

TRANSPORTATION RESEARCH BOARD

# **Drilled Shaft Design for Durability, Mix Stability, and Thermal Criteria**

**May 25, 2021**

**@NASEMTRB  
#TRBwebinar**



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- 1.5 Professional Development Hour (PDH) – see follow-up email for instructions
- You must attend the entire webinar to be eligible to receive PDH credits
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**REGISTERED CONTINUING EDUCATION PROGRAM**

## #TRBwebinar

# Learning Objectives

1. Identify drilled shaft concrete issues
2. Discuss requirements for workability, stability, and long-term durability of drilled shafts
3. Apply design methodology to establish performance criteria

**#TRBwebinar**



# Evaluation of Tremie Concrete for Deep Foundations

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J. Erik Loehr, Ph.D., P.E.  
University of Missouri and Dan Brown and Associates

TRB Webinar – Designing Drilled Shafts for Durability  
May 25, 2021



# Drilled Shafts – 1980's and 1990's





# Drilled Shafts – 1990's and 2000's





# Drilled Shafts – present





# Drilled Shafts – present





# Fundamental Demands

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## Construction

- Workability
- Workability retention
- Stability
- Passing ability

## Long-term performance

- Integrity
- Strength
- Durability

# FHWA Study Objectives

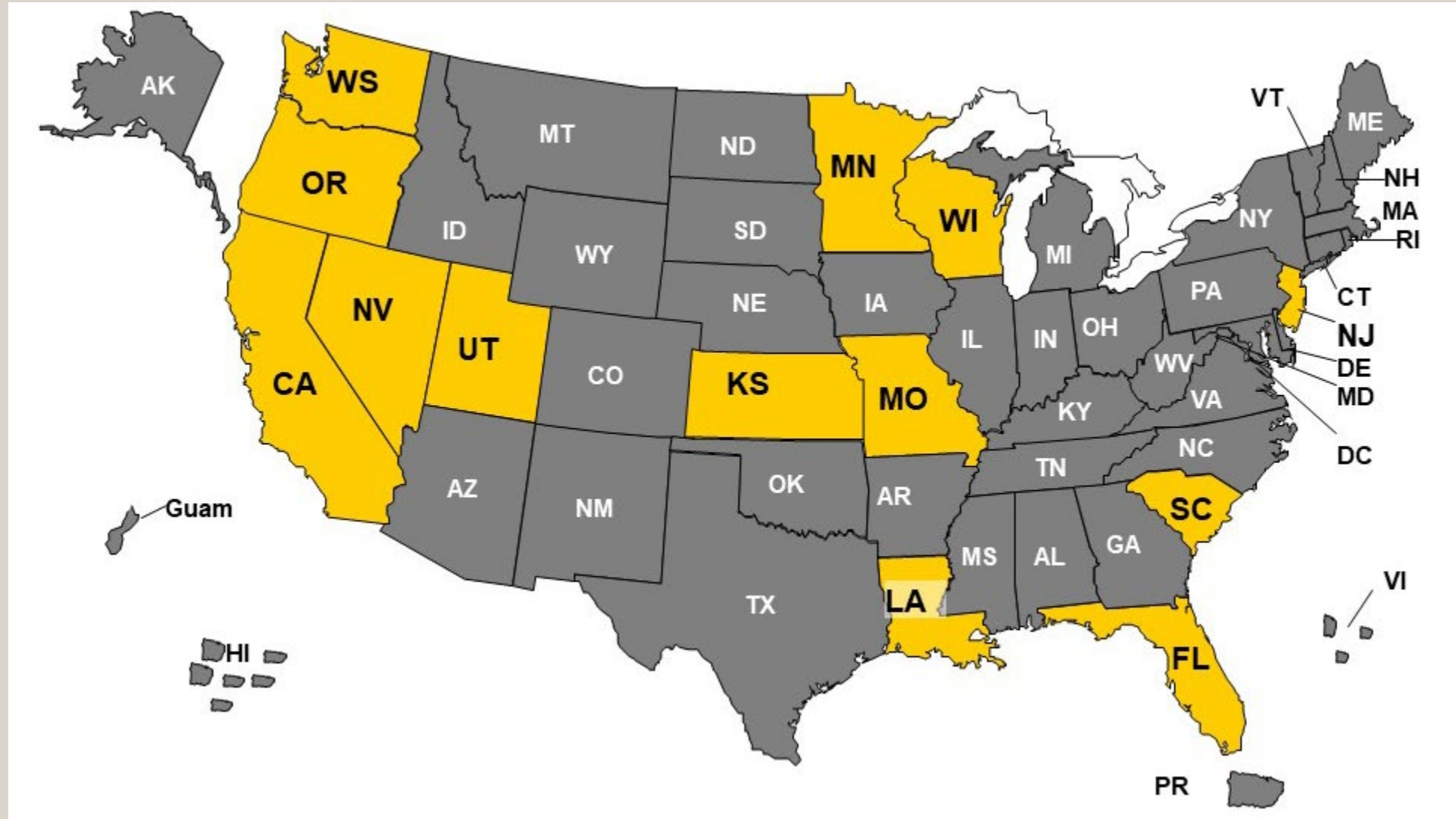
- Document current practice for select state agencies and identify current problems
- Develop and evaluate factors contributing to excessive bleed and evaluate potential tests to identify bleed-prone concrete
- Evaluate durability issues from heat of hydration and develop recommendations for appropriate criteria



From GEC-10: Brown, et al. (2018)



# Synthesis of Current Practices for Drilled Shafts



# Key Findings from Synthesis

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- Workability problems are rare, and generally understood and appreciated
- Segregation and bleed problems have become more common
- Mixed concern regarding thermal issues for “mass concrete” elements
- More complex mix designs have sometimes challenged producers

