American Concrete Institute®
Advancing concrete knowledge

Multi-Type Durability Attack, Part 1

ACI Fall 2011 Convention
October 16 – 20, Cincinnati, OH

ACI WEB SESSIONS

ACI Web Sessions

The audio for this web session will begin momentarily and will play in its entirety along with the slides.

However, if you wish to skip to the next speaker, use the scroll bar at left to locate the speaker's first slide (indicated by the icon in the bottom right corner of slides 9 and 34). Click on the thumbnail for the slide to begin the audio for that portion of the presentation.

Note: If the slides begin to lag behind the audio, back up one slide to re-sync.

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ACI Web Sessions

ACI is bringing you this Web Session in keeping with its motto of "Advancing Concrete Knowledge." The ideas expressed, however, are those of the speakers and do not necessarily reflect the views of ACI or its committees.

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ACI Web Sessions

ACI Web Sessions are recorded at ACI conventions and other concrete industry events. At regular intervals, a new set of presentations can be viewed on ACI's website free of charge.

After one week, the presentations will be temporarily archived on the ACI website or made part of ACI's Online CEU Program, depending on their content.

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ACI offers an easy-to-use Online CEU Program for anyone who needs to earn Continuing Education credits.

Once registered, you can download and study reference material. After passing a 10-question exam on the material, you will receive a certificate of completion that you can present to local licensing agencies.

Visit **www.concrete.org/education/edu_online_CEU.htm** for more information.

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ACI Conventions

ACI conventions provide a forum for networking, learning the latest in concrete technology and practices, renewing old friendships, and making new ones. At each of ACI's two annual conventions, technical and educational committees meet to develop the standards, reports, and other documents necessary to keep abreast of the ever-changing world of concrete technology.

With over 1,300 delegates attending each convention, there is ample opportunity to meet and talk individually with some of the most prominent persons in the field of concrete technology. For more information about ACI conventions, visit www.aciconvention.org.

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ACI Web Sessions

This ACI Web Session includes 2 speakers presenting at the ACI fall convention held in Cincinnati, OH, October 16 – 20, 2011.

Additional presentations will be made available in future ACI Web Sessions.

Please enjoy the presentations.

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Advancing concrete knowledge

Multi-Type Durability Attack, Part 1

ACI Fall 2011 Convention
October 16 – 20, Cincinnati, OH

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Dr. Kimberly (Kim) E. Kurtis is Professor in the School of Civil and Environmental Engineering at Georgia Institute of Technology, where she joined the faculty in January 1999. Dr. Kurtis earned her B.S.E. (1994) in Civil Engineering from Tulane University under a Deans Honor Scholarship and her Ph.D. (1998) in Civil Engineering from the University of California at Berkeley, where she was a Henry Hilp Fellow and a National Science Foundation (NSF) Fellow. Dr. Kurtis's innovative research on the multi-scale structure and performance of cement-based materials has resulted in more than 100 technical publications and two U.S. patents. In addition to her technical and educational service contributions at the American Concrete Institute (ACI), American Ceramics Society (ACerS), Portland Cement Association (PCA), Transportation Research Board (TRB), American Association of State and Highway Transportation Officials (AASHTO), and Federal Highway Administration (FHWA), she has held two leadership positions – Chair of ACI Committee 236, Materials Science of Concrete (2006-present), and Chair of American Ceramic Society's Cements Division (2008-2009) – central to advancing science-based research on cement-based materials. Dr. Kurtis has served as Associate Editor of ASCE Journal of Materials in Civil Engineering and is Editorial Board member of Cement and Concrete Composites. She has been honored with ACI's Walter P. Moore, Jr. Faculty Achievement Award (2005) and the ACI James Instruments Award for Research on NDE of Concrete (2008). Dr. Kurtis is Fellow of the American Concrete Institute and the American Ceramics Society.

