Kiewit

Mass Concrete – Thermal Control Overview

Oscar Antommattei, Kiewit

NORTH AMERICAN STANDARDS FOR MASS CONCRETE

TYPES OF MASS CONCRETE

- ***Traditional mass concrete:*** Use for structures such as dams, typically lightly reinforced, where the majority of the structure is mostly mass concrete and is constructed of sequential placements.

- ***Thermally-controlled concrete:*** Use for structures such as high-rise building foundations or bridges, typically heavily reinforced, where the majority of the structures are individual placements

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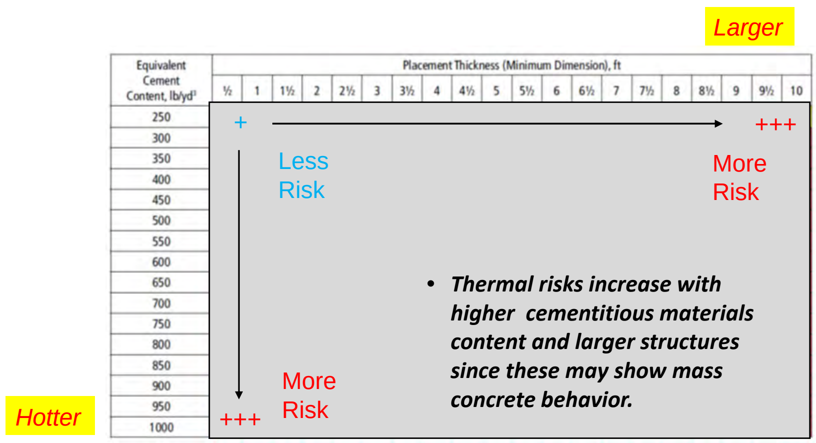
MASS CONCRETE – IN SIMPLE TERMS…



Ref. ACI 207.1-20 & Gajda et al 2018

ADIABATIC TEMPERATURE RISE (ATR)

- ATR is mainly affected by type and quantity of cementitious materials
- Reducing ATR
  - ✓ Reduce total cementitious materials
  - ✓ Use less Portland Cement
  - ✓ Use more low heat SCMs (Class F fly ash and slag)

Description		
Very low	*Traditional Mass Concrete*	ATR < 80°F (45°C)
Low		
Moderate	*Thermally Controlled Concrete*	ATR > 80°F (45°C)
High		
Very high		

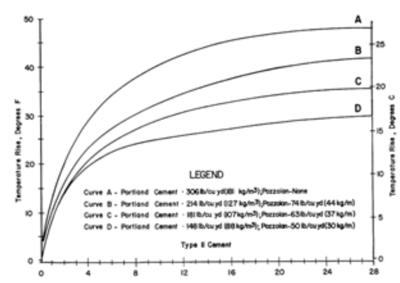
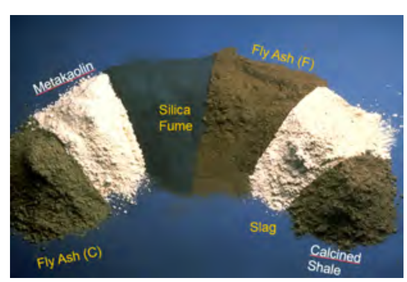


Fig. 7.1—Typical adiabatic temperature curves for mass concrete (Houghton 1969).



ADIABATIC TEMPERATURE RISE (ATR)

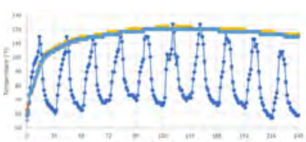
Methods	Description
Simplified approach	Use a mathematical expression such as Gajda et al, 2014: Rise = 0.16* (1.0*Cem + 0.5*FAsh + 0.8*CAsh + 1.2*SFMK + Factor*Slag), °F
Computer modeling	Use a simplified analytical/modeling software such as ConcreteWorks®; an advanced finite element analytical/modeling software; or a combination thereof.
Semi-adiabatic testing	Use a commercially available semi-adiabatic test chamber; a field fabricated super-insulated test block; a lab fabricated insulated box; or a combination thereof.
Adiabatic testing	Use adiabatic test method such as CRD-C 38, Method of Test for Temperature Rise in Concrete
Field placement	Use a field mass placement having large dimensions, such as a crane footing, with insulation and monitoring temperature at locations intended to be monitored during construction
Other methods	Use a method described in ACI 207.2R, such as Schmidt's method; or other method approved by the owner

