Performance of Concretes Made Using Portland Limestone Cement

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Outline for PLC Talk

• Motivation: Question What, Why, Who, How (Where)

• What are Potential Consequences

• Previous Shrinkage Study
  – Phase I – Clinker #1
  – Phase II – Using Added Limestone
  – Phase III – Clinker #2
    (4 Clinker study)

• Current Shrinkage Investigation
  – Three Systems – OPC, PLC, PLC-S

• Summary
Portland Limestone Cement
What is it?

- PLC has been added to current cement specifications ASTM C595/AASHTO M240
  - 5 to 15% interground limestone
  - Min. CaCO$_3$ content
  - Physical requirements same as OPC
  - New test requirements MBI and TOC
- Type IL blended cements, Type IT ternary cements
PLC – Why Do We Want It?
Cement and CO₂ Production

- You will hear cement accounts for 7-8% of global CO₂ (Mehta 1998)
- Where is the CO₂ coming from:
  - Calcination (50)
  - Combustion (40)
  - Transportation (10)
- Concrete has relatively low carbon emission per unit; however widespread use of concrete makes it a major contributor to manmade CO₂ emissions
Portland Limestone Cements
Why do we want it?

- **Sustainability**
  - less energy is consumed
  - Less CO\textsubscript{2} & greenhouse gases produced

![Diagram showing sustainability components]

- Life Cycle Performance
  - Reduce Clinker
  - Reduce Cement Content

Sustainable Solutions

Economic

Environmental

Social
Portland Limestone Cement
Who Has Used This Before?

- Technical information on use of limestone of up to 15% (PLC)

Summary of Contents
- environmental benefits
- history of use of cements with limestone
- chemical and physical effects on properties
Portland Limestone Cement
How is it Made ... In North America

• Similar performance to OPC is targeted
• PLC is generally ground finer than OPC
  – Overcome dilution
  – Higher fineness may act as a nucleating agent to increase early age strengths
  – Improve packing
• Higher reaction rates may show benefits of blending with other supplementary materials
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PLC Performance Studies

Matschei et al 2007

compressive strength measured

increase
decrease

relative change of porosity and compressive strength [%]

total porosity calculated

amount of CaCO₃ added [wt.-%]
Fineness and Shrinkage Cracking

- Burrows (1998) – Monogaph
- Bentz, D.P., et al. (2001) ACERS
- Chariton, T., and Weiss, W. J., (2002) ACI SP – Cracking Data shown

- Several reports say finer cements crack earlier
- Blaine fineness often used in these studies however we are not really after surface area
- Rather we are after the space between particles – pore sizes important
Origins of Shrinkage
(Young and Laplace Equation)

Thomas Young (1773 – 1829)
After Lura et al 2007

Pierre-Simon, marquis de Laplace (1749 - 1827)
Shrinkage Concepts (Young-Laplace)

\[ \sigma = \frac{2\gamma \cos \theta}{r} \]

- capillary stress (\( \sigma \))
- pore geometry (\( r \))
- surface tension (\( \gamma \))

\[ \gamma = 0.072 \text{ N/m} \]

\[ \gamma = 0.036 \text{ N/m} \]

- Sealed - SRA
- Unsealed - Plain
- Unsealed - SRA
- Sealed - LWA
- Unsealed - LWA
- Sealed - Plain
- Sealed - SRA
- Unsealed - Plain
- Unsealed - SRA
- Sealed - LWA
- Unsealed - LWA
- Sealed - Plain
Important Take Aways

- Shrinkage is related to the space between pores that empty
- Some pores are more important
  - pores less than a few nm (other effects)
  - pores greater than 50 nm (low stress)
- Pore size is related to the particle size distribution of the cement
Important Distinction Between Blaine Fineness for PLC and OPC Will Be Made

- Example of a PSD for Cement with different Blaine fineness from Bentz et al. (2001)
- You can notice that the change in Blaine fineness (a measure of permeability) also significantly alters the pore size distribution (shifting the entire curve)
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Bucher et al. (2009a) – Phase I Commercially Ground Blends

- 0%, 5%, 10% limestone replacement by mass
- 0% limestone, Type I/II, Blaine fineness 382 m$^2$/kg
- 5% limestone, Blend of 0% and 10%
- 10% limestone, Type GU, Blaine fine. 461 m$^2$/kg
- HRWRA
- w/cm = 0.30
- Mortar - 55% aggregate by volume
Restrained Ring Test

- Using an Instrumented Ring
- Measure Strain that Develops in Steel
- Determine the Pressure Required to Obtain that Strain
- Apply Pressure to Concrete and Obtain Tensile Stress

Hossain and Weiss, CCC, 2004
Restrained Ring Results

- The delay in time to cracking indicates that cements with limestone are slightly more resistant to cracking than plain cement systems.
Shrinkage in Paste

![Graph showing shrinkage in paste versus relative humidity. The graph includes data points for 0%, 5%, and 10% LSTN at 160 days.](image)

- Shrinkage $[\mu \varepsilon]$ on the y-axis.
- Relative Humidity [%] on the x-axis.
- Data points for 0% LSTN, 5% LSTN, and 10% LSTN at 160 days.
Phase II (Bucher 2009b) Cement with Limestone Replacement (Not Interground)

• Bucher et al. (2009) examined how limestone addition of limestone/replacement of cement influenced shrinkage & cracking of mortar.

