Portland-Limestone Cements: History, Performance, and Specifications

Paul D. Tennis, Ph.D.
Portland Cement Association
Today’s Objectives

- What is a portland-limestone blended cement
- History
- Environmental performance
- Concrete performance
- Changes to the specifications
Portland-Limestone Cement

- Why? Provides an option to implement proven technology to obtain desired performance and improve sustainability of concrete
What is Portland-Limestone Cement?

- ASTM C595 and AASHTO M 240 Blended Cement
- Type IL or Type IT with limestone
- 5% to 15% limestone
HISTORY
History of Limestone in Cements

- 1965 Cement with 20% limestone in Germany for specialty applications
- 1979 French cement standards allows limestone additions.
- 1983 CSA A5 allows up to 5% limestone in portland cement
- 1990 $15 \pm 5\%$ limestone blended cements routinely used in Germany
- 1992 UK specs allows up to 20% in limestone cement
- 2000 EN 197-1 allows 5% MAC (typ. limestone) in all 27 common cements,
History of Limestone in Cements

- 2000 EN 197-1 creates CEM II/A-L (6-20%) and CEM II/B-L (21-35%)
- 2004 ASTM C150 allows 5% in Types I-V
- 2006 CSA A3001 allows 5% in other Types than GU
- 2007 AASHTO M85 allows 5% in Types I-V
- 2008 CSA A3001 includes PLC containing 5%-15% limestone
European Cement Use

Cement Types in Europe (%)

- CEM V - Composite Cement
- CEM IV - Pozzolanic
- CEM III - Blast furnace slag
- CEM II - Portland-composite
- CEM II - Portland-limestone
- CEM II - Portland-fly ash
- CEM II - Portland-pozzolana
- CEM II - Portland-slag
- CEM I - Portland

Cembureau data
ENVIRONMENTAL BENEFITS
Barcelo, Kline and Walenta, 2012
from Ashby (2009)
Energy to Produce Cement

![Energy usage graph showing a decline from 1965 to 2015](image)
# Environmental Benefits

<table>
<thead>
<tr>
<th></th>
<th>10%</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Reduction</strong>*</td>
<td></td>
<td></td>
</tr>
<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>
<tr>
<td><strong>Emissions Reduction</strong>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₂ (lb)</td>
<td>581,000</td>
<td>870,000</td>
</tr>
<tr>
<td>NOₓ (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>CO₂ (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
Environmental Benefits

- Plant 1
  - Portland cement: 0.8 kg CO₂/kg cement
  - Portland-limestone cement: 0.7 kg CO₂/kg cement

- Plant 2
  - Portland cement: 0.8 kg CO₂/kg cement
  - Portland-limestone cement: 0.7 kg CO₂/kg cement

- Plant 3
  - Portland cement: 0.8 kg CO₂/kg cement
  - Portland-limestone cement: 0.7 kg CO₂/kg cement
Why 15%?
How Limestone Works

- Particle packing
  - Improved particle size distribution
- Nucleation
  - Surfaces for precipitation
- Chemical reactions
  - Only a small amount, but...
How Limestone Works

- Particle packing
  - Improved particle size distribution
- Nucleation
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How Limestone Works

- Particle packing
  - Improved particle size distribution
- Nucleation
  - Surfaces for precipitation
- Chemical reactions
  - Only a small amount, but...
ASTM AND AASHTO UPDATES
Process

- JAAHTG reviewed concept January 2010
  - Technical information from Europe and Canada considered
- Presented concept to AASHTO TS3a and ASTM C01.10 summer 2010
- TS3a ballot in 2011; SOM ballot December 2011.
- C01.10 ballot April 2011; C01 ballot October 2011
- Ballot items passed; 2012 AASHTO M240 and ASTM C595 published
AASHTO M240 & ASTM C595
Requirements

- **Type IL**—Portland-limestone blended cement
  - Example: Type IL(10) = 10% limestone

- **Type IT**—Ternary blended cement with limestone
  - Example 1: Type IT(L12)(P10) = 12% limestone and 10% pozzolan
  - Example 2: Type IT(S15)(L10) = 15% slag and 10% limestone

