60th Transportation Conference

Requirements for Mass Concrete Construction in Alabama

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Presentation Overview

- **Introduction**
- Mass Concrete Concerns
- High Early-Age Temperatures
- Thermal Cracking
- Temperature Control Strategies
- Closing Remarks

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What is Mass Concrete?

Hoover Dam

Wall Height: 727 ft
Wall Length: 1,244 ft
Wall thickness: 45 ft at crest and 660 ft at base
Concrete Volume: 3,250,000 yd^3

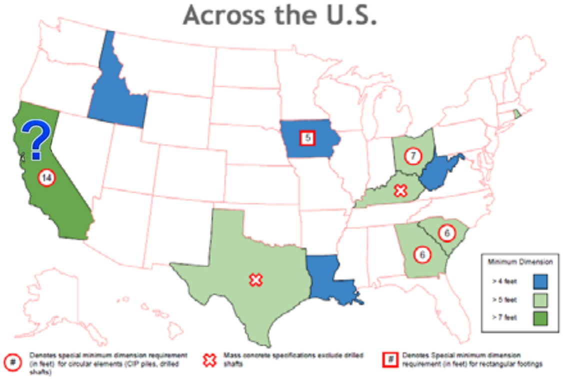
What is Mass Concrete?

ACI 207.1R Definition

"Mass concrete is any volume of concrete with dimensions large enough to require that measures be taken to cope with the **generation of heat from hydration of the cement** and attendant volume change to **minimize cracking**."

- This definition does not give a specific dimension, as high temperatures can be reached in many members depending on the mixture proportions, placement conditions, and constructions practices
- ACI 301-10: Members with least dimension ≥ **4 ft**

Mass Concrete Designation Across the U.S.



(Source: Drew Eiland, Auburn University, 2016)

Potential Mass Concrete Elements

Bent Caps

Footings

Bridge Piers

Presentation Objectives

The following will be covered:

- Why concrete temperature control is important during the construction of mass concrete elements
- Sample mass concrete temperature data collected from ALDOT projects
- Development of a preliminary ALDOT mass concrete specification
- Concrete temperature control strategies

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Mass Concrete Concerns

- Potential risks in mass concrete members:
  1) High Early-Age Temperatures:
  - **Delayed Ettringite Formation (DEF)**
    - In elements exposed to moisture, avoid excessively high early-age in-place concrete temperatures

  2) Excessive Temperature Differences:
  - **Thermal cracking**
    - Avoid large **temperature differences** between core and edge of element

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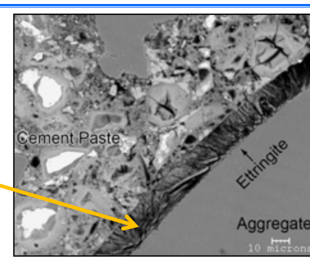
Delayed Ettringite Formation (DEF)

- DEF is **internal** sulfate attack:
  - Expansion in the paste due to DEF causes cracks in paste and around aggregates
  - High DEF risk in moist, **plain** portland cement concrete structures when early-age concrete temperatures **> 160 °F**
  - High DEF risk when temperatures **> 185 °F** are reached when concrete contains:
    i. ≥ **25%** Class F Fly Ash
    ii. ≥ **35%** Class C Fly Ash
    iii. ≥ **35%** Slag Cement
  - **Structures affected:**
    - Mass concrete members
    - Precast members

(Source: ACI 201.2R-16)

Delayed Ettringite Formation (DEF)

Gap



Expanded paste becomes detached from aggregates. This creates gaps at the paste-aggregate interface. Gaps are subsequently filled with larger ettringite crystals as shown here.

