Minnesota Concrete Council
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Concrete Sustainability versus Constructability – Closing the Gap

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The challenge: sustainability-driven concrete spec requirements and constructability influences

- Highly sustainable concrete mixtures must generally be lower in clinker content for lower carbon footprint and embodied energy
- Most common approach:
  - Higher replacement rates of portland cement with SCM's
  - More aggressive admixture use
- Constructability effects?

Celebrated projects & sustainability

- I-35 St. Anthony Falls Bridge, Minneapolis
  - Opened Sept. 2008
- 60 to 85% SCM mixes
  - 4000 to 5500 psi designs
  - ≤ 600 lb/yd^3 total cementitious content
  - 14-38% est. clinker factor
- Are similar mixtures acceptable for flatwork, other common projects?

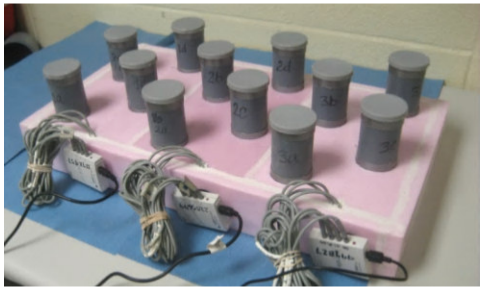
What about flatwork?

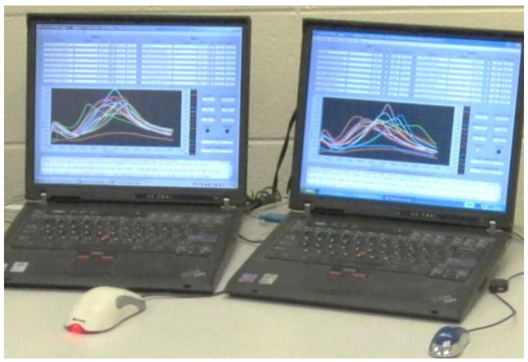
- Performance trends of high SCM content mixtures
  - Slow setting
  - Low early strengths
  - Temperature sensitivity
  - Incompatibility potential
- Concerns:
  - Finishing difficulties
  - Cracking
  - Flatness / profile specs
  - Surface durability
  - Aesthetics
- Are sustainable projects higher liability projects?

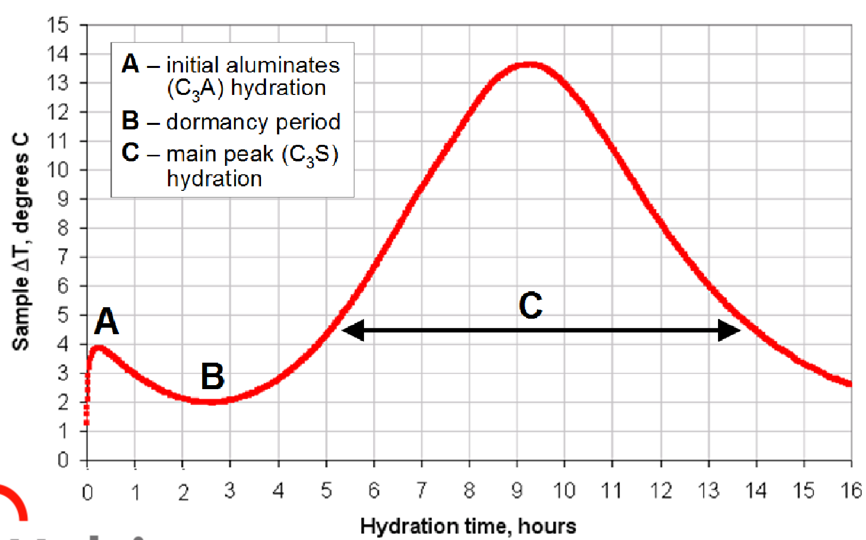
Development of *constructible*, sustainable mixtures

- In general:
  - Setting and early strength objectives similar to conventional mix designs
  - Selection of materials important
  - More WR admixture required for lower w/cm
  - Accelerating admixtures needed to restore set
- Must deal with:
  - Greater resulting temperature sensitivity
  - Increased possibility of incompatibility
- Simply increasing SCM replacement of an existing mix without engineering adjustments for side effects *will not likely be successful!*
- Simple performance screening tests needed!

Thermal profile testing as a mix development tool







- Simple, expedient testing of fresh concrete, mortar, or paste
- For mix development – lab paste mixtures (paste fraction of a possible concrete mix design)
- Approach: evaluating performance influences of multiple variables (materials and proportions) in similar mixtures, one change at a time
- Advantage: dozens of variables evaluated in a few hours, optimizing proportions for concrete trials

Document development in ASTM C01/09.48

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Standard practice for

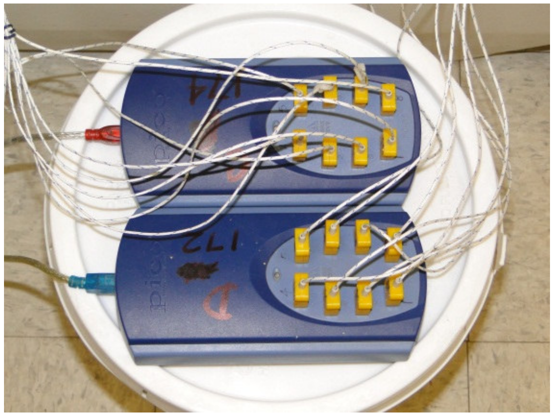
Evaluating hydration of hydraulic cementitious mixtures using thermal measurements

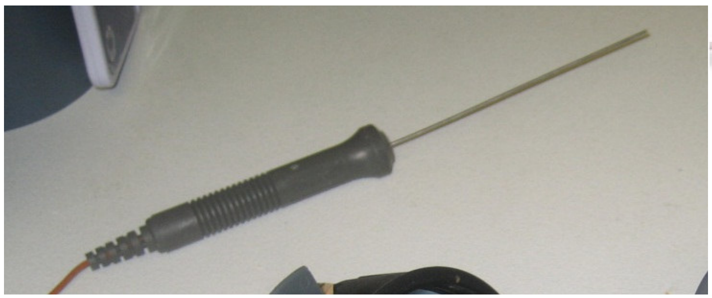
1. Scope

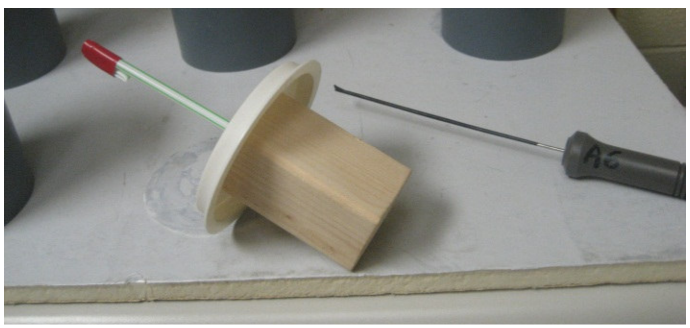
1.1 This practice describes the apparatus and procedure for evaluating relative differences in hydration of hydraulic cementitious mixtures in paste, mortar, or concrete, including those containing admixtures, various supplementary cementitious materials (SCM), and other fine materials, by measuring temperature change over time using temperature recording equipment.

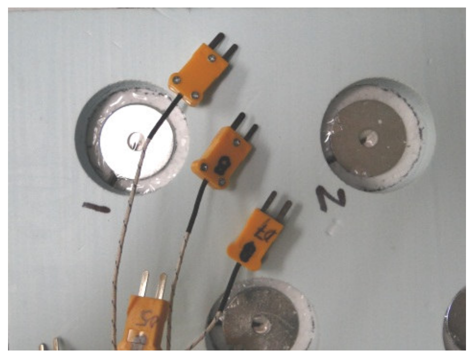
1.2 Calorimetry is the measurement of heat lost or gained during a chemical reaction such as cement hydration; these measurements as a function of time can be used to describe and evaluate hydration and related influences. Calorimetry may be performed under isothermal conditions (as described in C 1679) or under adiabatic or semi-adiabatic conditions. While the practice covered in this document cannot be described as calorimetry since measurements are not quantitative, it can be used for similar applications. Variables that should be considered are discussed in the

Inexpensive temperature sensors and loggers



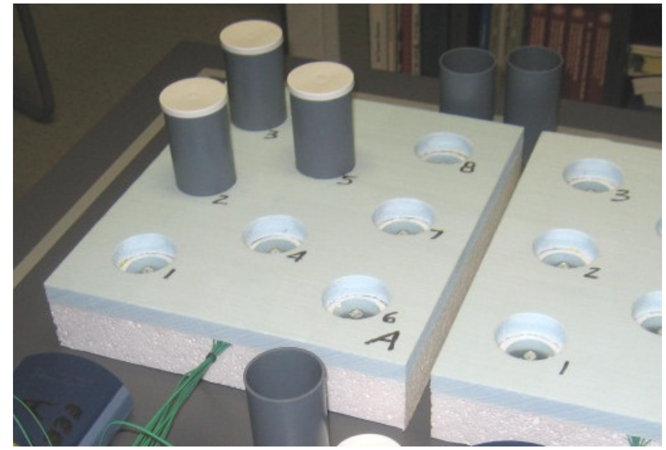
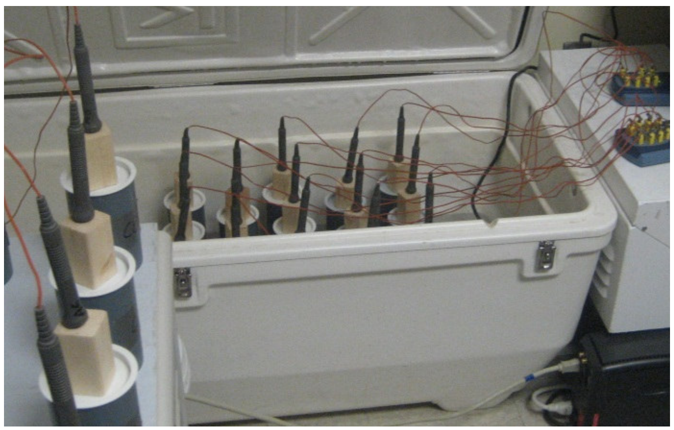
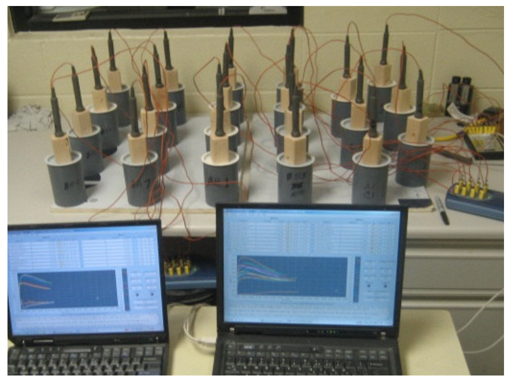