- Limestone content 5% to 15%
AASHTO M240 & ASTM C595 Requirements

- Same physical requirement as existing C595/M240 cement types
- Chemical requirements – sulfate content, LOI
- Sulfate resistance – no MS or HS in initial specifications
- Limestone characteristics – CaCO$_3$, MBI, TOC
<table>
<thead>
<tr>
<th></th>
<th>IP (LH), IL(LH), IT(L≥S)(LH)</th>
<th>IP(LH), IL(LH), IT(L≥P)(LH)</th>
<th>IS(≥70), IT(S≥70)</th>
<th>IS (&lt; 70) (HS), IT(P&gt;S&lt;70)(HS)</th>
<th>IS (&lt; 70) (MS), IT(P&gt;S&lt;70)(MS)</th>
<th>IP(MS), IT(P≥S)(MS)</th>
<th>IS (&lt; 70) (MS), IT(P&gt;S&lt;70)(MS)</th>
<th>IP(MS), IT(P≥S)(MS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
</tr>
<tr>
<td>Autoclave exp, max, %</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Autoclave contr, max %</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Vicat test: minutes, not less than hours, not more than</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Air content of mortar, volume %</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>IP</td>
<td>IS (&lt;70)</td>
<td>IL</td>
<td>IT (P ≥ S)</td>
<td>IT (P &gt; L)</td>
<td>IT (L ≥ S)</td>
<td>IT (L ≥ P)</td>
<td>IT (L &lt; S &lt; 70)</td>
<td>IT (P &lt; S &lt; 70)</td>
</tr>
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</tr>
<tr>
<td>IP</td>
<td>IS (&lt;70)</td>
<td>MS</td>
<td>IP</td>
<td>IT (P ≥ S)</td>
<td>IT (P &gt; L)</td>
<td>IT (L ≥ S)</td>
<td>IT (L ≥ P)</td>
<td>IT (L &lt; S &lt; 70)</td>
</tr>
<tr>
<td>IP</td>
<td>IS (&lt;70)</td>
<td>HS</td>
<td>IP</td>
<td>IT (P ≥ S)</td>
<td>IT (P &gt; L)</td>
<td>IT (L ≥ S)</td>
<td>IT (L ≥ P)</td>
<td>IT (L &lt; S &lt; 70)</td>
</tr>
</tbody>
</table>

Compressive strength, min., MPa (psi):

| 3 days | 13.0 | 11.0 | 11.0 | ... | ... |
| 3 days | (1890) | (1600) | (1600) | ... | ... |
| 7 days | 20.0 | 18.0 | 18.0 | 5.0 | 11.0 |
| 7 days | (2900) | (2610) | (2610) | (720) | (1600) |
| 28 days | 25.0 | 25.0 | 25.0 | 11.0 | 21.0 |
| 28 days | (3620) | (3620) | (3620) | (1600) | (3050) |

Heat of Hydration, max., kJ/kg (cal/g):

<p>| 7 days | 290 | 290 | 290 | ... | 250 |
| 7 days | (70) | (70) | (70) | ... | (60) |
| 28 days | 330 | 330 | 330 | ... | 290 |
| 28 days | (80) | (80) | (80) | ... | (70) |</p>
<table>
<thead>
<tr>
<th></th>
<th>IP</th>
<th>IS (&lt;70)</th>
<th>IL</th>
<th>IT(P≥S)</th>
<th>IT(P&gt;L)</th>
<th>IT(L≥S)</th>
<th>IT(L≥P)</th>
<th>IT(L&lt;S&lt;70)</th>
<th>IT(P&lt;S&lt;70)</th>
<th>IS (&gt;=70)</th>
<th>IT(S&gt;=70)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IS (&lt;70) (MS), IP(MS), IT(P≥S)(MS)</td>
<td>IS (&lt;70) (MS), IT(P&lt;S&lt;70)(MS)</td>
<td>IS (&lt;70) (HS), IP (HS), IT(P≥S)(HS)</td>
<td>IS(&gt;=70), IT(S&gt;=70)</td>
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<tr>
<td>Water req. max %</td>
<td>...</td>
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<tr>
<td>Drying shrinkage, max, %</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<tr>
<td>Mortar expansion, max, %:</td>
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<tr>
<td>14 days</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>8 weeks</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>Sulfate resistance, expansion, max, %:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 180 d</td>
<td>0.10</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 1 year</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Chemical Requirements for Blended Cements

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>IS(&lt;70), IT(P&lt;S&lt;70), IT(L&lt;S&lt;70)</th>
<th>IS(≥70), IT(S≥70)</th>
<th>IP, IT(P≥S), IT(P&gt;L)</th>
<th>IL, IT(L≥S), IT(L≥P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO, max, %</td>
<td>. . .</td>
<td>. . .</td>
<td>6.0</td>
<td>. . .</td>
</tr>
<tr>
<td>SO₃, max, %</td>
<td>3.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>S²⁻, max, %</td>
<td>2.0</td>
<td>2.0</td>
<td>. . .</td>
<td>. . .</td>
</tr>
<tr>
<td>Insol. res. max, %&lt;sup&gt;C&lt;/sup&gt;</td>
<td>1.0</td>
<td>1.0</td>
<td>. . .</td>
<td>. . .</td>
</tr>
<tr>
<td>LOI, max, %</td>
<td>3.0&lt;sup&gt;D&lt;/sup&gt;</td>
<td>4.0&lt;sup&gt;D&lt;/sup&gt;</td>
<td>5.0&lt;sup&gt;D&lt;/sup&gt;</td>
<td>10.0</td>
</tr>
</tbody>
</table>

<sup>C</sup> Insol res max does not apply to ternary blended cements.

<sup>D</sup> For ternary blended cements with limestone LOI max = 10%.
# Requirements for Limestone for Use in Blended Cements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Test Method</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO₃ content</td>
<td>C114/T105</td>
<td>Min. 70%</td>
</tr>
<tr>
<td>Methylene blue index</td>
<td>See Annex A2</td>
<td>Max. 1.2 g/100g</td>
</tr>
<tr>
<td>Total organic carbon</td>
<td>See Annex A3</td>
<td>Max. 0.5%</td>
</tr>
</tbody>
</table>
Limestone Testing

A2. METHYLENE BLUE INDEX TEST FOR LIMESTONE

A2.1 Scope

A2.1.1. This annex describes the laboratory procedures for the quantitative determination of methylene blue dye adsorption index of limestone for use as an ingredient in blended cement.

