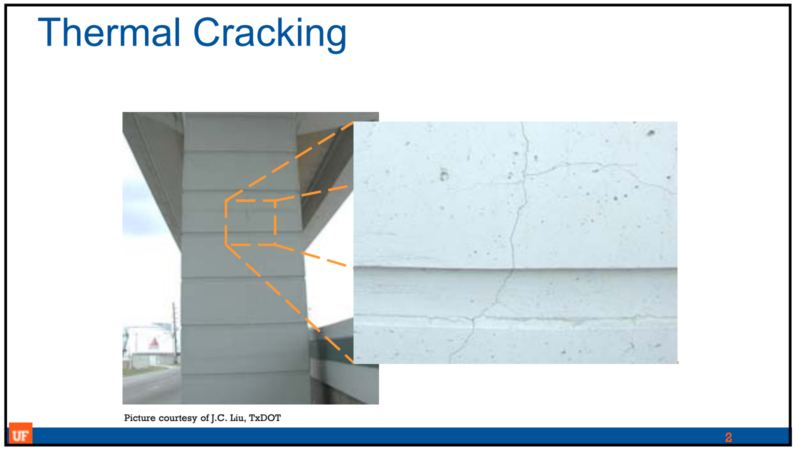
UF Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

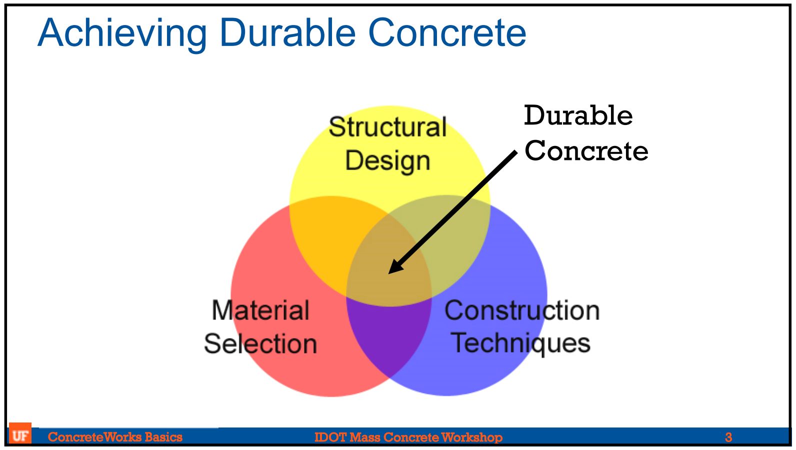
POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

# ConcreteWorks Software For Iowa Use

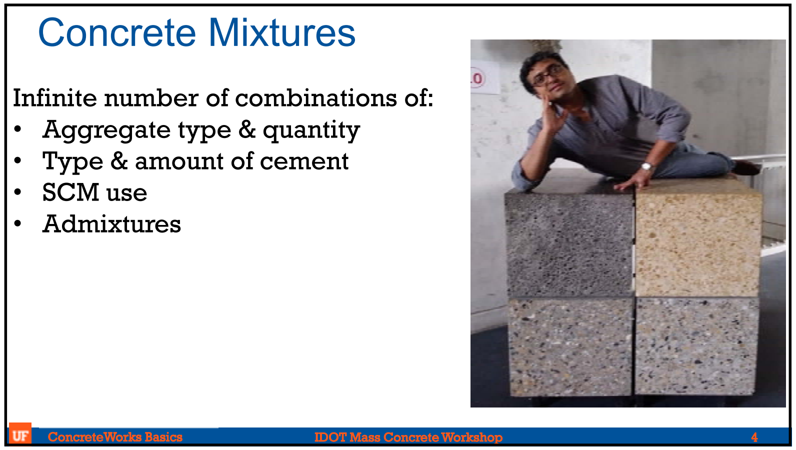


## Thermal Cracking

Picture courtesy of J.C. Liu, TxDOT



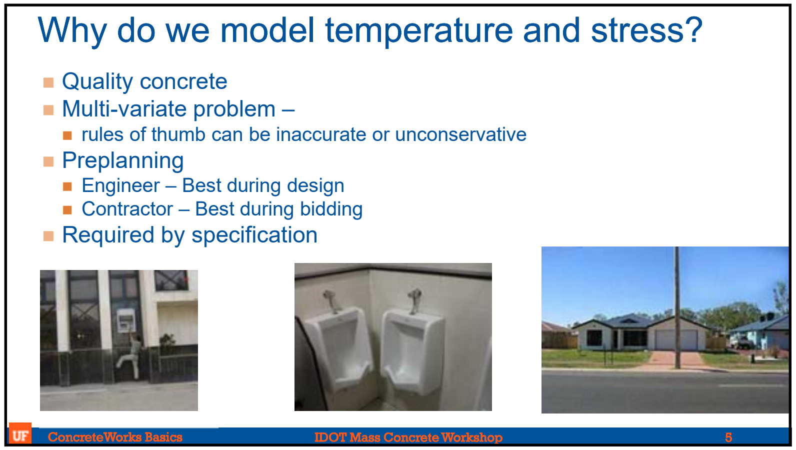
## Achieving Durable Concrete



## Concrete Mixtures

Infinite number of combinations of:

- Aggregate type & quantity
- Type & amount of cement
- SCM use
- Admixtures



## Why do we model temperature and stress?

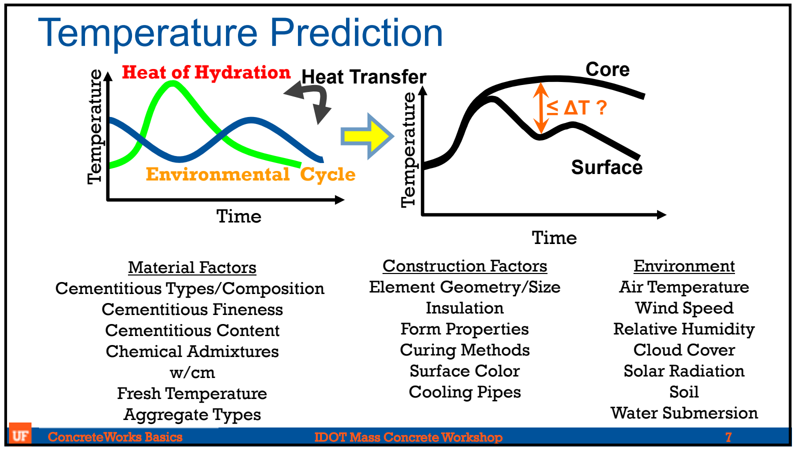
- Quality concrete
- Multi-variate problem –
  - rules of thumb can be inaccurate or unconservative
- Preplanning
  - Engineer – Best during design
  - Contractor – Best during bidding
- Required by specification

UF ConcreteWorks Basics IDOT Mass Concrete Workshop 5

## Self-Generated Restraint

- Why is the bread surface cut before baking?