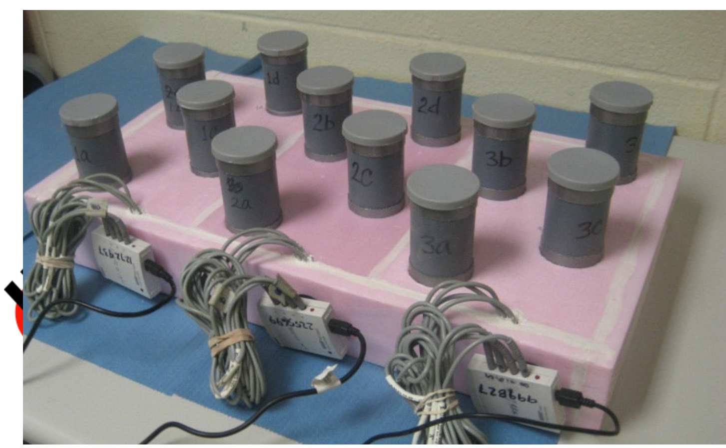




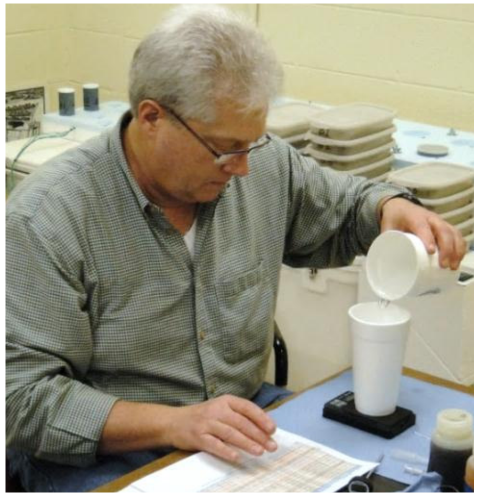
Manufactured and adapted equipment

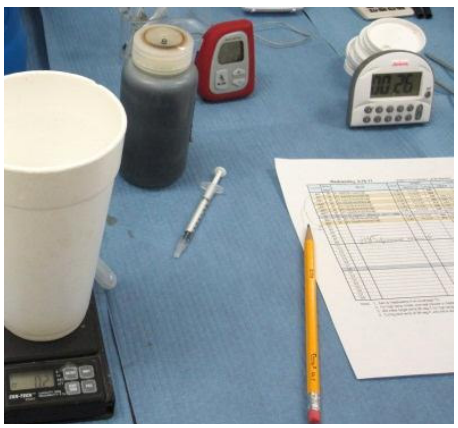


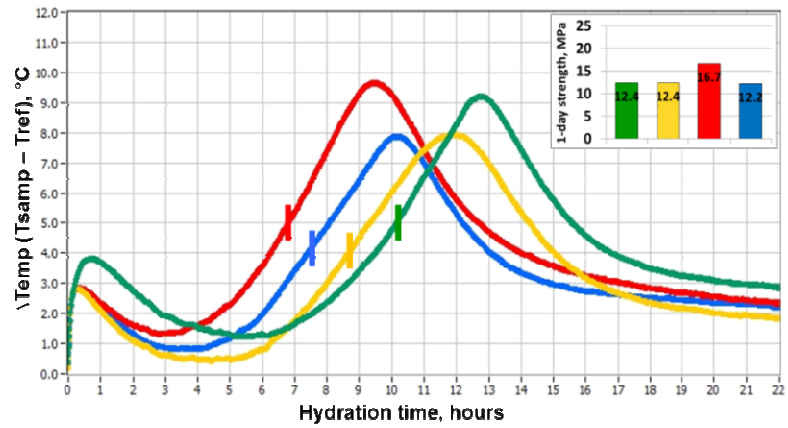







Lab testing of paste mixtures used in the development of complex mix designs

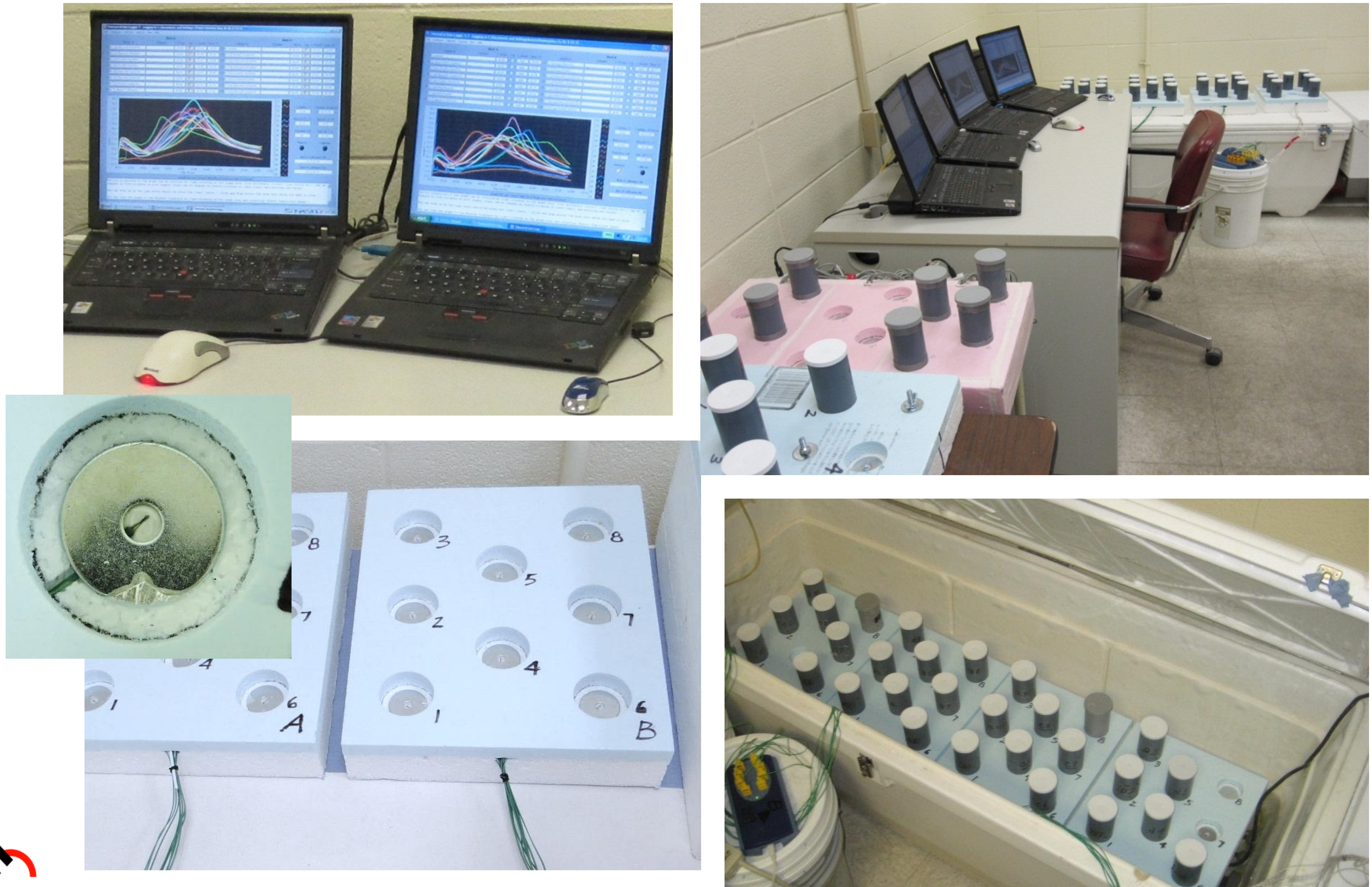







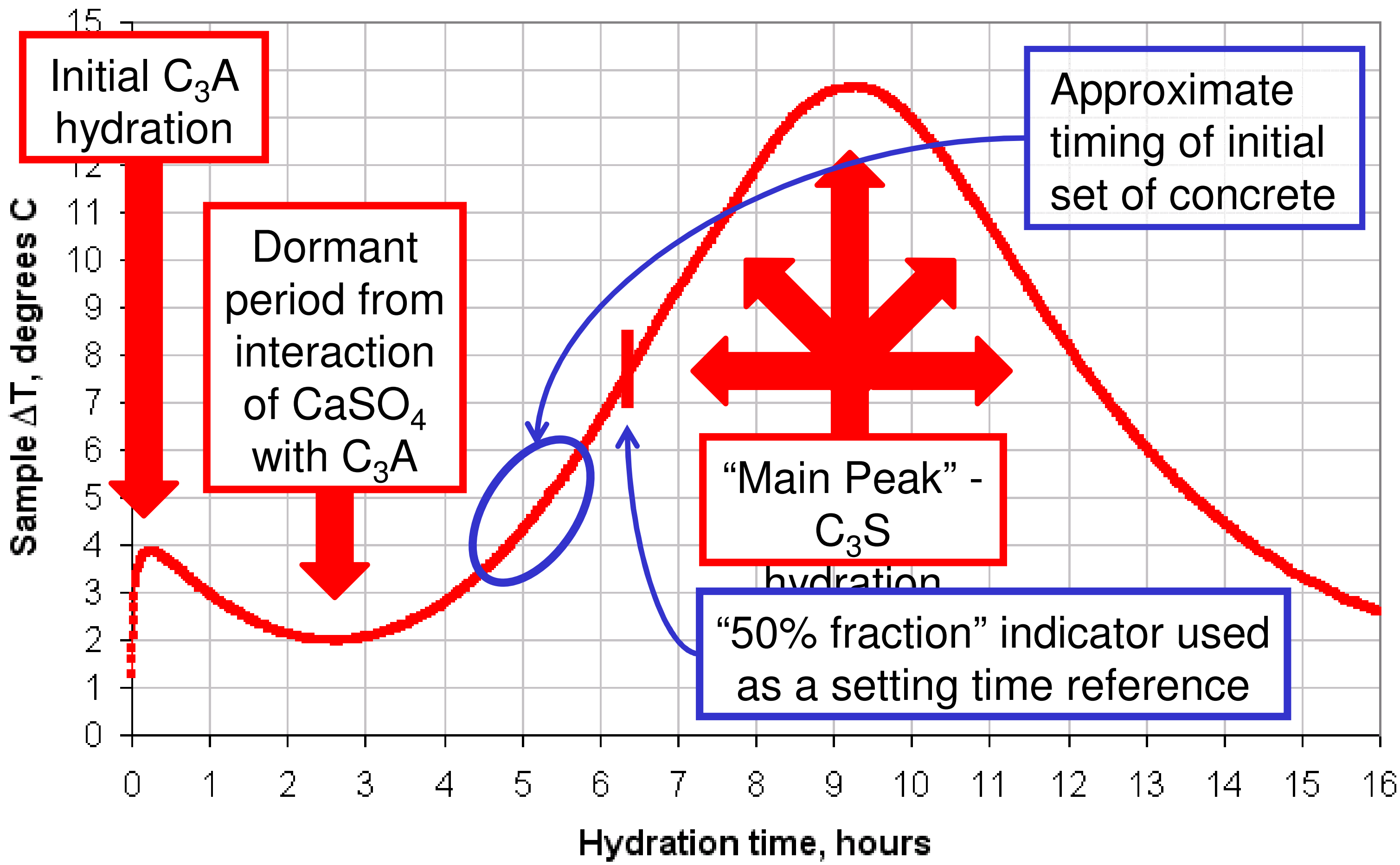

- Setting trends according to relative timing of thermal profiles
- Strength trends via compressive testing of hardened paste
- Evaluation of incompatibility potential

Data collection setups used for example data



Hydration and thermal profile indications

The temperature history of the first few hours of hydration (thermal profile) serves as a record of relative C_3A and C_3S hydration rates and the interaction of $CaSO_4$ (gypsum).

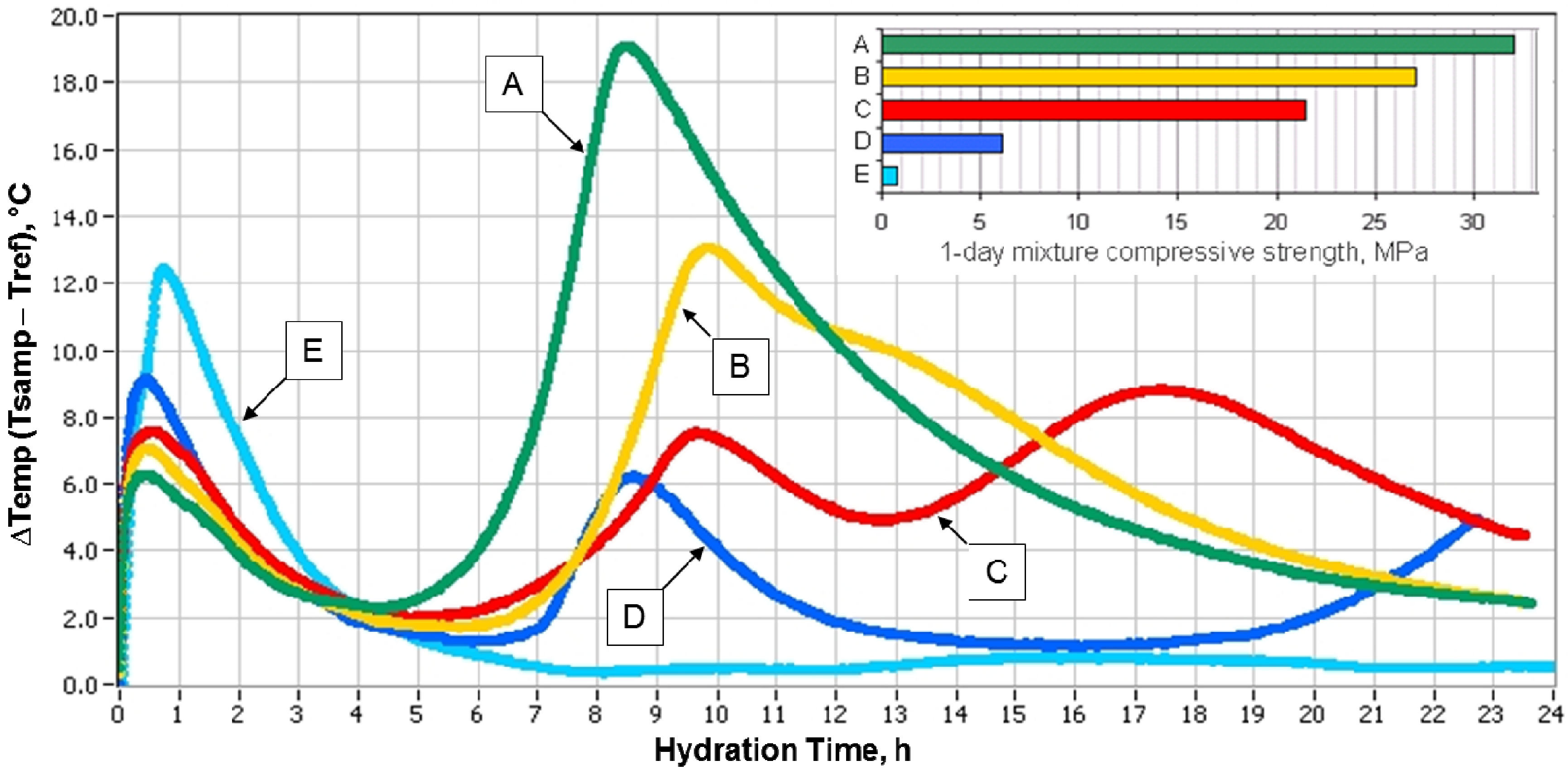


Uses and applications – thermal profile testing

