Mass Concrete

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CEE8813A – Material Science of Concrete

Lecture Overview

- General Overview
  - Definitions & Standards, Thermal Cracking, and Temperature Rise
- Temperature & Stress Prediction
- Factors Affecting Temperature Rise
  - Cement, Aggregate, Ambient Temp, SCMs, etc…
- Placement Techniques
- Post-Placement Techniques
  - Embedded Pipe Cooling
  - Formwork Insulation
- Thermal Expansion Reinforcement

General Overview

- Mass Concrete is defined as:
  - "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."

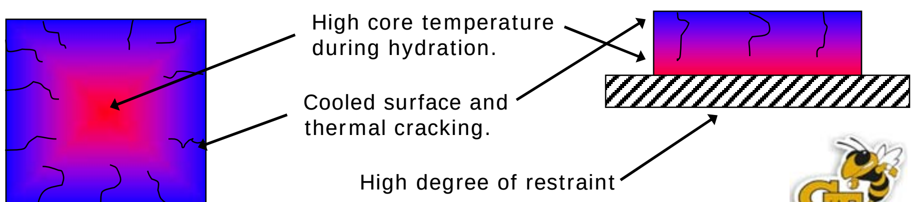
    (ACI Manual of Concrete Practice)
- Fundamental Papers on Mass Concrete
  - "Engineering Mass Concrete Structures" – PCA Professional Development Series
  - "Mass Concrete – ACI 207" ACI Manual of Concrete Practice

General Overview

- Cement Hydration is a very exothermic process, leading to a rise in temperature at the core of very large pours. **(Kelly)**
- If the surface temperature is allowed to deviate greatly from that of the core, thermal cracking will develop.
  - Most codes require a temperature differential of less than 36F from the surface to the core of the section. **(Gajda[1])**
- When dimensions are > 1m or 3ft, temperature rise should be considered. **(Panarese)**
- Common thought is mass concrete principles only apply to large dams. But they apply to any large pour:
  - Massive foundations, bridge piers, thick slabs, nuclear plants, structural columns, etc…

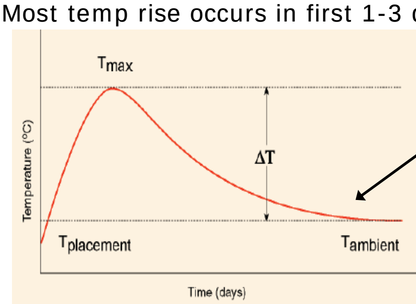
Thermal Cracking

- Cement hydration produces a rise in internal temperature.
- The outer surface cools faster than the core of the section.
- By thermal expansion/contraction, the temperature differential induces thermal (tensile) stresses at the surface. **(Mehta)**
- <u>Stresses **>** Tensile Strength => Thermal Cracking!</u>



Temperature Rise

- Temperature rise varies by many parameters:
  - Cement composition, fineness, and content
  - Aggregate content and CTE (Coeff. of Thermal Expansion)
  - Section geometry
  - Placement & ambient temperatures **(Mass)**
- Most temp rise occurs in first 1-3 days after placement.



For thick sections, cooling to ambient temps may take years.

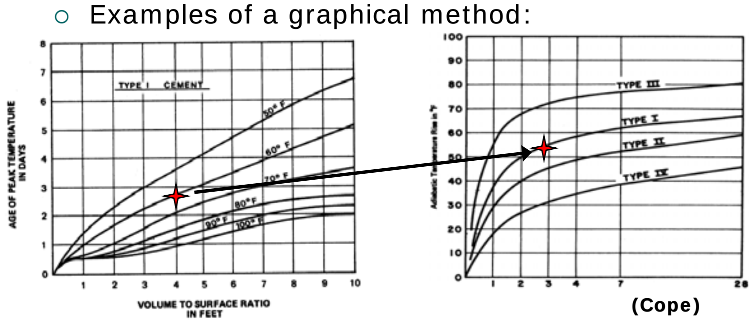
(Mehta)

