# Utilization of $CO_2$ in High-Performance Building and Infrastructure Products

**Nicholas DeCristofaro**

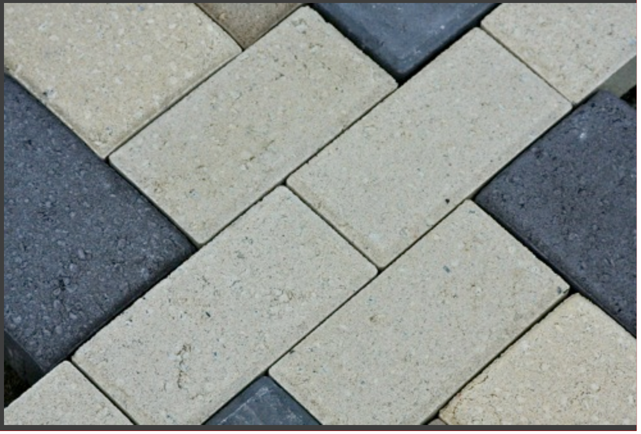
**DE-FE0004222**

U.S. Department of Energy
National Energy Technology Laboratory

Carbon Storage R&D Project Review Mtg

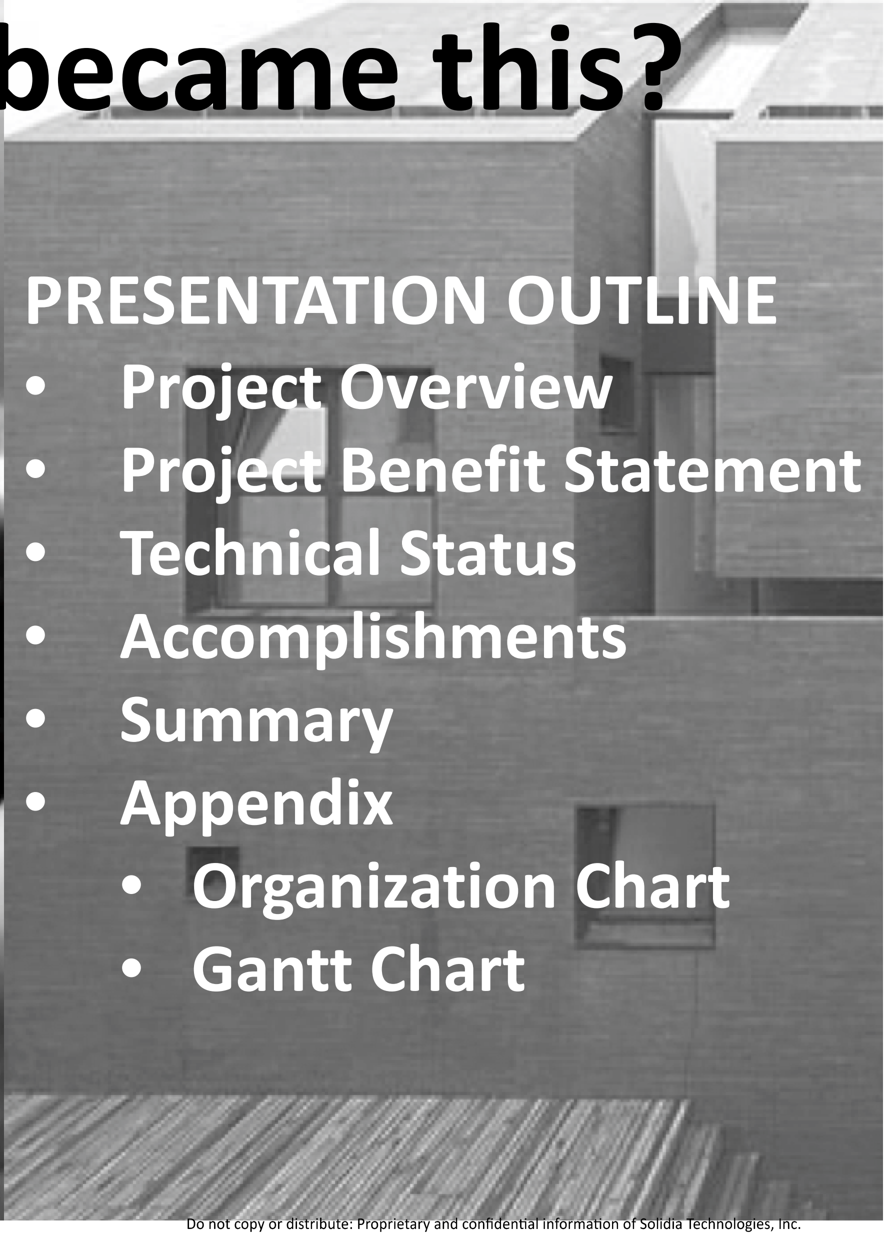
Developing the Technologies and Infrastructure for CCS