- QC tool for concrete & customer services
  - Setting time influences of SCM's, admixtures, dosages
  - Evaluation / selection of cements, SCM's, admixtures
  - Checking for incompatibility potential of combinations
  - Qualifying a new mix design under field temperatures
  - Evaluating material source variability or new sources
  - Alternative to ASTM C403 set time testing, field or lab
  - Troubleshooting field concrete problems
- QC tool for cement production
  - Sulfates optimization, sulfate balance checks – effects of new fuels, gyp sources, mill temps, etc.
  - Evaluation of setting time trends with SCMs & admixtures

Thermal profiles and sulfate-balance “incompatibility”

Simplest way to evaluate sulfate adequacy for a mixture of materials



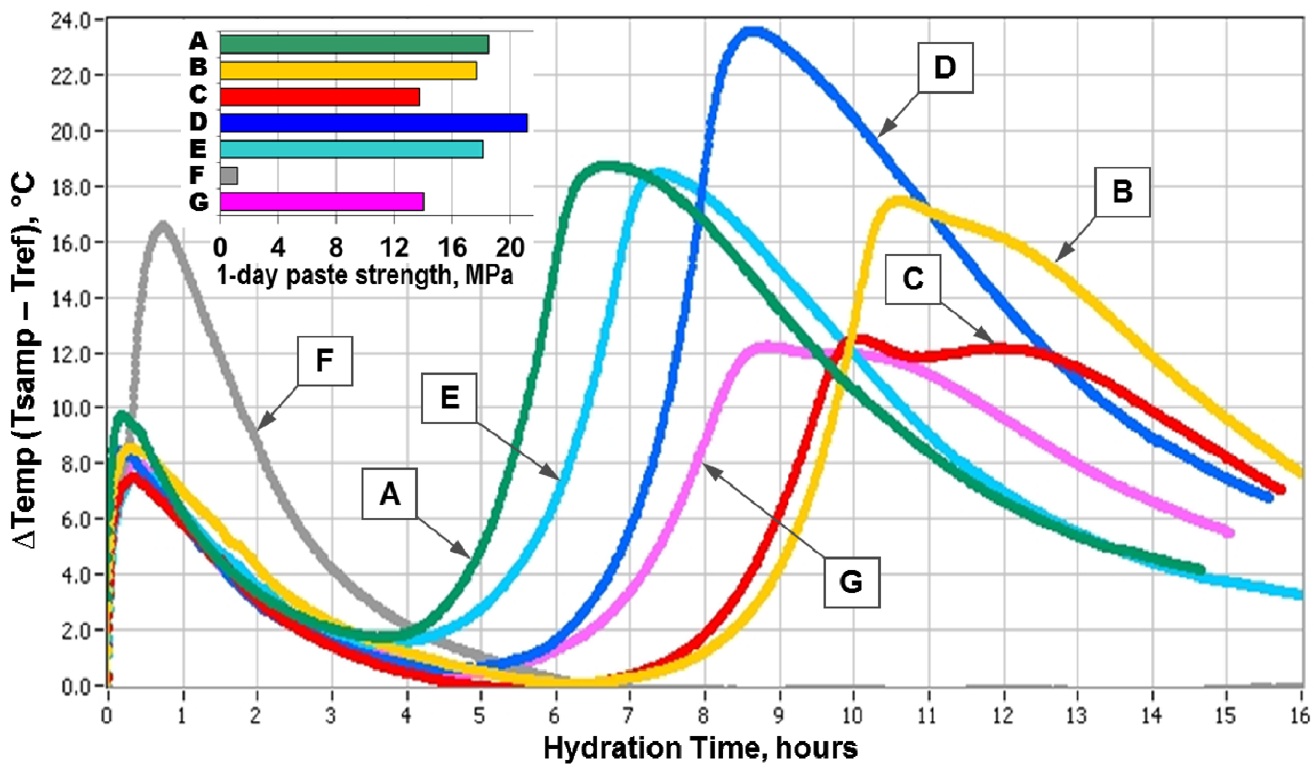
5 paste mixtures using the same cement sample with 25% C ash & incremental sulfate demand via admixture dosage adjustments

