
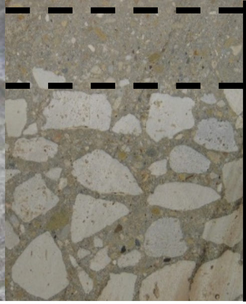
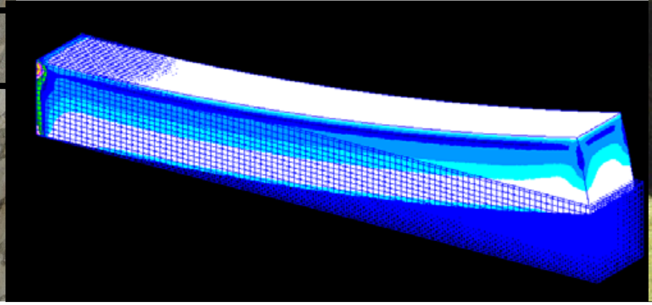

Self-Consolidating Concrete: Bridging Research and Practice

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Development of SCC Performance Criteria

Developed in Japan in the late 1980's

Flows into formwork without vibration or mechanical consolidation

Flowable properties achieved with:

- Ultra high-range water reducer (polycarboxylate)
- Viscosity Modifying Admixture (VMA)
- High cementitious materials or powder content
- Small coarse aggregate and higher sand fraction

ACI 237 ETS Report

Potential benefits of SCC

Improved consolidation

Reduced labor cost

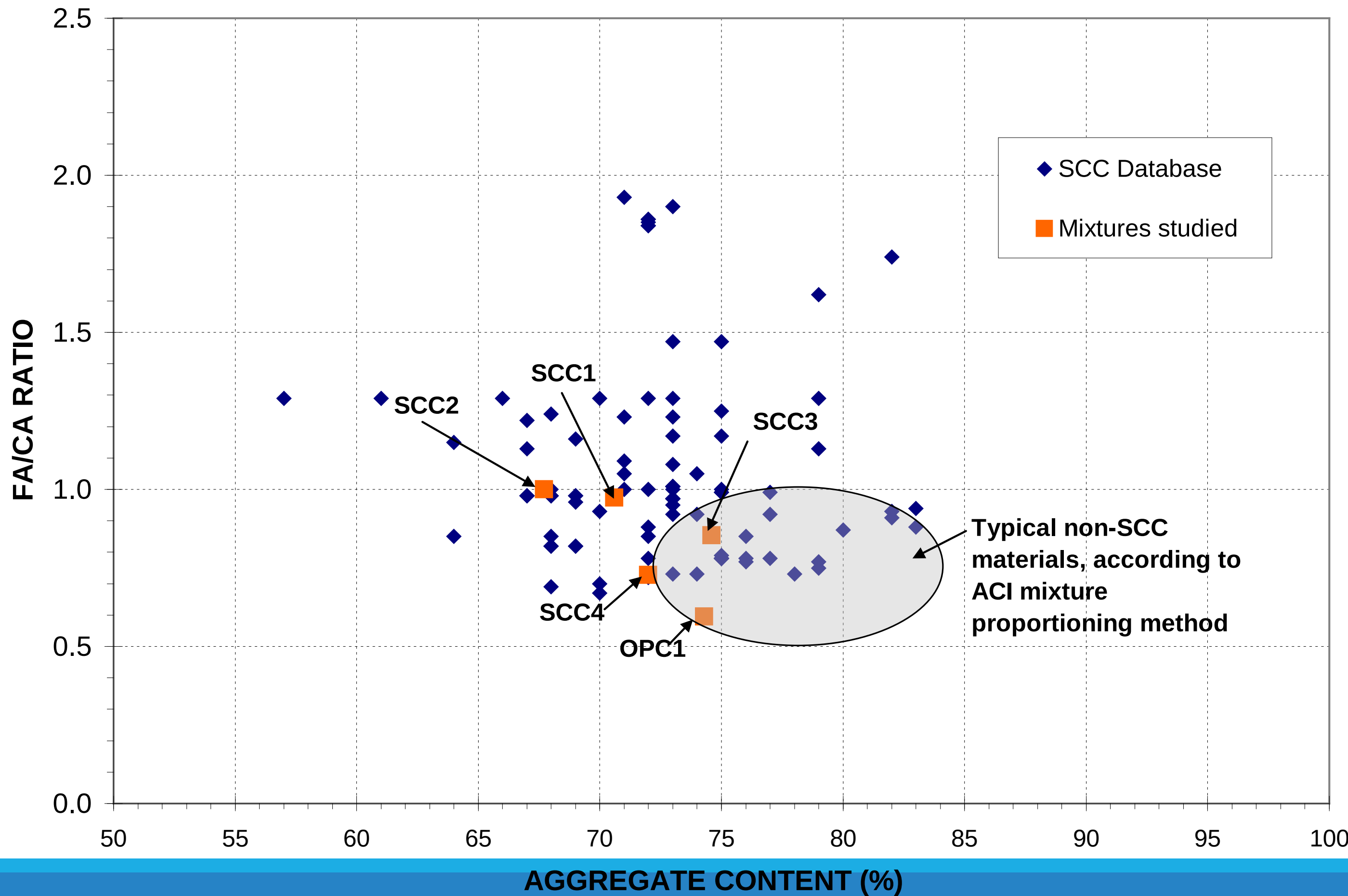
Accelerated construction

Reduced noise

Performance Requirements

- Flowability into formwork and through reinforcement
- Stability (resistance to segregation)
- but what about hardened concrete properties?

Database of SCC proportions shows a departure from "normal" OPC



Workability and Rheology

Workability: “The ease with which [concrete] can be mixed, placed, consolidated, and finished to a homogenous condition.”

SCC Flow Characteristics

Slump flow test (ASTM C1611)
Prestressed Engineering Corp, Blackstone, IL, USA

Flowing into double T beam forms
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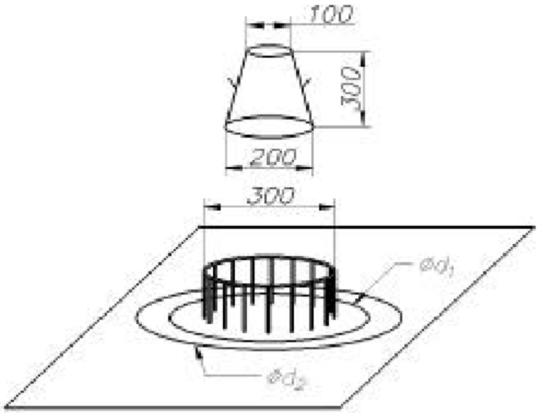
Standard tests have been developed

Prestressed Engineering Corp, Blackstone, IL, USA

J-ring test for passing ability (ASTM C1621)

Test is performed using a standard slump cone

Difference in diameter



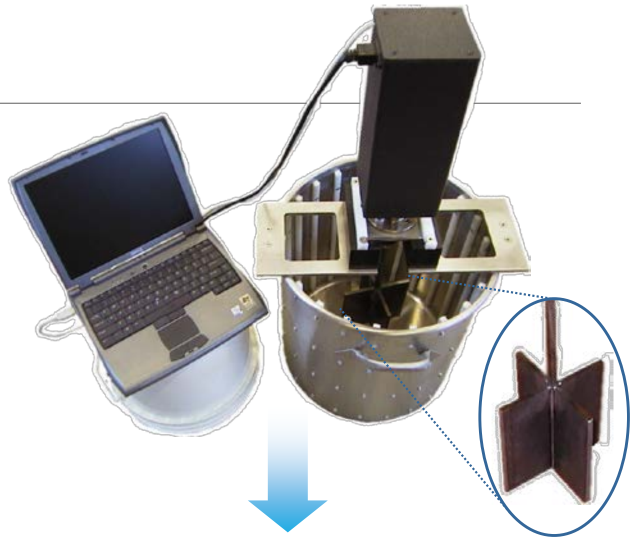
Rheology is the study of the flow of matter

