Slag Cement: The Other SCM

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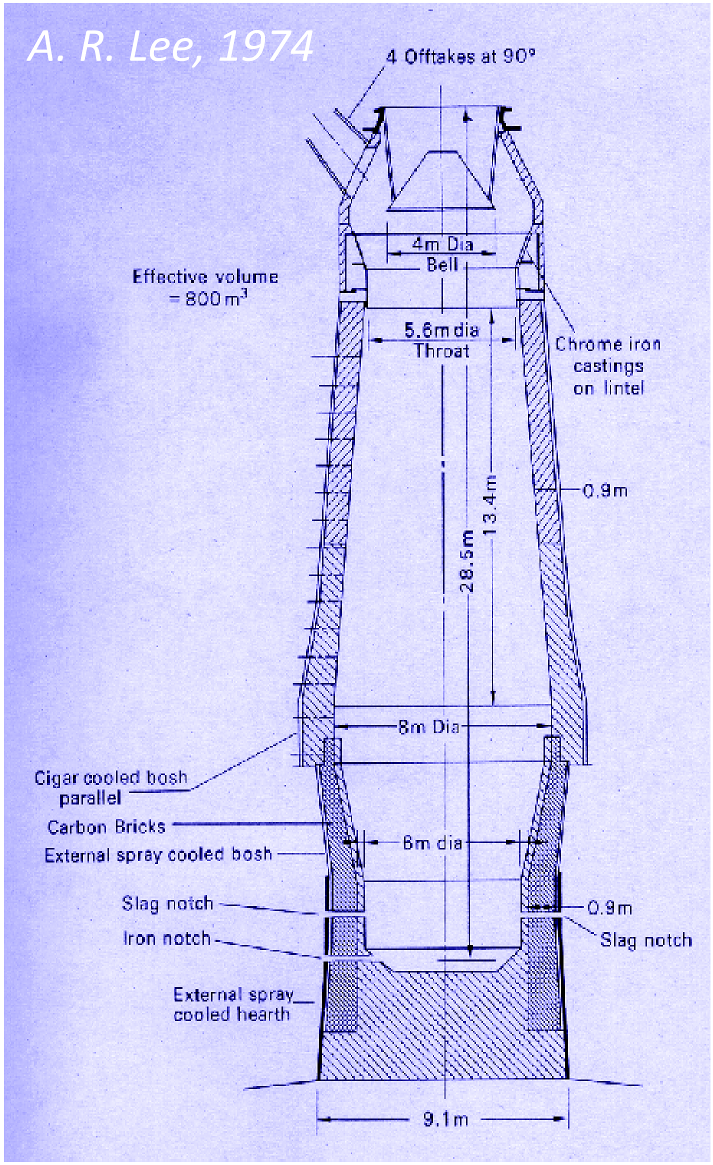
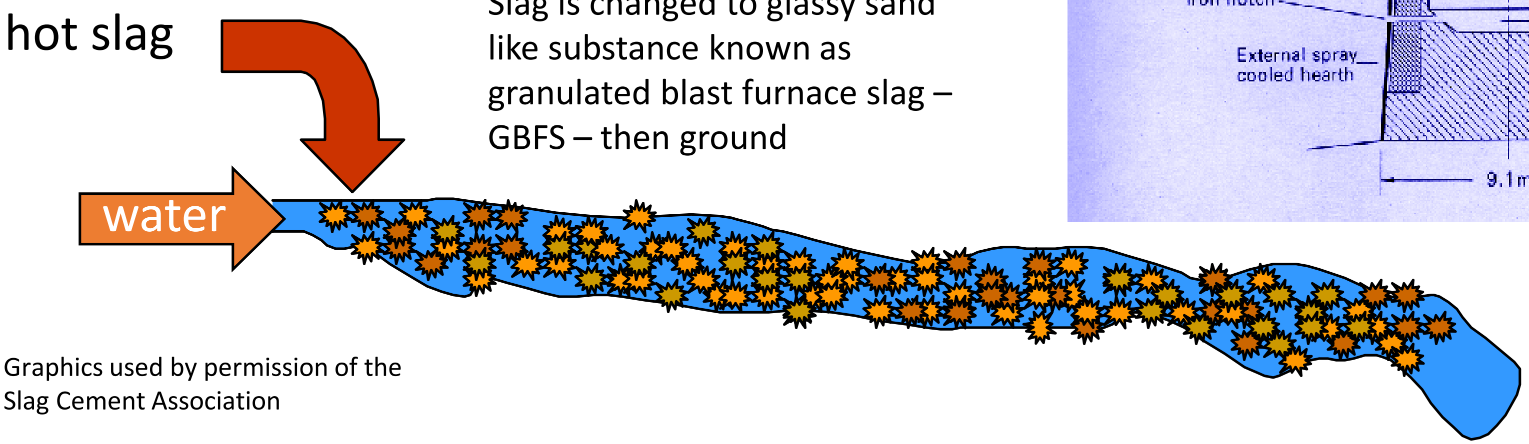
Slag Cement



Slag is changed to glassy sand like substance known as granulated blast furnace slag – GBFS – then ground



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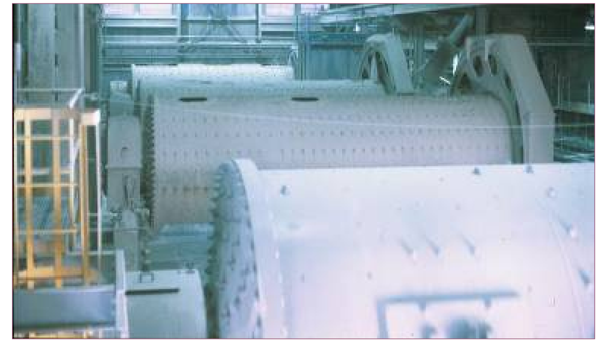
Slag Cement



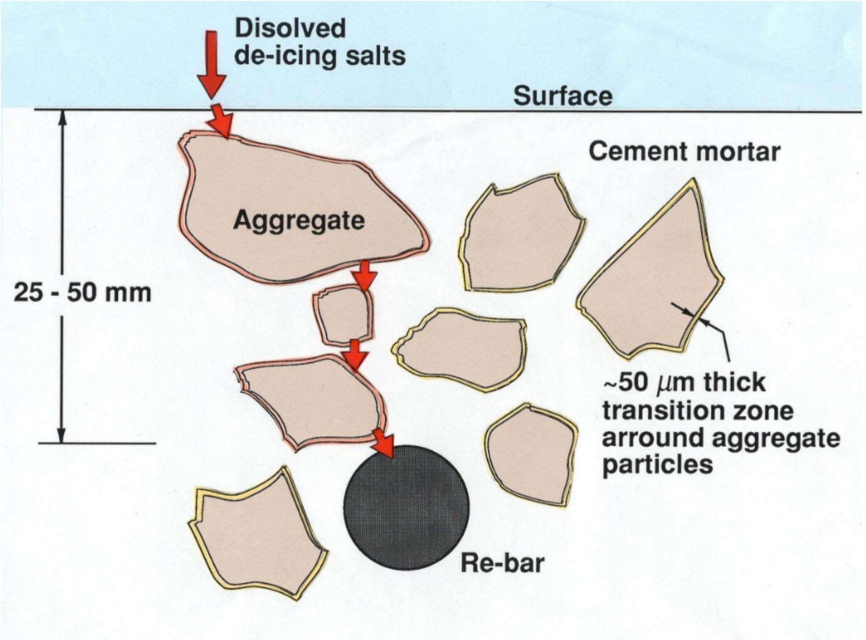
- CONSISTENCY!
  - Composition (iron ore/flux)
  - Glass content (granulation)
  - Fineness (grinding)

Slag Cement Hydration

- Slag cement is a *latent* hydraulic material
  - Sets on its own with water but significant hydration rates require activation
- Slag cement reacts slower than portland cement
  - Hydration of portland cement produces C-S-H and CH
  - CH reacts with the slag cement, breaking down the glass phases and causing the material to react with water and form C-S-H
- Slag cement is not pozzolanic
  - It does consume CH by binding alkalis in its hydration products
  - **Provides all the benefits of a pozzolan**

Slag Cement Hydration

- Concrete containing slag cement has significant improvement in durability compared to cement-only concrete
  - Reacts with CH to form more C-S-H
  - Reacts later filling capillary pore space from initial cement hydration
  - Reaction products fill/densify the ITZ



Courtesy D. Hooton

Slag Cement Hydration

- Cementitious mixtures with slag cement form C-S-H with lower Ca/Si ratio *
  - Leads to alkali being incorporated in C-S-H substituting for Ca
  - Reduces pore solution alkalinity
  - Reduces ASR attack of aggregates
- Higher alumina content leads to formation of C-A-S-H and other aluminate phases *
  - Binds more alkali and chlorides

* D. Hooton, Canadian Journal of Civil Engineering 27: 754-760 (2000)

Slag Cement - Specification

- ASTM C989 (AASHTO M 302) *Standard Specification for Slag Cement for Use in Concrete and Mortars*
  - Classifies the material under three categories: Grade 80, Grade 100, and Grade120
  - The grade classification refers to the relative strength of mortar cubes using the slag SAI test with a 50% replacement of OPC with a standard reference cement
    - 75% of the Control 28-day strength = Grade 80
    - 95% of the Control 28-day strength = Grade 100
    - 115% of the Control 28-day strength = Grade 120
- Also available as blended cement ASTM C595 Type IS(X) (portland cement + slag) or Type IT(X)(Y) (ternary blends)
  - (X) equals the targeted percentage of slag in the product, (Y) equals the targeted percentage of the tertiary component in the product

