Low-Carbon Concrete Implementation and the Role of Field Demonstrations

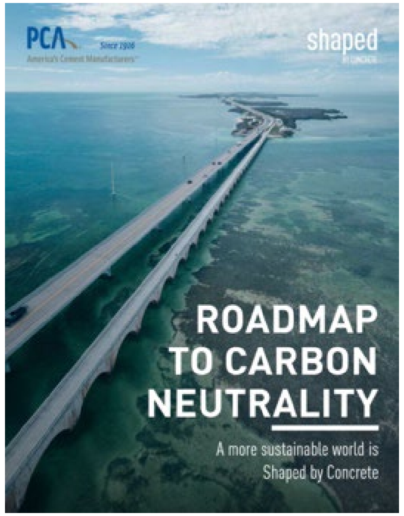
Larry Sutter Ph.D., P.E., F.ACI, F.ASTM

Principal Engineer
Sutter Engineering LLC
Houghton MI 49931

Professor Emeritus and Research Professor
Materials Science & Engineering
Michigan Technological University, Houghton MI

Everyone has a Roadmap

- The cement and concrete producers are committed to being net carbon neutral by 2050
- Common elements - address the carbon footprint across the entire concrete value chain
- Long-term (10-30 years out) - modification of cement production including carbon capture, utilization, and storage (CCUS)
- **Near term (next 5-10 years)** - significant progress must be achieved through enhancements in concrete production and use.

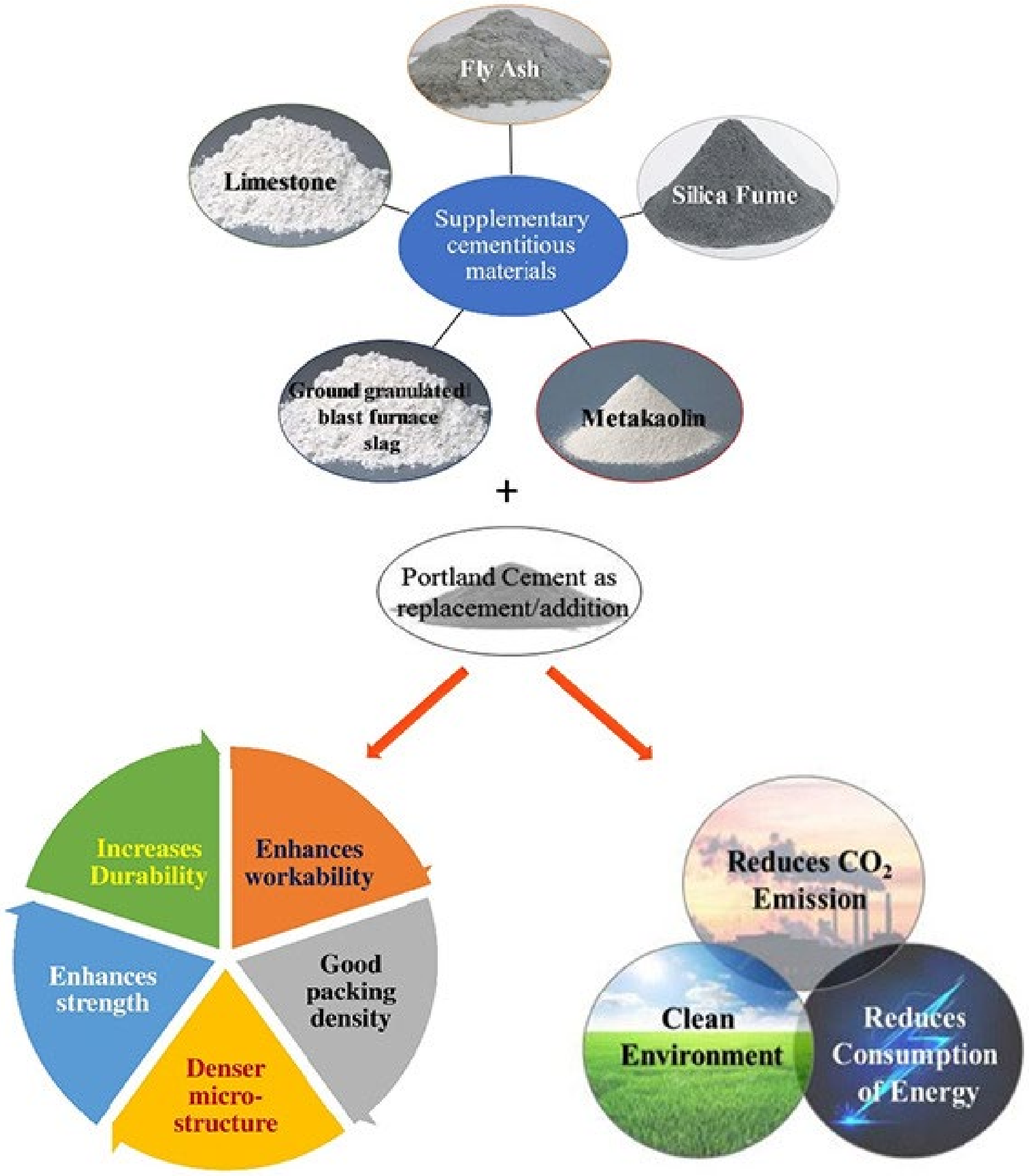


sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Pathways

- To achieve industry-wide carbon reduction goals, changes are needed.

- Increased use of SCMs,
- Use of alternative SCMs,
- Reduced cementitious contents in concrete, and
- More thoughtful use of concrete.



Anurag, R.K., S. Goyal, A. Srivastava. (2021) A comprehensive study on the influence of supplementary cementitious materials on physico-mechanical, microstructural and durability properties of low carbon cement composites. Powder Technology, Volume 394, Pp. 645-668.

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Near Term Boundary Conditions - Cement

- **Near-term (next 5-10 years)** - any **new cementitious product** introduced to replace portland cement, partially or fully, must:
  - Fit within the existing storage and shipping infrastructure of the cement and concrete industry,
  - Allow concrete producers to use the new material in existing concrete production facilities, and
  - Be competitive in cost to portland cement.

sutter engineering llc NCE mn DEPARTMENT OF TRANSPORTATION

Near Term Boundary Conditions - Concrete

- **Near-term (next 5-10 years)** - Changes made to **concrete and concrete-making materials** must:
    - Allow concrete designers to specify and design using the new concrete materials or mixtures, as they specify concrete today,
    - Allow concrete contractors to convey, place, finish, and "cure" the resulting concrete in a similar way as they use concrete today, and
    - Be competitive in cost to portland cement concrete.