Temperature & Stress Prediction

- General equations can be used to estimate the temperature rise and thermal stress developed.
- Simplistic way to find temperature rise:
  - Find equivalent cement content, adding SCMs, PC, etc...
  - Equivalent cement content **(lb/yd^3)** * .14 ~= Temp Rise **(F)**
    - 1 lb/yd3 of cement is counted as 1 lb/yd3 cement;
    - 1 lb/yd3 of class F fly ash is counted 0.5 lb/yd3 cement
    - 1 lb/yd3 of class C fly ash is counted 0.8 lb/yd3 cement
    - 1 lb/yd3 of slag cement (at 50 percent cement replacement) is counted as 0.9 lb/yd3 cement
    - 1 lb/yd3 of slag cement (at 75 percent cement replacement) is counted as 0.8 lb/yd3 cement. **(Gajda[2])**
- Many methods are available for the estimation of temperature rise

Temperature & Stress Prediction

- Examples of a graphical method:



(Cope)

-example for a Type 1 cement, 376 lb/yd^3, and 60F placement temperature

-other factors must be examined, such as heat flow to or from the environment

Temperature & Stress Prediction

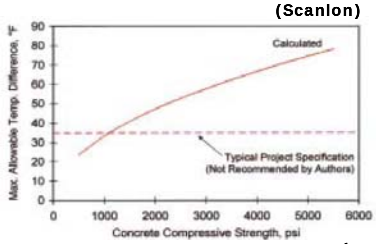
- Other prediction methods:

$$T_c = T_f + \frac{100 \times C}{e_c \times R} - \Delta t$$

where

T_i = placing temperature of concrete
T_f = final stable temperature of concrete
C = strain capacity (in millionths)
e_c = coefficient of thermal expansion per deg of temperature (in millionths)
R = degree of restraint (in percent)
Δt = initial temperature rise of concrete

(Scanlon)

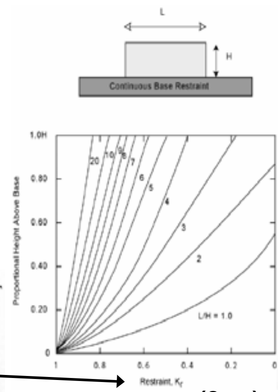


(Gajda[1])

$$\sigma_t = K_r \frac{E}{1+\varphi} \alpha \Delta T$$

where:
σt: tensile stress
Kr: degree of restraint
E: elastic modulus
α: coefficient of thermal expansion
ΔT: temperature change
φ: creep coefficient

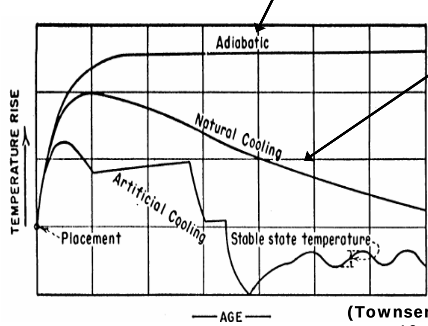
(Mehta)



(Cope)

Temperature & Stress Prediction

- For pours with complex geometries computer models are used.
- Genetic Algorithms are also used to model cement hydration to predict temperature distributions. **(Riding)**
- Adiabatic temperature rise can be used for a conservative estimate.



