Reducing Cracks in New Bridge Curbs

2019 NESMEA

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Outline

- Background
  - Curb Construction
  - Research Problem
  - Research Goals
- Research Methodology
- Results and Discussion
- Summary and Conclusions
- Recommendations
Background: Research Need

- NHDOT Bureau of Bridge Maintenance (BoBM)

Purpose:
- Supports guardrail
- Provides drainage characteristics to the bridge
- Non-structural

- NHDOT Standard Specifications for Road and Bridge Construction
**Background: Curb Construction**

- Prefer to replace deck and curb at the same time
- Typically replace one side at a time
Background: Curb Construction

- Curb removal
**Background: Curb Construction**

- Reinforcement and formwork installed
  - Guardrail post assemblies installed
  - Additional reinforcement around guardrail posts
**Background: Curb Construction**

- PCC on curbs is typically same as that used on deck (NHDOT AA class)

<table>
<thead>
<tr>
<th>Concrete Class</th>
<th>Minimum Expected 28 Day Compressive Strength (psi)</th>
<th>Maximum Water/Cement Ratio</th>
<th>Percent Entrained Air</th>
<th>Permeability Value (kΩ-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAA</td>
<td>5,000</td>
<td>0.444</td>
<td>5 to 9</td>
<td>20</td>
</tr>
<tr>
<td>AA</td>
<td>4,000</td>
<td>0.444</td>
<td>5 to 9</td>
<td>20</td>
</tr>
<tr>
<td>A</td>
<td>3,000</td>
<td>0.464</td>
<td>4 to 7</td>
<td>10</td>
</tr>
</tbody>
</table>

Adapted from NHDOT Standard Specifications for Road and Bridge Construction 2016
**Background: Curb Construction**

- **Wet Cure**
  - PCC is wet cured 5 to 7 days
  - Curbs are often placed in winter
  - Winter wet cure duration is often shortened
Background: Research Goals

- Develop a cracking index to quantify early-age cracking in curbs
- Use cracking index to document cracking on newly constructed bridge curbs with controls and various remedial variables
- Analyze cracking results and recommend changes to material specifications and construction and maintenance practices
Outline

- Background

- Research Methodology
  - Investigation Procedure
  - Cracking Indices
  - Data Organization
  - Site Variables
  - Investigation Challenges
  - Data Analysis

- Results and Discussion

- Summary and Conclusions

- Recommendations
Research Methodology: Investigation Procedure

- Investigation Process
  1) Pre-visit site research
  2) Site visits
  3) Additional data collection (batch slips, compressive strength etc.)
  4) Post-processing
Research Methodology: Cracking Indices (1/5)

- Length Index (LI)

<table>
<thead>
<tr>
<th>Length Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Partial or limited cracking on one or two faces.</td>
</tr>
<tr>
<td>2</td>
<td>Nearly full cracking along one face with partial cracking along another.</td>
</tr>
<tr>
<td>3</td>
<td>Full cracking along at least two faces or extending from guardrail post to roadway.</td>
</tr>
</tbody>
</table>
Research Methodology: Cracking Indices (2/5)

- Intensity Index (II)
  ACI 224R-01 Table 4.1
  0.007” for Deicing Chemicals
  0.016” Dry Air

<table>
<thead>
<tr>
<th>Intensity Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crack width &lt;0.007”</td>
</tr>
<tr>
<td>2</td>
<td>Crack width ≥ 0.007” but &lt;0.016”</td>
</tr>
<tr>
<td>3</td>
<td>Crack width ≥ 0.016”</td>
</tr>
</tbody>
</table>

[Photos of concrete cracks labeled 1, 2, 3]
Average Uncracked Length (AUL)

\[ AUL = \frac{\text{Curb Length}}{1 + (\# \text{ Cracks})} \]
Research Methodology: Cracking Indices (4/5)

- Severity Index (SI)

\[ SI = \sqrt{(LI) \times (II)} \]

- Curb Cracking Index, CCI

\[ CCI = \frac{\text{Average Uncracked Length}}{\text{Average Severity Index}} \]
Crack Volume