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 $CO_2$**

## Why?

- Cement industry: 2nd largest industrial emitter of $CO_2$
  (>2.4 Gt annually, or~5% anthropogenic $CO_2$ emissions)
- Concrete: 2nd most utilized substance on earth
  (~20 Gt annually, 2nd only to water)

## How?

- Replace OPC with mineral or synthetic Wallastonite ($CaSiO_3$)
- Cure $CaSiO_3$-based concrete with $CO_2$

## Criteria

- Reduce the $CO_2$ footprint of concrete by 30-90%
- $CO_2$-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 $CO_2$ emissions associated with cement production<br>▪ permanently sequesters $CO_2$ (in the form of $CaCO_3$) during concrete curing<br>▪ preserves the existing infrastructures of the cement and concrete industries |
| **$CO_2$ emissions reduction & sequestration** | When demonstrated and applied industry-wide, will enable:<br>▪ reduction $CO_2$ emissions reduction of up to 0.7 Gt/yr<br>▪ sequestration $CO_2$ 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

## $CO_2$-Curing Technology

- Drying
- Drying & Curing

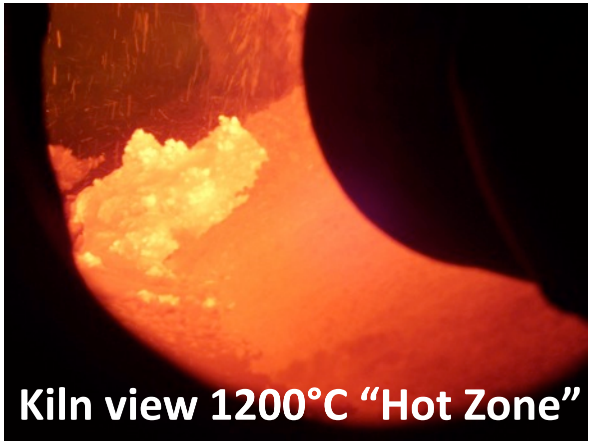
## $CO_2$-Curing Optimization

- $CO_2$-curing system modeling
- Applications development

# Calcium Silicate Cement Manufacturing

## > 5,000 tonnes of Solidia Cement produced and inventoried


OPC manufacturing facility


Kiln view 1200°C "Hot Zone"

### 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

$CO_2$ emissions ↓ 30% vs OPC

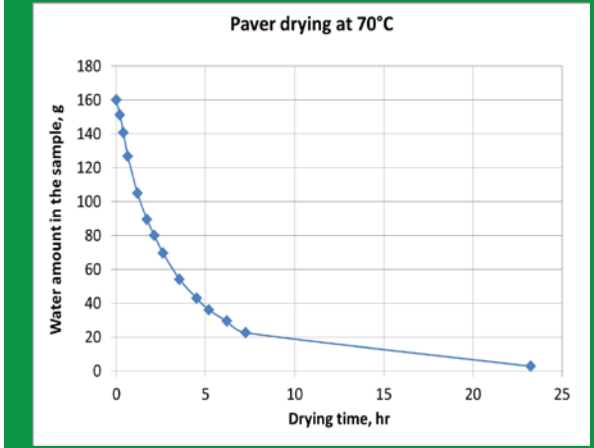
# $CO_2$-Curing Technology

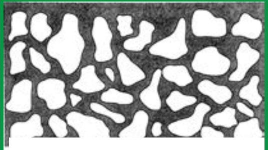
## Drying

**$CO_2$-curing and drying are linked:**

- Presence of liquid water critical to dissolve Ca & $CO_2$
- Drying follows classical behavior of porous solids
  - constant rate drying period – evaporation at surface
  - falling rate drying periods – evaporation in pores