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

The Path Forward for Concrete Carbon Reduction

Less clinker in cement, less cement in concrete, less concrete in construction

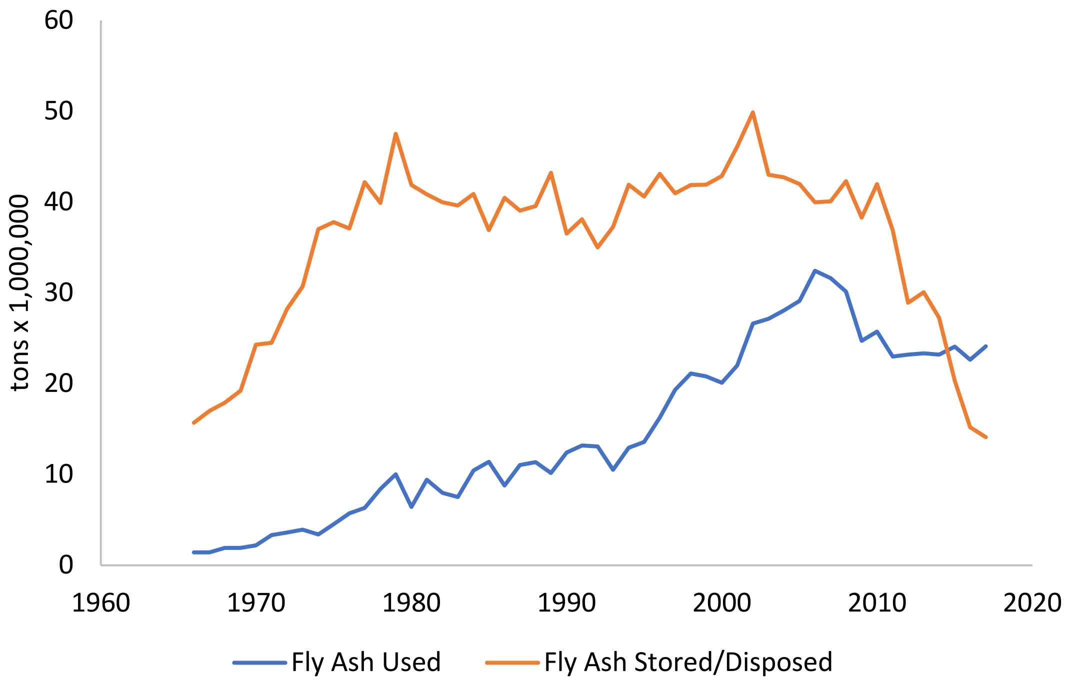
- Replace clinker content in cement
- Use less cementitious materials
- Optimize designs & implement new designs

sutter engineering llc NCE mn DEPARTMENT OF TRANSPORTATION

The Path Forward for Concrete Carbon Reduction

Less clinker in cement, less cement in concrete, less concrete in construction

- Replace clinker content in cement
  - Use blended cement (ASTM C595) or replace clinker with supplementary cementitious materials (SCMs) at concrete plant
  - Need significant increases in SCM use
    - Harvested ash
    - Slag cement
    - Alternative SCMs

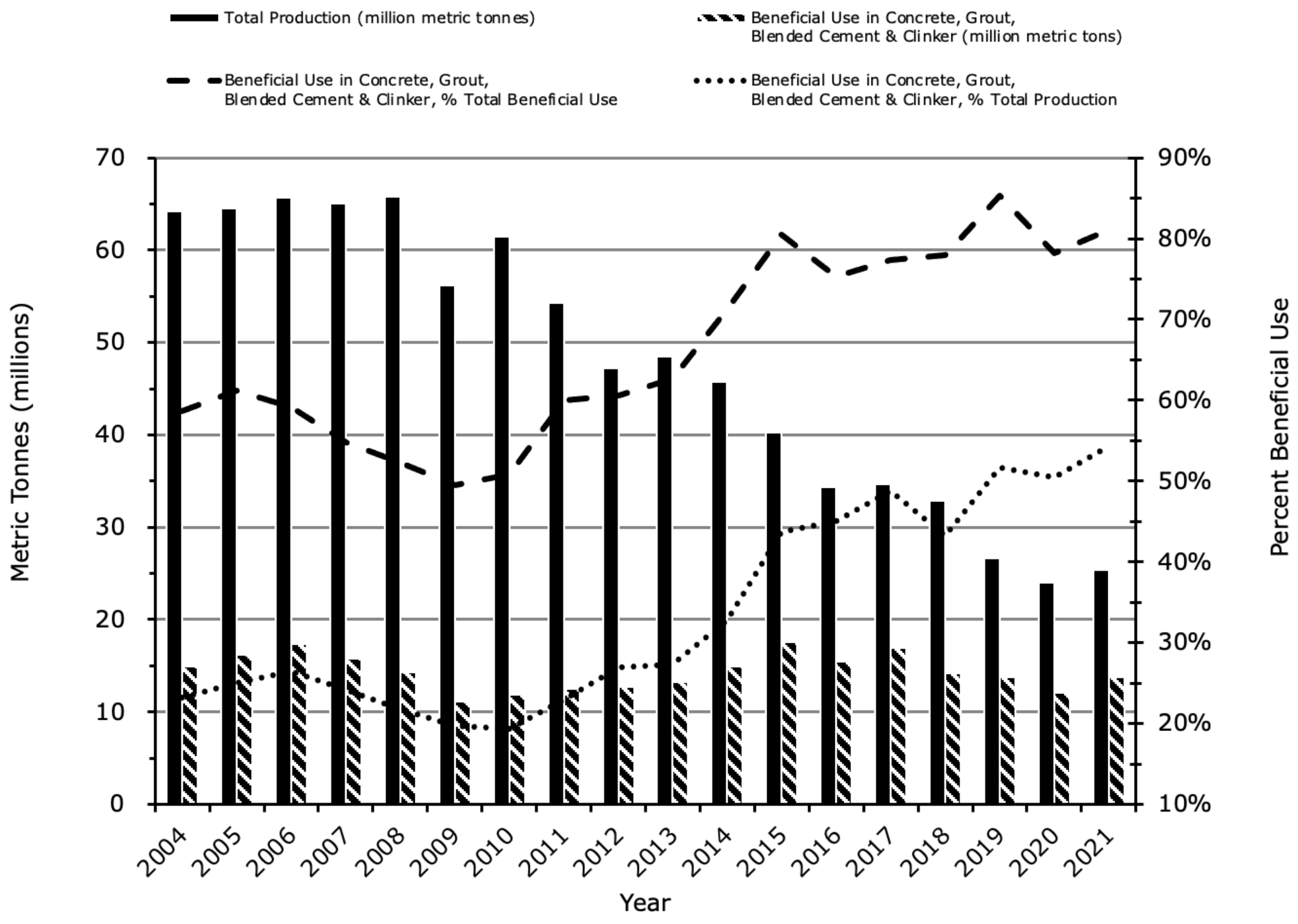


sutter engineering llc

NCE

DEPARTMENT OF TRANSPORTATION

Increase SCM Use?