ACI WEB SESSIONS

Audio will begin on next slide

Georgia Institute of Technology

Chemical, Biological, and Physical Deterioration Mechanisms in Concrete Piles Along Georgia's Coastline

Brett Holland

Co-researcher: Robert Moser
Advisors: Drs. Lawrence Kahn and Kimberly Kurtis
Sponsored by: Georgia DOT

10/19/2011

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Objectives

Georgia Institute of Technology

- Objective:
  - Characterize the degradation mechanisms present in prestressed concrete piles exposed to marine environments in Georgia.
- Outline
  - Introduction and Motivation
  - Assessment of Georgia Bridges
    - Inspection Reports
    - Interviews
    - Site visits
  - Forensic Study
    - Chemical Attack
    - Biological Attack
    - Chloride Induced Corrosion
  - Conclusions and Recommendations
  - Future Research

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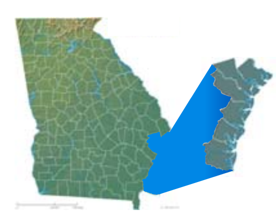
Assessment of Georgia Bridges

Georgia Institute of Technology

- Bridges with concrete substructures over bodies of water along coastal Georgia assessed for deterioration
- Interviewed GDOT maintenance engineers and inspection teams
- Develop understanding of durability concerns in concrete bridges



◆ Introduction Assessment of Georgia Bridges Forensic Study Conclusions Future Work ◆

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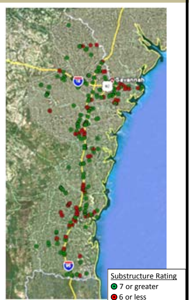
Assessment of Georgia Bridges

Georgia Institute of Technology

- Results cataloged according to NBIS substructure damage state:
  - 85 or 29.3% of coastal bridge substructures with rating of 6 or below
  - 205 had a rating of 7 or greater

Code	Description
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION - structural elements show some minor deterioration.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4	POOR CONDITION - advanced section loss, deterioration, spalling or scour.
3	SERIOUS CONDITION - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.

Cutoff



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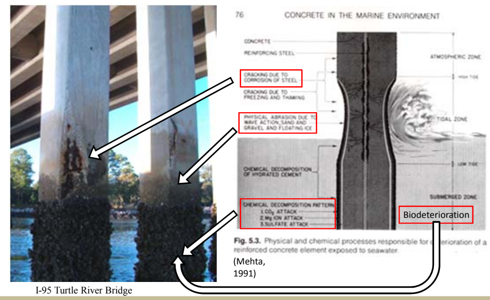
Introduction | Assessment of Georgia Bridges | Forensic Study | Conclusions | Future Work

Mechanisms of Deterioration

Georgia Institute of Technology



I-95 Turtle River Bridge

(Mehta, 1991)

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Reported Damage and Deterioration

Georgia Institute of Technology

- Splash and Tidal Zone Damage:
  - Rust staining
  - Cracking and spalling
  - Exposed rebar

I-95 at Savannah River

Harriett's Bluff Road at Deep Creek Bridge

US 17 at Back River Bridge

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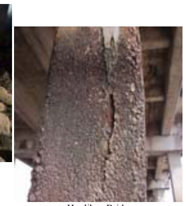
Reported Damage and Deterioration

Georgia Institute of Technology

- Splash and Tidal Zone
  - Surface abrasion due to wave and tidal action
  - Particulates or debris suspended in flow

Harrell Highway at Buffalo Swamp



Houlihan Bridge

Island Expressway at Wilmington River Bridge

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Reported Damage and Deterioration

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- Tidal and Submerged Zone
  - Oyster shell in tidal zone
  - Marine growth in submerged region

Torra's Causeway at Little River

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Reported Damage and Deterioration

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- Submerged Zone
  - Softening of concrete
  - Cracking and spalling of cover concrete
  - Efflorescence

Ocean Highway at Champney's River

I-95 at Champneys River

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Environmental Conditions

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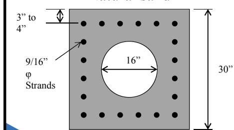
- Sampled water properties at 8 bridge locations

