Mass Concrete Thermal Control

2009 Structures Design Construction Quality Workshop

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What is Mass Concrete?

- ACI: “any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking”
- Intentionally vague
Factors Affecting Mass Concrete

- Concrete mix design: components
- Environmental condition:
  - Ambient temperature
  - Concrete mix temperature
  - Differential temperature
- Structural design: steel reinforcement
- Application: bridge elements
- Least dimension: 3’, 4’, or 5’?
Mass Concrete Hydration

- Significant heat is generated in the first few days after placement
- Expected to reach maximum temperature within 1 to 3 days after placement
- Heat is trapped and can not escape quickly resulting in:
  - Significant temperature difference: interior of concrete is much hotter than its surface (>35°F)
    - Thermal Cracking
  - Concrete mix getting too hot (>160°F)
    - Delayed Ettringite Formation (DEF)
Thermal Cracking

- Thermal cracking develops when the tensile stress exceeds the tensile strength of concrete:
  - Random map cracks in large foundation
  - A series of vertical cracks in walls (widest near the base)
  - Uniformly spaced cracks in beams (perpendicular to the longest dimension)
- Mostly, a durability issue: easy pathways for air and water
- In some severe cases, it may affect the structural capacity
Delayed Ettringite Formation (DEF)

- Development of unstable hydration
- Long-term effect that may not show for months or years after construction
- Can cause significant cracking
Thermal Control

• Objective: Eliminate thermal cracking by controlling temperature differential and mix temperature (prior to, during and after concrete placement)

• Control measures should be evaluated for costs vs. benefits
Thermal Control Measures

- Optimal concrete mix design
- Insulation
- Concrete cooling before placement
- Concrete cooling after placement
- Use of smaller placements
Optimal Concrete Mix Design

- Use low-heat cement such as Type II
- Use Class F fly ash and/or slag as a substitute for a portion of the cement
- Use low water-to-cementitious materials ratio
- Minimize the amount of cementitious materials in the mix
- Use Larger and better graded aggregates
- Limestone aggregates are better suited for mass concrete
Insulation

- To control temperature differential: core vs. surface
- Has no significant effect on maximum concrete temperature for placements of 5’ or greater
- Typical R-value recommended: 2 to 4 hr.ft² .°F/Btu
Concrete Cooling before Placement

- Each 1°F of precooling is expected to reduce the concrete temperature (after placement) by about the same amount.
- Chilled water: about 5°F (100% subs.) temperature reduction.
- Chipped or shaved ice: about 15°F to 20°F (75% subs.) temperature reduction.
- Liquid nitrogen (LN2): as low as 35°F reduction. Very effective but the most expensive option.
Concrete Cooling after Placement

• Cooling pipes:
  - Non-corrosive piping embedded prior to concrete placement
  - Uniformly distributed: typically 1”Ø pipes @ 2’ to 4’ on center
  - Removes heat from placed concrete by circulating cool water from a nearby source
Smaller Placements

- Multiple lifts
- Result in schedule delays and increased cost due to additional effort for multiple thermal control, and horizontal joint preparation
Case Study: I-80 over Missouri River
Iowa Mass Concrete Specifications

• Special Provision for Mass Concrete – Control of Heat of Hydration
  - Mix design
    • Cement: Type II, IP, or IS – min. 560 lbs
    • Slag and Class F fly ash substitution
    • Maximum water to cementitious ratio = 0.45
  - Thermal Control Plan (per 207.4R-05 ACI)
    • Concrete temperature at placement: 40°F-70°F
    • Max. Concrete temperature after placement: 160°F
    • Temperature differential: 35°F
    • Temperature sensing and recording
I-80 over Missouri River
Thermal Control Plan

- Value engineering proposal by Jensen Construction to modify project specifications
- Proposed a thermal control plan based on thermal modeling by CTL
Thermal Control Plan

- Concrete Mix
- Maximum Concrete Temperature
- Temperature Difference Limit
- Cooling System
- Insulation
- Temperature Monitoring & Reporting
Concrete Mix

- As developed by the supplier per project specifications
  - Type IP-F Cement: 420 lbs
  - Slag: 207 lbs
  - W/C ratio: 0.42
  - Class V sand-gravel: 1586 lbs
  - Limestone: 1322 lbs
  - Air content: 6.5%
Maximum Concrete Temperature

- Initial concrete temperature based on several-truck rolling average: maximum of 85°F instead of 70°F
- Concrete temperature after placement: maximum of 160°F as per specifications
Temperature Difference Limit

- A compromise between the constant limit and the performance-based limit
- Included a variable factor of safety
- More conservative in the early age but less conservative at the design strength
- Calculated specifically for the project mix design
* Maximum allowable temperature difference between the temperature sensor locations shown on Drawing Nos. 3 and 4.

** Actual compressive strength of the in-place concrete at the surface, not the design strength.
Cooling System

- Cooling piping system layout was developed for each component (footing, stem, cap, …)
- River water was continuously circulated through the cooling pipes until the insulation is removed
- Flow rate must be sufficiently high so that the water does not heat by more than 2°F to 3°F
Typical Cooling System - Footing
Typical Cooling System - Stem
Insulation

- Used on top surfaces, over side forms and to cover protruding reinforcing steel
- R-values in accordance with the Thermal Control Plan
- To remain in place throughout the monitoring period but may be temporarily removed to prepare for additional placements
Typical Insulation Blanket
Temperature Monitoring & Reporting

- To measure and report concrete temperatures at critical locations (center, surface, …)
- Two temperature sensors (a primary and backup) at each location
- Data is recorded on an hourly basis
- Report of temperature data (max. and differential) is issued
Typical Temperature Sensors
Typical Thermal Control Graph

TCP1b Footing #: Pier 7 Column final temps

Time/Date of Hour 0:
**Thermal Control Plan Elements**

<table>
<thead>
<tr>
<th>Pier</th>
<th>Size*</th>
<th>Date Cast</th>
<th>Cooling Pipes</th>
<th>Size*</th>
<th>Date Cast</th>
<th>Cooling Pipes</th>
<th>Least Dim.</th>
<th>Date Cast</th>
<th>Cooling Pipes</th>
<th>Least Dim.</th>
<th>Date Cast</th>
<th>Cooling Pipes</th>
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<td>39' x 4' x 7'</td>
<td>12/4/2008</td>
<td>No</td>
<td>4'</td>
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Completion of Thermal Control

- Hottest portion of concrete has reached and begun to cool from its maximum temperature
- Concrete has reached and begun to cool from its maximum temperature difference
- At least 3 days has elapsed
- Difference between the hottest portion of concrete and the average air temperature is $< \text{current difference limit}$
Summary

- The implementation of the Thermal Control Plan saved money and kept the project on schedule.
- No thermal cracking in concrete was reported.
References

• Iowa DOT Standard Specifications and Special Provisions
• Engineering Mass Concrete Structures, November 2006 – PCA by J. Gajda and E. Alsamsam
• ACI 207.4R-05
• I-80 over Missouri River Thermal Control Plan by CTL