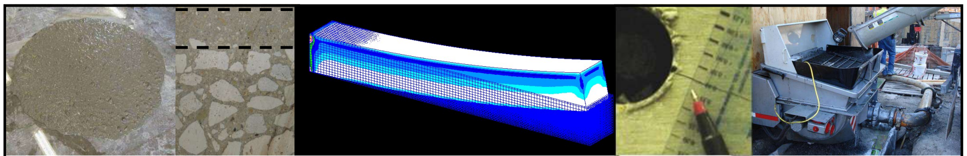

Bridging Research and Practice: High Strength, High-Performance, and Self-Consolidating Concrete

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Introduction

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BS in Civil Engineering, University of Iowa

MS, PhD, University of Illinois (ACBM)

Research Interests:
- Concrete mechanical behavior and durability
- Early-age volume change and mitigation
- Hygro-mechanical effects
- Self-Consolidating Concrete (SCC)

Adjunct Professor at Northwestern University

Recent projects










Development of Performance Engineered (PEM) Concrete

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, optimization

High Strength achieved with:
- Ultra high-range water reducer (polycarboxylate) for low w/cm
- High cementitious materials content
- SCMs, silica fume

Durability achieved with:
- Ultra high-range water reducer (polycarboxylate) for low w/cm
- SCMs
- Mitigate cracking (SRA, optimization)

ACI 237 ETS Report

Flow Characteristics

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

Flowing into double T beam forms
ACI 237 ETS Report

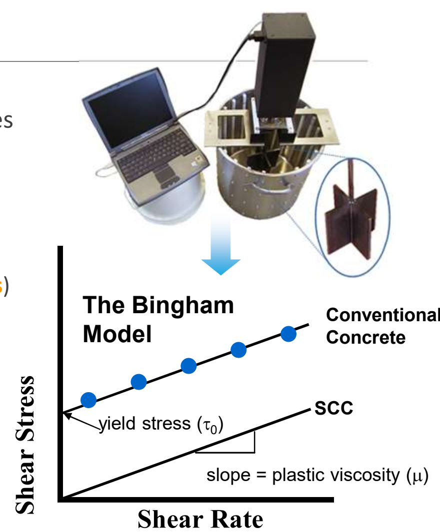
Rheology is the study of the flow of matter

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

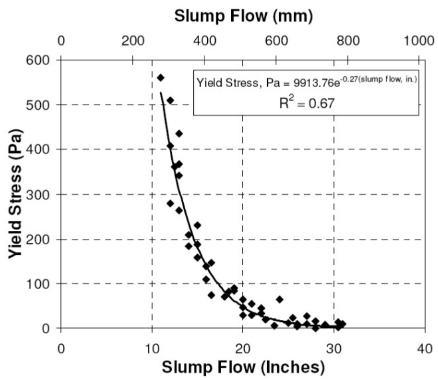
Bingham model:

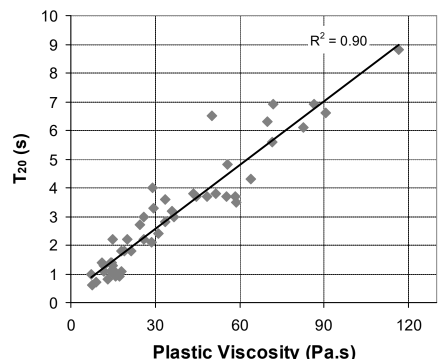
- **Yield stress**: minimum stress to initiate or maintain flow (**slump**)
- **Plastic viscosity**: the resistance to flow once yield stress is exceeded (**stickiness**)

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*.