Bridge Name	pH	% NaCl (g/g)	Tide	$[SO_4^{2-}]$ (mg/L)
Harriet's Bluff Road at Deep Creek Bridge	7.41	2.77	High	2070.75
Houlihan Bridge	7.04	0.05	Low	52.91
Island Expressway at Wilmington River Bridge	7.32	1.38	Low	1058.58
Long Bridge Road at Ebenezer Creek Bridge	5.88	0.00	Low	13.65
I-95 at Turtle River Bridge	7.47	1.99	High	1527.54
Torras Causeway at Little River Bridge	7.41	2.34	Mid	1746.22
Ocean Highway at Riceboro Creek Bridge	7.25	0.38	Low	219.95
Ocean Highway at Champney's River Bridge	7.18	0.00	High	22.65

Forensic Investigation

Georgia Institute of Technology

- Four piles extracted from Turtle River Bridge delivered to GT structures lab
- Concrete:
  - w/c ~0.50
  - Type III cement; no SCMs
  - Limestone coarse
  - Natural sand



Visual Survey of Damage

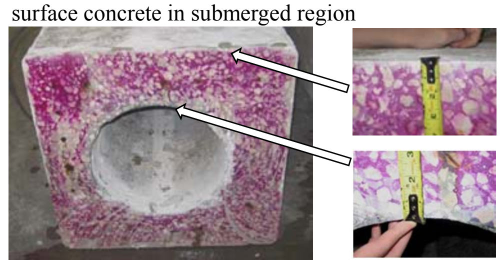
Georgia Institute of Technology

- Damage found:
  - Physical deterioration
  - Chemical attack
  - Biodeterioration
  - Corrosion

Chemical Attack – Carbonation

Georgia Institute of Technology

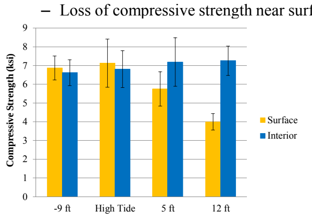
- Phenolphthalein pH indicator showed acidification of surface concrete in submerged region

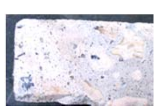


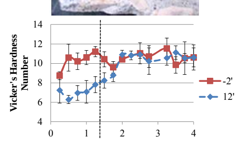
Chemical Attack – Sulfate Attack

Georgia Institute of Technology

- Deterioration of hydrated cement paste
  - Loss of surface hardness
  - Loss of compressive strength near surface



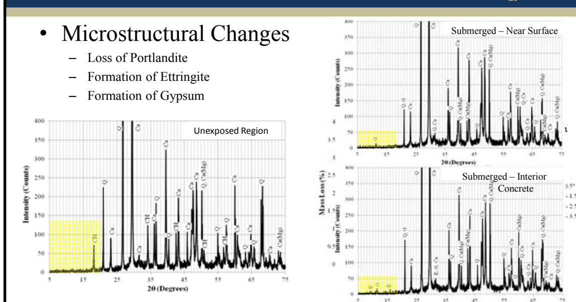




Chemical Attack – Sulfate Attack

Georgia Institute of Technology

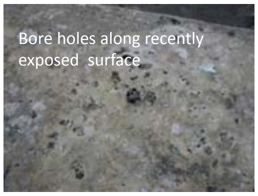
- Microstructural Changes
  - Loss of Portlandite
  - Formation of Ettringite
  - Formation of Gypsum



Biodeterioration

Georgia Institute of Technology

- Biodeterioration evident in submerged regions
- Attack isolated to porous limestone aggregates
  - 70% of cores taken had damage to aggregates
- May result in coupled bio/chemical deterioration



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Introduction · Assessment of Georgia Bridges · **Forensic Study** · Conclusions · Future Work