ADIABATIC TEMPERATURE RISE (ATR)

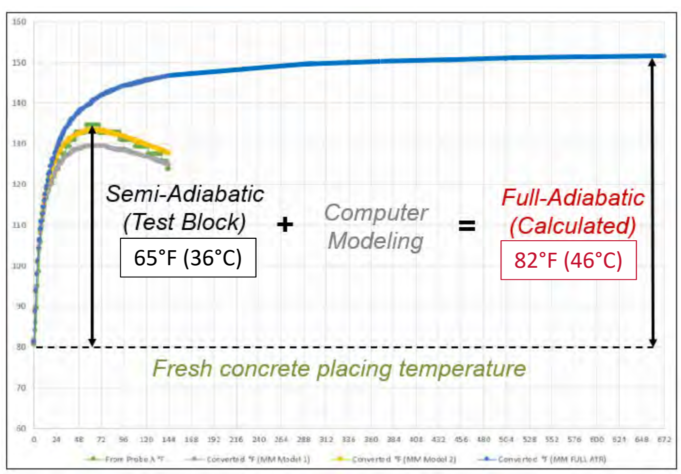
Testing




Computer Modeling



ATR Calibration Process



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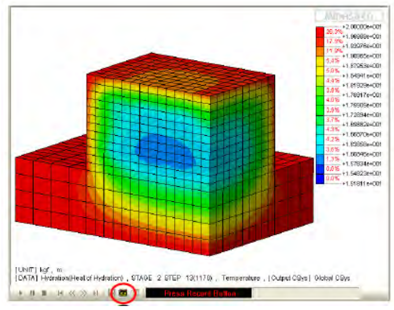
MAXIMUM CONCRETE TEMPERATURE

- **Main concerns**
  - ✓ Long term effect on strength and durability
- **Industry limits**
  - ✓ Default "safe" limit (ACI 301)
    - 158/160 °F (70 °C) – with / without mitigation
  - ✓ Alternative "safe" limit (ACI 201 / 301 / 308 & CSA A23.1)
    - 158/160 °F (70 °C) – without mitigation
    - Up to 185 °F (85 °C) – with mitigation (add SCMs)
    - Greater than 185 °F (85 °C) – not permitted (may be justified with testing)

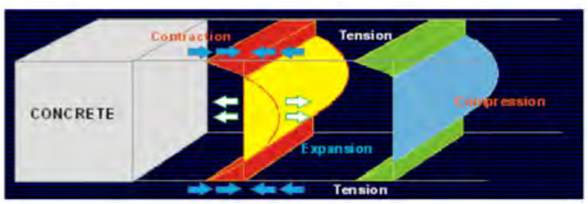
[*NOTE: Increased acceptance of alternative limits / values may vary with experience*]

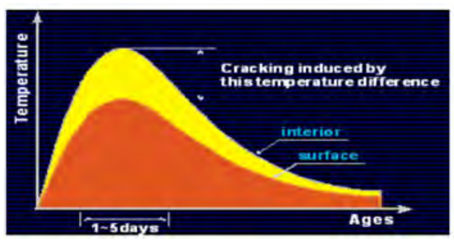


MAXIMUM CONCRETE T_{DIFF} LIMIT

- **Main concerns**
  - ✓ Thermal cracking
- **Industry limits**
  - ✓ Default "safe" limit (ACI 301)
    - 35°F (20 °C) fixed limit
  - ✓ Alternative "safe" limit (ACI 301 & CSA A23.1)
    - Higher than 35°F (20 °C) fixed limit w/low CoTE concrete
    - Incremental limit
    - Performance based with testing and analysis

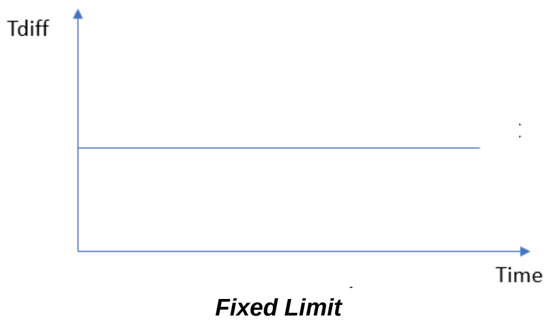
[*NOTE: Increased acceptance of alternative limits / values may vary with experience*]