(Townsend)

$T^{rise}_{actual} < T^{rise}_{adiabatic}$

-Due to heat flow to the surface

-Adiabatic: Q=0

Temperature & Stress Prediction

- Good articles on temperature & stress prediction:
  - "Mass Concrete – ACI 207" ACI Manual of Concrete Practice
  - "Evaluation of Temperature Prediction Methods for Mass Concrete Members" ACI Materials Journal
  - "Modeling Thermal Stresses at Early Ages in a Concrete Monolith" ACI Materials Journal
  - "Estimation of Thermal Crack Resistance for Mass Concrete Structures with Uncertain Material Properties" – ACI Structural Journal
  - "Early-age heat evolution of clinker cements in relation to microstructure and composition: implication for temperature development in large concrete elements" – Cement & Concrete Composites

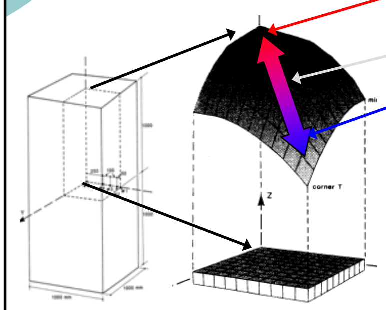
Temperature & Stress Prediction

- Finite Element Analysis can be performed to determine if thermal cracking will occur.
  - For analysis, time dependent function for the CTE, E, Tensile Strength etc… must be found for early-age effects!!! **(Wu)**

Thermal expansion of inner core of the column

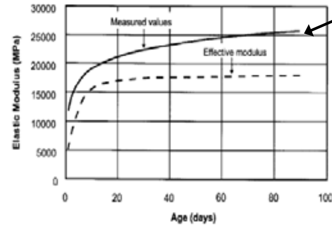
Temperature Differential

Cooling surface, in tension



Concrete Column: FE Model (Cook)

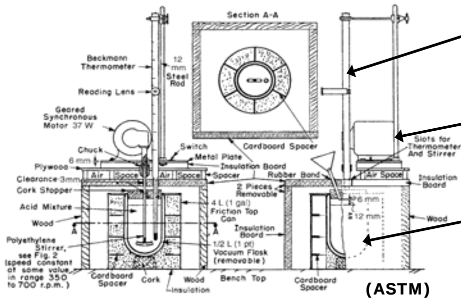
E(t)



(Ayotte)

Temperature & Stress Prediction

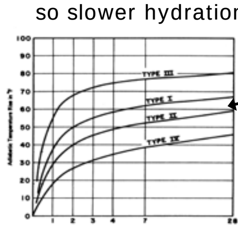
- Heat of Hydration
  - It is important to know the heat of hydration of the cement being used.
  - **ASTM C186** – Standard Test Method for Heat of Hydration of Hydraulic Cement



(ASTM)

Factors Affecting Temp. Rise

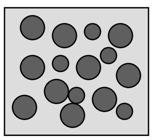
- Geometry
  - Pours with a large volume:surface area ratio are more susceptible to thermal cracking!
  - Research has been performed to produce more accurate dimensions for when temperature rise should be considered. **(Ulm)**
- Cement Composition
  - Cements used for Mass Concrete should have a low C_3S and C_3A content to reduce excessive heat during hydration.
  - Most Mass Concrete structure do not require early strength, so slower hydration is usually not harmful to construction.



(Cope)

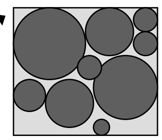
Factors Affecting Temp. Rise

- Cement Fineness
  - Cement with a lower fineness with slow hydration, and reduce temperature rise. **(Mass)**
- Cement Content
  - Mass Concrete mixtures should contain as low of a cement content as possible to achieve the desired strength. This lowers the heat of hydration and subsequent temperature rise. Can be as low as 170 lb/yd^3 **(Mehta)**
- Aggregate Content
  - Coarse Aggregate should be have an MSA of 6in if possible.
  - A higher coarse aggregate content (70-85%) can be used to lower the cement content, reducing temperature rise. **(Mass)**



Normal Concrete

Larger MSA + Better Packing = Less Cement, and less HEAT!

