Mass Concrete Fundamentals

Everything You Ever Wanted to Know... plus a little bit more!

John Gajda, PE, FACI
MJ2 Consulting, PLLC
847-922-1886
John@MJ2consulting.com
www.ThermalControlPlan.com

November 7-8, 2019
About the Presenter

• John Gajda, FACI, PE/PEng (31 jurisdictions)
  • Principal at MJ2 Consulting, PLLC
  • Former Chair of ACI 207 Mass and Thermally Controlled Concrete (2010 to 2016)
  • ACI 301 Specifications for Structural Concrete Subcommittee Chair of “Mass Concrete”
  • 1000+ Mass Concrete Projects
Outline

• Mass concrete definition
• Why treat something as mass concrete
  • What matters and why
• Specification requirements and limits
• Strategies for success
• Questions
What is Mass Concrete?

“any volume of concrete in which a combination of dimensions of the member being cast, the boundary conditions, the characteristics of the concrete mixture, and the ambient conditions can lead to undesirable thermal stresses, cracking, deleterious chemical reactions, or reduction in the long-term strength as a result of elevated concrete temperature due to heat from hydration”

– American Concrete Institute (ACI), 2010 and 2016
What is Mass Concrete?

“any volume of concrete in which a combination of dimensions of the member being cast, the boundary conditions, the characteristics of the concrete mixture, and the ambient conditions can lead to undesirable thermal stresses, cracking, deleterious chemical reactions, or reduction in the long-term strength as a result of elevated concrete temperature due to heat from hydration”

– American Concrete Institute (ACI), 2010 and 2016
Trends that lead to Mass Concrete

• Larger Elements
• Higher Strengths
• Flowable Concrete
• Rapid Construction
• Long Service Life
These Trends can Result in …

- High Concrete Temperatures
- Thermal Cracking
  - Durability concerns
  - Reduced service life
  - Structural concerns
What is Mass Concrete?
What is Mass Concrete?
What is Mass Concrete?

Other Stuff: Self Consolidating Concrete (SCC), Drilled Shaft Concrete, Grout, High Early Strength Highway Patching Material, etc.
When is it Mass Concrete?

• When rate of heat generation and thickness is such that heat is generated faster than it escapes.
• No requirements in ACI 207
• Per ACI 301:
  • Only when the EOR specifies it to be mass concrete
    • Thickness ≥4 ft.
    • >660 lbs/\text{yd}^3\ cementitious (2010 edition; not in current edition)
• DOTs: ≥2.5 to >7 ft.
When is it Mass Concrete?

<table>
<thead>
<tr>
<th>Equivalent Cement Content, lb/yd³</th>
<th>Placement Thickness (Minimum Dimension), ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>½</td>
</tr>
<tr>
<td>300</td>
<td>Yes</td>
</tr>
<tr>
<td>350</td>
<td>Yes</td>
</tr>
<tr>
<td>400</td>
<td>Yes</td>
</tr>
<tr>
<td>450</td>
<td>Yes</td>
</tr>
<tr>
<td>500</td>
<td>Yes</td>
</tr>
<tr>
<td>550</td>
<td>Yes</td>
</tr>
<tr>
<td>600</td>
<td>Yes</td>
</tr>
<tr>
<td>650</td>
<td>Yes</td>
</tr>
<tr>
<td>700</td>
<td>Yes</td>
</tr>
<tr>
<td>750</td>
<td>Yes</td>
</tr>
<tr>
<td>800</td>
<td>Yes</td>
</tr>
<tr>
<td>850</td>
<td>Yes</td>
</tr>
<tr>
<td>900</td>
<td>Yes</td>
</tr>
<tr>
<td>950</td>
<td>Yes</td>
</tr>
<tr>
<td>1000</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Published: *When Should Mass Concrete Requirements Apply?*, Aspire Bridge Magazine, Summer 2015. *Proposed Mass Concrete Definition Based on Concrete Constituents and Minimum Dimension*, ACI SP325, Fall 2018.

