American Concrete Institute®
Advancing concrete knowledge

Fiber-Reinforced Concrete – Smart Materials and Smart Sensors

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 10, 47, and 64). 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 Online CEU Program

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 3 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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Fall 2011 Seminars

These seminars, cosponsored by ACI and the Portland Cement Association (PCA), will cover all the major changes in the new edition of the **318-11 Building Code**.

DATE	LOCATION
December 1	Phoenix, AZ
December 6	Atlanta, GA
December 8	Washington, DC
December 13	Dallas, TX
December 15	San Francisco, CA

For more information, visit ACI Seminars.

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Antoine Naaman, FACI, is a Professor in the Department of Civil and Environmental Engineering at the University of Michigan. He is a member of ACI Committees 363, High-Strength Concrete; 440, Fiber Reinforced Polymer Reinforcement; 544, Fiber Reinforced Concrete; 549, Thin Reinforced Cementitious Products and Ferrocement; and Joint ACI-ASCE Committees 343, Concrete Bridge Design, and 423, Prestressed Concrete. His research interests include high-performance fiber-reinforced cement composites and prestressed concrete.

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ExxonMobil Development

SMA - Based Self-Stressed FRCs:
Material Behavior & Structural Use

Neven Krstulovic, *ExxonMobil*
Antoine Naaman, *Univ. of Michigan, Ann Arbor*

October 17, 2011

This presentation includes forward-looking statements. Actual future conditions (including economic conditions, energy demand, and energy supply) could differ materially due to changes in technology, the development of new supply sources, political events, demographic changes, and other factors discussed herein (and in Item 1A of ExxonMobil's latest report on Form 10-K or information set forth under "factors affecting future results" on the "investors" page of our website at www.exxonmobil.com). This material is not to be reproduced without the permission of Exxon Mobil Corporation.

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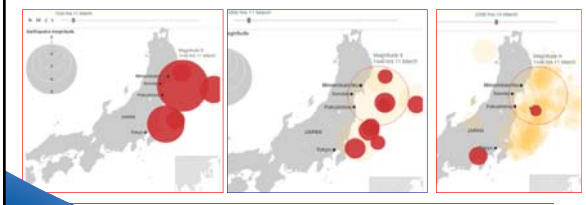
Background

- Structures capable of repairing / maintaining capacity & adjusting to overloads occurring:
  - for a prolonged time: e.g., 5 minutes long earthquakes, or
  - repeated over a continuous period of time: e.g., a week of continuous high-level earthquakes / aftershocks



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ExxonMobil Development

Agenda

1) SMA Behavior & Types

2) Self-Stressing (SS) Concept
   - Uniaxial & Multiaxial (**Active**) Confinement
   - Field Use

3) Seismic Uses → Super-Elasticity

4) Structural Applications: **Self-Actuating** FRC Fuses

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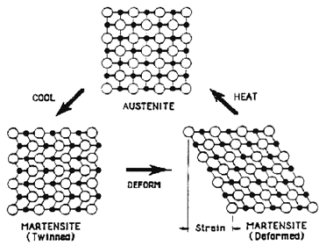
SMA Behavior & Types

- Transformation of Crystalline Structure



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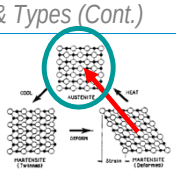
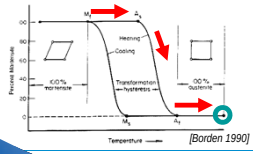
SMA Behavior & Types (Cont.)

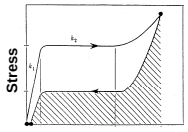


- **temperature** - induced transformation



[Borden 1990]

- **stress**- induced transformation (**Super-Elasticity**)



[Aiken et al. 1993]

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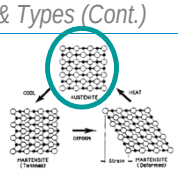
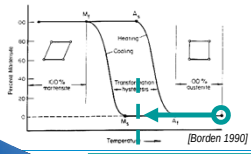
SMA Behavior & Types (Cont.)



- **temperature** - induced transformation



[Borden 1990]

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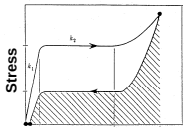

[Aiken et al. 1993]

Remains AUSTENITIC at Ambient Temp.

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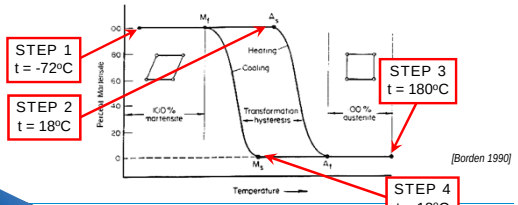
Self-Stressing FRCs (SS-FRCs)

- 1992 - Krstulovic & Naaman: Invention Disclosure - U. of Michigan, A. A.,
  1) STEP 1: at –72ºC SMA wires strained to $\varepsilon_{plastic}$ = 15%
  2) STEP 2: at room temp. wires restrained (cast in concrete)
  3) STEP 3: heat to + 180ºC to trigger shape recovery
  4) STEP 4: cool to room temp.