UF ConcreteWorks Basics IDOT Mass Concrete Workshop 6



## Temperature Prediction

| Material Factors | Construction Factors | Environment |
|---|---|---|
| Cementitious Types/Composition | Element Geometry/Size | Air Temperature |
| Cementitious Fineness | Insulation | Wind Speed |
| Cementitious Content | Form Properties | Relative Humidity |
| Chemical Admixtures | Curing Methods | Cloud Cover |
| w/cm | Surface Color | Solar Radiation |
| Fresh Temperature | Cooling Pipes | Soil |
| Aggregate Types | | Water Submersion |

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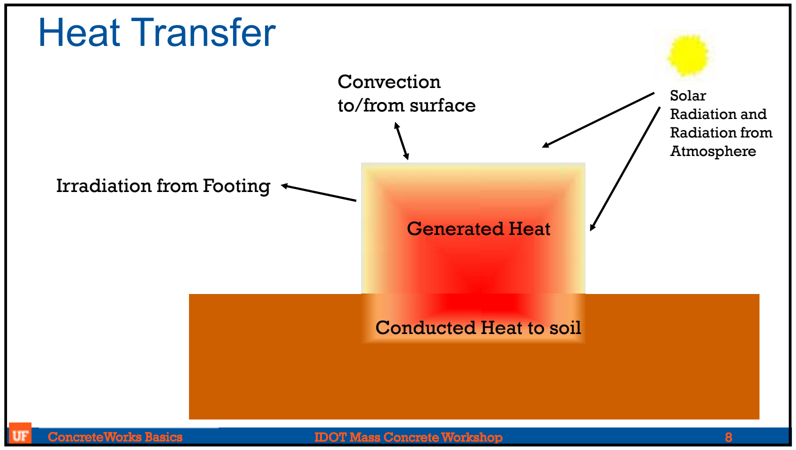

## Heat Transfer

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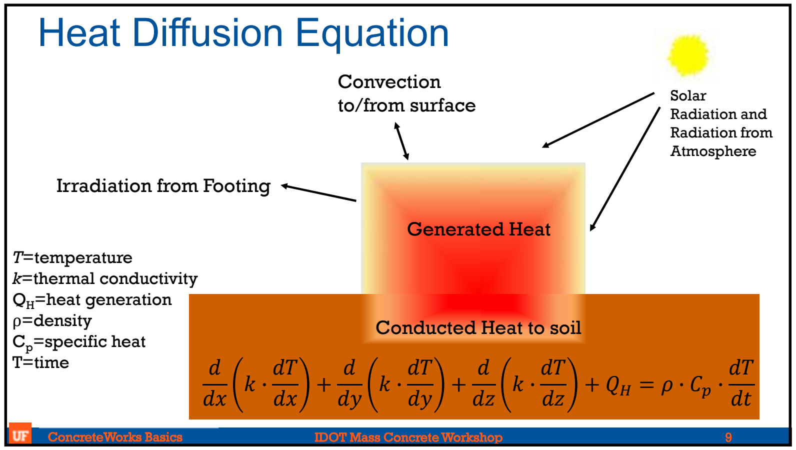


## Heat Diffusion Equation

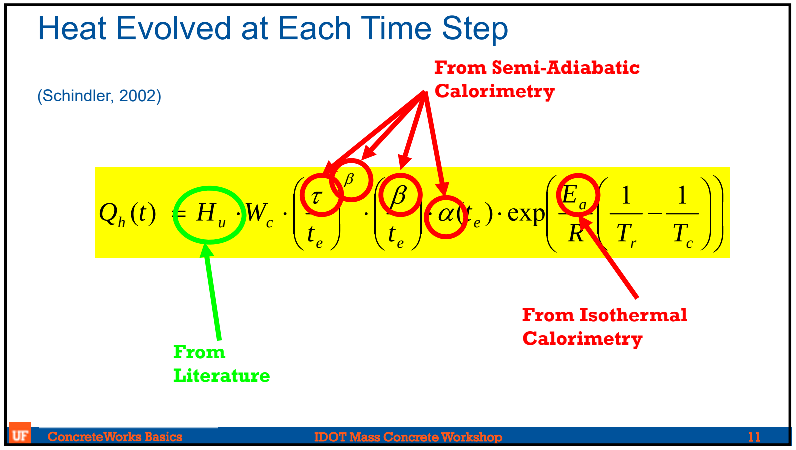
$T$=temperature
$k$=thermal conductivity
$Q_H$=heat generation
$\rho$=density
$C_p$=specific heat
T=time

$$\frac{d}{dx}\left(k\cdot\frac{dT}{dx}\right)+\frac{d}{dy}\left(k\cdot\frac{dT}{dy}\right)+\frac{d}{dz}\left(k\cdot\frac{dT}{dz}\right)+Q_H=\rho\cdot C_p\cdot\frac{dT}{dt}$$