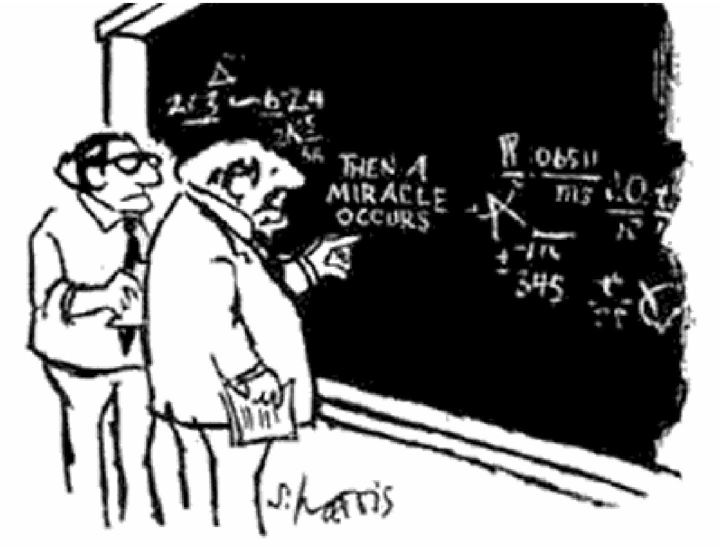
sutter engineering llc

NCE

DEPARTMENT OF TRANSPORTATION

Alternative Materials – Silver Bullet?

- Part of the solution – Particularly for supplementary cementitious materials (SCMs)
- Less so for cements (near term)
- Conventional materials in decreasing supply
  - Fly ash (decreasing coal power)
  - Slag (decreasing blast furnaces)
- Performance – can be better
- Carbon reduction and sequestration
- Increased uniformity possible

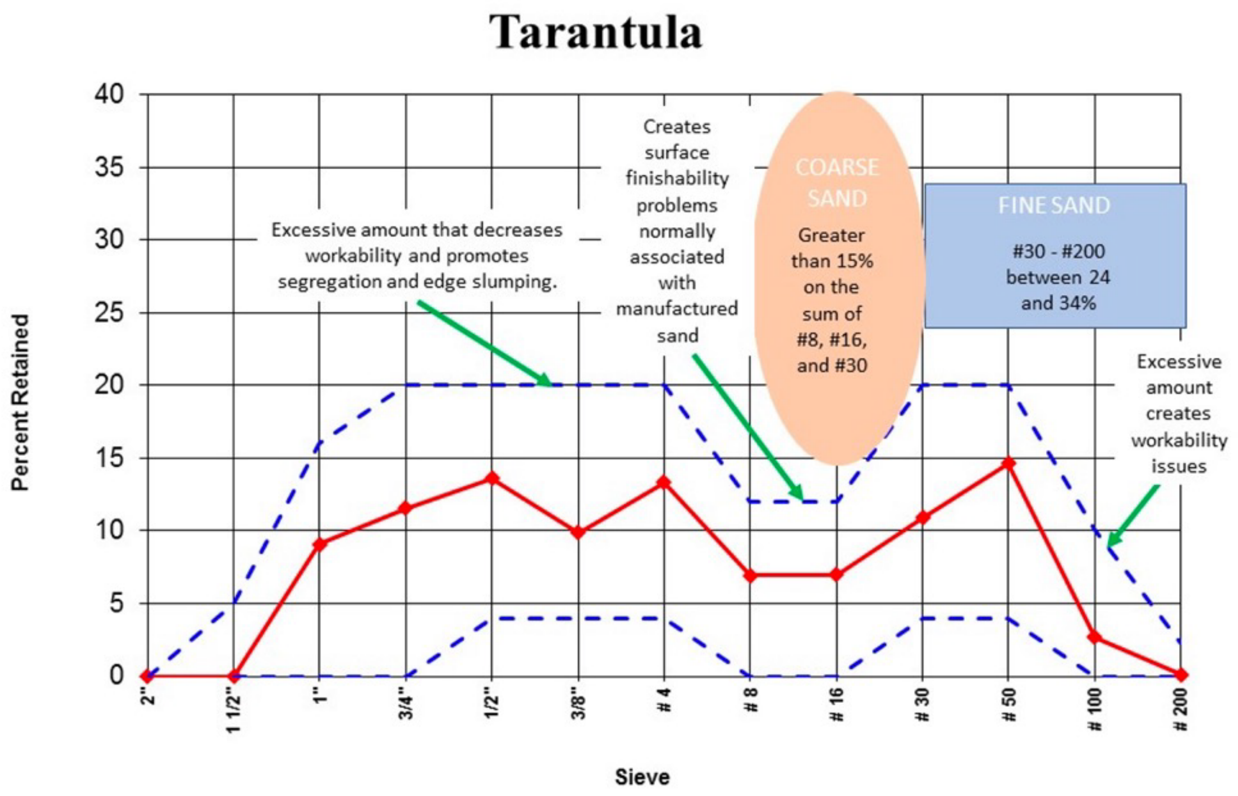


"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

The Path Forward for Concrete Carbon Reduction

Less clinker in cement, less cement in concrete, less concrete in construction

- Use less cementitious materials
  - Optimized aggregate grading
  - Lower cementitious content
  - Cement contents in general are higher than required



