Optimizing Concrete Pavement Mixes with Slag Cement

WCPA Workshop
February 12th, 2015
Oshkosh, WI
Today’s Topics

- What is slag cement?
  - How it is made
  - How it is used

- What effect does slag cement have on concrete?
  - Environmental impacts
  - Performance characteristics

- Projects
What do you call it?

“Ground granulated blast-furnace slag”
“GGBFS”
“Slag”
“Slag Cement”
What is slag cement?

- Non-metallic product of an iron blast furnace
- Granulated
What is slag cement?

- Non-metallic product of an iron blast furnace
- Granulated
- Ground
- Cementitious material
Chemistry of different materials

- Portland
- Slag
- F Ash
- C Ash
- Silica Fume
- Metakaolin
**Slag: Chemical Properties**

- Similar mineral oxides as portland cement, but in different proportions & phases

<table>
<thead>
<tr>
<th></th>
<th>Slag</th>
<th>Portland Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂, %</td>
<td>32-42</td>
<td>22</td>
</tr>
<tr>
<td>Al₂O₃, %</td>
<td>7-16</td>
<td>4.1</td>
</tr>
<tr>
<td>CaO, %</td>
<td>32-45</td>
<td>66</td>
</tr>
<tr>
<td>MgO</td>
<td>5-15</td>
<td>1.2</td>
</tr>
<tr>
<td>Fe₂O₃, %</td>
<td>0.1-1.5</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Note: Slag cement from a given source tend to be very consistent.
Slag Cement Reactions

- **Slag Cement + Alkalis + Water**
  - From Portland Cement
  - Hydraulic Reaction
  - Calcium-Silicate Hydrate

- **Slag Cement + Ca(OH)\textsubscript{2} + Water**
  - From Portland Cement
  - Calcium-Silicate Hydrate (Additional)
Slag Cement Reaction

Portland Cement
Concrete System

Aggregate

Calcium Silicate Hydrate

Voids and Ca(OH)_2

Aggregate

Portland Cement
Concrete System

Slag Cement

Portland-Slag Cement
Concrete System

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Slag Cement in Concrete - Standard Specifications

- Slag cement as a constituent of blended cement
  - ASTM C595 or AASHTO M 240 Standard Specification for Blended Hydraulic Cements
    - Type IS(35) = 65% PC + 35% Slag
    - Type IT(S25)(P15) = 60% PC + 25% Slag + 15% Pozzolan
    - Type IT(S25)(L10) = 65% PC + 25% Slag + 10% Limestone

- Slag cement as a SCM in concrete
  - ASTM C989 or AASHTO M 302 Standard Specification for Slag Cement for Use in Concrete and Mortar
### Slag-Activity Index and Grades

*(ASTM C989 and AASHTO M 302)*

<table>
<thead>
<tr>
<th>Grade</th>
<th>Min. 28-day Index* % of Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 80</td>
<td>75</td>
</tr>
<tr>
<td>Grade 100</td>
<td>95</td>
</tr>
<tr>
<td>Grade 120</td>
<td>115</td>
</tr>
</tbody>
</table>

Performance benefits of slag cement are achievable with all grades. Trial batches determine appropriate proportions for desired concrete performance characteristics.

* Average of 5 consecutive samples
Slag Cement in Concrete

Typical – binary mixtures:
- 25% to 50% for most general, structural applications, paving, precast and concrete product applications
- Up to 65% for high-durability/strength mixes
- Up to 80% for mass concrete

Typical – ternary mixtures:
- Portland (60-40%)/Slag Cement (25-35%)/Fly Ash (15-25%)
- Portland (72-48%)/Slag Cement (25-45%)/Silica Fume (3-7%)
### Environmental - Life Cycle Inventory for Portland vs. Slag Cements

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>*Portland Cement</th>
<th>*Slag Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Material</td>
<td>lb/ton</td>
<td>2,851</td>
<td>-</td>
</tr>
<tr>
<td>Energy</td>
<td>MBTU /ton</td>
<td>4.57</td>
<td>0.62</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>lb/ton</td>
<td>1,801</td>
<td>42</td>
</tr>
</tbody>
</table>