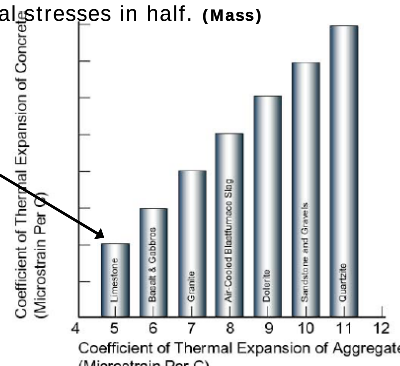


Factors Affecting Temp. Rise

- Coarse Aggregate Coefficient of Thermal Expansion
  - The CTE of the coarse aggregate is the main influence on the CTE of the concrete. Choosing an aggregate with a low CTE can cut thermal stresses in half. **(Mass)**

Lower CTE will provide more resistance to thermal cracking.

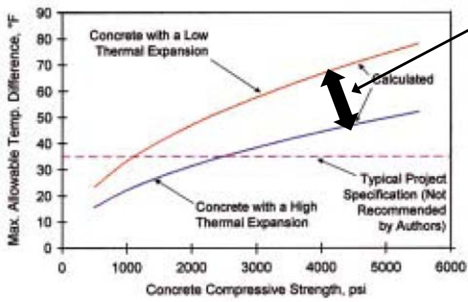
-Lower CTE aggregates tend to have a higher thermal conductivity; so heat is released faster from the core.



(Mehta)

Factors Affecting Temp. Rise

- Effect of concrete CTE:

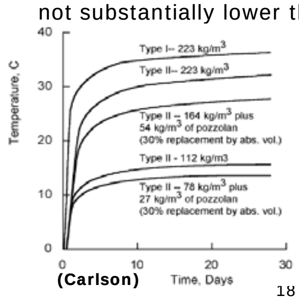


(Gajda[1])

Lower CTE allows for a higher temperature gradient

Factors Affecting Temp. Rise

- Supplementary Cementicious Materials (SCMs)
  - SCMs such as Fly Ash, and Slag can greatly reduce the heat of hydration. **(Liwu)**
  - Pozzolans such as FA (class F is best > slower hydration) and Slag will produce between 15-50% of the heat of normal Portland Cement. **(Atis)**
  - Highly reactive SCMs such as Silica Fume and Metakaolin do not substantially lower the heat of hydration. **(Alshamsi)**

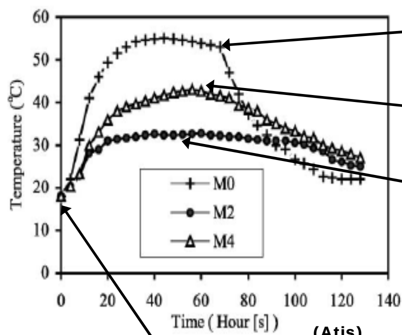


(Carlson)

Lower cement content + pozzolans greatly reduces temperature rise!

Factors Affecting Temp. Rise

- Use of SCMs such as FA and GGBFS is commonly up to 60-75% cement replacement. **(Atis)**



Normal Portland Cement

50% FA Replacement

70% FA Replacement

(Atis)

Placement temperature

Factors Affecting Temp. Rise

	Plain NPC	NPC/ microsilica	NPC/ microsilica/ggbs	Mortar mix
Time to reach peak temperature (minutes)	660	589	721	525
Peak temperature (°C)	91.7	89.2	81.9	59.1
Max. temperature rise (°C)*	69.6	63.2	54.9	31.4

(Alshamsi)

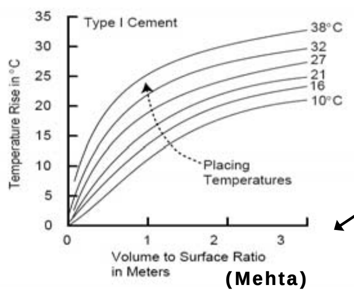
10% SF Replacement

10% SF & 50% GGBFS Replacement

- For more information on SCM replacement
  - "Heat Evolution of High-Volume Fly Ash Concrete" – Cement & Concrete Research
  - "Microsilica and Ground Granulate Blast Furnace Slag Effects on Hydration Temperature" – Cement & Concrete Research
  - "Dam Construction – Concrete Temperature Control Using Fly Ash" – Concrete International

