Performance of Concrete Made With Slag Cement and Portland-Limestone Blended Cement

Philadelphia, Pennsylvania
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Today’s Discussion

- The materials
  - Slag cement
  - Portland-limestone cement

- Use in concrete
  - Individually
  - Together

- Conclusions
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
Use of Slag Cement in Concrete
Standard Specifications

Slag cement as an SCM in concrete
- AASHTO M302 or ASTM C989 Standard Specification for Slag Cement for Use in Concrete and Mortars
  - Specs define Grades 80, 100, 120

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)(P10) = 65% PC + 25% Slag + 10% Pozzolan
Effect of Slag Cement on Concrete

- Enhanced performance
  - Strength
  - Durability
  - Reduced Heat

- Reduced environmental footprint
  - Raw materials
  - Energy
  - Greenhouse gas
Environmental Savings
Material, Energy and Greenhouse Gas

<table>
<thead>
<tr>
<th></th>
<th>Raw Material</th>
<th>Energy</th>
<th>Carbon Dioxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ready Mix (35% Slag)</td>
<td>7%</td>
<td>24%</td>
<td>31%</td>
</tr>
<tr>
<td>Ready Mix (50% Slag)</td>
<td>10%</td>
<td>34%</td>
<td>44%</td>
</tr>
<tr>
<td>Precast (50% Slag)</td>
<td>15%</td>
<td>37%</td>
<td>45%</td>
</tr>
</tbody>
</table>
Compressive Strength – Slag Cement

- **7 Day**
  - 100% Portland
  - 25% Slag Cement
  - 50% Slag Cement

- **28 Day**
  - 100% Portland
  - 25% Slag Cement
  - 50% Slag Cement

Compressive Strength (psi)
Compressive Strength Blended Cement – Type IS(25)

**Nominal Properties**
- \( w/cm = 0.45 \)
- 565 pcy (335 kg/m\(^3\)) 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)
Durability - Chloride Permeability
ASTM C1202

- Slag Cement Replacement (%)
- Charge Passed (Coulombs)

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

High
Moderate
Low
Very Low
Effect of Slag Cement on Sulfate Resistance

- Expansion, % vs. Age, days
  - OPC
  - 25% Slag Cement
  - 50% Slag Cement
  - 180-day Limit
  - 1-year Limit

ASTM C1012
Slag Cement and Total Concrete Alkali Loading

- Concrete Prisms ~ ASTM C1293
- Sudbury Aggregate

% Expansion at 2 Years

Concrete Alkali Content, kg/m³

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

- Concrete Prisms ~ ASTM C1293
- Sudbury Aggregate

From Thomas and Innis, 1998
Effect of Slag Cement on Heat of Hydration

Heat of Hydration, cal/g

Percentage of Slag Cement

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

- Temperature, F
- Temperature, C
- Days After Casting

- OPC
- 50% Slag Cement
- 70% Slag Cement
What is Portland-Limestone Cement?

- **ASTM C595/M240 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 for existing C595/M240 cements
  - More than 5% limestone not permitted in moderate sulfate (MS) or high sulfate (HS) resistant blended cements
Performance of Type IL Cement in Concrete

- Comparable performance to Type I portland cement
  - Without SCMs
  - With SCMs

- Reduced environmental footprint
  - Raw materials
  - Energy
  - Greenhouse gas
### Environmental Benefits

#### Energy Reduction*

<table>
<thead>
<tr>
<th></th>
<th>10%</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (million BTU)</td>
<td>443,000</td>
<td>664,000</td>
</tr>
<tr>
<td>Electricity (kWh)</td>
<td>6,970,000</td>
<td>10,440,000</td>
</tr>
</tbody>
</table>

#### Emissions Reduction*

<table>
<thead>
<tr>
<th></th>
<th>10%</th>
<th>15%</th>
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</thead>
<tbody>
<tr>
<td>SO$_2$ (lb)</td>
<td>581,000</td>
<td>870,000</td>
</tr>
<tr>
<td>NO$_x$ (lb)</td>
<td>580,000</td>
<td>870,000</td>
</tr>
<tr>
<td>CO (lb)</td>
<td>104,000</td>
<td>155,000</td>
</tr>
<tr>
<td>CO$_2$ (ton)</td>
<td>189,000</td>
<td>283,000</td>
</tr>
<tr>
<td>Total hydrocarbon, THC (lb)</td>
<td>14,300</td>
<td>21,400</td>
</tr>
</tbody>
</table>

* Per million tons cement
Set Time – Compressive Strength

<table>
<thead>
<tr>
<th></th>
<th>Compressive Strength - PSI</th>
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<tbody>
<tr>
<td>PC Type I</td>
<td>4000</td>
</tr>
<tr>
<td>PLC Type IL(10)</td>
<td>5000</td>
</tr>
<tr>
<td>PC 30% Slag</td>
<td>6000</td>
</tr>
<tr>
<td>IL(10) 30% Slag</td>
<td>7000</td>
</tr>
</tbody>
</table>

Set Time - minutes

- PC Type I: 7 day
- PLC Type IL(10): 5 day
- PC 30% Slag: 3 day
- IL(10) 30% Slag: 3 day

Initial Set

1 day 7 day 28 day Initial Set
Relative Resistance to Chloride Ion Penetration ASTM C1202

Coulombs – 28 days

Type I-II

Type IL

50IL/50S

500 lb cement

564 lb cement
ASR – Accelerated Mortar Bar Test (C1567)

Expansion, %

Control
30% Slag
40% Slag
50% Slag

GU
GUL

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

0
5
10
15
20
25
30

Exposure, days

Control
20% Fly Ash
25% Fly Ash
30% Fly Ash

GU
GUL

14d limit

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

0
5
10
15
20
25
30
C595/M240 does not permit more than 5% limestone in MS or HS blended cements

- Potential for thaumasite form of sulfate attack – deterioration of CSH matrix exposed to sulfates and carbonates in wet cool conditions
- Research indicates that appropriate use of slag cement, Class F fly ash, or metakaolin can effectively mitigate the potential for the thaumasite form of sulfate attack
- CSA A3001 permits blended cements to contain 5% to 15% limestone if:
  - They also contain at least 40% slag, 25% Class F fly ash, 15% metakaolin, or a combination of 5% silica fume and either 25% slag or 20% Class F fly ash
  - ASTM C1012 bars stored at 5°C must have expansions of less than 0.10% at 18 m (with a supplemental limit of 0.10% at 24 m if the increase in expansion between 12 and 18 m exceeds 0.03%)
Slag cement used with portland cement will reduce the environmental footprint of concrete and can enhance key performance characteristics, including strength and durability.

Portland-limestone cement, Type IL will reduce the environmental footprint of concrete and can provide comparable characteristics to a Type I portland cement.

Concrete mixtures containing slag cement and Type IL or blended Type IT(S)(L) will further reduce environmental impact and can provide desired strength and durability performance.
Use of slag cement, Class F fly ash, metakaolin, or combinations of silica fume and slag cement or Class F fly ash with Type IL cements or in Type IT cements that contain more than 5% limestone is a potential means of addressing potential for thaumasite form of sulfate attack.
Observations/Recommendations

Under ASTM and AASHTO terminology Type IL cements are considered binary blended cements. Therefore mixtures of Type IL cement with SCM’s are by definition ternary systems. A specification that prohibits ternary systems in effect precludes the use of a very effective option for providing durable concrete and minimizing environmental impact.

Consider incorporating ternary systems in state specifications.

Include performance-based options in specifications.
Thank You!

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