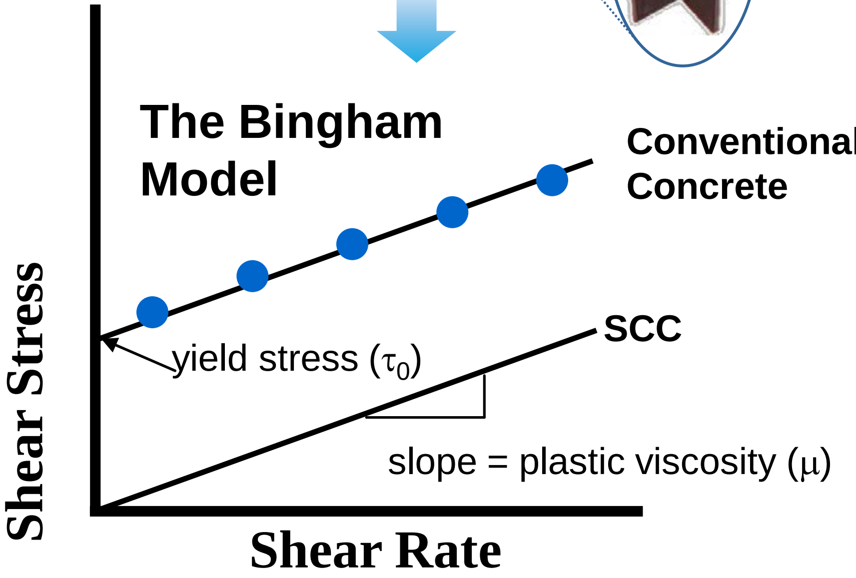
A concrete rheometer, determines resistance to shear flow at various rates

Bingham model:

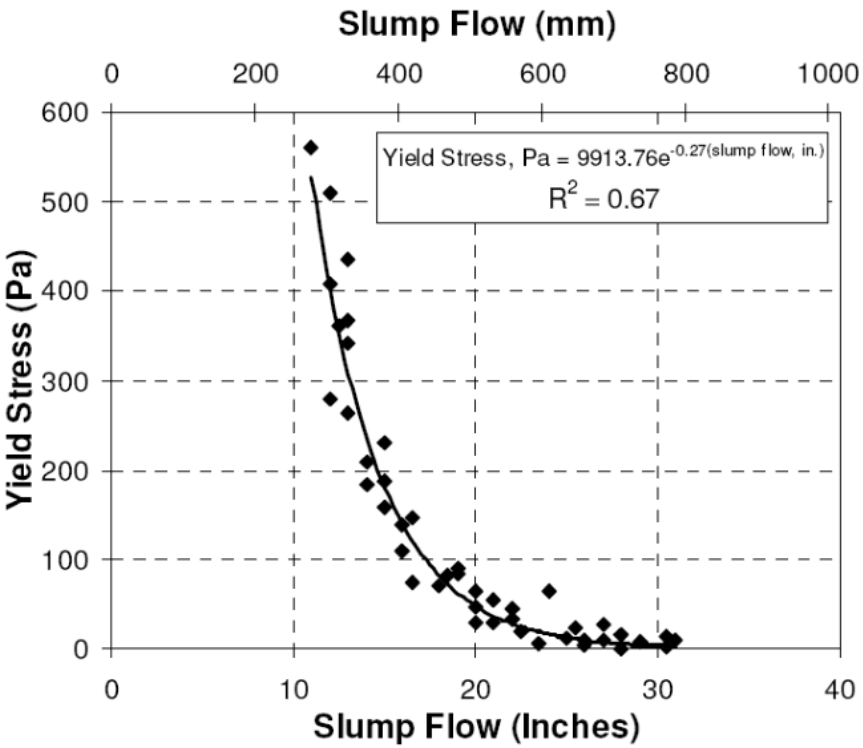
- **Yield stress**: minimum stress to initiate or maintain flow (**slump**)
- **Plastic viscosity**: the resistance to flow once yield stress is exceeded (**stickiness**)

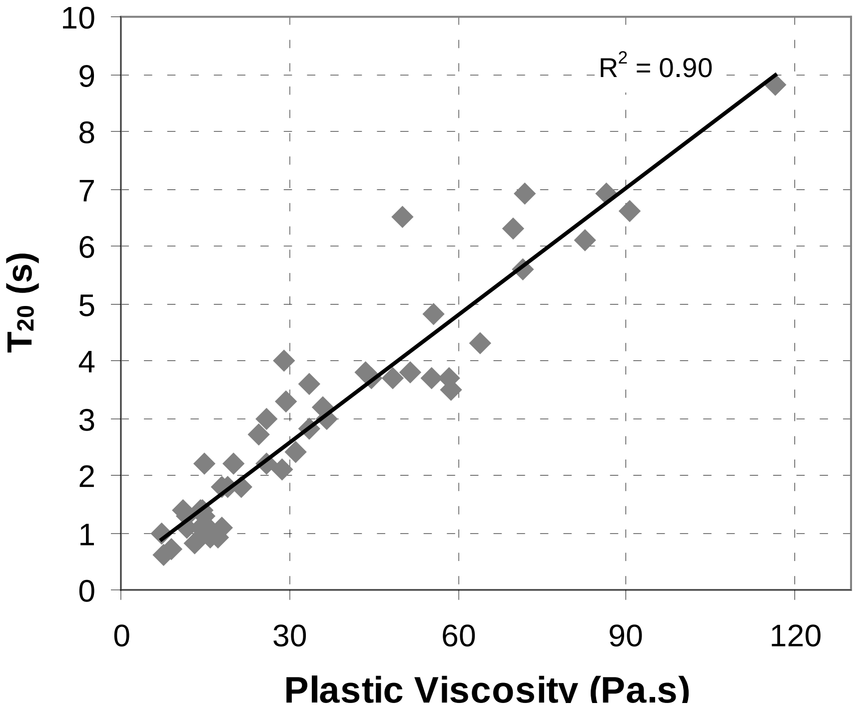
Slump, slump flow, stability, segregation, are concrete rheology terms





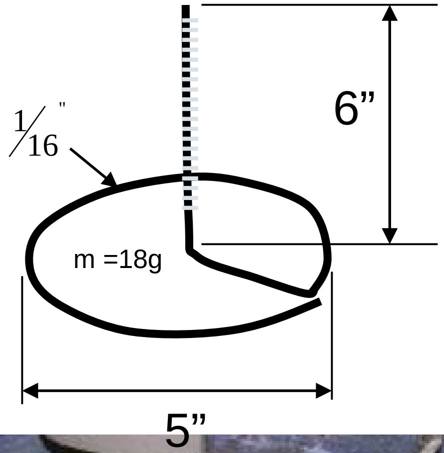
How to approximate rheological behavior





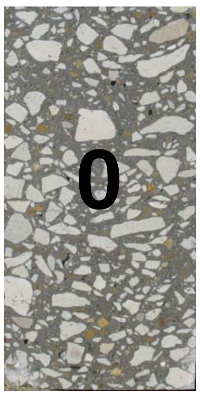
Reference: Koehler, E.P., Fowler, D.W. (2008). "Comparison of Workability Test Methods for Self-Consolidating Concrete" Submitted to *Journal of ASTM International*.

Stability and Cohesion of SCC



How do we evaluate segregation?

Hardened Visual Stability Index (VSI) Rating Criteria for Concrete Cylinder Specimens



0: Stable

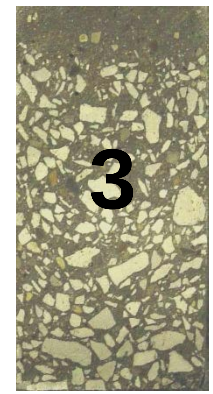
No paste or mortar layer visible at top of cylinder, no apparent difference in the size and area percentage of coarse aggregate through depth

1: Stable

No paste or mortar layer visible at top of cylinder, slight difference in the size and area percentage of coarse aggregate through depth

2: Unstable

Slight paste or mortar layer visible (<1”), slight difference in coarse aggregate through depth



3: Unstable

Significant paste or mortar layer visible (>1”), obvious difference in the size and area percentage of coarse aggregate through depth

Segregation Resistance

$$SI = \frac{M4 - M1}{\frac{1}{2}(M4 + M1)}$$

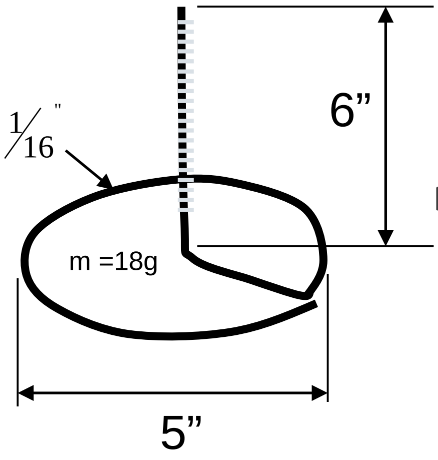
Gravitational Force
-density & size

$$\tau_0 \geq \frac{4}{3} g\left(\rho_{sphere} - \rho_{fluid}\right) R$$

Buoyancy + Resisting Force
-Paste rheology & density
-Aggregate shape & texture
-Aggregate lattice effect

Saak, A.W., Jennings, H.M., and Shah, S.P. (2001). "New Methodology for Designing Self-Compacting Concrete," *ACI Materials Journal*, 98(6), 429-439.

