Utilization of CO$_2$ in High-Performance Building and Infrastructure Products

Nicholas DeCristofaro

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Mtg
Developing the Technologies and Infrastructure for CCS
August 12-14, 2014
What if this...became this?

What if CO$_2$...meant green?

PRESENTATION OUTLINE

• Project Overview
• Project Benefit Statement
• Technical Status
• Accomplishments
• Summary
• Appendix
  • Organization Chart
  • Gantt Chart
### Project Overview – Goals

The development of alternative construction materials that can replace ordinary Portland cement (OPC) while consuming less energy and generating less CO₂

#### Why?

- **Cement industry:** 2nd largest industrial emitter of CO₂ (>2.4 Gt annually, or ~5% anthropogenic CO₂ emissions)
- **Concrete:** 2nd most utilized substance on earth (~20 Gt annually, 2nd only to water)

#### How?

- Replace OPC with mineral or synthetic Wallastonite (CaSiO₃)
- Cure CaSiO₃-based concrete with CO₂

#### Criteria

- Reduce the CO₂ footprint of concrete by 30-90%
- CO₂-cured concrete properties > hydrated concrete properties
**Project Benefits Statement**

The research project will demonstrate a new construction material that can replace conventional concrete.

| New Construction Material | ▪ reduces or eliminates the CO₂ emissions associated with cement production  
▪ permanently sequesters CO₂ (in the form of CaCO₃) during concrete curing  
▪ preserves the existing infrastructures of the cement and concrete industries |
|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| **CO₂ emissions reduction & sequestration** | When demonstrated and applied industry-wide, will enable:  
▪ reduction CO₂ emissions reduction of up to 0.7 Gt/yr  
▪ sequestration CO₂ up to 0.9 Gt/yr |
| **Supports Carbon Storage Program goals** | Supports effort to develop / validate technologies that can assure 99% storage effectiveness. |
### Technical Status

### Background

**Original Premise**

Mineral wollastonite (CaSiO$_3$) can be used as cementious materials in CO$_2$-cured concrete products:
- Carbon-neutral, high-performance concrete products, BUT...
- Address 0.1% of OPC market
- Reduce Global CO$_2$ emissions by ~2 Mt/yr

**Revised Premise**

Synthesized calcium silicate cement (Solidia Cement™) can be used:
- Made with processing equipment (rotary kilns) & raw materials (limestone, sand, clay) used in OPC production
- CO$_2$ emissions ↓ 250 kg/tonne of cement (30%)
- Ability to sequester 300 kg of CO$_2$/tonne of cement in concrete

### Thus....

- Address entire OPC market
- Reduce global CO$_2$ emissions by ~1.6 Gt/yr
Accomplishments

Calcium Silicate Cement Manufacturing

CO₂-Curing Technology
- Drying
- Drying & Curing

CO₂-Curing Optimization
- CO₂-curing system modeling
- Applications development
Calcium Silicate Cement Manufacturing
> 5,000 tonnes of Solidia Cement produced and inventoried

### Full-scale Production of Calcium Silicate Cement (Solidia Cement™)

- **March 2014 at Lafarge, Whitehall, PA**
- **Raw materials:**
  - Quarry rock (lime)
  - Sand (silica)
- **Firing temperature = 1200°C (vs 1450°C for OPC)**
  - Coal
  - Recycled plastic
  - Recycled tires
- **Energy usage ↓ 30% vs OPC**
- **CO₂ emissions ↓ 30% vs OPC**
**CO₂-Curing Technology**

**Drying**

**CO₂-curing and drying are linked:**

- Presence of liquid water critical to dissolve Ca & CO₂
- Drying follows classical behavior of porous solids
  - constant rate drying period – evaporation at surface
  - falling rate drying periods – evaporation in pores

\[
\text{CaSiO}_3 + \text{CO}_2 \rightarrow \text{SiO}_2 + \text{CaCO}_3
\]

**Evidence of Reaction Fronts**

- (a) Constant rate period
- (b) 1st falling-rate period
- (c) 2nd falling-rate period

- Pores Full-no CO₂-curing
- CO₂-curing at surface
- CO₂-curing in bulk
**CO₂-Curing Technology**

**Drying & Curing**

1. Heating, Drying & Curing

2. Heating (only)

3. Heating & Drying

- Drying and CO₂-curing occur simultaneously
- Two reaction fronts (large pores & small pores)
CO₂-Curing Optimization
Paver Modeling

- Based on commercial curing chamber for concrete blocks
  - 17’ h x 12’ w x 72’ d
  - Block dimensions (12” x 2.375” x 6” with 0.5” gap)
- Computational fluid dynamic “silver” model
  - 17’ h x 6’ w x 4’ d
  - 14 shelves
- Physical replica
  - ~6’ h x 6’ w x 4’ d
  - 5 shelves

CFD Model &
Physical Replica
Closely Match

Gas Flow Side View
Gas Flow Top View
Relative Humidity
CO₂-Curing Optimization
Railroad Tie

- Forming Using Concrete Vibrator
- Flipping the Mold to Release Uncured Tie
- CO₂ Gas Conditioning System
- Freshly Formed Concrete
- Tie in CO₂-Curing Vessel
- CO₂-Cured Railroad Ties