After Tyler Ley

sutter engineering llc

NCE

mn DEPARTMENT OF TRANSPORTATION

The Path Forward for Concrete Carbon Reduction

Less clinker in cement, less cement in concrete, less concrete in construction

- Optimize designs & implement new designs
  - Use new materials and designs to achieve reductions in cement content
  - Example : Ultra High-Performance Concrete (UHPC)
  - Known since early 90's
  - 2x the cement; 0.25x concrete, net 50% reduction

sutter engineering llc

NCE

mn DEPARTMENT OF TRANSPORTATION

The Path Forward for Concrete Carbon Reduction

Less clinker in cement, less cement in concrete, less concrete in construction

- Replace clinker content in cement
- Use less cementitious materials
- Optimize designs & implement new designs

- Barriers
  - Minimum cement specifications
  - Testing limitations
  - SCM availability
  - Design limitations
  - Codes
  - Educating stakeholders
  - Cost (Time)
  - Risk – Real & Perceived

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

The Path Forward for Concrete Carbon Reduction

Less clinker in cement, less cement in concrete, less concrete in construction

- Replace clinker content in cement
- Use less cementitious materials
- Optimize designs & implement new designs

- Barriers
  - Minimum cement specifications
  - Testing limitations
  - SCM availability
  - Design limitations
  - Codes
  - Educating stakeholders
  - Cost (Time)
  - Risk – Real & Perceived

RISK!!

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Risk - Life Safety

- Risk is a primary barrier to innovation
- Risk can be broadly organized into two categories: life-safety risk and the very broad category of economic risk.
- Life safety is not negotiable; the primary focus of building codes.

sutter engineering llc

NCE

DEPARTMENT OF TRANSPORTATION

Economic Risk

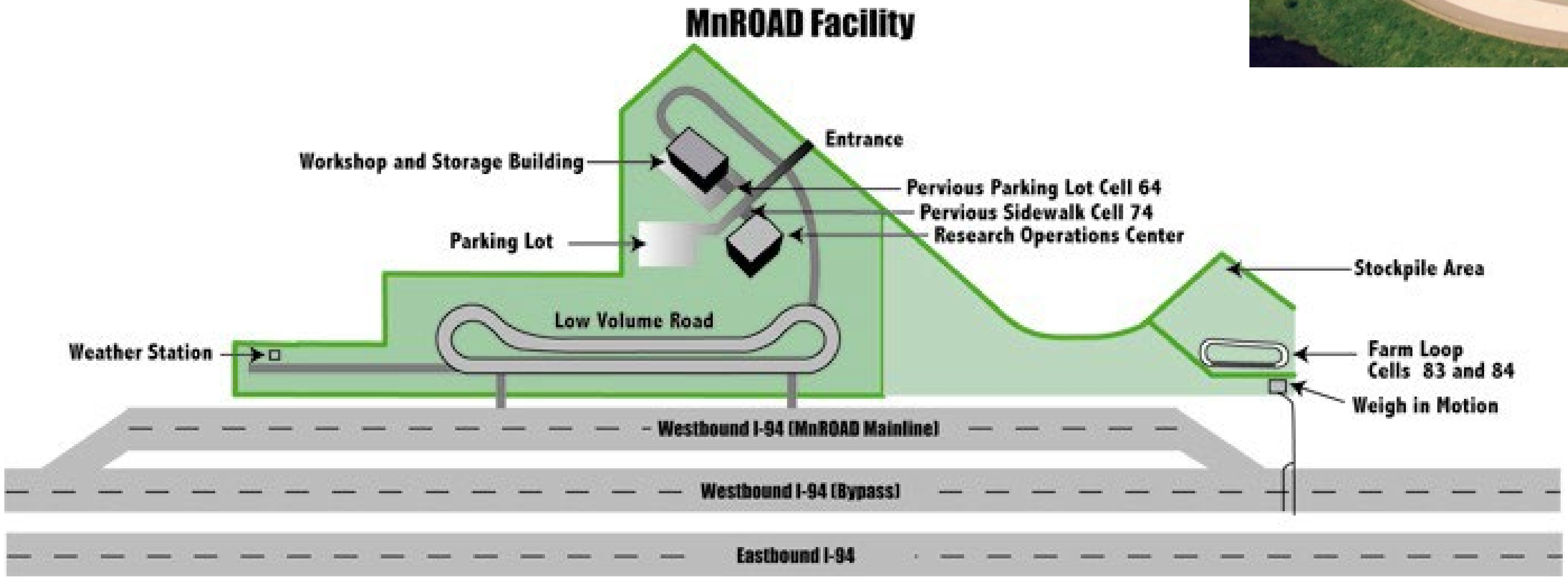
- Suppliers and contractors - risk when changes occur that lead to lost profitability by negatively impacting productivity or the ability to achieve full payment for their work.
- Owners - risk from loss in functionality, increased maintenance, and reduced service life if the changes result in poorer material performance.
- Adoption of new concrete materials technologies can only be advanced if the risk is either mitigated or shared.
- A non-equitable distribution of perceived risk can result in overdesign or high cost.

How to Mitigate the Risk?

- Education/Training
- Financial Incentives
- Changes in Contracting
- Performance Specifications (that include sustainability goals)
- Demonstration Projects

