ACI Foundation
Technology Forum 2023

Framework for Characterizing the Performance of High-Early Strength, High-Volume Fly Ash (HVFA) Concrete Structures

Matthew J. Gombeda, PhD

Assistant Professor of Civil Engineering
Department of Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
Chicago, IL

ILLINOIS INSTITUTE OF TECHNOLOGY
Armour College of Engineering

Thursday August 31, 2023
Portland, Oregon

My **Background**

Assistant Professor of Civil Engineering
Director of the Concrete Materials & Structures Laboratory
Department of Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
2019 - Present

PhD in Structural Engineering
Lehigh University
2019

MS in Structural Engineering
Lehigh University
2016

BS in Civil Engineering
Minor in Engineering Mechanics
Penn State University
2014

Research Areas

- Behavior and mechanics of concrete structures
- Innovative precast & prestressed concrete components
- Innovative cementitious materials
- Experimental methods

Highlights of **IIT** Concrete Materials **& Structures Laboratory**

Highlights of **IIT Concrete Materials & Structures Laboratory**

Background and **Motivation**

Fly ash (FA), a coal combustion residual (CCR), is one of the most commonly used supplementary cementitious materials (SCMs).

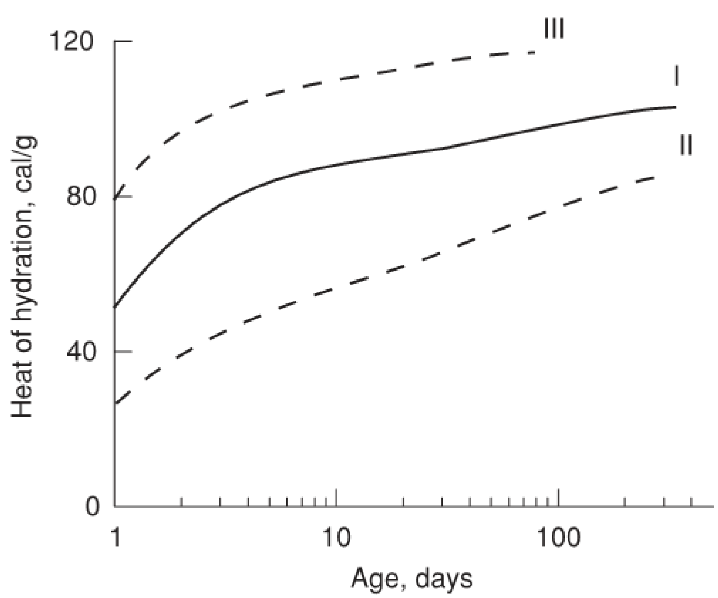
FA particles carried out of coal combustion chamber by exhaust gases and subsequently filtered out

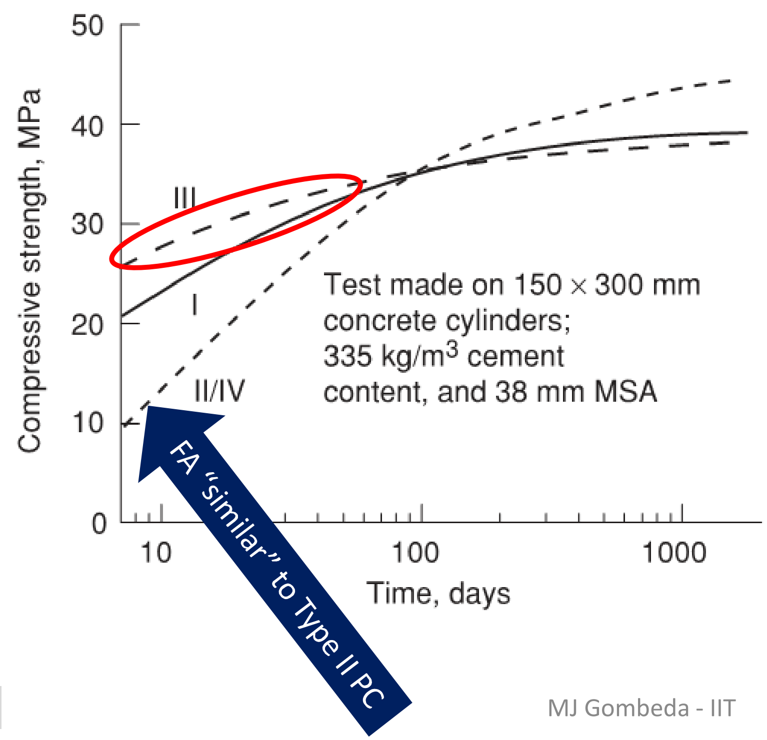
Two main classifications:
Class F → FA w/ pozzolan properties
Class C → FA w/ pozzolan & **cementitious** properties

Often used as a [partial] replacement of conventional Portland cement
→ With restrictions for high-early strength concretes
- → **Initial Prestress**
- → **Formwork Removal**
- → **Rapid re-opening of structure**

High early strength development in FA concretes is typically limited by relatively lower **heat of hydration**

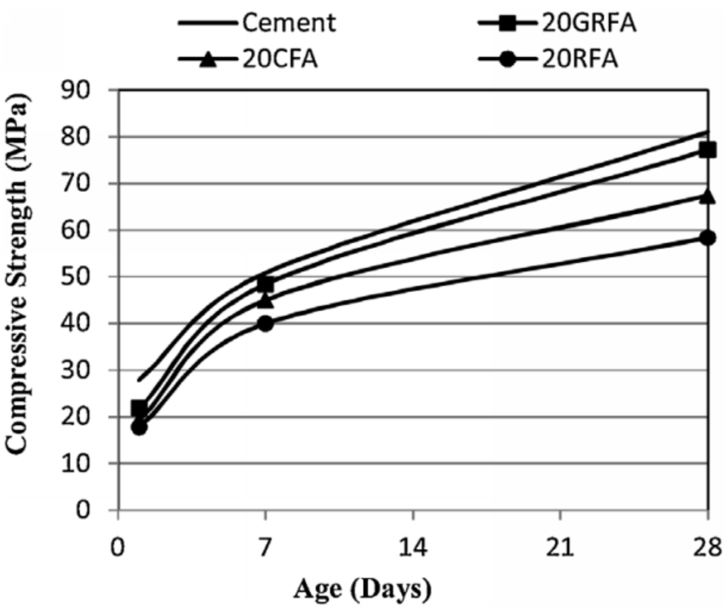
High early strength commonly achieved using Type III Portland cement
→ Type III PC exhibits high heat of hydration