Slag Cement vs. OPC Mixtures

- Most differences trace to the hydration characteristics of slag cement compared to cement-only
- Differences vary with replacement level
  - 25 – 50% typical, up to 80% in some applications
- SCM vs. Interground
  - As an SCM, often finer than the cement

Concrete application	Slag cement
Concrete paving	25 to 50 percent
Exterior flatwork not exposed to deicer salts	25 to 50 percent
Exterior flatwork exposed to deicer salts with *w/cm* < 0.45	25 to 50 percent
Interior flatwork	25 to 50 percent
Basement floors	25 to 50 percent
Footings	30 to 65 percent
Walls and columns	25 to 50 percent
Tilt-up panels	20 to 50 percent
Prestressed concrete	20 to 50 percent
Precast concrete	20 to 50 percent
Concrete blocks	20 to 50 percent
Concrete pavers	20 to 50 percent
High strength	25 to 50 percent
Alkali-silica reaction mitigation	25 to 70 percent
Sulfate resistance	
Type II equivalence	25 to 50 percent
Type V equivalence	35 to 65 percent
Lower permeability	25 to 65 percent
Mass concrete	50 to 80 percent
Percentages indicate replacement for portland cement by mass. These replacement rates are for individual applications and are based on historical performance. Variations in material sources and environmental conditions may require alternate substitution rates. Testing should be done with local project materials to verify intended performance.	

Table from ACI 233.R- 17 Guide to the Use of Slag Cement in Concrete and Mortar

Slag Cement vs. OPC Mixtures

- *Workability* – slump typically increases slightly at constant *w/cm*; rate of slump loss reduced; generally easier to compact by vibration
  - Slightly lower SG (2.85-2.94 vs. 3.15) results in higher paste contents with mass replacement
- *Time of Set* – typically increases with increasing slag cement contents (above 25%)
  - Depends on temperature and the specific portland cement
  - 30 – 60 minutes @ 50% replacement, 73 ºF
  - Minimal change above 85 ºF

Source: ACI 233.R- 17 Guide to the Use of Slag Cement in Concrete and Mortar

Slag Cement vs. OPC Mixtures

- *Saw Cutting Joints* – increased setting times may delay joint sawing
  - Rule of Thumb - ~30 minutes of delay for every 10% replacement of portland cement
- Dependent on placement temperatures
  - Replacements of up to 50% have been used in summer months
  - Slag cement content may need to be reduced in lower temperatures
- Early entry saws are often used
- Delay can be adjusted by using accelerating admixtures, heated water, or heated aggregates

Source: Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements, Volume I: Final Report; FHWA

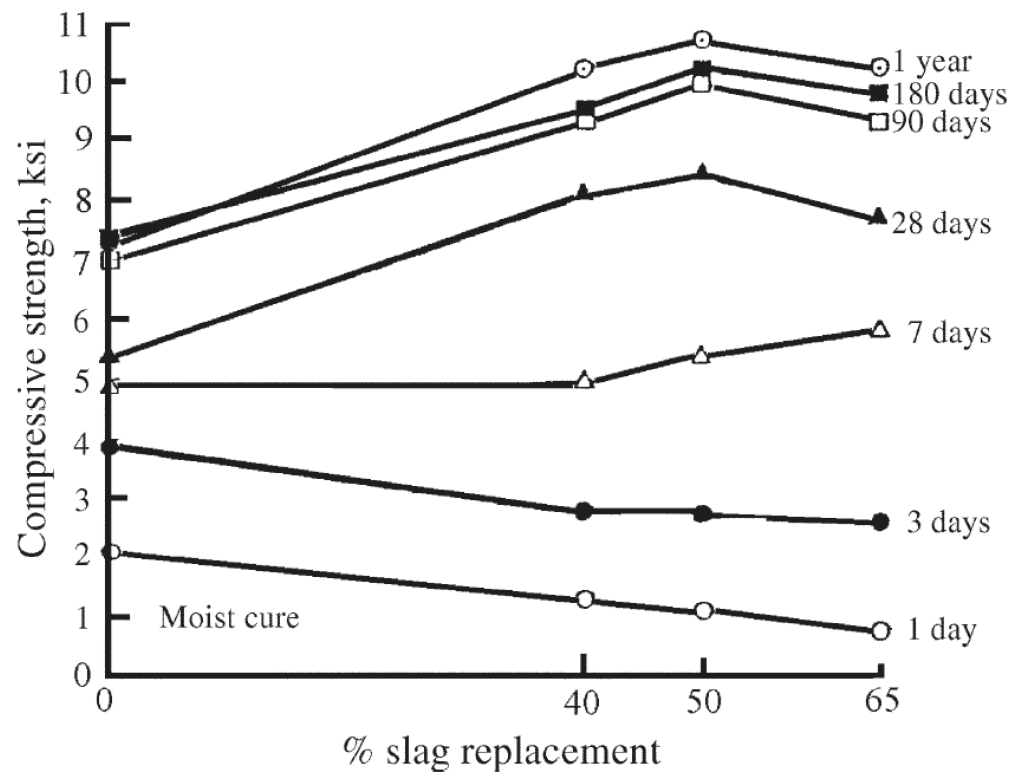
Slag Cement vs. OPC Mixtures

- *Air Entrainment* – typically no impact on AEA dosage
  - NO LOI ISSUES !!!
  - Entrapped air may be reduced due to improved workability
  - AEA dosage should always be verified as part of a mixture design process
- *Bleeding* – influenced by fineness of slag cement vs. OPC used; when slag cement is finer than OPC, bleed rate is reduced
- *Finishing* – with reduced bleed rates or lower temperatures, finishing may be extended 1-2 hours
  - Troweling before bleed finishes can contribute to scaling

Source: ACI 233.R- 17 Guide to the Use of Slag Cement in Concrete and Mortar

Slag Cement vs. OPC Mixtures

- *Strength* – reduced at early ages (1-3 d), increased at later ages (7 d and beyond)
  - Depends on Grade, *w/cm,* replacement, cement characteristics
  - Influenced greatly by temperature, accelerated curing can result in 1 day strengths greater than cement only



Source: ACI 233.R- 17 Guide to the Use of Slag Cement in Concrete and Mortar

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Slag Cement vs. OPC Mixtures

- *Reduced Corrosion of* Steel – through reduced permeability of chlorides and water, and reduced –OH concentrations
- *Temperature Rise* – A slower reaction rate and associated lower heat evolution makes slag cement an ideal ingredient for mass concrete placement where control of internal temperatures is critical to achieving durability
  - Depends on the Grade of slag and the replacement
- Up to 80% replacement of OPC with slag cement is used for mass concrete

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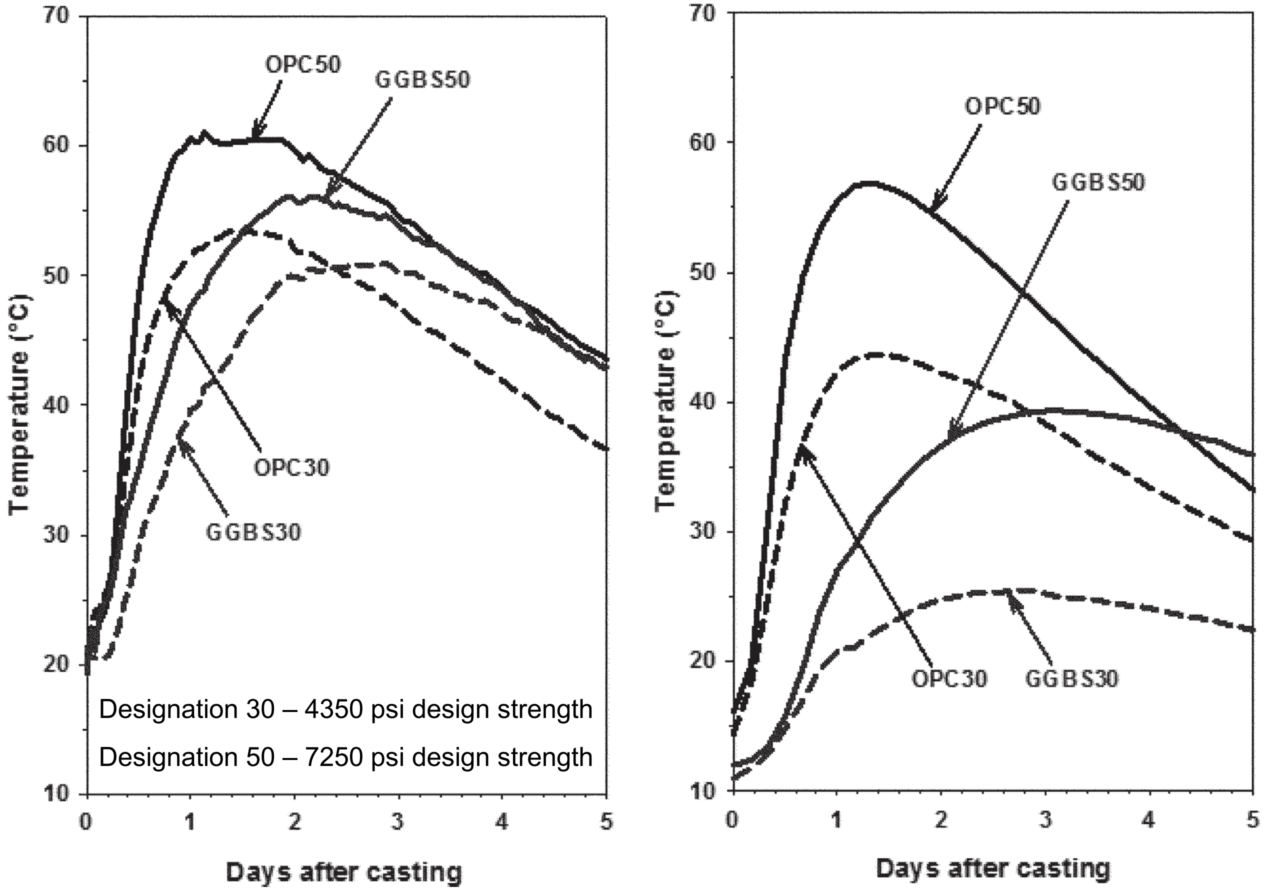
Source: ACI 233.R- 17 Guide to the Use of Slag Cement in Concrete and Mortar