[Borden 1990]

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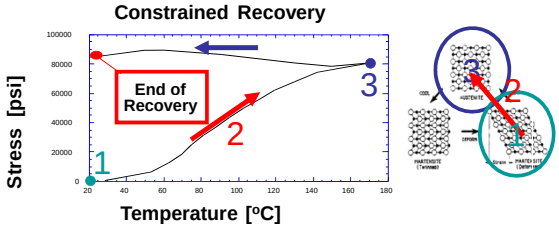
- 1992 - Invention Disclosure - U. of Michigan, A. A.,
  - Krstulovic & Naaman: "*Self-Stressing of Cement Composites Using SMAs*"



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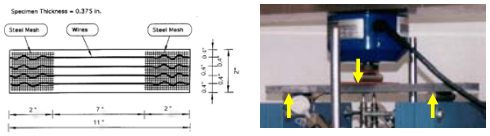

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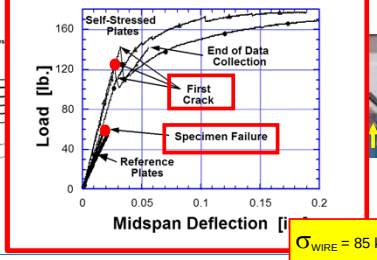


σ_{WIRE} = 85 ksi (590 MPa)
σ_{PSC} = 2.2 ksi (15 MPa)

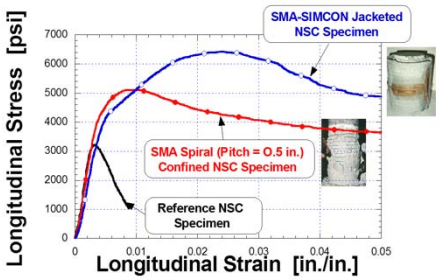
SS-FRCs: Active Confinement

- **1996** - NSF *(Director: J. Scalzi; PI: NKO)*: "Self – Stressing SMA–FRCs"

SMA Spiral Confinement	SMA-SIMCON Jacketed

- 1998 – Thiedeman: *"SMA - Based Self-Stressing High-Performance FRC for Active Confinement of Concrete Cylinders,"* MS thesis, NCSU.

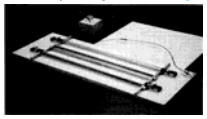
SS-FRCs: Active Confinement (Cont.)

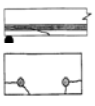


- 1998 – Thiedeman: *"SMA - Based Self-Stressing High-Performance FRC for Active Confinement of Concrete Cylinders,"* MS thesis, NCSU.

SS: Corroborating Evidence

- 1998 - Maji & Negret: Bending & bond tests, AE measurements

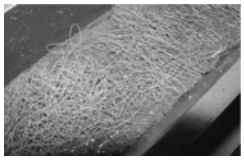




- 2004 - El-Tawil & Ortega-Rosales: SMA wire & beam tests

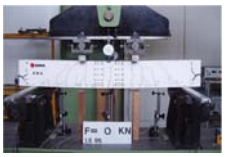
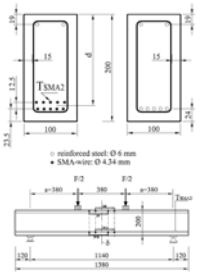
SS: Corroborating Evidence (Cont.)

- 2005 - Moser, Bergmaini, Christen & Czaderski: SMA - FRC



SS: Corroborating Evidence (Cont.)

- 2005 – Czaderski, Hahnebach & Motavalli: SMA Prestressed Beams

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SS: Corroborating Evidence (Cont.)

- 2003 - 2004 Song, Mo et al.: Intelligent Reinforced Concrete (IRC) using martensite SMA


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SS: Corroborating Evidence (Cont.)

- 2001 – Soroushian et al.: Field Application → Iron Based SMA




[Soroushian et al.2001]

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SS: Corroborating Evidence (Cont.)

- Active Confinement:
  - Choi, Chung, Cho & Nam 2008
  - Destrebecq & Balandraud 2010 → studied in detail interaction mechanics


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SS: Corroborating Evidence (Cont.)

- Active Confinement:
  - Choi, Chung, Cho & Nam 2008
  - Choi, Yang, Tae, Nam & Chung 2009


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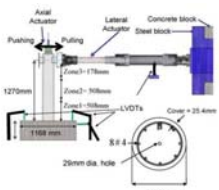
SS: Corroborating Evidence (Cont.)

- Active Confinement (cont.):
  - Andrews et al. 2010
  - Shin & Andrawes 2010

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SMAs in Seismic Applications

- Cross Braces *[Sasaki 1989]*

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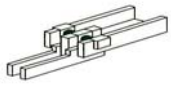
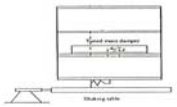
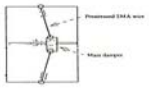
SMAs in Seismic Applications (Cont.)

- Diagonal Braces *[Witting & Cozzarelli 1992]*



- Tuned Mass Dampers *[Inaudi et al. 1993]*





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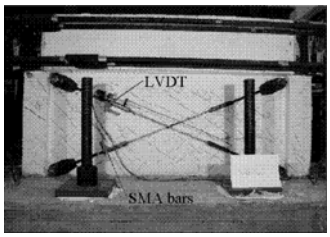
SMAs in Seismic Applications (Cont.)

- 2006 Song, Mo, Hsu et al.: super-elastic SMA devices
  - Seismic testing of low-rise shear walls



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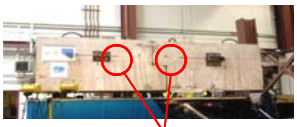
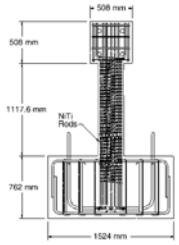
SMAs in Seismic Applications (Cont.)