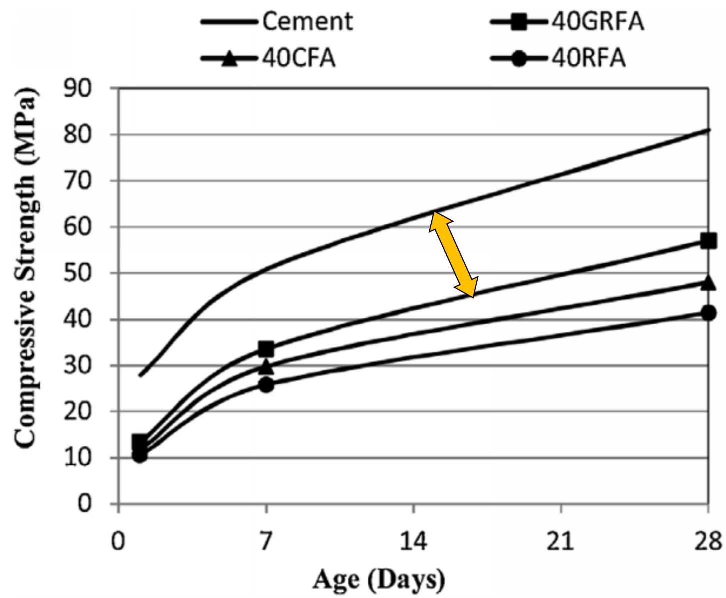


Mehta, PK, Monteiro, PJM. Concrete: Microstructure, Properties, and Materials, 3rd Edition, 2006, McGraw Hill

Increasing FA content for conventional mix designs usually leads to **slower compressive strength gain**
→ Note the larger offset from the control 'Cement' mix curve with increasing FA content



20% Fly ash content



40% Fly ash content

Moghaddam, F., Sirivivatnanon, V., and Vessalas, K. "*The effect of fly ash fineness on heat of hydration, microstructure, flow and compressive strength of blended cement pastes.*" Case Studies in Construction Materials 10 (2019) e00218. Elsevier Ltd.

Why is today's topic **important?** and **innovative?**

Push for more **"sustainable concretes"** is well known

Can we continue to further advance sustainability initiatives without sacrificing pertinent fresh & hardened properties?

+ Especially critical for high-early strength mixes

→ High replacements of OPC often result in low heats of hydration

→ Generally results in lower early-age strengths

Furthermore…

If we develop novel mix designs to meet such objectives, do we have a unified methodology to characterize their performance?

Are current methods or provisions still sufficient?

Outline of **Proposed Framework**

1) Gather Concrete Performance Requirements

2) HVFA Binder Optimization

3) Assess the Environmental Impact of Using HVFA Concretes

4) Scaling to HVFA Concrete Mix Designs

5) Characterization of HVFA Concrete Strength Development

6) Facilitating Extrapolation from Ideal Laboratory Conditions to Relevant Environments

7) Assessing the Behavior/Performance of HVFA Concrete Structures

8) Expected Durability and Long-Term Performance

9) Facilitating Updates/Revisions to Design Standards, Guidelines, etc.

1) Gather Concrete Performance Requirements

Mechanical Performance

+ Early-age compressive strength
(initial prestress, bridge re-opening, etc.)
+ Early-age flexural strength
(lifting & handling, etc.)

Think like *vectors* → (magnitude and time!)

Workability

+ SCC ?
(if so, follow a few extra steps later on)
+ Slump retention
+ Desired set time

Durability & Long-Term Performance

+ Air content
+ Formation Factor
+ Creep & Shrinkage

Environmental Impact

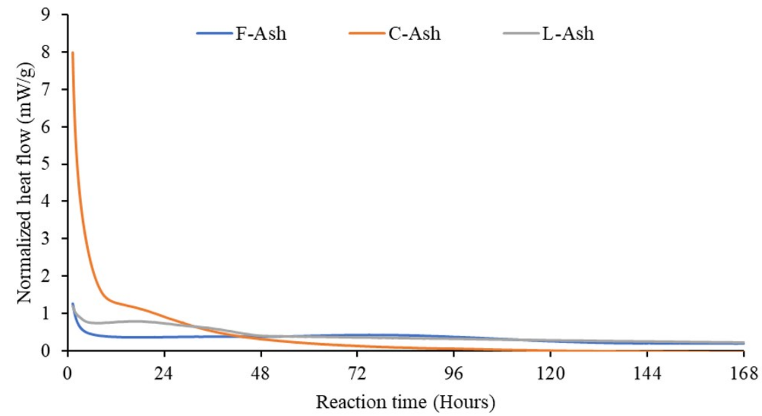
+ Limits on certain chemical contents
+ Leaching
+ Environmental life-cycle goals

2) HVFA Binder Optimization

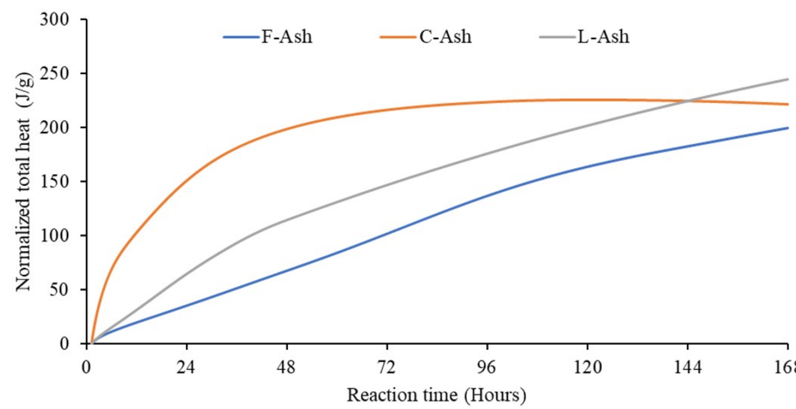
Reactivity

+ Measure the heat release of novel SCMs in a calorimeter @ 40°C (ASTM 1897-20)

+ In many ways, an important precursor to binder performance (and subsequently concrete strength development) characterization



(a)



(b)

https://www.humboldtmfg.com/digital-cement-calorimeter.html

Development of **Optimized HVFA Binders**

Ultimately evaluating mainly **compressive strength** and **flow** here

Binary Binders
→ HVFA & Type III Portland Cement w/ additional optimization

Ternary Binders
→ HVFA, Type III Portland Cement, [additional material] (w/ additional optimization)
→ Ex: CSA, slag, calcined clay, etc.