Slag Cement vs. OPC Mixtures

0% and 50% replacement at two ambient temperatures



Source: ACI 233.R- 17 Guide to the Use of Slag Cement in Concrete and Mortar

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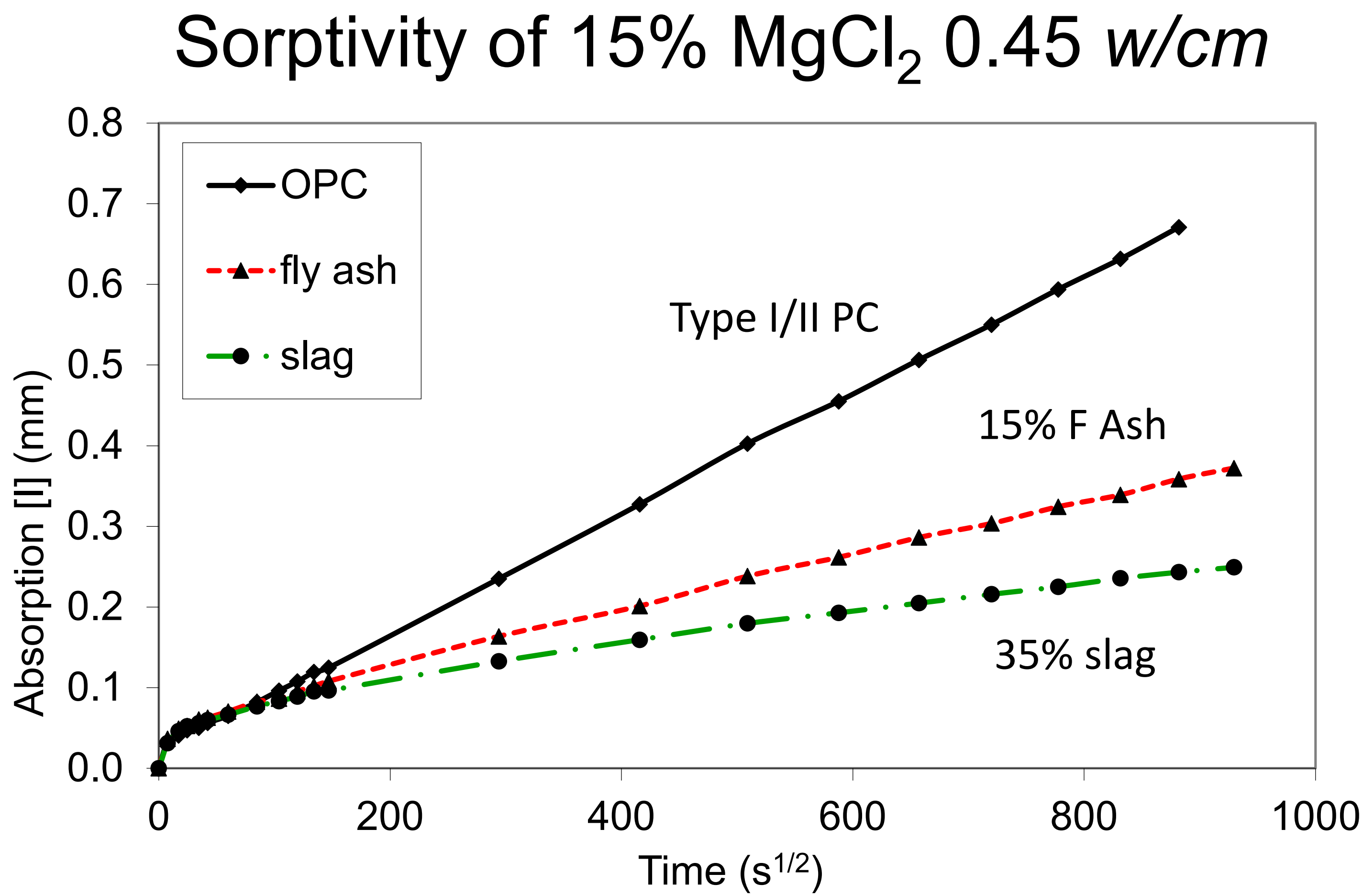
Slag Cement and Curing

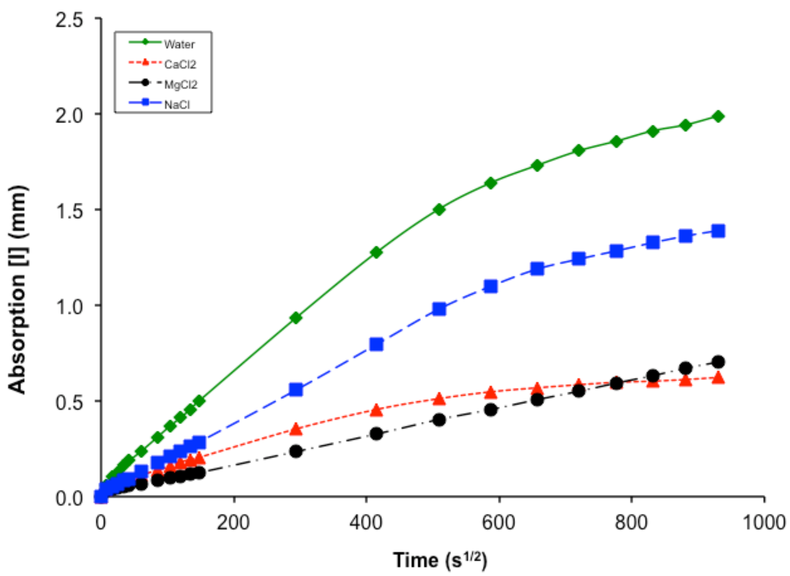
- Curing is always essential for achieving a quality product; it is even more critical with slag-cement-based concrete
- Because slag cement is slower to react, setting time can be increased significantly compared to OPC concrete
- The slower reaction rate, especially at lower temperatures, is often overlooked, and this can lead to durability issues such as scaling when not properly cured or finished