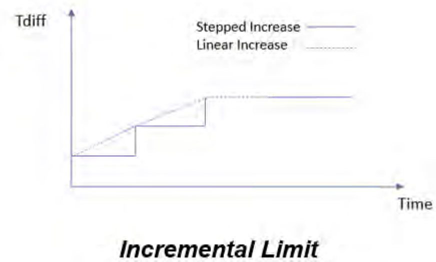


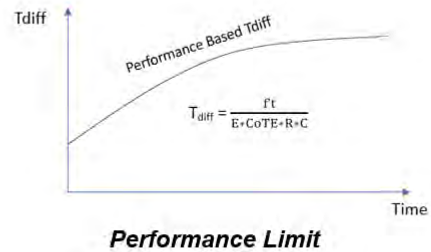


Ref. InTrans Project 10-384 (2014)

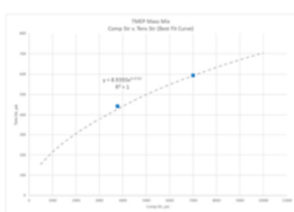
T_{DIFF} LIMITS (TRADITIONAL VS. ALTERNATIVE)

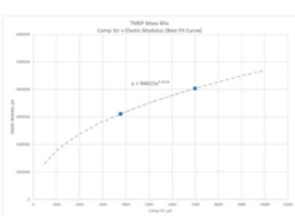


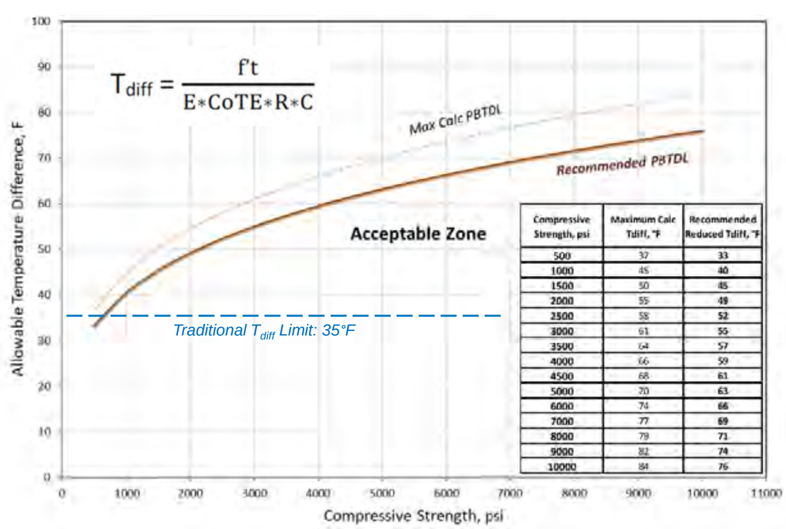




PERFORMANCE BASED TEMPERATURE DIFFERENCE LIMIT (PBTDL)







Compressive Strength, psi	Maximum Calc Tdiff, °F	Recommended Reduced Tdiff, °F
500	37	33
1000	45	40
1500	50	45
2000	55	49
2500	58	52
3000	61	55
3500	64	57
4000	66	59
4500	68	61
5000	70	63
6000	74	66
7000	77	69
8000	79	71
9000	82	74
10000	84	76

THERMAL CONTROL PLAN

- TOOL for the Contractor to plan, manage and execute mass placements:
  - ✓ Control & monitor temperature
  - ✓ Reduce thermal shrinkage
  - ✓ Minimize thermal cracks