*These are typical numbers*
Environmental Savings
Material, Energy and Greenhouse Gas

Savings (Percent)

Raw Material
- Ready Mix (35% Slag): 7%
- Ready Mix (50% Slag): 10%
- Precast (50% Slag): 15%
- Mass (80% Slag): 13%

Energy
- Ready Mix (35% Slag): 24%
- Ready Mix (50% Slag): 37%
- Precast (50% Slag): 34%
- Mass (80% Slag): 42%

Carbon Dioxide
- Ready Mix (35% Slag): 31%
- Ready Mix (50% Slag): 46%
- Precast (50% Slag): 45%
- Mass (80% Slag): 59%
Effects of Slag Cement on Concrete Properties

- Plastic Properties
- Setting Time
- Heat of Hydration
- Color
- Strength
- Durability
Reduced Water Demand

- Reduces water demand in concrete, typically by 0% to 5% with slag cement
- Also tends to have better slump retention
Reduced Water Demand

![Graph showing water content vs. slump for 100% Portland and 50% Slag Cement.]

- **100% Portland**
- **50% Slag Cement**

Water required to produce a 4” to 6” slump
Plastic Properties

Slag cement
- Improves pumpability
- Improves workability
- Easier to place, consolidate and finish
Effects on Setting Time

- Type I
- Type IS(25)
- Type IS(25)+15C
- Type IS(25)+15F

Initial Set, hr.

- 50F (10C)
- 73F (23C)
- 92F (33C)
Effect of Slag Cement on Heat of Hydration

Heat of Hydration, cal/g

Percentage of Slag Cement

0 50 60 70 80 90

0 10 20 30 40 50 60 70 80 90
Temperature Rise – 20-ft. (6-m) Mass Placement

Days After Casting

Temperature, °F

Temperature, °C

OPC

50% Slag Cement

70% Slag Cement
- Slag cement enhances the lightness and brightness of concrete
- Lighter concrete
  - provides greater safety on streets and parking lots due to higher reflectivity
  - Lighting requirements may be reduced
  - reflects more light, reducing the “urban heat island” effect
- Slag cement reduces efflorescence by reduced permeability and increasing the consumption of calcium hydroxide and alkalis

Portland vs. Slag cement concrete
Concrete Performance: Binary System Compressive Strength

Lower early strengths, but better later strengths (typical crossover 7 to 14 days)
Compressive Strength Blended Cement – Type IS(25)

Nominal Properties:
- w/cm = 0.45
- 565 pcy (335 kg/m³) cementitious material
- 4-in. (100-mm) slump
- 6.5% air content
- Moist cured 4x8-in. (100x200-mm) cylinders
- Type I strength at 28 days = 6120 psi (42 MPa)

Strength as Percent of Type I at 28 days

Age, days
Compressive Strength Development – Ternary Systems

Nominal Properties
- w/cm = 0.45
- 565 pcy (335 kg/m³) cementitious material
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- Moist cured 4x8-in. (100x200-mm) cylinders

Type I strength at 28 days = 6120 psi (42 MPa)
Effect of Slag Cement on Flexural Strength

- 100% OPC
- 50% OPC/50% Slag Cement

Flexural Strength, % of 28 day OPC

Age, days

7
28

OPC @28 days = 830 psi (5.7 MPa)

Calcium Silicate Hydrate

Aggregate

More

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Durability - Chloride Permeability
ASTM C1202

Charge Passed (Coulombs)

Slag Cement Replacement (%)

W/C = 0.45
W/C = 0.55
W/C = 0.70

More Calcium Silicate Hydrate

Aggregate
Effect of Slag Cement on Sulfate Resistance

Expansion, %

Age, days

ASTM C1012

OPC
25% Slag Cement
50% Slag Cement
180-day Limit
1-year Limit
Slag Cement and Total Concrete Alkali Loading