## Temperature Prediction Methods

Increasing Complexity

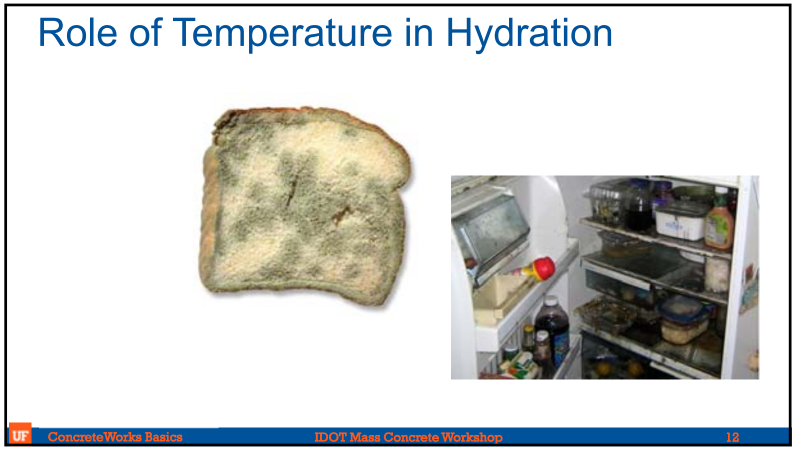
- Estimate Max Temperature
- Schmidt Method
- ConcreteWorks
- Proprietary software (Finite Element Analysis)



## Heat Evolved at Each Time Step

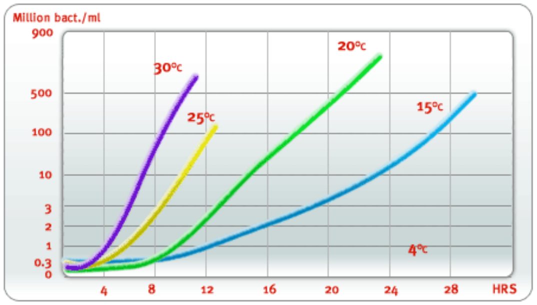
(Schindler, 2002)

$$Q_h(t)=H_u\cdot W_c\cdot\left(\frac{\tau}{t_e}\right)^{\beta}\cdot\left(\frac{\beta}{t_e}\right)\cdot\alpha(t_e)\cdot\exp\left(\frac{E_a}{R}\left(\frac{1}{T_r}-\frac{1}{T_c}\right)\right)$$



## Role of Temperature in Hydration

# Temperature Sensitivity Example



Effect of temperature on bacteria growth in milk

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# Arrhenius Equation

- Reaction Rate (S. Arrhenius, 1889)
  - Where
    - k = rate of reaction
    - A = constant (=0)
    - R = Universal gas constant (8.314)
    - T = reference temperature
    - $E_a$ = Activation Energy

$$\ln k = \ln A - \frac{E_a}{RT}$$

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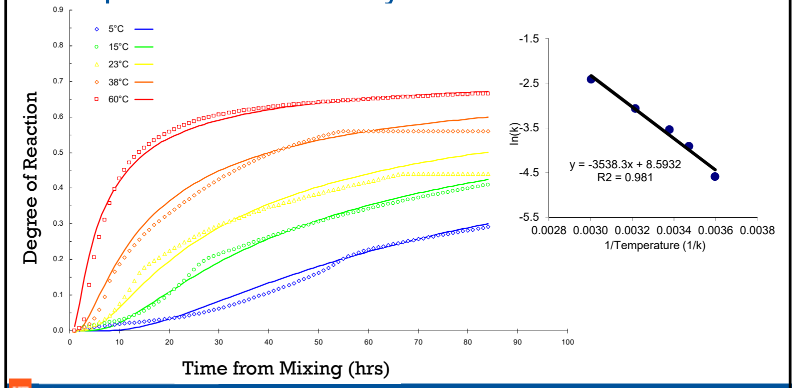
# Temperature Sensitivity of Cement Reaction



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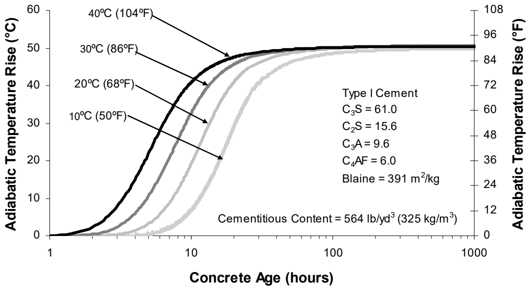
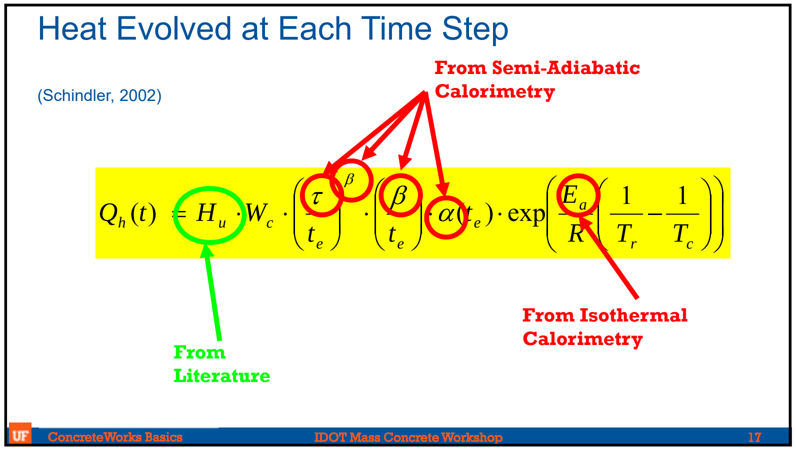
# Effects of Curing Temperature on Adiabatic Temperature Rise