- 2005 – 2009 Saiidi et al.: various super-elastic SMA devices
  - SMA bridge restrainers
  - SMA longitudinal re-bars





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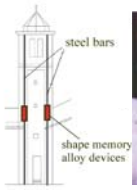
Seismic: Field Applications

- 2000 – Indirli et al.: Seismic Retrofit
  - Basilica of San Francesco, Assisi
  - Church of San Giorgio, Trignano
  - San Feliciano Cathedral, Filigno



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Structural Applications

Selective Active Confinement:

Self-Stressing FRC Fuses

*For details see *[Krstulovic et al. 2003]*

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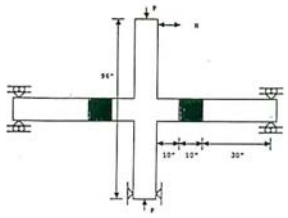
Selective Active Confinement

- Actively confining high-energy dissipation "fuse" zones

• **SIFCON** Fuse *(Naaman, Wight & Abdou1992)*



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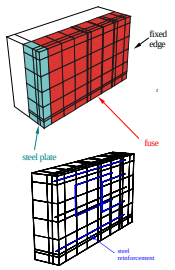
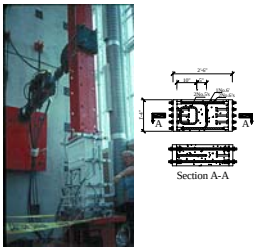
Model Verification: "Passive" Fuse

NUMERICAL	EXPERIMENTAL





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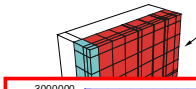
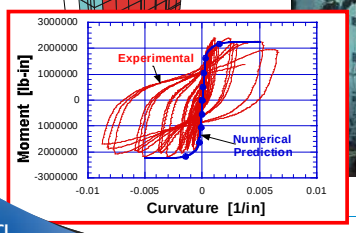
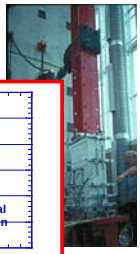
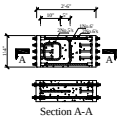
Model Verification: "Passive" Fuse

NUMERICAL	EXPERIMENTAL









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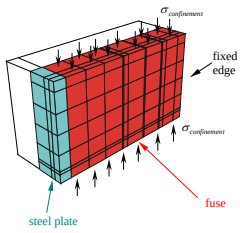
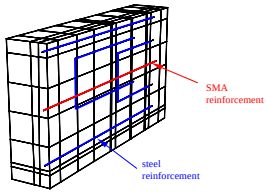
Self-Actuating FRC Fuse

- Multi – Axially (3D) actively confined SIFCON fuse
- Model-Based Simulation





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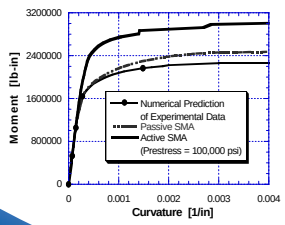
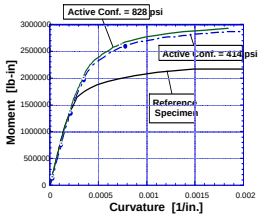
Model – Based Simulation

- Various levels of (a) longitudinal prestressing & (b) active confinement investigated

Longitudinal Prestressing Only	Active Confinement Only





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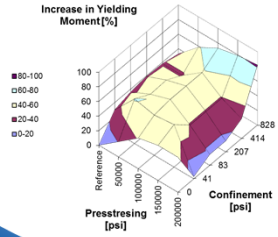
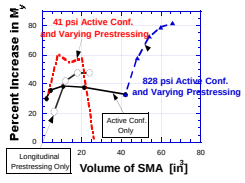
Model – Based Simulation (Cont.)

- Active confinement → more efficiently increases yield strength
- A few SELECTIVE OPTIMAL combinations maximize yield strength





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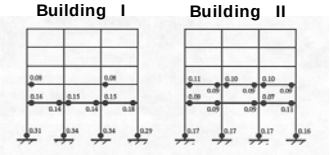
ExxonMobil Development

Example: Adaptable Energy Dissipation

- **Lower** Level Overload: "smart" fuses not activated in Building II

Building I Building II



Numbers show MCDD values

Building I	Building II
• More damage ….. DI = 0.3 ➢ higher level of damage at smaller number of locations	• Less damage … DI = 0.07 ➢ lower damage spread around the building

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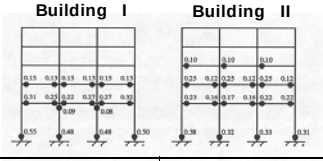
ExxonMobil Development

Example: Adaptable Energy Dissipation

- **Higher** Level Overload: "smart" fuses **activated** in Building II

Building I Building II



Numbers show MCDD values

Building I	Building II
• Not repairable …. DI = **0.4** • max. MCDD = 6.9 • first-story mechanism initiated	• Repairable … DI = 0.25 <<0.4 • lower max. MCDD = 2.1 ➢ MORE DESIREABLE response

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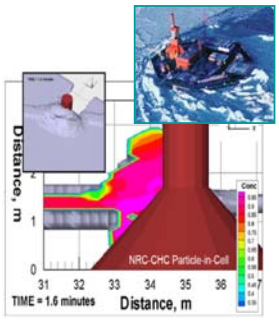
Example:



3 / 11 / 2011

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Acknowledgements: *Collaborators*

Research Assistants	Post-doctoral Research Associates	Faculty and Consultants
P. Thiedeman	J. Brzezicki	L. Krstulovic, *University of Split*
J. Becchio	J. Shannag	J. Nau, *NCSU*
B. Brezac		P. Wriggers, *University of Hannover*
E. Dogan		J. Hanson, *NCSU*
A. Erdmann		
A. Howell		
C. Ply		
J. Punchin		

Thank You for Your Attention

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Dr. Xun Yu, Dr. Xun Yu is an Associate Professor at the Department of Mechanical and Energy Engineering at the University of North Texas. His research interests cover nanotechnology, self-sensing concrete pavement, sensors, etc.

