Photo: Jae-Seong E. - Seoul Piece Bridge in Ductal® - By Rudy Ricciotti]

Pollution Prevention through Nanotechnology Conference
September 25, 2007

What's the matter with concrete?

Franz-Josef Ulm

Massachusetts Institute of Technology

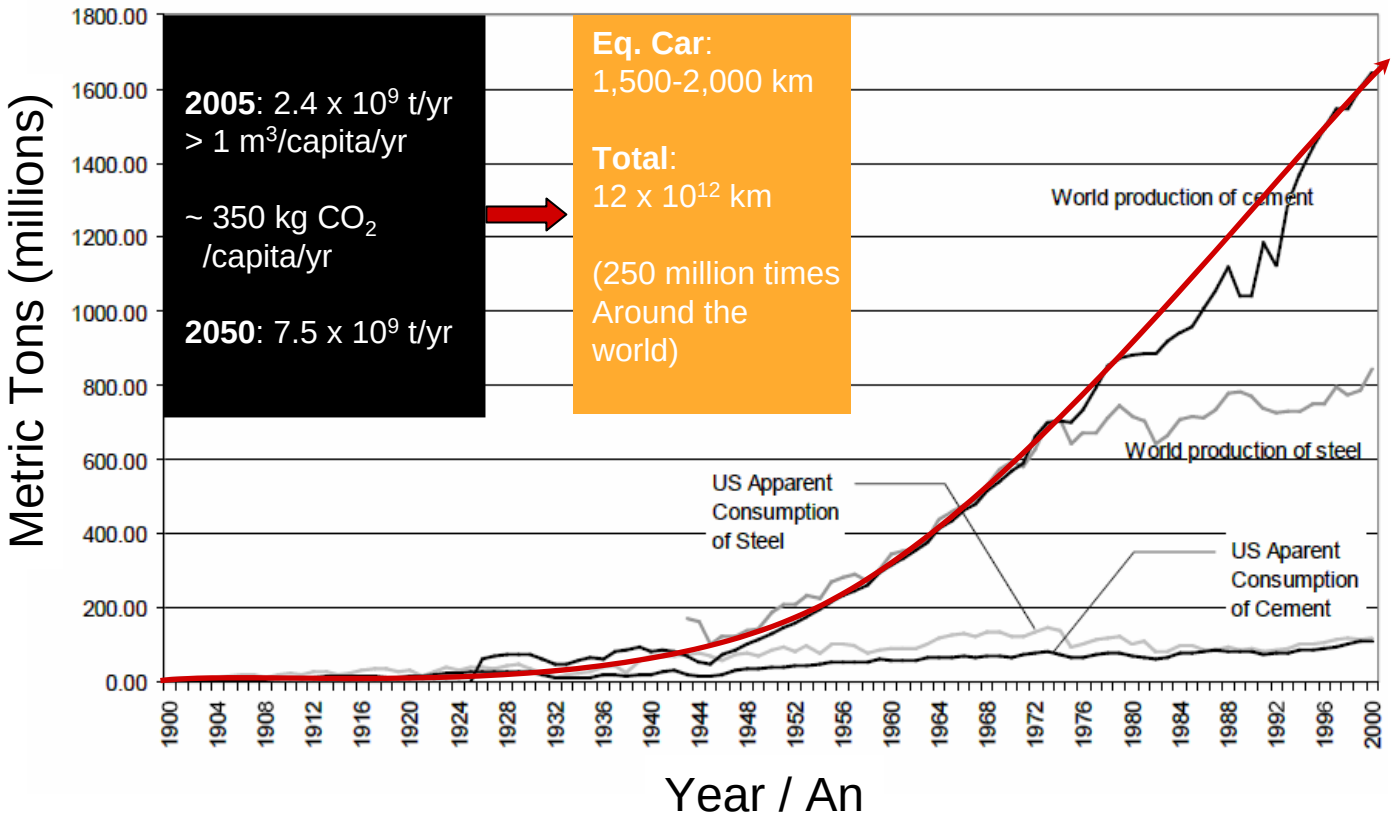
Department of
Civil & Environmental Engineering
Massachusetts Institute of Technology

What's the matter with concrete?

What do concrete and oranges and CO_2 have in common?

The Challenge of Consumption

- Worldwide Cement Consumption = CO_2 Emission



Chaturvedi, S. and Ochsendorf, J., "Global Environmental Impacts Due to Concrete and Steel," *Structural Engineering International*, 14/3, Zurich, Intl. Assoc. of Bridge and Structural Engineers, August 2004, 198-200.

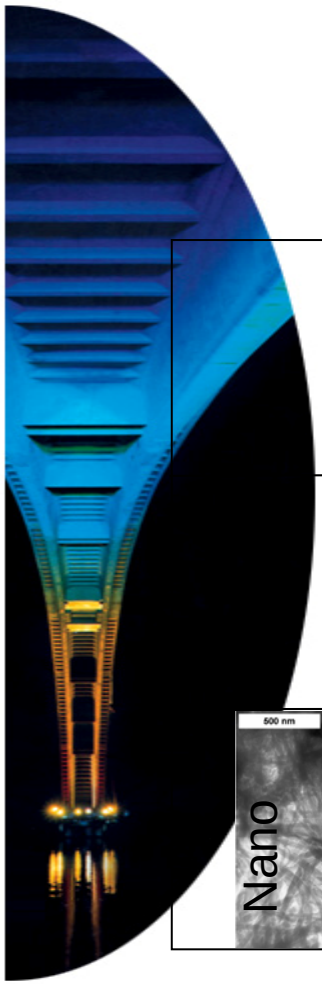
Worldwide Consumption of Materials

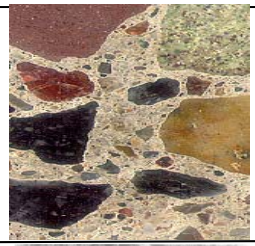
Data from P. Acker – January 2007

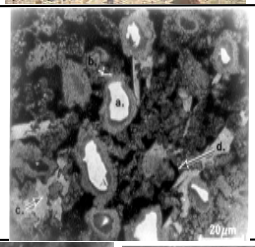
Cement:	**2,350**	**Million tons**
Concrete:	**20,000**	
Timber:	**3,200**	
***Ecological capacity of the Earth*:**	**2,500**	
Timber for construction:	**< 1,000**	
All metals:	**1,000**	
Steel:	**940**	
Steel for construction:	**< 400**	
Paper and cardboard:	**300**	
Plastics:	**120**	
Aluminium:	**32**	