A2.1.2. The text of this annex references notes and footnotes which provide (excluding those in tables and figures) shall not be considered as requirements of this annex.

A2.1.3. Units—The values stated in SI units are to be regarded as standard.

A2.1.4. This annex does not purport to address all of the safety concerns related to the use of this standard, establishing appropriate safety and health practices, or regulatory limitations prior to use.

A2.2 Summary of test

A2.2.1. The sample is reduced to a fine powder prior to testing. Increase successively to a suspension of the prepared test portion in water. The absorbance of each dilution of solution by carrying out a blank test on filter paper to detect the free dye is confirmed, the methylene blue index value (MBI) is calculated and of the sample tested.

A2.3 Significance and Use

A2.3.1. This annex provides a means to determine the amount of methylene blue index of limestone. Methylene blue dye is preferentially adsorbed by clay minerals that are adsorbed on related to the clay type and content. Certain clays may increase the cement's reactivity as it is added to the limestone as an ingredient in blended cement.

A2.4 Apparatus

A2.4.1. The equipment and materials, including the temperature and humidity control device, shall meet the requirements of C511, unless otherwise specified.

A2.4.2. The following equipment shall be included to perform this test:
- burette, with capacity of either 100 mL or 50 mL and graduated at 0.1 mL intervals;
- heating mantle for maintaining a water bath temperature of 45°C ± 5°C;
- magnetic stirrer;
- thermometer; and
- oven, able to maintain a temperature of 45°C ± 5°C;

A3. TOTAL ORGANIC CARBON CONTENT OF LIMESTONE

A3.1 Scope

A3.1.1. This annex specifies the laboratory procedures for the quantitative determination of the total organic carbon content of limestone for use as an ingredient in blended cement.

A3.1.2. The text of this annex references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of this annex.

A3.1.3. Units—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this annex.

A3.1.4. This annex does not purport to address all of the safety concerns related to the use of this standard, establishing appropriate safety and health practices, and/or regulatory limitations prior to use.

A3.2 Summary of test

A3.2.1. Total organic carbon is determined either on a sample from which the inorganic carbon has been removed through hydrochloric acid extraction or by difference of inorganic carbon from total carbon.

A3.3 Significance and Use

A3.3.1. This annex provides a means to determine the total organic carbon content of a sample of finely ground limestone. The organic carbon content of a limestone used as an ingredient in cement may increase the air-entraining agent dosage required to achieve adequate air content in concrete. The specification places a limit on the total organic carbon content of limestone permitted as an ingredient in blended cement.

A3.4 Apparatus

A3.4.1. The equipment shall meet the requirements of Specification C511, unless otherwise specified.

A3.4.2. The following equipment shall be included to perform this test:
- analytical balance, precision = 0.1 mg;
- beakers, 500 mL;
- vacuum flask, 1000 mL;
- glass stirrer 40 mm diameter, and porosity = G4;
- magnetic stirrer;
- magnetic stirrer bar;
- oven, able to maintain a temperature of 45°C ± 5°C;
- micro-pipette;
Summary

- Portland-limestone blended cements
  - 5% to 15% limestone
  - History of use: Europe, Canada, US
- Mechanisms
- An option to make greener concrete
State-of-the-Art Report on Use of Limestone in Cements at Levels of up to 15%

by P. D. Tennis, M. D. A. Thomas, and W. J. Weiss

The Durability of Concrete Produced with Portland-Limestone Cement: Canadian Studies

by Michael D. A. Thomas and R. Doug Hooton
Portland Limestone Blended Cement in ASTM C595 and AASHTO M240
Presented to ASTM C01.10 December 2010

Thank you!

PTennis@cement.org
North American PLC Pavements
Field Applications in Canada, Utah and Colorado

Todd Laker, Holcim (US) Inc.
Brooke Smartz, Holcim (US) Inc.
Portland-Limestone Cement Paving Projects

- +125 miles of concrete paving in Colorado and Utah
CDOT and UDOT Specifications

- Allow portland-limestone cements that meet ASTM C1157 performance specification for GU (General Use), MS (Moderate Sulfate Resistance) and HS (High Sulfate Resistance)

- Supplementary cementitious materials required for applications that require resistance for sulfate attack and/or alkali silica reactivity for both ASTM C150 and ASTM C1157 cements
Verifying Portland Limestone Cement Durability

- Holcim ASTM C595 (Type IL) or ASTM C1157 cements are tested for durability performance. Tests generally include:
  
  ‣ Fresh & Hardened concrete properties
    - Requirements are met through concrete mix design – ASTM
  
  ‣ Sulfate Resistance - ASTM C1012
  
  ‣ Alkali-Silica Reactivity - ASTM C1260/1567
  
  ‣ Freeze Thaw & Deicer Scaling Resistance - ASTM C666 & C672
  
  ‣ Shrinkage – ASTM C157
  
  ‣ Chloride Ion Penetration – ASTM C1202
## How do Portland-Limestone Cements compare?