Performance - Permeability

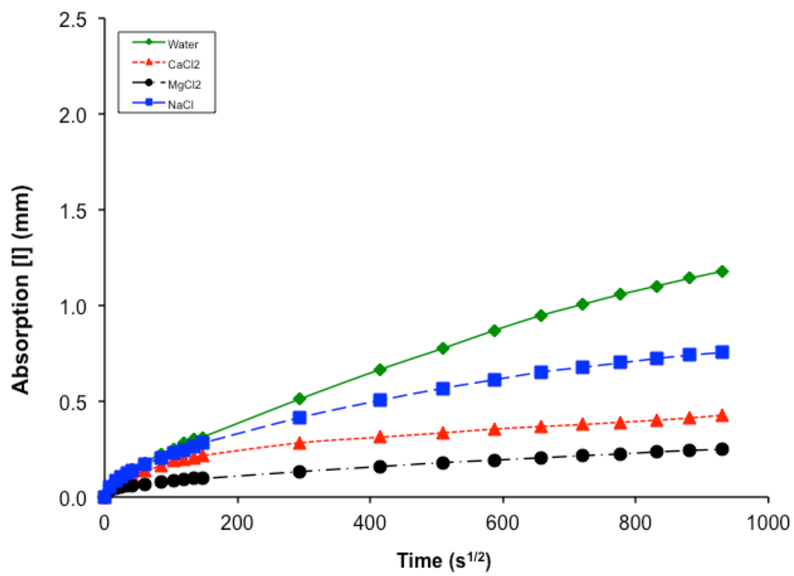


Performance - Permeability

0.45 *w/c* OPC

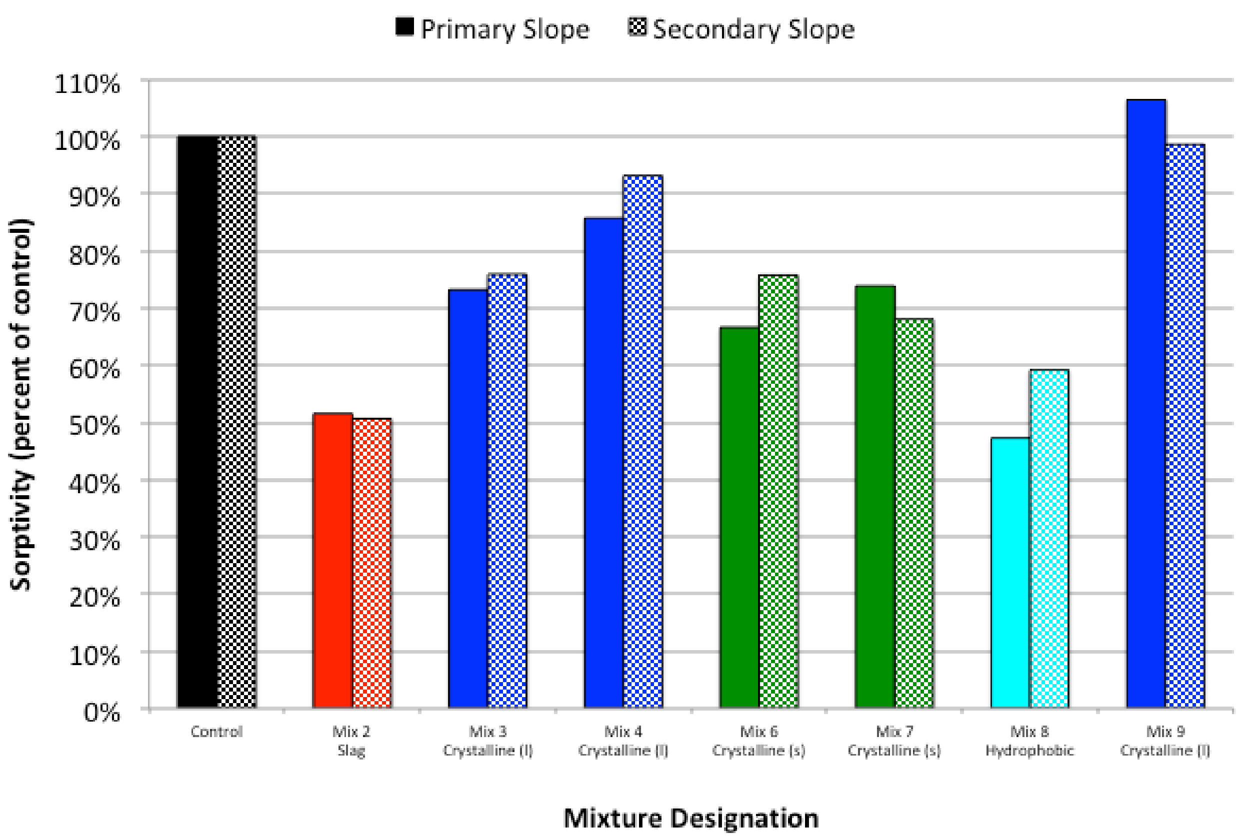


0.45 *w/c* OPC + 35% Slag



Performance - Permeability

ASTM C1585 Slopes of Primary
and Secondary Absorption Curves



Unpublished Michigan DOT Report

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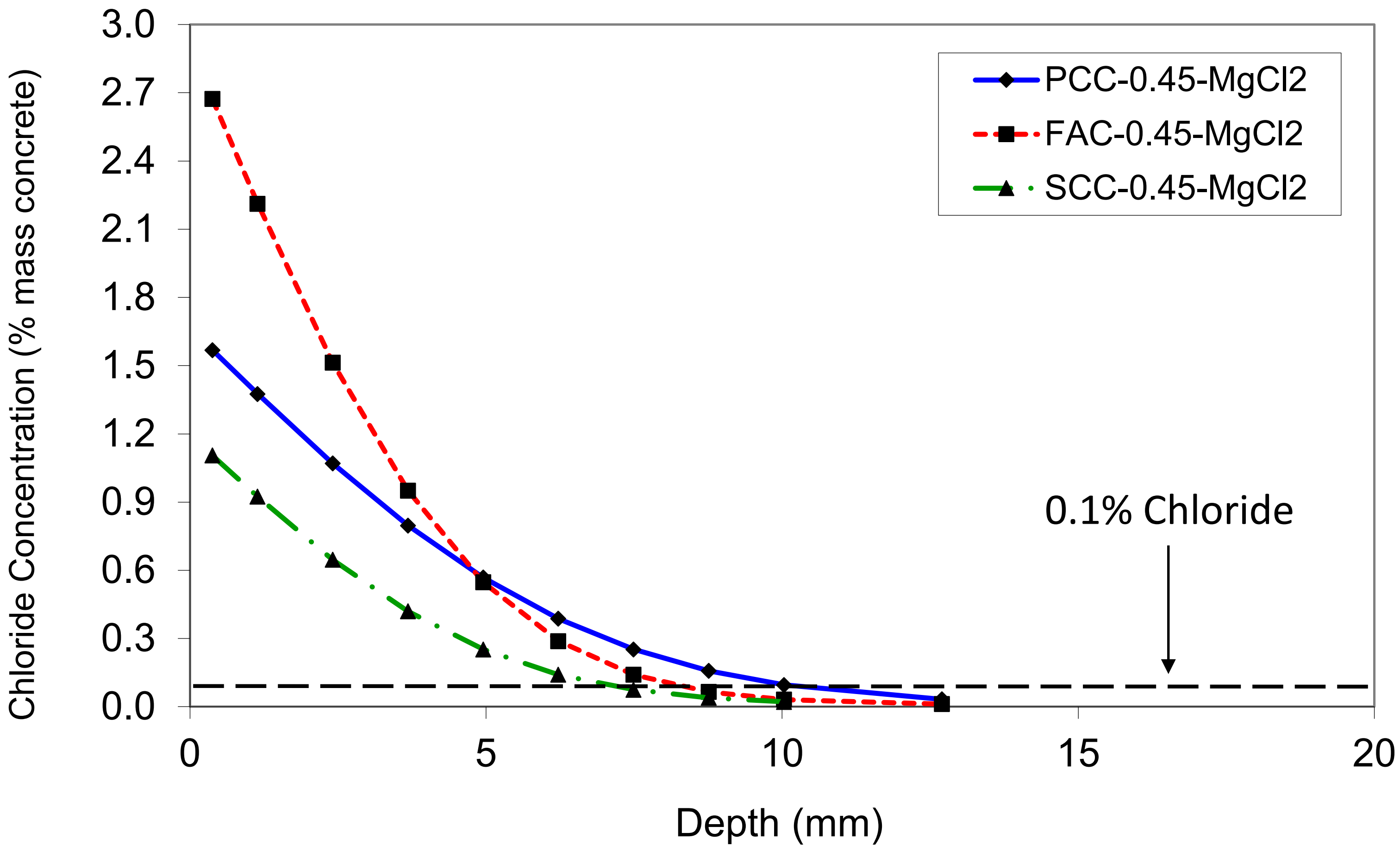
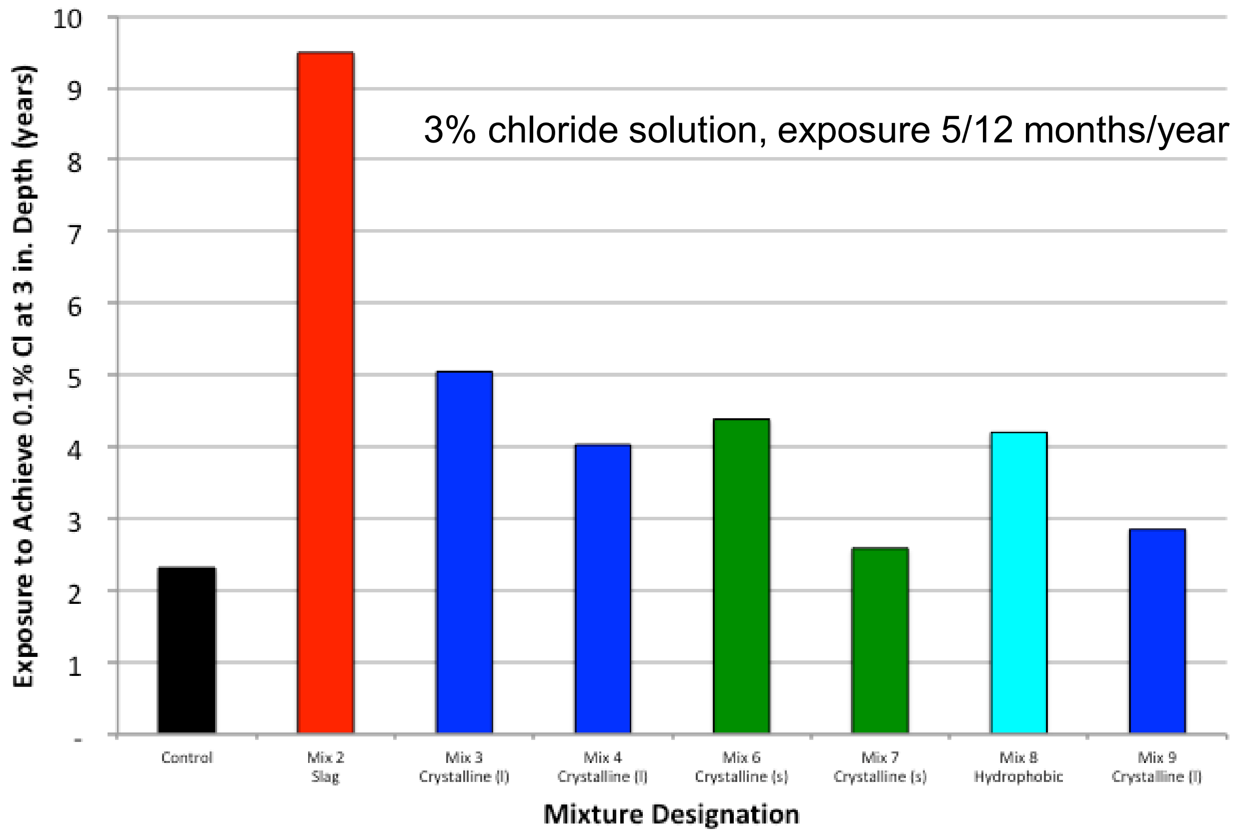
Performance - Permeability