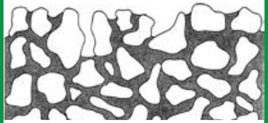
$$CaSiO_3 + CO_2 \xrightarrow{H_2O_{(l)}} SiO_2 + CaCO_3$$





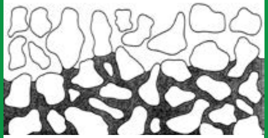
Pores Full-
no $CO_2$-curing

(a) Constant rate period



$CO_2$-curing
at surface

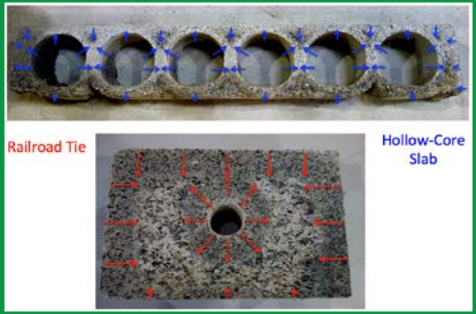
(b) 1st falling-rate period

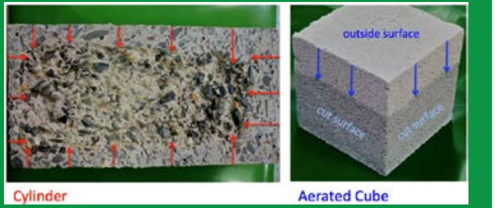


$CO_2$-curing
in bulk

(c) 2nd falling-rate period

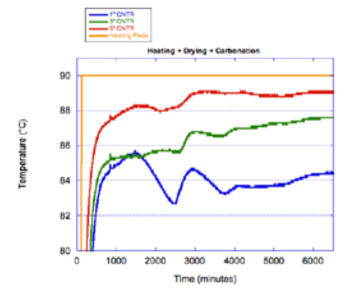
**Evidence of Reaction Fronts**



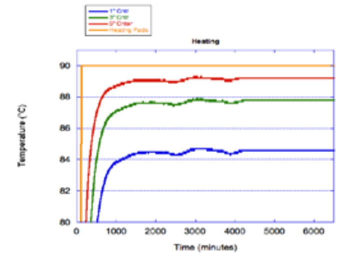


# $CO_2$-Curing Technology

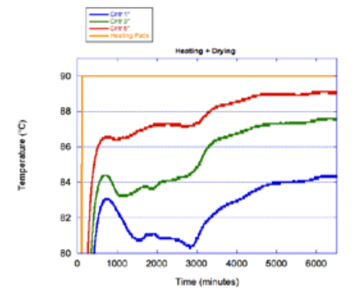
## Drying & Curing



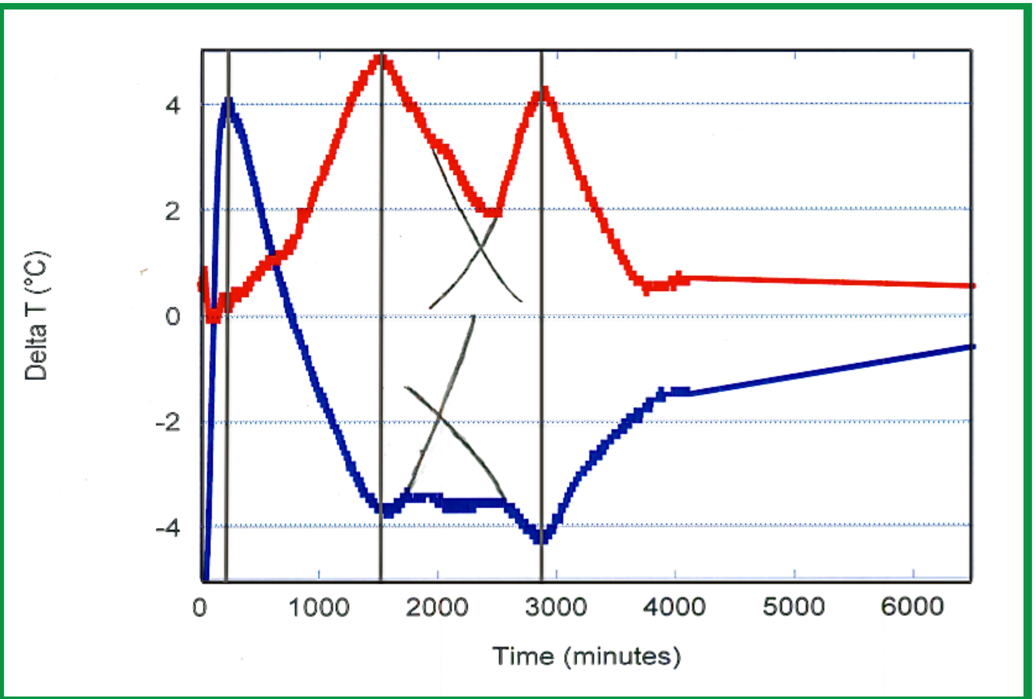