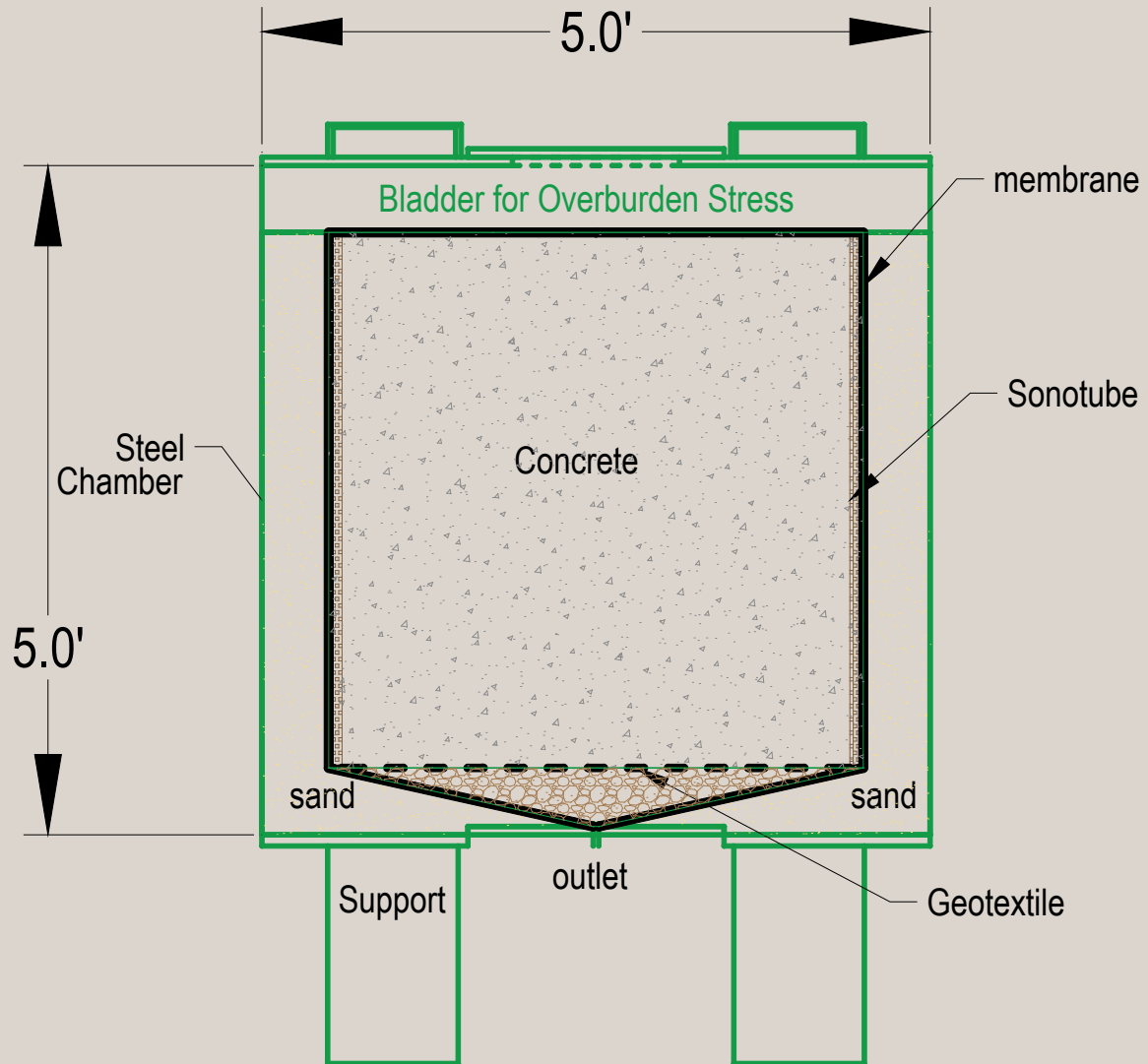


# Current Issues are Durability Issues

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- All affect permeability of concrete
  - Bleed channels
  - Thermal cracking from temperature differentials
  - Cracking from Delayed Ettringite Formation (DEF)
- While important, cannot solve these at expense of workability and strength

# Concrete Stability Testing





# QA/QC Tests for Concrete Stability

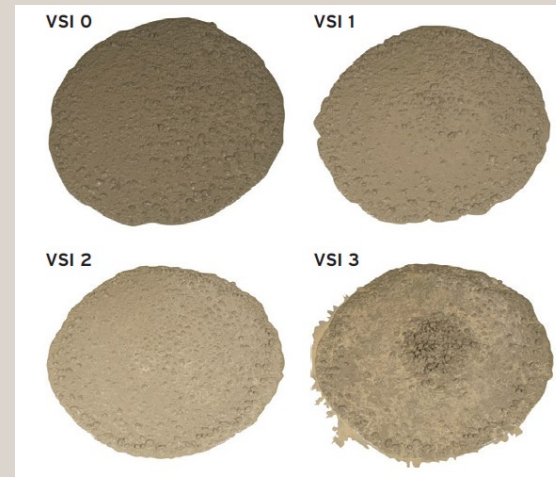
Slump



Slump Flow



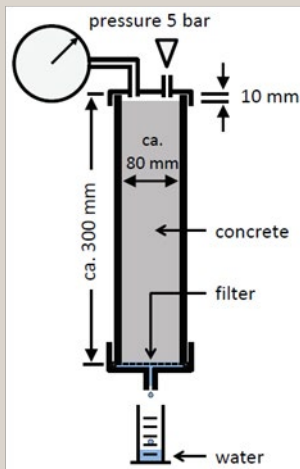
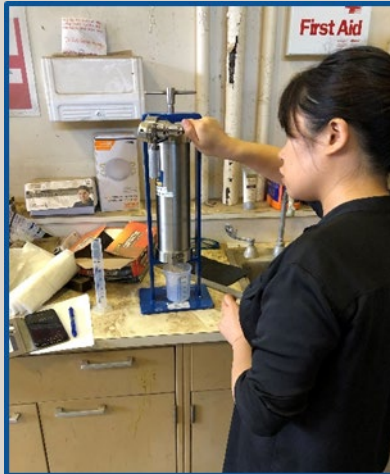
Visual Stability Index (VSI)