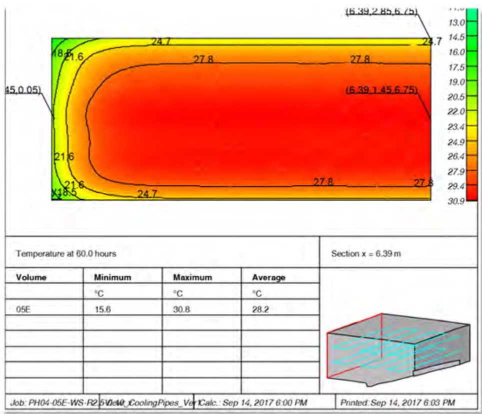
- Know the behavior, challenges and measures to meet the specified requirements:
  - ✓ Mixture proportions
  - ✓ Placing cycles, heat sinks, formwork or insulation removal
  - ✓ Maximum temp and temp difference
  - ✓ Duration of thermal control and monitoring
  - ✓ Corrective measures (e.g. pre-cooling or post-cooling)

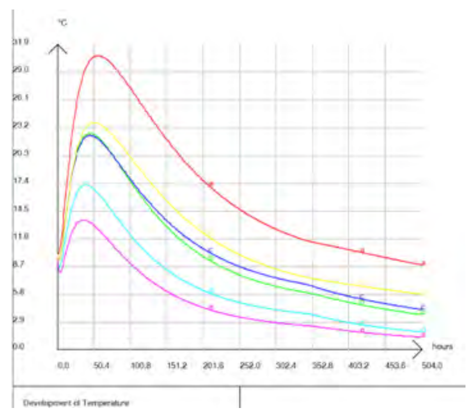
IMPLEMENTING A THERMAL CONTROL PLAN

<u>5-Step Process</u>

1. Analytical Modeling
2. Thermal Control Plan
3. Field Implementation
4. Verification and Validation
5. Revise and Update

STEP 1 - ANALYTICAL MODELING





STEP 2 - THERMAL CONTROL PLAN

Thermal Control Table
Block Pedestal
4500 PSI | 65% Grade 100 Slag

HOT WEATHER

COLD WEATHER

		No Insulation			Light Insulation[3]			Moderate Insulation[3]			Heavy Insulation[3]		
Ambient Temp[1] F°	Concrete Temp[2] F°	Max Core Temp F°	Max Temp Diff F°	End Thermal Control[4] Days	Max Core Temp F°	Max Temp Diff F°	End Thermal Control[4] Days	Max Core Temp F°	Max Temp Diff F°	End Thermal Control[4] Days	Max Core Temp F°	Max Temp Diff F°	End Thermal Control[4] Days
90	90	159	50	N/A	166	37	5.5	171	25	7.5	175	16	10.5
	80	149	43	N/A	155	32	5.0	160	22	7.0	164	14	9.5
	70	139	37	N/A	145	27	4.5	149	19	6.5	153	12	8.5
70	90	153	60	N/A	161	44	6.0	168	31	9.0	173	20	12.5
	80	142	53	N/A	150	39	5.5	157	28	8.0	161	18	12.0
	70	132	46	N/A	139	35	5.0	145	24	7.5	150	16	11.0
	60	121	39	N/A	128	30	4.5	134	21	7.0	138	14	10.0
	50	111	31	N/A	117	25	4.0	123	18	6.5	127	12	9.0
50	90	147	71	N/A	157	52	7.0	165	36	10.0	171	23	15.0
	80	133	62	N/A	144	46	6.5	152	32	9.5	158	21	14.0
	70	120	52	N/A	130	40	6.0	139	29	9.0	145	19	13.0
	60	107	42	N/A	117	34	5.5	125	25	8.5	132	16	12.0
	50	93	33	N/A	103	28	5.0	112	21	8.0	119	14	11.5
30[5]	70	107	59	N/A	121	47	6.5	132	34	9.5	141	22	13.5
	60	91	47	N/A	105	40	6.0	117	29	9.0	127	19	12.5
	50	76	36	N/A	90	32	5.5	102	25	8.5	112	17	12.0

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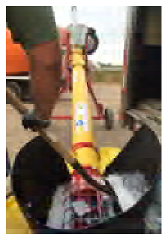
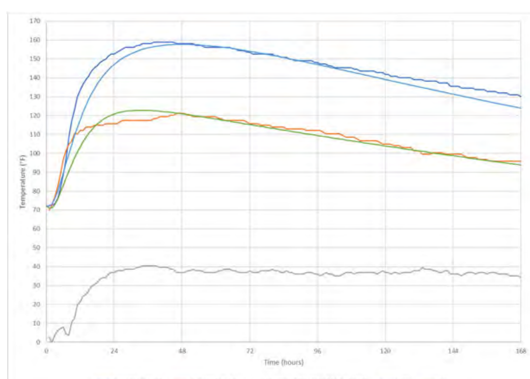
STEP 3 - FIELD IMPLEMENTATION