<table>
<thead>
<tr>
<th>ASTM Designation</th>
<th>PLC vs C150</th>
<th>PLC vs C150</th>
<th>PLC vs C150</th>
<th>PLC vs C150</th>
<th>PLC vs C150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength 28D (C39)</td>
<td>Equal</td>
<td>Better</td>
<td>Better</td>
<td>Better</td>
<td>Equal</td>
</tr>
<tr>
<td>Sulfate (C1012)</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
</tr>
<tr>
<td>ASR (C1260/C1567)</td>
<td>Better</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
</tr>
<tr>
<td>Freeze-Thaw (C666)</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
</tr>
<tr>
<td>Deicer Scaling (C672)</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
</tr>
<tr>
<td>Shrinkage (C157)</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
</tr>
<tr>
<td>Permeability (C1202)</td>
<td>Slightly Better</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
<td>Equal</td>
</tr>
</tbody>
</table>
How do Portland-Limestone cements perform in the field?

- Equal or improved to C150 cements
  - Strength
  - Set time
  - Water demand
  - Compatibility with fly ash
  - Compatibility with admixtures
- Improved finishability
- Lower environmental impact
Devil’s Slide, Utah Cements

- Type V clinker
  - $C_3A < 5\%$
- ASTM C150 Type II/V
  - High sulfate resistance
    - $C_3A < 5\%$
  - <5\% limestone per ASTM C150
  - Naeq <0.60\%
- ASTM C1157 Type GU/MS
  - General use/Moderate sulfate resistance
    - ASTM C1012, sulfate performance test
  - 10\% limestone
Utah PLC Case Studies

Performance & Lower Environmental Impact
Lost Creek Road Morgan, Utah

- Rural County Road
  - Constructed 2009
  - Major Truck Traffic
  - Construction Limitations
  - Mountain weather issues

- Performance System
  - 10% Limestone Cement
  - 20% Class F fly ash

- Compressive strength
  - design 4000 psi, average 5120 psi

- Flexural strength
  - design 650 psi, average 720 psi
104th South, Salt Lake City, Utah

- Pooled Fund Ternary Study (2009)
  - University of Utah* (Tikalsky)
  - 10% Limestone Cement
  - 25% Class F Fly ash
- Single days production
- Control Section Strength*
  - Compressive 4454 psi
  - 28Day
- Actual Test Section Strength*
  - Compressive 5396 psi
  - 28Day
SR 201, Salt Lake City, Utah

- Eastbound lanes paved August 2009 with ASTM C150 Type II/V

- Westbound lanes paved October 2009 with ASTM C1157 10% portland-limestone cement
  - Both mixes contained 25% Class F fly ash

- Eastbound Strength
  - Compressive ~5000 psi
  - Average Concrete Temp ~70 F

- Westbound Strength
  - Compressive ~4500 psi
  - Average Concrete Temp ~50 F
UTA FrontRunner South
Salt Lake City to Provo, Utah
UTA FrontRunner South
Salt Lake City to Provo, Utah

- Keystone Concrete Masonry Units (CMU)
  - 10% Limestone Cement
  - 15% Class F Fly ash
- 350,000 square feet or retaining wall
- Block on the project
  Averages:
  - 28 day Compressive Strength 6,500 psi
  - Absorption of 5.3%
- 37 Foot Tall Retaining Wall
  - 55 block courses above grade
  - 10 block courses below grade
Portland, Colorado Cements

- **Type II clinker**
  - $C_3A < 8\%$

- **ASTM C150 Type I/II**
  - General use/Moderate sulfate resistance
    - $C_3A < 8\%$
    - $<5\%$ limestone per ASTM C150
    - Naeq $> 0.70\%$

- **ASTM C595 Type IP(HS)**
  - $25\%$ Class F fly ash

- **ASTM C1157 Type GU/MS**
  - General use/Moderate sulfate resistance
    - ASTM C1012, sulfate performance test
    - $10\%$ limestone
Colorado PLC Case Studies

Performance & Lower Environmental Impact
City of Denver Concrete Paving
40th & Havana and Holly Street
City of Denver Concrete Paving

- Aligns with Denver Greenprint Program
  - 20% Class C fly ash
  - No noticeable performance differences
  - Winter construction
  - 25% Class C fly ash
City of Denver Concrete Paving
Central Park Boulevard
DIA Pena Boulevard
US HW 287 Near Lamar, CO

- 7 Miles PCCP (2008)
  - Hot dry summer construction
- Ports to Plains US Highway route
  - Heavy truck traffic
- 20% Class F fly ash
- 695 psi average 28-day flexural strength
- Contractor received quality incentive per CDOT specifications
- Used in concrete paving on a regular basis in Colorado
US HW I-25 Near Castle Rock, CO
US HW I-25 Near Castle Rock, CO