- Crack width and cracked area based on index values
- Determine the estimated volume of each crack
- Determine the total estimated volume of all the cracks on a curb
- Ratio of cracked volume to curbs volume

**Normalized Crack Volume**

\[
\text{Normalized Crack Volume} = \frac{\text{Total Cracked Volume}}{\text{Curb Volume}}
\]
Research Methodology: Data Organization

- Alexandria (174/146) Cracking Maps:

<table>
<thead>
<tr>
<th>Cracking Map - North Curb</th>
<th>AUL</th>
<th>Avg. LI</th>
<th>Avg. II</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 days</td>
<td>8.61 ft</td>
<td>3.00</td>
<td>1.33</td>
</tr>
<tr>
<td>80 days</td>
<td>5.74 ft</td>
<td>2.20</td>
<td>1.80</td>
</tr>
<tr>
<td>175 days</td>
<td>2.65 ft</td>
<td>1.58</td>
<td>1.33</td>
</tr>
<tr>
<td>425 days</td>
<td>2.30 ft</td>
<td>1.79</td>
<td>1.29</td>
</tr>
</tbody>
</table>
Research Methodology: Site Variables

- Bridge curb pairs replaced during the study had a variable applied to one of the curbs.

- Tested variables
  - 14-day wet cure compared to traditional 5 to 7-day wet cure
  - PCC mix, NHDOT A mix compared to NHDOT AA mix
Research Methodology: Data Analysis

1. Graphical comparisons
   – Cracking maps
   – Cracking indices

2. t-tests
   – Statistical significance testing

3. Pearson’s correlation
   – Describes how well the data matches a linear trend
Outline

- Background
- Research Methodology
- Results and Discussion
  - Crack Distribution
  - Bridge Length
  - Location Along Curb
  - Wet Cure Duration
  - PCC Composition
  - Proximity to Guardrail Posts
  - Crack Evolution with Time
- Summary and Conclusions
- Recommendations
Results and Discussion

23 Bridges Surveyed

- Existing Bridge Curbs (red)
  - 17 bridges visited constructed after 2008
  - Survey previous bridges and see if correlations exist

- New Bridge Curbs (green)
  - 8 new bridges
Results and Discussion

- New Bridge Curb Sites and Variables
  1. **Hampton** – No variable
  2. **Alexandria** – 14-day wet cure
  3. **Tamworth** – ‘A’ mix
  4. **Marlborough** – No variable, one curb replaced
  5. **Grantham** – 14-day wet cure
  6. **Westmoreland-1** – ‘A’ mix
  7. **Westmoreland-2** – 14-day wet cure and ‘A’ mix
  8. **Meredith** – 14-day wet cure and ‘A’ mix
## Results and Discussion

### Distribution of Cracks

- 83% are of reasonable width
- Shorter AUL, higher SI

<table>
<thead>
<tr>
<th>Intensity Index</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>525</td>
<td>64</td>
<td>116</td>
<td>705</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>14</td>
<td>100</td>
<td>136</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>547</td>
<td>78</td>
<td>224</td>
<td></td>
</tr>
</tbody>
</table>
Results and Discussion

Bridge Length

- Noticeable change near 40 ft in length
- Around 30-40 ft concrete slab structures are switched to steel I-beams with concrete deck
Results and Discussion

Bridge Length

<table>
<thead>
<tr>
<th>t-test</th>
<th>p-value</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;40 ft &amp; &gt;40 ft</td>
<td>α &lt; 0.05</td>
<td></td>
</tr>
<tr>
<td>Average Length Index</td>
<td>0.119</td>
<td>Not Significant</td>
</tr>
<tr>
<td>Average Intensity Index</td>
<td>0.077</td>
<td>Not Significant</td>
</tr>
<tr>
<td>Average Uncracked Length</td>
<td>0.0004</td>
<td>Significant</td>
</tr>
</tbody>
</table>
Results and Discussion

Bridge Length – Volume Method

![Graph showing the relationship between Bridge Length (ft) and Normalized Crack Volume (E-04)]

- Blue dots represent bridges less than 40 ft.
- Red dots represent bridges greater than 40 ft.