**1. Heating, Drying & Curing**



**2. Heating (only)**



**3. Heating & Drying**



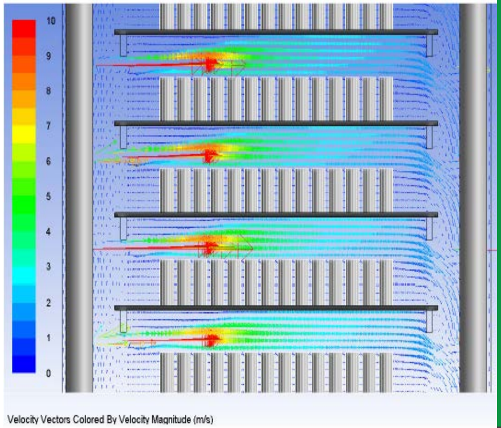
- Drying and $CO_2$-curing occur simultaneously
- Two reaction fronts (large pores & small pores)

# $CO_2$-Curing Optimization

## Paver Modeling

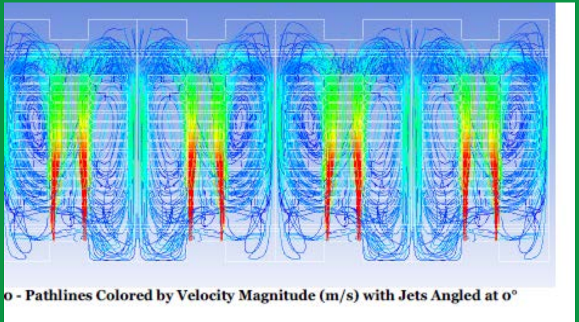
- Based on commercial curing chamber for concrete blocks
  - 17’ h x 12’ w x 72’ d
  - Block dimensions (12” x 2.375” x 6” with 0.5” gap)
- Computational fluid dynamic “silver” model
  - 17’ h x 6’ w x 4’ d
  - 14 shelves
- Physical replica
  - ~6’ h x 6’ w x 4’ d
  - 5 shelves