1. Temperature Monitoring
2. Pre-Cooling
3. Insulation
4. Post-Cooling



STEP 4 - VERIFICATION / VALIDATION

S/N:	9560692	9563135	9560259	8443100	8458430
Job:	PEDBRG	PEDBRG	PEDBRG TOP1	PEDBRG	PEDBRG
Location:	MID1	MID2	TOP 1	TOP2	AMBNT TEMP
Logger Sul	9	9	9	9	9
Run State:	Run	Run	Run	Run	Run
Start Date	2/6/2020 11:28	2/6/2020 11:29	2/6/2020 11:25	2/6/2020 11:27	2/6/2020 11:49
Last Down	2/14/2020 16:56	2/14/2020 16:56	2/14/2020 16:55	2/14/2020 16:56	2/14/2020 16:54
Elapsed Ti	197.47	197.45	197.5	197.48	197.08
Data Inter	60	60	60	60	60
Number o	198	198	198	198	198
Current Reading:					
Time (hrs)	Temperature (°F)	Temperature (°F)	Temperature (°F)	Temperature (°F)	Temperature (°F)
197.47	123.8	123.8	95	95	73.4
Maximum	159.8	158	120.2	122	
Logged Readings (198):					
Time(hrs)	Temperature (°F)	Temperature (°F)	Temperature (°F)	Temperature (°F)	Temperature (°F
0	35.6	35.6	41	39.2	51.8
1	41	41	51.8	50	44.6
2	48.2	46.4	53.6	51.8	42.8
3	71.6	68	48.2	48.2	42.8
4	73.4	71.6	46.4	44.6	39.2
5	73.4	71.6	46.4	46.4	39.2
6	73.4	73.4	69.8	68	39.2
7	77	75.2	68	68	39.2
8	82.4	80.6	68	68	37.4
9	89.6	87.8	68	68	33.8
10	96.8	96.8	69.8	69.8	33.8
11	109.4	107.6	71.6	73.4	33.8
12	118.4	116.6	77	77	35.6
13	123.8	122	82.4	82.4	39.2
14	131	129.2	87.8	89.6	39.2
15	134.6	132.8	96.8	96.8	37.4
16	138.2	134.6	100.4	102.2	41
17	140	138.2	104	105.8	42.8
18	141.8	140	105.8	107.6	35.6

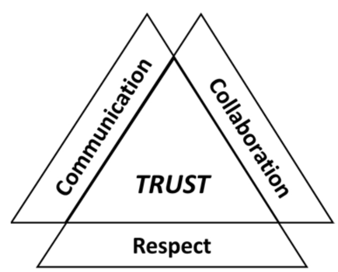


STEP 5 - REVISE / UPDATE

- When a revision or update may be necessary:
  - ✓ Field conditions are known, but model is not representative:
    - ✓ Model may be inaccurate and not conservative
    - ✓ Model may be inaccurate and very conservative
  - ✓ Changes in field conditions, dimensions, materials, means/methods, weather, etc.
- Other things to consider when evaluating the need for a revision or update that may not relate to the Thermal Control Plan, but the construction work:
  - ✓ Inadequate implementation
  - ✓ Different requirements
  - ✓ Concrete mix changes
  - ✓ Formwork or insulation changes
  - ✓ Field operations changes

THE FUTURE – PERFORMANCE DRIVEN & ENGINEERED APPROACH

- ✓ **North American Standards and Project Specifications**
  - Slowly adopting knowledge and practice
  - Specs are mostly dated (need change)
- ✓ **Developing and Qualifying Concrete Mixes**
  - Optimized concrete to reduce heat of hydration
- ✓ **Specifying Temperature Limits**
  - Decrease adiabatic temperature rise (ATR)
  - Reduce placing concrete temperatures
  - Mitigate maximum "peak" temperature (use SCMs)
  - Optimize maximum T_{diff} (use testing and analysis, PBTDL)
- ✓ **Implementing Thermal Control Plans**
  - Use thermal control plan ---- implement measures to reduce temperature and minimize thermal cracks