(Mehta and Monteiro (2006))

DEF Example in Mass Concrete

Pictures courtesy of
Dr. Folliard, UT Austin

San Antonio Y Overpass, TX

DEF Example in Bent Cap

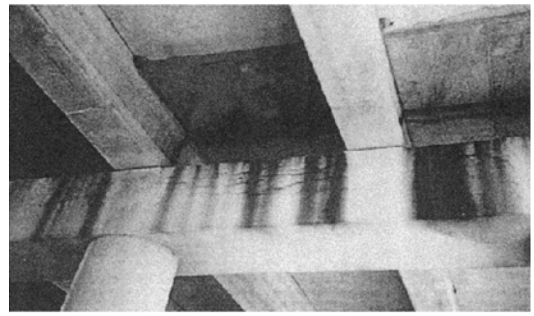


Figure 15 - A Cast-in-place Bent Cap with Premature Cracking from DEF (Lawrence et al. 1999)

Instrumented Mass Concrete Elements

1. Albertville
2. Scottsboro (×2)
3. Harpersville
4. Birmingham
5. Elba
6. Brewton

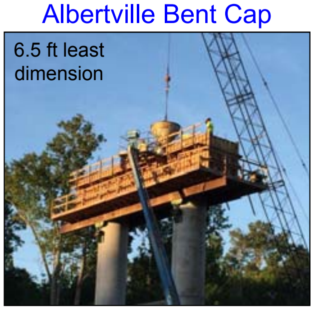
Instrumented Mass Concrete Elements

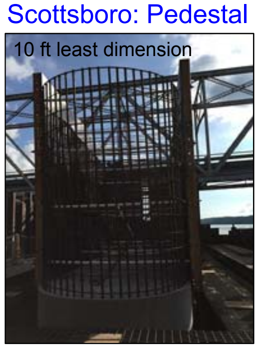
No.	ALDOT ID	Location	Site Description	Element Description
1	BRF-0075(511)	Marshall Co. near Albertville	Scarham Bridge Replacement	• Bent cap: **6.5 ft** least dimension
2	BRF-0035(504)	Jackson Co., Scottsboro	SR 35 over Tennessee River	• Pedestal: 3 lifts, each = **10 ft** ×12.5 ft ×34 ft • Bent Cap: **6.5**×7.5'×41'
3	BR-0025(500)	Shelby Co. near Harpersville	SR 25 over CSX RR	• Crash wall: **4'**×10'×48' (i.e. 4 ft least dim.)
4	STPBHF-I020(349)	Birmingham	12th Avenue North and 31st Street over I20/59	• Column: **4.5 ft** diameter • Pier Caps: **5.0 ft** least dimension
5	NHF-0203(523)	Coffee Co., Elba	Bridge for SR 203 over Pea River	• Bent Cap: **5.0 ft** least dimension
6	BR-0041(501)	Escambia Co., Brewton	Conecuh River Bridge Repl. on SR 41	• Bent Cap: **6.0 ft** least dimension

Example of Instrumented Elements

Scottsboro: Pedestal

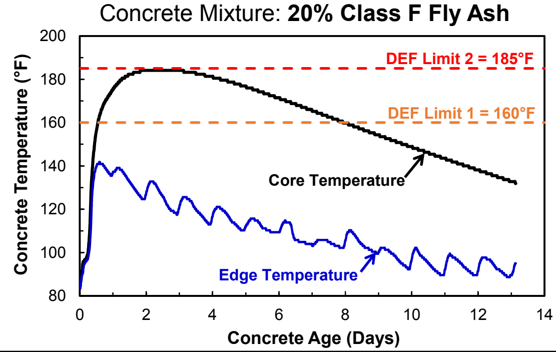
Albertville Bent Cap





Example for Scottsboro Pedestal

Concrete Mixture: **20% Class F Fly Ash**



Summary of Results

- High DEF risk when temperatures > **160 °F in plain** portland cement concrete
- High DEF risk when temperatures > **185 °F** when concrete contains: ≥ **25%** F Fly Ash or ≥ **35%** C Fly Ash