**CFD Model & Physical Replica Closely Match**

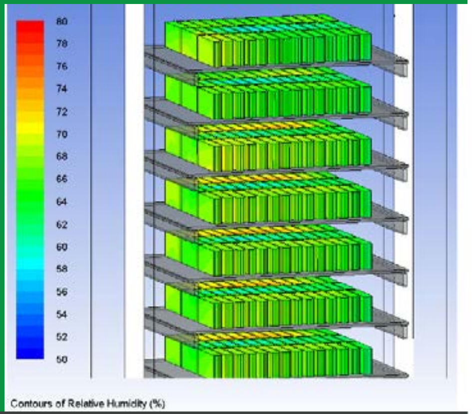


Gas Flow Side View

Gas Flow Top View



Relative Humidity



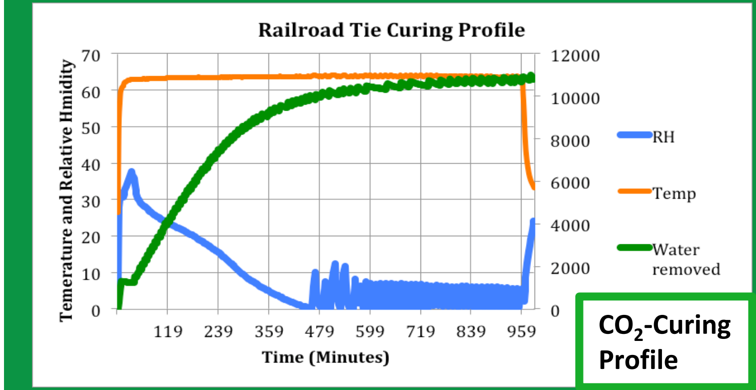
# $CO_2$-Curing Optimization

## Railroad Tie

Forming Using Concrete Vibrator

Flipping the Mold to Release Uncured Tie

$CO_2$ Gas Conditioning System



**$CO_2$-Curing Profile**

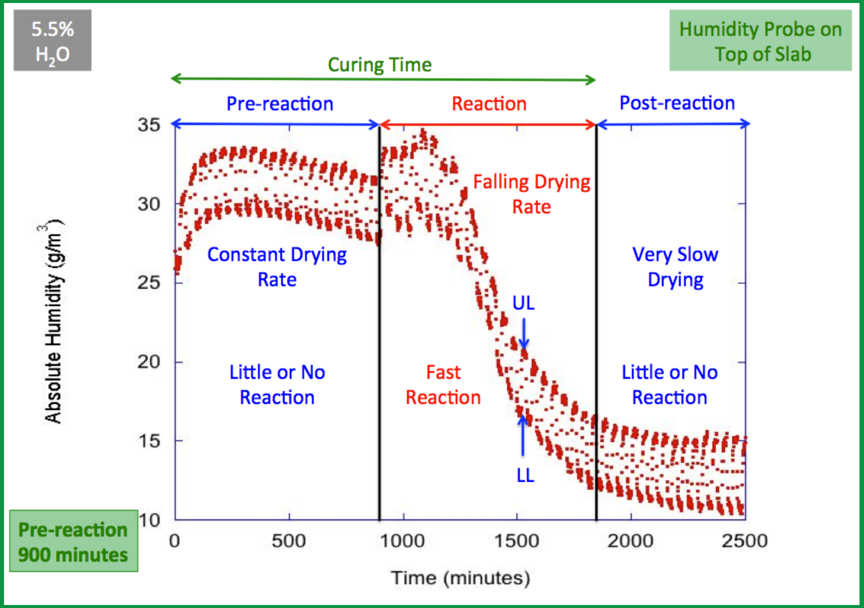
Freshly Formed Concrete

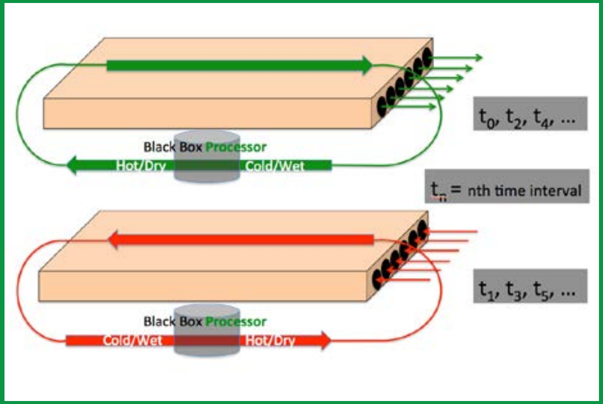
Tie in $CO_2$-Curing Vessel

$CO_2$-Cured Railroad Ties

# $CO_2$-Curing Optimization

## Hollow Core Slab





# Summary

## Key Findings / Lessons Learned

**Calcium Silicate cement (Solidia Cement) now available on commercial scale**

- Able to support commercial development of $CO_2$-cured concrete

**Water / $CO_2$ concentration & distribution controls concrete curing rate on macroscopic (bulk) scale**

- Drying & $CO_2$-curing of concrete closely linked

**Management of the curing atmosphere parameters permits economical, $CO_2$-curing of bulk concrete parts**

- Temperature, humidity, flow rate

# Summary

## Future Plans

Transfer $CO_2$-curing processes developed in NETL De-FE0004222 to commercial concrete manufacturing