Gypsum Optimization

Determine SO_3 Content of Binder

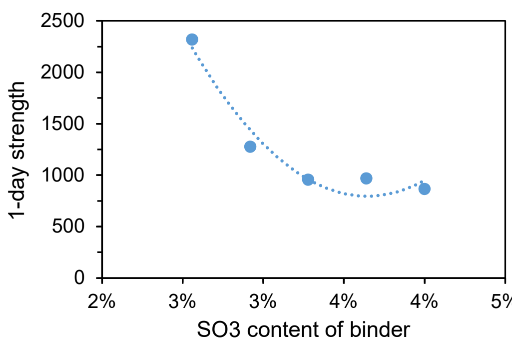
Material	SO_3 (XRF)
Type III	2.80%
Class F	2.20%
Class C	2.00%
Landfilled	0.46%
Gypsum	46.5%

ASTM - C563: Standard Guide For Approximation of Optimum SO_3 in Hydraulic Cement

ASTM- C595: Standard Specification for Blended Hydraulic Cements determines the maximum sulfate reported as SO_3 as **"4%"**

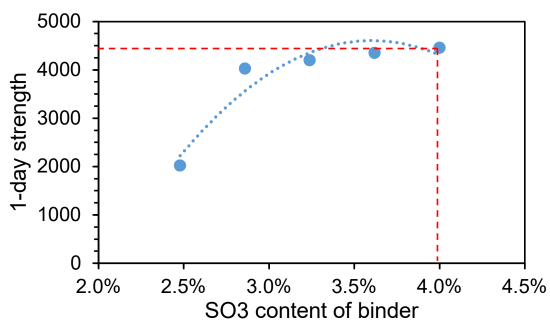
Class F

Mix	SO_3 Content	1 day strength
F-G0	2.56%	2319
F-G1	2.92%	1276
F-G2	3.28%	954
F-G3	3.64%	967
F-G4	4.00%	865



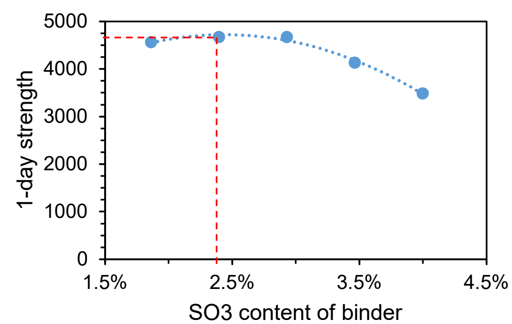
Class C

Mix	SO_3 Content	1 day strength
C-G0	2.48%	2017
C-G1	2.86%	4025
C-G2	3.24%	4200
C-G3	3.62%	4349
C-G4	4.00%	4455



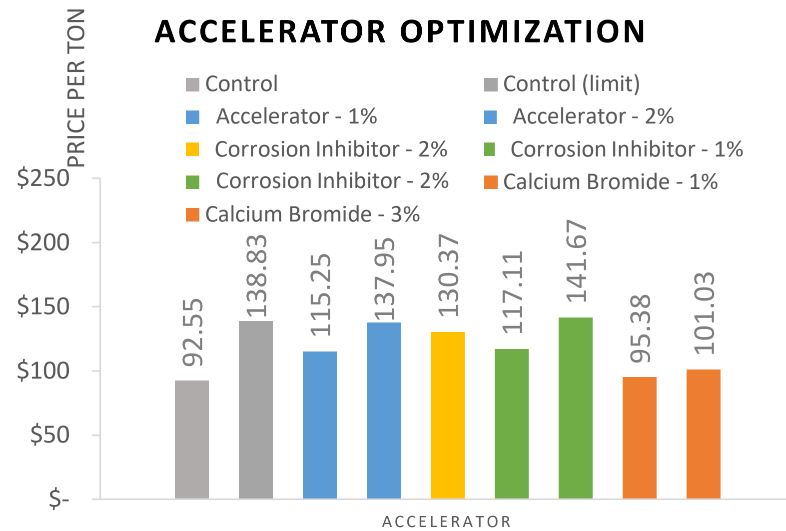
Landfilled

Mix	SO_3 Content	1 day strength
L-G0	1.86%	4563
L-G1	2.40%	4670
L-G2	2.93%	4671
L-G3	3.47%	4131
L-G4	4.00%	3483



Accelerator [admixture] **Optimization**

→ **MAIN GOAL:** Balancing cost and high-early *binder* strength performance

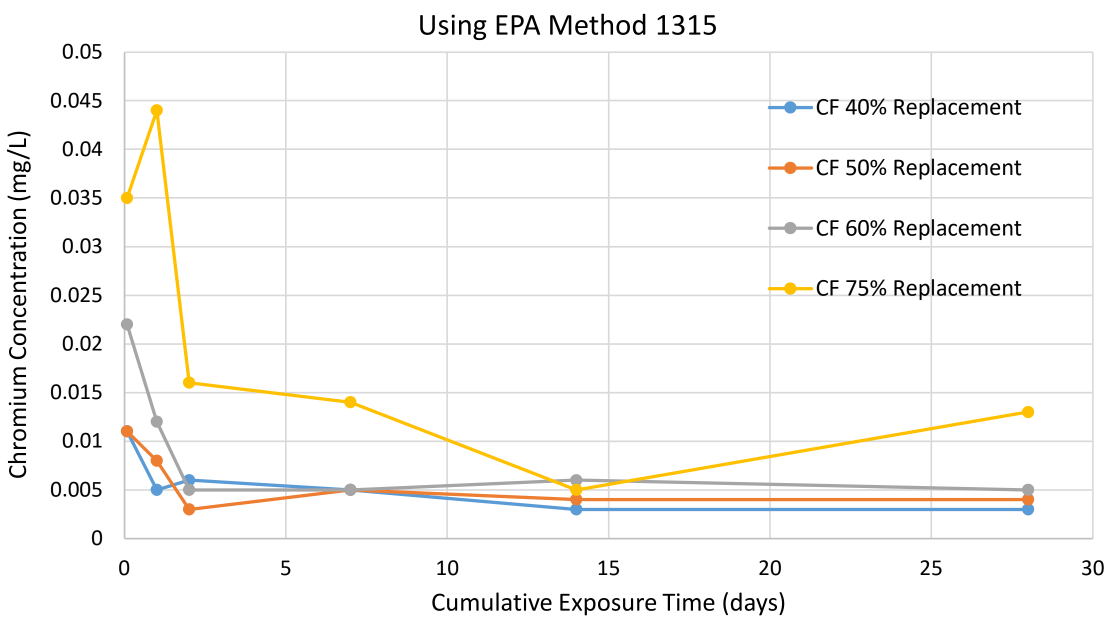


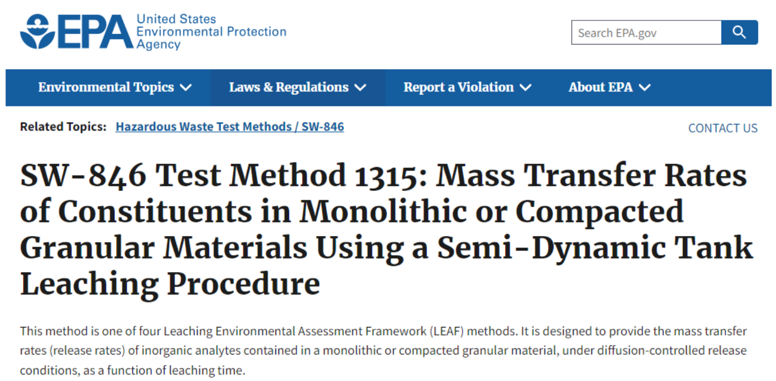
	Class F				Class C				Harvested F			
	Corrosion Inhibitor	Accelerating Admixture	Calcium Bromide	Strength/Hardening Accelerator	Corrosion Inhibitor	Accelerating Admixture	Calcium Bromide	Strength/Hardening Accelerator	Corrosion Inhibitor	Accelerating Admixture	Calcium Bromide	Strength/Hardening Accelerator
Optimal % (wt.)	1%	1%	1.50%	0.50%	0%	0%	0.50%	0%	1%	1%	1.50%	0.50%
24 hr. Cube Strength (psi)	4688	4167	5505	4446	4455	4455	5156	4455	5476	5269	5554	5134

