Sustainability of Concrete for Infrastructure

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Overview

• Background and research at OSU
• Sustainability and the link to durability
• What limits sustainability in concrete materials?
  – Degradation: Alkali-silica reaction
  – Environmental Impacts
• What can we do about it?
  – Augmenting current materials
  – Materials that show promise for the future
  – Selected resources
• Perspectives
Research Emphasis

• Development of new and augmentation of existing engineering materials:
  – Resistance to aggressive environments
  – Need for infrastructure rehabilitation and rapid repair
  – Instrumentation and monitoring to track performance

• Testing methods for assessing long-term performance
  – Accelerated laboratory tests
  – Bench marking of long-term data is crucial to actual field performance

• Focus on increasing durability of cement-based materials
  – Combined Forms of Attack
    • Alkali-silica reaction
    • Sulfate attack (internal and external)
    • Freeze-thaw deterioration
    • Corrosion
  – Sustainability driven
Research Sponsors

US Navy, NAVFAC – ESC:
- Technologies and Methodologies to Prevent Alkali-Silica Reaction in New Concrete

Oregon Department of Transportation (ODOT)
- Internal Curing of Concrete Bridge Decks

Northwest Transportation Consortium (NWTC)
- Impact of Climate Change on Pacific Northwest and Alaska Transportation Infrastructure

Oregon Transportation Research and Education Consortium (OTREC)
- Durability Assessment of Recycled Concrete Aggregates
Courses

(F) CE 526 – Advanced Concrete Materials
Cement chemistry, microstructure, dimensional stability, durability

(W) CCE 422/522 - Green Building Materials
Critical evaluation of the entire construction process to determine if materials are truly “green”

(S) CCE 321 – Civil and Construction Materials
Aggregates, asphalt, concrete, wood, steel

Images: www.stollervineyards.com
PCA Archives
How does this relate to civil engineering materials?

Durability – meeting serviceability requirements
Life-cycle analysis
Systems approach (versus a component approach)
Long-term planning is crucial but often avoided

$$$
### Scope and Extent of Infrastructure Problem

Grades given by the American Society of Civil Engineers (ASCE)

<table>
<thead>
<tr>
<th>2005</th>
<th>2009</th>
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<tbody>
<tr>
<td>• D infrastructure over all grade</td>
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<td>• $1.6 Trillion estimated investment (5 yr)</td>
<td>• $2.2 Trillion estimated investment (5 yr)</td>
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For developed countries, 40-50%++ of annual construction budget is for repair/rehabilitation.

Problems are only getting worse...

We Need Solutions

– New construction
  ✓ Must be durable, sustainable
  ✓ Improved and innovative materials

– Existing structures in need of repair
  ✓ “Get in, Get out, Stay out!”
  ✓ Innovative materials
  ✓ Rapid repair materials
  ✓ Innovative repair strategies
  ✓ These materials and methodologies must exceed the performance of current materials
Cement and Concrete Production

• Concrete is the most widely used material on earth is produced at over 6 km$^3$ per year or at least 1 m$^3$ per person*

• Cement production $\approx 1.7 \times 10^9$ ton/year*

• For 1 m$^3$ of concrete about 0.2 t of CO$_2$ are produced, mostly from the production of portland cement*

Cement Production

Responsible for 5-7% of the world's CO$_2$ production

Lafarge – largest cement manufacturer in the world

—Committed to reduce total global CO$_2$ by **15%** and to reduce its average CO$_2$ emission per ton of cement by **20%** by 2010*

Sustainability and Concrete -- the good news...

- Concrete has a very low “Embodied Energy”
- Enables designers to design very efficient structures
  - Thermal mass can moderate temperature fluctuations
  - Light colours reflect heat and light
- Cement and concrete can be made with a lot of recycled materials
- Concrete typically produces structures with low maintenance
  - Durability
- High strength can reduce the amount of concrete required
- Concrete is recyclable
Concrete Has Low Embodied Energy

Relative Energy Requirements for Construction Materials

Source: “The Cement Industry’s Contribution to Canada’s Green Plan” CPCA
June 1991
What limits the sustainability of concrete?

- Corrosion
- Alkali-silica reaction
- Freeze-thaw attack
- Sulfate attack
  - Internal (delayed ettringite formation)
  - External (sulfate containing soils and groundwater)
Alkali – Silica Reaction

- 3 constituents required
  - Reactive source of silica (amorphous vs. crystalline)
  - Alkalis (Na$^+$ and K$^+$ from cement)
  - Moisture

- Reaction occurs between the OH$^-$ ions in the pore solution and the reactive silica phase. The released silica then combines with alkalis to form ASR gel.
- This gel imbibes water and swells resulting in tensile forces throughout the concrete matrix resulting in cracking
Mechanism of Cracking due to ASR

When the expanding pressure exceeds the tensile strength of the concrete, the concrete cracks.
Mitigating ASR in Hardened Concrete