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

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

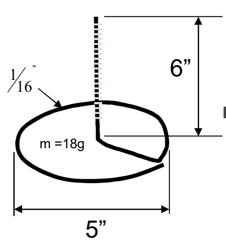
Gravitational Force
-density & size

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

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

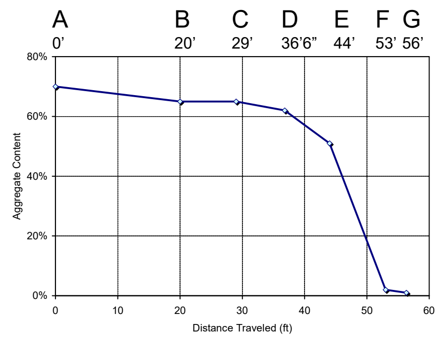
Wait for 15 min, avoid excessive disturbance

Put ring on surface gently

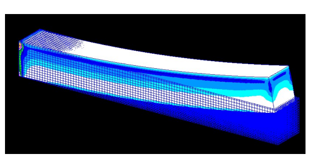
Wait for at least 2 min until ring stops settling

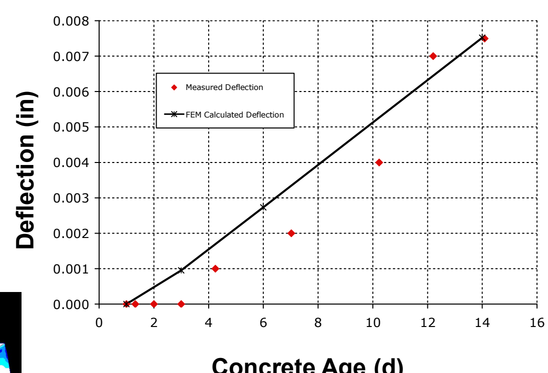
Take reading

Static segregation tests do not predict dynamic segregation



Model validates segregation acceptance criteria





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

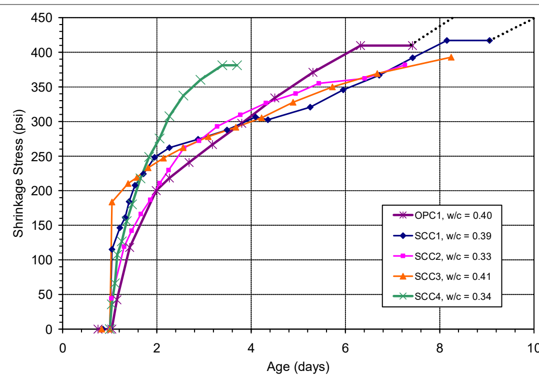
Use smaller aggregate

Use more paste (Cracking!)

To achieve "high performance," designers often **add cement…**

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

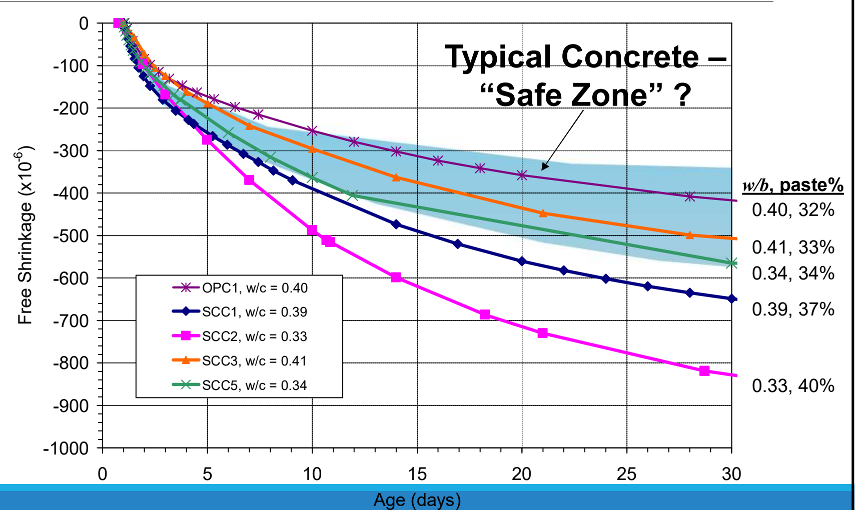
Stress development indicates severe cracking risk