J-Ring



Bauer Filter Press



Static Segregation



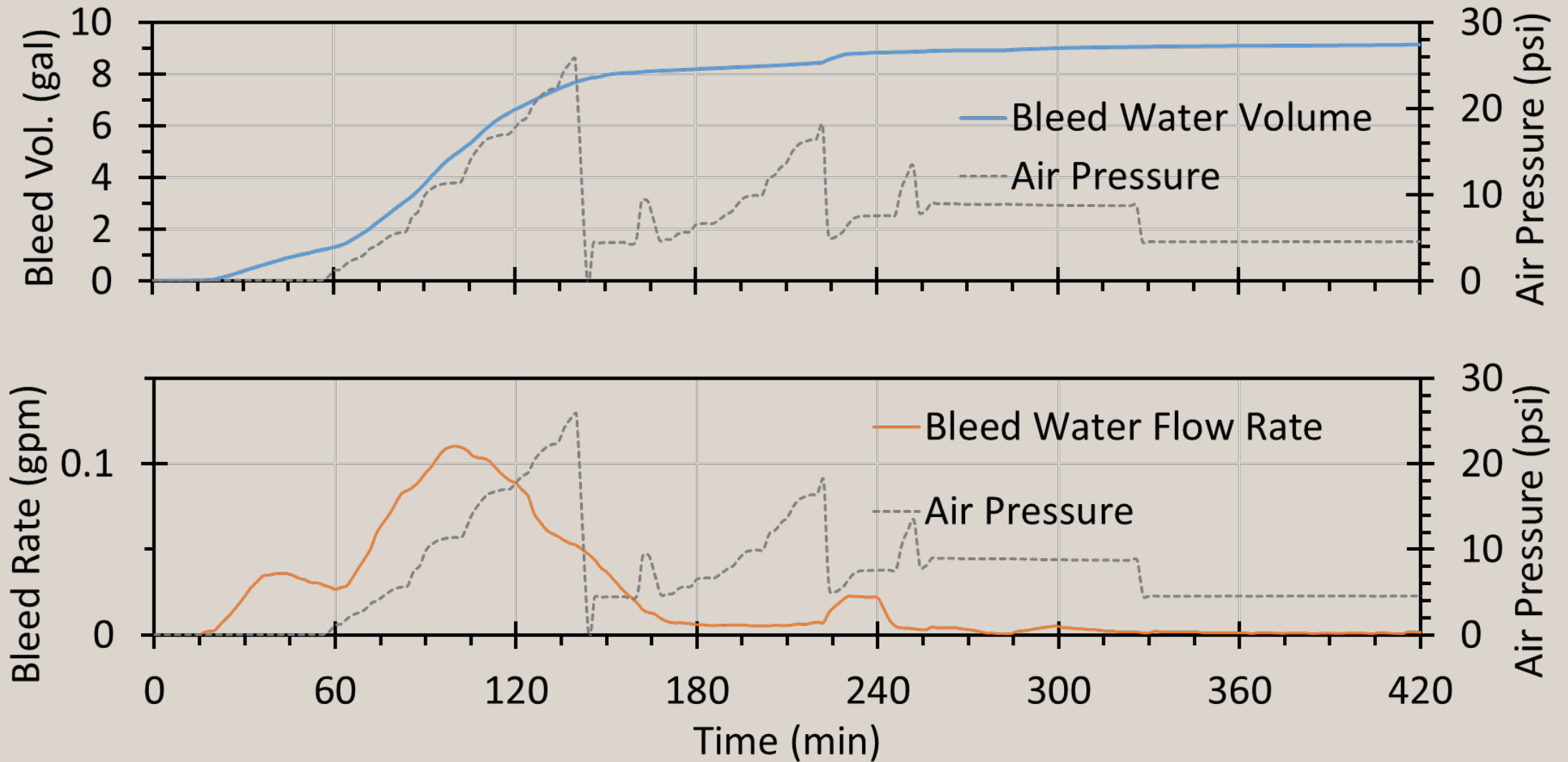
Static Bleed



# Concrete Mixes

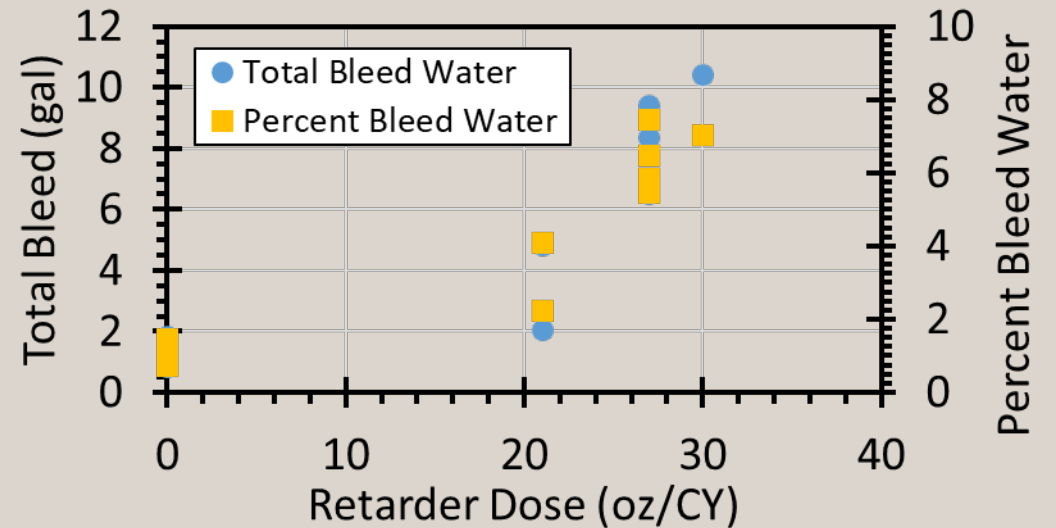
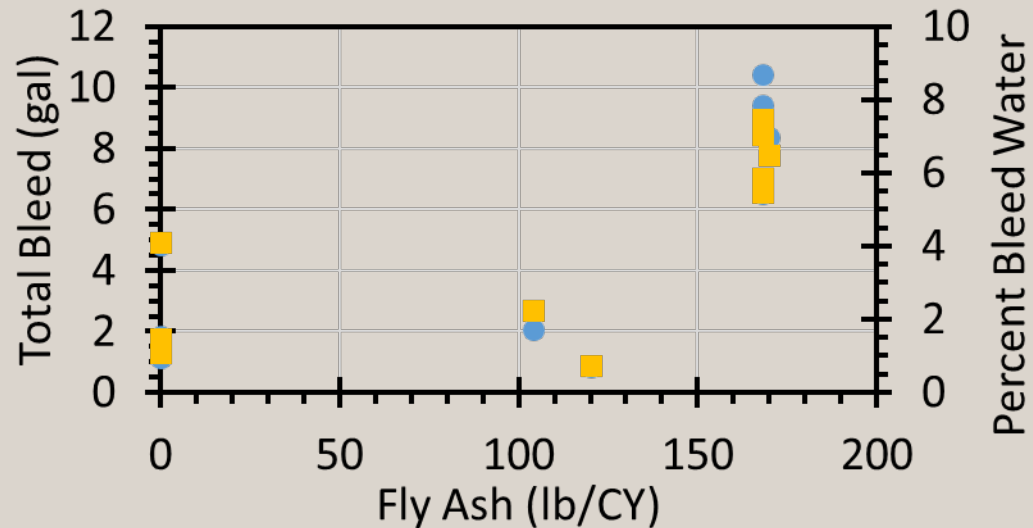
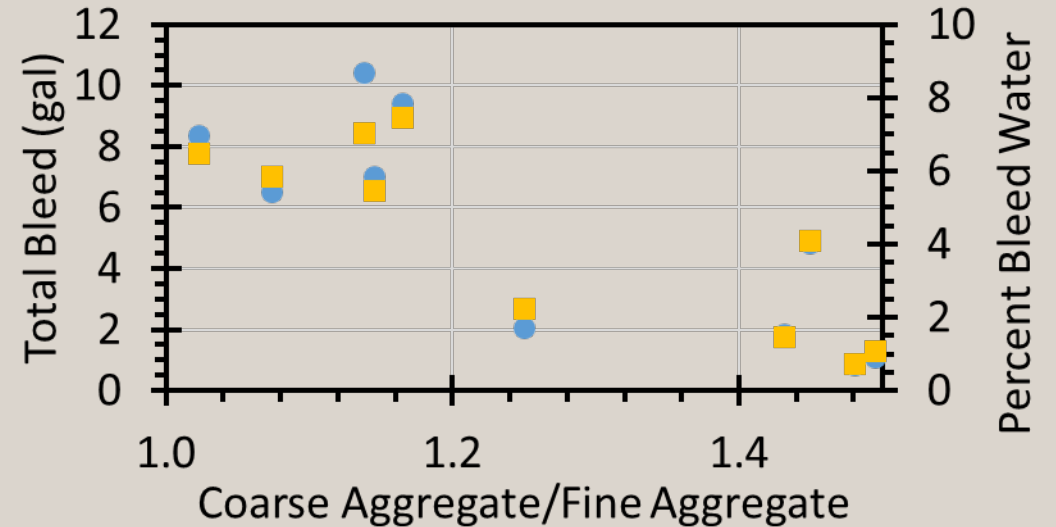
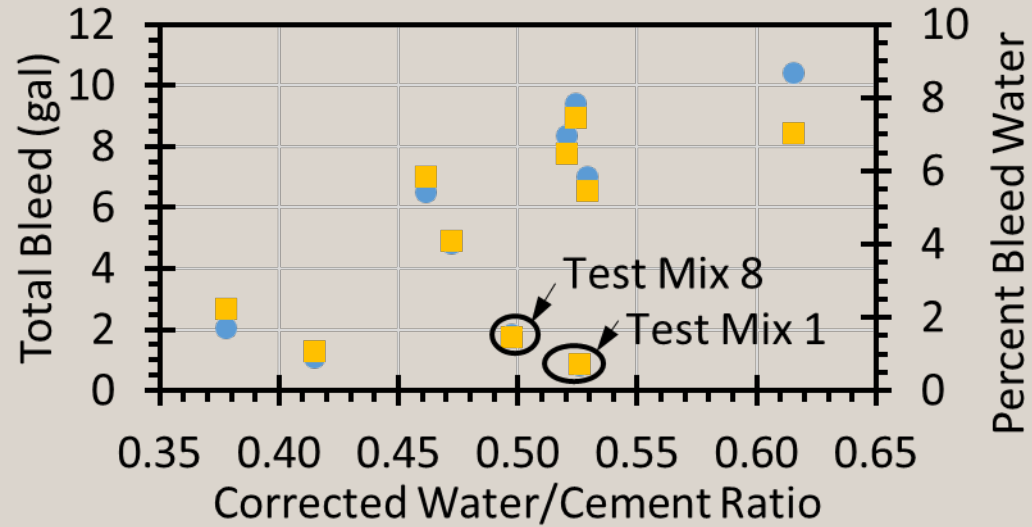
Mix Parameter	1	2	3	4	5	6	7	8	9	10
Max. Course Agg. (in)	1.0	1.0	3/8	3/8	3/8	3/8	3/8	1.0	1.0	1.0
Coarse Agg (lb/CY)	1767	1773	1733	1693	1560	1653	1680	1727	1527	1720
Fine Agg (lb/CY)	1193	1187	1387	1453	1453	1453	1467	1207	1493	1187
Cement (lb/CY)	490	699	568	501	504	501	504	708	523	696
Fly Ash (lb/CY)	120		104	168	168	168	168		170	
Corrected w/c (--)	0.526	0.415	0.378	0.524	0.461	0.615	0.529	0.497	0.520	0.472
MRWR (oz/CY)		21.3	28.3	20.7	20.0	30.0	20.3	21.3	21.3	21.0
HRWR (oz/CY)	30	30	47	32	53	27.6	45.4	42.6	39.7	25.3
Retarder (oz/CY)			21	27	27	30	27		27	21
VMA (oz/CY)			13	13	13	13			13	
Air (oz/CY)	15	7						11.7		7
Slump Flow (in)	18.5	16.5	15.25	18	23.5	33.25	25	28.5	23.5	24
Bauer Press (mL)	29.5	30.0	37.6	44.7	18.1	48.5	40.3	30.0	21.3	30.4
Static Bleed (%)	0	0	0.8	7.3	3.4	5.6	1.9	0.2	1.2	1.0