Mixture development process

- Materials selection – avoiding incompatibility influences, maximizing synergies, minimizing retardation contributions
- Screening tests with lab paste, thermal profiles & strengths:
  - Establishment of performance targets via reference mixes
  - Effects of increasing SCMs to proposed levels
  - W/cm adjustments with admixtures to restore early strengths
  - Compensating for retardation effects with admixtures
  - Sulfate balance checks at field temps
- Concrete trials & final mix refinement
- Additional adjustments, if needed, for changing temps

Materials selection – cement

- Desirable characteristics:
  - Good synergy with SCMs
  - Good sulfate balance trends, amply sulfated
  - Relatively short setting times, high early strengths



Sulfate adequacy compared for 7 cements in a high sulfate demand paste mix using 25% C ash, upper-limit dose of Type A/D WR, and 35ºC (95ºF) mix and cure temps

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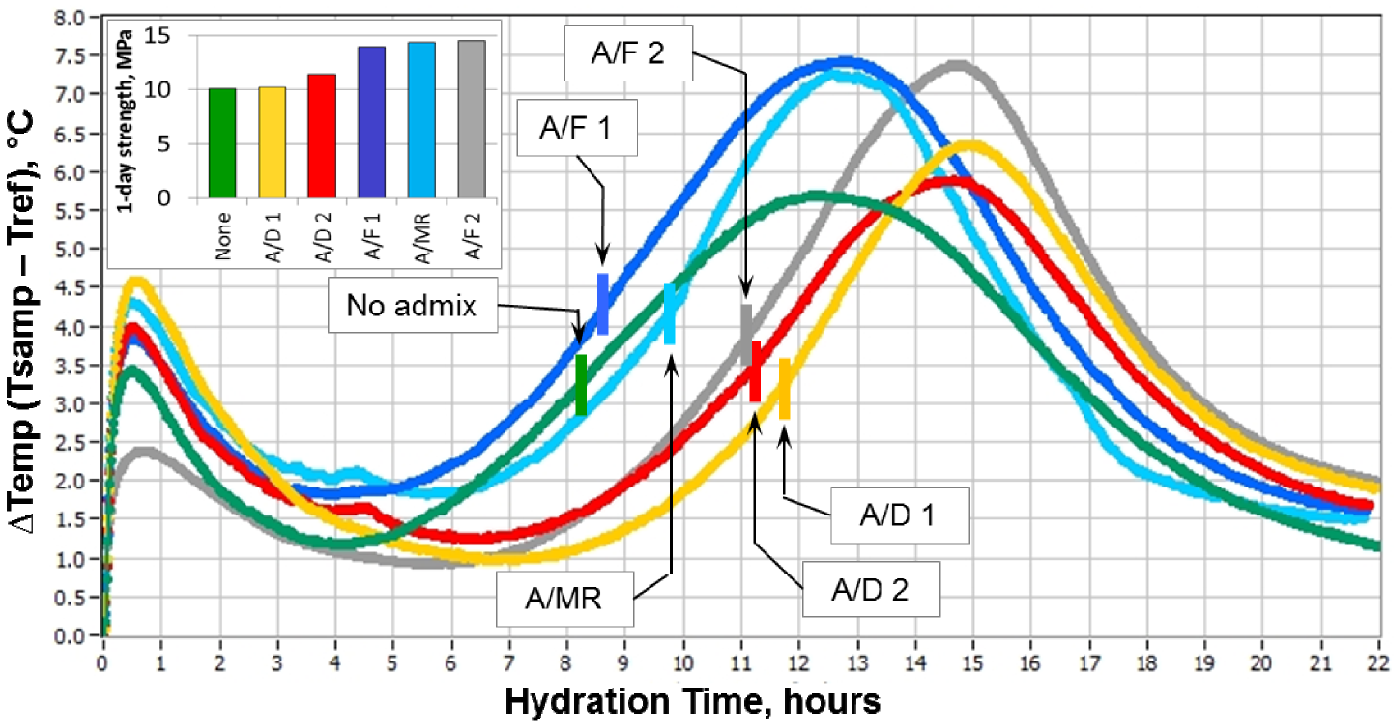
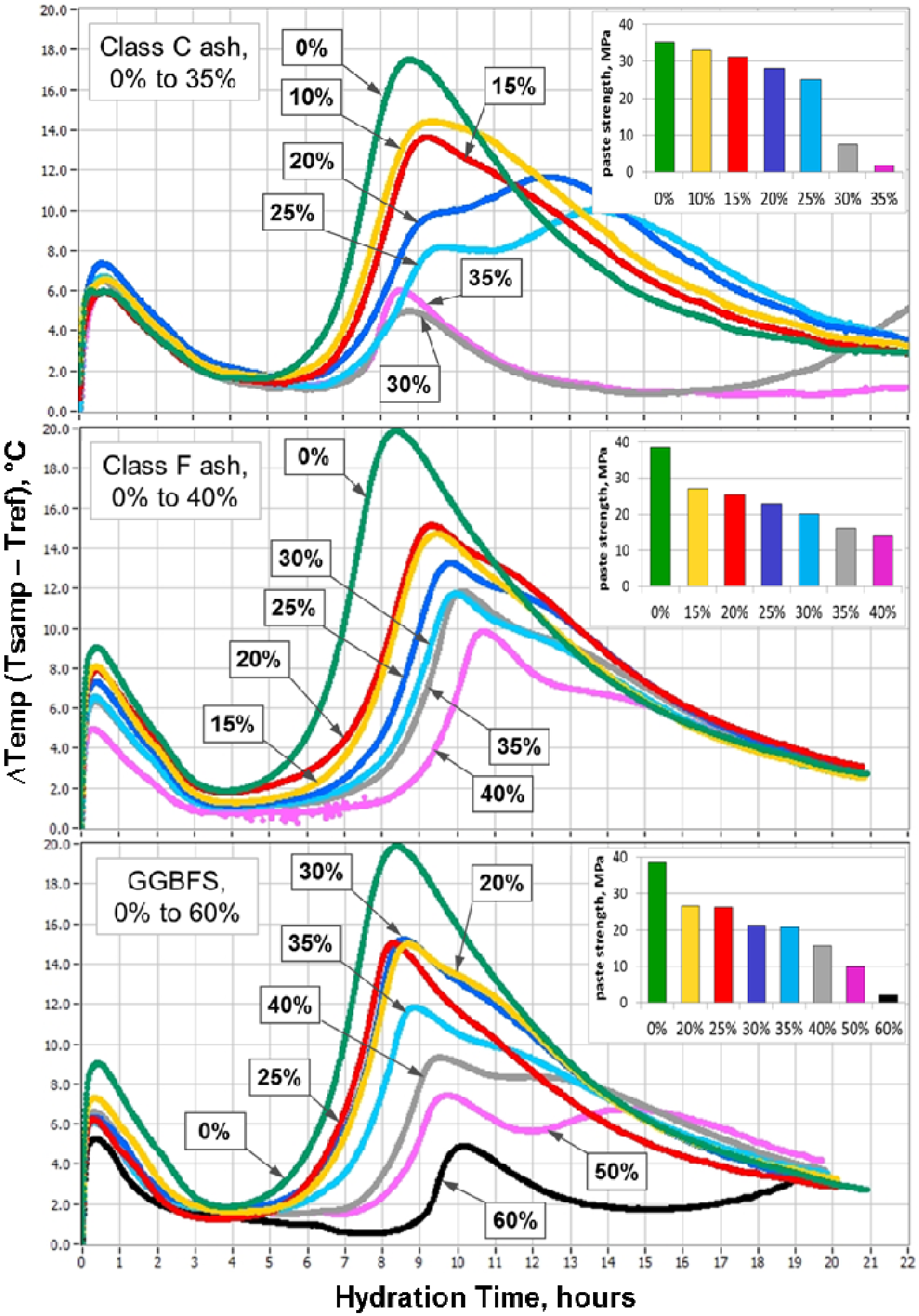
Materials selection – water reducing admixtures

- Desirable characteristics:
  - Higher range water reduction capability, dosage flexibility
  - Minimal retardation influences



Set time effects compared for 5 different water reducing admixtures, dosage selected for 6% water reduction, paste mixtures with 30% C ash, w/cm = 0.40, 21ºC (70ºF) mix and cure temps, shown with 50% fraction markers for reference



Materials selection – SCMs

Desirable characteristics:
Minimal incompatibility impact!

At left, thermal profiles and 1-day strengths comparing 3 different SCMs (C ash, F ash, and slag cement) in moderate sulfate demand mixtures, with incremental replacement rates.