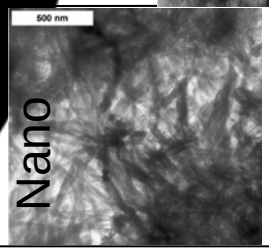
1 ton of cement = 1 ton of CO_2 = $85 future damage

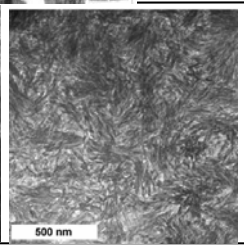
Progress on the Concrete Front











Macro

Micro

Nano

1900

1980

1990

2000

2010

Ordinary Concrete

High Performance Concrete (HPC)

Ultra High Performance Concrete (UHPC)

"C"-Crete?

Log-Length Scale

-3

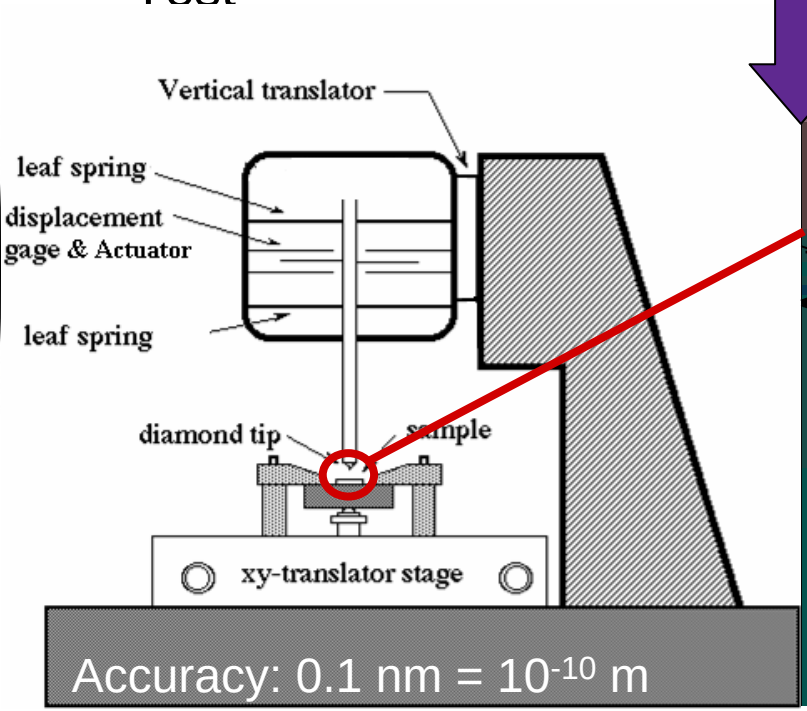
-6

-9

Breakthrough in Research

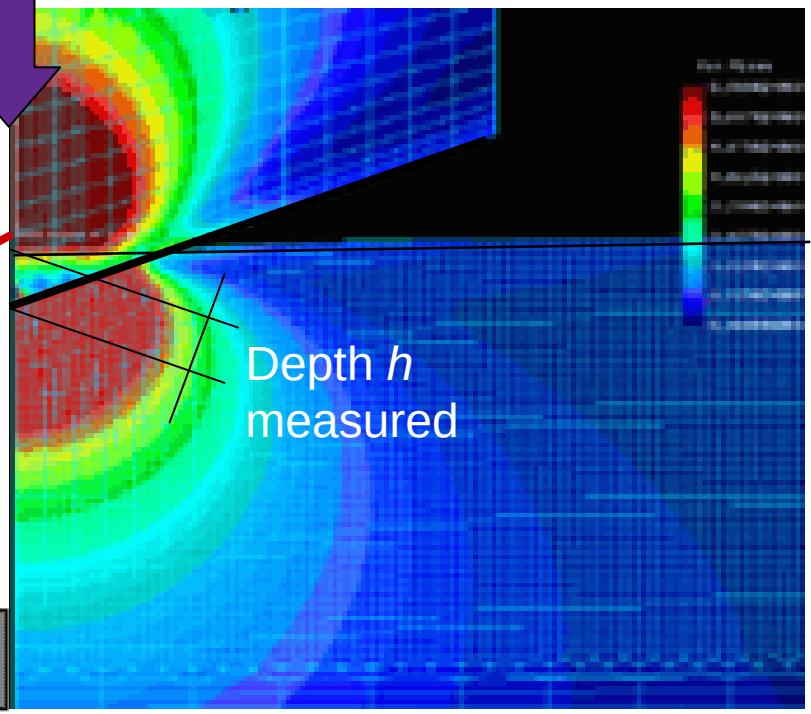