- 5 Miles PCCP (2008)
- Major Interstate Highway
- 20% Class F fly ash
- 720 psi average 28-day flexural strength
- Contractor received quality incentive per CDOT specifications
- Used in concrete paving on a regular basis in Colorado
Canada PLC Case Studies


**QEW Barrier Wall GUL Trial**

- First GUL use for a public wall section in Canada in 2009
- Various durability tests will be carried out at UofT
- Initial strength test results show comparable performance of GU and GUL
- GU & GUL AVS results similar
- RCPT similar in cylinder but GUL higher in core samples (@ 62d 1600 vs. 1400 C)
- Similar scaling test results
Keep in mind…

- No cement or scm’s can offset low quality concrete

- Durable concrete depends on:
  - Appropriate mixture proportions
  - Lower w/cm
  - Air entrainment in F/T conditions
  - Proper placement
  - Curing
  - Maintenance

- When good practices are followed, concrete will attain its expected service life
Projects demonstrate concrete made with portland-limestone cements are readily constructible and can easily achieve specified strength requirements.

Durability testing shows similar or improved performance to ASTM C150 cements.

Portland-limestone cements can provide performance and lower environmental impact.
Over 125 miles of paving in Colorado and Utah
Thank You!

Any Questions?

Todd Laker, LEED AP
Holcim (US) Inc.
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Brooke Smartz, LEED AP
Holcim (US) Inc.
brooke.smartz@holcim.com or 303-716-5288
Performance of PLC Concrete: Fresh, Hardened and Durability Properties

Michael Thomas
University of New Brunswick

TRB Webinar: Portland Limestone Cement (PLC) - A Technology to Improve the Sustainability of Concrete Pavements – November 13, 2012
Portland Cement (PC) Manufacture

CaCO₃ (limestone)
2SiO₂•Al₂O₃ (clay, shale)
Fe₂O₃ (iron oxide)
SiO₂ (silica sand)

Calcination: CaCO₃ → CaO + CO₂
~ 0.50 ton CO₂ per 1.0 ton of clinker

Fuel:
~ 0.25 to 0.65 ton CO₂ per ton of clinker

Kiln

~ 1450°C or 2640°F

CaO•SO₃•2H₂O
Gypsum + Clinker

3CaO•SiO₂
2CaO•SiO₂
3CaO•Al₂O₃
4CaO•Al₂O₃•Fe₂O₃

Finished cement interground
Cement production accounts for approximately 7% to 8% of CO\textsubscript{2} globally (Mehta, 1998) ...

... and approximately 2.8% of CO\textsubscript{2} emissions in Canada (Neitzert, 1997)

Calcination: \( \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \uparrow \) (gas)

Energy: \( C + O_2 \rightarrow \text{CO}_2 \uparrow \) (gas)

www.cement.ca
Portland Limestone Cement (PLC) Manufacture

CaCO₃ (limestone)
2SiO₂•Al₂O₃ (clay, shale)
Fe₂O₃ (iron oxide)
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Kiln

~ 1450°C or 2640°F

CaSO₄•2H₂O
Gypsum + Clinker

3CaO•SiO₂
2CaO•SiO₂
3CaO•Al₂O₃
4CaO•Al₂O₃•Fe₂O₃

Finished cement
interground
Tests carried out with Canadian materials: 2007-10

• Portland-limestone cements (PLC) were produced in different grinding circuits with various clinkers ($C_3A$ from 4.5 to 12%) and limestones.
• Amount of limestone varied between 3 and 19% (to keep within limits, the real CSA PLC max. will be ~13%).
• Standard mortar tests and chemical analyses were performed on the different PLCs.
• Concrete with various $w/cm$ ratio’s 0.35 to 0.80 were produced. The cement contents in the mixed varied between 225 and 420 kg/m$^3$
• Concrete tests with different PLC’s (10 to 22 %LS) and various amounts of slag (15, 25, 30%) and fly ash (20%) were performed
• Slump, slump retention and air were measured
• Durability tests were performed, e.g. RCP, freeze/thaw, salt scaling, shrinkage, sulfate resistance, and ASR
• Testing conducted by cement companies and universities
• **Field trials**
Durability of PLC Concrete: Canadian Studies

- PLC with up to 15% limestone - equivalent performance as portland cement from the same clinker
- Equivalent performance achieved by increasing Blaine by 100 to 120 m²/kg
- Performance in this study was evaluated based on:
  - Strength
  - Resistance to freeze-thaw and de-icer salt scaling
  - “Chloride permeability” and chloride diffusion.
  - Alkali-silica reaction
## CSA A3001-08 Types of Hydraulic Cement

<table>
<thead>
<tr>
<th>Portland cement type</th>
<th>Blended hydraulic cement type*</th>
<th>Portland-limestone cement type†‡</th>
<th>Name§</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU</td>
<td>GUb</td>
<td>GUL</td>
<td>GULb</td>
</tr>
<tr>
<td>MS</td>
<td>MSb</td>
<td>–</td>
<td>MSLb</td>
</tr>
<tr>
<td>MH</td>
<td>MHb</td>
<td>MHL</td>
<td>MHLb</td>
</tr>
<tr>
<td>HE</td>
<td>HEb</td>
<td>HEL</td>
<td>HELb</td>
</tr>
<tr>
<td>LH</td>
<td>LHb</td>
<td>LHL</td>
<td>LHLb</td>
</tr>
<tr>
<td>HS</td>
<td>HSb</td>
<td>–</td>
<td>HSLb</td>
</tr>
</tbody>
</table>

*The suffix “b” indicates that the product is a blended hydraulic cement.
†The suffix “L” indicates that the product is portland-limestone cement.
‡Portland-limestone cements should not be used in an environment subjected to sulphate exposure as defined in Table 3 of CAN/CSA-A23.1.