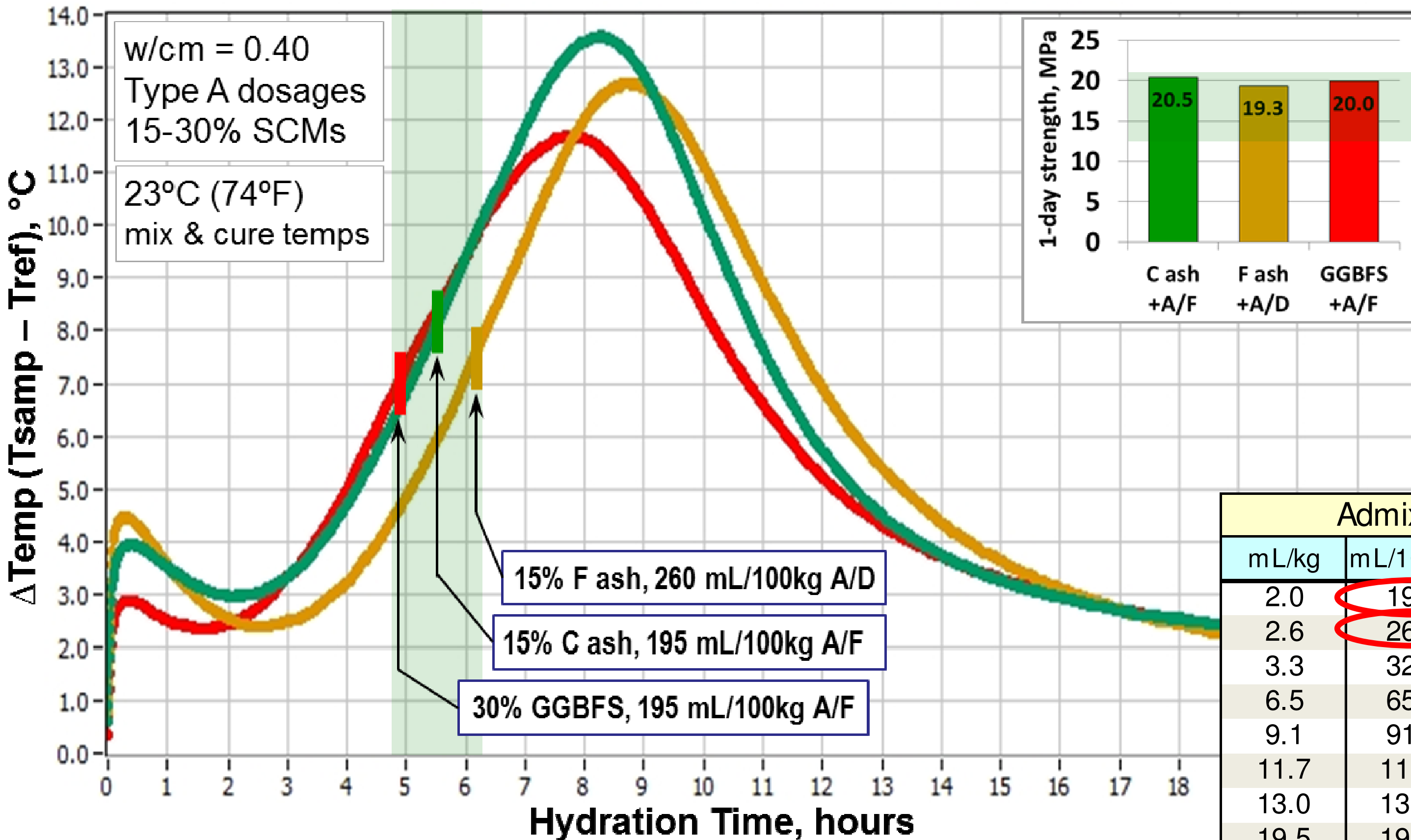
A single sample of Type I/II cement was used, w/cm = 0.40, upper-limit dosage of Type A/D admixture, 32ºC (90ºF) mix and cure temps.

C ash mixtures suggest problems at higher replacement rates.

Slag cement may be most likely for very high replacement rates.

Performance of traditional low-SCM mixtures

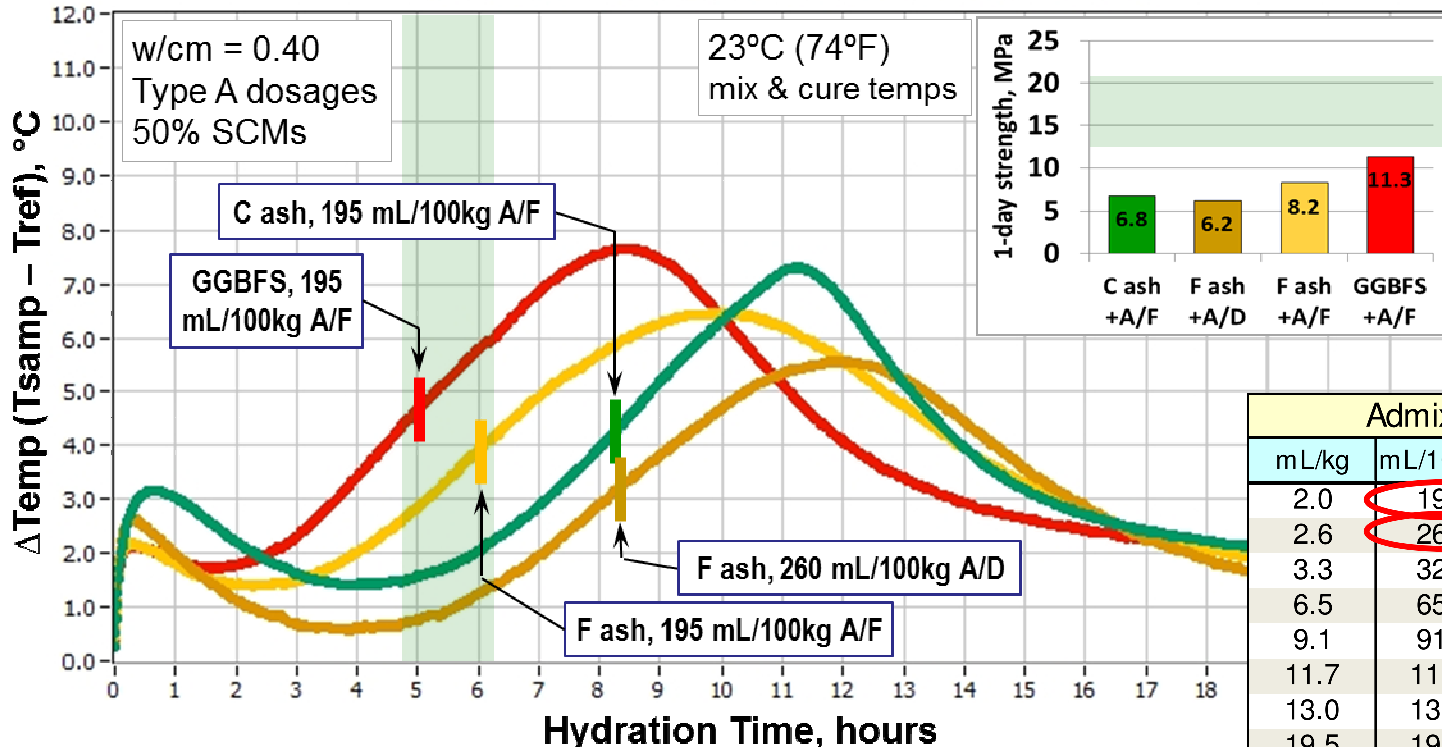
- “Reference” mixtures to establish performance targets for mix development
- 15% C ash, 15% F ash, 30% slag cement with mild WR dosages
- For these examples, criteria to be based on these mixtures (green bands), 50% fraction thermal set indications and 1-day strengths in bar charts



Admixture dosages			
mL/kg	mL/100kg	L/100kg	fl oz/cwt
2.0	195	0.20	3
2.6	260	0.26	4
3.3	325	0.33	5
6.5	650	0.65	10
9.1	910	0.91	14
11.7	1170	1.17	18
13.0	1300	1.30	20
19.5	1950	1.95	30
26.0	2600	2.60	40

Effects of SCM replacement rate increased to 50%

- Same temps & admix dosages, with the addition of an F ash mix w/ A/F WR
- Set time with F ash and A/D WR driven by admix
- Good set performance with slag and F ash + A/F
- C ash set time goes quite long (indication of potential issues)
- 1-day strengths all now unacceptable



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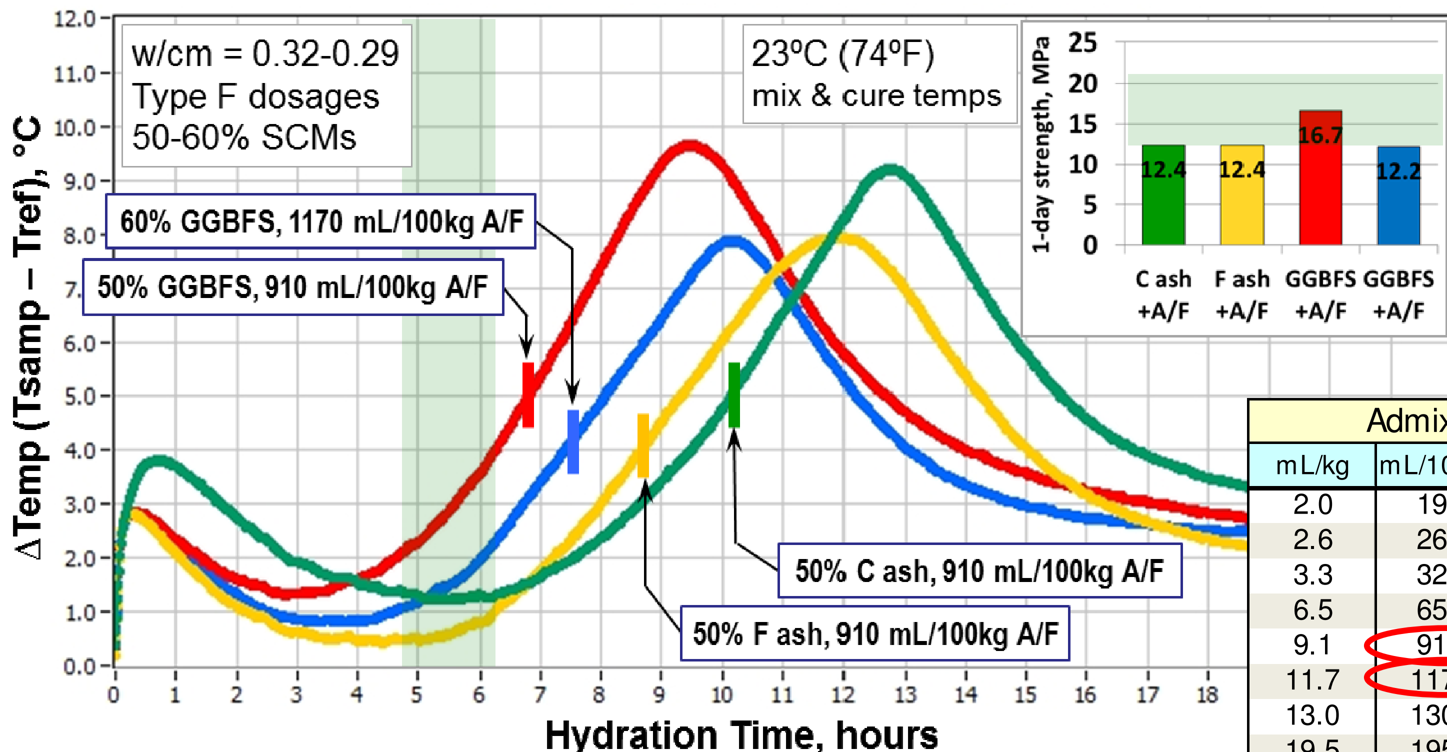
Effects of lower w/cm using HRWR dosages