Demonstration of bulk concrete curing in raw & reconditioned flue gas

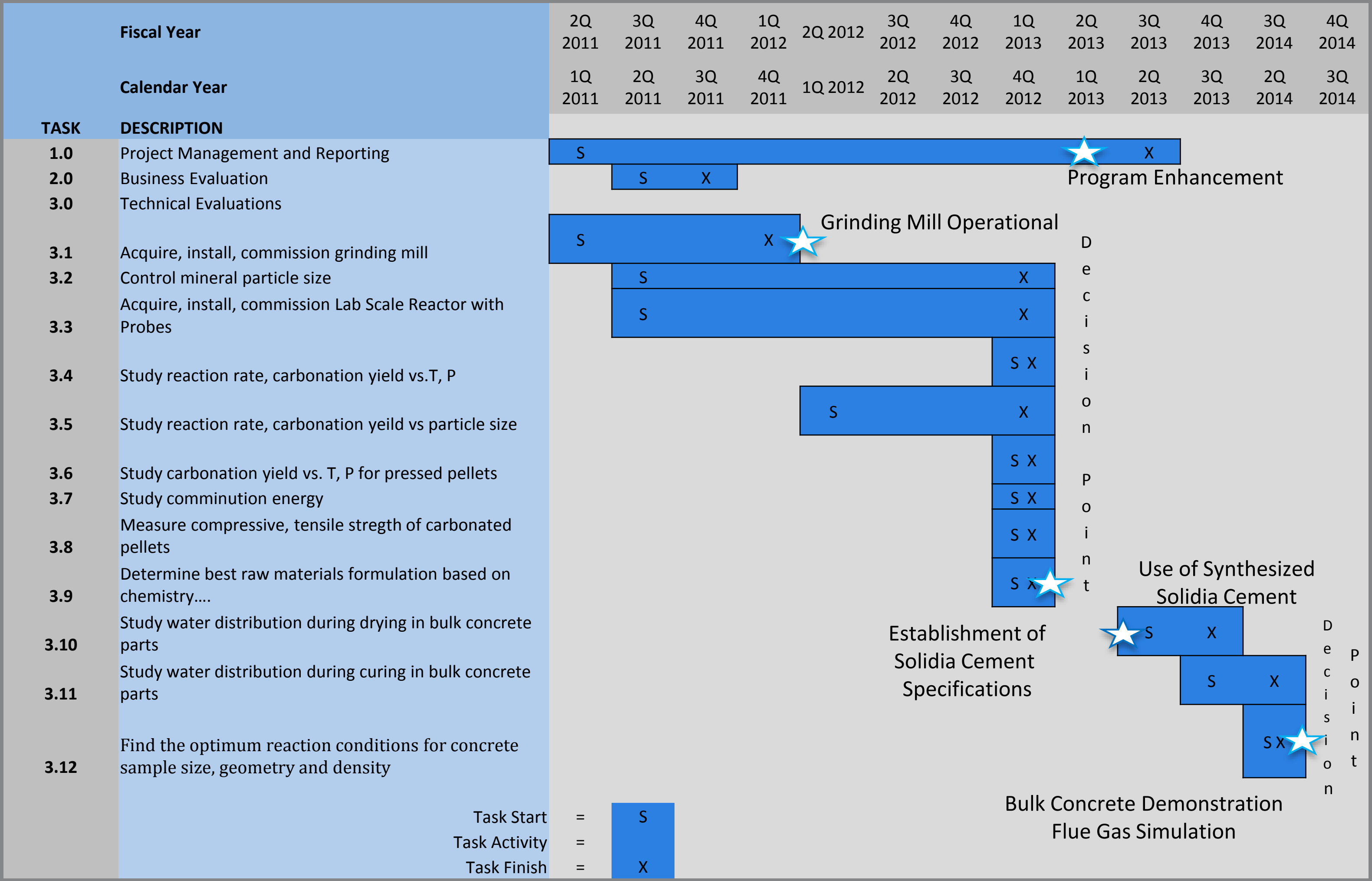
# Appendix


Research Autoclave
CDS Curing Chamber
Elematic Hollow Core Extruder
Elliptical Mixer
Columbia Paver Press

# Organization Chart

| **Rutgers University**<br>▪ Materials science<br>▪ Analytical techniques | | | **Solidia Technologies**<br>▪ Cement & concrete production/analysis<br>▪ Applications | |
|---|---|---|---|---|
| | | **Task** | | |
| ▪ **R. Riman,** Ph.D. Mat. Sci. | Project Mgmt. | 1 | ▪ **L. McCandlish,** Ph.D. Chem. | Proj. Mgmt. |
| | | 2 | ▪ **G. Badiozamani,** MBA<br>▪ **J. Krishnanan,** MBA | Market / Impact Analysis |
| ▪ **M. Bitello,** grad student, Mat. Sci.<br>▪ **Q. Li,** Ph.D. Chem.<br>▪ **R. Riman** | General<br>Equipment/Milling<br>Reaction kinertics<br>Analytical techniques | 3.1 thru 3.9 | ▪ **L. McCandlish** | $CO_2$ sequestration chemistry |
| | | 3.10 thru 3.12 | ▪ **N. DeCristofaro,** Ph.D. Mat. Sci.<br>▪ **O. Deo** Ph.D. CE<br>▪ **X. Hu,** Ph.D. Chem. E.<br>▪ **L. McCandlish**<br>▪ **D. Ravikumar,** Ph.D. CE<br>▪ **D. Paten**<br>▪ **K. Smith**<br>▪ **R. Boylan,** MBA | General<br>Particle size effects<br>Process modeling<br>Aerated concrete<br>Hollow core slab<br>Railroad tie<br>Pavers and blocks<br>Equipment<br>Applications marketing |

# Gantt Chart



| | Fiscal Year | 2Q 2011 | 3Q 2011 | 4Q 2011 | 1Q 2012 | 2Q 2012 | 3Q 2012 | 4Q 2012 | 1Q 2013 | 2Q 2013 | 3Q 2013 | 4Q 2013 | 3Q 2014 | 4Q 2014 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Calendar Year | 1Q 2011 | 2Q 2011 | 3Q 2011 | 4Q 2011 | 1Q 2012 | 2Q 2012 | 3Q 2012 | 4Q 2012 | 1Q 2013 | 2Q 2013 | 3Q 2013 | 2Q 2014 | 3Q 2014 |