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ACI Fall 2011 Convention, Oct. 16-20, 2011, Cincinnati, Ohio

Self-Sensing Carbon-Nanotube/Cement Composite

Xun Yu, Ph.D
Associate Professor

Department of Mechanical and Energy Engineering
University of North Texas

New affiliation

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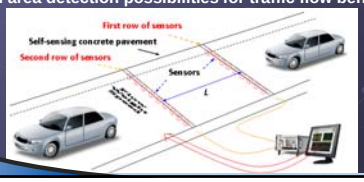
Objective and Research Approach

- Enable the *concrete pavement itself* to have a sensing capability: traffic flow detection, pavement structural health monitoring.
- Sections of a given roadway are paved with piezoresistive carbon-nanotube (CNT)/cement composites.
- CNTs can also enhance the mechanical strength
- Advantages:
  - **Long service life and low maintenance cost**
  - **Spot and area detection possibilities for traffic flow behavior**



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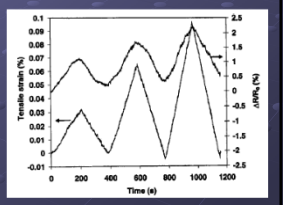
Literature Review - Carbon fiber/cement

- Carbon fibers (CFs)/cement composites have been investigated by Chung *et. al.*
- CF/cement composite shows piezoresistive response.
- CFs also improve the flexural strength of the pavement

Problem:

- The piezoresistivity of the CFs is ***irreversible*** due to the fiber breakage when the strain is larger than 0.2%



D. D. L. Chung, *Journal of Intelligent Material Systems and Structures*, vol. 13, 2002, pp.599-609.
S. Wen, and D. D. L. Chung, *Cement and Concrete Research*, vol. 29, 1999, pp.445-449.
S. Wen, S. Wang, and D. D. L. Chung, *Journal of Materials Science*, vol. 35, 2000, pp.3669-3675.

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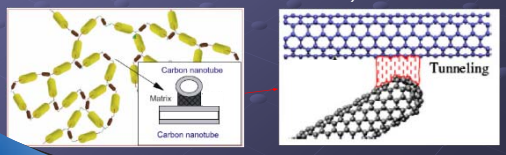
Piezoresistive Response Mechanism

Several mechanisms can contribute to the composite's piezoresistive property:

- Intrinsic CNT piezoresitive properties
- Contact resistance changes under stress
- Tunneling effect could be dominant (separation distance between CNTs decreases when stressed)



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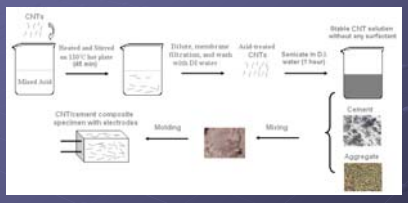
Experiments

Method #1: covalent surface modification with acid treatment



Method #2: non-covalent surface modification with surfactant, Surfactants, such as sodium dodecyl sulfate (SDS) and dodecylbenzene sulfonate (NaDDBS), can be wrapped around the nanotubes, which in turn can render CNTs to be dispersed in water and mixable with cement

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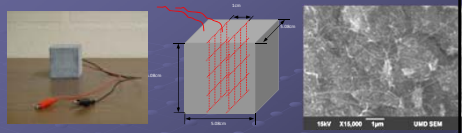
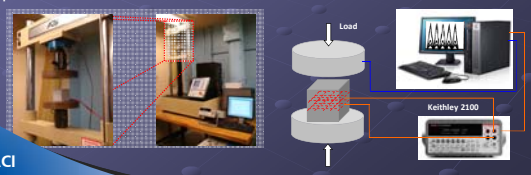
Experiments -measurement

- Illustration of specimen and arrangements of electrodes



- Experimental setup for piezoreisitive tests



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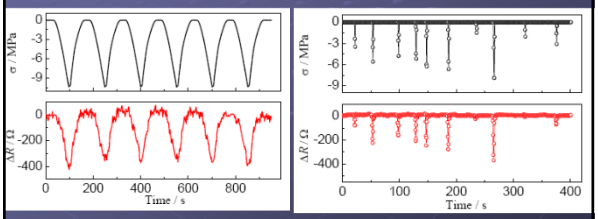
Lab Test Results – Method #2 (NaDDBS)

CNT composite fabricated with *method #2 (NaDDBS surfactant)*



Piezoresistive response of the CNT/cement composite *(CNT: 0.2 wt %)*

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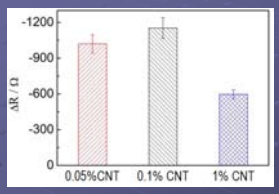
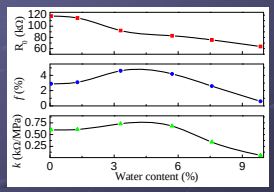
Effects of CNT doping level and water contend level





- The piezoresitive sensitivity does not increase linearly with CNT doping level and water content level.
- High CNT doping level can shorten the tunneling channel, but it will be stabilized if over the percolation threshold.
- The field emission effect on the nanotube tip can be enhanced by the adsorption of water molecules

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Preliminary Road Test Results

CNT composite fabricated with *method #2 (NaDDBS surfactant)* ***(CNT: 0.1 wt %)***

2" X 2" X 2" sample

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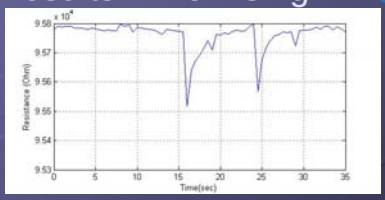
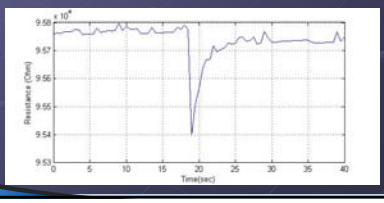
Road Test Results - Promising!