The Segregation Probe



Applicability:

Rapid surface segregation measurement

Sensitive to small changes in stability of SCC

Suitable for field measurement

Procedure:

Cast fresh concrete into 6 x 12” cylinder

Wait for 15 min, avoid excessive disturbance

Put ring on surface gently

Wait for at least 2 min until ring stops settling

Take reading

Design for Segregation Resistance

Segregation resistance increased with:

- Higher yield stress (static and dynamic yield stress assumed equal initially)
- Higher plastic viscosity
- Higher thixotropy

Reduce Flow

Use smaller aggregate

Use more paste

Reference: Koehler, E.P., and Fowler, D.W. (2008). "Static and Dynamic Yield Stress Measurements of SCC" Proceedings of SCC 2008, Chicago, IL.

SCC Formwork Pressure

SCC approaches full hydrostatic pressure during rapid placement

Will SCC change the way we design formwork?

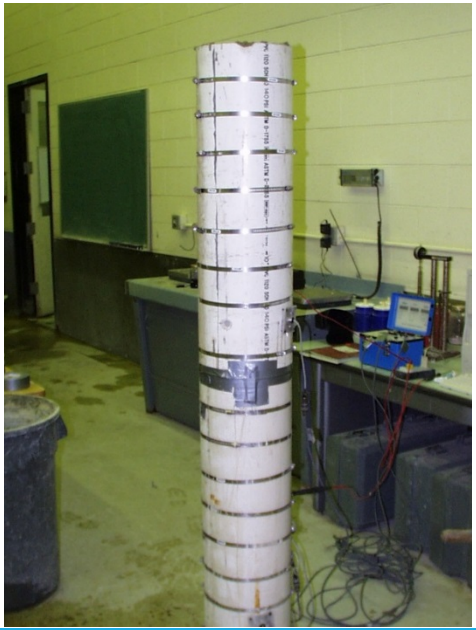
Pressure decrease is a combination of physical (internal friction) and chemi-physical (gelation) phenomena

Internal friction is a function of the aggregate content and the workability of concrete

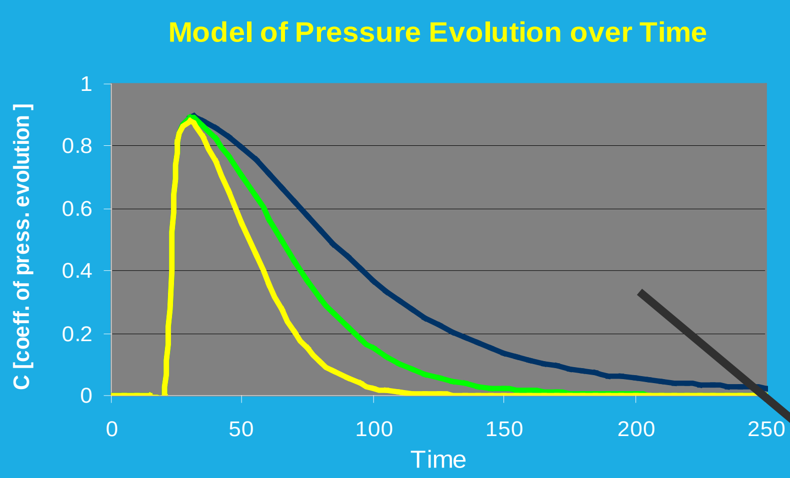
Set modifying admixtures will affect formwork pressure

Initial pressure drop is independent of cement hydration

Temperature is a significant factor



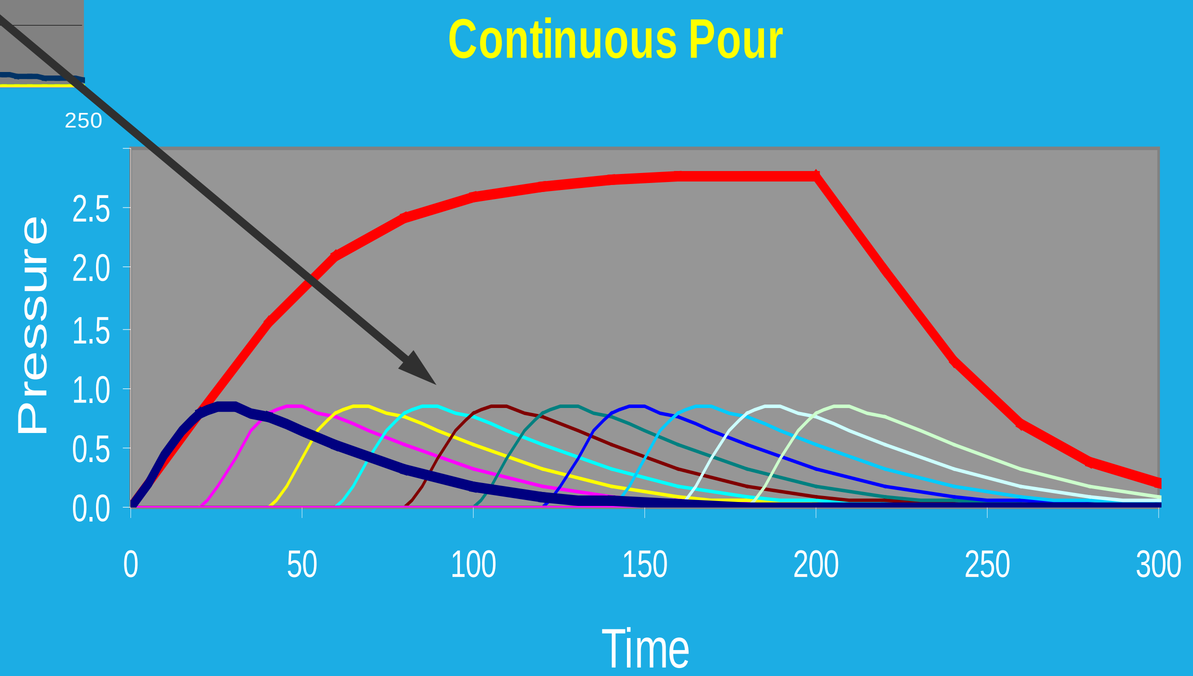
Models are needed to describe pressure for design



$$P(t) = \gamma(R\Delta t)\sum_{i=1}^{n} C_i(t)$$

$$C = \frac{C_0}{(Bt^2+1)^{\alpha}}\left(e^{-(\sqrt{(t^2+b)}-t)}\right)$$

The coefficient alpha describes different pressure decay rates over time.