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

This Brings Us to MnROAD



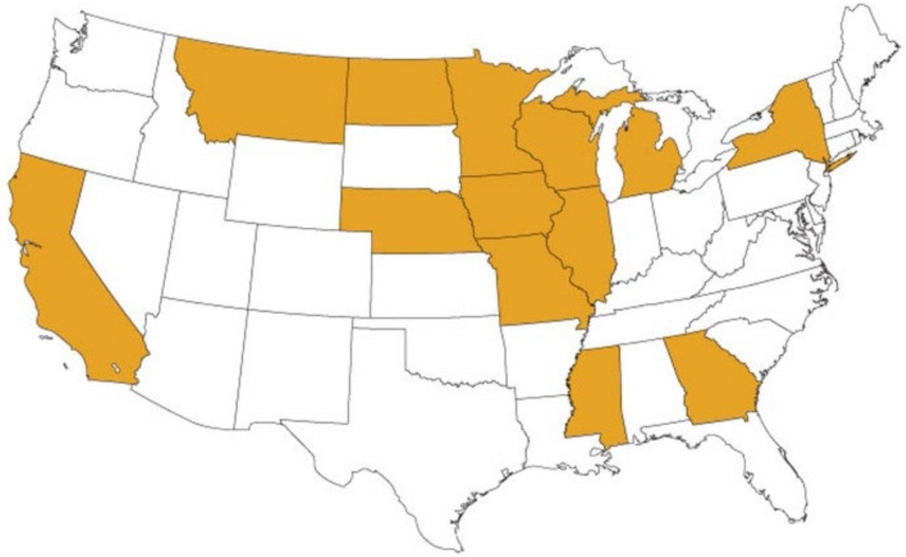
Constructed 1990-93

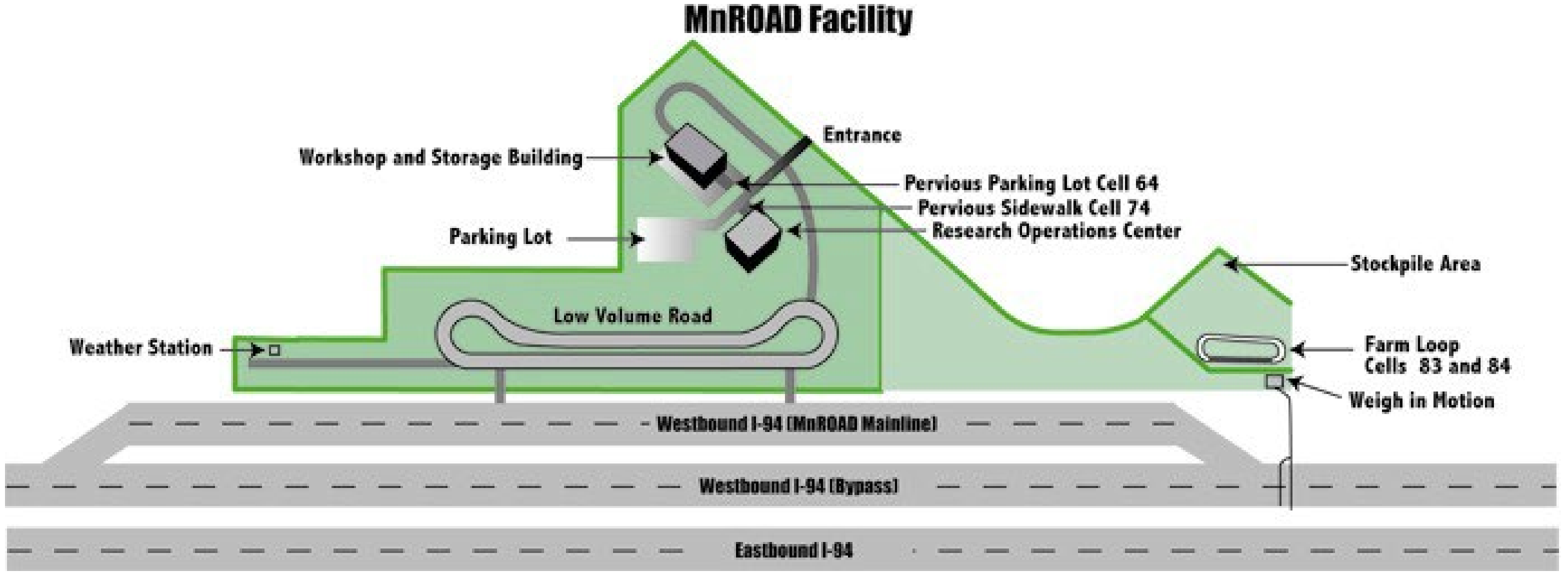
A partnership between Minnesota Department of Transportation and the Minnesota Local Road Research Board

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

MnROAD - NRRA

- 3.5 mile of I-94 operated by **MnDOT**
- Partnership with the **National Road Research Alliance (NRRA)**
- 11 states, 50 industries, associations, and academia
- Designed to test new technologies in a real-world environment





sutter engineering llc NCE mn DEPARTMENT OF TRANSPORTATION

Project Ramp-Up

- MnDOT contracted with NCE and Sutter Engineering LLC to help structure and execute the experiment
  - Identify materials providers
  - Establish mixture requirements
  - Manage trial batching
  - Coordinate logistics (i.e., herd cats)
  - Structure the testing program to support the desired research

sutter engineering llc NCE mn DEPARTMENT OF TRANSPORTATION

Project Requirements

- General Requirements
  - Portland cement mixtures will use an ASTM C595 Type IL(10) blended cement
  - Mixtures shall meet performance requirements based on AASHTO R 101 Developing Performance Engineered Concrete Pavement Mixtures *(required 500 psi flex @ 28 days, 5-8% air)*
  - Batched and mixed at a central ready mixed plant and paved using conventional slip-form paving equipment

sutter engineering llc NCE mn DEPARTMENT OF TRANSPORTATION

Possible Technologies - Alternative SCMs

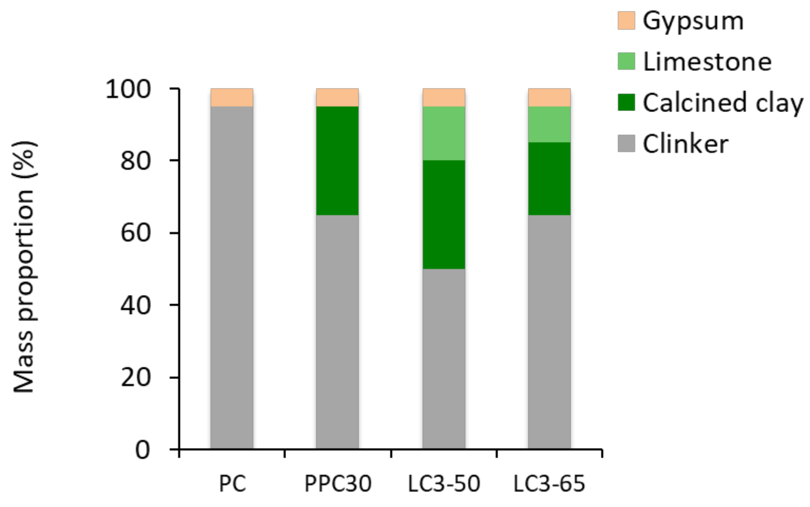
- Harvested coal ash
  - From landfills and ponds
  - Mix of fly ash and bottom ash
  - Requires processing
- Ground glass pozzolan
  - ASTM C1866
- Manufactured SCMs
  - ASTM is working on standards for alternative SCMs

© Boral Resources 2019, used with permission

sutter engineering llc NCE mn DEPARTMENT OF TRANSPORTATION

Possible Technologies - Alternative Cements

- Non-traditional blended hydraulic cements
  - LC3 – portland cement, ground limestone, calcined clay,
  - High-limestone replacement blended cements
- Alkali-activated hydraulic cements
  - Alkali activator – liquid or powder; hydration occurs
  - Precursor containing calcium and alumino-silica minerals
    - e.g., Class C fly ash, slag cement
- Alkali-activated non-hydraulic cements (geopolymers)
  - Alkali-activated non-hydraulic reaction based on low calcium alumino-silica minerals
  - Dissolution and polymerization process