The Indentation Test

- Instrumented indentation Test



Nix Group, Stanford - http://mse.stanford.edu

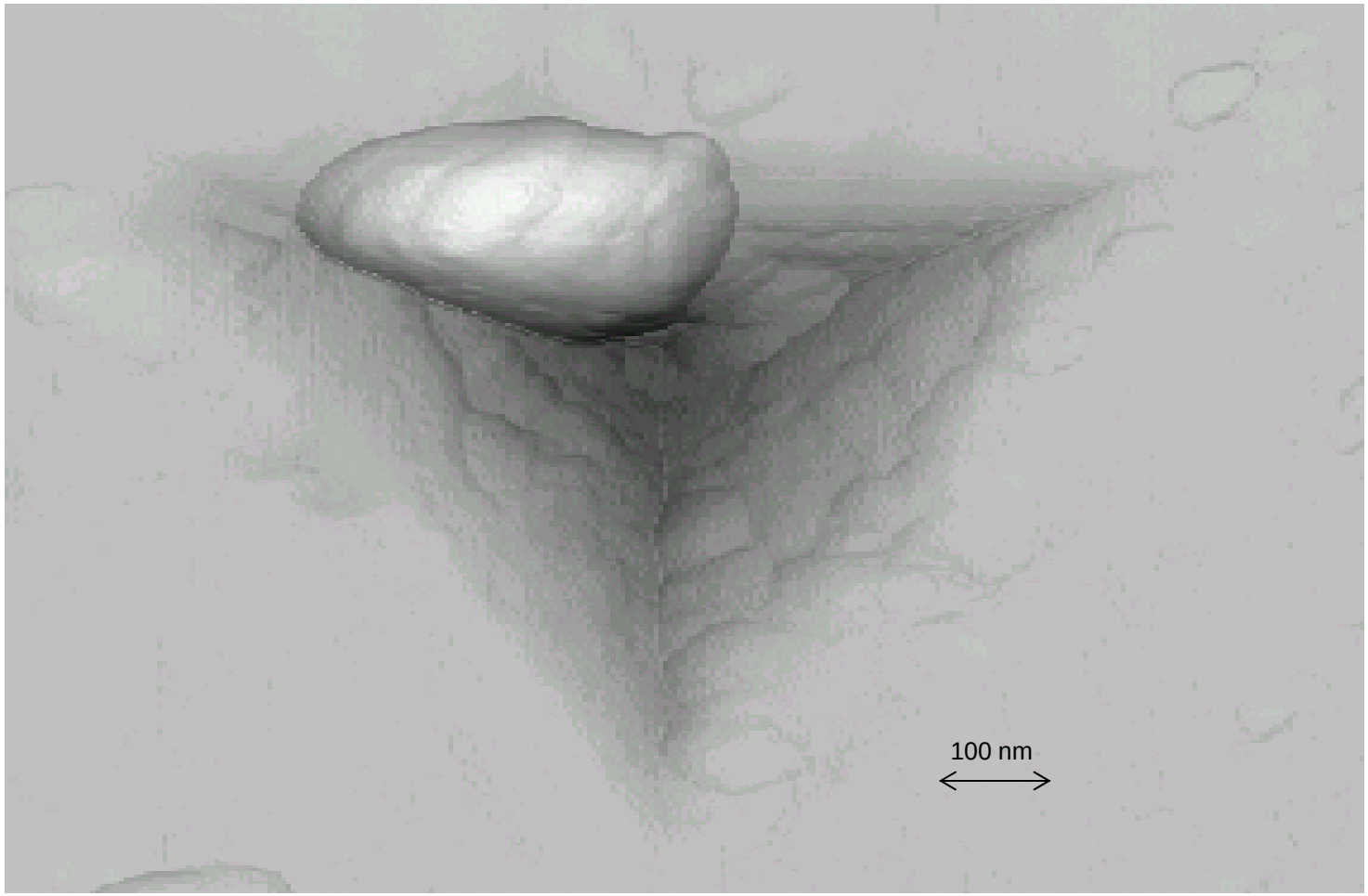
Force *P* applied



http://www.mts.com/

This is not an Egyptian Pyramid, nor…

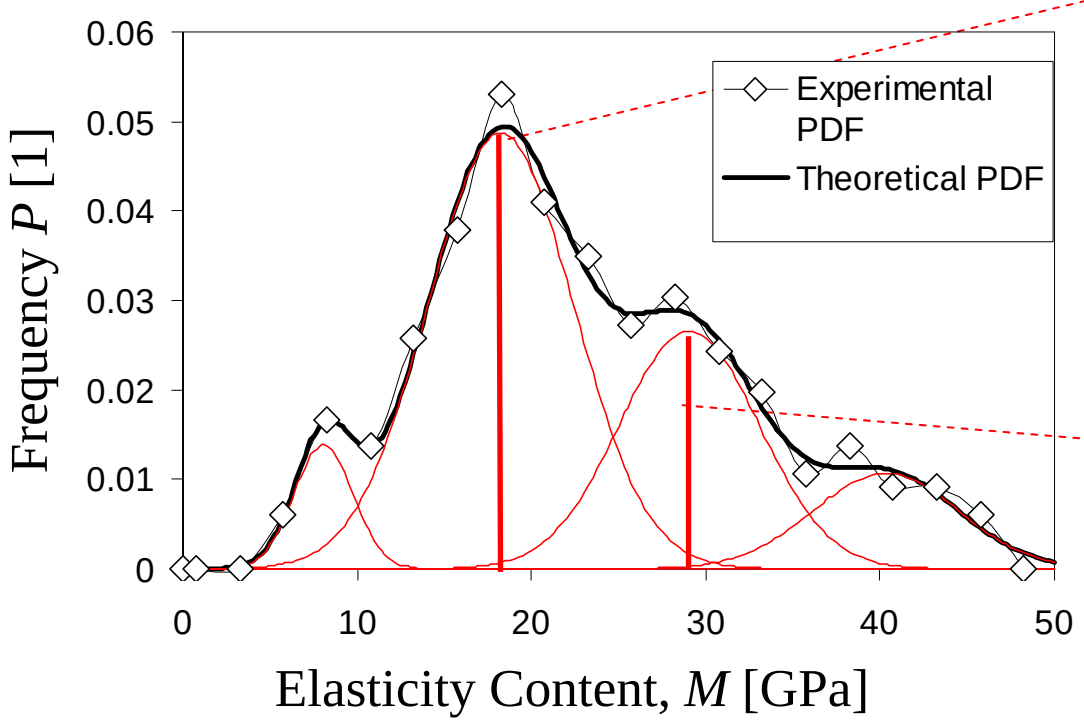
- But the nano-mechanical signature of concrete



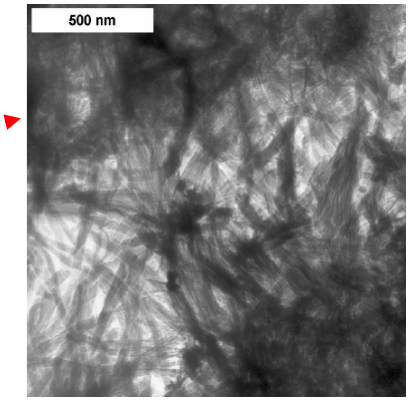
AFM image by Chris Bobko, MIT, 2006

A Genomic Code of cementitious materials?