Formwork Pressure

Formwork pressure is related to concrete rheology
- Pressure increases with slump
- SCC exhibits high formwork pressure due to high fluidity

Concrete at rest in forms, static yield stress is relevant
- Static yield stress is affected by dynamic yield stress and thixotropy
- SCC is placed in lifts, which takes advantage of thixotropy

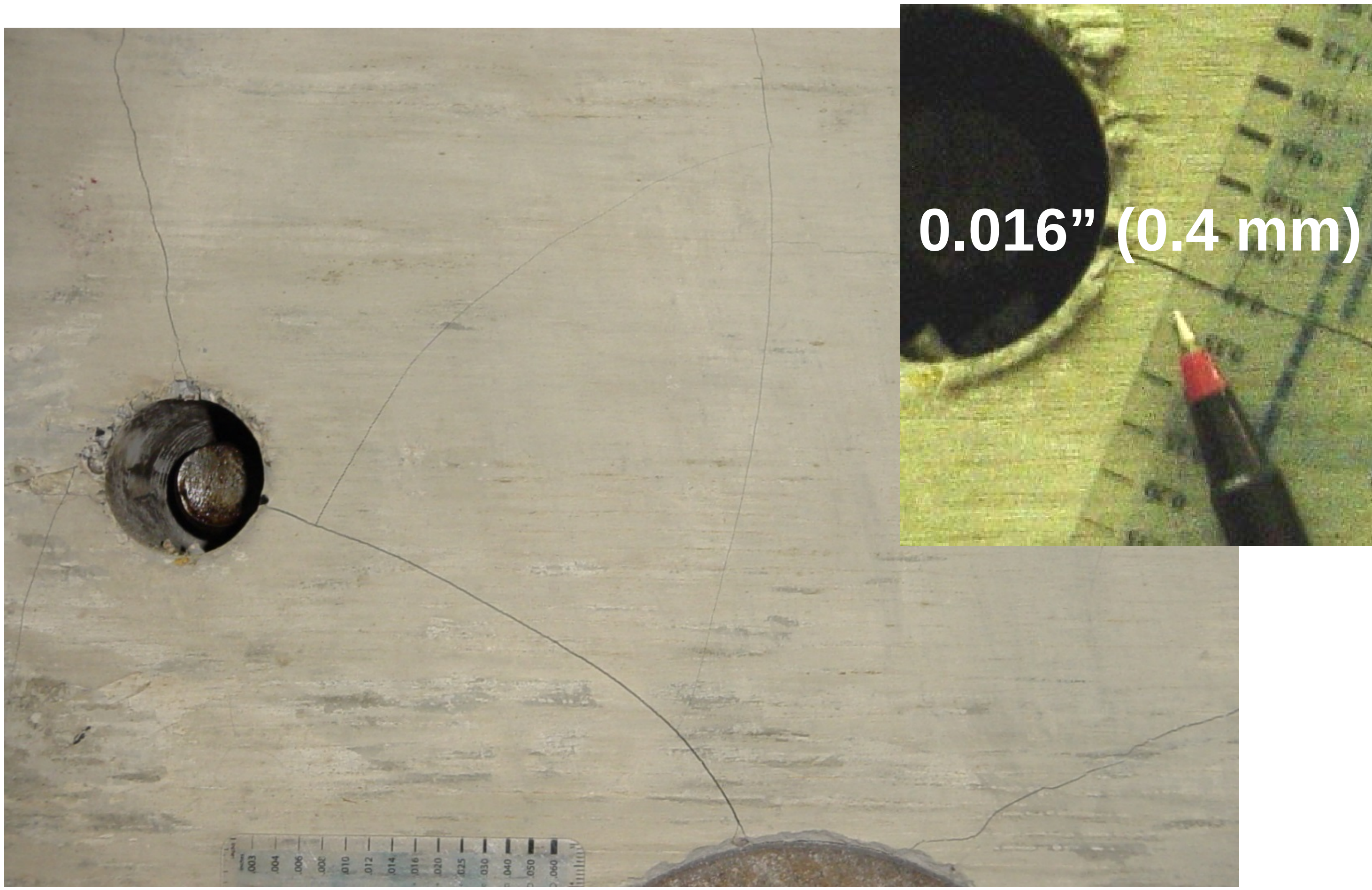
SCC must be designed to flow under its own mass and exert low formwork pressure
- Low dynamic yield stress (self flow)
- Fast increase in static yield stress (reduced formwork pressure) – **gelation or structural build up**

Place concrete in lifts to allow build-up of thixotropic structure

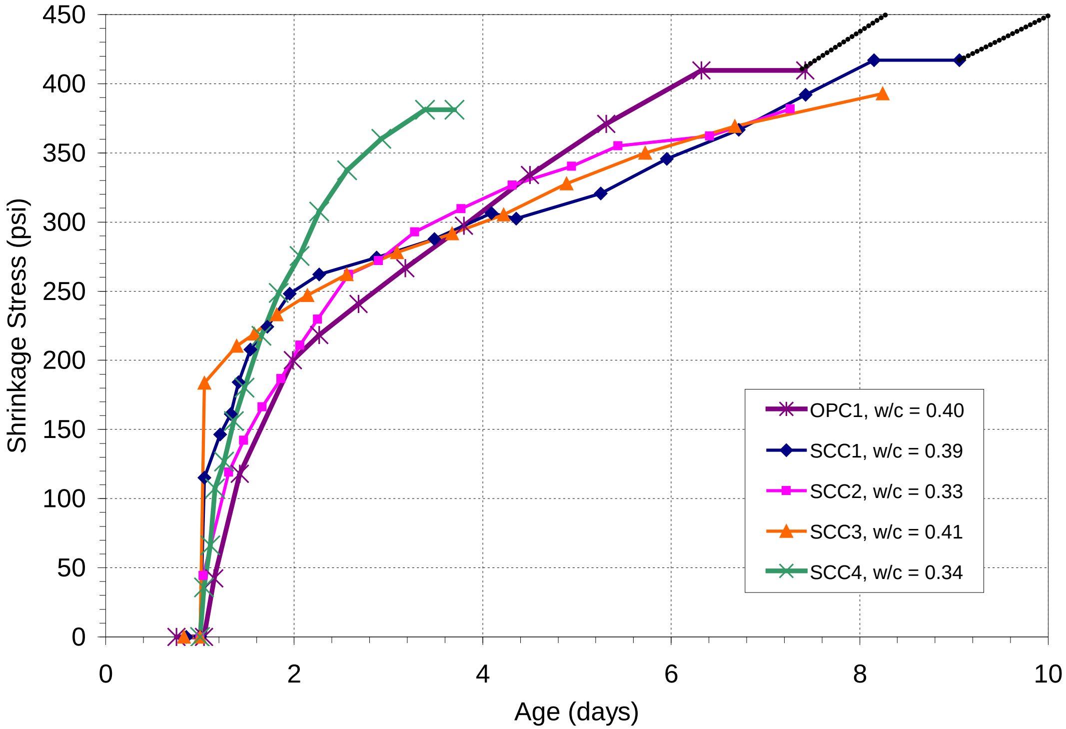
Limit pour heights and rates based on concrete rheology

Do not vibrate concrete

Early Age Cracking



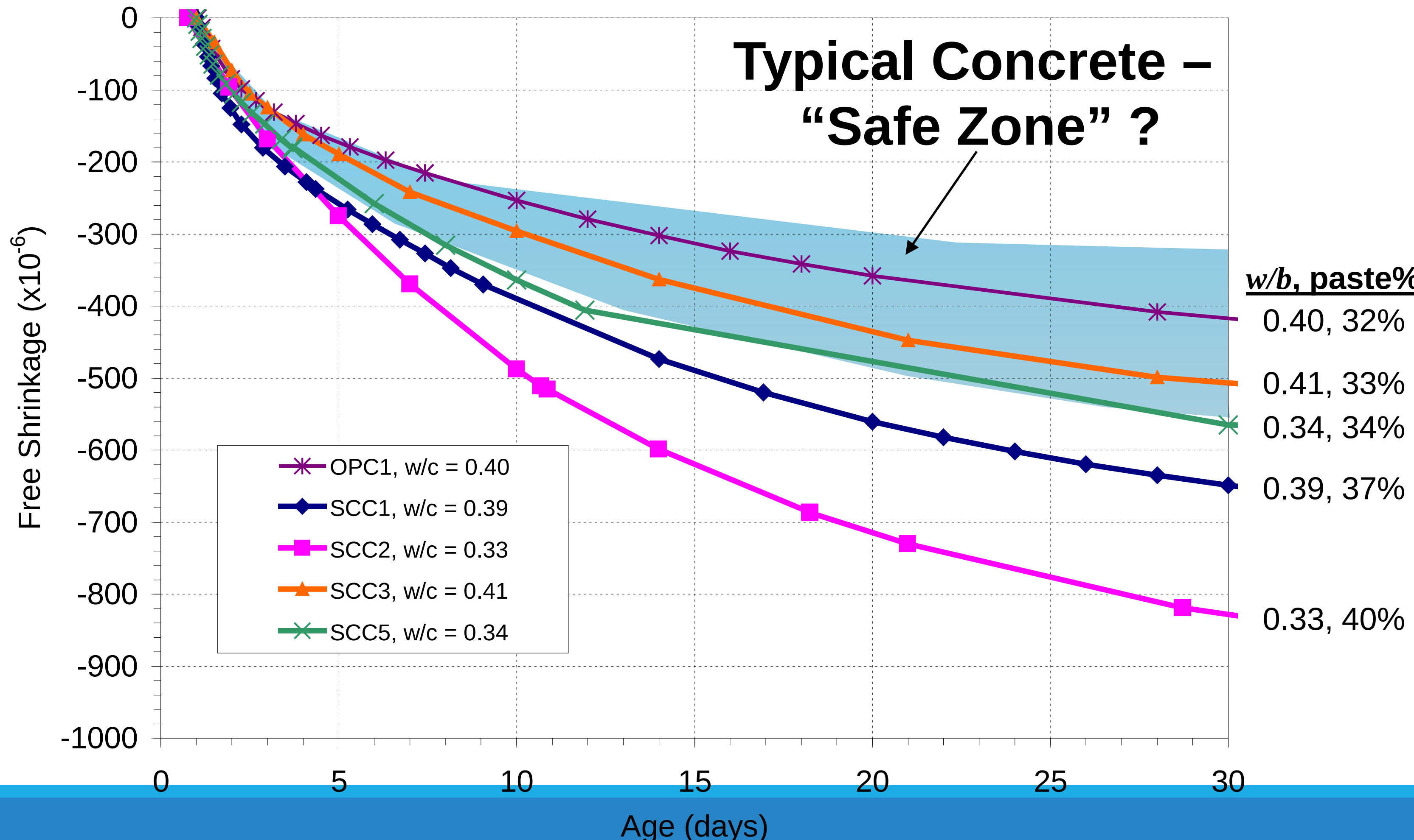
Stress development in SCC indicates cracking risk