- Lower w/cm needed to restore early strengths, A/F WR dose increased
- All 1-day strengths now marginally acceptable, slag mix healthiest
- 60% replacement mix with slag added, still acceptable strength
- All set times now unacceptable, need help from accelerators (esp. C ash)



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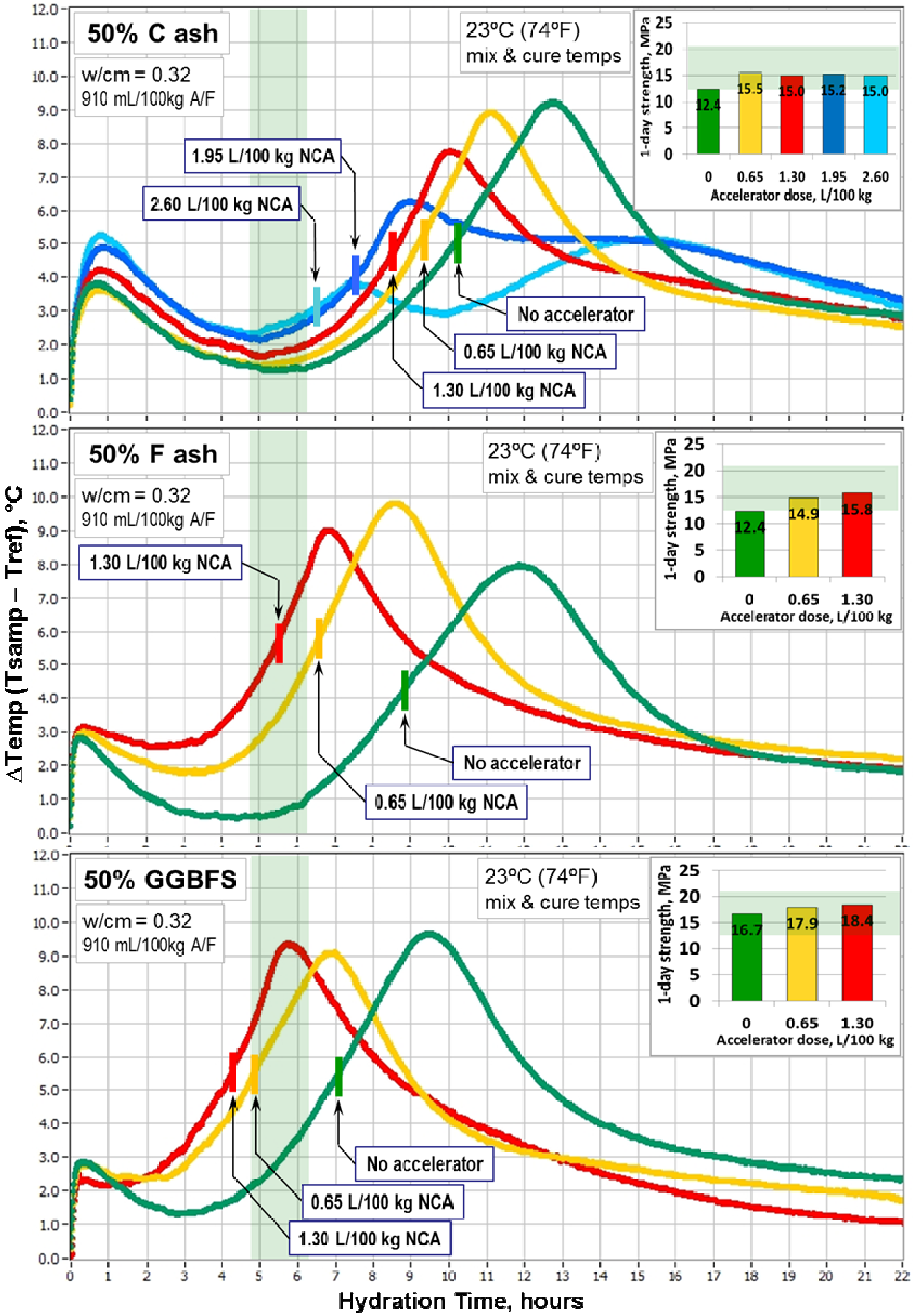

Compensating for delayed set with accelerating admix

- All mixtures repeated with varying & incremental dosages of non-chloride accelerator (NCA)
- Moderate dosages restore acceptable set for F ash and slag
- NCA less effective with C ash and seems to create sulfate balance issues (incompatibility) at higher dosages (in pursuit of restored set)
- 1-day strengths benefit from NCA

Admixture dosages			
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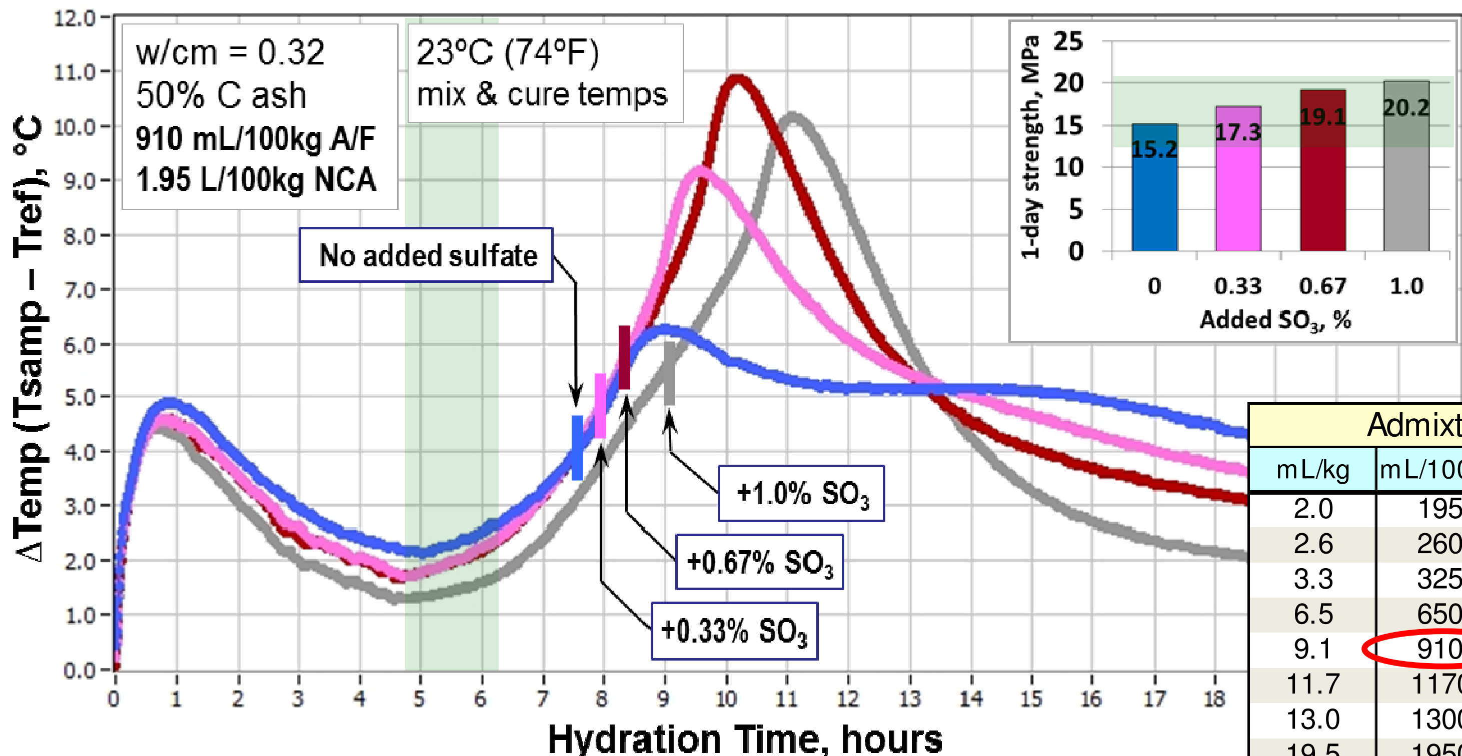
Sulfate balance evaluation of the C ash mix

- An affected mixture using NCA repeated with incremental $CaSO_4$ additions
- Profile shapes and 1-day strengths improve with additions, but not set time
- Confirms sulfate balance issues
  - C ash not considered a candidate for 50% replacement mix design
  - Lower replacement mix could be developed