Biodeterioration

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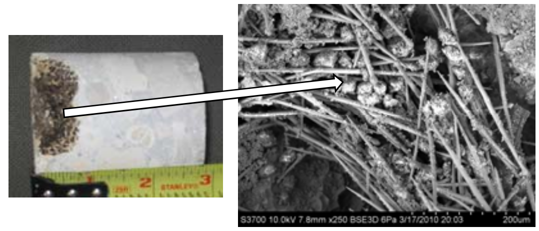
- Boreholes in aggregates examined by ESEM



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Biodeterioration

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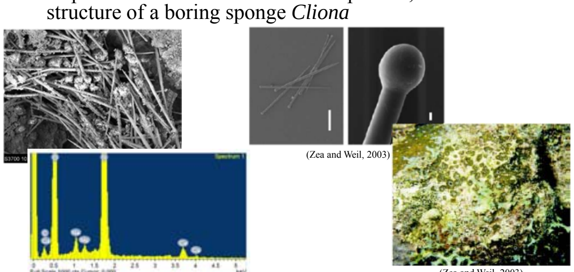
- Deposits in boreholes found to be spicules; the skeletal structure of a boring sponge *Cliona*



(Zea and Weil, 2003)

(Zea and Weil, 2003)

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Chloride Induced Corrosion

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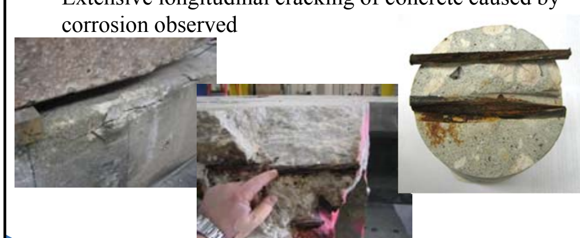
- Chloride-induced corrosion in splash zone
- Extensive longitudinal cracking of concrete caused by corrosion observed



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Chloride Induced Corrosion

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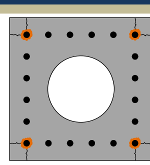
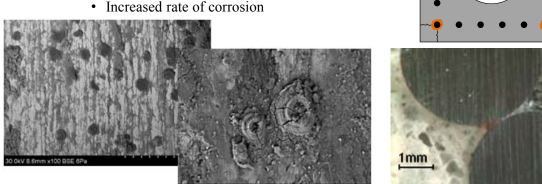
- Corrosion Damage
  - Crevice and pitting corrosion of prestressing steel
  - Cracking and spalling of concrete
    - Loss of section
    - Increased rate of corrosion





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Chloride Induced Corrosion

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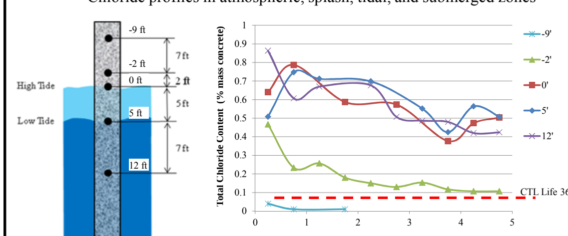
- Chloride Ingress
  - Chloride profiles in atmospheric, splash, tidal, and submerged zones



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Conclusions and Recommendations

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- Conclusions:
  - Chloride induced corrosion caused loss of reinforcement and cracking and spalling of cover concrete
  - Chemical attack caused 40% decrease in compressive strength in the submerged regions of the piles
  - Biological attack of the coarse aggregate weakened concrete and decreased effective cover distance to reinforcement
- Recommendations:
  - Eliminate use of calcium carbonate based aggregates
  - Use sulfate resistant binders in brackish water exposures
  - Eliminate use of corner strand to extend service life due to chloride induced corrosion

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Future Research

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- Ongoing research:
  - Development of high performance concretes capable of 100+ year lifespan in marine environments
  - Influence of self-healing of pile driving induced cracks on durability properties of prestressed piles
  - Development of corrosion-resistant prestressing strands
- Areas for future work:
  - Understanding of species causing biological attack, as well as, the rate and effects of their ingress
  - The influence of limestone powder addition as a source of nutrients for species that can cause biological attack