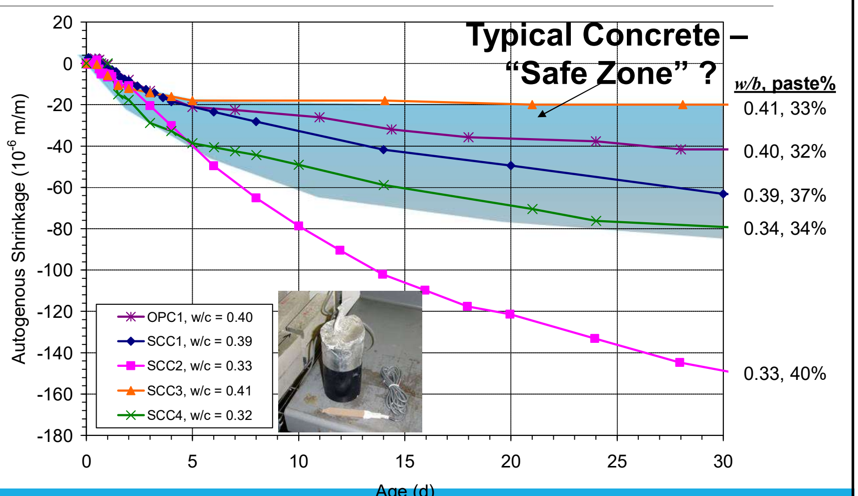
Autogenous shrinkage in low w/c materials generates significant stress at early age

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

Early age shrinkage = potential cracking risk



Low w/c drives autogenous shrinkage



Restrained Ring Testing

ASTM C1581 vs AASHTO T334

- Carlson, R. W., 1937
- Grzybowski, M. and Shah, S. P.,1990
- Krauss, P.D. and Rogalla, E.A., 1996
- Whiting, D. A., Detwiler, R. J. and Lagergren, E. S., 2000
- Attiogbe, E. K., See, H. T. and Miltenberger, M. A, 2001
- Hossain A. B., Pease B. and Weiss W. J, 2003
- Lange, D'Ambrosia, Grasley, et al., 2003

What does the ring test tell us?

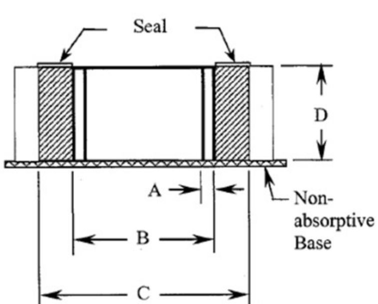
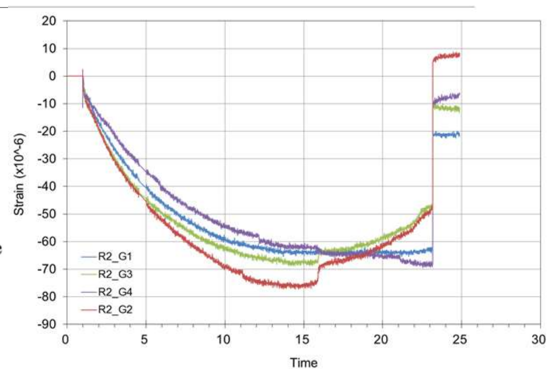


Illustration from ASTM C1581



Ring test gives relative cracking tendency

Allows for cracking risk assessment between different mixture strategies

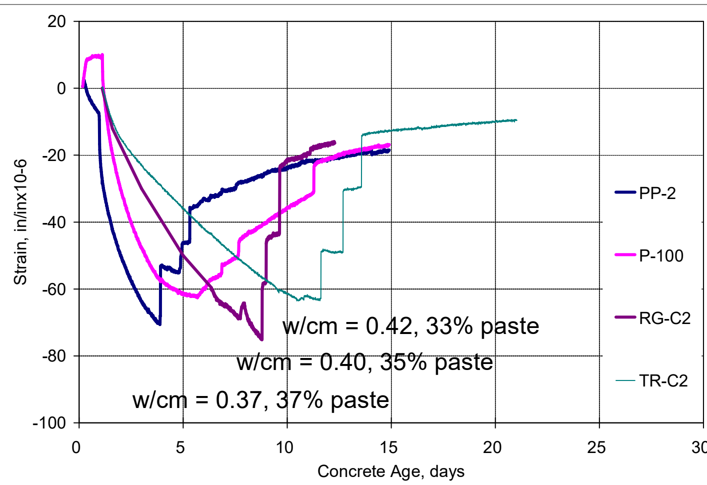
Incorporates the influence of rate of stress development vs tensile strength

Starts immediately after casting – HPC can not benefit from 7-28 day soak of ASTM C157