Location	Element	Least Dim.	Concrete	Max. Temp.
Albertville	Bent Cap	6.5 ft	**25% F Ash**	168 °F
Harpersville	Crash Wall	4 ft	20% C Ash	**168 °F**
Scottsboro	Pedestal	10 ft	20% F Ash	**185 °F**
Scottsboro	Bent Cap	6.5 ft	20% F Ash	**167 °F**
Elba	Bent Cap	5 ft	20% F Ash	127 °F
Birmingham	Column	4.5 ft	20% C Ash	111 °F
Brewton	Bent Cap	6 ft	20% C Ash	133 °F

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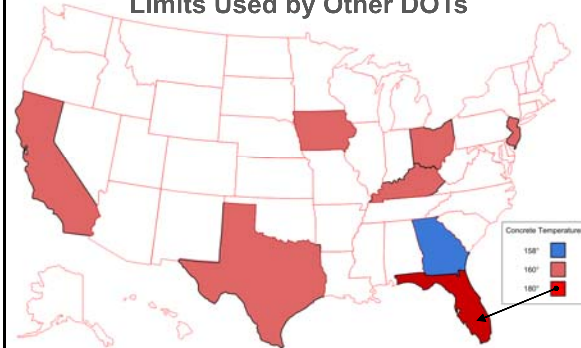
Maximum Concrete Temperatures
Limits Used by Other DOTs



(Source: Drew Eiland, Auburn University, 2016)

Proposed Specification to Control DEF
(Based on ACI 201.2R-16)

Maximum In-Place Concrete Temperature (T_{max})	Specification Requirements
T_{max} < 160°F	None.
160 °F ≤ T_{max} ≤ 185 °F	Use any portland cement, except Type III, with any of the following: i. ≥ **25%** Class F Fly Ash ii. ≥ **35%** Class C Fly Ash iii. ≥ **35%** Slag Cement iv. ≥ 5% Silica Fume + ≥ 20% Class F Fly Ash v. ≥ 5% Silica Fume + ≥ 25% Slag Cement
T_{max} > 185 °F	This condition is not allowed.

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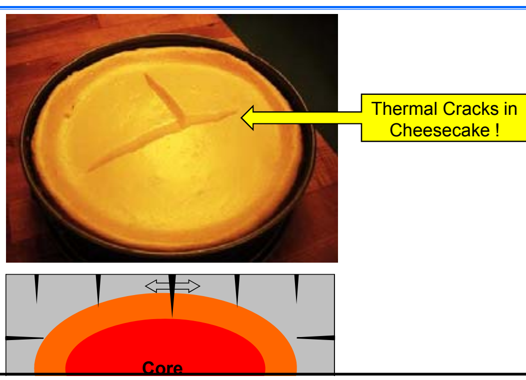
Temperature Difference



Thermal Stress

$$\text{Thermal Stress} = \Delta T \cdot CTE \cdot E_c \cdot K \cdot R$$

Where:

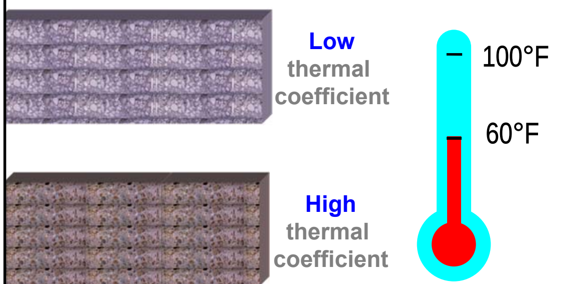
ΔT = Temperate change (°F)
CTE = Coefficient of thermal expansion (in./in./°F)
E_c = Modulus of elasticity (psi)
K = Creep factor (0.65 for AL early-age concrete)
R = Degree of restraint factor (0.0 to 1.0)