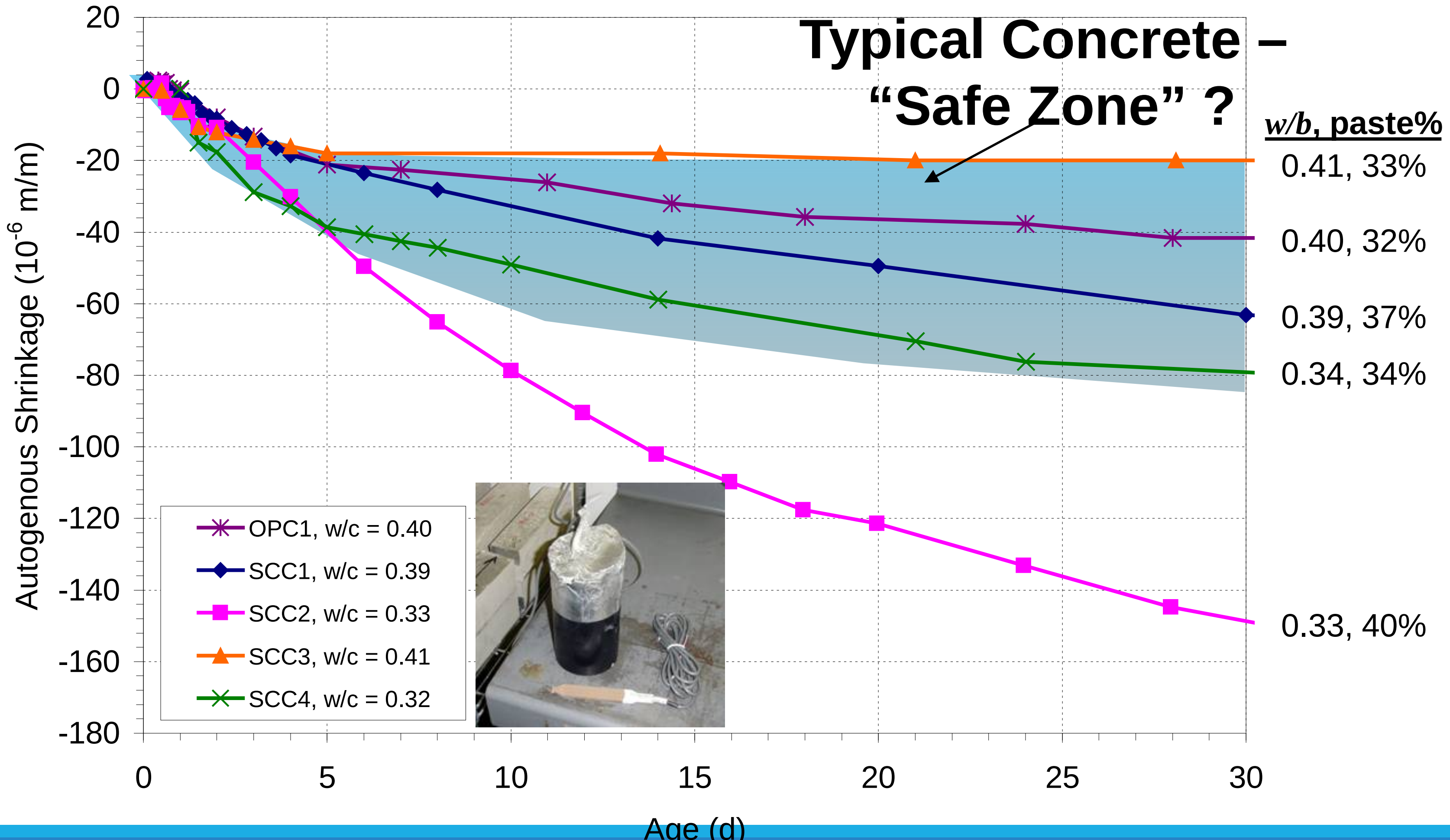
Autogenous shrinkage in low w/c materials generates significant stress at early age