Abernethy Bridge – Mass Concrete Case Study

Justin Torkilson, Kiewit

OUTLINE

Scope of work

Specification Alterations

Concrete Mix Development

- Developed 8 to 10 mix designs
- Thermal generation vs. ACI formwork pressures (high slag content pushes the math) vs. strength gain vs. shrinkage results vs. supply issues vs. extreme retarding (crossbeams)

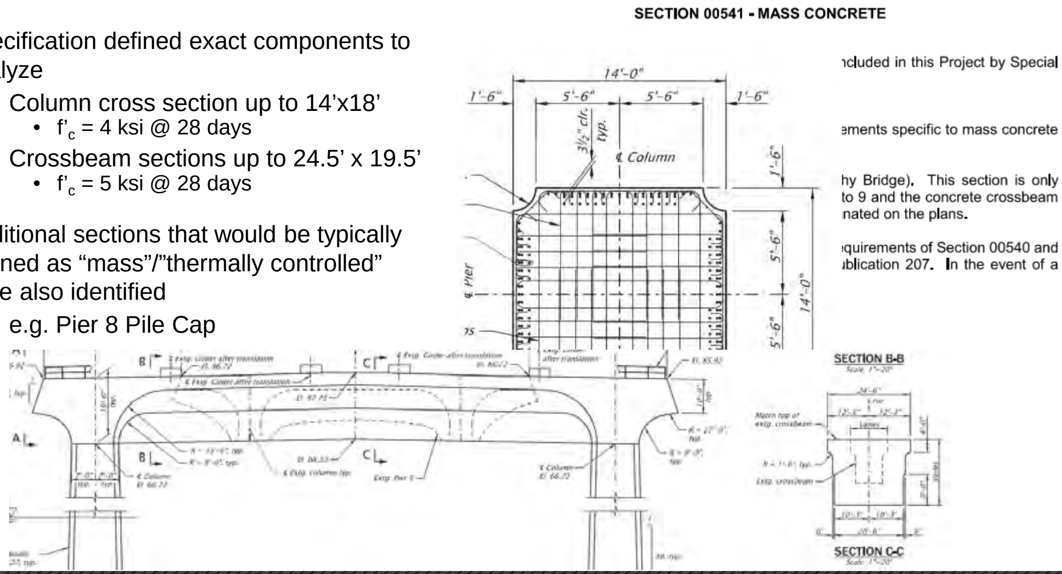
Substructures in practice

- Lower 5A challenges – Lower 5B successes
  1. Benefit of no cooling tubes to client (cost, complexity, etc.)

Crossbeams

SCOPE OF MASS CONCRETE

- Specification defined exact components to analyze
  - Column cross section up to 14'x18'
    - f'_c = 4 ksi @ 28 days
  - Crossbeam sections up to 24.5' x 19.5'
    - f'_c = 5 ksi @ 28 days
- Additional sections that would be typically defined as "mass"/"thermally controlled" were also identified
  - e.g. Pier 8 Pile Cap



SPECIFIED LIMIT (Thermal Maximum)

(b) Thermal Control Plan - Submit a Thermal Control Plan for each mass concrete placement using thermal modeling and methods in accordance with ACI 207, or submit for the Engineer's approval a plan to implement performance based temperature difference limit with qualification testing and analysis, and to implement a peak temperature limit between 160 °F and 185 °F, conforming to ACI 201. Address the adiabatic temperature rise of the concrete, initial concrete temperature at placement, construction methodology including pour dimensions and time between consecutive pours, formwork insulation, surrounding environmental conditions, curing methods, and cooling systems (if used). State all input parameters for the analysis in the Thermal Control Plan. Submit supporting computations to demonstrate compliance with the curing temperature requirements for concrete sections that are evaluated for thermal control, as described in 00541.01, and for those sections that do not require a thermal control plan.