# Example Test Response





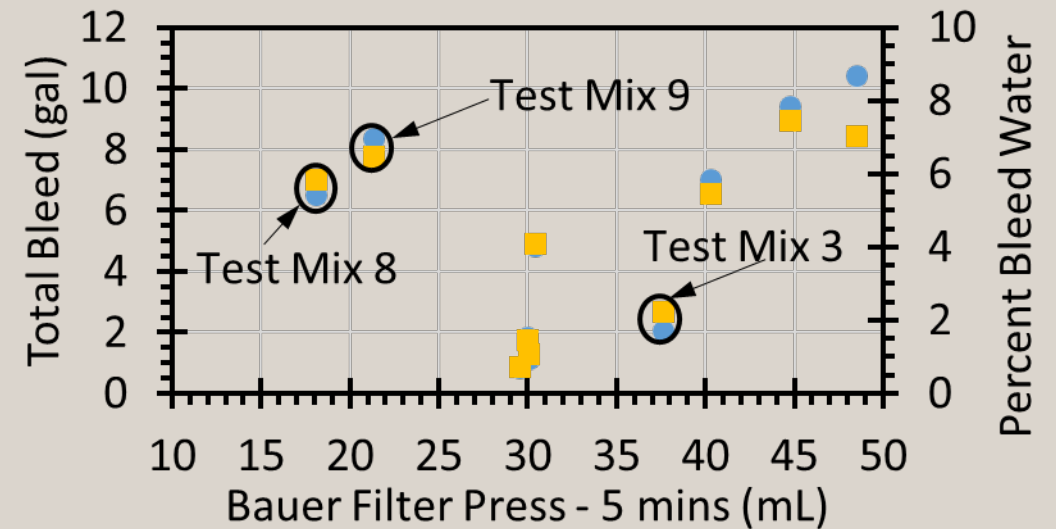
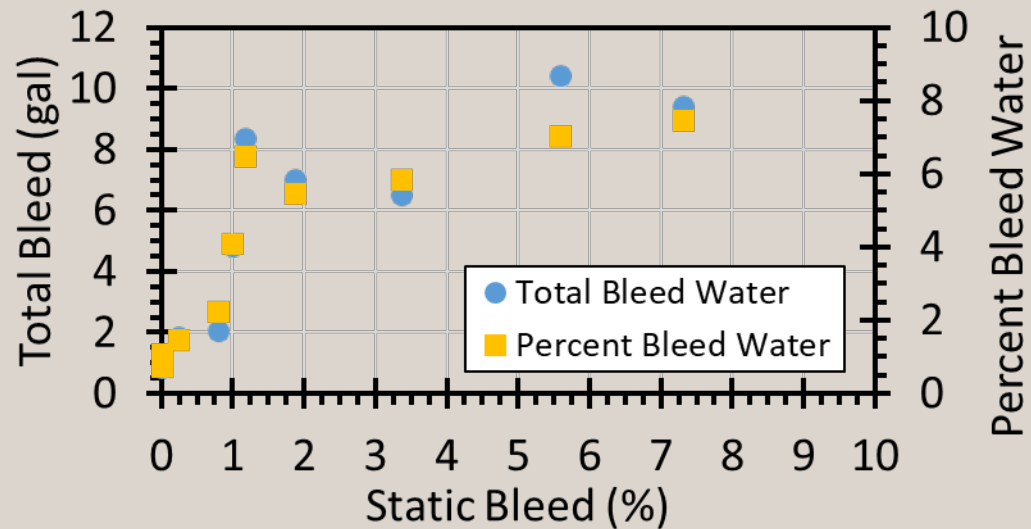
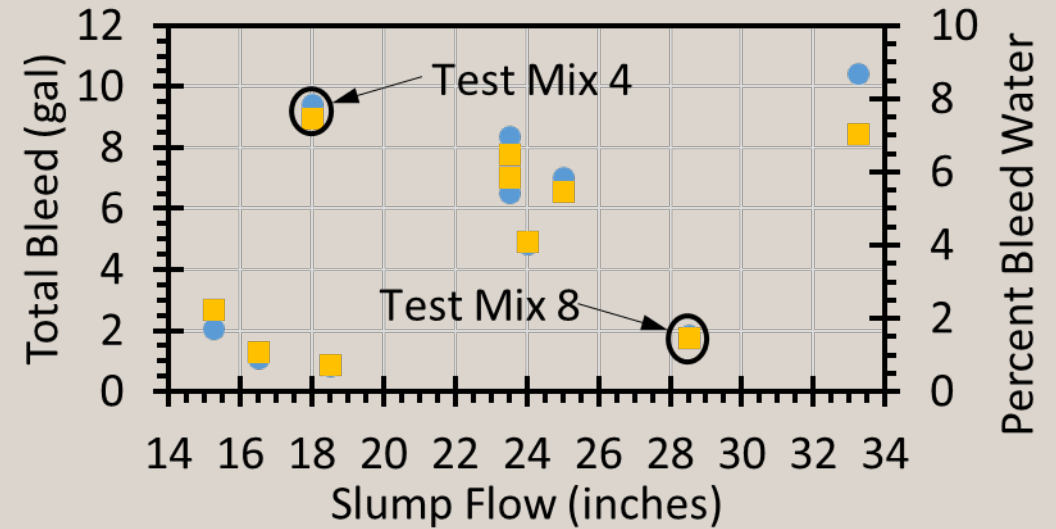
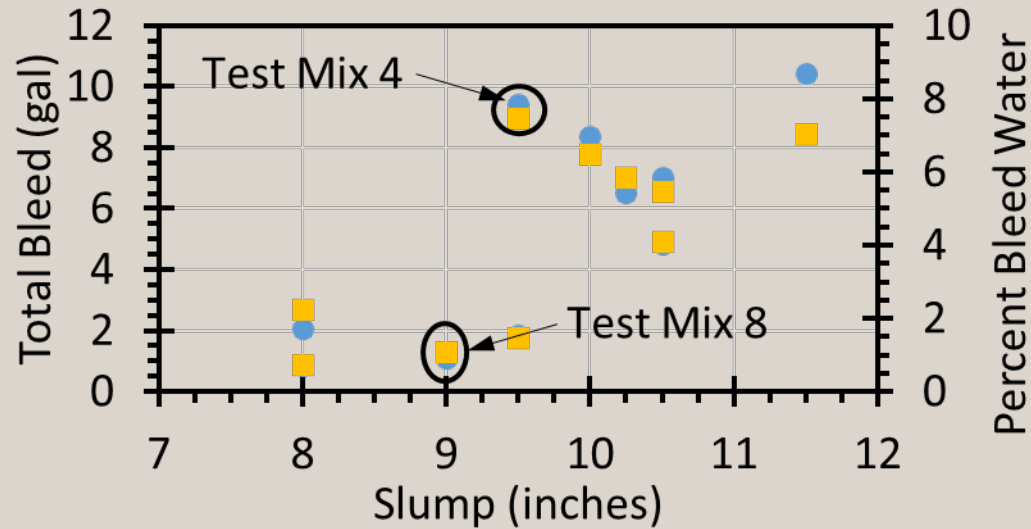
# Mix Characteristics



# Mix Characteristics Producing Excessive Bleed

- Characteristics of test mixes producing excessive bleed:
  - Actual  $w/cm$  greater than 0.5
  - Fly ash greater than 150 lb/CY
  - Greater than 25 oz/CY of retarding admixture
  - Coarse-to-fine aggregate ratio less than 1.2
- Other mix parameters provided no clear indication:
  - Total aggregate or coarse aggregate
  - VMA, HRWR, MRWR dose
  - Total cementitious content

# QA/QC Tests





# QA/QC Test Indicators for Excessive Bleed

- Best indicators from testing program:
  - Slump > 10 inches
  - Slump flow > 22 inches
  - Static bleed > 1 %
  - Bauer Filter Press bleed > 40 mL
- Static segregation test impractical for routine use
- Slump flow probably best test at present
- VSI and static segregation tests were poor indicators of excessive bleed

# Summary of Significant Findings

- Workability problems of the past have largely been addressed, but excessive bleed has become more prevalent
- Prediction of excessive bleed based on mix design or QA/QC tests remains elusive and requires more work
  - Tests suggest carefully considering and controlling  $w/cm$ , fly ash content, retarder dose, and aggregate proportions
  - Slump flow is best current option for indicating excessive bleed