A minimum w/c ratio can reduce early age cracking in restrained concrete

Early age shrinkage causes cracking risk



Low w/c drives autogenous shrinkage

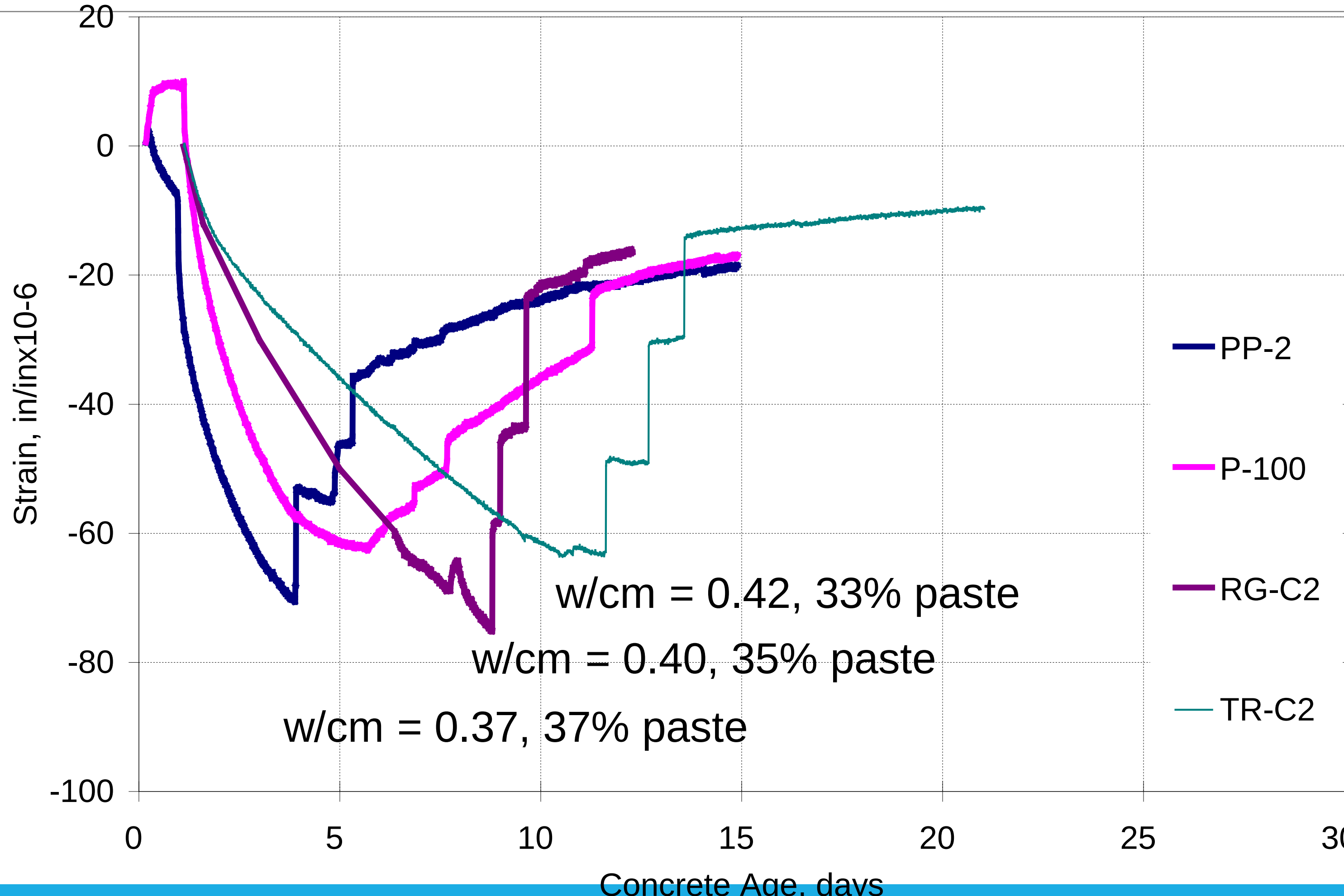


NEED: Measurement of cracking tendency

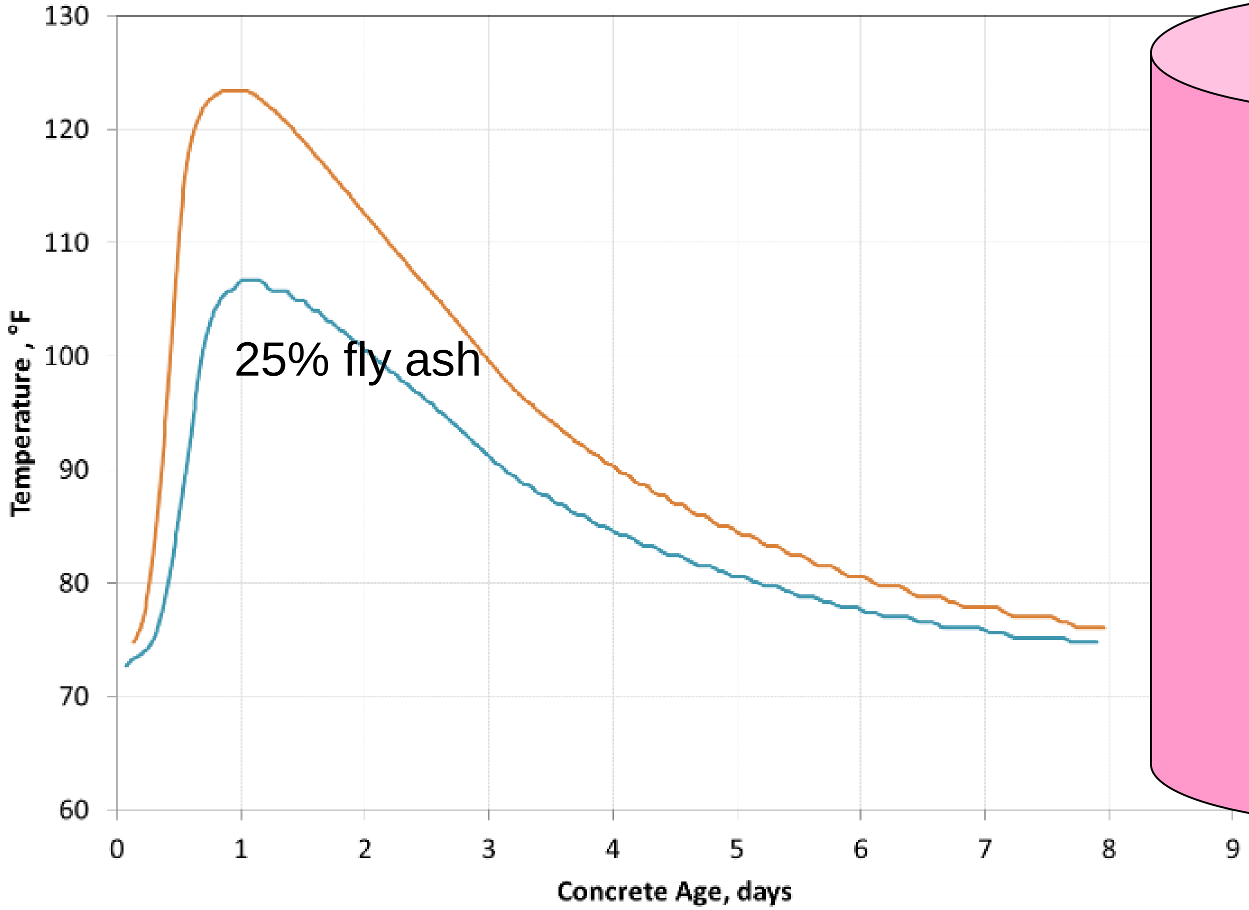
ASTM C1581

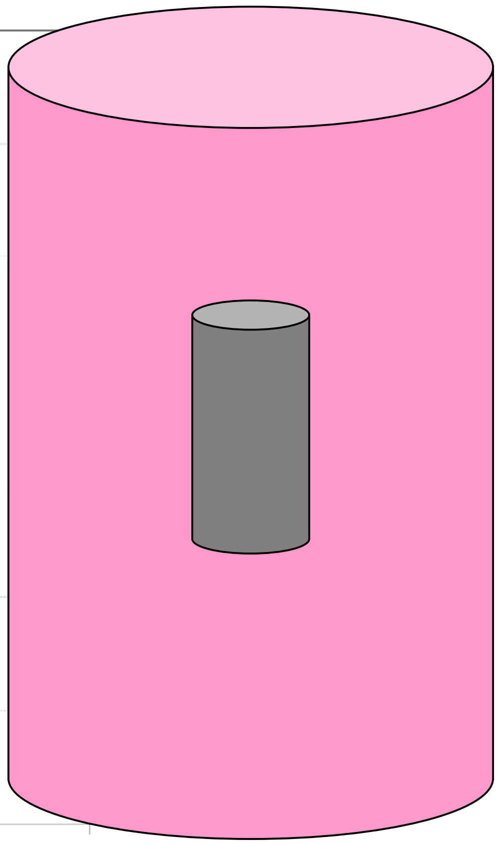
•Concrete shrinks around the steel ring causing tensile stress in concrete
•Stress relaxes due to tensile creep
•Strain measurements in steel are proportional to stress in concrete
•When tensile stress exceeds strength, cracking occurs

Cracking time is improved with higher w/cm, and/or lower paste content



NEED: Concrete temperature rise





NEED: Shrinkage and cracking mitigation

SRA – Shrinkage reduction through chemistry

SLA – Shrinkage reduction through internal curing

Optimization – Reduce cement paste %

SCMs – Reduce autogenous, temperature, modulus

Preventing SCC cracking

Some SCC mixtures have high risk for cracking, specs should utilize performance tests

Mechanical properties controlled by paste content and w/cm

Autogenous shrinkage is early age issue

Recommendations:

- Use the lowest possible cement paste content that still achieves desired flow characteristics
- Avoid low w/b ratios that lead to high autogenous shrinkage

Back to Specifications…

What is the “real performance” we need to ensure?