| **TASK** | **DESCRIPTION** | | | | | | | | | | | | | |
| **1.0** | Project Management and Reporting | S | | | | | | | | ★ | X | | | |
| **2.0** | Business Evaluation | | S | X | | | | | | | | | | |
| **3.0** | Technical Evaluations | | | | | | | | | | | | | |
| **3.1** | Acquire, install, commission grinding mill | S | | | X ★ | | | | | | | | | |
| **3.2** | Control mineral particle size | | S | | | | | | X | | | | | |
| **3.3** | Acquire, install, commission Lab Scale Reactor with Probes | | S | | | | | | X | | | | | |
| **3.4** | Study reaction rate, carbonation yield vs.T, P | | | | | | | | S X | | | | | |
| **3.5** | Study reaction rate, carbonation yeild vs particle size | | | | | S | | | X | | | | | |
| **3.6** | Study carbonation yield vs. T, P for pressed pellets | | | | | | | | S X | | | | | |
| **3.7** | Study comminution energy | | | | | | | | S X | | | | | |
| **3.8** | Measure compressive, tensile stregth of carbonated pellets | | | | | | | | S X | | | | | |
| **3.9** | Determine best raw materials formulation based on chemistry.... | | | | | | | | S X ★ | | | | | |
| **3.10** | Study water distribution during drying in bulk concrete parts | | | | | | | | | | ★ S | X | | |
| **3.11** | Study water distribution during curing in bulk concrete parts | | | | | | | | | | | S | X | |
| **3.12** | Find the optimum reaction conditions for concrete sample size, geometry and density | | | | | | | | | | | | S X ★ | |