Two passenger veh (mid-size) pass over the sample



A mini-Van



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Road Tests in MN-ROAD research facility

Two CNT/cement composite sensors were installed: one is pre-made in lab, another one is fabricated onsite.

(Size: 6' (L)x 8"(W) x 4" (D)

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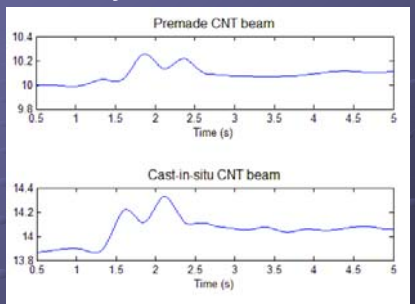
Road Tests in MN-ROAD research facility



Sensor responses to a passing van

ACI WEB SESSIONS

Acknowledgement

- Funding supported:
  - -- Federal Highway Administration (Grant # DTFH61-10-C-00011)
  - -- National Science Foundation (CMMI-0856447)
- Dr. Eil Kwon, University of Minnesota Duluth
- Dr. Baoguo Han, Dr. Kun Zhang (Research Associates in our group)
- Mr. Tom Burnham, MnDOT

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Thank you!

Comments and questions?

Xun Yu
Associate Professor
Department of Mechanical and Energy Engineering
University of North Texas

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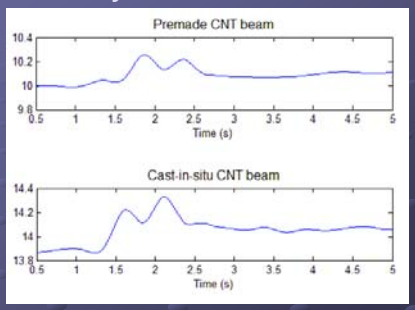
Road Tests in MN-ROAD research facility



Sensor responses to a passing van

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Thank you!

Comments and questions?

Xun Yu
Associate Professor
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Konstantin Sobolev, is an Associate Professor in the Department of Civil Engineering and Mechanics, College of Engineering & Applied Science at the University of Wisconsin-Milwaukee, and a Professor of Civil Engineering at the Universidad Autonoma de Nuevo Leon, Mexico. He is Chair of ACI Subcommittee 236D, Nanotechnology of Concrete and a member of ACI Committees 236, Material Science of Concrete; 363, High-Strength Concrete; 544, Fiber Reinforced Concrete; 523, Cellular Concrete; 338, Workability of Fresh Concrete. He is a member of the Mexican Academy of Sciences and Task Force on Nanotechnology-Based Concrete Materials at Transportation Research Board of National Academies. His research interests include advanced construction materials, high-strength concrete, application of chemical admixtures and nanomaterials in concrete.

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UNIVERSITY of WISCONSIN
UWMILWAUKEE

Electrical and Mechanical Properties of Carbon Nano-Fiber Reinforced Cement Composites

Ismael Flores-Vivian
Konstantin Sobolev
Joshua Hoheneder
Petr Zilberman
Zhibin Lin

University of Wisconsin-Milwaukee

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*INSPIRATION FOR THE RESEARCH

+

=

= smart **piezoresistive** stress-sensing material (SPSSM)

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SPSSMS PRODUCED BELOW THE PERCOLATION THRESHOLD

Poor fiber dispersion

Good fiber dispersion

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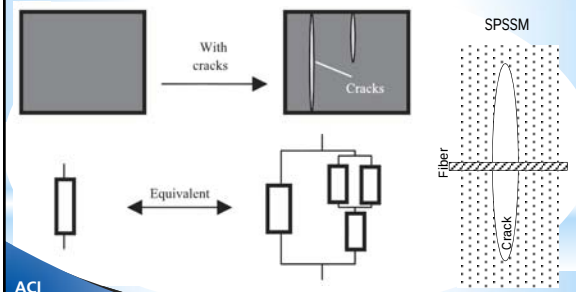
MECHANISM OF PIEZORESISTIVITY IN SPSSM



H. Li et al. / Cement and Concrete Research 34 (2004) 435-438

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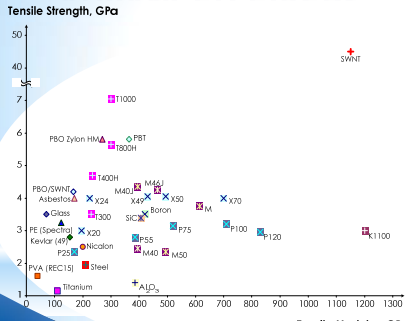
ADVANCED FIBERS



Top left (Tx) are PAN-based carbon fibers, which include the highest tensile strength fiber available on the market (T1000 from Torayca);

Bottom right (Px) are pitch-based carbon fibers, which include the highest tensile modulus fiber on the market (K1100 from Amoco)

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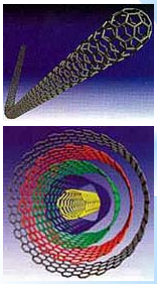
CLASSIFICATION OF CARBON NANOTUBES

Carbon nanotubes consist of molecular cylinders of pure, hexagonally-arranged carbon atoms that resemble rolled-up sheets of chicken wire with a diameter measured in a few nanometres and a length of many microns.

They occur in two main types, the single-wall carbon nanotube (SWNT) composed of a single cylinder of carbon, and the multi-wall version (MWNT) consisting of concentric tubes or cylinders of carbon. The ends of the tubes are usually closed off by a carbon end-cap. Other variations on this theme include the double-wall tube, 'herringbone' and 'bamboo' structures.