Introduction · Assessment of Georgia Bridges · Forensic Study · Conclusions · **Future Work**

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Acknowledgements

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GDOT Georgia Department of Transportation · SCP Standard Concrete Products

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  - Paul Liles
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  - Armin Vasough
  - Jeremy Mitchell
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  - Richard Potts
  - Alan Pritchard

The opinions and conclusions expressed herein are those of the authors and do not represent the opinions, conclusions, policies, standards or specifications of the Georgia Department of Transportation.

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Dr. Benjamin J. Mohr, Associate Professor, Department of Civil and Environmental Engineering, Tennessee Technological University, Cookeville, TN. He is a member of ACI Committees 231, Properties of Concrete at Early Ages; 236, Material Science of Concrete; and 308, Curing Concrete. Dr. Mohr's current research interests involve the multi-scale characterization of portland cement-based materials. These aspects include chemical and physical durability, microstructure, and chemistry of cement-based materials, early-age behavior of cement and concrete, fiber-reinforced concrete, supplementary cementitious materials, and novel material characterization/analytical techniques.

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Mechanisms of Expansion Due to Delayed Ettringite Formation

October 19, 2011

Multi-Type Durability Attack, American Concrete Institute

Benjamin J. Mohr, Associate Professor

Department of Civil and Environmental Engineering

Tennessee Technological University, Cookeville, TN

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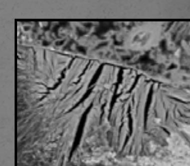
Delayed Ettringite Formation (DEF)

- There are several factors essential for DEF-related damage to occur. In order for ettringite to grow, curing temperatures have to exceed 70 ^{o}C.
- Ettringite formation typically forms clusters of needle-like crystals.
- Storing the mortar bars under water helps to accelerate the expansion process.
- However, despite many attempts to develop a fundamental understanding of DEF, the mechanisms involved in DEF still remain unclear.



