Slag Cement: The Other SCM

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Slag Cement

hot slag

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

water

Graphics used by permission of the Slag Cement Association
Slag Cement

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

Graphics used by permission of the Slag Cement Association
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

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 Grade 120
  - 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

<table>
<thead>
<tr>
<th>Concrete application</th>
<th>Slag cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete paving</td>
<td>25 to 50 percent</td>
</tr>
<tr>
<td>Exterior flatwork not exposed to deicer salts</td>
<td>25 to 50 percent</td>
</tr>
<tr>
<td>Exterior flatwork exposed to deicer salts with $w/cm &lt; 0.45$</td>
<td>25 to 50 percent</td>
</tr>
<tr>
<td>Interior flatwork</td>
<td>25 to 50 percent</td>
</tr>
<tr>
<td>Basement floors</td>
<td>25 to 50 percent</td>
</tr>
<tr>
<td>Footings</td>
<td>30 to 65 percent</td>
</tr>
<tr>
<td>Walls and columns</td>
<td>25 to 50 percent</td>
</tr>
<tr>
<td>Tilt-up panels</td>
<td>20 to 50 percent</td>
</tr>
<tr>
<td>Prestressed concrete</td>
<td>20 to 50 percent</td>
</tr>
<tr>
<td>Precast concrete</td>
<td>20 to 50 percent</td>
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<tr>
<td>Concrete blocks</td>
<td>20 to 50 percent</td>
</tr>
<tr>
<td>Concrete pavers</td>
<td>20 to 50 percent</td>
</tr>
<tr>
<td>High strength</td>
<td>25 to 50 percent</td>
</tr>
<tr>
<td>Alkali-silica reaction mitigation</td>
<td>25 to 70 percent</td>
</tr>
<tr>
<td>Sulfate resistance</td>
<td></td>
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<tr>
<td>Type II equivalence</td>
<td>25 to 50 percent</td>
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<tr>
<td>Type V equivalence</td>
<td>35 to 65 percent</td>
</tr>
<tr>
<td>Lower permeability</td>
<td>25 to 65 percent</td>
</tr>
<tr>
<td>Mass concrete</td>
<td>50 to 80 percent</td>
</tr>
</tbody>
</table>

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.
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 °F
  - Minimal change above 85 °F

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

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
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

Sorptivity of 15% MgCl₂ 0.45 w/cm³

Absorption [I] (mm)

Time (s^{1/2})

- OPC
- fly ash
- slag

Type I/II PC

15% F Ash

35% slag

Final Report South Dakota SDOT – SD2002-01
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
Performance - Permeability

**Graph**

- Chloride Concentration (% mass concrete) vs Depth (mm)
- Lines represent:
  - PCC-0.45-MgCl2
  - FAC-0.45-MgCl2
  - SCC-0.45-MgCl2
- Note: 0.1% Chloride

**Source**
Final Report South Dakota SDOT – SD2002-01
Performance - Permeability

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

3% chloride solution, exposure 5/12 months/year

Unpublished Michigan DOT Report
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
Performance - 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**

Performance - ASR

700 lbs/cy cementitious  0.42 – 0.45 w/cm

Based on 1.25% Na₂Oₑq of cement only

After Thomas and Innis 1998
Performance - ASR

700 lbs/cy cementitious 0.42 – 0.45 w/cm

Based on 1.25% Na₂Oₑ₅ of cement + slag

0% slag, 8.85 lb/cy Alkali Content
25% slag, 8.85 lb/cy Alkali Content
35% slag, 8.85 lb/cy Alkali Content
50% slag, 8.85 lb/cy Alkali Content
65% slag, 8.85 lb/cy Alkali Content

after Thomas and Innis 1998
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 C₃A – dilutes the C₃A 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

* Source: ACI 233.R-17 Guide to the Use of Slag Cement in Concrete and Mortar
States Using Slag Cement – June 2018

Slag Cement Availability

Source: Slag Cement Association
Slag Cement Availability

Top Ten States in Slag Cement Consumption – June 2018

Source: Slag Cement Association
THE FOXCONN DILEMMA
FATE OF MANUFACTURING PLANT UNCERTAIN
U.S. Data from 2017 showed a 14 percent increase in slag shipments over 2016 and a 12 percent gain the year before.
Slag Cement Availability

Slag Cement Shipments – Regional 2016 and 2018 Thru June

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 \( \text{Al}_2\text{O}_3 > 11\% \) 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?

ilsutter@mtu.edu
Additional Slides:
Case Studies Available from the Slag Cement Association
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.


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

2014 Algonquin area Il 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)

- 30% slag cement
- Construction segment on west side of Columbus loop.

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

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

Fig above and below—Columbus: curing compound applied; saw-cut joints
Hobart/Merrillville, IN (2012)

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.
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 CO₂
Ohio DOT since 1996
- Hundreds of bridge parapet walls and piers have included 30% slag cement
- Ternary mixes allowed in decks with slag cement

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

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

Began ~1000 cy pier foundations castings with a 4000 psi 25% fly ash mixture & experienced cracking.

\( f'_c = 8000 \text{ psi pier stems began (piers 1 & 2) with high-cmtns. silica fume conc. Some honeycombing. Switched to a lower-cementitious 42% slag mixture. Thereafter, no voids, and achieved ~12,000 psi. Associated roads and decks used slag concrete.} \)
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: $4 +/- 1.5\%$