Performance - Permeability

Chloride Diffusion Expressed as Time to Reach a Concentration of 0.1% chloride at 3” depth



Unpublished Michigan DOT Report

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Performance - ASR

- Slag cement is very effective at mitigating ASR
- Numerous sources of information and guidance
  - AASHTO R 80-17 Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction
    - Performance *OR* Prescriptive Approach
  - FHWA Alkali-Aggregate Reactivity (AAR) Workshops for Engineers and Practitioners - Reference Manual
    - https://www.fhwa.dot.gov/pavement/concrete/asr/pubs/reference.pdf

Performance - ASR

- Slag cement is very effective at mitigating ASR
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ACI MATERIALS JOURNAL TECHNICAL PAPER

Title no. 95-M71

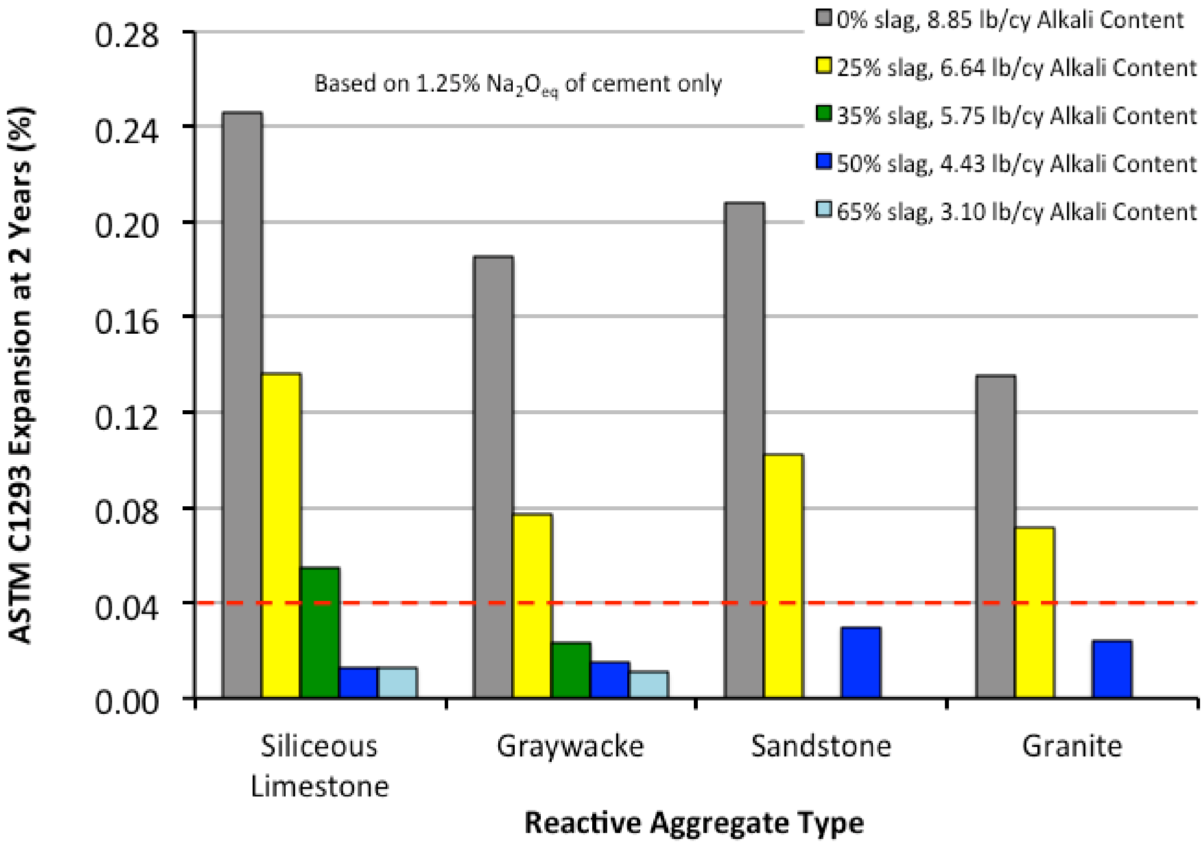
Effect of Slag on Expansion Due to Alkali-Aggregate Reaction in Concrete

by M. D. A. Thomas and F. A. Innis

Thomas, M.D.A. and Innis, F.A. 1998. “Effect of Slag on Expansion Due to Alkali-Aggregate Reaction in Concrete.” ACI Materials Journal 95 (Dec. 1998), 716–24.

Performance - ASR

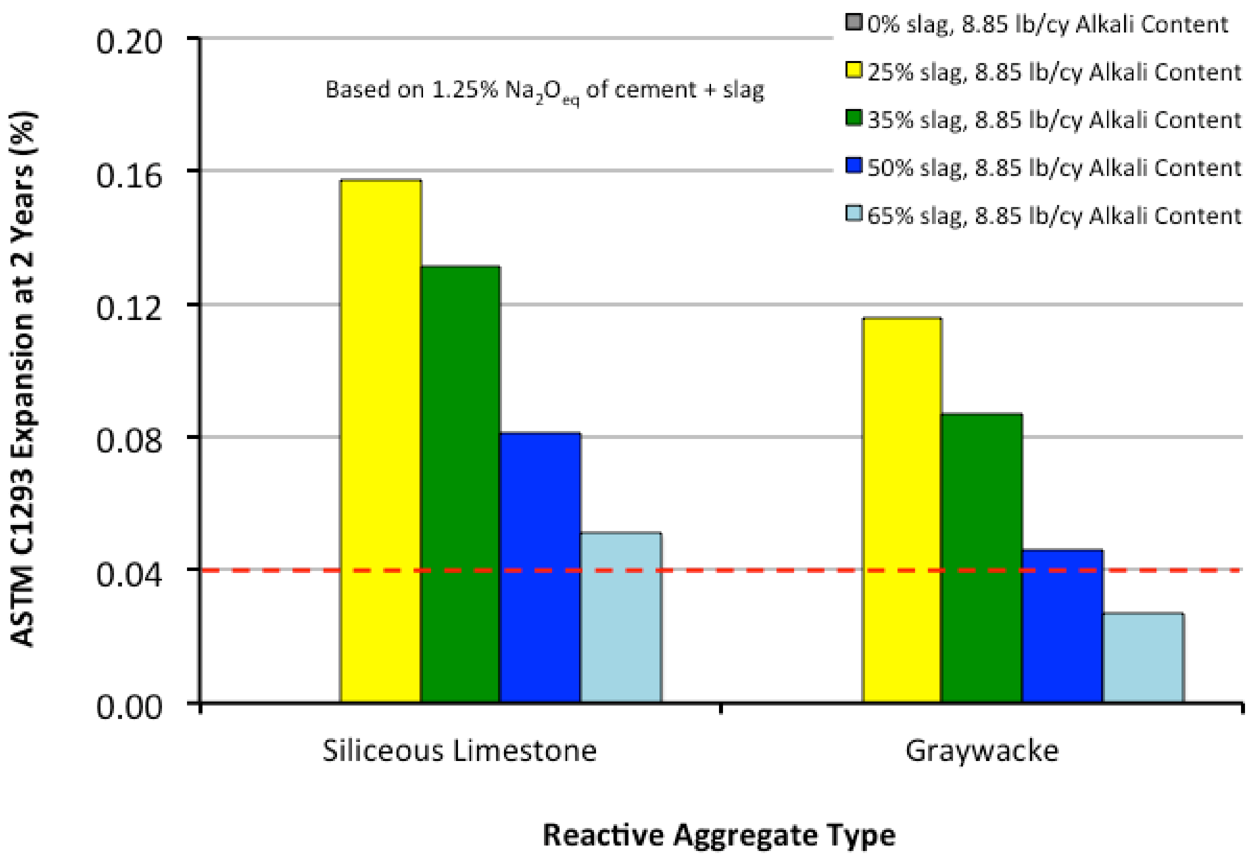
700 lbs/cy cementitious   0.42 – 0.45 *w/cm*