3) Assess the Environmental Impact of Using HVFA Concretes

Environmental Performance

3) Assess the Environmental Impact of Using HVFA Concretes





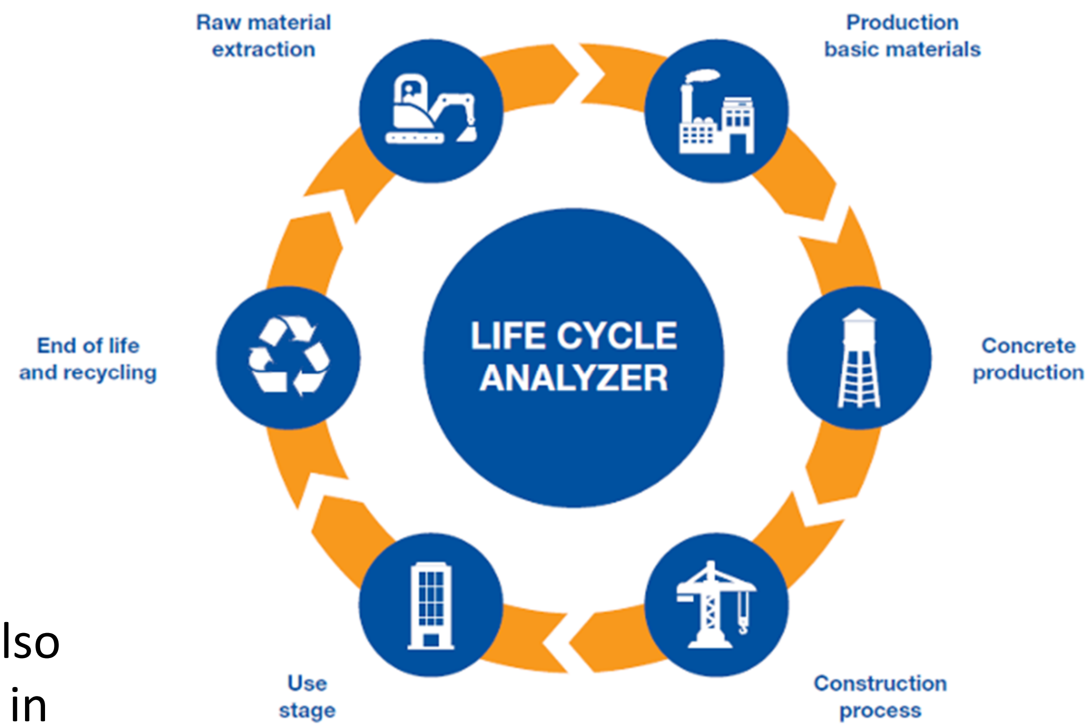
Environmental Life-Cycle Analyses

3) Assess the Environmental Impact of Using HVFA Concretes

→LCA analysis framework has been built to quantify the environmental impact of using HVFA concretes

→The framework accounts for source of raw (or recycled) materials, transportation costs, end use of the concrete structure(s), etc.

→Global warming potential (GWP) will also be quantified to aid precast producers in meeting sustainable construction requirements with HVFA mixes



https://sphere-project.eu/wp-content/uploads/sites/10/2021/01/Picture-2.png

4) Scaling to HVFA Concrete Mix Designs

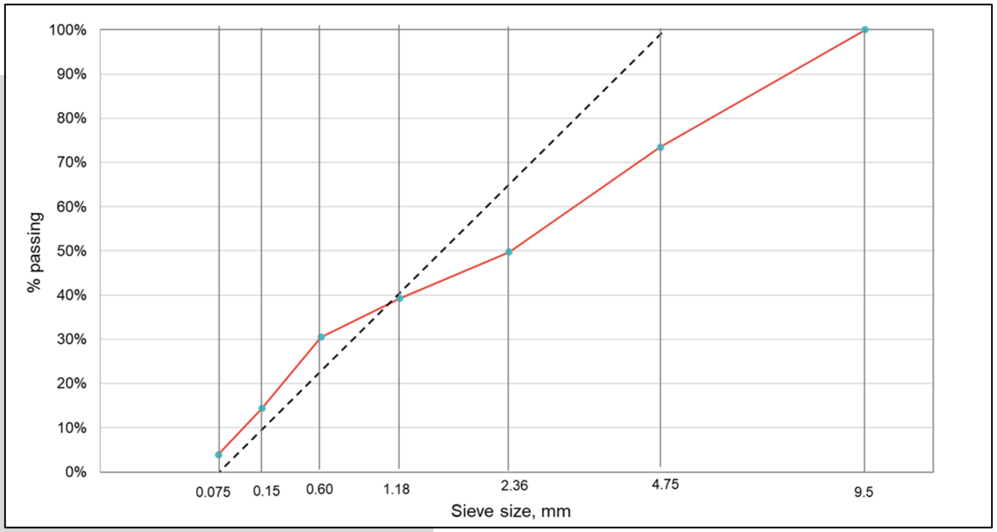
Optimized Mix Proportioning

4) Scaling to HVFA Concrete Mix Designs

Optimization of the following:

1) Aggregate Packing

+ Power 0.35 or 0.45 curve [ACI 237R-07] may be used to improve workability & water demand for SCC mixes



2) Admixture Dosage

+ Admixtures need to be assessed/optimized again at concrete stage
+ Facilitate proper workability in the presence of larger aggregates
+ Maintain desired slump (or slump flow for SCC) and retention

3) w/c ratio

+ Shouldn't be only reliance for enhanced strength
+ Enhances strength gain as long as workability is maintained
  → Usually less of a problem for SCC mixes

HVFA Concrete Batching

4) Scaling to HVFA Concrete Mix Designs

5) Characterization of HVFA Concrete Strength Development

→ Evaluate **compressive** and **flexural strength** at several points during early-age period (e.g., within ~12-24 hours – don't forget 28 days!)