***Note*: Thermal stresses can be large !**

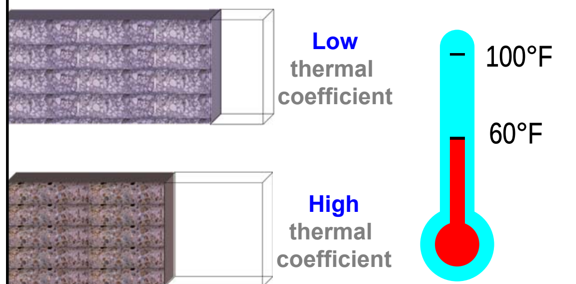
Consider: ΔT = **35°F decrease**

Stress = (35°F)(7x10^{-6} in./in./°F)(4.0x10^{6} psi)(0.65)(0.8)
= 510 psi (Tension) **> Tensile strength !**

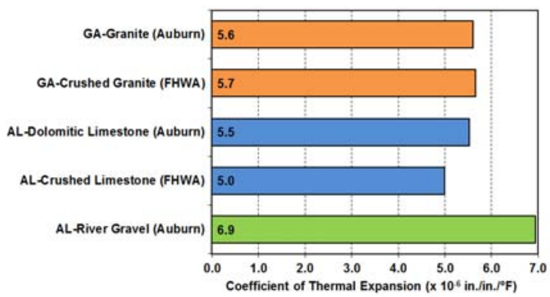
Thermal Coefficient of Expansion



Thermal Coefficient of Expansion



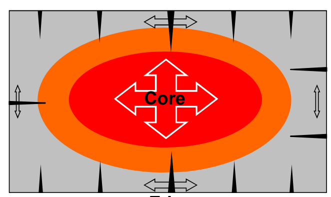
Typical Regional CTE Values



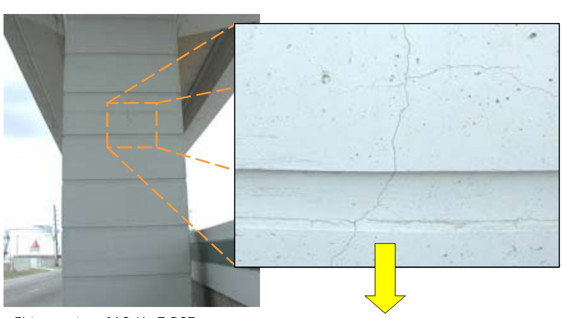
(Source: ALDOT Project 930-645, 2010)

Temperature Difference Limit (**ΔT**)

- Temperature difference between interior and surface
  - Limit **ΔT** to minimize thermal cracking
  - Crack width is a function of: **ΔT** = $T_{Core} - T_{Edge}$



Thermal Cracking Example



Picture courtesy of J.C. Liu, TxDOT

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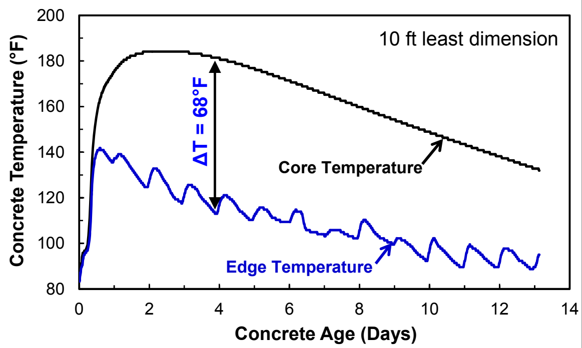
Temperature Difference Limit (**ΔT**)

- Most used limit: **ΔT ≤ 35°F**
  - Derived by Bamforth in 1980s based on **river gravel** aggregate

Aggregate	Gravel	Limestone
CTE (×10^{-6}/°F)	6.67	4.44
ΔT_{max} (°F)	**36**	70

  - Is **very** conservative as it does not account for concrete with lower CTE (i.e. limestone)
  - Using a constant limit does not account for the gain in concrete tensile strength with time