Accounts for effect of modulus increase with HPC

Accounts for creep relaxation, or lack thereof

Cracking is mitigated with higher w/cm + lower paste



Recommended ring test specification limits

High early strength, patching, low restraint, prestressed beams

- **10 days** minimum time to cracking has correlated with minimal to no shrinkage cracking in patch mixtures

High restraint, long service life, or mass concrete applications

- **28 days** minimum time to cracking correlates to minimal to no shrinkage cracking in bridge decks and mass concrete

Preventing cracking

Mixtures with high risk for cracking 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 and prevents segregation
- Avoid low w/b ratios that lead to high autogenous shrinkage

Specifications…

What is the "performance" we need to ensure?

- More that strength

Spec writers need to emphasize constructability

- 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

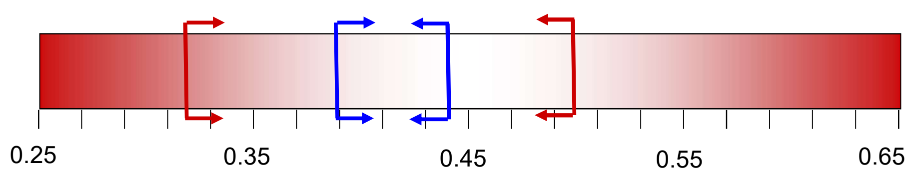
Water-cementitious ratio "safe zone"

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

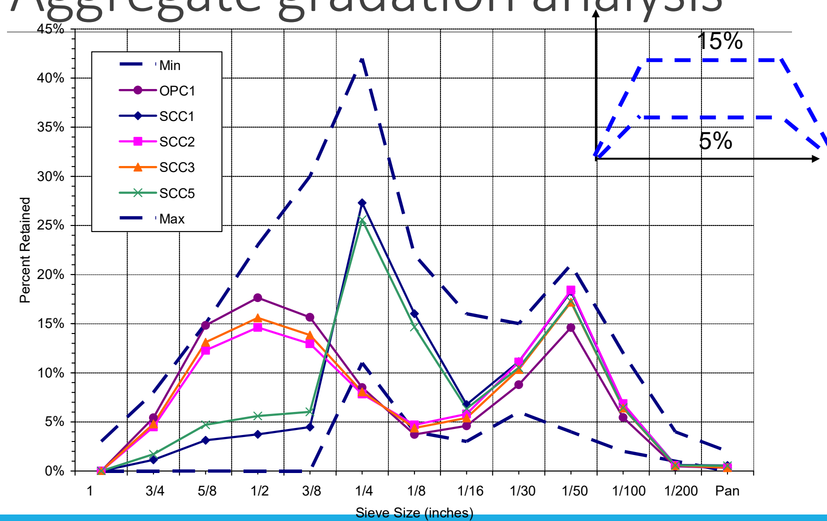
Above 0.50, drying shrinkage is a concern

Strength and durability also affected

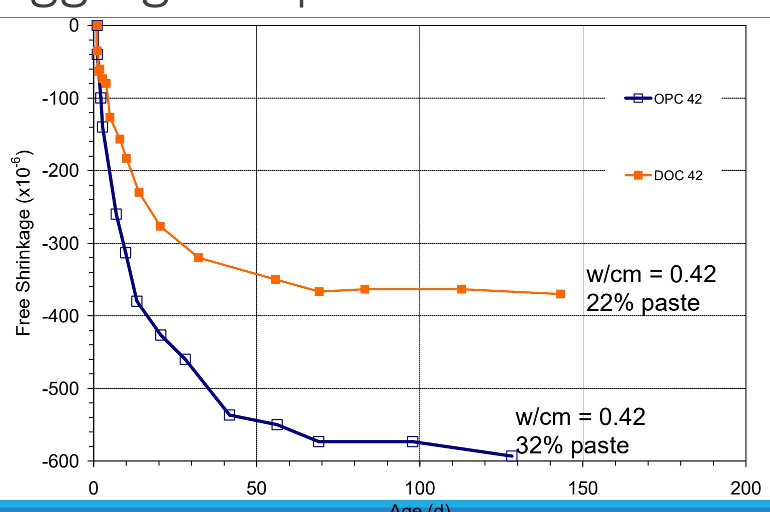
Good range for minimum "total" shrinkage is 0.38 to 0.44