Program Enhancement

Grinding Mill Operational

Decision Point

Establishment of Solidia Cement Specifications

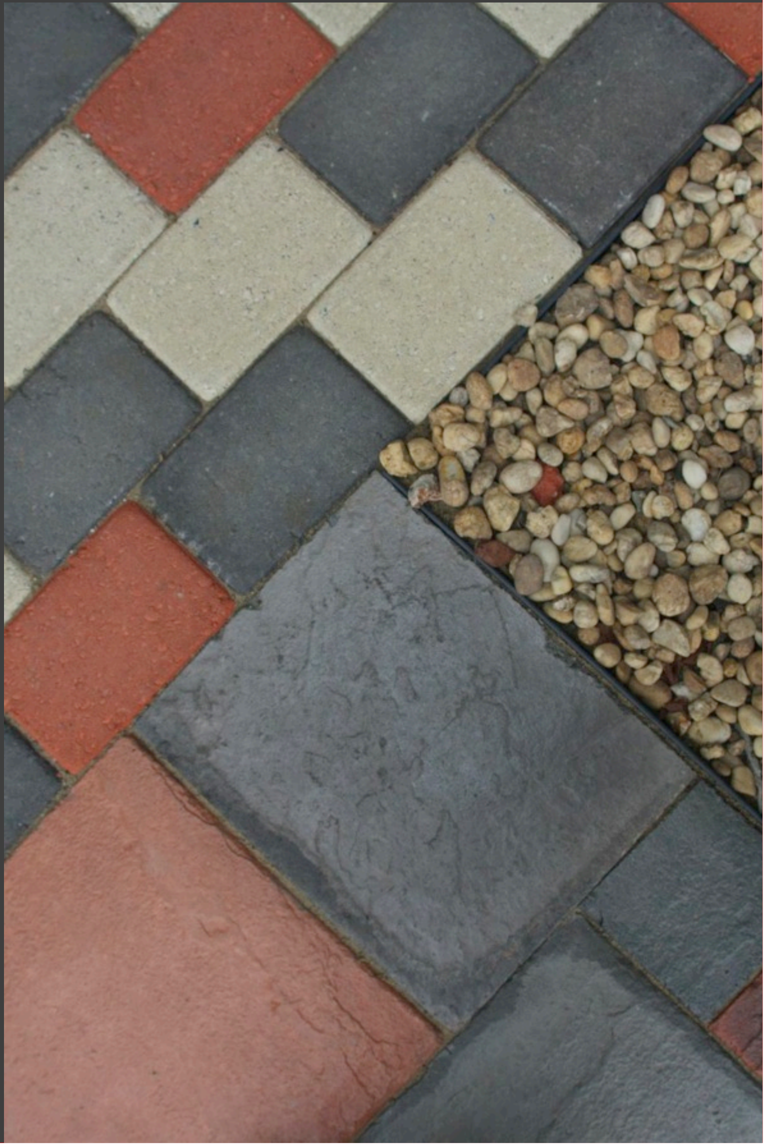
Use of Synthesized Solidia Cement

Decision Point

Bulk Concrete Demonstration Flue Gas Simulation

Task Start = S
Task Activity =
Task Finish = X

# Solidia Technologies®



Where $CO_2$ means green and sustainability meets profitability.℠