## Heat Evolved at Each Time Step

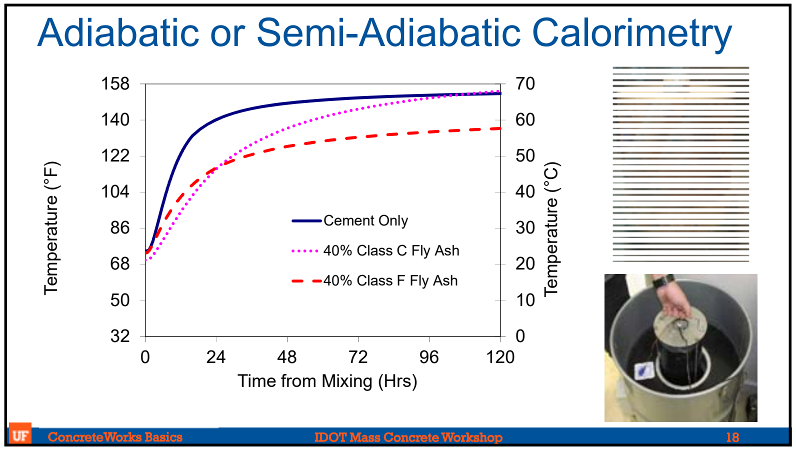
(Schindler, 2002)

**From Semi-Adiabatic Calorimetry**

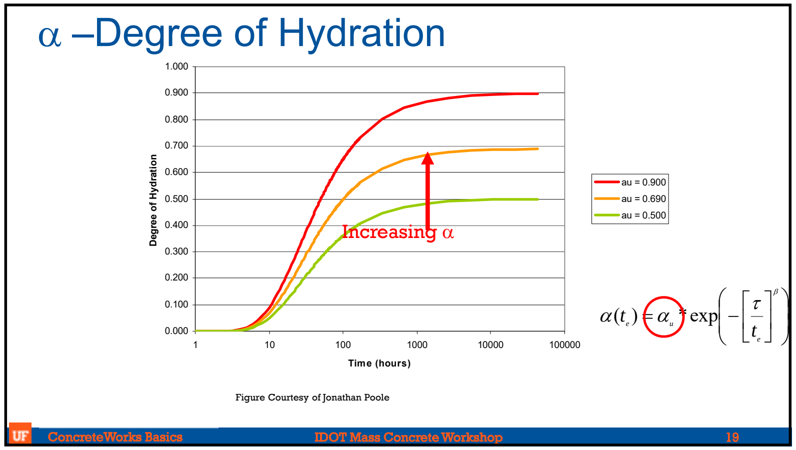
$$Q_h(t) = H_u \cdot W_c \cdot \left(\frac{\tau}{t_e}\right)^{\beta} \cdot \left(\frac{\beta}{t_e}\right) \cdot \alpha(t_e) \cdot \exp\left(\frac{E_a}{R}\left(\frac{1}{T_r} - \frac{1}{T_c}\right)\right)$$

**From Literature**

**From Isothermal Calorimetry**



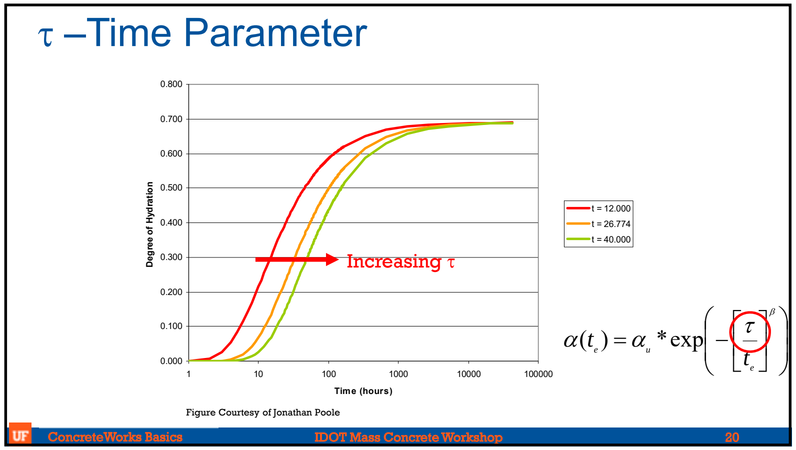
## Adiabatic or Semi-Adiabatic Calorimetry



## α –Degree of Hydration

$$\alpha(t_e) = \alpha_u * \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right)$$

Figure Courtesy of Jonathan Poole

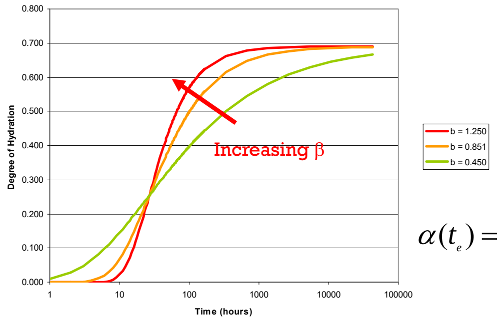


## τ –Time Parameter

$$\alpha(t_e) = \alpha_u * \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right)$$

Figure Courtesy of Jonathan Poole

# β –Slope Parameter



$$\alpha(t_e) = \alpha_u * \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right)$$

Figure Courtesy of Jonathan Poole

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# Model for Hydration Built From:

- $E_a$ Trends – From 116x5 Isothermal tests
- $\alpha_u$, $\tau$, $\beta$, $H_u$ Trends – From Semi-Adiabatic Data – 204 Semi-Adiabatic Tests
- Validation performed using data from Schidler (2005), Ghe Li (2006), and field sites – 58 Semi-Adiabatic Tests
- Variability of test methods is quantified – 63 Semi-Adiabatic Tests.
- A brief overview of the trends seen in the study is shown next.