# Acknowledgements

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  - Erik Loehr
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  - Ray Castelli
- DFI/EFFC Tremie Concrete Task Force
- ADSC – The International Association of Foundation Drilling
- Many state DOT's and private consultants



# **Designing for Durability: Drilled Shaft Thermal Issues**

**Andy Boeckmann, Ph.D., P.E.**

**Dan Brown and Associates**

**TRB Webinar**

**May 25, 2021**



# Motivation

- Large diameter shafts are increasingly common
- Large diameter shafts frequently develop high temperatures
- High concrete temperatures are associated with potential durability problems
- Some agencies have begun to impose “mass concrete” specifications
- The specifications have significant consequences for constructability

# What are “thermal issues”?

- Two main concerns with high concrete temperatures:
  - (1) Delayed Ettringite Formation (DEF) in response to large peak temperatures
  - (2) Thermal cracking in response to large temperature differentials

# Mass Concrete

- Mass concrete specifications address thermal issues. Generally include four components:
  - (1) Definition of mass concrete, e.g. any element with minimum dimension  $\geq 4$  ft
  - (2) Maximum allowable  $T_{max}$
  - (3) Maximum allowable  $\Delta T$
  - (4) Thermal control plan requirements





# But for Drilled Shafts??

- No evidence of drilled shaft thermal damage
- Concrete is heavily reinforced
- Concrete is confined
- Consequences would be limited, and likely negligible
- Cure is worse than the disease
- No evidence of drilled shaft thermal damage



# Yes, for Drilled Shafts

- No one has looked for damage
- Damage has been documented in above-ground concrete elements that are
  - Smaller
  - Subjected to less extreme temperatures
- Experience with large-diameter shafts is relatively green
- Service life and durability requirements should not be overlooked

# FHWA Research by University of Missouri

- Developed methods to consider thermal issues in design
  - Prevent DEF
  - Mitigate thermal cracking
- Methods are rational, i.e. rather than adhering to rigid temperature limits, account for
  - *Concrete is heavily reinforced*
  - *Concrete is confined*
  - *Consequences would be limited*
- Adopt methods from literature

# Summary of Procedure

1. Define input parameters (there are many!)
2. Predict concrete temperatures
3. Address DEF potential
4. Establish allowable temperature differentials
5. Compare predicted and allowable temperature differentials
6. Mitigate excessive temperature differentials
7. Measure temperatures (if necessary)



# 1. Input Parameters

Parameter	Analysis Requirements		
	Thermal Model	DEF Potential	Thermal Cracking
Concrete mix design	X	X	X
Cement content and type of cement	X	X	
Aggregate coefficient of thermal expansion			X
Concrete tensile strength			X
Concrete elastic modulus			X
Concrete placement temperature	X		
Drilled shaft diameter	X		
Drilled shaft reinforcement			X
Drilled shaft concrete cover distance			X
Soil or rock density	X		
Soil or rock thermal conductivity	X		
Soil or rock specific heat	X		
Soil or rock temperature	X		

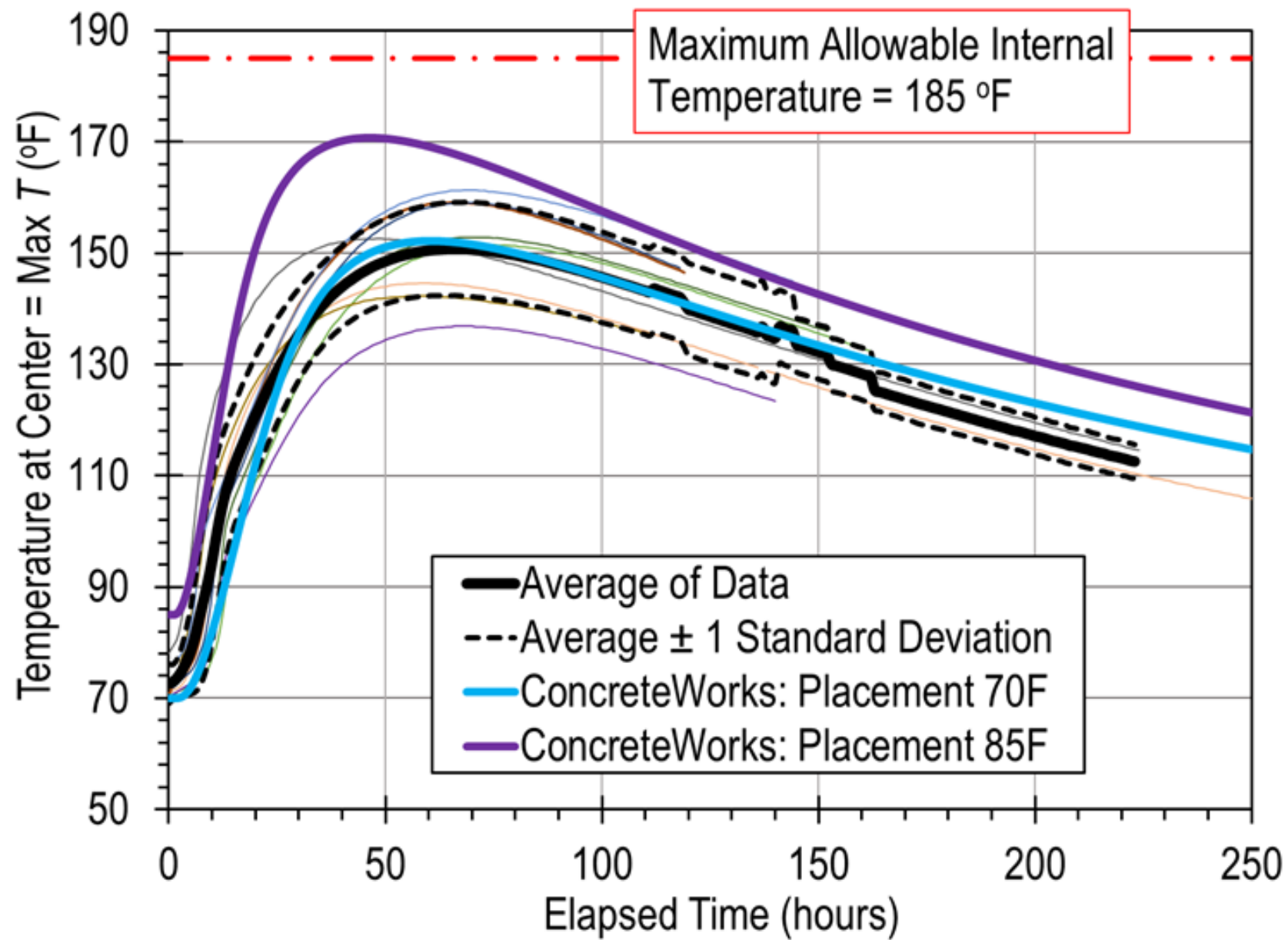
## 2. Predict Temperatures

- Potential thermal models:
  - Hand calcs
    - ACI charts
    - Schmidt method
  - Finite difference models
  - Finite element models