Adopted: Not yet but in draft versions of ACI 207.1R and ACI 207.2R.
Equivalent Cement Content (ECC)

\[ \text{ECC} = \text{portland cement} + \]
\[ \text{factor} \times \text{slag cement} + \]
\[ 0.5 \times \text{fly ash (class F)} + \]
\[ 0.8 \times \text{fly ash (class C)} + \]
\[ 1.2 \times (\text{silica fume} + \text{metakaolin}) \]

<table>
<thead>
<tr>
<th>Slag (0-20%)</th>
<th>1.0-1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag (20-45%)</td>
<td>1.0</td>
</tr>
<tr>
<td>Slag (45-65%)</td>
<td>0.9</td>
</tr>
<tr>
<td>Slag (65-80%)</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Main Considerations

• Maximum Temperature
  • Can reduce strength and durability

• Temperature Difference
  • Can result in thermal cracking
  • During thermal control and just after thermal control ends

• Thermal Shock
  • Don’t stop thermal control too soon
Maximum Temperature

- Often limited
  - No consensus in specifications
  - Safe limit: 158/160°F (70°C)
  - Europe uses 149°F (65°C)
- Concrete mixture design
  - Cement (type and quantity)
  - SCMs (type and percentage)
Maximum Temperature (cont.)

- 100% Cement
- 70/30 Blend of Cement and Fly Ash
- 25/75 Blend of Cement and Slag
Potential long term durability issue that can occur only when all three of the following occur:

- Concrete temperature exceeds 158/160°F
- Cementitious materials have a particular chemistry
- External water available during service life

Expansion and cracking 1+ year from now

Delayed Ettringite Formation (DEF)
Maximum Temperature Estimation


- Initial Temperature
  - As low as economically practical (Payback of 1:1)
- Temperature Rise depends on Mix Design
  - Equivalent cement content (ECC)
- For placements >5 ft. thick
Ballpark Temperature Rise

Estimated Rise (°F) = 0.16*ECC

\[ ECC = \text{portland cement} + \text{factor}*\text{slag cement} + 0.5*\text{fly ash (class F)} + 0.8*\text{fly ash (class C)} + 1.2*(\text{silica fume} + \text{metakaolin}) \]

<table>
<thead>
<tr>
<th>Slag (%)</th>
<th>Estimated Rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20%</td>
<td>1.0-1.1</td>
</tr>
<tr>
<td>20-45%</td>
<td>1.0</td>
</tr>
<tr>
<td>45-65%</td>
<td>0.9</td>
</tr>
<tr>
<td>65-80%</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Concrete Foundation
Concrete with 400 lb/yd³ cement and 300 lb/yd³ class F fly ash
70°F delivered concrete
6 ft. thick

Temperature Rise =
0.16*(400 + 0.5*300) = 88°F

Max. Initial Temperature =
160°F - 88°F = 78°F
Temperature Difference

• Limited to prevent/minimize thermal cracking
Extreme Thermal Cracking
Typical Thermal Cracking
Typical Thermal Cracking
Typical Thermal Cracking
Temperature Difference

- Limited to prevent/minimize thermal cracking
- ACI 224R has cracking limits

Table 4.1—Guide to reasonable* crack widths, reinforced concrete under service loads

<table>
<thead>
<tr>
<th>Exposure condition</th>
<th>Crack width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in.</td>
</tr>
<tr>
<td>Dry air or protective membrane</td>
<td>0.016</td>
</tr>
<tr>
<td>Humidity, moist air, soil</td>
<td>0.012</td>
</tr>
<tr>
<td>Deicing chemicals</td>
<td>0.007</td>
</tr>
<tr>
<td>Seawater and seawater spray, wetting and drying</td>
<td>0.006</td>
</tr>
<tr>
<td>Water-retaining structures†</td>
<td>0.004</td>
</tr>
</tbody>
</table>

* It should be expected that a portion of the cracks in the structure will exceed these values. With time, a significant portion can exceed these values. These are general guidelines for design to be used in conjunction with sound engineering judgement.
† Excluding nonpressure pipes.
Temperature Difference Limit

• Often limited to a maximum of 35°F (20°C)
  • Generalized “rule-of-thumb”
  • “Discovered” during construction of unreinforced dams in Europe 75+ years ago
  • May not prevent thermal cracking
  • Simple to use and understand
  • Extends construction time

• Stepped limit
  • Steps up with age (20-30-40-50°F)
  • Shortens construction time
  • Simple to use and understand
Temperature Difference Limit (Cont.)