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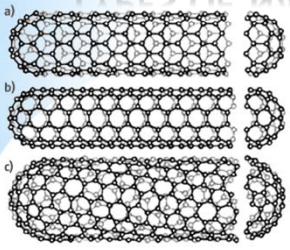
TYPES OF NANOTUBES



Different SWNT structures:
(a) a zig-zag-type nanotube,
(b) an armchair type nanotube,
(c) a helical nanotubes.

High resolution transmission electron microscopy image (longitudinal view) of a concentric multiwall carbon nanotube (c-MWNT) prepared by electric arc.

Top, sketch of the Russian-doll-like display of graphenes

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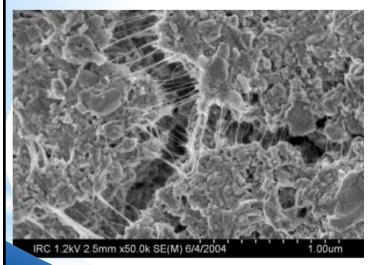
APPLICATION OF CARBON NANOTUBES



J.M. Makar

<u>"Ultimate" reinforcing material:</u>
- E ~ 1 TPa, UTS > 80 GPa
- 7-10% elastic deformation
- Very high electrical and thermal conductivity
- Very quick crack interruption

<u>Applications:</u>
- Ultrahigh performance concrete: bridges, pre-stressed structures, blast resistant structures, power plants, dams
- Repair materials

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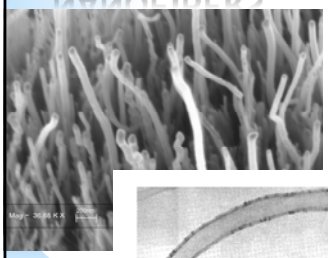
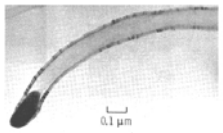
CARBON NANOFIBERS





Pyrograf is a highly graphitic, yet low cost, carbon nanofiber. Pyrograf is available in diameters ranging from 70 and 200 nanometers and a length of 50-100 microns. Therefore, nanofibers are much smaller than conventional continuous or milled carbon fibers (5-10 microns) but significantly larger than carbon nanotubes (1-10 nm).

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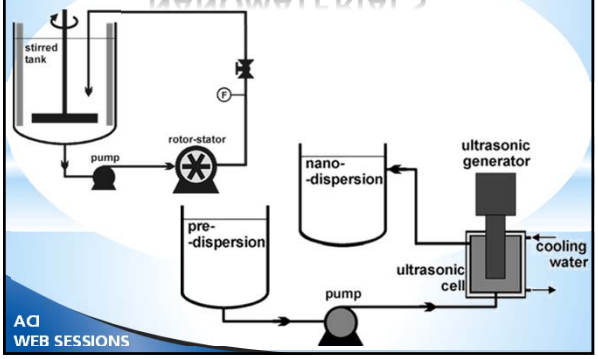
PREPARATION OF NANOMATERIALS



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NANOBOOSTER UNIT

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NANOBOOSTER UNIT

http://www.youtube.com/watch?v=G7EHyyoc86A

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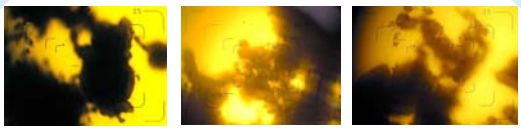
DISPERSION OF CARBON FIBERS

- Carbon fibers were added to the media (water) at 0.4%vol/2%w
- Mix was dispersed using ultrasound mixer and observed for periods of 10, 30, and 60 minutes at 100x magnification



- Poor dispersion: clumping and non-random
- Need for additives

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DISPERSION OF CARBON FIBERS

- Need: to disperse carbon fibers without clumping
- No adverse effects on the concrete mix
- Improve the workability of cement mix

SOLUTION:

- Use surfactants - compounds that lower the surface tension between a liquid and a solid
- Polycarboxilate superplasticizer which is used in concrete technology
- Good compatibility with portland cement system
- Improves workability

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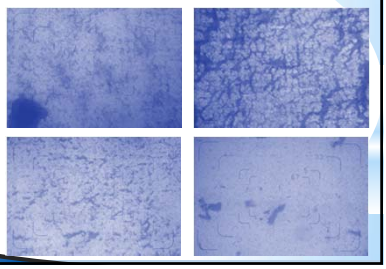
DISPERSION OF CARBON FIBERS

- The surfactant and water were premixed
- The carbon fibers were mixed with water and surfactant
- The carbon fibers were added and dispersed using ultrasound for 20 minutes
- The effect of ultrasonification observed at 5, 10, 15 and 20 minutes using optical microscope.



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SPSSM COMPOSITIONS

Composition	Ref	0CF	1CF	2CF
PVA fibers, % vol	3	3	3	3
Carbon nanofibers, %vol	0	0.1	0.2	0.4
Carbon nanofibers, % weight	0	0.5	1	2
S/C	0.5	0.5	0.5	0.5
W/C	0.3	0.3	0.3	0.3
SP, % w. cement	0.125	0.125	0.125	0.125

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PROPERTIES OF PVA FIBERS

PVA Fiber	Density (dtex)	Length (mm)	Tenacity (cN/dtex)	Elongation (%)	Modulus (cN/dtex)
RECS 7x6mm	7	6	12	7	300

Note: 1 dtex= 1 x 10^{-7} kg/m =0.9 denier

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EXPERIMENTAL PROGRAM

- Stress-strain behavior (4-point bending)
- Test on current-voltage characteristics
- Test on piezoresistivity:
  - Different moisture conditions
  - Effect of NaCl exposure (24 hours)
  - Effect of cyclic loading
  - Effect of ultimate loading