Equation: \( y = 1E-06x - 4E-05 \)

\( R^2 = 0.6247 \)
Results and Discussion

Location Along Curb

- Each crack assigned a value of 0 to 1
  - 0 corresponds to center of curb
  - 1 corresponds to end of curb
- Less cracking at the ends of the curb
- Statistical testing confirms these findings
Results and Discussion

Location Along Curb – Volume Method

![Graph showing crack location along curb](image_url)
Results and Discussion

Wet Cure Duration

- t-tests do not indicate significance (all data)
- Curb pairs indicate 14-day wet cure reduces the amount of cracking compared to 7-day

![Graph showing comparison between Grantham Curbs and Alexandria Curbs with average uncracked length in feet for 7 and 14 days of wet cure duration.]
**Results and Discussion**

**Wet Cure Duration – Volume Method**

![Bar graph showing normalized crack volume at different bridge sites (Alexandria and Grantham) for 7-Day and 14-Day periods.](image-url)
Results and Discussion

Cementitious Materials Content

- Not significant according to t-tests
- Curb pairs indicate lower cementitious content produces curbs with a greater AUL
Results and Discussion

Cementitious Materials Content – Volume Method
Results and Discussion

28-day Compressive Strength

- Curb pairs indicate higher compressive strength leads to shorter AULs

![Graph showing the relationship between 28-day compressive strength and average uncracked length for different curbs.](image)
Results and Discussion

28-day Compressive Strength – Volume Method

![Graph showing normalized crack volume vs. 28-day compressive strength for Hampton, Tamworth, and Grantham curbs]
Results and Discussion

Proximity to Guardrail Posts

![Graph showing the relationship between the percentage of cracks within 1.5 feet of guardrail posts and the percentage of curb within the same area. The graph includes a trendline with the equation y = 0.93x.](image-url)
Results and Discussion

Proximity to Guardrail Posts (Curbs with more than 2 Cracks)

Graph: 100% on y-axis, 0% on x-axis, linear trend with equation y = 0.99x
Results and Discussion

Cracking Over Time: AUL

- Alexandria 174/146 North
- Grantham 140/069 North
- Hampton 207/094 North
- Tamworth 095/162 North
- Westmoreland 111/072 East
- Marlborough 090/127 North
- Alexandria 174/146 South
- Grantham 140/069 South
- Hampton 207/094 South
- Tamworth 095/162 South
- Westmoreland 111/072 West

![Graph showing cracking over time for different locations with days after placement on the x-axis and average uncracked length on the y-axis.](image_url)
Overview

- Background
- Research Methodology
- Results and Discussion
- Summary and Conclusions
- Recommendations
Summary

- 25 Bridges Surveyed: 8 placed during the study
- 2 Variables tested:
  - Wet Cure Duration
  - PCC Mix
- Cracks were assigned two index values (scale: 1 – 3) depending on length and width
- The amount of cracking on a curb was related to the average length between cracks or the curb face to account for variations in curb lengths
- Approximated crack volumes were compared between curbs
## Summary and Conclusion

### Summary of Results

<table>
<thead>
<tr>
<th></th>
<th>Average Uncracked Length (AUL)</th>
<th>Length Index (LI)</th>
<th>Intensity Index (II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge Length</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location on Curb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curing Duration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCC Mix</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water/Cementitious Materials Ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cementitious Content</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-day Compressive Strength</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guardrail Post</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather After Placement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Daily Traffic</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusions (1 of 2)

- 83% of curb cracks are less than the maximum reasonable width as outlined by ACI 224R-01
- Curbs with more cracking tend to have more severe cracking
- Curbs on bridges over 40 ft. in length tend to have more cracking
- Less cracking occurs at the ends of curbs compared to the rest of the curb
Conclusions (2 of 2)