LC^3 is a family of cements, the figure refers to the **clinker** content

K. Scrivener, 2020

sutter engineering llc   NCE   mn DEPARTMENT OF TRANSPORTATION

Final Test Site Construction

- Test cells were constructed at MnROAD to evaluate strategies to reduce GHG emission in concrete paving
- 16 test cells
  - 2 control cells
  - 1 optimized mixture (based on control)
  - 3 CarbonCure™ cells
  - 8 alternative SCM cells
  - 2 alternative cements
- Construction completed August 2022

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Project Specific Mixtures

- **Control Mixtures** – Standard MnDOT paving mixture
  - 570 pcy total cementitious with 30% Class F fly ash (Coal Creek)
  - Water-to-cementitious materials ratio of 0.40
- Two control mixtures were needed to accommodate carbon mineralization study
  - One control mixture and the three CarbonCure™ cells will use one set of constituent materials
  - Other control mixture and remaining cells will use another set of constituent materials

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Project Specific Mixtures

- **Optimized Mixture** – designed with conventional materials with reduced cementitious materials content
  - Mixture Design by Iowa State University (P. Taylor)
  - Mixture Design – 501 pcy total cementitious; 30% Coal Creek Class F
- **CarbonCure™**
  - One mixture designed by CarbonCure™ with CO_2 injection – 558 pcy total cementitious; 30% Coal Creek Class F
  - Same mixture as above without the CO_2 injection
  - Control mixture with CO_2 injection

Project Specific Mixtures - ASCMs

- **Carbon Upcycling**
  - Fly ash processed by grinding in a pressurized carbon-rich environment
  - Mixture Design – 500 pcy total cementitious; 30% treated ash
- **Urban Mining**
  - Ground-glass pozzolan meeting ASTM C1866
  - Mixture Design – 570 pcy total cementitious; 30% GGP
- **TerraCO2**
  - Manufactured SCM resembling fly ash
  - Mixture Design – 570 pcy total cementitious; 35% manufactured ASCM

Alternative SCMs - Examples

- ***Carbon Upcycling***
- Patented technology (reactor)
- Ball milling of the material in a CO_2 environment
- Size reduction plus carbonation of components in the ash
- Claim the process works with fly ash, bottom ash, slag, ground glass, natural pozzolans and other natural minerals (e.g., talc)

20 tonne reactor

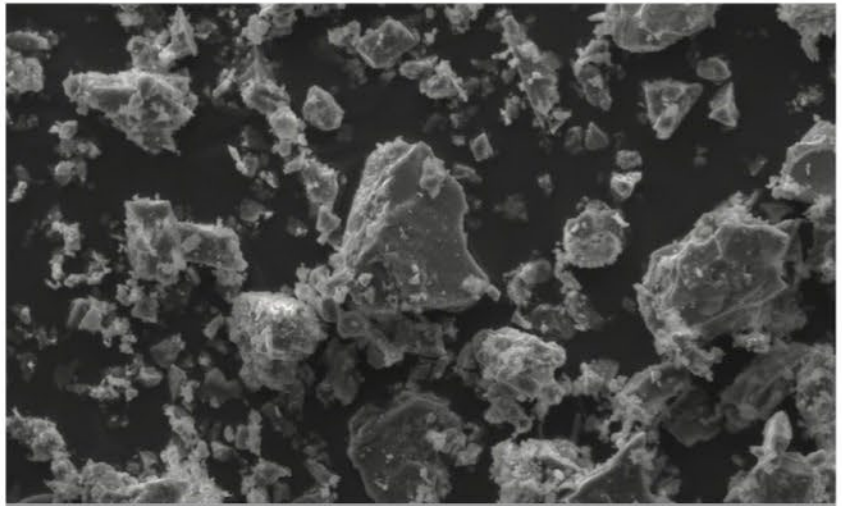
sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Project Specific Mixtures - ASCMs

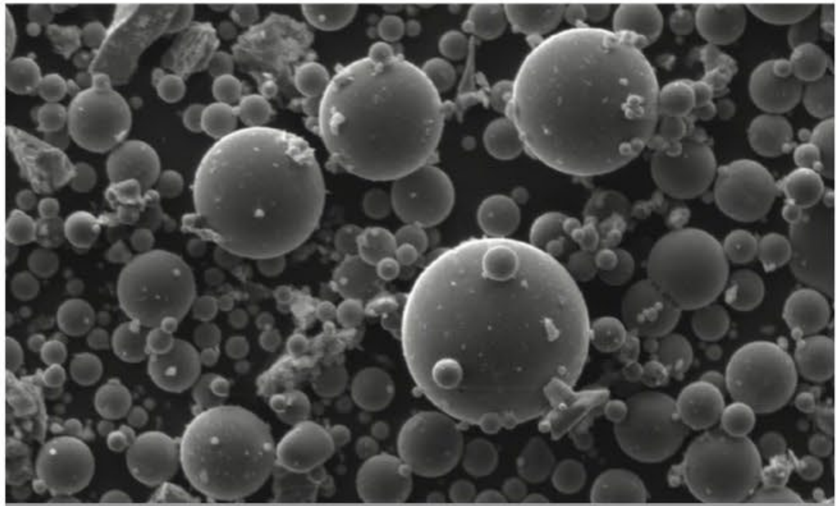
- **Carbon Upcycling**
  - Fly ash processed by grinding in a pressurized carbon-rich environment
  - Mixture Design – 500 pcy total cementitious; 30% treated ash
- **Urban Mining**
  - Ground-glass pozzolan meeting ASTM C1866
  - Mixture Design – 570 pcy total cementitious; 30% GGP
- **TerraCO2**
  - Manufactured SCM resembling fly ash
  - Mixture Design – 570 pcy total cementitious; 35% manufactured ASCM