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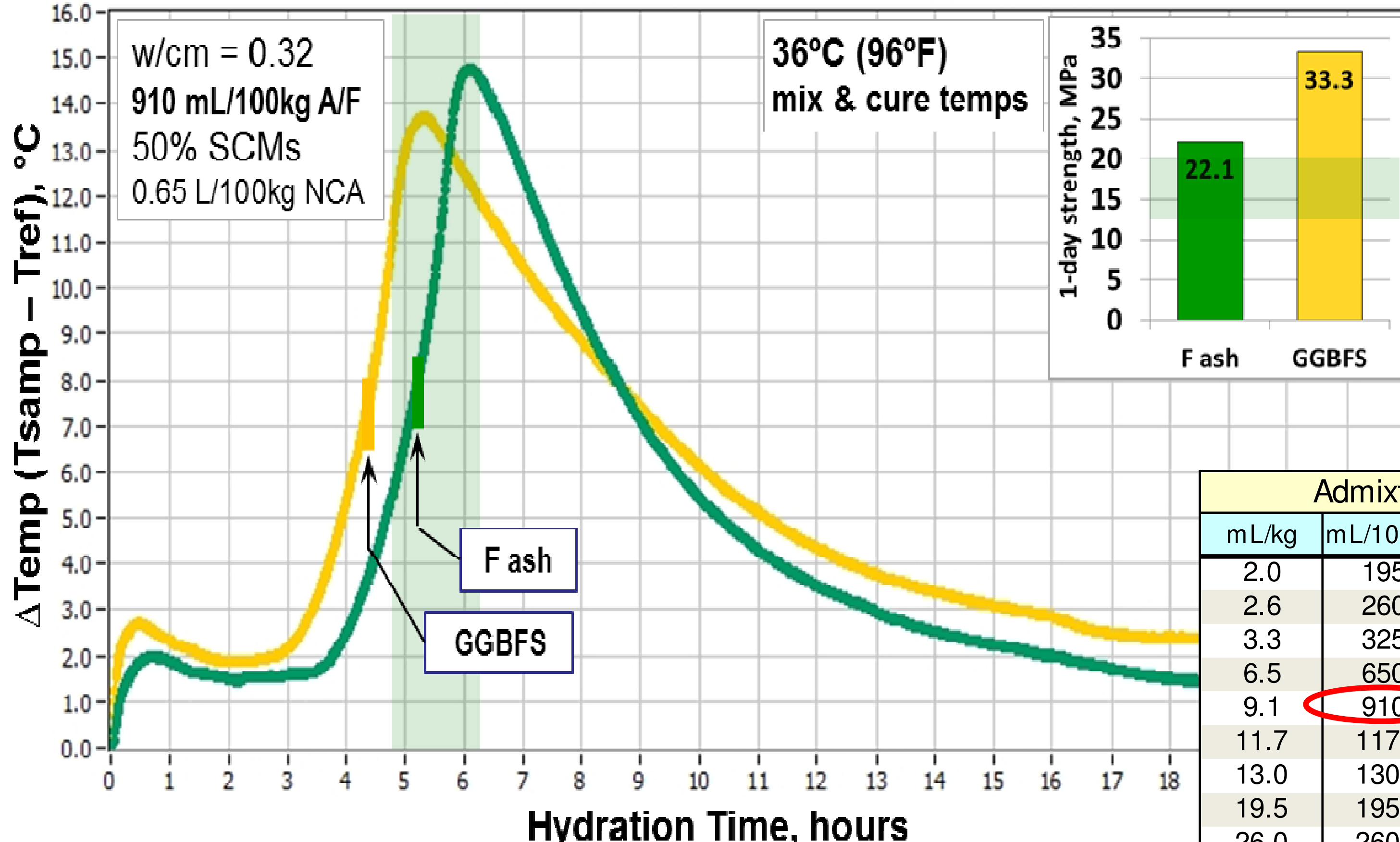
Verification of proportions at extreme field temps

- F ash and slag mixtures with same A/F dose & max NCA dose repeated at highest envisioned concrete field temps: 36ºC (96ºF) mix and cure temps
- No sulfate balance issues indicated; NCA dosages could be reduced
- OK to proceed to trial concrete mixtures



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Summary of examples

- F ash or slag cement sources OK for 50% replacement with these materials (possibly higher for slag)
- C ash source should not be used at 50% with these materials, lower replacement mix could be developed
- W/cm at 0.32 should produce acceptable early strengths
- Mild NCA dosage should restore acceptable set
- Proportions (F ash & slag) OK for sulfate balance to 36ºC (96ºF) in the field
- Next step – trial concrete mixtures, refinements of proportions for specific requirements or temp changes

Paper for 10th ICCP, Quebec, July 2012

- Portland-limestone cement in sustainable, high SCM mixtures
  - Inherent sustainability benefits
  - Synergies of both setting and strength with SCM's
  - Both physical and chemical contributions to hydration efficiency
  - Benefit proportional to total available $CaCO_3$ surface area

Preliminary Optimization of Concrete Paving Mixtures for Sustainability and Performance

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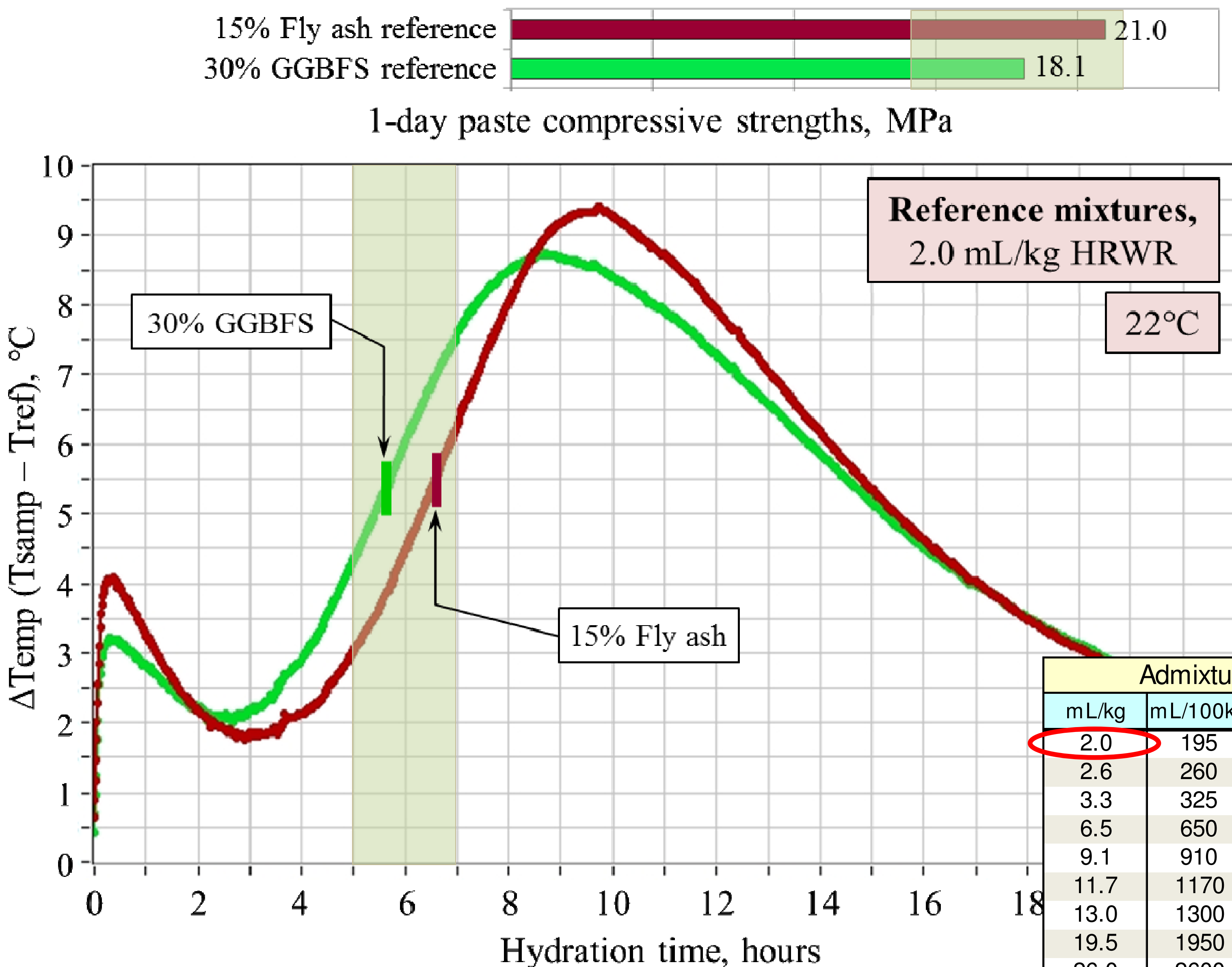
Abstract
Greater sustainability in concrete construction projects generally requires higher replacement of portland cement clinker-based binder materials with byproduct supplementary cementitious materials (SCM's). There may be serious constructability-related performance side effects of such concrete mixtures, however, including delayed setting, slower strength gain, and increased sensitivity of the mixture to changing temperatures. Related impacts for paving applications may include placement and finishing issues, cracking, surface profile and durability concerns, and various other quality and scheduling implications. Mix designs often require more aggressive chemical admixture use and performance side effects are difficult to

Paper for 10th ICCP, Quebec, July 2012

- PLC properties & influences evaluated using OPC with ground limestone of 2 fineness levels used as an additive
  - Median particle sizes of 4 and 12 µm
  - 5% and 10% replacement of cementitious by mass
- Effects compared with chemical accelerators & combinations

Particle Size Summary by % of Volume, µm					
	OPC	Fly Ash	GGBFS	4 µm LS	12 µm LS
<10%	2.1	2.6	1.3	1.1	1.5
<25%	7.5	7.8	3.3	1.9	4.2
<50% (median)	15.3	17.5	8.8	4.1	12.3
<75%	24.9	41.0	15.5	8.1	22.2
<90%	31.8	107.2	21.5	12.7	30.4