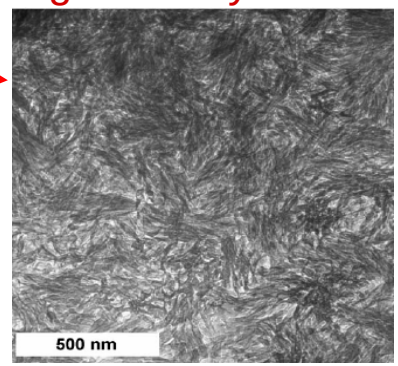
- Ordinary Cement Paste: w/c = 0.5



Low Density ~70%



High Density ~30%



Nano-mechanical Signature of concrete

Constantinides, G., and Ulm, F.-J., "The effect of two types of C-S-H on the elasticity of cement-based materials: Results from nanoindentation and micromechanical modeling," *Cement and Concrete Research* 34 (2004) 67–80.

Ordinary Concrete

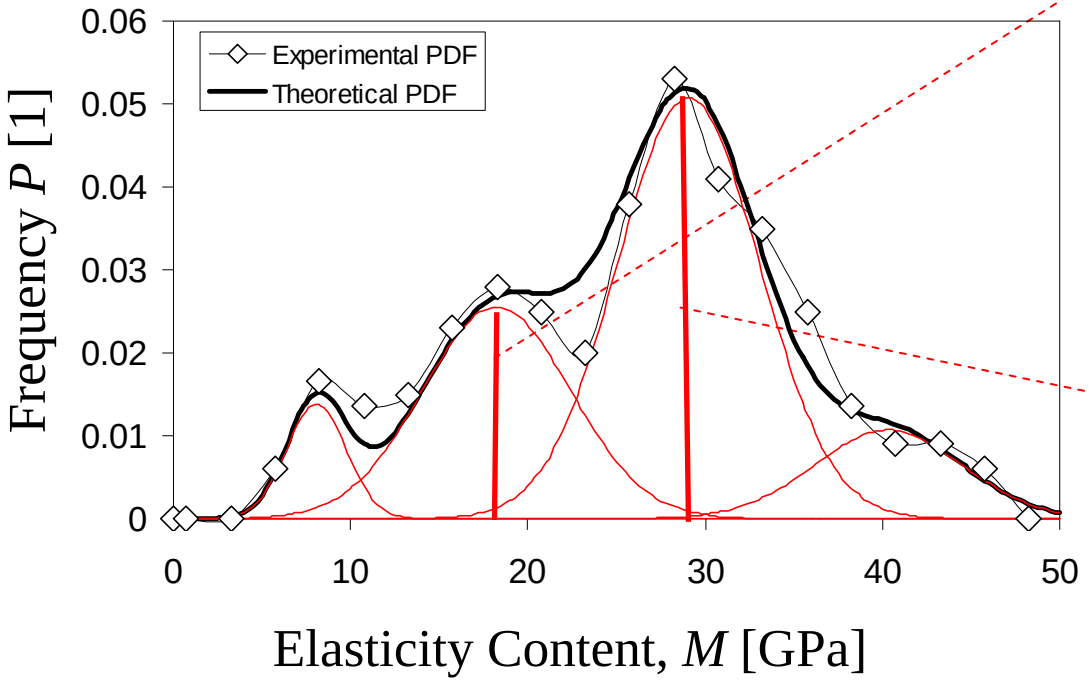
- 1900–1985 Industrialization/Standardization

The romance of modernism wrought in concrete*

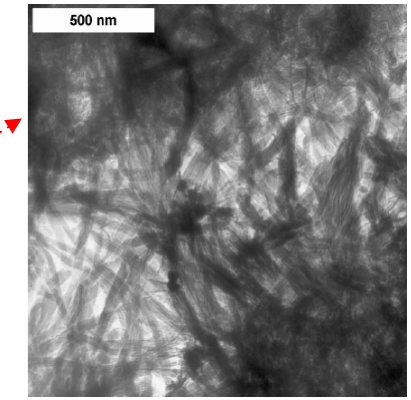
(*) Murray, H., (2004). Boston Architecture.

A Genomic Code of cementitious materials?

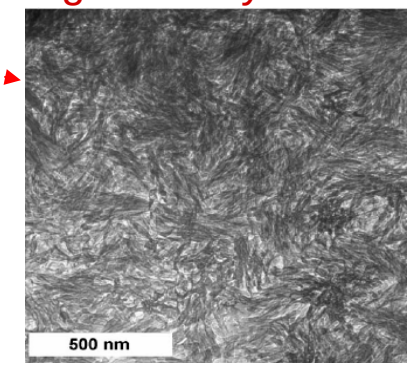
- High performance concrete (w/c = 0.4)



Low Density ~30%



High Density ~70%



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High Performance Concrete

- 1985-95 Re-discover Diversity

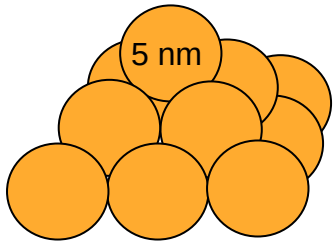
Normandy Bridge (1990s), Le Havre, France, 900m free span - Picture Credit: www.lcpc.fr

