Unintended Consequences – How Reduced Instrumentation and Monitoring of Mass Concrete Structures Can Lead to Increased Cracking and Reduced Durability

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Definition of Mass Concrete
Factors affecting stress development
Review of 346-3.3 Mass Concrete
Temperature Limitations
Factors affecting need for temperature control
Inaccuracy of Schmidt Model
“Reduced Monitoring” and “No Monitoring”
Field Problems
Suggested specification modifications
Questions to be answered by research
What is Mass Concrete (ACI)?

Definition of Mass Concrete

ACI 301 Specifications for Structural Concrete

Mass Concrete: Concrete placements where maximum temperatures and temperature differences must be controlled due to factors including the content and type of cementitious materials, environment surrounding placement, and minimum dimension of placement should be designated mass concrete. Evaluate the requirements for each portion of project. In general, a placement of structural concrete with a minimum dimension equal to or greater than 4 ft should be considered mass concrete. Similar considerations should be given to other concrete placements that do not meet this minimum dimension but generate high heat at early ages such as concretes that contain Type III cement, accelerating admixtures, or have high cementitious materials contents...
What is Mass Concrete (FDOT)?

Florida DOT Structures Design Guidelines

Section 1.4.4 Mass Concrete

Mass Concrete is defined as: "Any large volume of cast-in-place or precast concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume change so as to minimize cracking."

For All Bridge components Except Drilled Shafts and Segmental Superstructure Pier and Expansion Joint Segments: **When the minimum dimension of the concrete exceeds 3 feet and the ratio of volume of concrete to the surface area is greater than 1 foot, provide for Mass Concrete.**

**Example:**

Cube: volume = $x^3$  
When $x = 3$ ft, volume = 27 ft$^3$, area = 54 ft$^2$, ratio = 0.5 ft  
area = 6 $x^2$  
When $x = 6$ ft, volume = 216 ft$^3$, area = 216 ft$^2$, ratio = 1.0 ft
Compositional Effects Can Outweigh the Dimensional Effects

- Typically, only the concrete element dimensions are considered to determine if the element should be treated as mass concrete.
- This ignores the effect of high cementitious material contents.

This was not mass concrete based on the FDOT definition, but the element developed high enough thermal stresses to crack the concrete.

The development of thermal stresses depends on a number of factors that should be considered to designate an element as having mass concrete characteristics.

Segmental Bridge Pier Segment

- High-strength concrete: 8500 psi
- Volume to Surface Area ratio: 0.97 ft.
- Was not deemed Mass Concrete

“Pilot Project for Maximum Heat of Mass Concrete - Research Highlights”
2013 FTBA Construction Conference, Adrian Lawrence
The tensile stresses developed during the cooling stage are influenced by the following:

- Thermal differential ($\Delta T_{\text{core-surface}}$)
- Rate of temperature change (temperature gradient, $\Delta T/\Delta x$)
- Coefficient of thermal expansion
- Modulus of elasticity
- Creep or relaxation and
- The degree of restraint.
Thermal stresses and strains develop due to changes in the mass concrete volume

**Primary causes of volume change:**
- Increase in concrete temperature from heat generated by hydration of cementitious materials (rate of heat generation exceeds rate of heat loss)
- Subsequent decrease in temperature as heat dissipates (rate of heat loss exceeds rate of heat generation)
- Daily cycles of ambient temperature.

**Measures to reduce volume changes include:**
- Reduce heat generated by reducing cementitious content
- Reduce initial placement temperature of the concrete
- Limit maximum ambient temperature at time of placement
When mass concrete is designated in the Contract Documents, use a Specialty Engineer to develop and administer a Mass Concrete Control Plan (MCCP). Develop the MCCP in accordance with Section 207 of the ACI Manual of Concrete Practice to ensure concrete core temperatures for any mass concrete element do not exceed the maximum allowable core temperature of 180°F and that the temperature differential between the element core and surface do not exceed the maximum allowable temperature differential of 35°F. Submit the MCCP to the Engineer for approval at least 14 days prior to the first anticipated mass concrete placement. Ensure the MCCP includes and fully describes the following:

1. Concrete mix design proportions,
2. Casting procedures,
3. Insulating systems,
4. Type and placement of temperature measuring and recording devices,
5. Analysis of anticipated thermal developments for the various mass concrete elements for all anticipated ambient temperature ranges,
6. Names and qualifications of all designees who will inspect the installation of and record the output of temperature measuring devices, and who will implement temperature control measures directed by the Specialty Engineer,
7. Measures to prevent thermal shock, and
8. Active cooling measures (if used).
(Comply with Mass Concrete Control Plan) Fully comply with the approved MCCP. The Specialty Engineer or approved designee shall personally inspect and approve the installation of temperature measuring devices and verify that the process for recording temperature readings is effective for the first placement of each size and type mass component. The Specialty Engineer shall be available for immediate consultation during the monitoring period of any mass concrete element. Record temperature measuring device readings at intervals no greater than six hours, beginning at the completion of concrete placement and continuing until decreasing core temperatures and temperature differentials are confirmed in accordance with the approved MCCP. Leave temperature control mechanisms in place until the concrete core temperature is within 50°F of the ambient temperature. Within three days of the completion of temperature monitoring, submit a report to the Engineer which includes all temperature readings, temperature differentials, data logger summary sheets and the maximum core temperature and temperature differentials for each mass concrete element.
(Reduced Monitoring) Upon successful performance of the MCCP, reduced monitoring of similar elements may be requested. Submit any such requests to the Engineer for approval at least 14 days prior to the requested date of reduced monitoring. **If approved, the Specialty Engineer may monitor only the initial element of concrete elements meeting all of the following requirements:**

1. All elements have **the same least cross sectional dimension**, 
2. All elements have **the same concrete mix design**, 
3. All elements have **the same insulation R value and active cooling measures (if used)**, and 
4. Ambient temperatures during concrete placement for all elements is **within minus 10°F or plus 5°F of the ambient temperature during placement of the initial element**.

**Install temperature measuring devices for all mass concrete elements. Resume the recording of temperature monitoring device output for all elements if directed by the Engineer.** The Department will make no compensation, either monetary or time, for any impacts associated with reduced monitoring of mass concrete elements.
(No Monitoring) Mass concrete control provisions are not required for drilled shafts supporting sign, signal, lighting or intelligent transportation (ITS) structures. At the Contractor’s option, instrumentation and temperature measuring may be omitted for any mass concrete substructure element meeting all of the following requirements:

1. Least cross sectional dimension of six feet or less,
2. Insulation R value of at least 2.5 provided for at least 72 hours following the completion of concrete placement,
3. The environmental classification of the concrete element is Slightly Aggressive or Moderately Aggressive,
4. The concrete mix design meets the mass concrete proportioning requirements of 346-2.3, and
5. The total cementitious content of the concrete mix design is 750 lb/cy or less.
(Remediation Procedure when Temperature Limits are Exceeded)

If either the maximum allowable core temperature or temperature differential of any mass concrete element is exceeded, implement immediate corrective action as directed by the Specialty Engineer to remediate. The approval of the MCCP shall be revoked. Do not place any mass concrete elements until a revised MCCP has been approved by the Engineer. Submit an Engineering Analysis Scope in accordance with 6-4 for approval, which addresses the structural integrity and durability of any mass concrete element which is not cast in compliance with the approved MCCP or which exceeds the allowable core temperature or temperature differential. Submit all analyses and test results requested by the Engineer for any noncompliant mass concrete element to the satisfaction of the Engineer. The Department will make no compensation, either monetary or time, for the analyses and tests or any impacts upon the project.
ACI Temperature Limitations for Mass Concrete

ACI 301 Specifications for Structural Concrete

➢ Section 8.1.3 Temperature Limits:
  ➢ Maximum temperature in concrete after placement shall not exceed 160°F
  ➢ Maximum temperature difference between center and surface of placement shall not exceed 35°F

➢ The higher the max temperature:
  ➢ The greater the temperature differentials
  ➢ The greater the temperature gradient => increase in cracking potential
  ➢ The longer the time required to cool to 50°F above ambient for removal of temperature control measures (forms and insulation)
Section 346-3.3 Mass Concrete:

- When mass concrete is designated in the Contract Documents, use a Specialty Engineer to develop and administer a Mass Concrete Control Plan (MCCP). Develop the MCCP in accordance with Section 207 of the ACI Manual of Concrete Practice to ensure concrete core temperatures for any mass concrete element do not exceed the maximum allowable core temperature of 180°F and that the temperature differential between the element core and surface do not exceed the maximum allowable temperature differential of 35°F.

- Leave temperature control mechanisms in place until the concrete core temperature is within 50°F of the ambient temperature.
Some Factors that Affect the Need for Temperature Control of Concrete

Temperature control is needed when the maximum temperature or temperature differentials are predicted to exceed the specified maximums, potentially producing stresses due to volume changes that are large enough to cause cracking.