Example: Scottsboro Pedestal



Summary of Results

- Most used limit: Cracking when **ΔT** > **35°F**

Location	Element	Least Dim.	Concrete	Max. ΔT
Albertville	Bent Cap	6.5 ft	25% F Ash	40 °F
Harpersville	Crash Wall	4 ft	20% C Ash	31 °F
Scottsboro	Pedestal	10 ft	20% F Ash	68 °F
Scottsboro	Bent Cap	6.5 ft	20% F Ash	51 °F
Elba	Bent Cap	5 ft	20% F Ash	21 °F
Birmingham	Column	4.5 ft	20% C Ash	19 °F
Brewton	Bent Cap	6 ft	20% C Ash	21 °F

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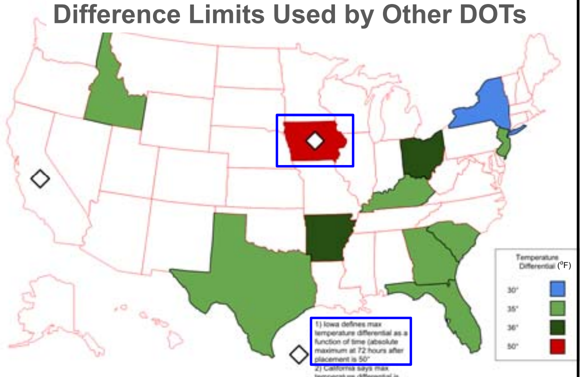
Maximum Concrete Temperature Difference Limits Used by Other DOTs



(Source: Drew Eiland, Auburn University, 2016)

Temperature Difference Limit (ΔT)

- In this study **ΔT** limits were determined for ALDOT concrete by performing early-age stress analysis
  - This allows larger ΔT limits, which will be more economical
  - This accounts for:
    - Strength and modulus development with age
    - Measured ALDOT early-age creep response
    - Coefficient of thermal expansion
    - Use of fly ash, slag cement, etc.

Thermal Cracking Tests Performed

- Quantified the early-age creep
- Developed a calibrated thermal cracking prediction model

Placement

Testing

Temperature Difference Limit (ΔT)

Thermal Stress = $\Delta T \cdot CTE \cdot E_c \cdot K \cdot R$

$$\Delta T_{max}(t) = \frac{f_t(t)}{E_c(t) \times CTE \times K \times R}$$

Where:

$\Delta T_{max}(t)$ = Maximum temperature difference (°F)
$f_t(t)$ = Concrete tensile strength (psi)
CTE = Coefficient of thermal expansion (in./in./°F)
$E_c(t)$ = Modulus of elasticity (psi)
K = Creep factor (**0.65** for early-age AL concrete)
R = Degree of restraint factor (**0.5** > 0.42 = Bamforth)

Effect of Concrete Age

- Compressive strength development for Type I cement:

$$f_c(t) = f_{c28}\left(\frac{t}{4+0.85\times t}\right) \quad \text{(ACI 209 2008)}$$

where, $f_c(t)$ = compressive strength
f_{c28} = 28-day strength = 4,000 psi
t = concrete age (days)

- Based on cores tested, this strength development was found to be applicable for field cured concrete (ALDOT Research Project 930-828)

Tensile Strength and Stiffness Models

- Splitting Tensile Strength of Mass Concrete:

$$f_t = 1.7\cdot\left(f_c\right)^{(2/3)} \quad \text{(Raphael, 1984)}$$

Where, f_t = concrete tensile strength (psi)
f_c = concrete compressive strength

- Modulus of Elasticity:

$$E_c(t) = w_c^{1.5}\times 33\sqrt{f_c(t)} \ \ (psi) \quad \text{(AASHTO LRFD)}$$

Where, $E_c(t)$ = concrete modulus of elasticity (psi)
w_c = concrete unit weight (pcf)
f_c = concrete compressive strength (psi)

Temperature Difference Limit (ΔT)