New in 2008 → Blended PLC – 2010 Amendment

**PLC is produced to provide equivalent performance to PC in Canada**

So requirements for Type GUL (up to 15% limestone) same as Type GU (< 5%)

## CSA A23-09 Use of Portland Cement in Concrete

- Portland limestone cement is permitted for use in all classes of concrete except for sulfate exposure classes (S-1, S-2, S-3)
Beneficial Effects of Limestone Addition

- Limestone (primarily CaCO₃) chemically reacts with C₃A to form carboaluminates—at least at replacements of 5-10%

\[
C₃A + C\overline{C} + xH \xrightarrow{hydration} C₃A \cdot C\overline{C} \cdot H_x
\]

- Finer limestone particles fill the voids between clinker particles improving the grain packing of cement

- Fine limestone particles as nucleation sites for hydration products at early hydration ages accelerating the hydration and consequently improving the early strength

Limestone is not totally inert!
Testing in Canada indicates that the Blaine of PLC needs to be increased by approx 100 – 120 m²/kg compared with PC to obtain equivalent performance.
To achieve equivalent performance, PLC is ground to a higher fineness.
Limestone fineness in the interground product is significantly finer than the clinker fraction.

- D_{50} Limestone: 7 to 10 μm
- D_{50} Clinker: 15 μm
## Cementitious Materials used in Field Trials

<table>
<thead>
<tr>
<th>CSA Type</th>
<th>Description</th>
<th>ASTM Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU</td>
<td>“General Use” portland cement, <strong>PC</strong></td>
<td>C 150 Type I</td>
</tr>
<tr>
<td>GUL</td>
<td>“General Use” portland limestone cement, <strong>PLC</strong></td>
<td>C 1157 Type GU</td>
</tr>
<tr>
<td>GUb-15S</td>
<td>“General Use” blended hydraulic cement</td>
<td>C 595 Type IS</td>
</tr>
<tr>
<td>GULb-15S</td>
<td>“General Use” blended limestone cement</td>
<td>C 1157 Type GU</td>
</tr>
<tr>
<td>F</td>
<td>Fly ash &lt; 8% CaO</td>
<td>C 618 Class F</td>
</tr>
<tr>
<td>CI</td>
<td>Fly ash 8-20% CaO</td>
<td>C 618 Class F</td>
</tr>
<tr>
<td>S</td>
<td>Ground granulated blastfurnace slag</td>
<td>C 989</td>
</tr>
</tbody>
</table>
Objective:

- Field test performance of PLC concrete with various levels of SCM in an exterior flatwork application.
- Control sections with Type GU + SCM

Eight Concrete Mixes:

<table>
<thead>
<tr>
<th>Cement</th>
<th>SCM Replacement Level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Type GU (PC)</td>
<td>X</td>
</tr>
<tr>
<td>Type GUL (PLC)</td>
<td>X</td>
</tr>
</tbody>
</table>

Cementing Materials:

- Type GU with 3.5% limestone (PC)
- Type GUL with 12% Limestone (PLC)
- Blended SCM = 2/3 Slag + 1/3 Fly Ash
Exshaw Cement Plant, Alberta

- Sept 2009
- Paving, Curbs & pumped concrete
- PC & PLC cements
- 15, 25 & 30% fly ash
Brookfield Cement Plant, Nova Scotia

- Oct 2009
- Paving
- Blended PC & PLC cements containing 15% slag
- 15 & 20% fly ash

<table>
<thead>
<tr>
<th>CSA Type</th>
<th>Abbrev.</th>
<th>Gypsum (%)</th>
<th>Limestone (%)</th>
<th>Slag (%)</th>
<th>Clinker (%)</th>
<th>Target Blaine (m²/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type GU</td>
<td>PC</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>91</td>
<td>380</td>
</tr>
<tr>
<td>Type GUb</td>
<td>PC-Slag</td>
<td>5</td>
<td>0</td>
<td>15</td>
<td>80</td>
<td>450</td>
</tr>
<tr>
<td>Type GULb</td>
<td>PLC-Slag</td>
<td>5</td>
<td>12</td>
<td>15</td>
<td>68</td>
<td>500</td>
</tr>
</tbody>
</table>

PC, PC-Slag & PLC-Slag compared in laboratory mixes
Only PC-Slag & PLC-Slag compared in field mixes
Testing of Concrete Produced for Laboratory Trials