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| **Variable** | **Range of Tests** | **Effect on $\tau$** | **Effect on $\beta$** | **Effect on $\alpha_u$** |
|---|---|---|---|---|
| Fly Ash (%Replacement) | 15-55% | → | ↘ | ↓ |
| Fly Ash (CaO%) | 0.7-28.9% CaO | → | ↖ | Varies |
| GGBF slag | 30-70% | Large → | Small ↘ | Varies |
| Silica Fume | 5-10% | None | None | Small ↑ |

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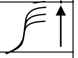
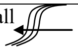
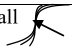
| **Variable** | **Range of Tests** | **Effect on $\tau$** | **Effect on $\beta$** | **Effect on $\alpha_u$** |
|---|---|---|---|---|
| LRWR | 0.22-0.29% | Varies | Small ↖ | Varies |
| WRRET | 0.18-0.53% | Large → | Large ↖ | Large ↓ |
| MRWR | 0.34-0.74% | Large → | Small ↖ | Varies |
| HRWR | 0.78-1.25% | None | Small ↖ | Large ↓ |
| PCHRWR | 0.27-0.68% | None | Small ↖ | Large ↓ |
| ACCL | 0.74-2.23% | Small ← | None | Varies |
| AEA | 0.04-0.09% | None | None | None |

| Variable | Range of Tests | Effect on $\tau$ | Effect on $\beta$ | Effect on $\alpha_u$ |
|---|---|---|---|---|
| Increasing w/c | 0.32-0.68 | None | None | Large  |
| Placement Temp | 15-38 °C<br>(50-100 °F) | None | None | None |
| Increase Cement Fineness | 350-540 $m^2/kg$ | Small  | Small  | Varies |

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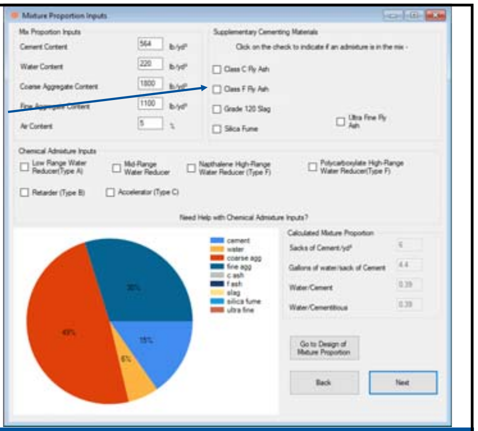
# Proportions

Click checkboxes to use an SCM



Mixture Proportion Inputs

Mix Proportion Inputs
Cement Content 564 lb/yd³
Water Content 220 lb/yd³
Coarse Aggregate Content 1800 lb/yd³
Fine Aggregate Content 1100 lb/yd³
Air Content 5 %

Supplementary Cementing Materials
Click on the check to indicate if an admixture is in the mix -
☐ Class C Fly Ash
☐ Class F Fly Ash
☐ Grade 120 Slag
☐ Silica Fume
☐ Ultra Fine Fly Ash

Chemical Admixture Inputs
☐ Low Range Water Reducer(Type A)
☐ Mid-Range Water Reducer
☐ Napthalene High-Range Water Reducer (Type F)
☐ Polycarboxylate High-Range Water Reducer(Type F)
☐ Retarder (Type B)
☐ Accelerator (Type C)

Need Help with Chemical Admixture Inputs?

Calculated Mixture Proportion
Sacks of Cement/yd³ 6
Gallons of water/sack of Cement 4.4
Water/Cement 0.39
Water/Cementitious 0.39

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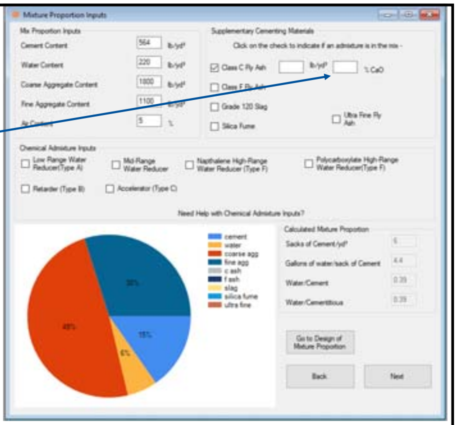
# Proportions

Don't forget to enter CaO content of fly ashes

Check when admixtures used.



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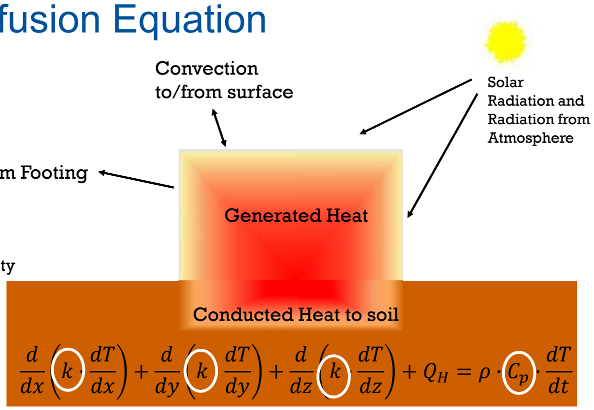
# Heat Diffusion Equation



Convection to/from surface

Solar Radiation and Radiation from Atmosphere

Irradiation from Footing

Generated Heat

Conducted Heat to soil

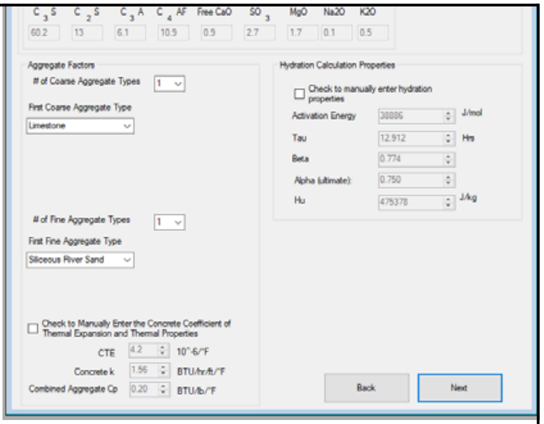
$T$=temperature
$k$=thermal conductivity
$Q_H$=heat generation
$\rho$=density
$C_p$=specific heat
T=time

$$\frac{d}{dx}\left(k\cdot\frac{dT}{dx}\right)+\frac{d}{dy}\left(k\cdot\frac{dT}{dy}\right)+\frac{d}{dz}\left(k\cdot\frac{dT}{dz}\right)+Q_H=\rho\cdot C_p\cdot\frac{dT}{dt}$$

# Aggregates

Material Properties Input Screen

- Concrete thermal properties based on aggregate combination selected
- Can input your own thermal properties by checking box (for example, to use lightweight aggregate)



| $C_3S$ | $C_2S$ | $C_3A$ | $C_4AF$ | Free CaO | $SO_3$ | MgO | Na2O | K2O |
|---|---|---|---|---|---|---|---|---|
| 60.2 | 13 | 6.1 | 10.5 | 0.5 | 2.7 | 1.7 | 0.1 | 0.5 |