Filling the Voids

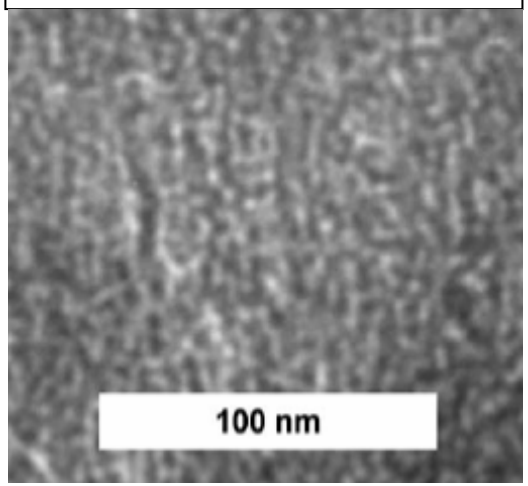
The Nano-Granular Nature of C-S-H*

- HD C-S-H

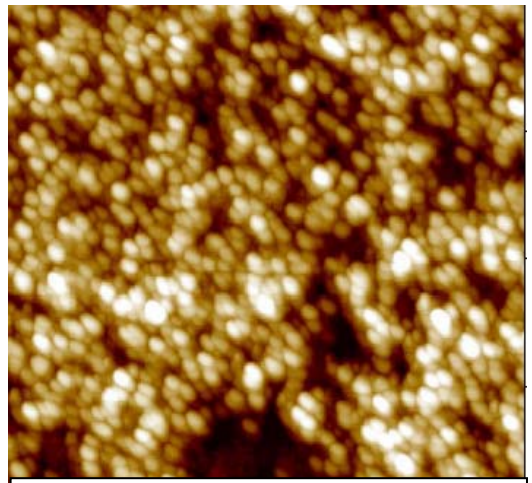
Spherical Limit Packing
Density = 0.74
No. of contact = 12/ sphere



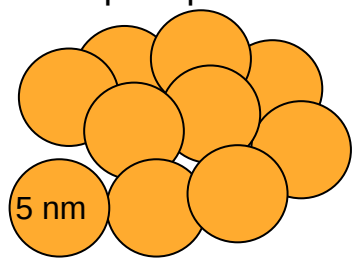
Nature, 1998



- LD C-S-H



Random Packing Limit = 0.64
No. of contact (mean)
= 6/par sphere



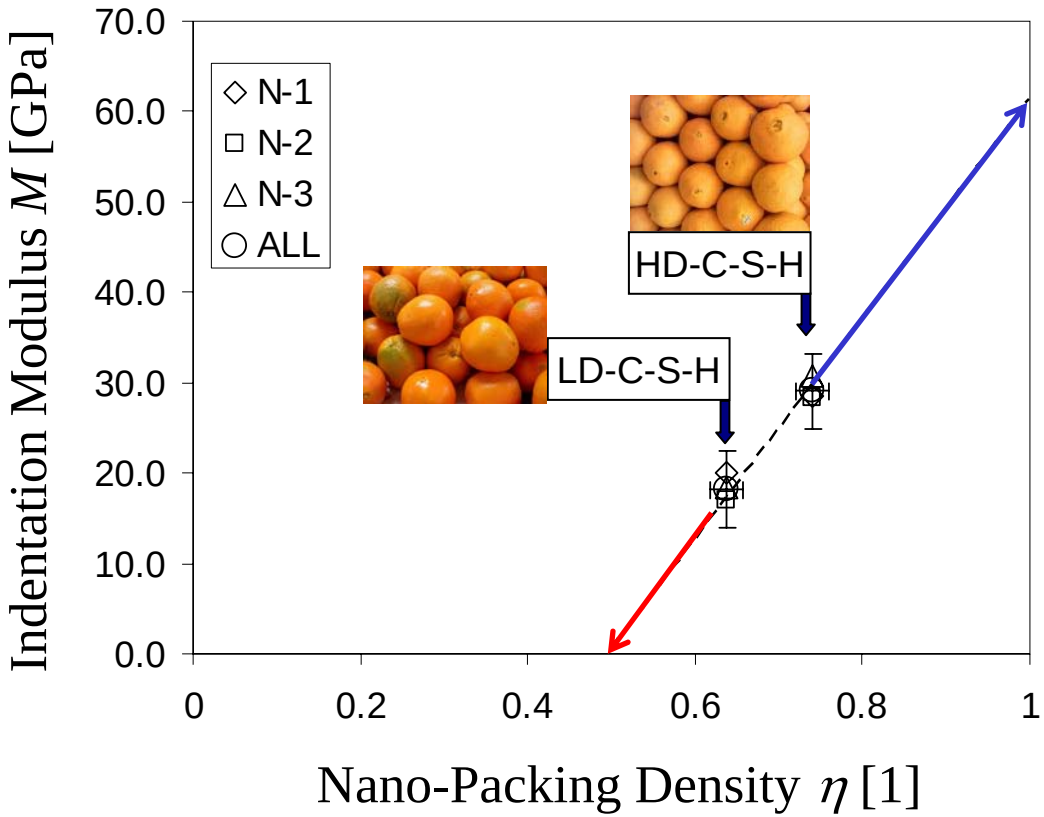
Science, 2004

(*) Constantinides, G., Ulm, F.-J., (2007). The nanogranular nature of C-S-H, JMPS, January 2007

Picture Credit: Richardson, 2004; Nonat 2004

Nano-Granular Nature of C-S-H*

- Link: Nano-Mechanical Property and Packing



To make a long story short:

- Extrapolation to zero shows **Percolation Threshold**

  Measured: ~ 48 %
  Theory: ~ 50 %

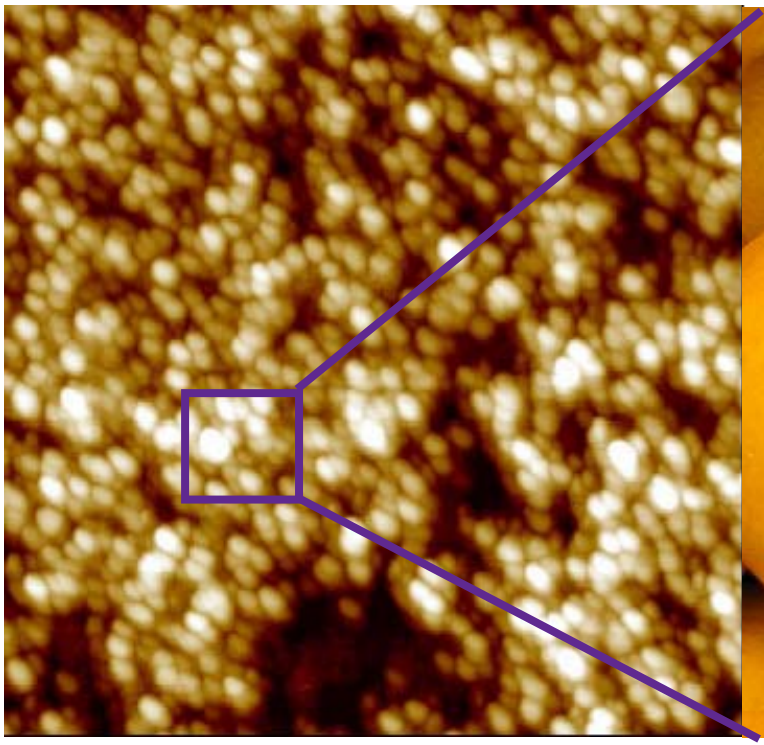
- Extrapolation to ONE yields particle stiffness

  m_s ~ 65 GPa

(*) Constantinides, G., Ulm, F.-J., (2007). The nanogranular nature of C-S-H, JMPS, January 2007.

The Nano-Granular Nature of C-S-H*

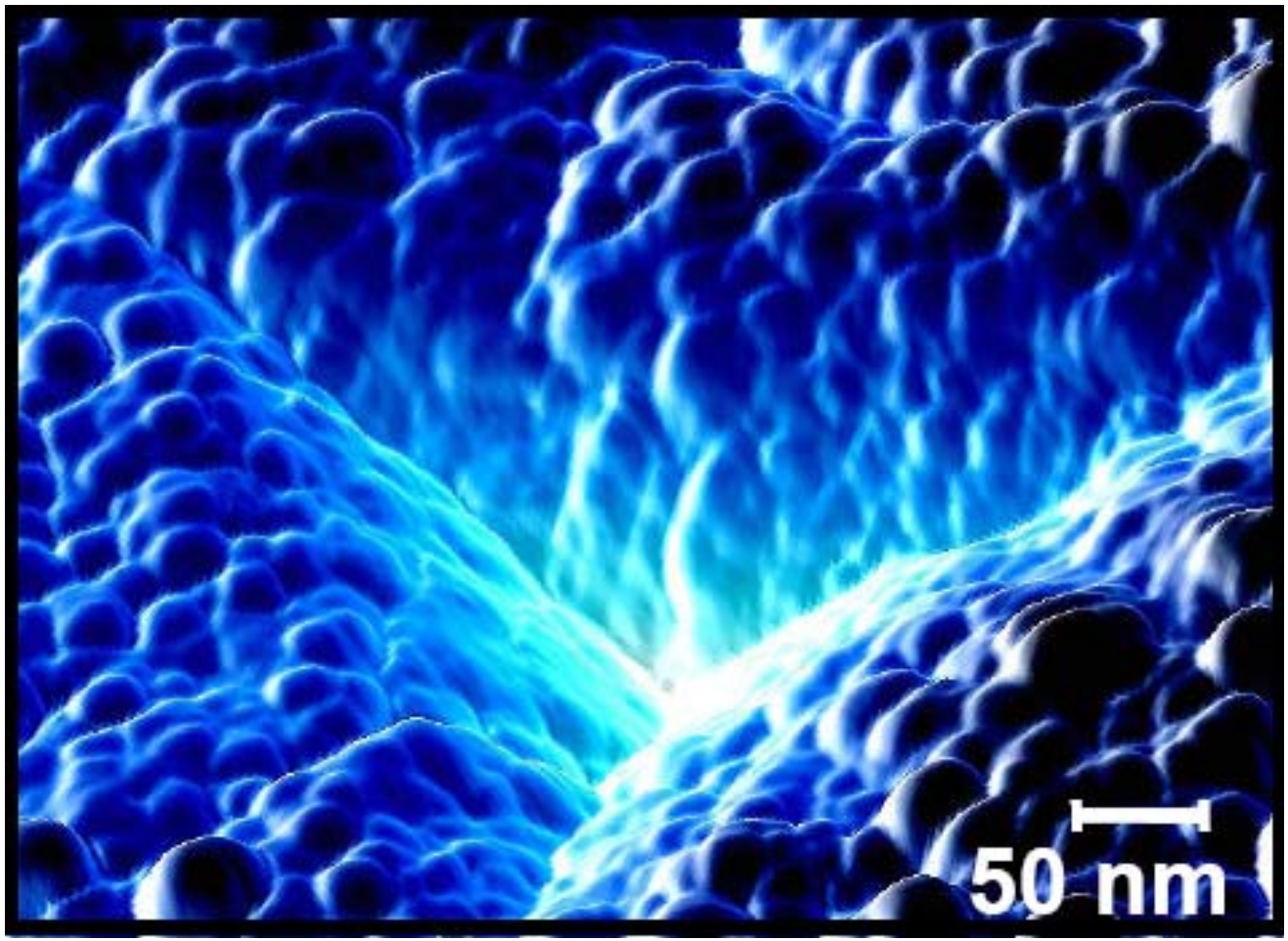
- What concrete and Oranges have in Common?