Factors Affecting Temp. Rise

- Placement Temperature
  - Pouring at lower temperatures will reduce the thermal stresses in the section. **(Cope)**
    - Slows hydration > lowers heat of hydration
    - Lowers temperature differential between the core and the outer surface



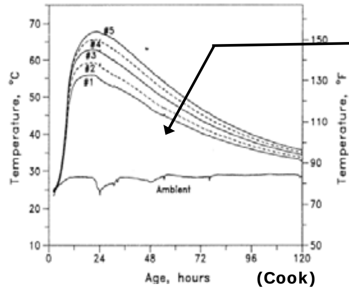
(Mehta)

Lower ambient temps produce less temperature rise!

Lower volume:surface ratio produce less temperature rise!

Factors Affecting Temp. Rise

- W/C has a large effect on temperature rise.
- Most Mass Concrete mixtures have a **<u>~0-2in slump.</u>** **(Dixon)**



(Cook)

Decreasing w/c

-w/c = .25-.4 is common

-WRs or Superplasticizers may have to be used to retain workability.

- For more information on Mass Concrete mix design:
  - “Mass Concrete Mix Proportioning – ACI 211” – ACI Manual of Concrete Plactice

Placement Techniques

- Cooling of aggregate by flushing with cold water is frequently done to reduce placement temperatures.
- Replacing mix water with flaked/crushed ice can greatly reduce the temperature of the mix.
  - Cooling the aggregate and use ice in mix water can reduce placement temperatures up to 20F
  - For heat transfer calculations, all components are changed to water equivalents.

(Scanlon)

Core sample from a large column with thermal cracks.

(Gajda[2])

Placement Techniques

Ingredient	Batch weight	Specific heat	Batch heat content	Water equivalent
	lb	Btu/lb·deg F	Btu/deg F	lb
Coarse aggregate	2500	0.18	450	450
1 percent moisture	25	1.00	25	25
Fine aggregate	1100	0.18	198	198
5 percent moisture	55	1.00	55	55
Cement	235	0.21	49	49
Added water	110	1.00	110	110
	4025		887	887

Temp reduction by cooling coarse aggregate to 38F before placement

$$\frac{475 \text{ moist C.A. water equiv (lb)} \times (75\text{ F} - 38\text{ F})}{887 \text{ concrete water equiv (lb)}} = 19.8\text{ F}$$

Temp reduction by adding mix water at 35F

US units: $$\frac{110\text{ (lb)} \times (70\text{ F} - 35\text{ F})}{887 \text{ water equivalent (lb)}} = 4.3\text{ F}$$

Temp reduction by replacing mix water with ice

US units: $$\frac{110\text{ (lb)} \times 144\text{ (Btu/lb)}}{887 \text{ water equivalent (Btu/deg F)}} = 17.9\text{F}$$

(Scanlon)

-The examples shown above are just for one mix design

Placement Techniques

- Flushing the mix is Liquid Nitrogen can reduce temps.
  - Costs ~$75 to cool a truckload of concrete by 25F

(Beaver)

(Gajda[2])

Post-Placement Techniques

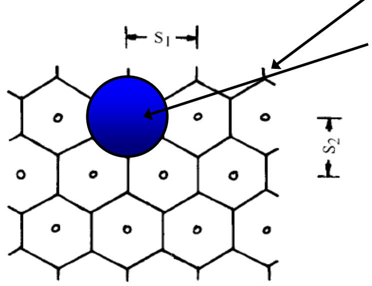
- Two schools of thought exist on post-placement techniques to reduce thermal cracking:
  - 1) Cool the core of the concrete to reduce the temperature differential.
  - 2) Insulate the outer surface to reduce the temperature differential. **(Scanlon)**
- For more information on cooling and insulation techniques:
  - “Cooling and Insulating systems for Mass Concrete” – ACI Manual of Concrete Practice