<table>
<thead>
<tr>
<th><strong>Test</strong></th>
<th><strong>Method</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump</td>
<td>C 143</td>
</tr>
<tr>
<td>Air (plastic concrete)</td>
<td>C 231</td>
</tr>
<tr>
<td>Set time</td>
<td>C 403</td>
</tr>
<tr>
<td>Hardened air voids</td>
<td>C 457</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>C 39</td>
</tr>
<tr>
<td>“Rapid chloride permeability”</td>
<td>C 1202</td>
</tr>
<tr>
<td>Freeze-thaw resistance</td>
<td>C 666 (Proc. A)</td>
</tr>
<tr>
<td>Salt-scaling resistance</td>
<td>C 672</td>
</tr>
<tr>
<td>Diffusion coefficient</td>
<td>C 1556</td>
</tr>
</tbody>
</table>
Fresh concrete properties:
- Slump
- Air
- Temperature
- Density

Hardened concrete properties on site-cast specimens:
- Strength
- RCPT
- Hardened Air-Void Parameters
- Freeze-thaw (ASTM C 666: Proc. A)
- Salt Scaling (ASTM C 672 & BNQ Method)

Properties of 35-Day-Old Cores:
- Strength
- RCPT
- Chloride diffusion coefficient
# Brookfield Trial: Type PC-Slag versus Type PLC-Slag

## Mix Proportions (lb/yd³)

<table>
<thead>
<tr>
<th></th>
<th>No Fly Ash</th>
<th>15% Fly Ash</th>
<th>20% Fly Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC-Slag</td>
<td>PLC-Slag</td>
<td>PC-Slag</td>
</tr>
<tr>
<td>PC-Slag</td>
<td>653</td>
<td>-</td>
<td>545</td>
</tr>
<tr>
<td>PLC-Slag</td>
<td>-</td>
<td>384</td>
<td>-</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>0</td>
<td>0</td>
<td>95</td>
</tr>
<tr>
<td>Water</td>
<td>272</td>
<td>283</td>
<td>277</td>
</tr>
<tr>
<td>W/CM</td>
<td>0.42</td>
<td>0.44</td>
<td>0.43</td>
</tr>
</tbody>
</table>
# Brookfield Trial: Type PC-Slag versus Type PLC-Slag

## Fresh Concrete Properties

<table>
<thead>
<tr>
<th></th>
<th>No Fly Ash</th>
<th>15% Fly Ash</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC-Slag</td>
<td>PLC-Slag</td>
<td>PC-Slag</td>
</tr>
<tr>
<td>Air (%)</td>
<td>5.8</td>
<td>6.6</td>
<td>6.1</td>
</tr>
<tr>
<td>Slump (mm)</td>
<td>3</td>
<td>2¼</td>
<td>3¼</td>
</tr>
</tbody>
</table>
PLC Trial Pour at Gatineau
Ready-Mixed Concrete Plant – October 6, 2008

• Results published in Concrete International (Jan 2010)
• SCM had significant impact on properties
• No consistent difference between the durability results for PLC versus PC at the same level of SCM
• Mix with PLC-50% SCM contained just 42% clinker by mass of cementing material. Compare with mix with PC only – 92% clinker
• CO₂ reduced by 1 ton per 8-yd³ truck through combined use of limestone and SCM
### PLC Trial Pour at Gatineau – Results of Tests on Cores taken at 35 Days

#### RCPT Results

<table>
<thead>
<tr>
<th>Cement</th>
<th>Charge Passed in 6 Hours (Coulombs)</th>
<th>0% SCM</th>
<th>25% SCM</th>
<th>40% SCM</th>
<th>50% SCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td></td>
<td>2395</td>
<td>1410</td>
<td>570</td>
<td>491</td>
</tr>
<tr>
<td>PLC</td>
<td></td>
<td>2345</td>
<td>1308</td>
<td>617</td>
<td>520</td>
</tr>
</tbody>
</table>

#### Chloride Diffusion Coefficients

<table>
<thead>
<tr>
<th>Cement</th>
<th>Charge Passed in 6 Hours (Coulombs)</th>
<th>0% SCM</th>
<th>25% SCM</th>
<th>40% SCM</th>
<th>50% SCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td></td>
<td>15.0</td>
<td>3.77</td>
<td>1.51</td>
<td>1.25</td>
</tr>
<tr>
<td>PLC</td>
<td></td>
<td>11.9</td>
<td>2.91</td>
<td>1.22</td>
<td>1.81</td>
</tr>
</tbody>
</table>
PLC Trial Pour at Gatineau - Chloride Profiles for Cores taken at 35 Days and Immersed in NaCl for 42 Days
PLC Trial Pour at Gatineau – Scaling Test Results

BNQ Test Method

Scaled Mass Loss (g/m²)

0% SCM 25% SCM 40% SCM 50% SCM
PC PLC

ASTM C 672

Scaled Mass Loss (g/m²)

0% SCM 25% SCM 40% SCM 50% SCM
PC PLC

40 30 10 30 50 80 230 400 114 127 142 380 400 320 497
Initial Trials at Brookfield – Type GU versus Type GUb – with & without Fly Ash