→ Specific metrics are a function of the corresponding project/application

40% Fresh Class C FA – Example Cases

Minimum Goal Here
3500 psi comp. strength @ 24 hours

	Mix Design			
	C40-SCC-030-B	C40-G97-SCC-030-C	C40-G97-CABR2-SCC-030-A	C40-G97-ACC-SCC-030-A
Main Accelerators	None (control)	Optimized Gypsum	Opt. Gyp. w/ CaBr2	Opt. Gyp. w/ non-Cl Liq. Accel.
Air Content (C231)	4.3%	6.8%	4.8%	5.5%
	12-hour Compressive Strength		16-hour Compressive Strength	
Average (psi)	1193.3	603	2903	3017
	18-hour Compressive Strength		20-hour Compressive Strength	
Average (psi)	2513.3	2750	**3837**	**3700**
	24-hour Compressive Strength			
Average (psi)	**3750**	**3760**	**4317**	**4210**

	Mix Design			
	C40-SCC-030-B	C40-G97-SCC-030-C	C40-G97-CABR2-SCC-030-A	C40-G97-ACC-SCC-030-A
Main Accelerators	None (control)	Optimized Gypsum	Opt. Gyp. w/ CaBr2	Opt. Gyp. w/ non-Cl Liq. Accel.
	12-hour Modulus of Rupture		16-hour Modulus of Rupture	
Average (psi)	202.7	161	515	526
ACI 318 f_r (psi)	259.1	184	404	412
	18-hour Modulus of Rupture		20-hour Modulus of Rupture	
Average (psi)	336.0	463	562	556
ACI 318 f_r (psi)	376.0	393	465	456
24-hour Modulus of Rupture				
Average (psi)	439.9	565	599	607
ACI 318 f_r (psi)	459.3	460	493	487

40% Fresh Class F FA – Example Cases

Minimum Goal Here
3500 psi comp. strength @ 24 hours

	Mix Design		
	F40-FP20-SCC-030-A	F40-CI-SCC-030-B3	F40-SH-S40C-SCC-030-H
Main Accelerators	non-Cl Liq. Accel.	calcium nitrite Accel.	non-Cl Liq. SH Accel.
Air Content (C231)	5.8%	7.0%	9.0
16-hour Compressive Strength			
Average (psi)	3023	3029	**3613**
20-hour Compressive Strength			
Average (psi)	**3613**	**3578**	**4157**
24-hour Compressive Strength			
Average (psi)	**3978**	**3998**	**4360**

	Mix Design		
	F40-ACC-SCC-030-A	F40-CI-SCC-030-B3	F40-SH-S40C-SCC-030-H
Main Accelerators	non-Cl Liq. Accel.	calcium nitrite Accel.	non-Cl Liq. SH Accel.
16-hour Modulus of Rupture			
Average (psi)	523	552	549
ACI 318 f_r (psi)	412	413	451
20-hour Modulus of Rupture			
Average (psi)	562	582	595
ACI 318 f_r (psi)	451	449	484
24-hour Modulus of Rupture			
Average (psi)	567	591	662
ACI 318 f_r (psi)	473	474	495

40% Harvested Class F FA – Example Cases

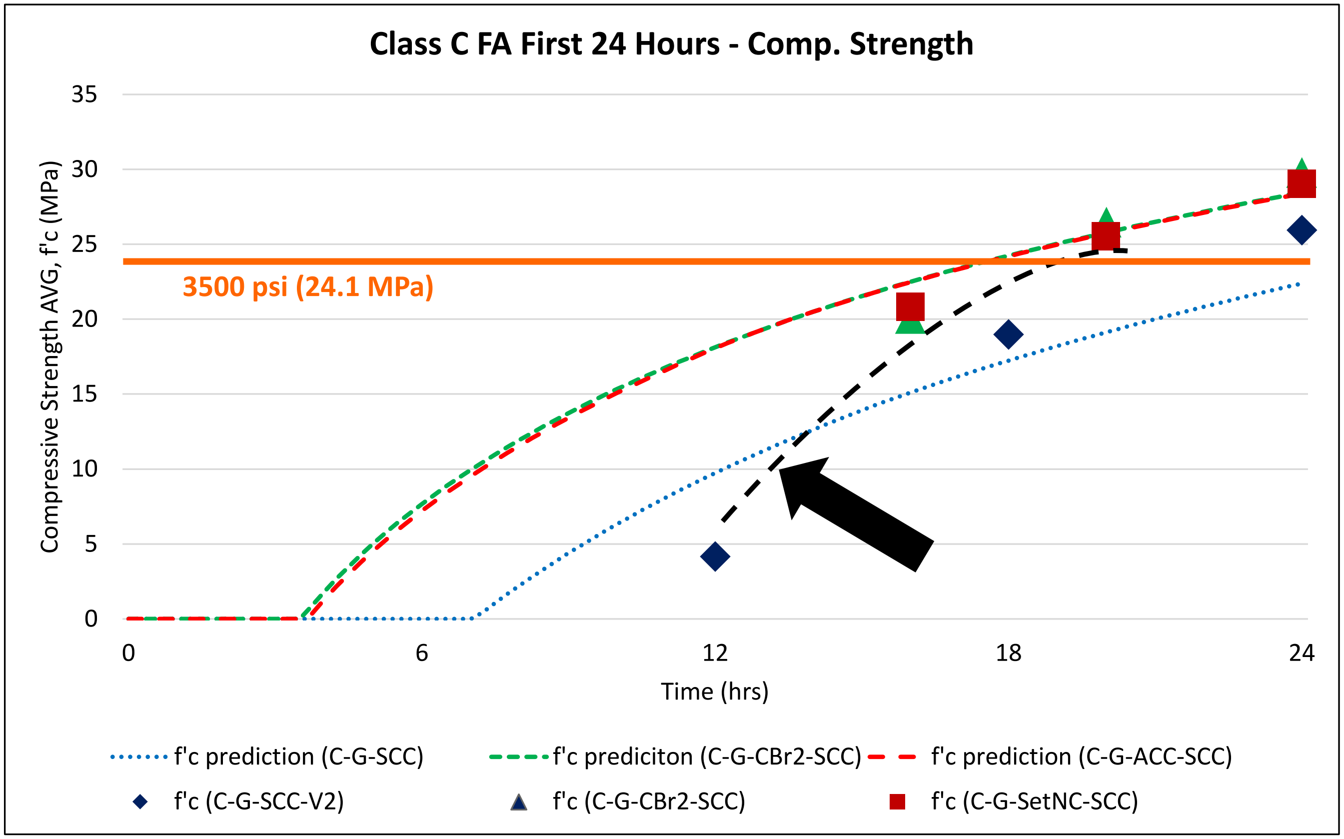
Minimum Goal Here
3500 psi comp. strength
@ 24 hours

	Mix Design	
	L40-SCC-030-A	L40-G97-SH-SCC-030-A
Main Accelerators	Optimized Gypsum	Opt. Gyp. w/ non-Cl Liq. SH Accel.
Air Content (C231)	6.4%	7.5%
16-hour Compressive Strength		
Average (psi)	2183	3147
20-hour Compressive Strength		
Average (psi)	3003	**3633**
24-hour Compressive Strength		
Average (psi)	3373	**3977**