Aggregate Factors
\# of Coarse Aggregate Types: 1
First Coarse Aggregate Type: Limestone
\# of Fine Aggregate Types: 1
First Fine Aggregate Type: Siliceous River Sand
☐ Check to Manually Enter the Concrete Coefficient of Thermal Expansion and Thermal Properties
CTE: 4.2 10^-6/°F
Concrete k: 1.56 BTU/hr/ft/°F
Combined Aggregate Cp: 0.20 BTU/lb/°F

Hydration Calculation Properties
☐ Check to manually enter hydration properties
Activation Energy: 38886 J/mol
Tau: 12.912 Hrs
Beta: 0.774
Alpha (ultimate): 0.750
Hu: 475378 J/kg

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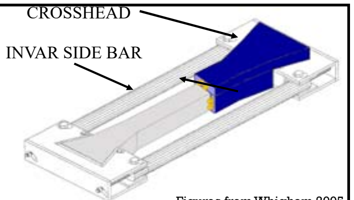
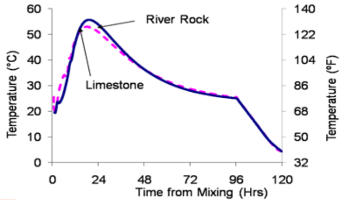
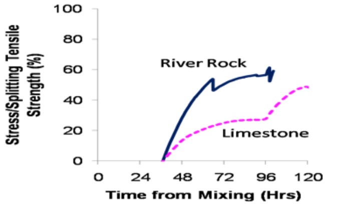
# Aggregate Type

| Coarse Aggregate | Concrete CTE |
|---|---|
| River Rock | 10.5 με/° C |
| Limestone | 6.6 με/° C |



Figures from Whigham 2005





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# Aggregates

$$\alpha_{cteh} = \frac{\alpha_{ca}\cdot V_{ca} + \alpha_{fa}\cdot V_{fa} + \alpha_{p}\cdot V_{p}}{V_{ca} + V_{fa} + V_{p}}$$

| Material | Coefficient of Thermal Expansion values used in ConcreteWorks (με/°C) | Coefficient of Thermal Expansion from Emanuel and Hulsey, 1977 (με/°C) |
|---|---|---|
| Hardened Cement Paste | 10.8 | 10.8 |
| Limestone Aggregate | 3.5 | 3.5 - 6 |
| Siliceous River Gravel and Sand | 11 | 11 – 12.5 |
| Granite Aggregate | 7.5 | 6.5 – 8.5 |
| Dolomitic Limestone Aggregate | 7 | 7 - 10 |

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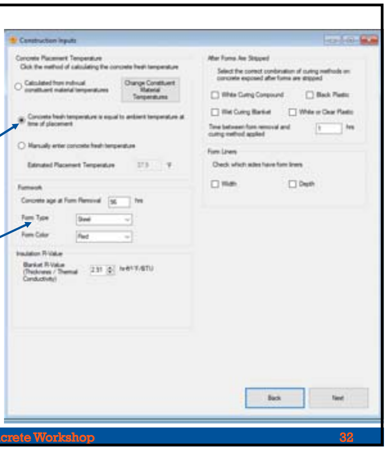
# Construction Inputs

Default is use air temperature at placement

Options: steel, wood, and insulated steel formwork

*If insulated steel forms used, form insulation value appears



Construction Inputs

Concrete Placement Temperature
Click the method of calculating the concrete fresh temperature
○ Calculated from individual constituent material temperatures
● Concrete fresh temperature is equal to ambient temperature at time of placement
○ Manually enter concrete fresh temperature
Estimated Placement Temperature [illegible] °F

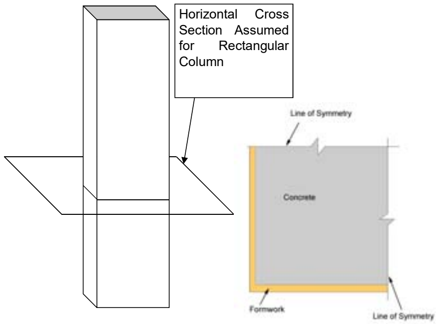
Formwork
Concrete age at Form Removal: 96 hrs
Form Type: Steel
Form Color: Red

Insulation R-Value
Blanket R-Value (Thickness / Thermal Conductivity): 2.31 hr·ft²·°F/BTU

After Forms Are Stripped
Select the correct combination of curing methods on concrete exposed after forms are stripped
☐ White Curing Compound
☐ Black Plastic
☐ Wet Curing Blanket
☐ White or Clear Plastic
Time between form removal and curing method applied: 1 hrs

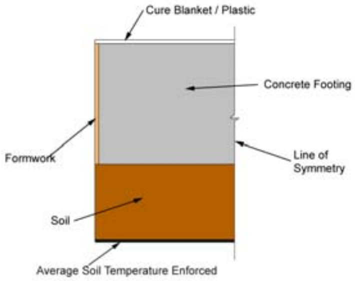
Form Liners
Check which sides have form liners
☐ Width
☐ Depth