- Initial Specified Limits:
  - Thermal Max = 160°F
  - Thermal Differential = 35°F
- To Meet Requirements – Cooling Pipes would be Required
  - Likely Pre-Cooling Efforts (e.g. liquid nitrogen)
- Revised Limits
  - Thermal Max = 185°F
  - Thermal Differential = Performance-Based

REVISED SPECIFIED LIMIT – MIX DESIGN DEVELOPMENT

- Mix design work with Heidelberg Materials (formerly Cadman, Inc.)
- Developed 10+ mix designs focusing on:
  - Thermal Performance
  - Strength
  - Workability Life
  - Flow (SCC)
  - Thermal generation vs. ACI formwork pressures (high slag content pushes the math) vs. strength gain vs. shrinkage results vs. supply issues vs. extreme retarding (crossbeams)
- Met specified requirements while targeting lower adiabatic temperature rise (ATR)

REVISED SPECIFIED LIMIT - ATR

- Specified - ASTM C186-98 "Heat of Hydration of Hydraulic Cement"
- Alternate approach – Semi- Adiabatic Test Block
  - Heavily Insulated – R-31 effective
  - Actual Concrete
  - Representative
- Model Match
  - Determines ATR

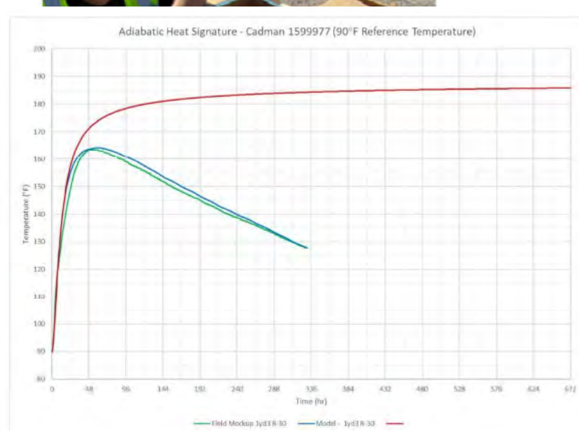
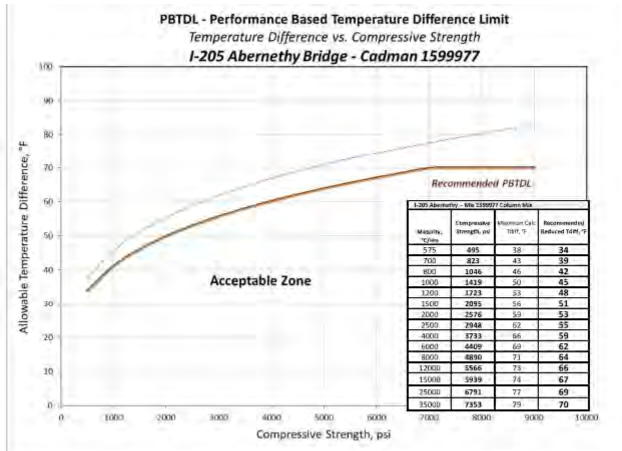


Figure B 8 – Step 3 - Fully Adiabatic Heat Signature from Matched Model (ATR 96°F)

Figure B 7 – Step 2 - Matched Thermal FEM Model of ATR Cube vs. Collected Data (Note: Model set to calculate conservative results at all ages)

REVISED SPECIFIED LIMIT - PBTDL

- Default Limit of 35°F – Restrictive
- Performance-Based Recognized by:
  - ACI PRC 207.1-21 – Mass Concrete, Guide
  - CSA A23.1-19 – Concrete Materials and Methods of Construction
- Mix Design Dependent
- Allows higher differential based on material strength
  - Below threshold of cracking caused by thermal stress



I-205 Abernethy – Mix 1599977 Column Mix

Maturity, °C/Hrs	Compressive Strength, psi	Maximum Calc. Tdiff, °F	Recommended Reduced Tdiff, °F
575	495	38	34
700	823	43	39
800	1046	46	42
1000	1419	50	45
1200	1723	53	48
1500	2095	56	51
2000	2576	59	53
2500	2948	62	55
4000	3733	66	59
6000	4409	69	62
8000	4890	71	64
12000	5566	73	66
15000	5939	74	67
25000	6791	77	69
35000	7353	79	70

Figure C1: Performance Based Temperature Difference Limit, Mix 1599977.