after Thomas and Innis 1998

Performance - ASR

700 lbs/cy cementitious   0.42 – 0.45 *w/cm*



after Thomas and Innis 1998

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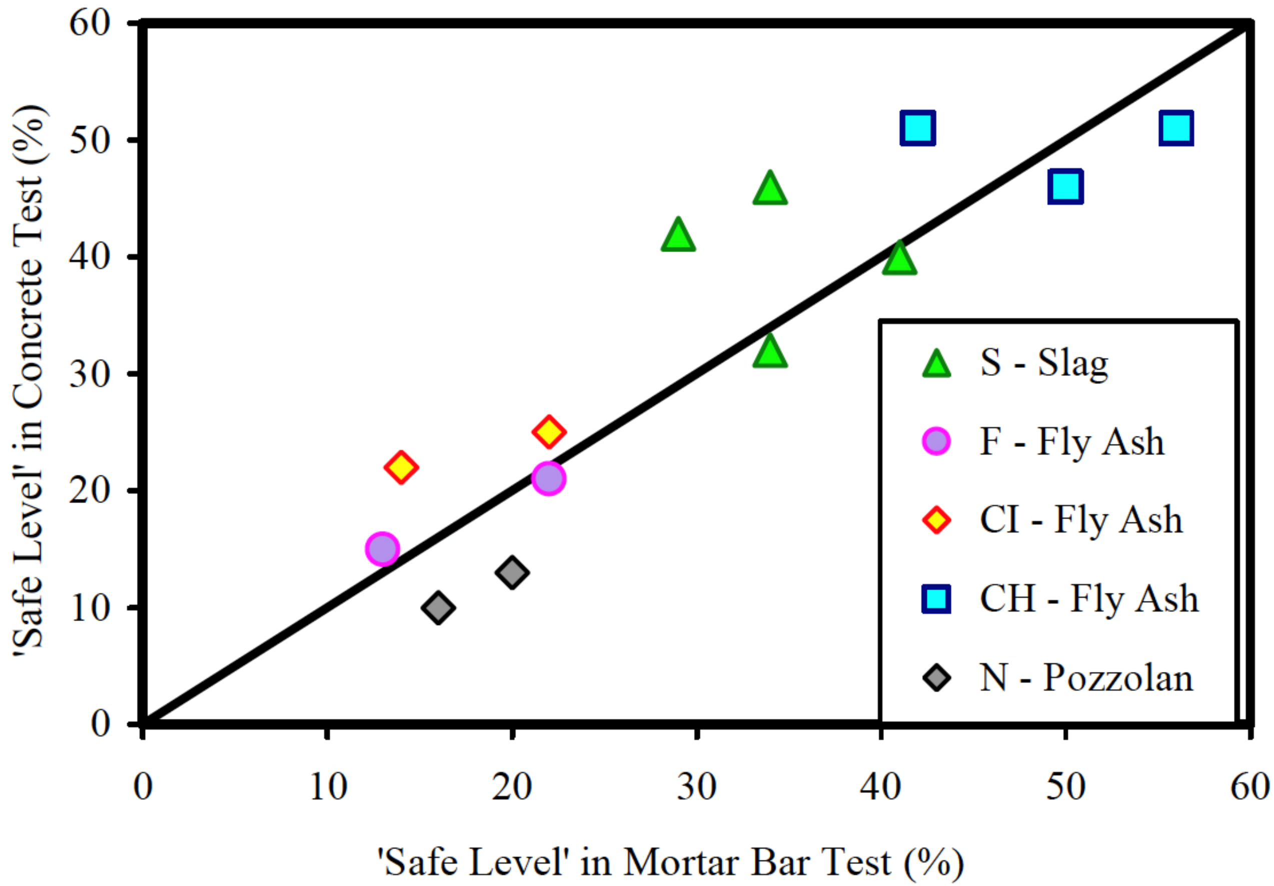
Performance - ASR



after Thomas and Innis 1998; graphic from FHWA Alkali-Aggregate Reactivity (AAR) Workshops for Engineers and Practitioners - Reference Manual

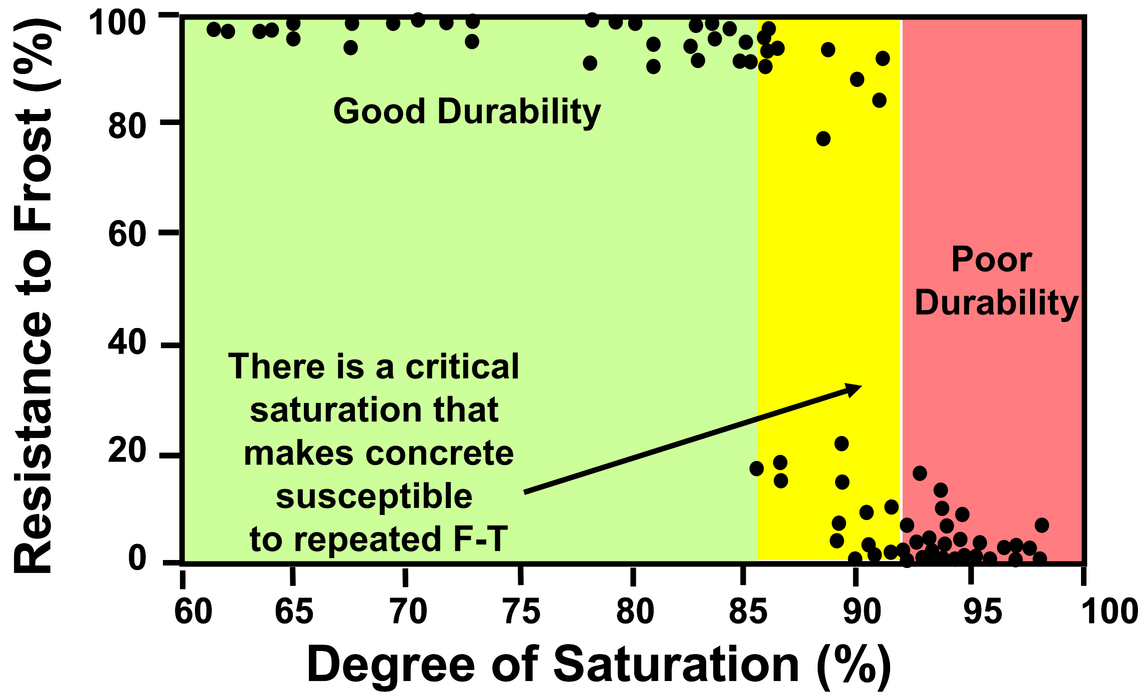
Performance – Sulfate Resistance

- Slag cement will mitigate sulfate attack
  - Slag cement does not contain C_3A – dilutes the C_3A from the portland cement
  - Slag cement reduces permeability – sulfate solutions limited from penetrating the concrete
  - Slag cement consumes CH – forms more C-S-H to strengthen the concrete and resist expansive forces
    - Typical replacement levels for Type I portland cement are 50% for slag cements with an alumina content <11%
    - Replacement levels for Type I portland cement are 60 - 70% for slag cements with an alumina content >11%
  - Test mixtures with ASTM C1012

Source: ACI 233.R- 17 Guide to the Use of Slag Cement in Concrete and Mortar

Performance – Freeze/Thaw

- Performance in a FT environment is typically the same or improved *
- Improvement comes from reduced permeability