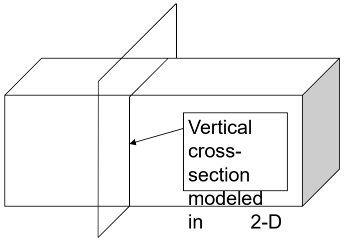
## ConcreteWorks Geometry: Columns



Horizontal Cross Section Assumed for Rectangular Column

## ConcreteWorks Geometry: Footings





Vertical cross-section modeled in 2-D

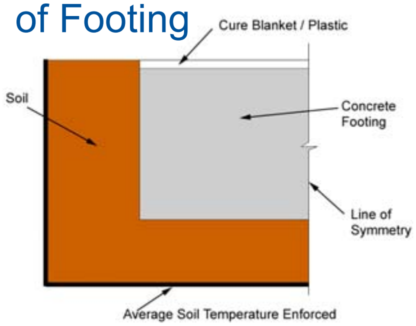
footing

## Foundation Thermal Properties

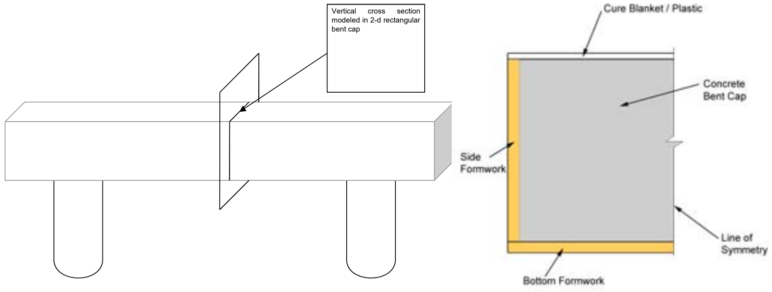
| Subbase Material | Density (kg/m3) | Thermal Conductivity (W/m/K) | Specific Heat (J/kg/K) | Reference |
|---|---|---|---|---|
| Clay | 1460 | 1.3 | 880 | Incropera and Dewitt, 2002 |
| Granite | 2630 | 2.79 | 775 | |
| Limestone | 2320 | 2.15 | 810 | |
| Marble | 2680 | 2.8 | 830 | |
| Quartzite | 2640 | 5.38 | 1105 | |
| Sandstone | 2150 | 2.9 | 745 | |
| Sand | 1515 | 0.27 | 800 | |
| Top Soil | 2050 | 0.52 | 1840 | |
| Concrete* | - | - | - | |

*Concrete is assumed to have the same thermal properties of the concrete used on the footing, with a degree of hydration equal to 0.6.

## ConcreteWorks Geometry: Soil on Sides of Footing



# Bent Cap



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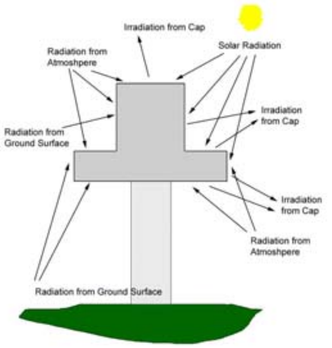
# T-shaped Bent Caps



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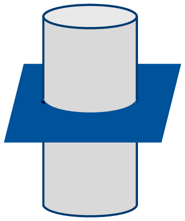
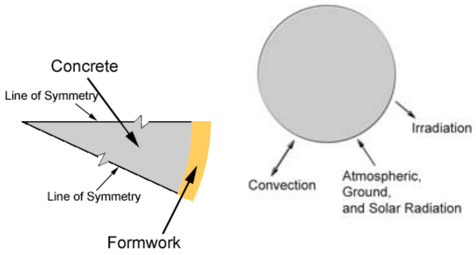
# Circular Column/ Drilled Shaft





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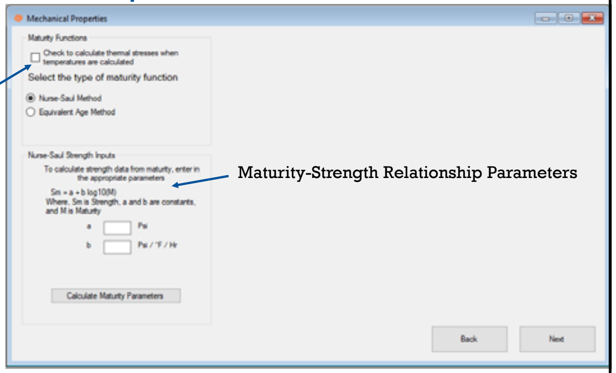
# Mechanical Properties

Check to calculate stresses – can be slow, not recommended for more than 4-5 days of analysis



Mechanical Properties

Maturity Functions

☐ Check to calculate thermal stresses when temperatures are calculated

Select the type of maturity function

● Nurse-Saul Method
○ Equivalent Age Method

Nurse-Saul Strength Inputs

To calculate strength data from maturity, enter in the appropriate parameters

Sm = a + b log10(M)
Where, Sm is Strength, a and b are constants, and M is Maturity

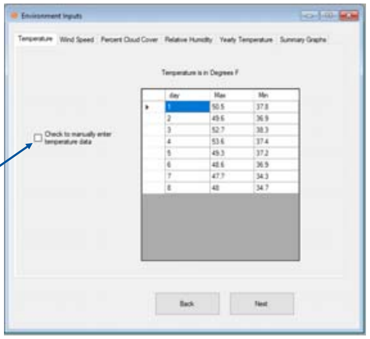
a ☐ Psi
b ☐ Psi / °F / Hr

Maturity-Strength Relationship Parameters

# Environment Inputs (Weather)

Weather data based on 30 year average values

Click here to manually change values



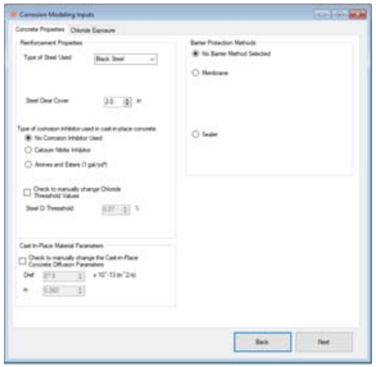
☐ Check to manually enter temperature data

Temperature is in Degrees F

| day | Max | Min |
|---|---|---|
| 1 | 50.5 | 37.8 |
| 2 | 49.6 | 36.9 |
| 3 | 52.7 | 38.3 |
| 4 | 53.6 | 37.4 |
| 5 | 49.3 | 37.2 |
| 6 | 48.6 | 36.9 |
| 7 | 47.7 | 34.3 |
| 8 | 48 | 34.7 |

# Service Life Modeling

Used for corrosion service life model inputs



Type of Steel Used: Black Steel

Steel Clear Cover 2.0 in

Type of corrosion inhibitor used in cast-in-place concrete
● No Corrosion Inhibitor Used
○ Calcium Nitrite Inhibitor
○ Amines and Esters (1 gal/yd³)