(AFM – Image: C-S-H Nanoparticles
From Nonat, 2004)

(*) Constantinides, G., Ulm, F.-J., (2007). The nanogranular nature of C-S-H, JMPS, January 2007

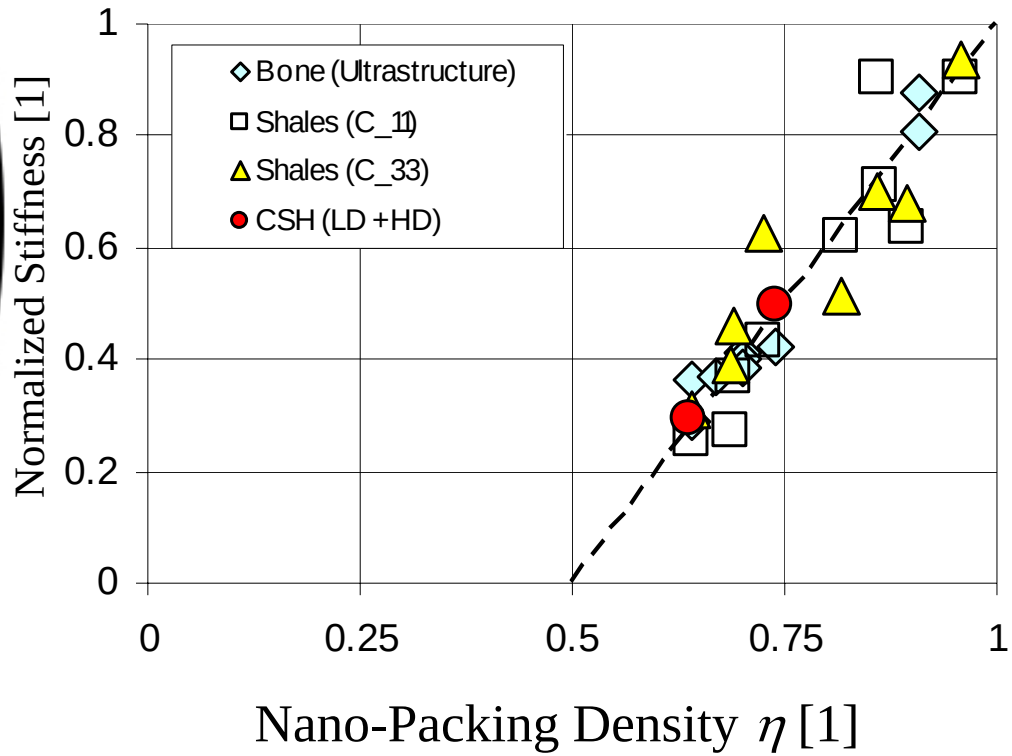
The Nano-Granular Nature of Bone*



(*) Tai, K., Ulm, F.-J., Ortiz, C. (2006). “Nanogranular origins of the strength of bone”, NanoLetters.

“Nano” - Dazzling

- Nano-granular Nature of all (inorganic) natural composites(*)



Nanogranular Materials

- Concrete: C-S-H
- Compacted Clays (petroleum, nuclear waste storage)
- Bone: Hydroxyapatite

A Genomic Behavior – a Geo-genome code?

(*) Ulm, F.-J., et al. JACE, 2008.

The true challenge of Sustainable Development

Economic Growth – Social Progress – Minimizing Ecological Footprint

How to translate scientific progress into day-to-day engineering applications

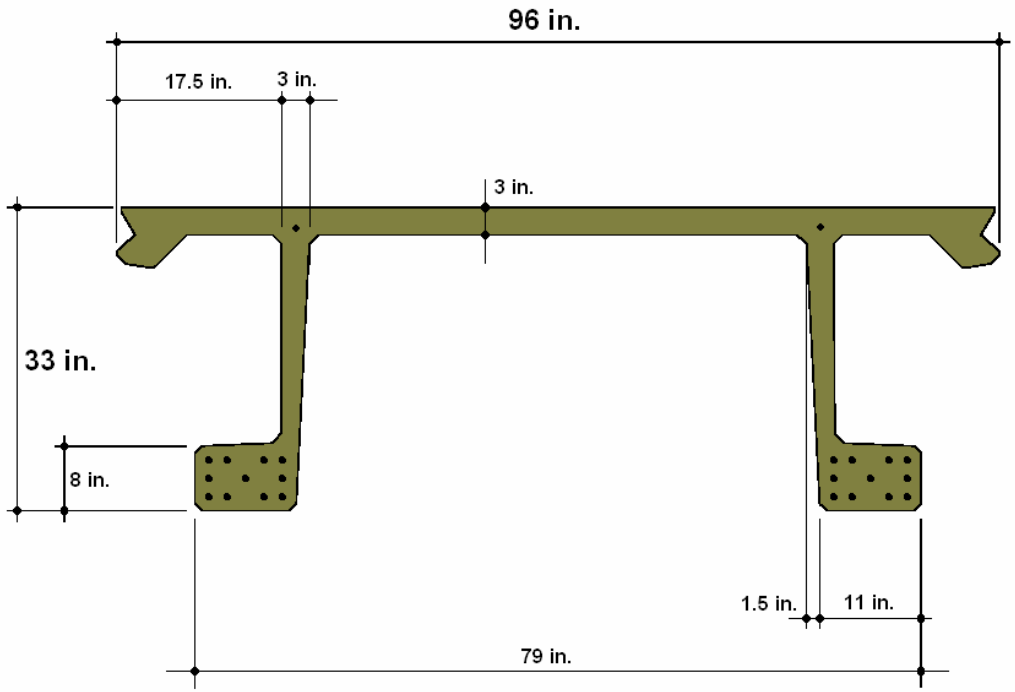
…

For the benefit of society, while minimizing the Ecological Footpring

Nano Engineering of Concrete

UHPC Bridge for US Highways

- Prototype Development at MIT
  (FHWA project: “bridge of the future”)