• 3 sizes of limestone were used to replace 10% of the cement by volume (Unlike Other Phases)
  – small 3 micron
  – medium 17 micron, and
  – large 100 micron

• Note these are not equivalent performance
Phase II (Bucher 2009b) Shrinkage and Cracking Studies Cement/Limestone

- Fineness influences stress
- Fine limestone was similar
- Binder was a cement with additional limestone of different particle sizes
- Note these are not equivalent performance
Phase III – An Additional System Investigated (Barrett et al. 2012)

- Used a commercially interground cement
- No increase in cracking tendency
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  What, Why, Who, How (Where)

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• Current Shrinkage Investigation (IV)
  – Three Systems – OPC, PLC, PLC-S

• Summary
Phase IV - Objectives

- Shrinkage and cracking potential in 3 systems
- Clinker and limestone interground (industrial)
- w/c = 0.39, mortar with 55% sand volume

**OPC (3.7% L)**

**PLC (11% L)**

**PLC-Slag (10% L + 12% Slag)**
Study Outline

• Task 1: Particle Size and Pore Size Distribution
Particle Size Distribution - Cumulative

- GU OPC
- GUL PLC
- GULB-S PLC

Cumulative Volume (%)

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Density (g/cm³)</th>
<th>Mean particle size (µm)</th>
<th>Median particle size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU OPC</td>
<td>3.13</td>
<td>13.98</td>
<td>9.71</td>
</tr>
<tr>
<td>GUL PLC</td>
<td>3.06</td>
<td>11.84</td>
<td>8.51</td>
</tr>
<tr>
<td>GULB-S PLC</td>
<td>3.06</td>
<td>10.92</td>
<td>8.13</td>
</tr>
</tbody>
</table>
Pore Size Distribution

![Graph showing the pore size distribution of OPC, PLC, and PLC-slag](image-url)

- **OPC**
- **PLC**
- **PLC-slag**

The graph plots differential porosity (g of water / g of oven dry sample (%) against Kelvin radius (nm) for different materials.
Study Outline

- Task 2: Chemical Shrinkage
Fundamental Volume Change

- Le Chatelier
- 1850-1936
- Volume of the reactants larger than the volume of the products
- Chemical Shrinkage

\[
\text{Chemical Shrinkage} = \text{Volume of reactants} + \text{Volume of products}
\]
Chemical Shrinkage

- Observed by Le Chatelier over a century ago
- “the volume reduction associated with the hydration reactions in a cementitious material”
- Powers conceptual model shown ~ 6.4% reduction
Chemical Shrinkage per gram of binder

![Graph showing chemical shrinkage over days for different mixes: GU OPC, GUL PLC, GULB-S PLC with w/b = 0.34.]
Study Outline

- Task 1: Particle Size and Pore Size Distribution
- Task 2: Chemical Shrinkage
- Task 3: Autogenous Shrinkage
- Task 4: Restrained Shrinkage
Autogenous strain is “the bulk strain of a closed, isothermal, cementitious material system not subjected to external forces.”

![Diagram showing the stages of hydration](after Jensen & Hansen 2001)

**Chemical Shrinkage**
- Capillary Water
- Hydration Product Gel
- Hydration Ceases
- Hydration Product
- Solid
- Unhydrated Cement

**Autogenous Shrinkage**
- Measured by External Deformation of a Sealed Body

(after Powers)
ASTM C 1698 Autogenous Shrinkage

- Autogenous shrinkage (Corrugated Tube)
- OPC and PLC have similar shrinkage
- PLC-S has a slightly lower early shrinkage
Study Outline

- Task 4: Restrained Shrinkage
Restrained Shrinkage

- Dual restrained ring test
- Shows similar stress development and age of cracking

![Graph showing tensile stress vs. age of specimen for different concrete mixes with w/b = 0.34.](image-url)
Study Outline - Summary

• Task 1: Particle Size and Pore Size Distribution
  – Less big particles PLC, PLCS
  – pores similar as related to shrinkage

• Task 2: Chemical Shrinkage
  – Less early age chemical shrinkage

• Task 3: Autogenous Shrinkage
  – Lower shrinkage for PLC, PLCS

• Task 4: Restrained Shrinkage
  – OPC, PLC, PLCS Similar
Summary

- PLC is not just a dilution of OPC
- PLC, PLC-Slag are engineered differently to obtain ‘Similar Performance’ (f’c at 28 days)
- Have shown similar or less autogenous shrinkage and similar or less restrained shrinkage cracking
- Explained using Young-Laplace equation showing that the increase in Blaine fineness does not alter pores in range of interest