- Curbs with a 7-day wet cure have more cracking as compared to their neighboring curb wet cured for 14-days.
- Curbs placed with a higher cementitious content have more cracking compared to their neighboring curb.
- Curbs with a higher compressive strength have more cracking compared to their neighboring curb.
- Proximity to guardrail post have minimal effect on cracking behavior.
Overview

- Background
- Research Methodology
- Results and Discussion
- Summary and Conclusions

**Recommendations**
- Practice Changes
- Future Research
Recommendations: Practice Changes

- Prioritize maintenance on longer bridges
- Wait one year after placement before sealing problem cracks or make sure to revisit after 1 year
- Increase the wet cure duration from 7-days to 14-days
- Use PCC with a lower cementitious content and lower 28-day compressive strengths
  - Specify NHDOT “A” mix
Recommendations: Future Research

- Refinement of Field Data Analysis
  - Further develop the volume method and determine normalized crack volumes that correspond to curbs in good, fair, and poor condition
  - Revisit the study looking at only cracks with an intensity index of 2 or 3

- Structural Analysis
  - Further investigation of relationship between cracking and bridge length
  - Investigate structural and dynamic aspects of loading on curbs
  - Use of strain gauges in curb reinforcement and concrete maturity measurements
Recommendations: Future Research

- Contraction Joints at Guardrail Posts
Thank you for your attention!

Questions?
Research Methodology: Investigation Challenges

- Cracks are only documented when visible
- Crack expansion and contraction
- Dust, road salt, and polymers in cracks
- Ice and snow
Appendix – Curing Temperature

The graph shows the curing temperature over time for different locations:
- East End of North Curb
- Middle of Curb
- West End of Curb

The temperature is measured in °F and is plotted against date and time from 4/24/2018 to 4/28/2018 at hourly intervals.
Results and Discussion

Curing Temperature
- Indicates curing procedure prevents concrete freezing or becoming too hot at an early age.
Appendix – w/cm
Appendix – w/cm
Appendix – Cementitious Content
Appendix – Compressive Strength

![Graph showing the relationship between 28-Day Compressive Strength (psi) and Average Length Index (for <40 ft and >40 ft categories).](image1)

![Graph showing the relationship between 28-Day Compressive Strength (psi) and Average Intensity Index (for <40 ft and >40 ft categories).](image2)
Appendix – Guardrail Posts

![Graph showing the relationship between the percentage of cracks within 1.5 feet of a guardrail post and the percentage of curb within 1.5 feet of the guardrail post. The graph includes data points for different distances (<40 ft and >40 ft), with linear equations for each category: y = 0.6585x for the linear equation of <40 ft, and y = 1.0358x for the linear equation of >40 ft. The graph also shows an equivalent line for direct comparison.]
### Appendix – Guardrail Posts

<table>
<thead>
<tr>
<th>t-test</th>
<th>p-value ( \alpha &lt; 0.05 )</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Uncracked Length, Bridge Length &lt;40 feet</td>
<td>0.256</td>
<td>Uncracked length near posts does not significantly differ than that of the entire curb.</td>
</tr>
<tr>
<td>Average Uncracked Length, Bridge Length &gt;40 feet</td>
<td>0.691</td>
<td>Uncracked length near posts does not significantly differ than that of the entire curb.</td>
</tr>
<tr>
<td>Average Length Index, Bridge Length &lt;40 feet</td>
<td>0.514</td>
<td>Crack length near posts does not significantly differ than that of the entire curb.</td>
</tr>
<tr>
<td>Average Length Index, Bridge Length &gt;40 feet</td>
<td>0.981</td>
<td>Crack intensity near posts does not significantly differ than that of the entire curb.</td>
</tr>
<tr>
<td>Average Intensity Index, Bridge Length &lt;40 feet</td>
<td>0.72</td>
<td>Crack intensity near posts does not significantly differ than that of the entire curb.</td>
</tr>
<tr>
<td>Average Intensity Index, Bridge Length &gt;40 feet</td>
<td>0.934</td>
<td>Crack intensity near posts does not significantly differ than that of the entire curb.</td>
</tr>
</tbody>
</table>
## Appendix – Weather After Placement