River Gravel Aggregate	
Concrete Age (hrs)	Maximum Temperature Difference, $\Delta T_{max}(t)$ (°F)
12	36
24	40
36	42
48	44
60	45
72	46
84	46
96	47
108	47
120	48
132	48
144	49
156	49
168	49

$$\Delta T_{max}(t) = \frac{f_t(t)}{E_c(t)\times CTE\times K\times R}$$

= Bamforth's constant value

If CTE known, then adjust limits in table by multiplying values with:

$$F_{CTE} = \frac{6.95\ \times 10^{-6}\ \text{in./in./°F}}{CTE_{measured}}$$

= Iowa uses 50°F at 3 days

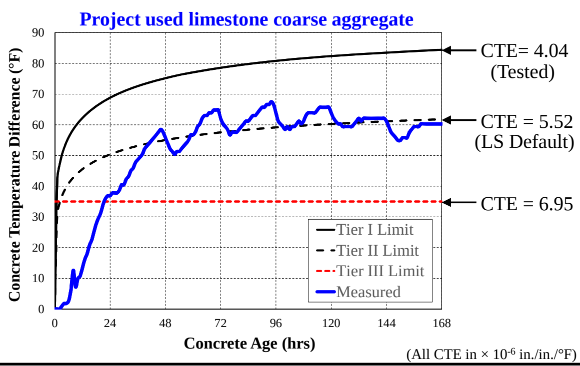
Time-Dependent ΔT Limit:

Proposed Tiered ALDOT Specification

Tier	Requirement	ALDOT Specification
I	CTE of project concrete tested with ASHTO T336	Use **measured** CTE value to calculate **age-dependent ΔT limit**
II	Coarse aggregate type of project concrete is known, but concrete CTE has not been tested	Use defined **default** CTE value to calculate **age-dependent ΔT limit**
III	Coarse aggregate type of project concrete is unknown	Use **constant ΔT limit** of **35 °F**

Assessment of Tiered Specification:

Scottsboro Pedestal Data



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Mass Concrete: Temperature Control Strategies

1) Proper material selection:
   - Reduced cement contents
   - Use high volumes of fly ash and/or slag
2) Precool the concrete
3) Insulate surfaces
4) Place concrete in lifts
5) Cooling pipes

Thermal Control Plan (TCP)

- TCP is required for all mass concrete elements
  - TCP must be approved before placement
- Demonstrates contractor's methods to:
  - Comply with temperature control requirements of mass concrete specification
  - **DEF:**
    - Ensure maximum concrete temperatures remain < 160°F or 185°F
  - **Thermal cracking:**
    - Keep ΔT ≤ Tier I, II, III limits
  - Location of all temperature sensors
    - Core and on rebar close to element edge

States Requiring a TCP for Mass Concrete

(Source: Drew Eiland, Auburn University, 2016)

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Closing Remarks

- By controlling concrete temperatures we can ensure that durable mass concrete members are built
- Avoid the following in mass concrete:
  1) **High Early-Age Concrete Temperatures**
     - This may lead to DEF
     - Recommended limits = **160 °F** and **185 °F**
  2) **Excessive Temperature Differences (ΔT)**
     - This is to control thermal cracking
     - The use of a time-dependent limit is best
     - Recommended limits = Tier I, II, or III

Acknowledgements

- **ALDOT Contributions**:
  - **Materials and Test Bureau:** Scott George, Lyndi Blackburn, Sergio Rodriguez, and Shannon Golden
  - **Bridge Bureau:** Tim Colquett and Randall Mullins
  - **Construction Bureau:** Scott Overby and Will Samford
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  - **Scottsboro**: Derrick Wilson, Randall Roe, Steven Beeler, Joan Taylor, and Kelvin Stewart
  - **Harpersville**: Gary Smith, Tommy Andrews, & Ty Wilson
  - **Elba**: Lee Yelverton and Kendall Chappell
  - **Brewton**: Ken Owens, Mickey Jones, and John Curry
  - And many others …

Thank you for listening.

Questions are welcome !

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