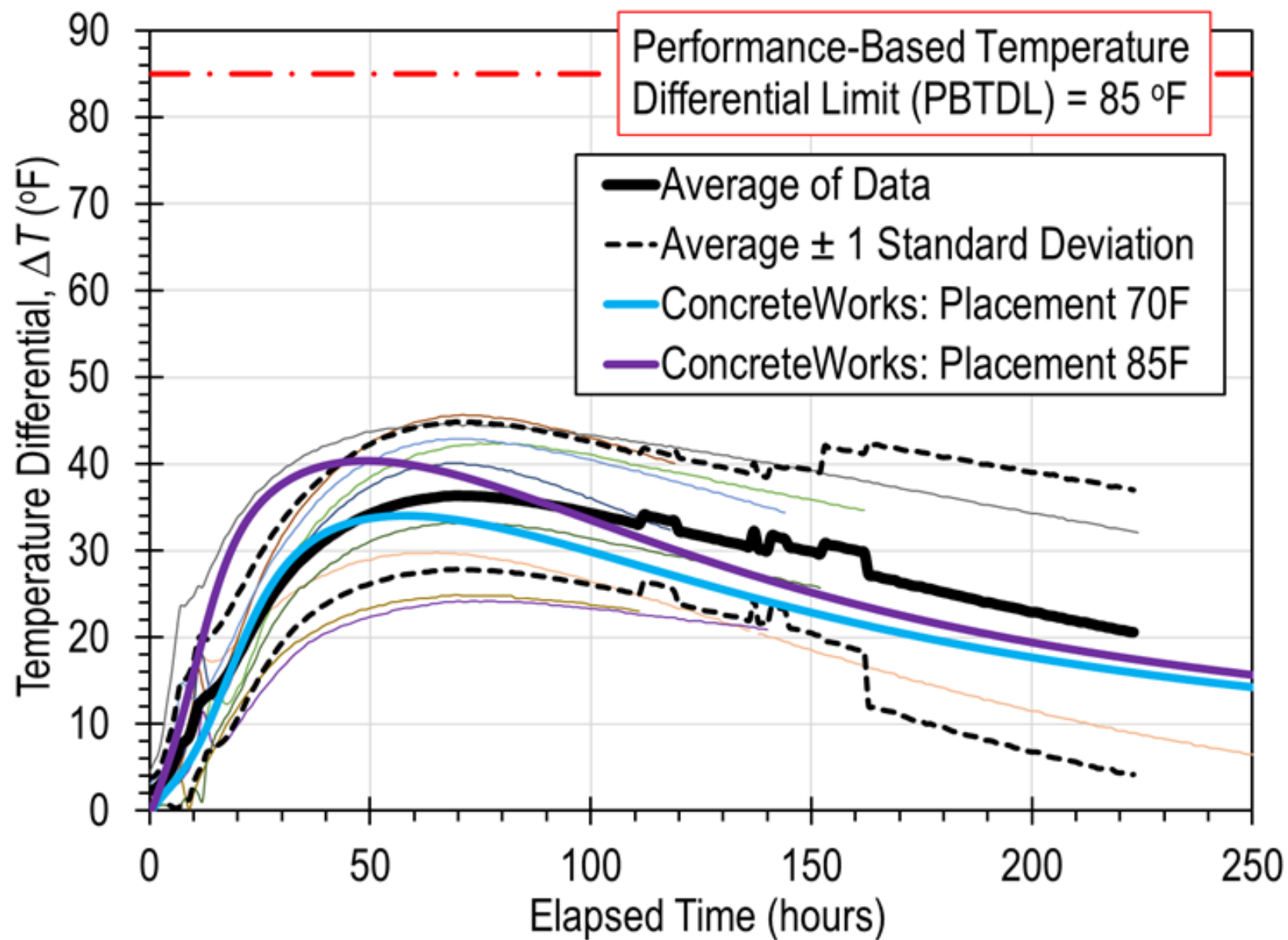


# ConcreteWorks

- Finite difference modeling software
- Developed via TXDOT research
- Free!
- Includes drilled shaft model
- FHWA/University of Missouri research:  $\pm 10$  °F
- Limitations
  - Stuck with default thermal properties for sand/clay/rock
  - Effect of groundwater?







### 3. Preventing DEF

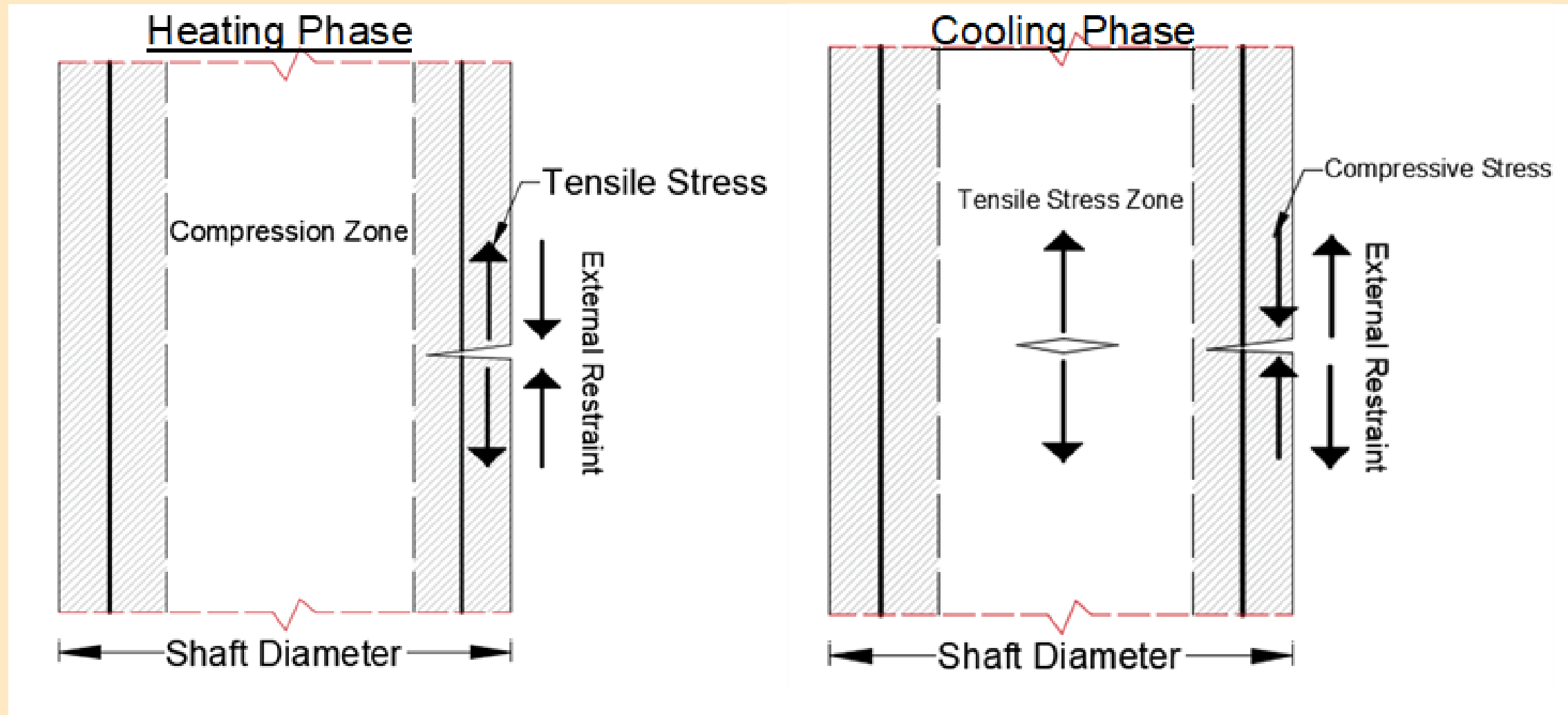
- Many specifications limit  $T_{max}$  to 160 °F
- Proposed provision allows  $T_{max}$  up to 185 °F if mix design parameters are satisfied
- Based on ACI 201.2R *Guide to Durable Concrete*

Maximum Concrete Temperature, $T$	Prevention Required
$T \leq 158\text{ }^{\circ}\text{F}$	No prevention required.
$158\text{ }^{\circ}\text{F} < T \leq 185\text{ }^{\circ}\text{F}$	<p>Use one of following to minimize risk of expansion:</p> <ol style="list-style-type: none"> <li>1. Low-alkali Portland cement having moderate or high sulfate resistance (ASTM C150/C150M)</li> <li>2. Portland cement with 1-day mortar strength <math>\leq 2850</math> psi (ASTMC109/C109M)</li> <li>3. Portland cement in combination with the following supplementary cementitious materials (SCMs) <ol style="list-style-type: none"> <li>a. <math>\geq 25\%</math> Class F fly ash (ASTM C618)</li> <li>b. <math>\geq 35\%</math> Class C fly ash (ASTM C618)</li> <li>c. <math>\geq 35\%</math> slag cement (ASTM C989/C989M)</li> <li>d. <math>\geq 5\%</math> silica fume (ASTM C1240) with <math>\geq 25\%</math> slag cement</li> <li>e. <math>\geq 5\%</math> silica fume (ASTM C1240) with <math>\geq 20\%</math> Class F fly ash</li> <li>f. <math>\geq 10\%</math> metakaolin (ASTM C618)</li> </ol> </li> <li>4. Blended hydraulic cement with SCM content listed in Item 3 (ASTM C595/C595M or ASTM C1157/C1157M).</li> </ol>
$T > 185\text{ }^{\circ}\text{F}$	Not permissible under any circumstances.