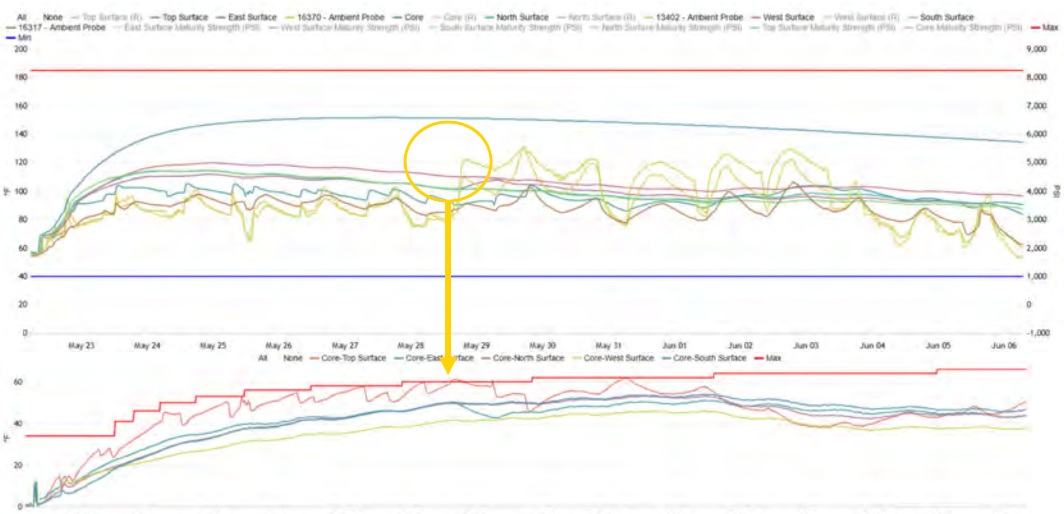
COLUMNS - THERMAL CONTROL IN PRACITCE LOWER 5A

COLUMNS - THERMAL CONTROL IN PRACITCE LOWER 5A

COLUMNS - THERMAL CONTROL IN PRACITCE LOWER 5A - RESULTS

COLUMNS - THERMAL CONTROL IN PRACITCE LOWER 5B

COLUMNS - THERMAL CONTROL IN PRACITCE LOWER 5B



CROSSBEAMS – THERMAL CONTROL PLANNING

- Cooling Pipes Required
  - Cross section and mix design
- Optimized Layout
- Duration of Thermal Control / Design Considerations

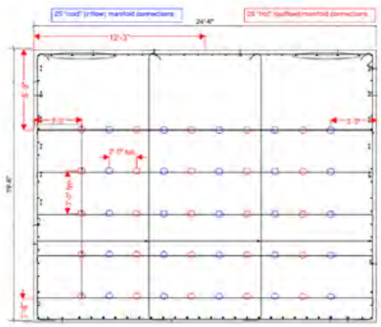


Figure F.1: Pier 5 Crossbeam Placement 1 Rebar-mounted Cooling Pipes Layout, Section View

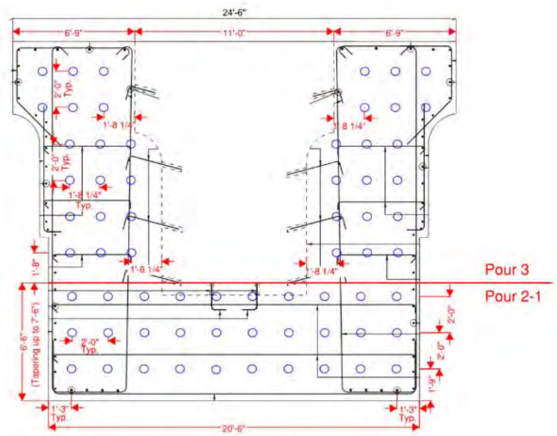


Figure F.3: Pier 5 Crossbeam Placements 2-1 and 2-3 Cooling Pipes Layout, Section View

SUMMARY

- Benefits of Technical Approach
  - Cooling pipes not needed in columns
    - Lower cost
    - Lower complexity
  - Concrete Cooling Efforts
    - Liquid nitrogen not required
  - Optimized Mix Designs through Partnership
  - Sustainability
  - Constructability

QUESTIONS?