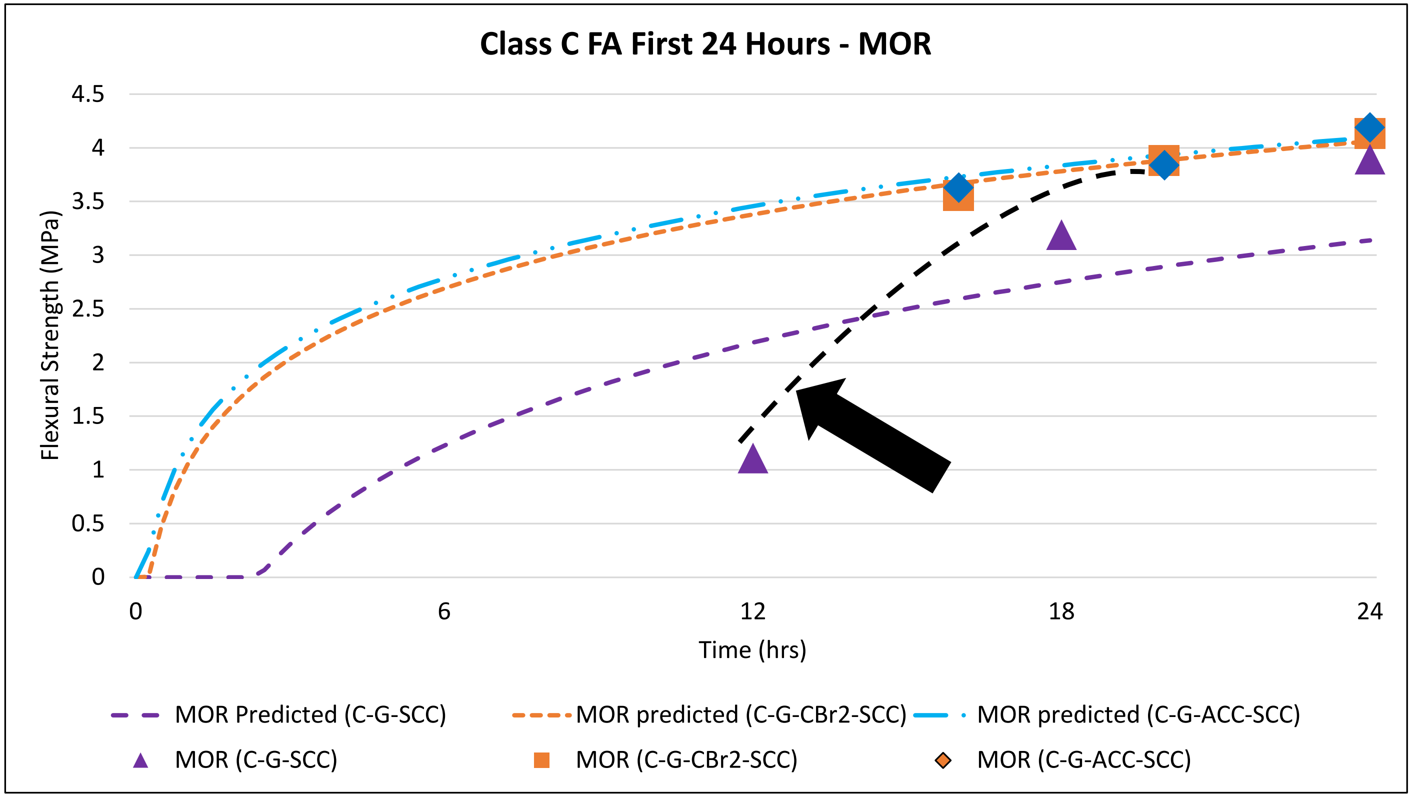
	Mix Design	
	L40-SCC-030-A	L40-G97-SH-SCC-030-A
Main Accelerators	Optimized Gypsum	Opt. Gyp. w/ non-Cl Liq. SH Accel.
16-hour Modulus of Rupture		
Average (psi)	414	499
ACI 318 f_r (psi)	350	421
20-hour Modulus of Rupture		
Average (psi)	470	524
ACI 318 f_r (psi)	411	452
24-hour Modulus of Rupture		
Average (psi)	548	561
ACI 318 f_r (psi)	436	473

Slump flow test for an L40 mix.
High stability with no segregation was observed.