Post-Cooling

- Post-Cooling utilizes cold water flowing through pipes embedded into the concrete. This helps to transfer heat from the core, and reduce the temperature differential. **(Zhu)**

Example of embedded pipe grid

Area cooled by one pipe

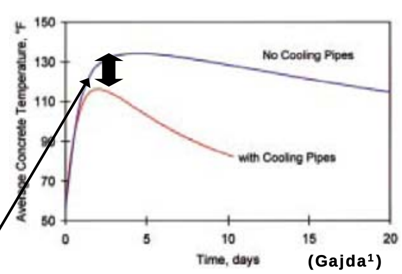


-Pipe spacing is judged by heat transfer principles. Must be spaced in a manner which achieved the desired temperature differential.

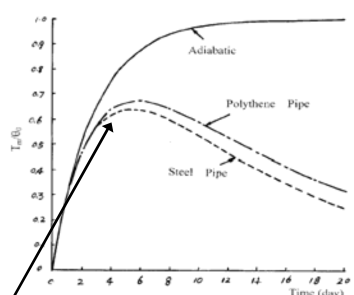
(Zhu)

Post-Cooling

- Instrumentation is used to monitor temperature, to determine flow-rates through cooling pipes. **(Whittier)**



(Gajda[1])



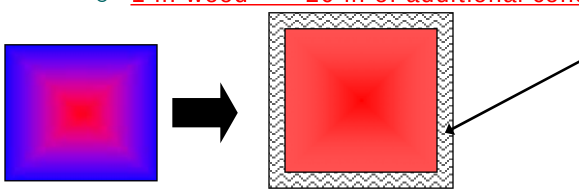
(Zhu)

Lowered temp. from cooling pipes

Steel pipes are the most effective at extracting heat from the core.

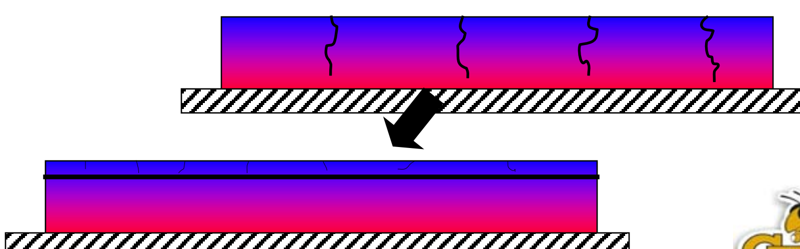
Insulation After Placement

- Insulating formwork after placement is another technique to reduce the temperature gradient.
  - By limiting the heat loss from the surface, the difference in temperature between the surface and the core is minimized. This is especially important in very cold conditions. **(Scanlon)**
- Removing formwork to soon can cause “thermal shock” to the surface, and extensive cracking will occur.
- Metal formwork is very conductive to heat, so additional insulation may be needed to limit heat loss. **(Whittier)**
- 1 in wood ~= 20 in of additional concrete!



Expansion Reinforcement

- Expansion Reinforcement can be used to lessen thermal cracking.
  - Must be designed in addition to loads placed onto the structure.
  - Expansion reinforcement distributes thermal stresses to minimize crack widths.
  - Expansion reinforcement is impractical for very large pours. **(Cope)**



Expansion Reinforcement

- General procedure for expansion reinforcement design.
  - Determine maximum temperature gradient
  - Determine section restraint characteristics (K_r)
  - Determine physical properties of the concrete:
    - CTE, E, Tensile Strength
  - Determine the allowable crack width:
    - Must consider durability and permeability
  - Determine area of steel required to limit cracking

(Cope)

- Specs and equations for the design of expansion reinforcement are presented in:
  - "Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete" – ACI Manual of Concrete Practice

Questions ???