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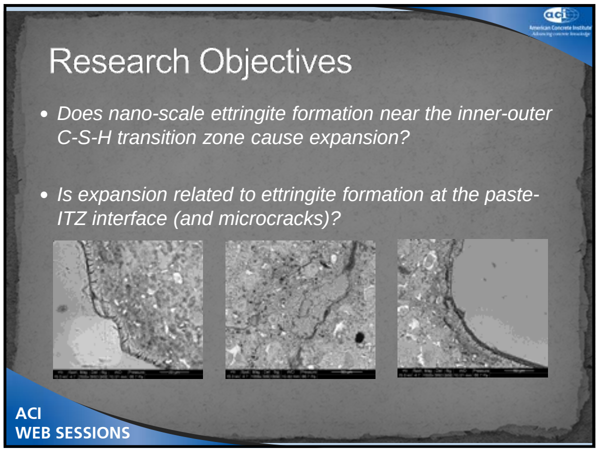
Research Objectives
• Does nano-scale ettringite formation near the inner-outer C-S-H transition zone cause expansion?
• Is expansion related to ettringite formation at the paste-ITZ interface (and microcracks)?
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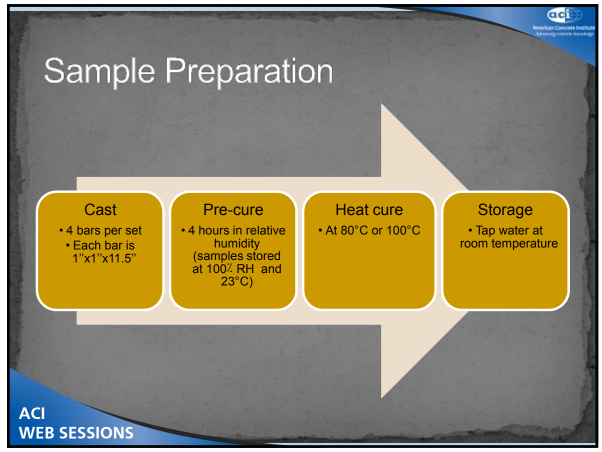
Sample Preparation
Cast
• 4 bars per set
• Each bar is 1"x1"x11.5"
Pre-cure
• 4 hours in relative humidity (samples stored at 100% RH and 23°C)
Heat cure
• At 80°C or 100°C
Storage
• Tap water at room temperature
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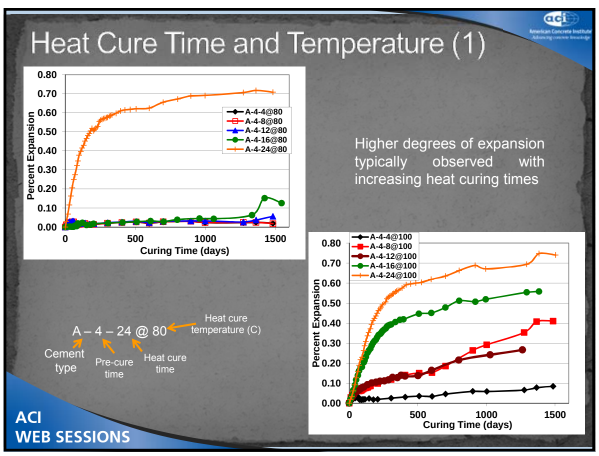
Heat Cure Time and Temperature (1)
Percent Expansion
Curing Time (days)
A-4-4@80
A-4-8@80
A-4-12@80
A-4-16@80
A-4-24@80
A-4-4@100
A-4-8@100
A-4-12@100
A-4-16@100
A-4-24@100
Higher degrees of expansion typically observed with increasing heat curing times
A – 4 – 24 @ 80
Cement type
Pre-cure time
Heat cure time
Heat cure temperature (C)
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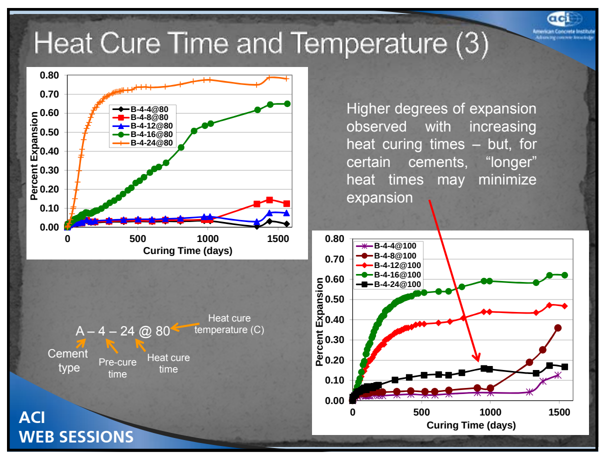
Heat Cure Time and Temperature (3)
Percent Expansion
Curing Time (days)
B-4-4@80
B-4-8@80
B-4-12@80
B-4-16@80
B-4-24@80
B-4-4@100
B-4-8@100
B-4-12@100
B-4-16@100
B-4-24@100
Higher degrees of expansion observed with increasing heat curing times – but, for certain cements, "longer" heat times may minimize expansion