- More that strength

Spec writers need to assert more control

- Example: SCC needs limits on segregation, shrinkage cracking, min. aggregate content, min. w/c
- Limit temperature rise for mass concrete applications
- Modulus and Creep
- Ring test for cracking

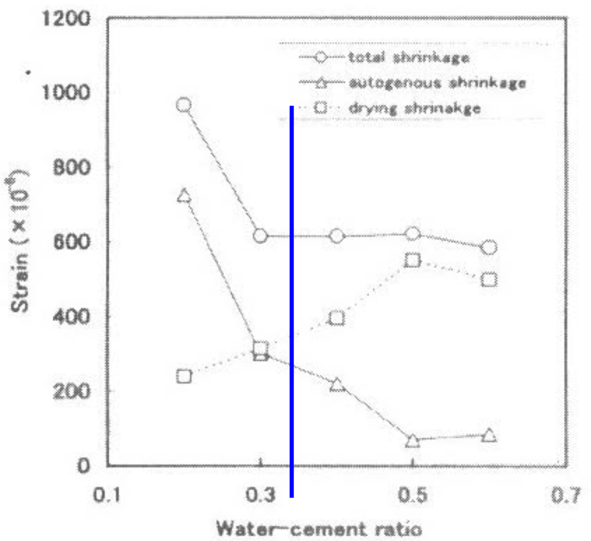
Suggestions for Practice

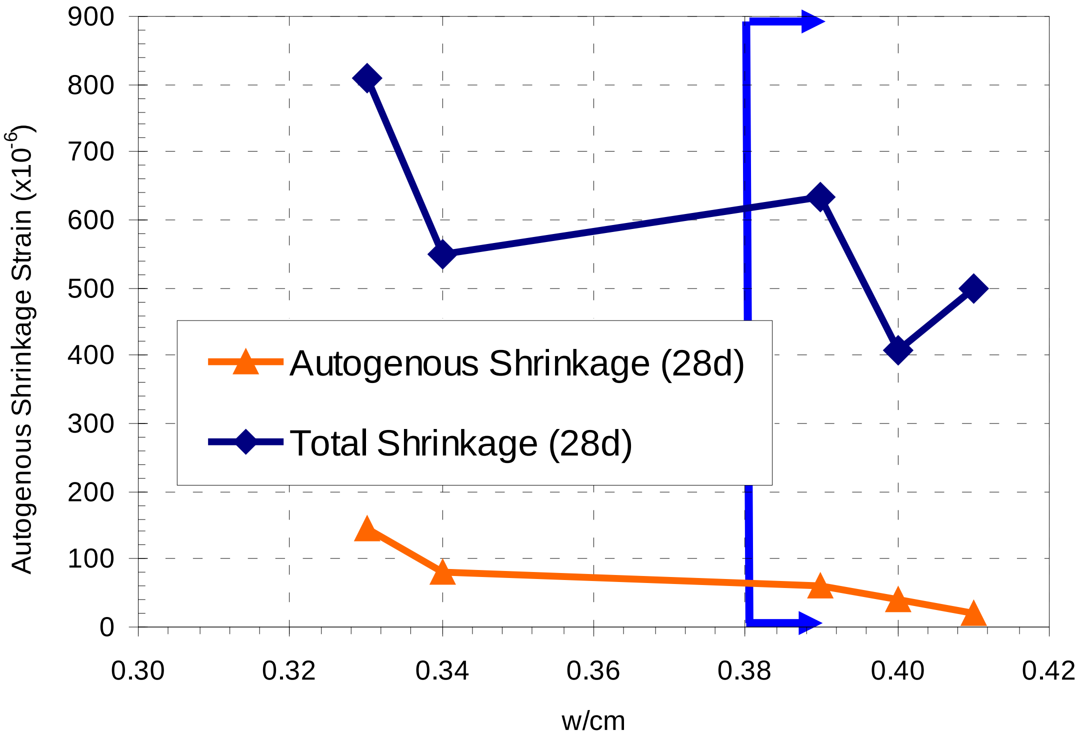
Acceptance Criteria: w/cm ratio

0.42 eliminates autogenous shrinkage

Application specific limits

- High Restraint: 0.42
- Med Restraint: 0.38
- Low Restraint: 0.32





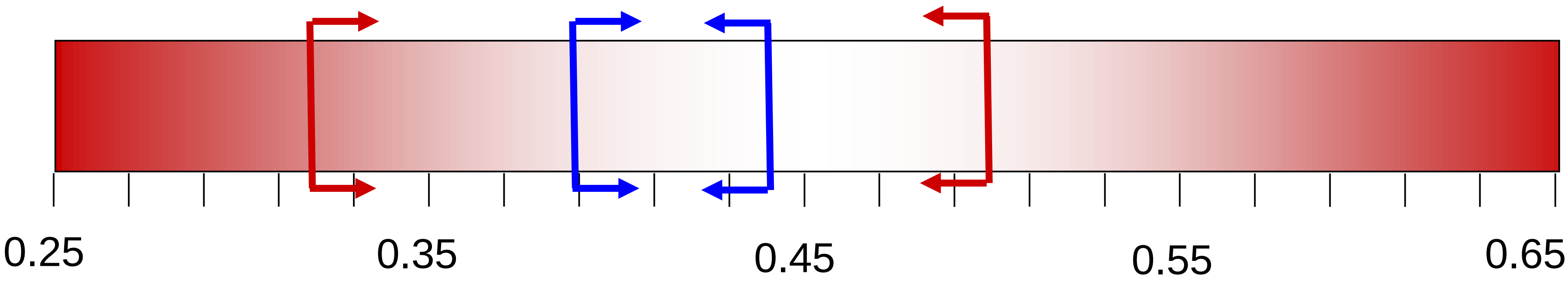
Water-cementitious ratio "safe zone"

Below 0.32 autogenous shrinkage can cause severe cracking when concrete is restrained