☐ Check to manually change Chloride Threshold Values

Steel Cl Threshold %

☐ Check to manually change the Cast-in-Place Concrete Diffusion Parameters

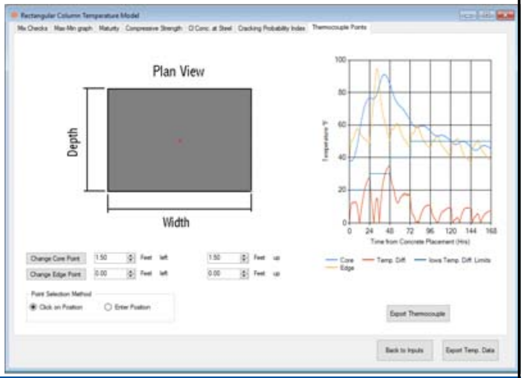
Dref x 10^-13 (m^2/s)

m

● No Barrier Method Selected
○ Membrane
○ Sealer

# Thermocouple Points

Allows the user to select where sensors would be placed to give realistic estimate of values they would measure



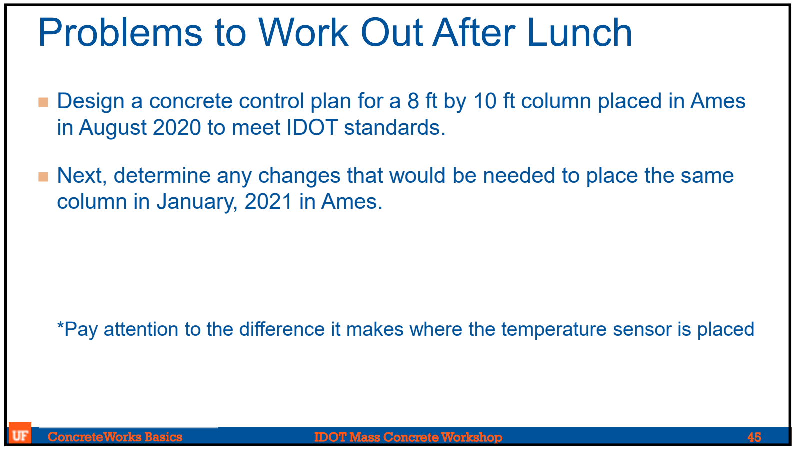
Change Core Point 1.50 Feet left 1.50 Feet up

Change Edge Point 0.00 Feet left 0.00 Feet up

Point Selection Method
● Click on Position ○ Enter Position

# Acknowledgements

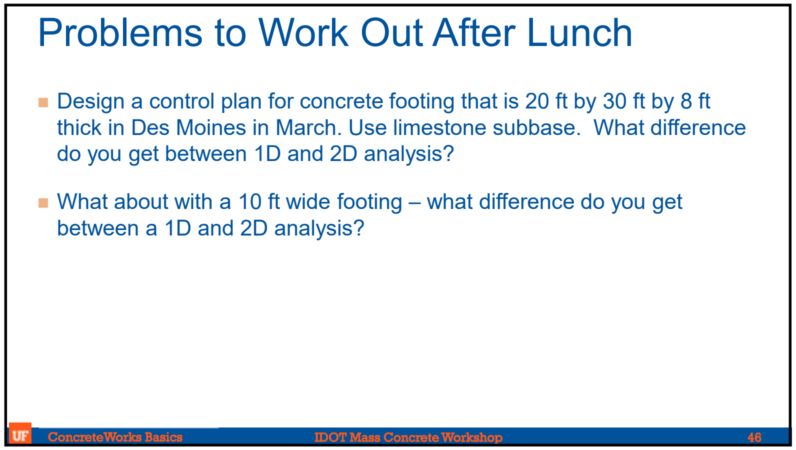
- TxDOT (original software development) & IDOT for providing funding for this work



## Problems to Work Out After Lunch

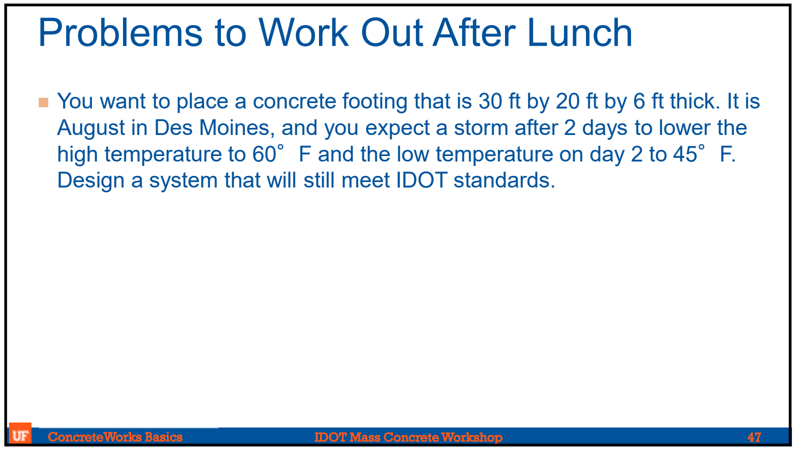
- Design a concrete control plan for a 8 ft by 10 ft column placed in Ames in August 2020 to meet IDOT standards.
- Next, determine any changes that would be needed to place the same column in January, 2021 in Ames.

*Pay attention to the difference it makes where the temperature sensor is placed



## Problems to Work Out After Lunch

- Design a control plan for concrete footing that is 20 ft by 30 ft by 8 ft thick in Des Moines in March. Use limestone subbase. What difference do you get between 1D and 2D analysis?
- What about with a 10 ft wide footing – what difference do you get between a 1D and 2D analysis?



## Problems to Work Out After Lunch

- You want to place a concrete footing that is 30 ft by 20 ft by 6 ft thick. It is August in Des Moines, and you expect a storm after 2 days to lower the high temperature to 60° F and the low temperature on day 2 to 45° F. Design a system that will still meet IDOT standards.