A – 4 – 24 @ 80
Cement type
Pre-cure time
Heat cure time
Heat cure temperature (C)
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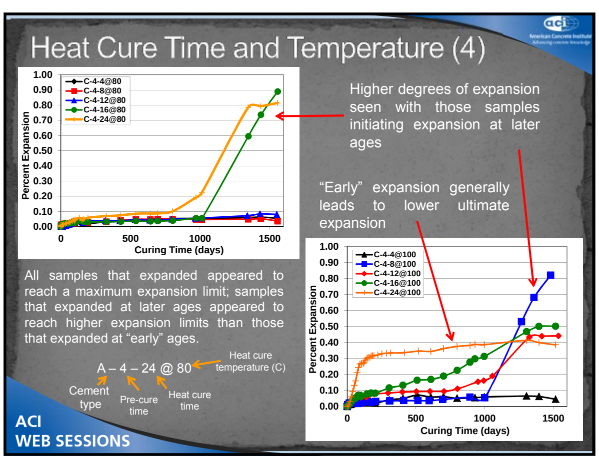
Heat Cure Time and Temperature (4)
Percent Expansion
Curing Time (days)
C-4-4@80
C-4-8@80
C-4-12@80
C-4-16@80
C-4-24@80
C-4-4@100
C-4-8@100
C-4-12@100
C-4-16@100
C-4-24@100
Higher degrees of expansion seen with those samples initiating expansion at later ages
"Early" expansion generally leads to lower ultimate expansion
All samples that expanded appeared to reach a maximum expansion limit; samples that expanded at later ages appeared to reach higher expansion limits than those that expanded at "early" ages.
A – 4 – 24 @ 80
Cement type
Pre-cure time
Heat cure time
Heat cure temperature (C)
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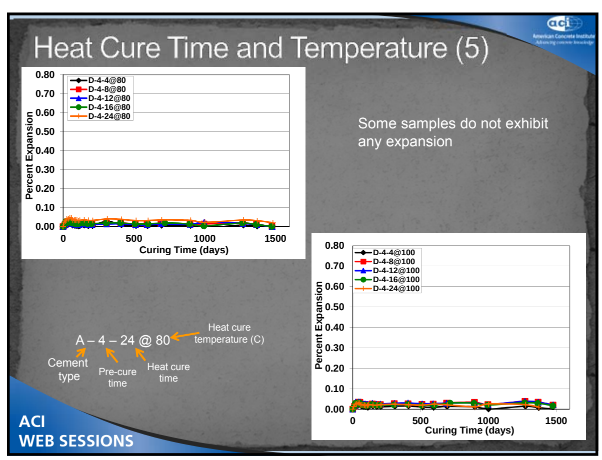
Heat Cure Time and Temperature (5)
Percent Expansion
Curing Time (days)
D-4-4@80
D-4-8@80
D-4-12@80
D-4-16@80
D-4-24@80
D-4-4@100
D-4-8@100
D-4-12@100
D-4-16@100
D-4-24@100
Some samples do not exhibit any expansion
A – 4 – 24 @ 80
Cement type
Pre-cure time
Heat cure time
Heat cure temperature (C)
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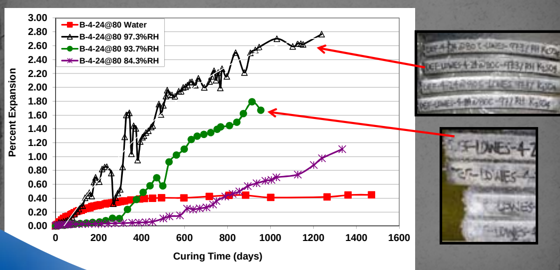
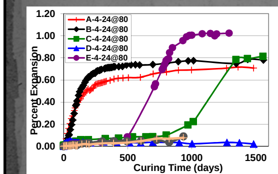
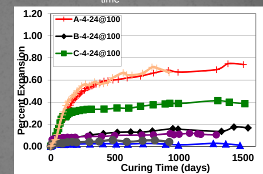
Storage Method