- Total cementitious material content in concrete
- Type and quantity of SCMs used in concrete
- Volume of concrete - size of element (shortest core-surface dimension)
- Concrete temperature at placement
- Ambient temperature at placement
- Daily ambient temperature variations

Composition
Shortest Dimension
Concrete Temperature
Ambient Conditions
ACI Committee 207 has proposed a chart that determines the potential for a concrete element to need temperature control measures based on cementitious material content and the length of the minimum dimension of the element.

<table>
<thead>
<tr>
<th>Equivalent Cement Content, lb/yd³</th>
<th>Placement Thickness (Minimum Dimension), ft</th>
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Chart of placement versus equivalent cement content for normal-weight concrete. Red is mass concrete, green is non mass concrete. Yellow is a buffer zone that is left to the discretion of the specifier. Chart: John Gajda.

Factors Affecting Temperature Distribution

The maximum core temperature, temperature gradients, and temperature differentials attained by mass concrete are affected by the following:

- Quantity and type of cementitious material
- Size and shape of cast element
- Concrete temperature at placement
- Ambient temperature at placement and early-age daily temperature profiles
- Temperature control measures
Why Temperatures Should be Limited

➢ The higher the maximum temperature:
  ➢ The greater the temperature differentials and gradients
  ➢ The greater the temperature gradient and the greater the cracking potential
  ➢ The longer the time required to cool to 50°F above ambient for removal of temperature control measures (formwork and insulation)

➢ Temperatures above 160°F have been associated with a tendency for form delayed ettringite (DEF)
  ➢ Some SCMs have been found to mitigate DEF
  ➢ It is best to limit maximum temperatures until research establishes safe ranges for PC-SCMs
Portland Cement Concrete without Pozzolans
Significant DEF at Curing Temperatures above 160°F

## ACI 201.2R-16 Guide to Durable Concrete

### Table 6.2.2.2—Recommended measures for reducing potential for DEF in concrete exposed to elevated temperatures at early ages*

<table>
<thead>
<tr>
<th>Maximum concrete temperature $T$</th>
<th>Prevention required</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T \leq 158^\circ F$ (70°C)</td>
<td>No prevention required</td>
</tr>
</tbody>
</table>
| $158^\circ F < T \leq 185^\circ F$ (70°C < $T \leq 85^\circ C$) | Use one of the following approaches to minimize the risk of expansion:
  1. Portland cement meeting requirements of ASTM C150/C150M moderate or high sulfate-resisting and low-alkali cement with a fineness value less than or equal to 430 m$^2$/kg
  2. Portland cement with a 1-day mortar strength (ASTM C109/C109M) less than or equal to 2850 psi (20 MPa)
  3. Any ASTM C150/C150M portland cement in combination with the following proportions of pozzolan or slag cement:
     a) Greater than or equal to 25 percent fly ash meeting the requirements of ASTM C618 for Class F fly ash
     b) Greater than or equal to 35 percent fly ash meeting the requirements of ASTM C618 for Class C fly ash
     c) Greater than or equal to 35 percent slag cement meeting the requirements of ASTM C989/C989M
     d) Greater than or equal to 5 percent silica fume (meeting ASTM C1240) in combination with at least 25 percent slag cement
     e) Greater than or equal to 5 percent silica fume (meeting ASTM C1240) in combination with at least 20 percent Class F fly ash
     f) Greater than or equal to 10 percent metakaolin meeting ASTM C618
  4. An ASTM C595/C595M or ASTM C1157/C1157M blended hydraulic cement with the same pozzolan or slag cement content as listed in Item 3 |
| $T > 185^\circ F$ (85°C)          | The internal concrete temperature should not exceed 185$^\circ F$ (85°C) under any circumstances. |

*Assembled from Ghorab et al. (1980), Ramlochan et al. (2003), Thomas (2001), Thomas et al. (2008b).*

Note that these are guidelines that were found effective for the particular materials used and are not guaranteed to prevent problems. Test in Lab before using in field.
The Schmidt Model is used in the Mass Concrete Control Plan (MCCP) to model the expected temperature profile to determine the temperature control measures needed to mitigate thermal stresses. This model typically underestimates the actual temperatures developed (FE Model much better).