### Graph

- **x-axis:** Average Low Temperature for the Week After Placement, °F
- **y-axis:** Average Uncracked Length, ft
- **Data Points:**
  - <40 ft
  - >40 ft

### Table

<table>
<thead>
<tr>
<th>t-test</th>
<th>p-value α &lt; 0.05</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Length Index Daily Low on Day of Placement &lt;32°F &amp; &gt;32°F</td>
<td>0.428</td>
<td>Average length index of a curb does not significantly differ for curbs placed below 32°F compared to those placed above 32°F.</td>
</tr>
<tr>
<td>Average Intensity Index Daily Low on Day of Placement &lt;32°F &amp; &gt;32°F</td>
<td>0.804</td>
<td>Average intensity index of a curb does not significantly differ for curbs placed below 32°F compared to those placed above 32°F.</td>
</tr>
<tr>
<td>Average Uncracked Length Daily Low on Day of Placement &lt;32°F &amp; &gt;32°F</td>
<td>0.858</td>
<td>Average uncracked length of a curb does not significantly differ for curbs placed below 32°F compared to those placed above 32°F.</td>
</tr>
</tbody>
</table>
Appendix – Weather After Placement

![Graph 1: Length Index vs. Average Low Temperature for the Week After Placement, °F]

![Graph 2: Intensity Index vs. Average Low Temperature for the Week After Placement, °F]
Appendix – ADT
### Appendix – ADT

#### Scatter Plot

- **Intensity Index** vs. **ADT**
  - Points represent different traffic conditions:
    - Blue dots: <40 ft
    - Red dots: >40 ft

#### Table

<table>
<thead>
<tr>
<th>t-test</th>
<th>p-value</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Length Index</td>
<td></td>
<td>Average length index of a curb does not significantly differ for curbs on bridges with ADT below 5000 compared to those with ADT above 5000.</td>
</tr>
<tr>
<td>Average Daily Traffic <code>&lt;5000 &amp; &gt;5000</code></td>
<td>0.803</td>
<td></td>
</tr>
<tr>
<td>Average Intensity Index</td>
<td></td>
<td>Average intensity index of a curb does not significantly differ for curbs on bridges with ADT below 5000 compared to those with ADT above 5000.</td>
</tr>
<tr>
<td>Average Daily Traffic <code>&lt;5000 &amp; &gt;5000</code></td>
<td>0.642</td>
<td></td>
</tr>
<tr>
<td>Average Uncracked Length</td>
<td></td>
<td>Average uncracked length of a curb does not significantly differ for curbs on bridges with ADT below 5000 compared to those with ADT above 5000.</td>
</tr>
<tr>
<td>Average Daily Traffic <code>&lt;5000 &amp; &gt;5000</code></td>
<td>0.456</td>
<td></td>
</tr>
</tbody>
</table>
## Results and Discussion

Cementitious Materials Content

Water-Cement Ratio, w/cm

<table>
<thead>
<tr>
<th>Pearson Correlation</th>
<th>r</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/cm, Average Uncracked Length</td>
<td>-0.295</td>
<td>w/cm: Weak negative correlation</td>
</tr>
<tr>
<td>Cementitious Content, Average Uncracked Length</td>
<td>-0.520</td>
<td>Cementitious Content: Weak negative correlation</td>
</tr>
</tbody>
</table>
Results and Discussion

Cracking Over Time: Length Index

- Alexandria 174/146 North
- Grantham 140/069 North
- Hampton 207/094 North
- Tamworth 095/162 North
- Westmoreland 111/072 East
- Marlborough 090/127 North
Results and Discussion

Cracking Over Time: Intensity Index

[Graph showing the intensity index over time for various locations, including Alexandria 174/146 North and South, Grantham 140/069 North and South, Hampton 207/094 North and South, Tamworth 095/162 North and South, Westmoreland 111/072 East and West, and Marlborough 090/127 North.]
Results and Discussion

Cracking Over Time: Normalized Crack Volume

[Graph showing normalized crack volume over time for different locations with linear trend lines and markers for each location.]