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MOISTURE CONTENT

	Moisture Content, %		
Specimens	Dry	24hW	24hC
Ref	0.00	2.44	2.56
2CF	0.00	1.26	1.28

- Dry specimens - dried at 80±5°C for 24±1h
- 24hW specimens – stored in water for 24±1h
- 24hC specimens – stored in 2% chloride water for 24±1h

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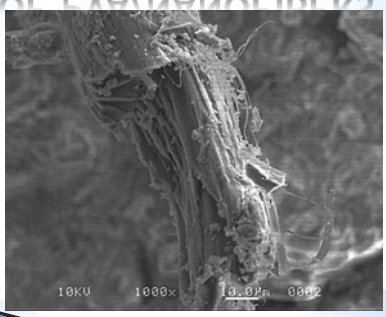
INCORPORATION OF PVA/NANOFIBERS



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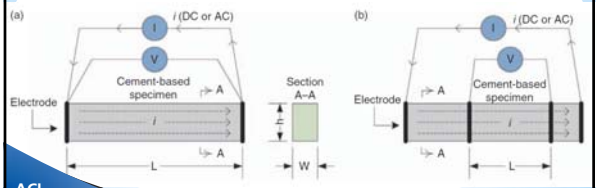
*EXPERIMENTAL SETUP

Electrical Conductivity Testing:

- 2-probe method (a)
- 4-probe method (b)
- DC or AC current



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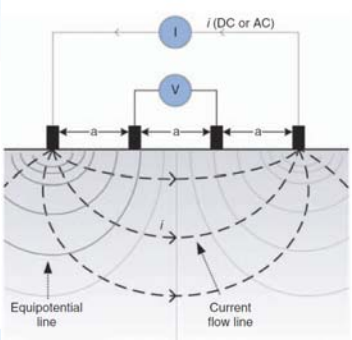
T.-C. HOU and J. P. LYNCH

*EXPERIMENTAL SETUP



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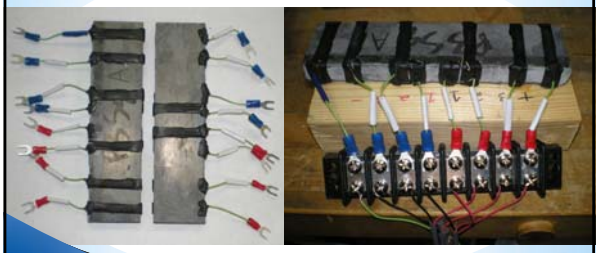
T.-C. HOU and J. P. LYNCH

*EXPERIMENTAL SETUP



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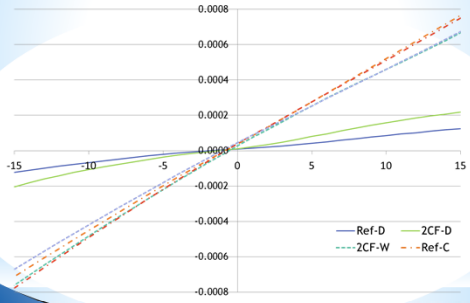
*CURRENT-VOLTAGE CHARACTERISTICS



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*CYCLIC TESTING

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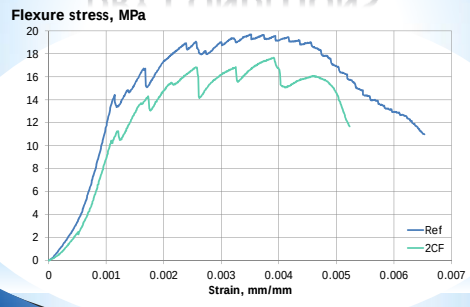
*SPECIMENS TESTED IN DRY CONDITIONS