Aggregate gradation analysis



Shrinkage reduced through aggregate optimization



Recommendations

Place limits on maximum paste content

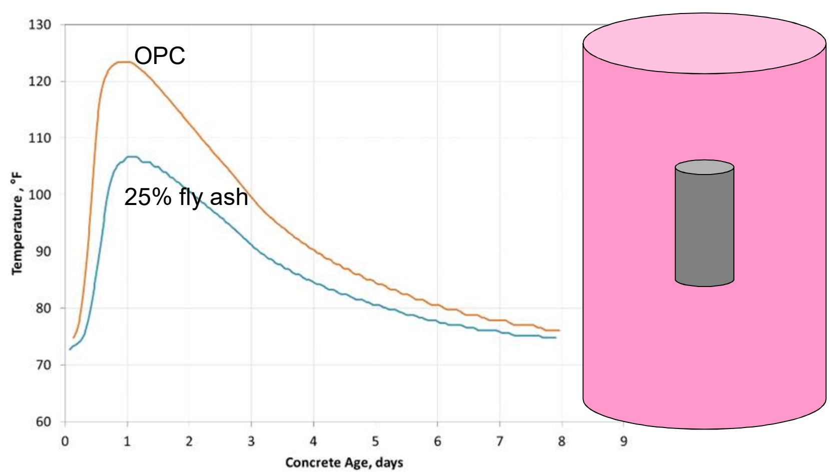
Place lower limit on w/cm

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

Cement hydration causes concrete temperature rise



Temperature rise prediction

Estimated Rise =

{0.14 to 0.16} * (*cement* +

{***0.8 to 0.9}*slag cement***+

0.5*Class F fly ash +

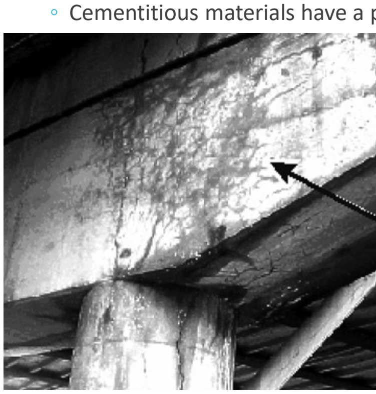
1.2*silica fume)

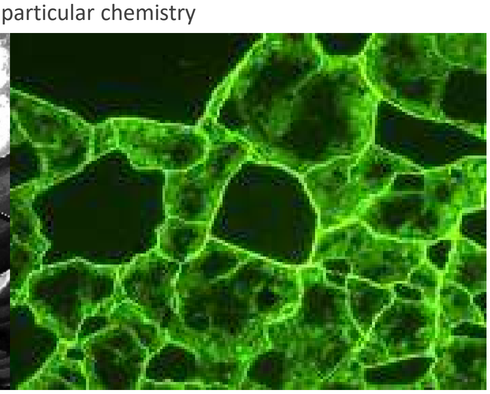
Factors based on *reactivity*

Delayed Ettringite Formation (DEF)

Degradation occurs when:

- Concrete temperature exceeds ~160°F
- Cementitious materials have a particular chemistry





Projects Considering Service Life

Illinois Tollway Move Illinois Program

Large International Design Build Projects

Many Large Bridge and Tunnel Structures (AASHTO LRFD)
- Tappan Zee Replacement (The New NY Bridge)
- Ohio River Bridges
- Goethals Bridge
- Bayonne Bridge
- Norfolk Midtown Tunnel

Energy (Nuclear), Desalination, Wastewater Plants

Dairy Milking Platforms and Clocks

Pitfalls of Service Life Requirements

Clear Design Requirements a Must!!
- Define "service life"
- Define testing and validation requirements
- If possible, identify specific modeling requirements
- Define resolution protocol
- Address cracking
- Address durability concerns other than corrosion

Bridging Research and Practice

PEMs have many benefits
- Improved consolidation for tight forms or bar spacing
- Labor cost savings
- Aesthetic finish
- Rapid placement
- Enhanced durability and longer life

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

Specifications
- 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