Alternative SCMs - Examples

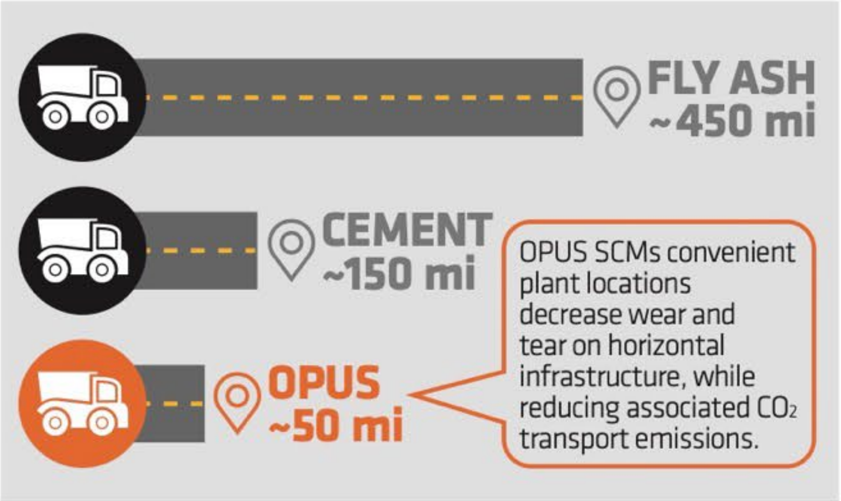
- ***Company: TerraCO2***
- Synthetic fly ash
- Taking rock with a composition similar to Class F ash, partially melting, cooling in an air stream to form spherical glass particles
- Composition, structure, morphology, particle size all mimic Class F ash



SEM image of raw feedstock at 1600x



SEM image of OPUS SCM at 1600x



Transport emissions: State of Colorado example

Project Specific Mixtures - ASCMs

- **Carbon Limit**
  - Proprietary material, ground limestone, natural pozzolan
  - Mixture Design – 570 pcy total cementitious; 30% ASCM
- **Hess Pumice**
  - Pumice-based natural pozzolan meeting ASTM C618
  - Mixture Design – 570 pcy total cementitious; 30% pozzolan
- **3M**
  - Baghouse dust from shingle granules; natural pozzolan meeting ASTM C618
  - Mixture Design – 570 pcy total cementitious; 15% 3M pozz, 15% Portage Station Class F
- **Burgess Pigments**
  - Metakaolin natural pozzolan
  - Mixture Design – 570 pcy total cementitious; 12% metakaolin, 18% Coal Creek Class F

Alternative SCMs - Examples

- ***Company: Carbon Limit***
- Non-calcined mineral admixture
- Replaces cement
- Adds a catalyst to increase CO_2 uptake
- Claims to adsorb more CO_2 in hardened state than portland cement concrete

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Project Specific Mixtures - ASCMs

- **Carbon Limit**
  - Proprietary material, ground limestone, natural pozzolan
  - Mixture Design – 570 pcy total cementitious; 30% ASCM
- **Hess Pumice**
  - Pumice-based natural pozzolan meeting ASTM C618
  - Mixture Design – 570 pcy total cementitious; 30% pozzolan
- **3M**
  - Baghouse dust from shingle granules; natural pozzolan meeting ASTM C618
  - Mixture Design – 570 pcy total cementitious; 15% 3M pozz, 15% Portage Station Class F
- **Burgess Pigments**
  - Metakaolin natural pozzolan
  - Mixture Design – 570 pcy total cementitious; 12% metakaolin, 18% Coal Creek Class F

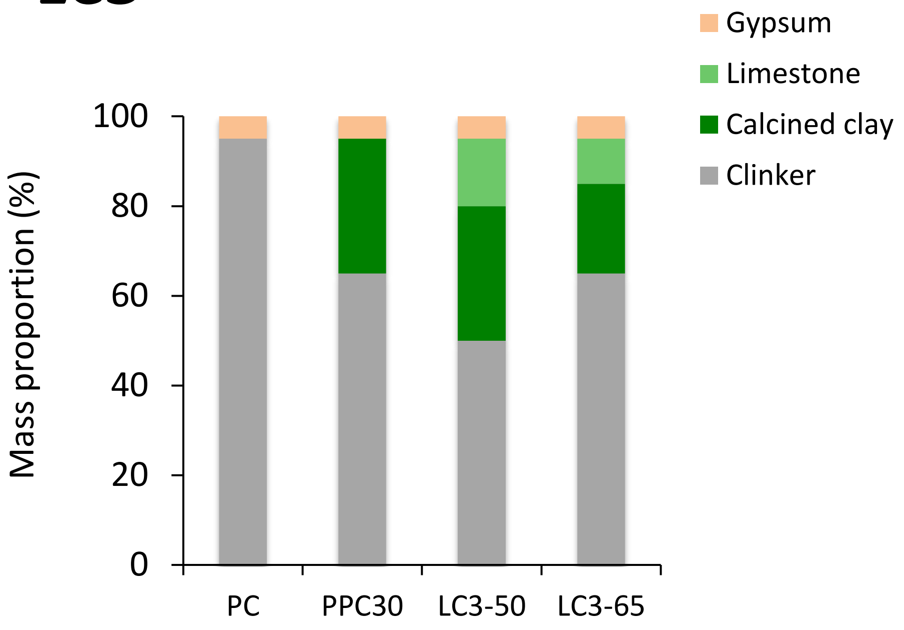
Project Specific Mixtures - ACMs

- **Ash Grove – IP(30)**
  - Thought we were getting LC3 using 50% clinker, 30% calcined clay, 15% limestone
  - Mixture Design – 570 pcy total cementitious using calcined clay as the pozzolan
- **Continental Cement – High Limestone [Type IL(20)]**
  - Blended cement with 20% limestone, 30% Class F ash
  - Mixture Design – 570 pcy total cementitious
- **UltraHigh Materials**
  - 0% portland cement clinker-based hydraulic cement (meets ASTM C1157)
  - Mixture Design – 650 pcy total cementitious