Reference Performance of traditional mixtures



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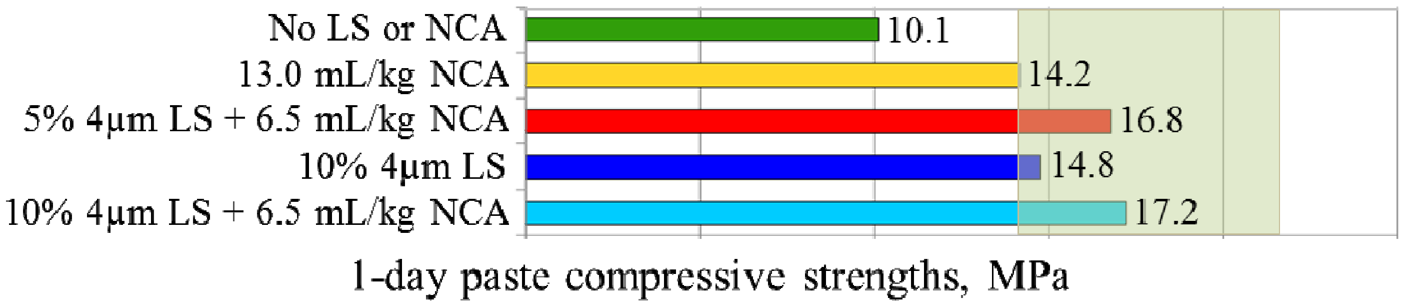
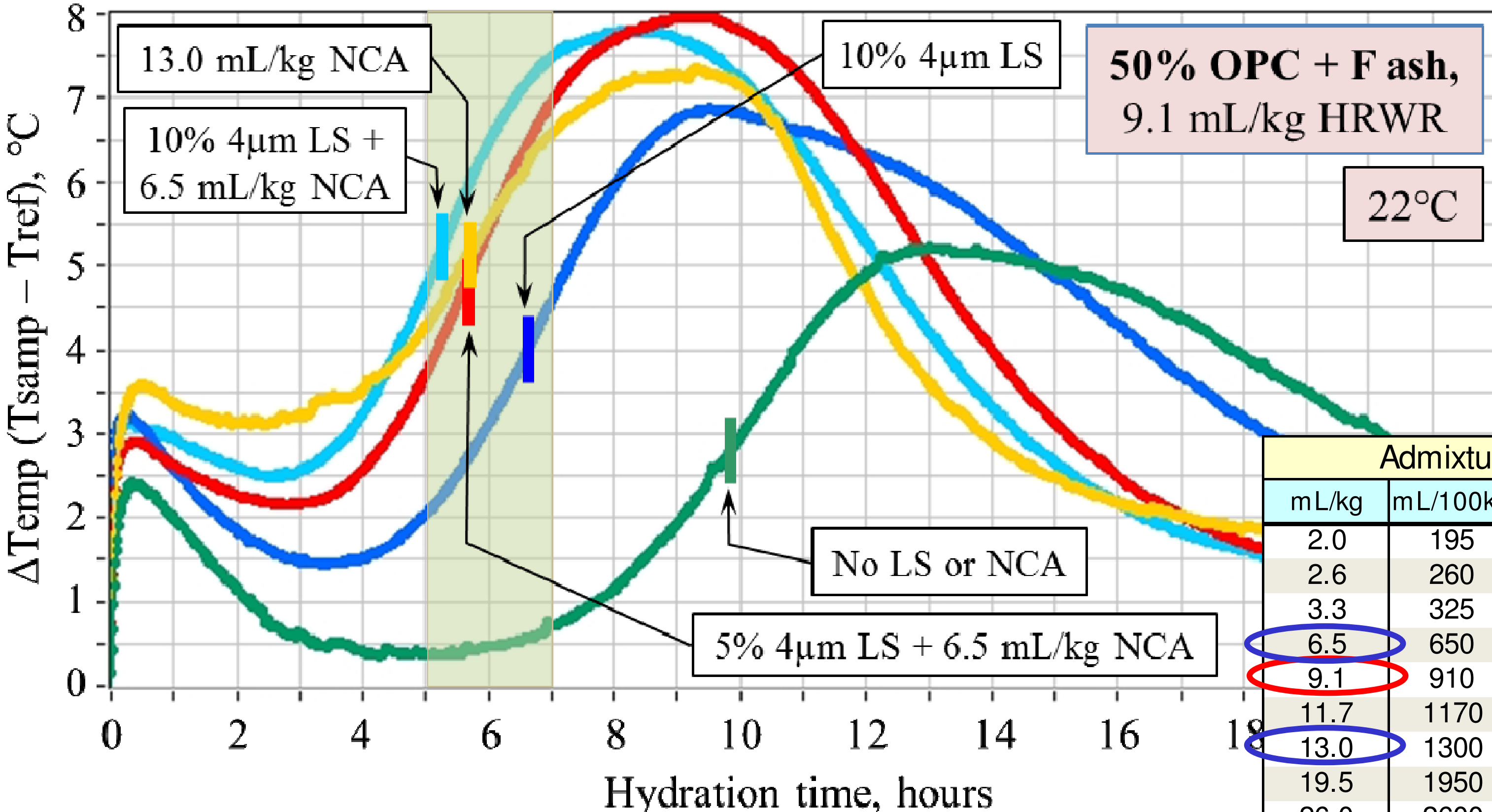
50% cement replacement with F ash





Admixture dosages

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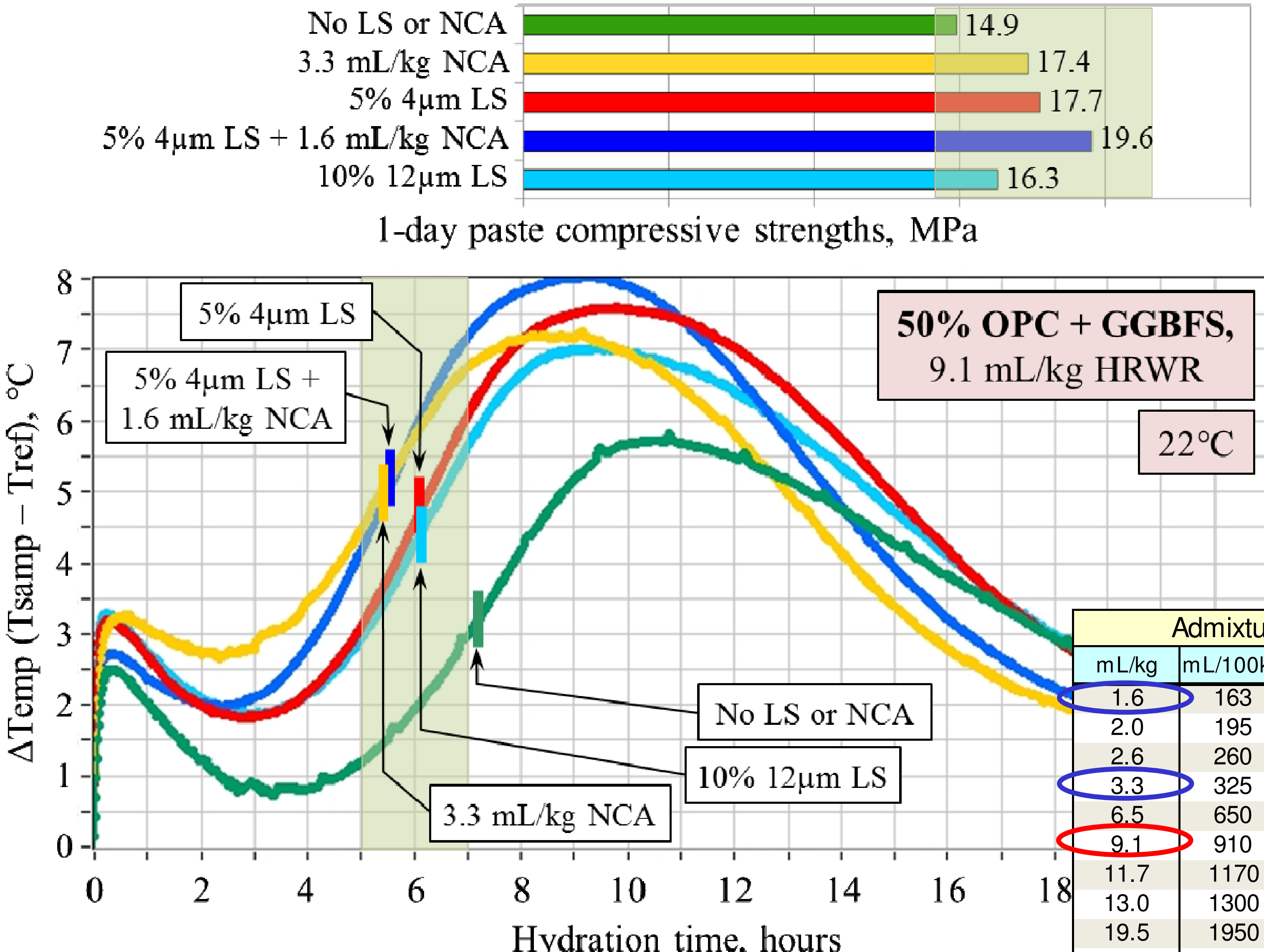
50% cement replacement with GGBFS



Admixture dosages			
mL/kg	mL/100kg	L/100kg	fl oz/cwt
1.6	163	0.16	2.5
2.0	195	0.20	3
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3.3	325	0.33	5
6.5	650	0.65	10
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Summary and conclusions

- Higher SCM mixtures for common apps appear possible and practical, without significant performance impacts.
- Thermal profile & compressive strength testing of lab paste mixtures can help screen & optimize performance, eliminating most required concrete batches and significantly reducing necessary lab time.
- Successful strategies include:
  - Lower w/cm with HRWR for required early strength
  - Acceleration using chemical admixtures and/or limestone
- Sulfate balance checks and seasonal effects can be evaluated using similar mixture sets
- Next step – trial concrete mixtures, refinements of proportions for specific requirements or temp changes

Questions?

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