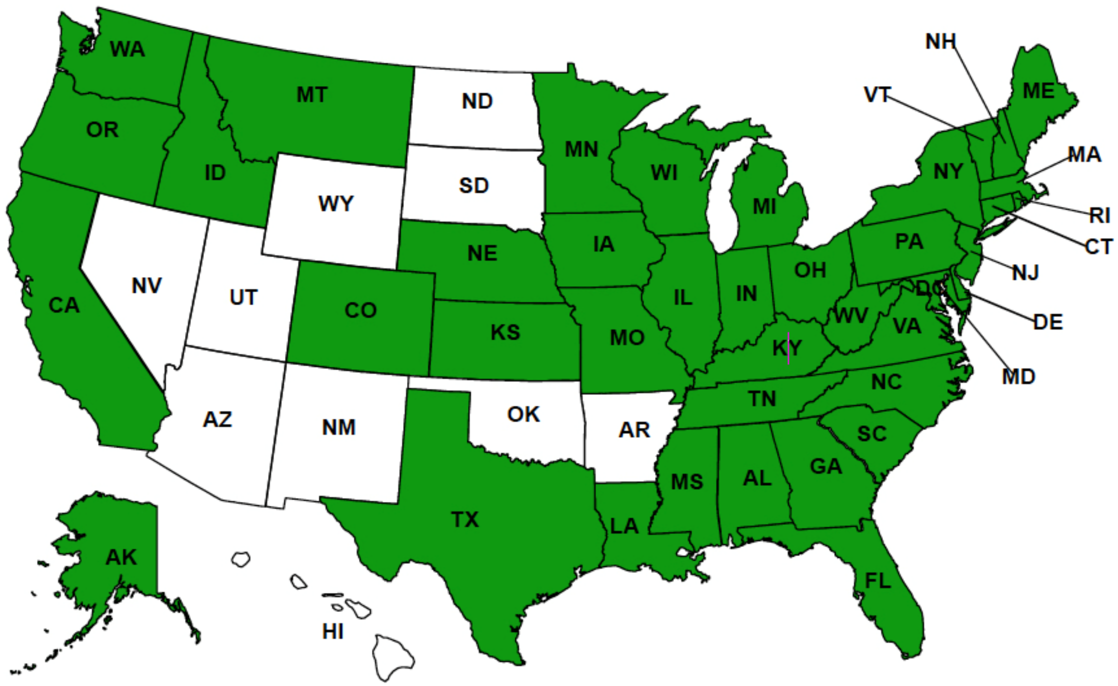


After CEB 1957

* Source: ACI 233.R- 17 Guide to the Use of Slag Cement in Concrete and Mortar

Slag Cement Availability

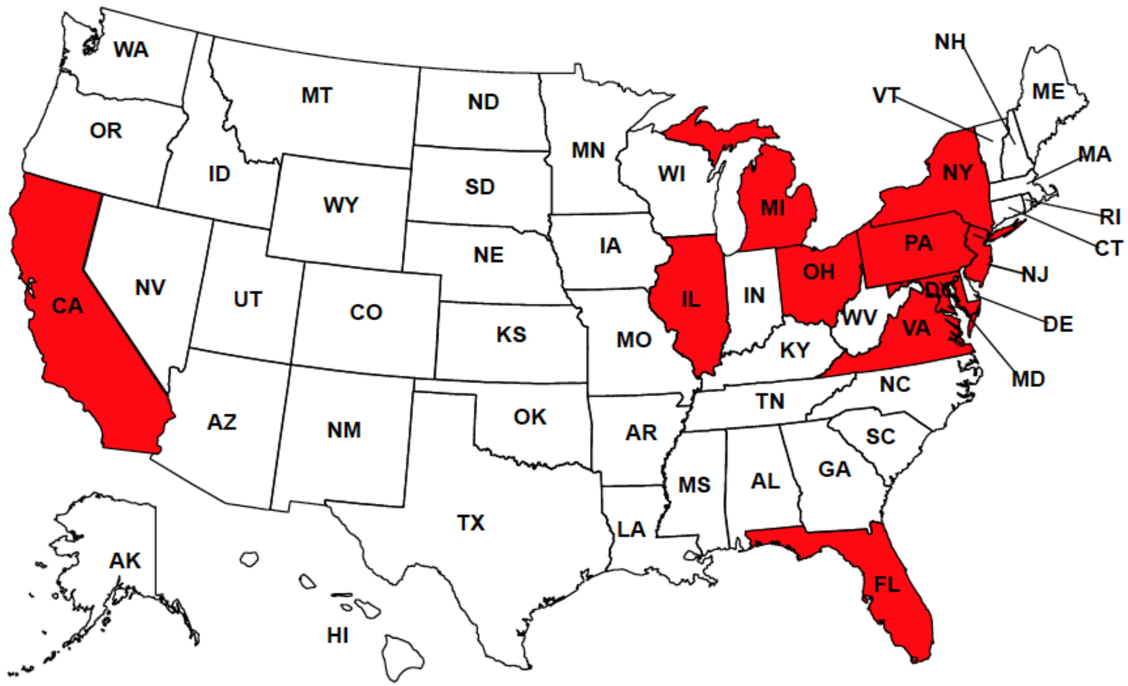
States Using Slag Cement – June 2018



Source: Slag Cement Association

Slag Cement Availability

Top Ten States in Slag Cement Consumption – June 2018



Source: Slag Cement Association

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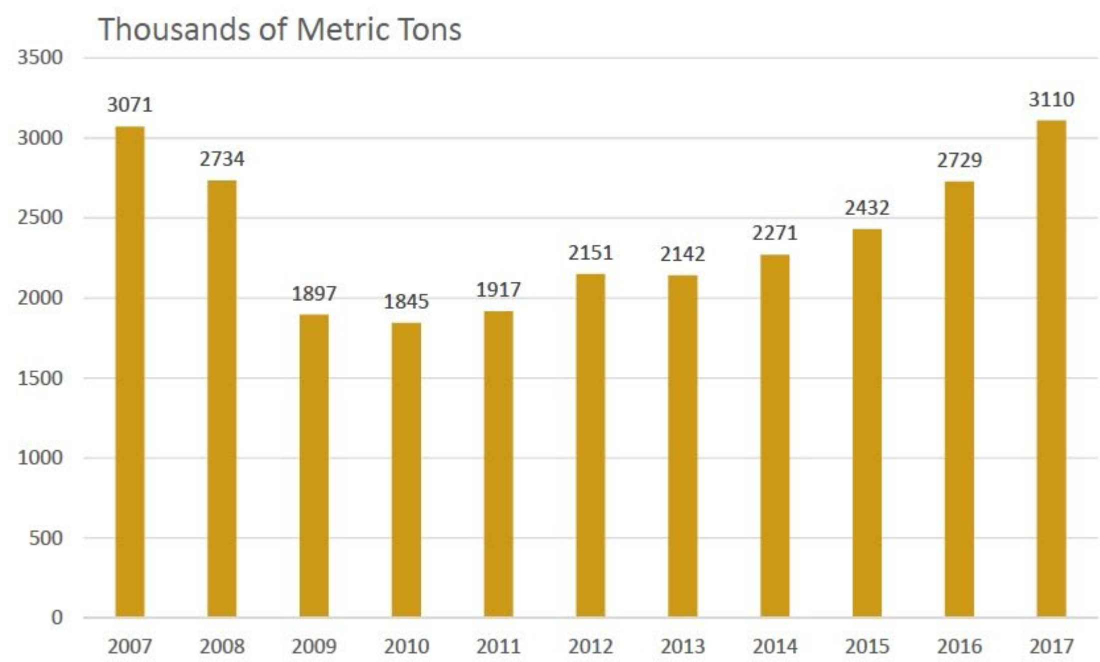
Slag Cement Availability

U.S Slag Cement Shipments (ASTM C989)



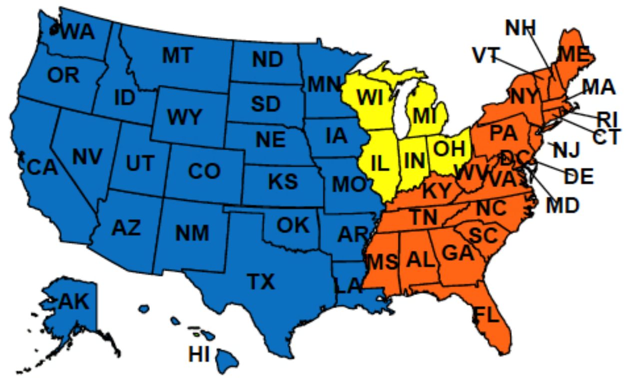
U.S. Data from 2017 showed a 14 percent increase in slag shipments over 2016 and a 12 percent gain the year before.

Source: Slag Cement Association

Slag Cement Availability

Slag Cement Shipments – Regional
2016 and 2018 Thru June

Region
East
GL
West



Region	2016 - SC	2018 - SC	% Change
East	754,045	955,695	21.1%
Great Lakes	266,896	310,786	14.1%
West	187,901	273,330	31.3%
Total	1,208,842	1,539,811	21.5%

Source: Slag Cement Association

Summary

- Slag cement offers improved consistency of properties when compared to fly ash
- Used as a replacement of 25 – 80% portland cement
- Not a pozzolan but provides the same performance benefits of a pozzolan
- Latent hydraulic material so setting times are extended and the rate of strength gain is slower
- Typically results in equal or higher ultimate strengths than portland cement only

Summary

- Available for use as an SCM or in a blended cement
- Significantly improves durability of concrete
  - Does not impact air entrainment
  - Slag reduces permeability and chloride penetration
  - Slag can eliminate ASR expansion / damage
  - Slag reduces rate of steel corrosion in concrete
  - 35-50% slag can exceed Type V performance for sulfate resistance when used with Type I or II cements (slags with Al_2O_3 >11 % may require higher % slag)
  - 50-75% slag reduces heat of hydration and risk of thermal cracking

Summary

- Slag cement availability is increasing in the US
- Slag cement has been used successfully in numerous transportation-related projects
  - See addendum of selected case studies in this presentation
- For additional information see the Slag Cement Association
  - https://www.slagcement.org

Questions?

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Additional Slides:

Case Studies Available from the Slag Cement Association

Pavements: Chicago Edens Expressway I-94 (1977-1978)

Edens Expressway, Chicago, the construction of 1977-1978; between 25% and 45% slag supplied as ASTM C595 Type IS blended cements to various lengths of the pavement.

The blended cements were made at the Buffington Station cement plant, near where Indiana and Illinois meet at Lake Michigan.

Illinois DOT → included slag cement in the IL DOT Specification in the early 1990s, in part, after a 1994-1995 review of the Edens Expressway performance.

Good Showing for Edens Expressway after 17 years in service evaluation. ‘High degree of wear resistance.

Greater Chicago Area Paving
Tollway jobs in 2014 summing to 250,000 cy

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← **2014 Algonquin area II Tollway paving job using Type I/II low-alkali cement with 25% slag cement (photo courtesy of Steve Strike, then of Meyer and now of Ozinga, 4/22/14)**

Marengo, IL Illinois Tollway project → segment by K-Five Construction. Barrier wall base using Type IL(10) cement (an ASTM C595/AASHTO M 240 Type IL material) with 25% slag cement.
(photo 4/22/14 by Steve Strike)

Ohio DOT (since 1993) Chicago—I-290 / Hwy 53 (2006)

- Columbus, OH— I-270 (~1993) Ohio DOT 1st use of slag-cement concrete in mainline paving.
- 30% slag cement
- Construction segment on west side of Columbus loop.

← Mainline paving by Athens OH, 2006. 30% slag cement. Curing compound used.

Fig above and below—Columbus: curing compound applied; saw-cut joints

Chicago — I-290 / Hwy 53 (2006): The project segment was several miles along Schaumburg. 25% slag cement.

Hobart/Merrillville, IN (2012)

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SLAG CEMENT ASSOCIATION

I-65 near Hobart/Merrillville, IN.

- 565 total pcy total cementitious with 25% slag cement as the only non-portland-cement component.
- InDOT required flexural strength of at least 570psi @ 7 days
- The concrete consistently exceeded 700 psi.

← WI DOT—50% slag- → cement concrete pavements tend to be whiter than other concrete pavements. In the figure at right, an adjacent pavement is visible in the distance, for comparison.

