ice, place at night in mid-summer
- Pumpable even with 1.5-in. slump
- Finishing delayed at end abutments
- Bullfloating worked well, cannot use fogging as finishing aid
- Perfect art of placing burlap, keeping wet
- Cure barriers same as deck
- Careful of cold-weather curing
Bridge placements

Bridge superintendent observed that he preferred working with optimized concrete with cement content of 540 lb/yd$^3$ to traditional mix with cement content of 602 lb/yd$^3$. 
Bridge 1: November 2005
Cores of deck show that finishing methods leave large coarse aggregate particles close to the upper surface of the deck.
Conclusions - Experiences

- Optimized concrete mixes with relatively low cement (paste) contents are very pumpable, placeable, and finishable.

- Temperature can be controlled using ice.
• Techniques can be learned easily and workers can become proficient in a short period of time

• Bid prices are dropping as contractors become more familiar with the methods involved
Laboratory Work - Briefly
Average Free Shrinkage (Drying Only).  535 lb/yd³ Type I/II Cement
Average Free Shrinkage (Drying Only). 535 lb/yd$^3$ Type I/II Cement $w/cm = 0.42$, 23.26% paste
Class F Fly Ash Replacement

- 40% Class F FA 14-Day Cure
- 20% Class F FA 14-Day Cure
- Control 14-Day Cure

Average Free Shrinkage (Drying Only). \( \text{w/cm} = 0.42, 23.26\% \text{ paste} \)
Average Free Shrinkage (Drying Only). $w/cm = 0.42, 23.26\%$ paste
Summary

Background

Experiences

Laboratory Work – in brief
Questions?
The University of Kansas

JoAnn Browning, Ph.D., P.E.
Associate Professor

Dept. of Civil, Environmental & Architectural Engineering
2142 Learned Hall
Lawrence, Kansas, 66045-7609
(785) 864-3723    Fax: (785) 864-5631

joann@ku.edu
The University of Kansas

David Darwin, Ph.D., P.E.
Deane E. Ackers Distinguished Professor
Director, Structural Engineering & Materials Laboratory

Dept. of Civil, Environmental & Architectural Engineering
2142 Learned Hall
Lawrence, Kansas, 66045-7609
(785) 864-3827    Fax: (785) 864-5631

daved@ku.edu
The University of Kansas

Heather A. K. McLeod, P.E.
Graduate Research Assistant

Dept. of Civil, Environmental & Architectural Engineering
2142 Learned Hall
Lawrence, Kansas, 66045-7609
(785) 864-3853   Fax: (785) 864-5631

hmcleod@ku.edu
Costs

- Qualification Slabs 1 & 2
  - $4205/yd³

- Bridges 1 & 2
  - $1741 & $1698/yd³

- Control Bridge 1 & 2
  - $770/yd³
Costs

- Qualification Slabs 3 – 6
  - $995-$1154/yd³

- Bridges 3 – 6
  - $655-$751/yd³

- Control Bridges 3 – 6
  - $608-$656/yd³
Costs

- Qualification Slab 7
  - $573/yd³
- Bridge 7
  - $623/yd³
- Control Bridge 7
  - $725/yd³
<table>
<thead>
<tr>
<th>Category</th>
<th>Cost Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualification Slab 8-10</td>
<td>$906-956/yd³</td>
</tr>
<tr>
<td>Bridge 8-10</td>
<td>$569-774/yd³</td>
</tr>
<tr>
<td>Control Bridge 8-10</td>
<td>$371/yd³</td>
</tr>
</tbody>
</table>
Costs

- Qualification Slab 12
  - $1070/yd³

- Bridge 12
  - $1275/yd³

- Control Bridge 12
  - $401/yd³
Average Free Shrinkage (Drying Only).  $w/cm = 0.42, 23.26\%$ paste

- SRA and GGBFS
  - Control 14-Day Cure
  - 60% GGBFS (#1) 7-Day Cure
  - 60% GGBFS (#2) 7-Day Cure
  - 60% GGBFS (#1) 14-Day Cure
  - SRA 7-Day Cure
  - 60% GGBFS (#2) 14-Day Cure
  - SRA 14-Day Cure
Free Shrinkage, Microstrain vs. Time, Days for different cement types and curing conditions.
Silica Fume Replacement

- 3% SF 7-Day
- Control 7-Day
- Control 14-Day
- 6% SF 7-Day
- 3% SF 14-Day
- 6% SF 14-Day

Free Shrinkage, Microstrain vs. Time, Days
Class F Fly Ash

Free Shrinkage, Microstrain

<table>
<thead>
<tr>
<th>Time, Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

- **Class F Fly Ash Replacement**
  - 40% Class F FA 7-Day
  - 40% Class F FA 14-Day
  - 20% Class F FA 7-Day
  - 20% Class F FA 14-Day
  - Control 7-Day
  - Control 14-Day
Ground Granulated Blast Furnace Slag

The graph shows the free shrinkage in microstrain over time for various GGBFS (S-2) replacement levels and times. The x-axis represents time in days, ranging from 0 to 180, while the y-axis represents free shrinkage in microstrain, ranging from -50 to 500. The lines on the graph indicate different replacement levels and times, with legend entries for Control 7-Day, Control 14-Day, 60% G120 (S-2) 7-Day, 60% G120 (S-2) 14-Day, 80% G120 (S-2) 7-Day, and 80% G120 (S-2) 14-Day.
Ground Granulated Blast Furnace Slag

Free Shrinkage, Microstrain

Time, Days

GGBFS Replacement
- Control 7-Day
- Control 14-Day
- 60% G120 (S-1) 7-Day
- 60% G120 (S-1) 14-Day
- 60% G120 (S-2) 7-Day
- 60% G120 (S-2) 14-Day
- 60% G100 7-Day
- 60% G100 14-Day

-50 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180

0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180

500 450 400 350 300 250 200 150 100 50 0 -50
Work in Progress

- Ternary Mixtures with Reduced Paste Content
  - CF 273 kg/m³ (460 lb/yd³)
  - 60% - 80% GGBFS
  - 6% Silica Fume

- Aggregate type

- Permeability testing of mineral admixture batches

- Scaling tests for slag mixes