Cement Composition

A – 4 – 24 @ 80
Cement type
Pre-cure time
Heat cure time
Heat cure temperature (C)





	A	B	C	D	E	F	G
DEF Index (Zhang et al 2002)	0.963	0.87	0.79	0.57	1.60	0.84	0.79
DEF Index (Heinz and Ludwig 1989)	2.0715	2.23	2.01	1.90	2.47	1.73	1.83
DEF Index (Heinz 1986)	0.6756	0.72	0.67	0.98	0.66	0.62	0.61
DEF Index (Taylor 1994)	1	1	0	0	1	1	0
DEF Index (Kelham 1996)	-1.235	-0.83	-1.07	-1.71	0.14	-1.45	-0.58

Though cement composition (e.g., alkalis) may influence expansion, no method exists that can consistently predict whether expansion will occur.

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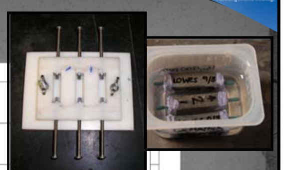
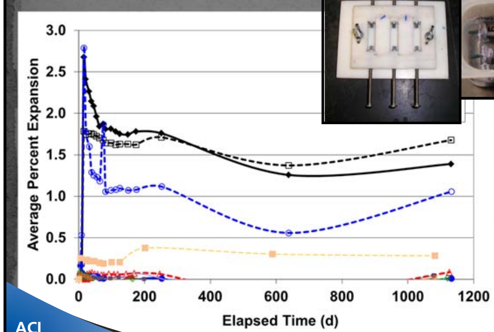
Paste vs. Mortar





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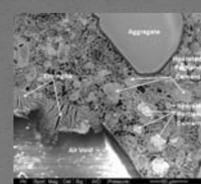
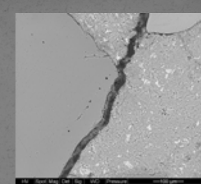
ESEM Observations





- Ettringite is found within the ITZ of all mortar samples analyzed, regardless of observed expansion. It is believed that the micro-ettringite is an innocuous product, while nano-ettringite is responsible for expansions.
- This suggests that the ITZ around aggregates simply increases the permeability of the cementitious matrix, allowing for easier ingress of water in mortar samples, as compared to paste samples.

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Summary (1)

- **Heat curing temperature** has an impact on rate of expansion, possibly from altering the microstructure. Samples that significantly expanded at 80 C did not necessarily expand when heat cured at 100 C.
- All samples that expanded appeared to reach a maximum expansion limit; samples that expanded at later ages appeared to reach higher expansion limits than those that expanded at "early" ages.
- Using a paste mix versus a mortar mix plays a role in expansions. All paste mixes cast show no expansion.
- Cement composition appears to influence rate of expansion. Higher cement alkali content led to higher degrees of expansion.

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Summary and Future Work (2)

- **Only when supersaturation of critical size capillary pores occurs** will nano-ettringite (4-20nm – Flatt and Scherer 2008) lead to expansion and subsequent cracking.
- Pore size refinement reaching critical size (i.e., critical confinement) may explain why some samples initiate expansion at later ages, despite higher tensile strengths.
- *SAXS and WVSI will be used to determine pore size distribution correlated with initial expansion.*
- *Nanoindentation coupled with SEM will be used to investigate inner versus outer C-S-H roles in nano-ettringite formaiton.*

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Summary and Future Work (3)

- Samples that expand at later ages also exhibit increased overall expansion compared to those that expanded at "early" ages possibly due to prolonged supersaturation allowing for more ettringite growth.
- However, it is believed that a pore size threshold exists below which expansion will not occur, as evidenced by the effectiveness of longer heat curing times and SCMs at mitigating expansion (among other factors).
- *Thermodynamic modeling will be employed to assess supersaturation effects on expansion.*

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Questions?

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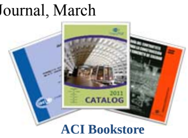
Related Documents

Multi-Type Durability Attack

- 201.2R-08: Guide to Durable Concrete (Chapter 6)
- Cracking of Prestressed Concrete in Seawater (Concrete International, December 1999)
- Long-Term Expansion of Mortars and Concretes (Special Publication, January 1999)
- Field Survey of Delayed Ettringite Formation-Related Damage in Concrete Bridges in the State of Maryland (Special Publication, March 2006)
- Laboratory Evaluation of Alkali-Silica Reaction in Concrete from Saunders Generating Station (Materials Journal, March 1995)



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