ODOT Project 10-0281
IR–75/IR-475 Interchange

- Toledo, Ohio project included
  - New interchange, six bridge reconstructions, 4 new bridges, 3,700 ft cast-in-place retaining walls, four noise-abatement walls, and replacement of 2.1 miles of pavement
- Used ternary mixture for bridge decks and substructure
  - 25% slag cement and 25% fly ash
  - Exceeded 28-day 4,500 psi *f'c* with average 5650 7-day and 7910 28-day strengths
  - ASTM C1202 RCP—752 coulombs
- reduced environmental footprint

Delaware DOT State Route 1

- Built 1989-2004
- **1 Million cy** concrete
- 35-50% slag cement
- Mitigated ASR
- Allowed use of local aggregates
- Approx. savings:
  - 221,000 tons mat'l
  - 490,000 mbtu
  - 109,000 tons CO_2

BRIDGES: Ohio DOT (since 1996, and with ternary mixes, too); MO DOT (ternary mixes since 2004)

Ohio DOT since 1996
- Hundreds of bridge parapet walls and piers have included 30% slag cement
- Ternary mixes allowed in decks with slag cement

← 1st ODOT use of slag cement concrete in a bridge deck. Notice wet-burlap curing (early 1990s).

MoDOT (since 2004) Ternary bridge decks w/ </=40% slag cement+fly ash placed routinely.

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Missouri River MoDOT I-70 Blanchette Bridge rebuild, 2012-2013; 7800 cy of ternary 60:25:15 PC:SC:C-ash in 110 pcf lightweight concrete deck. MoDOT has allowed ternary concrete since 2004, which is commonly used. No load rejections on job—and all results were acceptable.

Up to about 1000 ft of conveyor placed concrete on larger deck placements. →

BRIDGES: St Louis Stan Musial Veterans Memorial Bridge—Opened February 9, 2014

Most of 16,000 cy in pylon concrete used 30:70 PC:SC concrete. All results were acceptable.

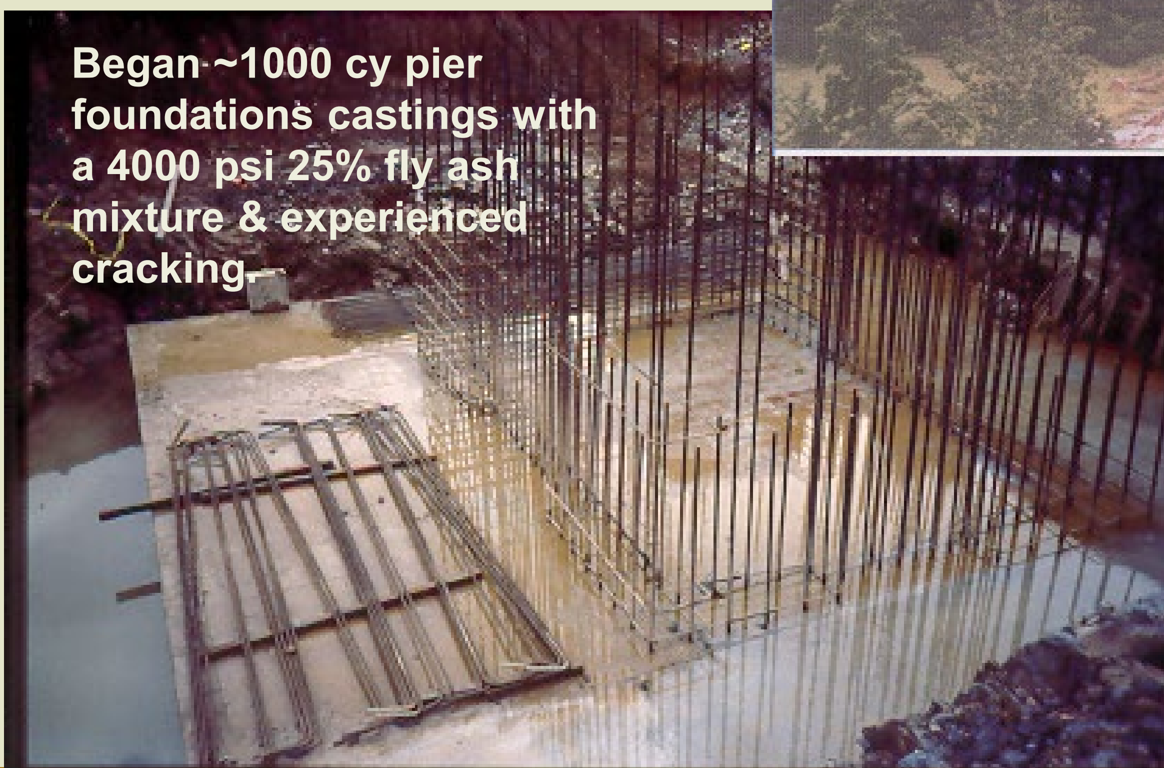
Westphalia province, Germany: 61%+ slag content

A big English bridge (at right) and a big German bridge (at left)

Queen Elizabeth II bridge; Perfleet, England

Smart Highway Bridge
Virginia DOT (2000-2001)

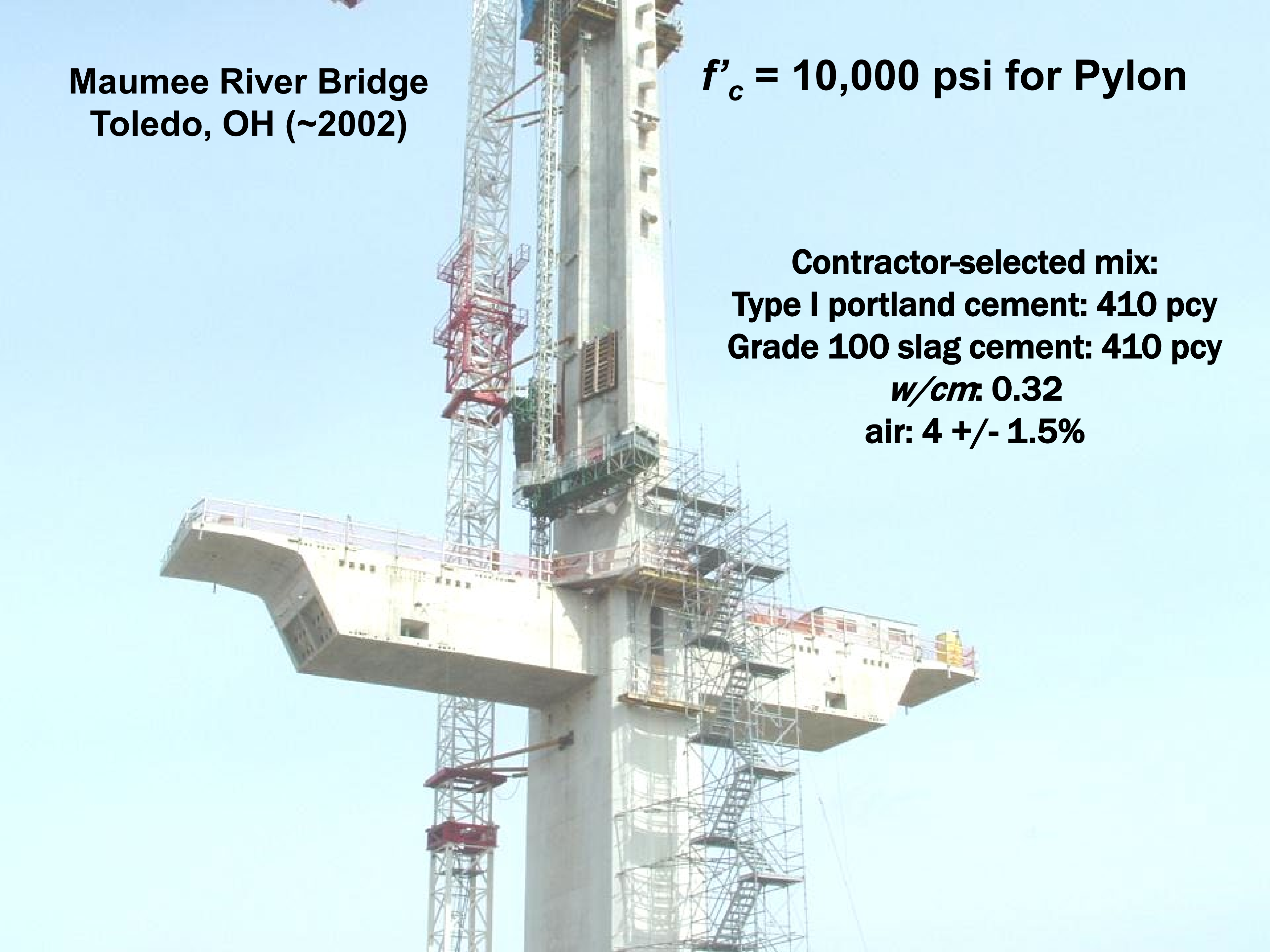
On 3d and 4th pier foundations, used 50% slag cement concrete successfully. Immediately after job, VA changed specifications to allow 70%.



f'_c = 8000 psi pier stems began (piers 1 & 2) with high-cmts. silica fume conc. Some honeycombing. Switched to a lower-cementitious 42% slag mixture. Thereafter, no voids, and achieved ~12,000 psi. Associated roads and decks used slag concrete.

BRIDGES: Spanning the Missouri River along Highway 364 between St Louis and St Charles counties

Page Av. Extension, St. Louis, Mo. Opened fall 2013. 70% slag cement in foundations and pier stems.


Maumee River Bridge
Toledo, OH (~2002)
f'c = 10,000 psi for Pylon
Contractor-selected mix:
Type I portland cement: 410 pcy
Grade 100 slag cement: 410 pcy
w/cm: 0.32
air: 4 +/- 1.5%