CO₂-Curing Profile

![Graph showing CO₂-Curing Profile](image-url)
CO$_2$-Curing Optimization
Hollow Core Slab

Humidity Probe on Top of Slab

5.5% H$_2$O

Curing Time

Pre-reaction 900 minutes

Time (minutes)

Absolute Humidity (g/m$^3$)

Constant Drying Rate

Falling Drying Rate

Very Slow Drying

Pre-reaction

Reaction

Post-reaction

Little or No Reaction

Fast Reaction

Little or No Reaction

Do not copy or distribute: Proprietary and confidential information of Solidia Technologies, Inc.
Summary

Key Findings / Lessons Learned

Calcium Silicate cement (Solidia Cement) now available on commercial scale
- Able to support commercial development of CO₂-cured concrete

Water / CO₂ concentration & distribution controls concrete curing rate on macroscopic (bulk) scale
- Drying & CO₂-curing of concrete closely linked

Management of the curing atmosphere parameters permits economical, CO₂-curing of bulk concrete parts
- Temperature, humidity, flow rate

Do not copy or distribute: Proprietary and confidential information of Solidia Technologies, Inc.
Summary
Future Plans

Transfer CO₂-curing processes developed in NETL De-FE0004222 to commercial concrete manufacturing

Demonstration of bulk concrete curing in raw & reconditioned flue gas
### Organization Chart

#### Rutgers University
- Materials science
- Analytical techniques

#### Solidia Technologies
- Cement & concrete production/analysis
- Applications

<table>
<thead>
<tr>
<th>Task</th>
<th>Rutgers University</th>
<th>Solidia Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R. Riman, Ph.D. Mat. Sci.</td>
<td>L. McCandlish, Ph.D. Chem.</td>
</tr>
<tr>
<td></td>
<td>Project Mgmt.</td>
<td>Proj. Mgmt.</td>
</tr>
<tr>
<td>2</td>
<td>M. Bitello, grad student, Mat. Sci.</td>
<td>G. Radiozamani, MBA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J. Krishnanan, MBA</td>
</tr>
<tr>
<td></td>
<td>General</td>
<td>Market / Impact Analysis</td>
</tr>
<tr>
<td></td>
<td>Equipment/Milling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reaction kinertics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Analytical techniques</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.1 thru 3.9</td>
<td>N. DeCristofaro, Ph.D. Mat. Sci.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O. Deo, Ph.D. CE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X. Hu, Ph.D. Chem. E.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L. McCandlish</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D. Ravikumar, Ph.D. CE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D. Paten</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K. Smith</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R. Boylan, MBA</td>
</tr>
<tr>
<td></td>
<td>3.10 thru 3.12</td>
<td>General</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Particle size effects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process modeling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hollowed concrete</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hollow core slab</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Railroad tie</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pavers and blocks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Applications marketing</td>
</tr>
</tbody>
</table>
### TASK DESCRIPTION

<table>
<thead>
<tr>
<th>TASK</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Project Management and Reporting</td>
</tr>
<tr>
<td>2.0</td>
<td>Business Evaluation</td>
</tr>
<tr>
<td>3.0</td>
<td>Technical Evaluations</td>
</tr>
<tr>
<td>3.1</td>
<td>Acquire, install, commission grinding mill</td>
</tr>
<tr>
<td>3.2</td>
<td>Control mineral particle size</td>
</tr>
<tr>
<td>3.3</td>
<td>Acquire, install, commission Lab Scale Reactor with Probes</td>
</tr>
<tr>
<td>3.4</td>
<td>Study reaction rate, carbonation yield vs. T, P</td>
</tr>
<tr>
<td>3.5</td>
<td>Study reaction rate, carbonation yield vs particle size</td>
</tr>
<tr>
<td>3.6</td>
<td>Study carbonation yield vs. T, P for pressed pellets</td>
</tr>
<tr>
<td>3.7</td>
<td>Study comminution energy</td>
</tr>
<tr>
<td>3.8</td>
<td>Measure compressive, tensile strength of carbonated pellets</td>
</tr>
<tr>
<td>3.9</td>
<td>Determine best raw materials formulation based on chemistry….</td>
</tr>
<tr>
<td>3.10</td>
<td>Study water distribution during drying in bulk concrete parts</td>
</tr>
<tr>
<td>3.11</td>
<td>Study water distribution during curing in bulk concrete parts</td>
</tr>
<tr>
<td>3.12</td>
<td>Find the optimum reaction conditions for concrete sample size, geometry and density</td>
</tr>
</tbody>
</table>

The Gantt chart illustrates the timeline and progress of various tasks and milestones within the project. Each task is assigned a start (S) and finish (X) date, with a decision point (D) marking significant milestones.

### Key Milestones:
- **Establishment of Solidia Cement Specifications**
- **Use of Synthesized Solidia Cement**
- **Grinding Mill Operational Program Enhancement**
- **Bulk Concrete Demonstration Flue Gas Simulation**
Solidia Technologies®

Where CO₂ means green and sustainability meets profitability.℠