• Engineered (tailored) limit
  • Accounts for concrete’s ability to withstand higher thermal stresses as strength increases
  • Based on concrete properties and structure
  • ACI 207.2R-95 and CIRIA C660
Temp. Difference and Time Savings

Temperature, °F

Time, Days

Calculated dT

35°F dT

Allowable Temp. Diff., °F

In-Place Compressive Strength, psi

Specified 35°F

Calculated (Example)
Thermal Control Strategies

• Thermal control plan (TCP)
  • Document that demonstrates contractor’s methods to:
    • Comply with mass concrete specifications
    • Ensure maximum temperature doesn’t exceed 158°F/160°F
    • Limit the temperature difference to minimize/prevent thermal cracking
  • Based on modeling and/or mockups
Control Strategies (Cont.)

- Low temperature rise concrete
- Less cementitious
- Higher SCMs and/or low heat cement

<table>
<thead>
<tr>
<th>Mass Mix</th>
<th>7 days</th>
<th>28 days</th>
<th>56 days</th>
<th>90 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement, Type II/V, pcy</td>
<td>320</td>
<td>5955</td>
<td>8570</td>
<td>10,840</td>
</tr>
<tr>
<td>Fly Ash, Class F, pcy</td>
<td>320</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete Sand, pcy</td>
<td>1544</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#8 Coarse Aggregate pcy</td>
<td>365</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#57 Coarse Aggregate, pcy</td>
<td>1460</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>w/cm</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Est. Temp. Rise, °F</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass Mix</th>
<th>Comp. Strength, psi</th>
<th>7 days</th>
<th>28 days</th>
<th>56 days</th>
<th>90 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Content</td>
<td>3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slump, in.</td>
<td>9¾</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C157 Shrinkage, 28 days</td>
<td>0.33%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Control Strategies (Cont.)

• Reduced placement sizes
  (with adequate time for cooling)
Control Strategies (Cont.)

• Keep the surface warm
  • Surface insulation
    • Time ≈ \( \frac{3}{4} \times \text{Thickness}-1 \)
    • No exposed steel!
  • Added heat?
Control Strategies (Cont.)

- Precool the concrete
  - Use cold batch water
    - 2-3°F reduction
  - Replace batch water with ice
    - Up to 20°F reduction
  - Liquid nitrogen precooling
    - Unlimited precooling
Control Strategies (Cont.)

• Post-cool with cooling pipes
  • Remove internal heat after placement
  • Reduces the overall temperature rise and maximum temperature
• Reduces the time of thermal control
• ¾” or 1” plastic pipe
• Typically uses water
• Filled with grout afterwards

![Graph showing temperature change over time with and without cooling pipes]
Cooling Pipes
Cooling Pipes
Temperature Monitoring

- Monitor temperatures to ensure (prove) limits not exceeded
- Typical locations
  - Geometric center of placement
  - 2-3” below the surface at center of large surface
- Hourly data
Things to Avoid

• Poor insulation
• Uninsulated steel
• Water curing
Summary

• Mass concrete is not always massive!
• Cracking can be minimized/prevented through control of temperatures and temperature differences.
• Insulation is (almost) always required.
• Increased time of construction (but this can be minimized).
• Helps ensure service life is achieved.
Resources

• ACI 301-10 or ACI 301-16 (www.concrete.org)
• PCA Publication EB547 (www.cement.org)
• ACI 207.7R (to be published “soon”)
• www.ThermalControlPlan.com
Thank you!