- Concrete Prisms ~ ASTM C1293
- Sudbury Aggregate

- Control
- 25% Slag
- 35% Slag
- 50% Slag
- 65% Slag

From Thomas and Innis, 1998
Slag Cement and Total Concrete Alkali Loading

- Concrete Prisms ~ ASTM C1293
- Sudbury Aggregate

Control

25% Slag

35% Slag

50% Slag

65% Slag

% Expansion at 2 Years

Concrete Alkali Content, kg/m³

From Thomas and Innis, 1998
Deicer Salt Scaling Resistance
Laboratory vs. Field

In **field** exposures:
- Slag cement performs very well up to 50% slag cement
- “Good” concrete will scale if not finished/cured properly

In **laboratory** studies:
- Scaling tends to increase with higher levels of slag cement or fly ash
- At high levels of slag (>50%) or fly ash (>25%), scaling can reach a high level
### Deicer Salt Scaling Resistance
**ACI 318 – Building Code Requirements**

<table>
<thead>
<tr>
<th>Cementitious Materials</th>
<th>Maximum % of Total Cementitious Materials Deicing Chem. Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag cement, ASTM C989</td>
<td>50</td>
</tr>
<tr>
<td>Fly ash/other pozzolans, ASTM C618</td>
<td>25</td>
</tr>
<tr>
<td>Silica fume, ASTM C1240</td>
<td>10</td>
</tr>
<tr>
<td>Slag + Pozzolan + Silica Fume</td>
<td>50</td>
</tr>
<tr>
<td>Pozzolan + Silica Fume</td>
<td>35</td>
</tr>
</tbody>
</table>
Use of Slag Cement with Portland-Limestone Cement

ASTM C595/AASHTO M 240 (first included in 2012 Editions)

- 5% to 15% limestone
- Type IL(10) = 90% PC + 10% LS
- Type IT(S35)(L10) = 55% PC + 35% Slag + 10% LS
- Same physical requirements as existing C595/M240 cements
- not permitted in moderate sulfate (MS) or high sulfate (HS) resistant blended cements

Note: WisDOT established a nominal replacement level of 10% limestone and allows the same SCM replacement levels as previously instituted
Set Time – Compressive Strength
PC, PLC and Slag Cement

Compressive Strength - PSI

Set Time - minutes

PC Type I
PLC Type IL(10)
PC 30% Slag
IL(10) 30% Slag

1 day
7 day
28 day
Initial Set
PC, PLC, and Slag Cement
C1202 Chloride Ion Penetration

![Bar chart showing chloride ion penetration for different types of cement.](chart.png)
Delaware DOT State Route 1

- Built 1989-2004
- 1 Million cy concrete
- 35-50% slag cement
- Mitigated ASR
- Allowed use of local aggregates
Miami Access Tunnel

- Access between the seaport and I-395 & I-95
- Slag cement used in soil stabilization at 70% and in precast concrete liners at 51%
- Precast ternary mix design
  - 150 year design life
  - Sulfate resistance and chloride penetration resistance
  - $f'c = 6,000 \text{ psi}$
I-70 Mississippi River Bridge Pylons

- St Louis Missouri-Illinois
- 1500-ft span
- 70% Slag cement - mass concrete
  - Exceeded 6000 psi f’c – often > 8000 psi
  - Peak temperature of 119 F (met 150 F limit)
- Triple Bottom Line
  - Enhanced performance
  - Construction efficiency
  - Reduced Environmental Footprint
Considerations for Specifications

- Slag cement grades – performance benefits can be achieved with all grades
- Total concrete alkali specifications for ASR – calculations are based on alkalis from portland cement
- Consider use of ternary (and quaternary) cementitious systems, including portland-limestone cements
- Provide for performance options
Use of Slag Cement for Sustainable and Performance

- Reduced environmental footprint
  - Raw materials
  - Energy
  - Greenhouse Gas

- Improves concrete performance
  - Fresh Properties
  - Heat of Hydration
  - Long-term Strength
  - Durability
Thank You!

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