![Bar graph showing compressive strength (MPa) for different cement types at 1 day, 7 days, and 28 days. The graph compares GU-0FA, GUb-0FA, GU-20FA, and GUb-20FA.](Image)
Laboratory Mixes at Brookfield – Type GU, Type GUb & Type GULb

<table>
<thead>
<tr>
<th></th>
<th>Gypsum (%)</th>
<th>Limestone (%)</th>
<th>Slag (%)</th>
<th>Clinker (%)</th>
<th>Target Blaine (m²/kg)</th>
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<td>Type GU</td>
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</tr>
<tr>
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<td>5</td>
<td>0</td>
<td>15</td>
<td>80</td>
<td>450</td>
</tr>
<tr>
<td>Type GULb</td>
<td>5</td>
<td>12</td>
<td>15</td>
<td>68</td>
<td>500</td>
</tr>
</tbody>
</table>
Field Trials at Brookfield – Compressive Strength

0% Fly Ash
- w/cm = 0.417
- Air = 5.8%

15% Fly Ash
- w/cm = 0.443
- Air = 6.6%

20% Fly Ash
Field Trials at Brookfield & Exshaw – Salt Scaling

Typical limits in Canadian Specs: 800 to 1000 g/m²

Alberta - Concrete with GU or GUL
Nova Scotia - Concrete with GUb or GULb
Field Trials at Brookfield & Exshaw – RCPT

Concrete tested at 56 days
- Concrete tested at 100 days

Charge Passed (Coulombs)

Alberta - Concrete with GU or GUL
Nova Scotia - Concrete with GUb or GULb

0% FA, 15% FA, 25% FA, 30% FA, 0% FA, 15% FA, 20% FA
Field Trials at Brookfield – Chloride Diffusion Coefficients

\[ C_x = C_0 \left( \frac{x}{\sqrt{4D_a \cdot t}} \right) \]

<table>
<thead>
<tr>
<th></th>
<th>No Fly Ash</th>
<th>20% Fly Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_a \times 10^{-12} \text{ m}^2/\text{s})</td>
<td>6.1</td>
<td>6.4</td>
</tr>
</tbody>
</table>

No fly ash
20% fly ash
Brookfield Cement Plant, Nova Scotia

<table>
<thead>
<tr>
<th></th>
<th>Gypsum (%)</th>
<th>Limestone (%)</th>
<th>Slag (%)</th>
<th>Clinker (%)</th>
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<td>15</td>
<td>68</td>
<td>500</td>
</tr>
</tbody>
</table>

- Type GULb contains 23% less clinker than Type GU

Approx 23% reduction in clinker (& CO₂ emissions)
# Mixes used in Gatineau Field Trial

<table>
<thead>
<tr>
<th>Concrete Mix</th>
<th>Composition of Binder (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gypsum</td>
</tr>
<tr>
<td>GU + 0% SCM</td>
<td>5</td>
</tr>
<tr>
<td>GUL + 50% SCM</td>
<td>2.5</td>
</tr>
</tbody>
</table>

- Mix with GUL + 50% SCM contains approximately 50% less clinker in the binder than mix with straight Type GU cement.

**Type GU Cement**

- 91% Clinker
- 5% Gypsum
- 4% Limestone

**Type GULb Cement**

- 41.5% Clinker
- 2.5% Gypsum
- 6% Limestone
- 50% SCM

Approx 50% reduction in clinker (& CO₂ emissions)
Gatineau Field Trial

Clinker Contents of Mixes used for Paving Trials (355 kg/m³ cementitious material)

<table>
<thead>
<tr>
<th>Concrete Mix</th>
<th>Clinker in Cement (%)</th>
<th>Clinker in concrete without SCM (kg/m³)</th>
<th>Clinker in concrete with 50% SCM (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU + 0% SCM</td>
<td>91</td>
<td><strong>323</strong></td>
<td>162</td>
</tr>
<tr>
<td>GUL + 50% SCM</td>
<td>83</td>
<td>295</td>
<td><strong>147</strong></td>
</tr>
</tbody>
</table>

- 176 kg/m³ reduction in cement clinker (= 176 kg/m³ reduction in CO₂) by combined use of Type GUL cement plus SCM compared with Type GU
- **CO₂ reduced by almost 1½ tonne per 8-m³ truck**
- 293 lb/yd³ reduction in cement clinker (= 293 lb/yd³ reduction in CO₂) by combined use of Type GUL cement plus SCM compared with Type GU
- **CO₂ reduced by almost 1½ ton per 10-yd³ truck**
Overall Summary

• Portland-limestone cement (PLC) with 12% limestone, when optimized for equal strength, can provide equivalent performance to Portland cement (Type PC)

• Blended portland-limestone cement with 12% limestone and 15% slag also provided equivalent performance to PC with 23% less clinker

• PLC performs well with (further) additions of SCM at the ready-mixed concrete plant (providing further opportunities to reduce CO$_2$ emissions).

• Using a combination of PLC or blended PLC together with (further) SCM additions at the concrete plant provides the opportunity to reduce the clinker content of paving mixes by up to 50%. Such reductions can translate to CO$_2$ reductions of the order of 1 to 1½ tons per concrete truck!