Above 0.50, drying shrinkage is a concern

Strength and durability also affected

Good range for minimum "total" shrinkage is 0.38 to 0.44



Acceptance Criteria: Paste Content

IDOT max cement factor: 7.05 cwt/yd^3

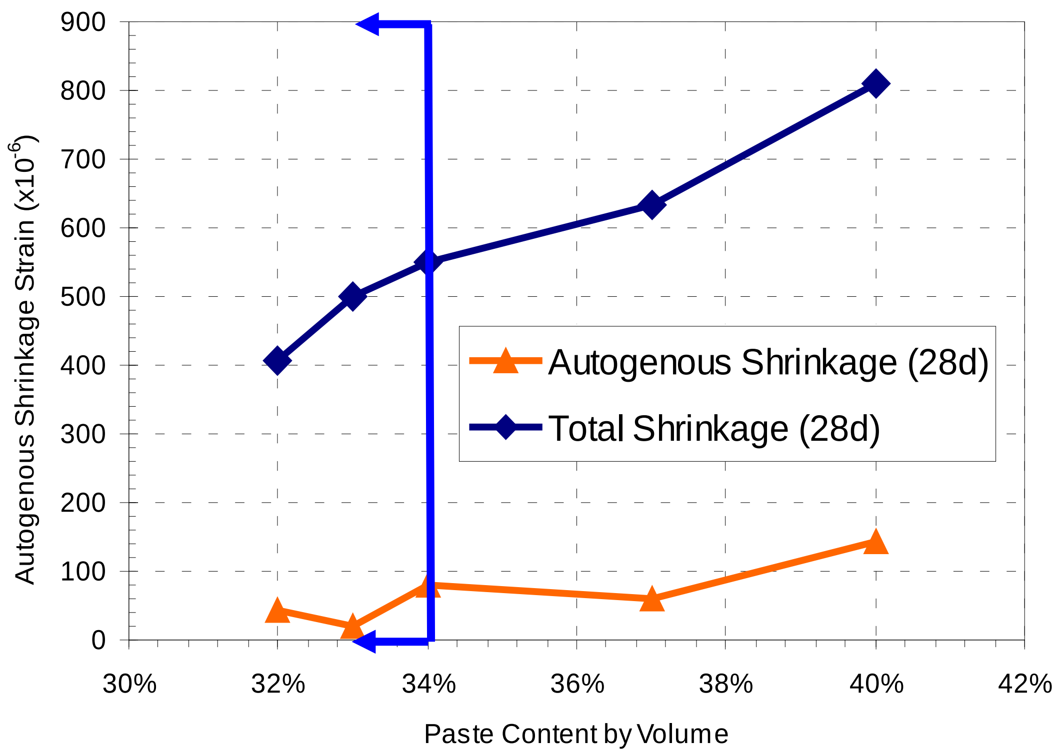
At 705 lb/yd^3, 0.44 *w/cm* = 34% paste

Below 32%, SCC has questionable fresh properties

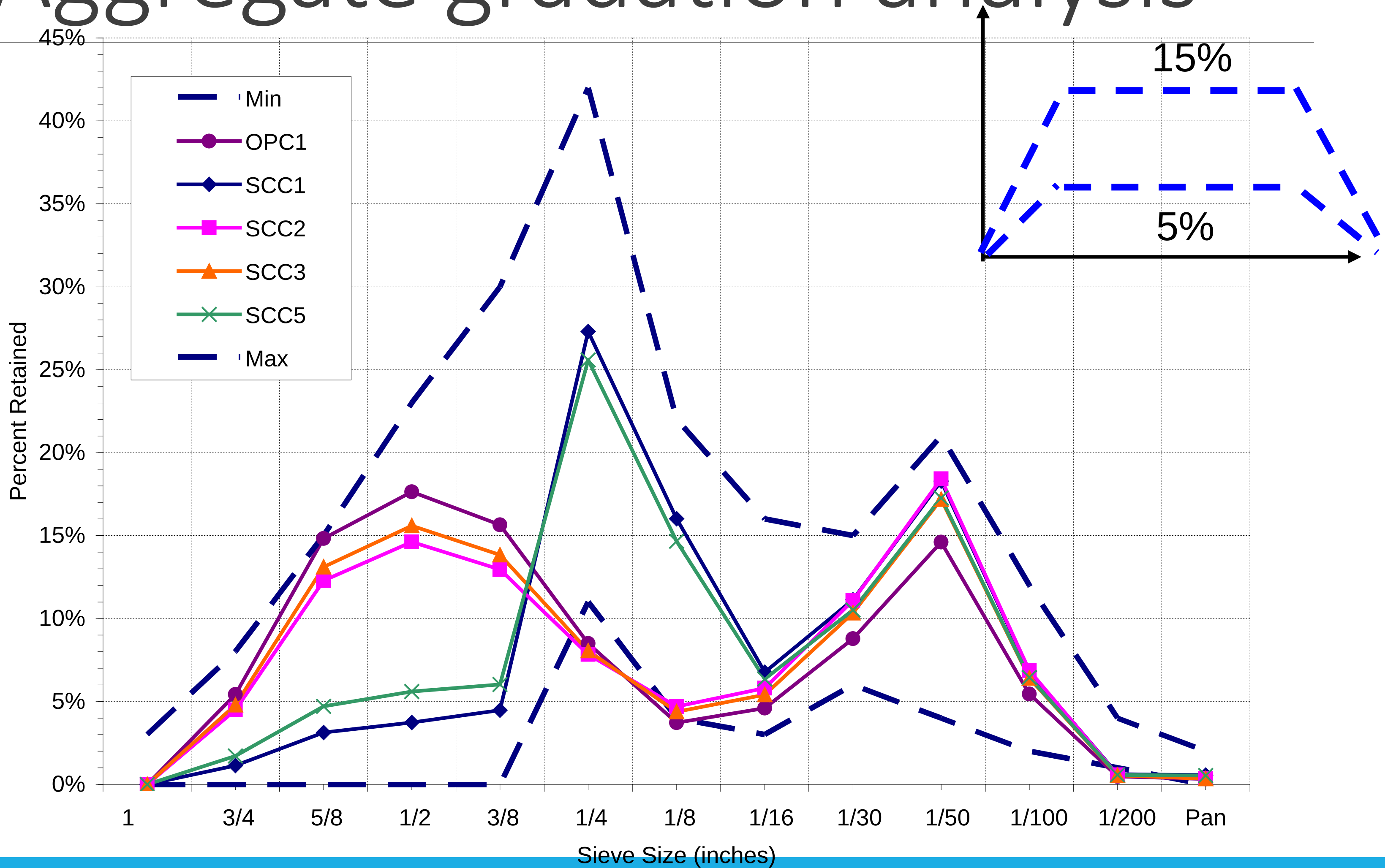
Application specific limits

- High Restraint: 30%
- Med Restraint: 34%
- Low Restraint: 36%

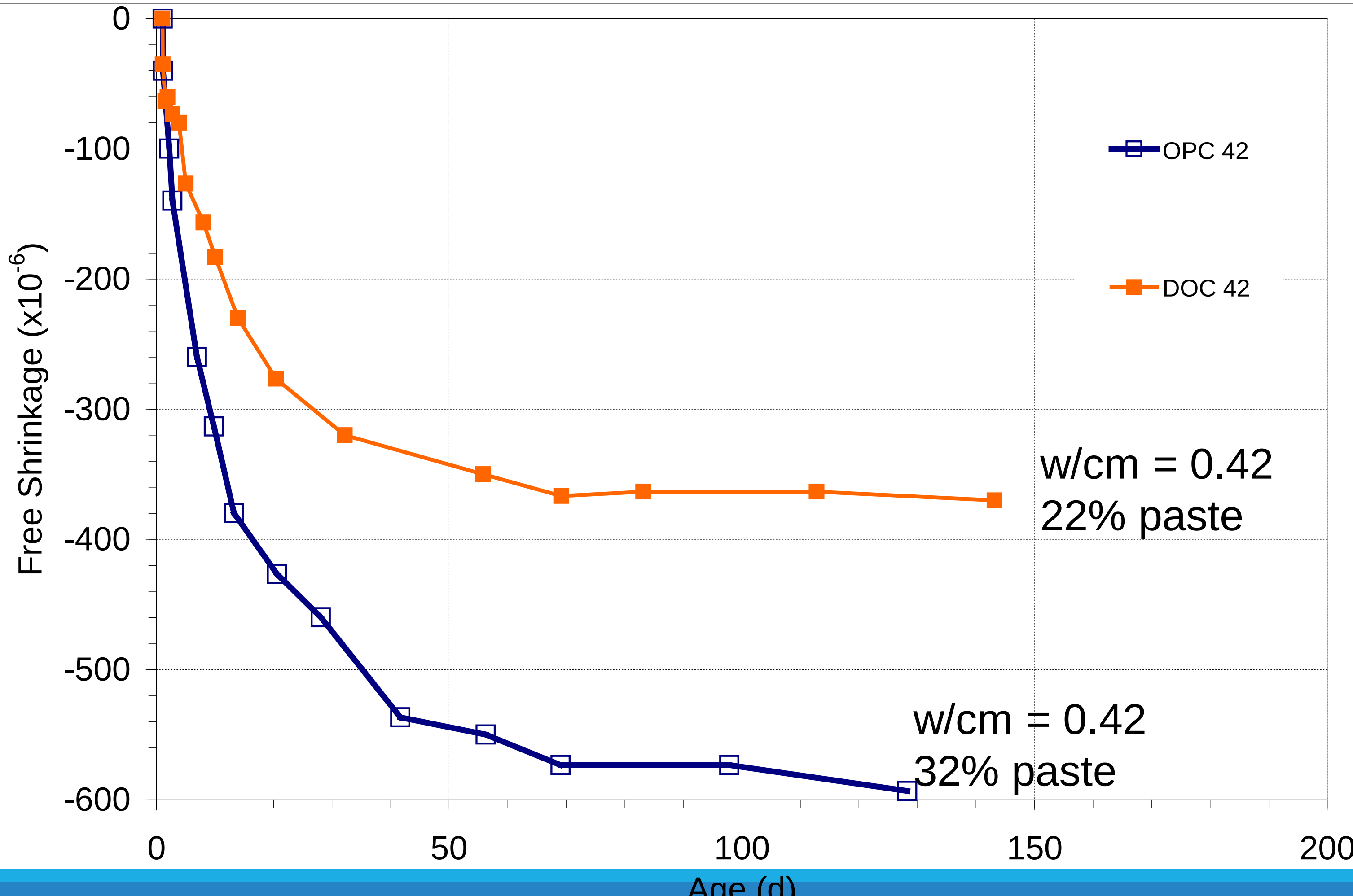
TABLE 4.3 – From ACI 237 ETS	
Summary of Self-Consolidating Concrete Proportioning Trial Mix Parameters	
Coarse aggregate by volume	28% - 32%
Paste Content by volume	**34% - 40%**
Mortar Fraction by volume	68%-72%
Typical w/cm	0.32 – 0.45
Typical powder content	650* – 800 pounds



Aggregate gradation analysis



Shrinkage reduced through aggregate optimization



Recommendations

Place limits on maximum paste content

Place lower limit on w/cm

Use well graded aggregates to reduce the need for high paste%

Recommend supplementary cementitious materials to replace cement

Recommend autogenous shrinkage test for w/cm below 0.38

SCC: Bridging Research and Practice

SCC has many benefits
- Improved consolidation for tight forms or bar spacing
- Labor cost savings
- Aesthetic finish
- Rapid placement

Research is available to help solve problems
- Rheology testing is becoming more common
- Avoid segregation problems with proper testing in the lab and field
- Pressure models assist formwork design
- Cracking can be avoided through careful mixture development or mitigation

Specifications must
- Limit w/b and paste content or utilize mitigation to avoid cracking
- Use performance testing for rheological characterization, avoid segregation, form pressure, and pumpability problems