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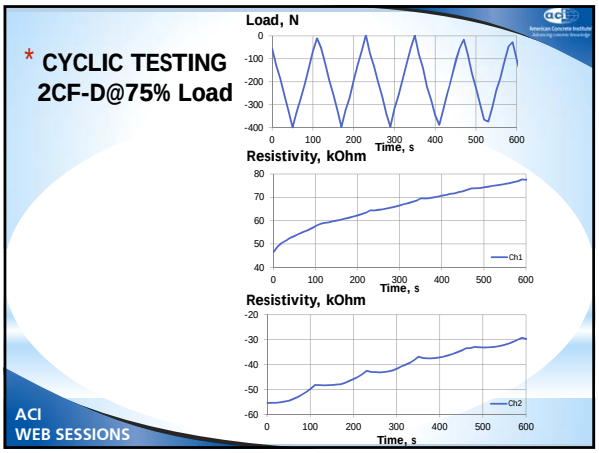
* CYCLIC TESTING
2CF-D@75% Load
Load, N
Time, s
Resistivity, kOhm
Ch1
Resistivity, kOhm
Ch2
ACI
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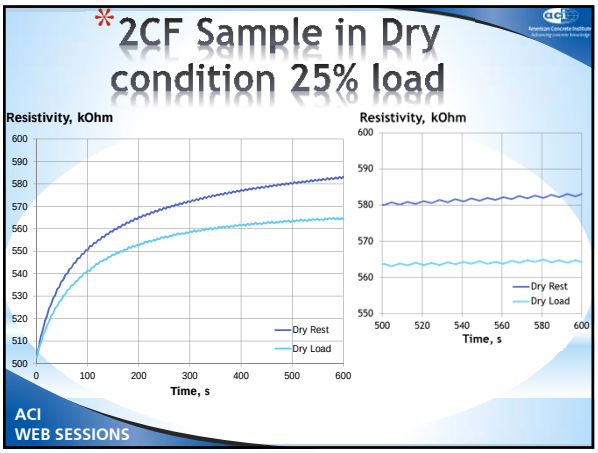
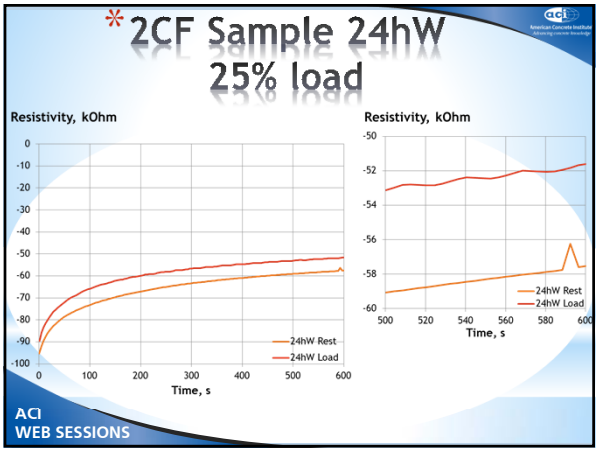
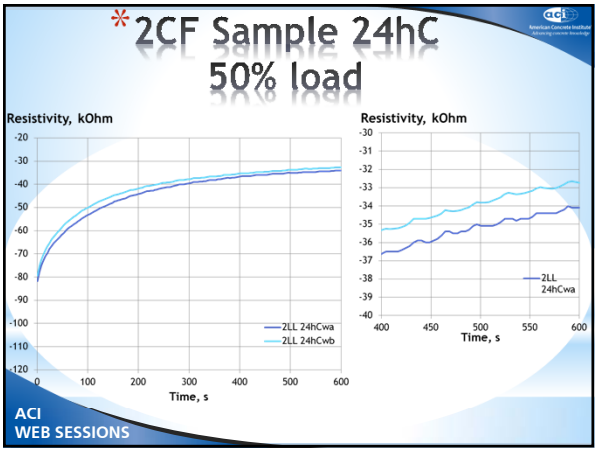
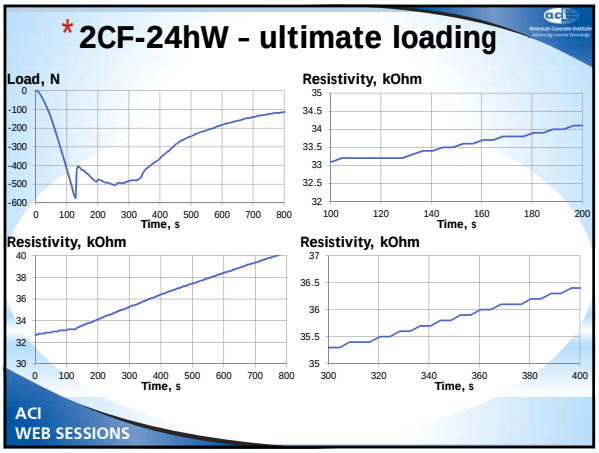

* 2CF Sample in Dry condition 25% load
Resistivity, kOhm
Dry Rest
Dry Load
Time, s
Resistivity, kOhm
Dry Rest
Dry Load
Time, s
ACI
WEB SESSIONS


* 2CF Sample 24hW 25% load
Resistivity, kOhm
24hW Rest
24hW Load
Time, s
Resistivity, kOhm
24hW Rest
24hW Load
Time, s
ACI
WEB SESSIONS


* 2CF Sample 24hC 50% load
Resistivity, kOhm
2LL 24hCwa
2LL 24hCwb
Time, s
Resistivity, kOhm
2LL 24hCwa
Time, s
ACI
WEB SESSIONS


* 2CF-24hW - ultimate loading
Load, N
Time, s
Resistivity, kOhm
Time, s
Resistivity, kOhm
Time, s
Resistivity, kOhm
Time, s
ACI
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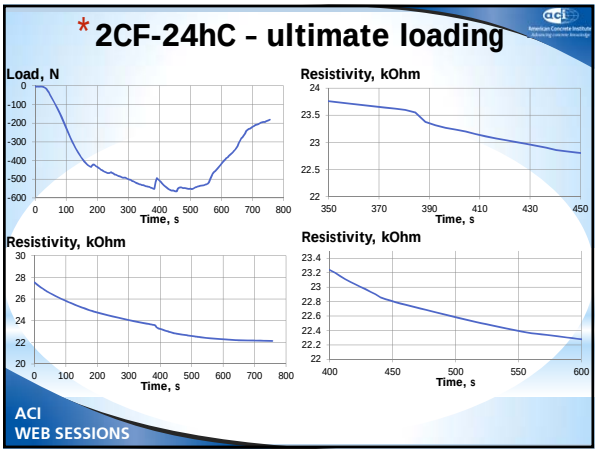
* 2CF-24hC - ultimate loading
Load, N
Time, s
Resistivity, kOhm
Time, s
Resistivity, kOhm
Time, s
Resistivity, kOhm
Time, s
ACI
WEB SESSIONS

*CONCLUSIONS

*The composition of fiber-reinforced cement composites can be fine-tuned so resulting material possesses piezoresistive stress-sensing properties.

*Smart piezoresistive stress-sensing materials (SPSSM) can be developed by combining ECC and carbon nanofibers.

*The piezoresistance response of SPSSMs depends on moisture and chloride content and potentially can be used for moisture and chloride detection.

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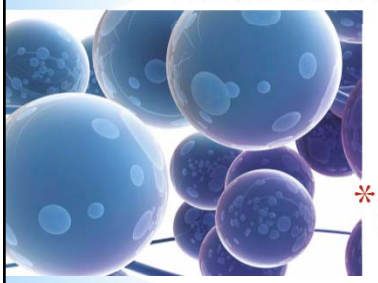
*Thank You!!!



*Questions?

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