Characterizing **HVFA Early Strength** Development – **f'c**

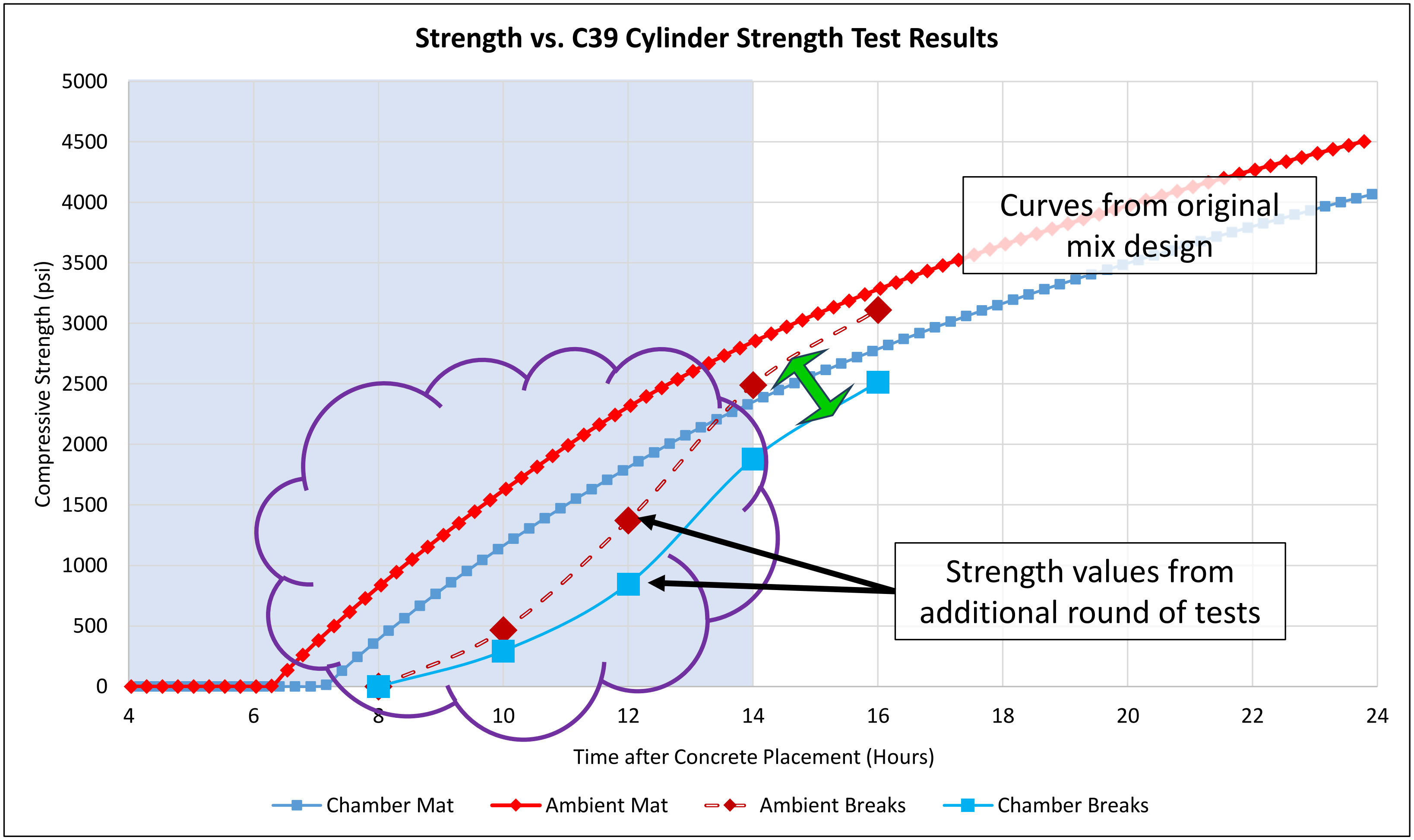


Characterizing **HVFA Early Strength** Development – **MOR**

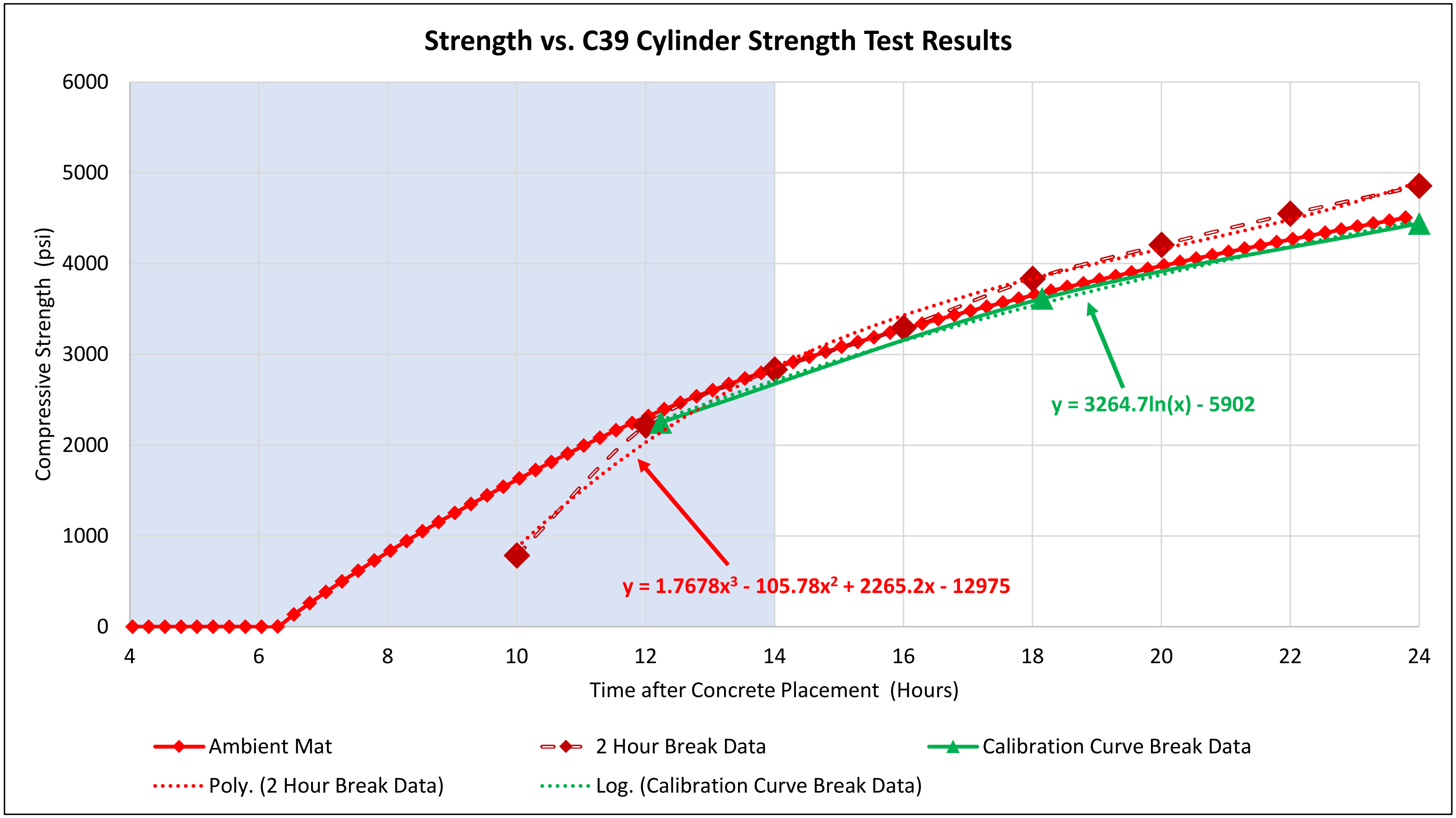


6) Facilitating Extrapolation from Ideal Laboratory Conditions to Relevant Environments

Towards **Maturity Method**



Towards **Maturity Method**



7) Assessing the Behavior/Performance of HVFA Concrete Structures

Examples of some critical early-age milestones:

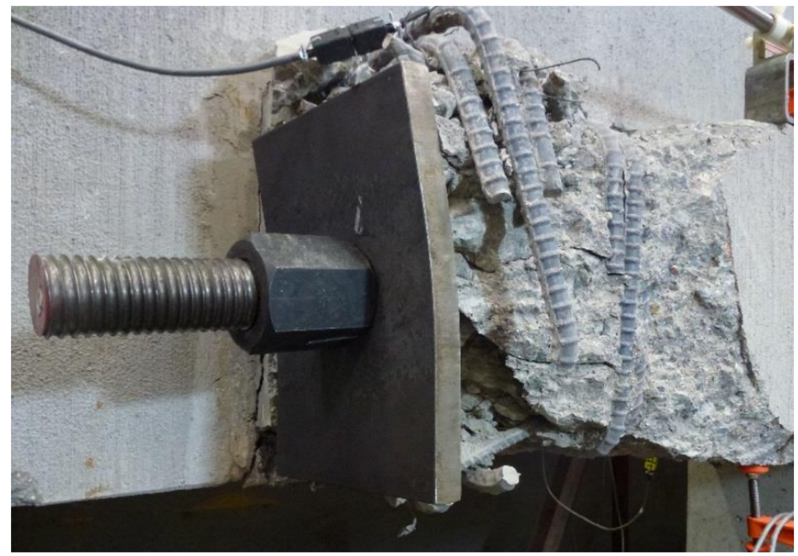
+ **Formwork Removal** (precast or CIP)
+ **Lifting/Handling** (precast/tilt-up)
+ **Initial Prestress** (precast)
+ **Rapid bridge deck construction** or **repairs**