Treat the Symptom
• Fill Cracks
  • Aesthetics
  • Protection (e.g. Cl\textsuperscript{-} ingress)
• Restraint
  • Prevent expansion
  • Strengthen and stabilize
• Stress Relief

Treat the Causes
(Mitigate deleterious reaction)
• Drying
  • Sealants
  • Cladding
  • Improved drainage
• Chemical Injection
  • Lithium Salts
Repair Strategies – Treat the Causes

Silane Coating

- Prevents water ingress during wet periods and dries concrete during dry periods
- Applied by painting or spray application
- Treatment often coupled with crack filling
- Structure maintains historical appearance
Repair Strategies – Treat the Causes

Lithium Nitrate (LiNO$_3$)

Applied via Topical Application

- LiNO$_3$ penetrates cracked concrete surface
- Applied by atomizing spray application
- Structure maintains historical appearance

Applied via Vacuum Impregnation

- LiNO$_3$ penetrates by vacuum pressure
- Vacuum applied for 1 hour
- Structure maintains historical appearance
Repair Strategies – Treat the Causes

Lithium Nitrate ($\text{LiNO}_3$)

Applied via Topical Application
Depth of Lithium Penetration

Applied via Vacuum Impregnation
Depth of Lithium Penetration

![Graphs showing concentration and lithium levels over depth](image)
Bridge Structure in Houston, Texas

Bridge column in Houston, TX
Constructed ~2002
Made with RCA
RCA source had ongoing ASR

OTREC – RCA Project at OSU
Phase I/II
Characterization/Mitigation
Best Practices
Asset Management Database
Repair Strategies – Treat the Causes

**Lithium Nitrate (LiNO$_3$)**
Applied via Electrochemical Treatment

- Ingress of Li$^+$ ions by electrical current
- Treatment duration 4 – 8 weeks
- After treatment structure maintains historical appearance

Source: Whitmore, Vector Construction Group
Repair Strategies – Treat the Causes

Lithium Nitrate (LiNO₃)
Applied via Electrochemical Treatment

Profile of Alkali Ions (Li, Na & K)

![Graph showing the profile of alkali ions (Li, Na & K) in concrete at different depths.](image-url)
Repair Strategies – Treat the Symptoms

Carbon Fiber Reinforced Polymer (CFRP)

- Restrain expansion of concrete
- Elements are wrapped with CFRP fabric for service life of structure
- Structure façade altered
Case Study - Background

Bibb Graves Memorial Bridge
Location: Wetumpka, Alabama
Completion: 1929 – 1930
Case Study – Monitoring Techniques

Monitoring:
- Expansion measurements
- Qualitative crack mapping
- Core extraction
  - Petrography Evaluation
  - Damage Rating Index
  - Thin Section Examination
  - Concrete Equivalent Alkali Content
Case Study – Residual ASR Expansion

Bibb Graves Memorial Bridge
Arch 3 Core 5

Time (days)

Avg. Expansion (%)

Bibb Graves Memorial Bridge
Arch 4 Core 2

Time (days)

Expansion (%)
Case Study - Structure Status and Recommendations

- Severe and moderate damage in two of four arches
- Residual expansion testing indicates likely continued deterioration
- Continued monitoring
- Remediation
  - Crack filling with epoxy injection on top of arch
  - Silane coating on sides recommended to maintain historical attributes
# Repair Strategies - Summary

<table>
<thead>
<tr>
<th>Monitoring Techniques</th>
<th>Historical Integrity</th>
<th>Structural Integrity</th>
<th>Durability Integrity</th>
<th>Repair Effectiveness</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Silanes</td>
<td>++</td>
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<tr>
<td>Crack Filling/Silanes</td>
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<td>LiNO₃ via Topical Application</td>
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<td>LiNO₃ via Electrochemical</td>
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## Rating Scale:

| + + | Excellent |
| +   | Good      |
| +/- | Fair      |
| -   | Poor      |
| --  | Very Poor |
What can be done?

Sustainable development can be achieved by:

– Minimizing resources in producing concrete (e.g., using supplementary cementing materials (SCMs) or other by-products in concrete)

– Ensuring long-term durability (proper design, construction, material selection, etc.)

– Changes to manufacturing and construction processes
The concrete industry uses tons of by-product and waste materials...

Alternative fuels for cement production
  – Tires, some investigations into bio fuels

Supplementary cementing materials (SCMs)
  – Fly ash
  – Slag
  – Silica fume
  – Others – rice husk ash, calcined clay, metakoalin, etc.