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$T > 185\text{ }^{\circ}\text{F}$	Not permissible under any circumstances.



## 4, 5. Thermal Cracking



# Bamforth, 2007

- *Early Age Thermal Crack Control in Concrete*
- Report to CIRIA (Construction Industry Research and Information Association), a UK trade group

# Preventing Thermal Cracking

$$\Delta T_{max} = \frac{\epsilon_{ctu}}{K \cdot \alpha_c \cdot R} = \frac{3.7 \cdot \epsilon_{ctu}}{\alpha_c}$$

$\Delta T$  = temperature difference between center and outer surface

$\epsilon_{ctu}$  = tensile strain capacity  
=  $\frac{f_t}{E_c}$  =  $\frac{\text{tensile strength}}{\text{modulus of elasticity}}$

$K$  = coefficient accounting for stress relaxation due to creep, assume 0.65

$\alpha_c$  = coefficient of thermal expansion

$R$  = restraint factor, assume 0.42

# Mitigating Thermal Cracking

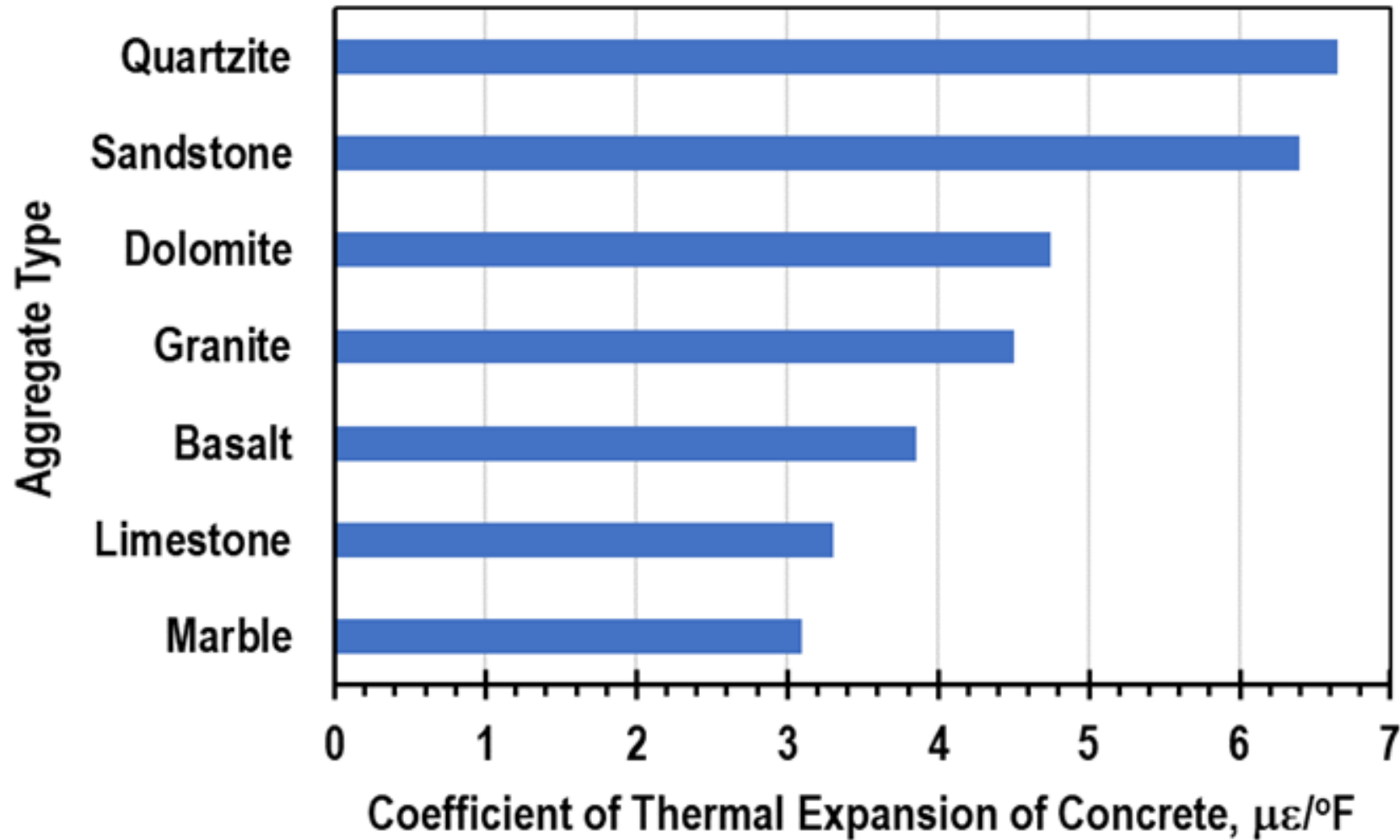
$$\Delta T_{max} = \frac{\left( \frac{w_{lim}}{3.4c + 0.425 \frac{0.8 \cdot \varphi}{\rho_{p,eff}}} \right) + 0.5 \cdot \varepsilon_{ctu}}{0.27 \cdot \alpha_c}$$

$w_{lim}$  = limiting crack width

$c$  = cover distance

$\varphi$  = reinforcing bar diameter

$\rho_{p,eff}$  = reinforcement ratio



Boeckmann, A.Z., Z. El-tayash, and J.E. Loehr (2021), "Establishing and Satisfying Thermal Requirements for Drilled Shaft Concrete Based on Durability Considerations," *Transportation Research Record*, Transportation Research Board, 13 p.



# Limiting Crack Width: ACI 224R-01

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

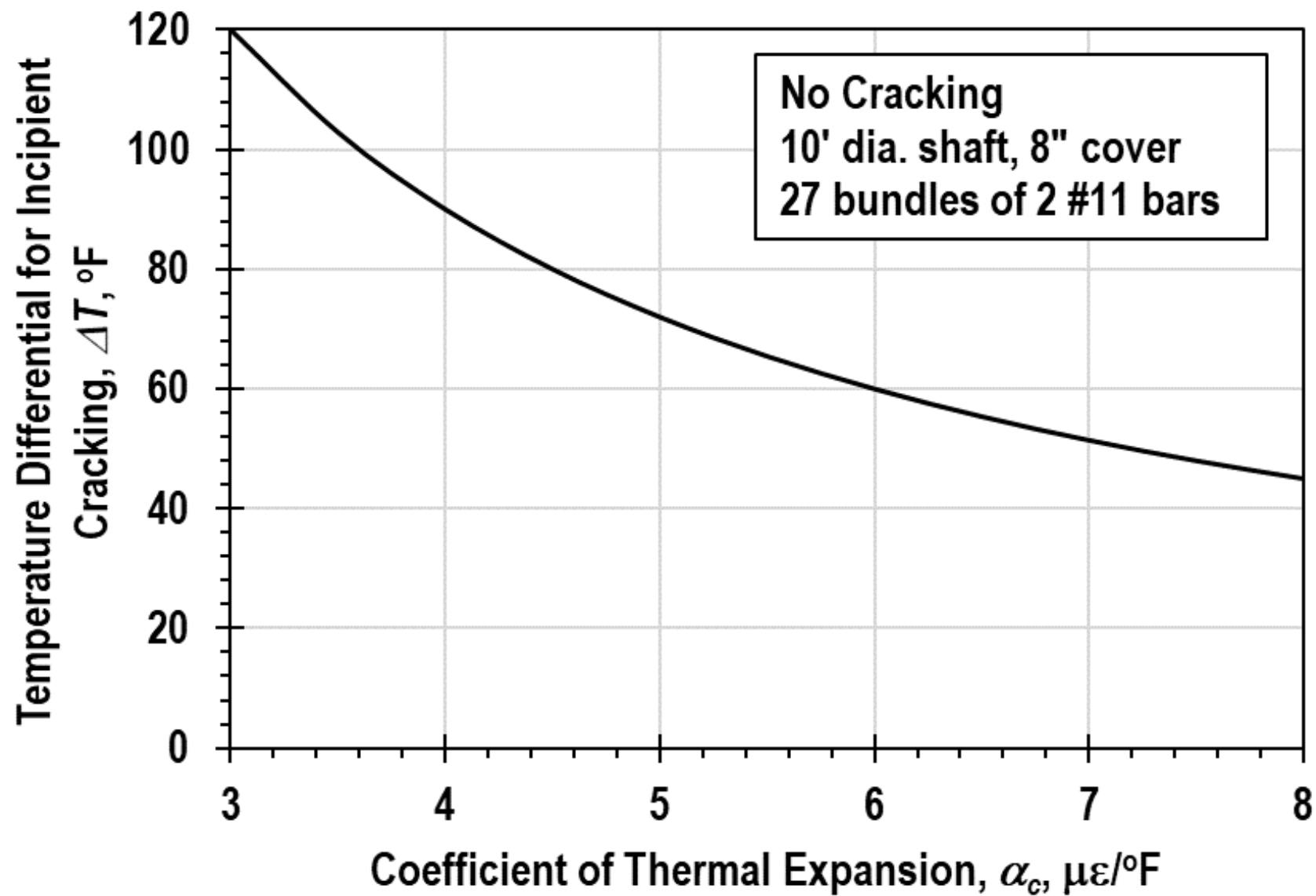
Exposure condition	Crack width	
	in.	mm
Dry air or protective membrane	0.016	0.41
Humidity, moist air, soil	0.012	0.30
Deicing chemicals	0.007	0.18
Seawater and seawater spray, wetting and drying	0.006	0.15
Water-retaining structures <sup>†</sup>	0.004	0.10