Main Objective: Confirmation of service or strength limit states for the structural member

7) Assessing the Behavior/Performance of HVFA Concrete Structures

Tests @ 12 hrs. in this case

7) Assessing the Behavior/Performance of HVFA Concrete Structures



https://weckenmann.com/media/55705/img_0047.jpg?maxwidth=3200

8) Expected Durability and Long-Term Performance

[SELECT] **Pertinent Metrics:**

[Standard] Air Content

→ ASTM C231-22 (pressure method)
→ Facilitates improved freeze-thaw durability
→ Additionally enhances workability

Super Air Meter (SAM) Test

→ Related to C231-22 test
→ Measures air void spacing factor
  → Better distribution of smaller aid voids generally facilitates enhanced durability

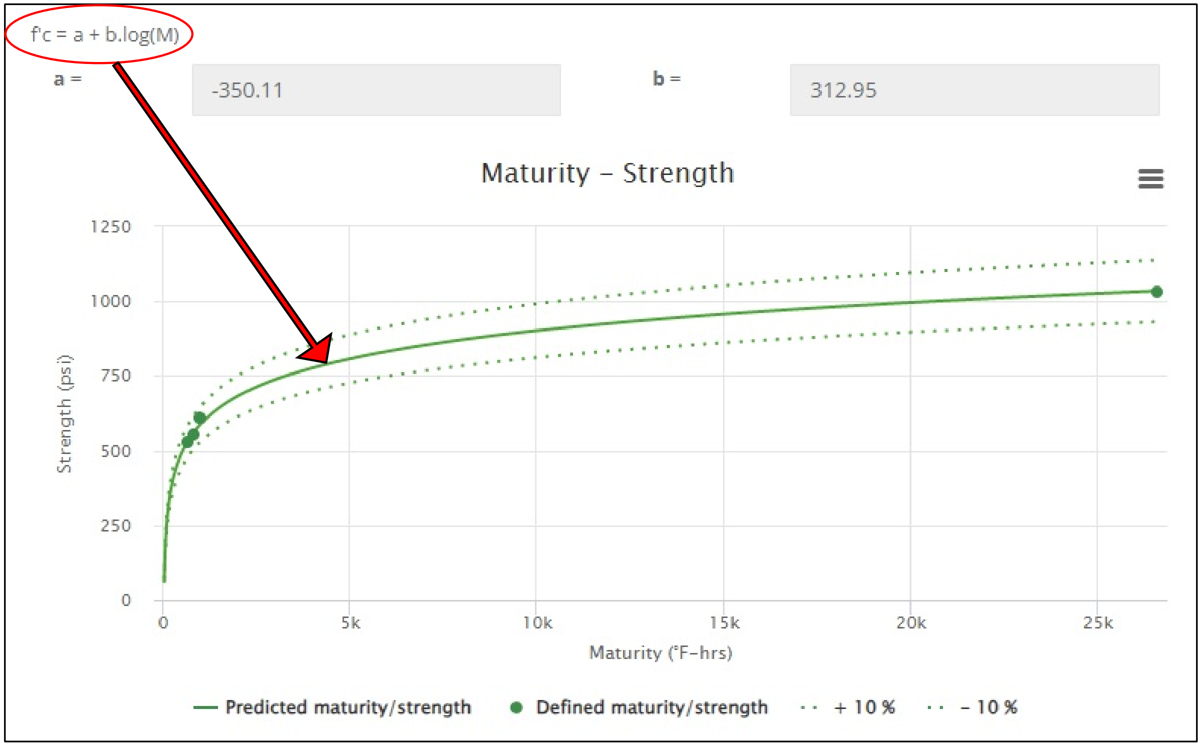
Creep under Compression

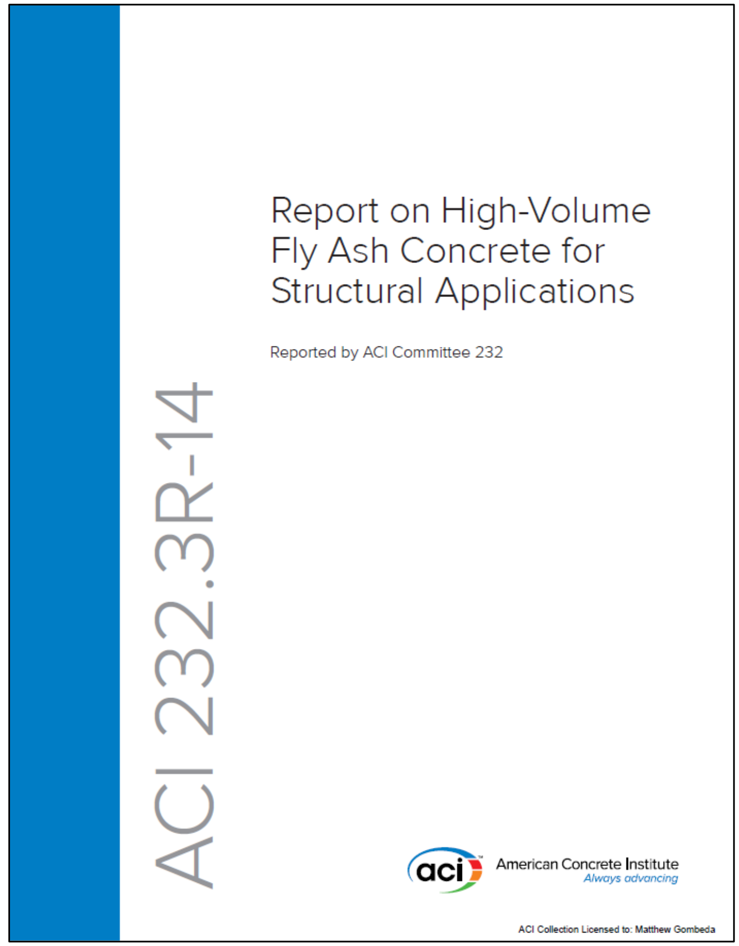
→ ASTM C512-15
→ Deflections under sustained dead load
→ Necessary for comparing long-term HVFA concrete performance vs. standard mix designs

Formation Factor

→ AASHTO TP119
→ Measure of electrical resistivity to assess micro-structure (pore) for durability

9) Facilitating Updates/Revisions to Design Standards, Guidelines, etc.





[Some] **Future Research Needs**

+ Characterization of other SCMs

+ Additional structural testing (prestressing, etc.)

+ More data with further reductions of Portland cement

+ Latest developments in concrete admixture technology

+ More investigation on slump/slump flow retention

+ Full-scale integration into precast production

Acknowledgment: This material is based upon work supported by the Department of Energy under Award Number(s) DE-FE0031931.

Questions ?

Thank You!