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2013 FTBA Construction Conference, Adrian Lawrence
346-3.3:

➢ Upon successful performance of the MCCP, **reduced monitoring of similar elements** may be requested. Submit any such requests to the Engineer for approval at least 14 days prior to the requested date of reduced monitoring. If approved, the Specialty Engineer may monitor only the initial element of concrete elements meeting all of the following requirements:

➢ All elements have the **same least cross sectional dimension**, 
➢ All elements have the **same concrete mix design**, 
➢ All elements have the **same insulation R value and active cooling measures** (if used), and 
➢ Ambient temperatures during concrete placement for all elements is **within minus 10°F or plus 5°F of the ambient temperature during placement of the initial element**.
Requirements to Allow Omission of Monitoring of Mass Concrete

346-3.3 ("No Monitoring"): Mass concrete control provisions are not required for drilled shafts supporting sign, signal, lighting or intelligent transportation (ITS) structures. At the Contractor’s option, instrumentation and temperature measuring may be omitted for any mass concrete substructure element meeting all of the following requirements:

- Least cross sectional dimension of six feet or less,
- Insulation R value of at least 2.5 provided for at least 72 hours following the completion of concrete placement,
- The environmental classification of the concrete element is Slightly Aggressive or Moderately Aggressive,
- The concrete mix design meets the mass concrete proportioning requirements of 346-2.3, and The total cementitious content of the concrete mix design is 750 lb/cy or less.
346-3.3 States that for Reduced Monitoring it is necessary to:

- Install temperature measuring devices for all mass concrete elements. Not being done.
- Resume the recording of temperature monitoring device output for all elements if directed by the Engineer. Cannot be done if elements are not instrumented.

In the Field, the following have become common practices:

- For “Reduced Monitoring,” only the first element is being instrumented.
- For “No Monitoring,” MCCPs are not being submitted.

This has resulted in very few structures being instrumented.
Problems with the Use of Reduced Monitoring and No Monitoring

➢ Two of the most important means of reducing the potential for thermal cracking involve the measurement and monitoring of the surface and core temperatures of the concrete

➢ Limiting the core-surface temperature differential to 35°F (cannot be reliably done without recording temperatures)

➢ Keeping forms and thermal control measures in place until the core-ambient temperature differential is ≤ 50°F (cannot be reliably done without recording temperatures)

➢ These procedures greatly reduce the number of instrumented mass concrete elements for which differential temperatures can be recorded.
Problems with the Use of Reduced Monitoring and No Monitoring

Some mass concrete is attaining significantly higher temperatures for longer periods of time than predicted in the MCCP (Schmidt model)

- Up to 5 days above 170°F
- Up to 10 days above 160°F
- Over 14 days with core-ambient differential temperature > 50°F

Without monitoring, even if the Schmidt Model is used to predict when the core-ambient differential is less than 50°F, formwork and temperature control measures may be removed too early.
Without temperature monitoring, there is no reliable means to determine when it is considered safe to remove forms

- Eight (8) non-instrumented concrete elements cracked on I-4 Ultimate project after removing forms at 3 days.
- Calculations based on Schmidt model temperatures in MCCPs indicated that > 7 days would have been more appropriate.
- MCCP Acceptance Letter revised in November 2017 to require that form removal for unmonitored mass concrete elements must not be done until the core temperature, as predicted in the Specialty Engineer’s models, is no greater than 50°F above that of the measured ambient temperature.
(Changes in red to 346-3.3 Reporting): “Within three days of the completion of temperature monitoring, submit a report to the Engineer and State Materials Office (Concrete Materials Engineer, Structural Materials Research Engineer, and Structural Materials Research Specialist) that includes, in Excel format, the project and mass element information, all temperature readings, temperature differentials, data logger summary sheets and the maximum core temperature and temperature differentials for each mass concrete element.”

➢ This will enable creation of a database for statistical analyses of the data and determination of any correlations relevant to the quality of the mass concrete.
Questions That Need to be Answered

➢ What are safe maximum temperatures for each combination of portland cement and SCMs?
➢ Are particular portland cement-SCM combinations more susceptible to cracking?
➢ What should the maximum core-surface and core-ambient temperature differentials (gradients) be?
➢ How should maximum concrete temperatures at placement be determined to mitigate cracking?
➢ Should analyses using finite element modeling programs replace the use of physical and compositional characteristics to indicate likelihood of mass concrete behavior and how to mitigate?
Areas of Research Under Consideration

Research Needed

➢ Keep core-surface differential temperature at 35°F?
➢ Keep core-ambient differential temperature at 50°F?
➢ Replace differentials with temperature gradients?
➢ Lower FDOT max temperature from 180°F to 160°F?
➢ Lower the allowed placement temperatures?
➢ Reduce cementitious material contents?
➢ Evaluate current FEA modeling programs or modify/develop new ones
Questions?