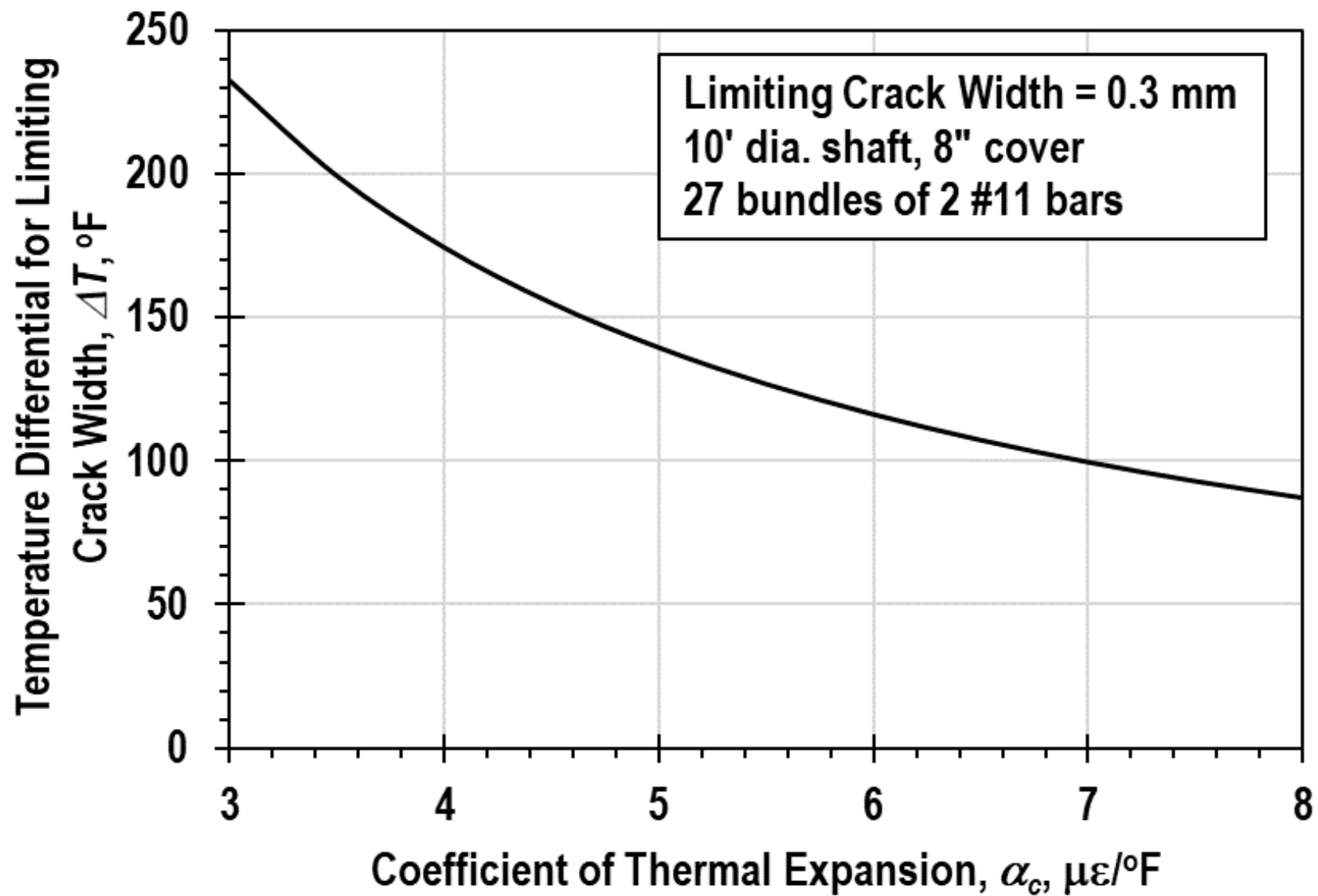
\*It should be expected that a portion of the cracks in the structure will exceed these values. With time, a significant portion can exceed these values. These are general guidelines for design to be used in conjunction with sound engineering judgement.

<sup>†</sup>Excluding nonpressure pipes.

# Limiting Crack Width: AASHTO LRFD BDS

- Section 5.6.7:
  - “all reinforced concrete members are subject to cracking under any load condition, including thermal effects...”
  - Addresses the spacing of concrete reinforcement to control cracking
  - Uses an allowable crack width of 0.017 in. (0.43 mm) for applications tolerant of cracking because of “reduced concerns of appearance, corrosion, or both.”







## 6. Mitigation Methods

### 1. Mix design

- Use fly ash
- Limit cement content

### 2. Batching

- Use chilled mix water
- Replace some mix water with ice
- Flush aggregate with cool water

### 3. Placement

- Restrictions on placement based on ambient temperature



## 6. Mitigation Methods cont'd

### 4. Post-cooling

### 5. Analysis: more legwork or laboratory tests to determine

- Calculation of maximum allowable values of  $T_{max}$ ,  $\Delta T$  per previous slides, rather than using default
- Coefficient of thermal expansion
- Concrete tensile strain capacity
  - Direct
  - Tensile strength and modulus
- Analysis mitigation techniques likely least costly



# Consequences of Mitigation Measures

- Modifications to concrete mix design
  - Stray from established mixes with history of success
  - Can reduce workability, pumpability
- Batching
  - Pre-cooling measures are often costly
- Restrictions on placement temperature
  - Schedule implications during summer months
- Post-cooling
  - Where does the tremie go??
  - Reinforcing cage congestion

# Summary of Procedure

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# Conclusions

- Consideration of thermal issues is appropriate for durability design.
- Commonly adopted criteria typically do not consider
  - Durability requirements (e.g. Can minor cracking be tolerated?)
  - Drilled shaft reinforcement
  - Drilled shaft confinement
  - Constructability consequences associated with satisfying criteria
- Recommended procedure provides rational methodology for addressing DEF and thermal cracking.



# Future Research Needs

- Durability for deep foundation elements
  - Need measurements of historical durability
  - Effect of cover? Effect of cracking? Effect of ground conditions?
- Batching practices
  - Reliability of fresh concrete
  - Especially related to aggregate moisture
  - Affects most transportation construction!
- Bleed
  - Develop additional test methods
  - Develop a better understanding of bleed mechanisms.



# Today's Panelists

## #TRBWebinar



Erik Loehr



Moderated by:  
Monica Prezzi,  
*Purdue University*



Andrew Boeckmann



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