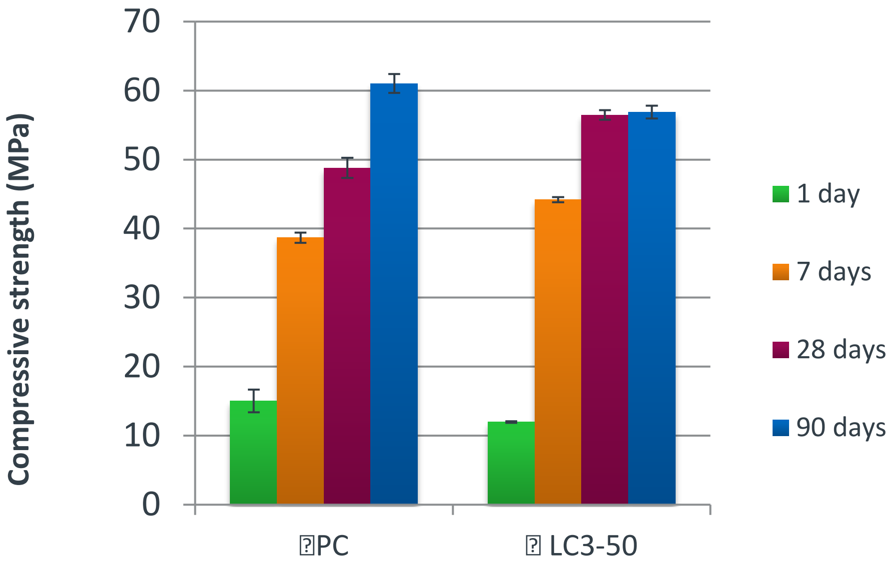
sutter engineering llc NCE mn DEPARTMENT OF TRANSPORTATION

Alternative Cements - Examples

- ***LC3***



LC^3 is a family of cements,
the figure refers to
the **clinker** content



- 50% less clinker
- 40% less CO_2
- Similar strength
- Better chloride resistance
- Resistant to alkali silica reaction

K. Scrivener, 2020

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Project Specific Mixtures - ACMs

- **Ash Grove – IP(30)**
  - Thought we were getting LC3 using 50% clinker, 30% calcined clay, 15% limestone
  - Mixture Design – 570 pcy total cementitious using calcined clay as the pozzolan
- **Continental Cement – High Limestone [Type IL(20)]**
  - Blended cement with 20% limestone, 30% Class F ash
  - Mixture Design – 570 pcy total cementitious
- **UltraHigh Materials**
  - 0% portland cement clinker-based hydraulic cement (meets ASTM C1157)
  - Mixture Design – 650 pcy total cementitious

Alternative Cements - Examples

- ***Company: Continental Cement***
- Blended cement with 20% limestone replacement

4. Classification

4.1 This specification applies to the following types of blended cement that generally are intended for use as indicated.

4.1.1 Blended hydraulic cements for general concrete construction.

4.1.1.1 *Type IS*—Portland blast-furnace slag cement.

4.1.1.2 *Type IP*—Portland-pozzolan cement.

4.1.1.3 *Type IL*—Portland-limestone cement.

4.1.1.4 *Type IT*—Ternary blended cement.

INTERNATIONAL

Designation: C595/C595M – 21

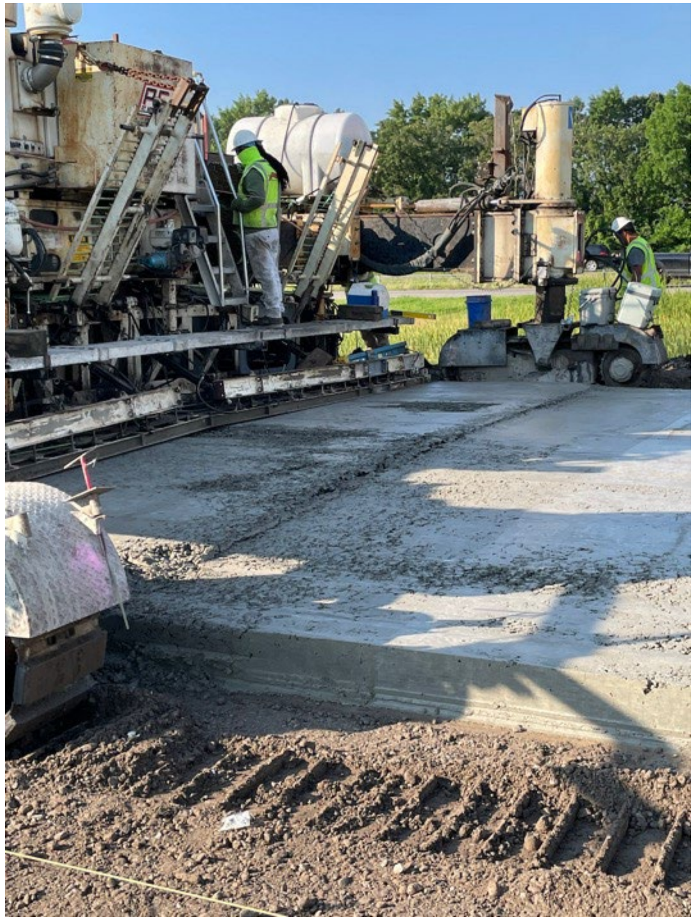
Standard Specification for Blended Hydraulic Cements[1]

7.1.5 *Portland-limestone Cement*—Portland-limestone cement shall be a hydraulic cement in which the limestone content is more than 5 % but less than or equal to 15 % by mass of the blended cement.

Project Specific Mixtures - ACMs

- **Ash Grove – IP(30)**
  - Thought we were getting LC3 using 50% clinker, 30% calcined clay, 15% limestone
  - Mixture Design – 570 pcy total cementitious using calcined clay as the pozzolan
- **Continental Cement – High Limestone [Type IL(20)]**
  - Blended cement with 20% limestone, 30% Class F ash
  - Mixture Design – 570 pcy total cementitious
- **UltraHigh Materials**
  - 0% portland cement clinker-based hydraulic cement (meets ASTM C1157)
  - Mixture Design – 650 pcy total cementitious

Construction



Everyone learned a lot…

sutter engineering llc

NCE

DEPARTMENT OF TRANSPORTATION

The Research

- Three research teams have been selected by NRRA
- Data from construction obtained by local testing firm and FHWA Mobile Trailer
- Post-construction testing will be performed by local firm and FHWA Turner-Fairbank
- Research teams will monitor pavement performance over 2 years
- Teams will report on performance including LCA

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

NRRA Research Projects

- Use of Carbon Dioxide for Sustainable and Resilient Concrete Pavements – *Iowa State University*
- Use of Alternative Pozzolanic Materials Towards Reducing Cement Content in Concrete Pavements – *APTech*
- Use of Alternative Cementitious Materials in Concrete Pavements – *NCE*

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Closing Thoughts

- Off the shelf technologies exist to achieve a 50% clinker reduction or more
- Does not require alternative materials; however
- Alternative materials can help achieve more significant reductions

sutter engineering llc NCE DEPARTMENT OF TRANSPORTATION

Questions?

llsutter@mtu.edu

or

sutter.engineering@gmail.com

sutter engineering llc

periculosum est tempus indoctus