Chemical admixtures (many are based on by-products from the wood/paper industry)

Wash water

Recycled concrete (as aggregates)

Others (in small quantities)
Use of SCMs

Supplementary Cementing Materials
fly ash (25-50%), HVFA > 50%
ground granulated blast furnace slag (40-60%)
silica fume (lower quantities 5-8%)
natural pozzolans (10-30%)
   rice husk ash
   metakaolin
   calcined clays
other activated silica bearing materials
Let’s look at fly ash usage as an example

Source: TVA

Source: FHWA Archives

Source: www.btg.com
1966-2007 CCP Beneficial Use v. Production

Source: American Coal Ash Association
EPA Regions 8-9-10 - CCP 2007 Production

**FATonsProd**
- 2,690,622 62.180%

**BATonsProd**
- 1,034,389 23.905%

**FGD Wet Scrub Tons Prod**
- 396,716 9.168%

**FGD Dry Scrub Tons Prod**
- 152,999 3.536%

**FBC Ash Tons Prod**
- 52,400 1.211%

Legend:
- CCP Type
- Short Tons Produced
- Percent of Total Produced

Note: Data is unextrapolated and is derived from actual survey responses.

Source: American Coal Ash Association
Challenges to using fly ash in concrete?

Some ashes do not meet ASTM C 618 (or similar standard)s
  • High carbon content (big impact on air entrainment)
  • High alkali content
    • Issue being addressed in research currently underway at OSU
  • heavy metals contamination (a big issue right now)

Specifications may restrict use of fly ash

Not enough demand in some areas

Availability
Case Study: Mactaquac Generation Station
Mactaquac Generation Station

**Intake Structure**
Grown vertically by 175 mm (2007)
Removed 450 mm of concrete by perpendicular slot cutting
120 to 150 microstrain/year of unrestrained expansion

**Aggregate: Greywacke**
Testing methods at the time showed it was "non-reactive"

**Service Life** - ~150 years, will last ½ that or less
2025 – Complete replacement
Mactaquac Generation Station
Evaluation of Mitigation Options

ASTM C 1567

Concrete prisms (stored above water) at 38°C

1 N NaOH at 80°C

ASTM C 1293
Outdoor Exposure Site Testing

University of Texas at Austin

University of New Brunswick

CANMET/MTL

Treat Island, ME

5 July 2006 Davos, Switzerland
Ultimately decided to use a 40-50% dosage of fly ash
Mactaquac Demonstration Project
Mactaquac Generation Station
Overview

• Background and research at OSU
• Sustainability and the link to durability
• What limits sustainability in concrete materials?
• **Where are we at now?**
  – Augmenting current materials
  – **Materials that show promise for the future**
  – Selected resources

• Perspectives
What else can we do?

• Ordinary portland cement concrete
  – SCMs
  – Proper curing
  – Construction techniques
  – Increased understanding of micro-scale properties to enhance macro-scale performance

• Other Materials?
  – Let’s take a look at one innovative cementitious materials
  – Calcium Aluminate Cement

• Others
  – TiO$_2$ Cements
  – Calera: www.calera.com
Advantages of Calcium Aluminate Cement Concrete (CACC)

Normal setting (adjustable by admixtures)
Rapid hardening (i.e. rapid strength gain)
Resistance to Chemical Attack

acid attack induced by bacteria sulfate attack

PORTLAND Cement completely eroded > 60 mm

CAC max erosion < 10 mm

Sewage linings
12 year field trial, South Africa

Images Courtesy: K. Scrivener
Resistance to Abrasion

Further improved with synthetic aggregate

DIRECT CONSEQUENCE OF CHANGED MICROSTRUCTURAL FORMATION

Images Courtesy: K. Scrivener
CAC with Synthetic Aggregate

Excellent interfacial bond between paste and aggregate

Slide Courtesy: K. Scrivener
Ordinary Portland Cement and Calcium Aluminate Cement

Special Cements do not compete in applications where portland cement performs well, applications justified by advantageous properties.
Usable strength

Schematic: K. Scrivener
Early-Age Volume Change in Rapid Repair Materials

Calcium Aluminate Cement Concrete
Due to high heat generation, concerns with early-age volume change

To reduce the risk:
Conservative construction practices limit this problem
Tight joint spacing, casting in grid patterns (3 m²)
CACC used for pipe linings is steam cured to minimize cracking risk

Current research at OSU
investigate early-age volume change of calcium aluminate cement systems
provide recommendations to the end user for successful application of this material
Selected Resources

• AASHTO – American Association of State Highway and Transportation Officials
  – www.transportation.org/

• ACPA - American Concrete Paving Association
  – www.acpa.org

• ACI – American Concrete Institute
  – www.aci-int.org

• PCA – Portland Cement Association
  – www.cement.org

• Green Highways Initiative
  – www.greenhighways.org

• US Green Building Council - LEED
  – www.usgbc.org/leed
Concrete industry has a responsibility to implement sustainability into the design and construction of concrete structures.

The use of SCMs, recycled materials and different construction and manufacturing processes are a viable means towards sustainable development.

Design for long-term durability!!

Look beyond conventional concrete.

Take advantage of the Green Building movement.
With the buzz words of green building materials, innovative materials and new materials...

Are we really ready for new materials when using existing materials is still challenging?

Should focus on enhancing our existing materials and developing new materials that will exceed the performance of existing materials.

– Long-term performance verification is needed
– Accelerated testing
– Modeling
– Life cycle analysis programs
Thank you!

Questions?