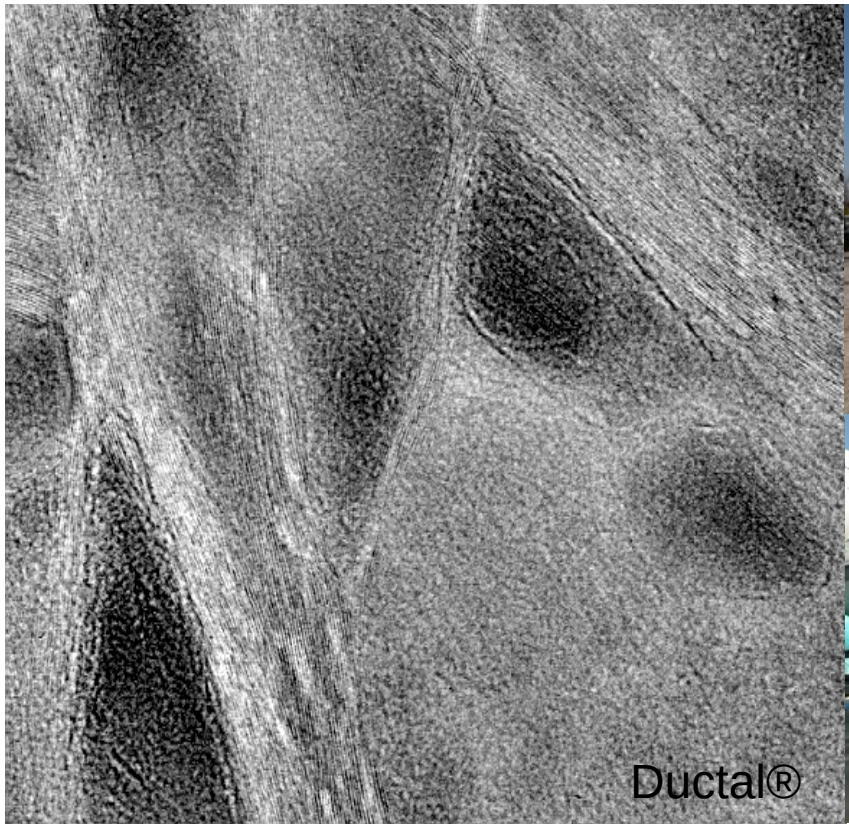
- Max L/H ~ 30
- Weight Reduction 30%
- Durability (Low maintenance)
- Rapid Construction (circulation)
- **30% CO2 Reduction**

- Construction: Prestress Services, Kentucky
- Material: DUCTAL®

To replace 150,000 bridges (of 450,000)

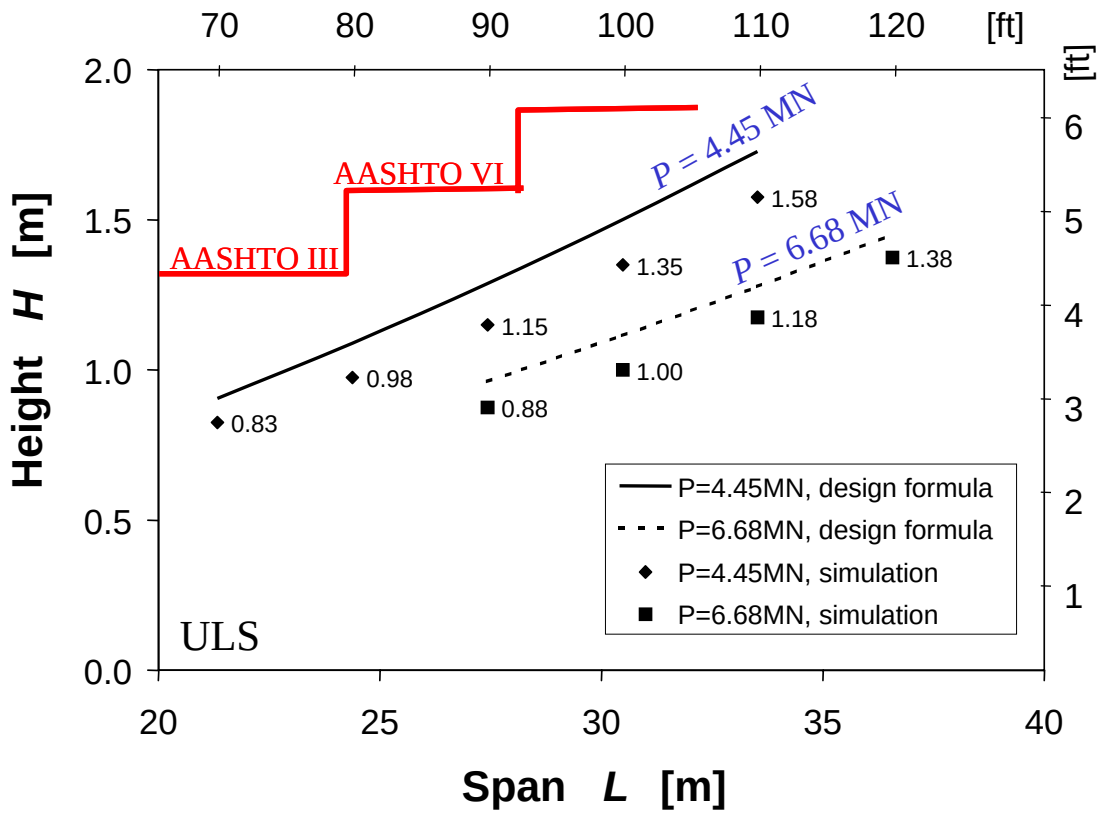
~ US$ 10^{12} >> FHWA FY 07 bdg. ~US$ 40 10^{9}

Translate Progress in NanoScience into Engineering … and Social Progress



UHPC Design

- Prototype Development at MIT ("bridge of the future")



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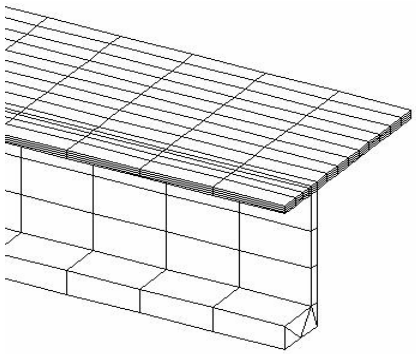
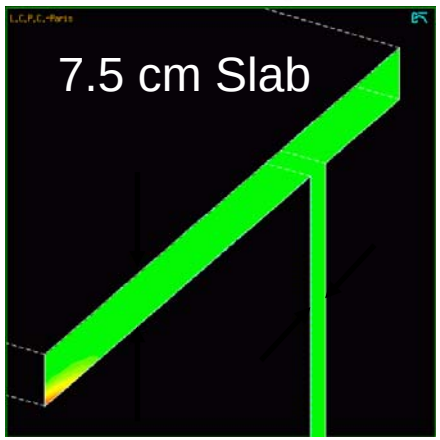
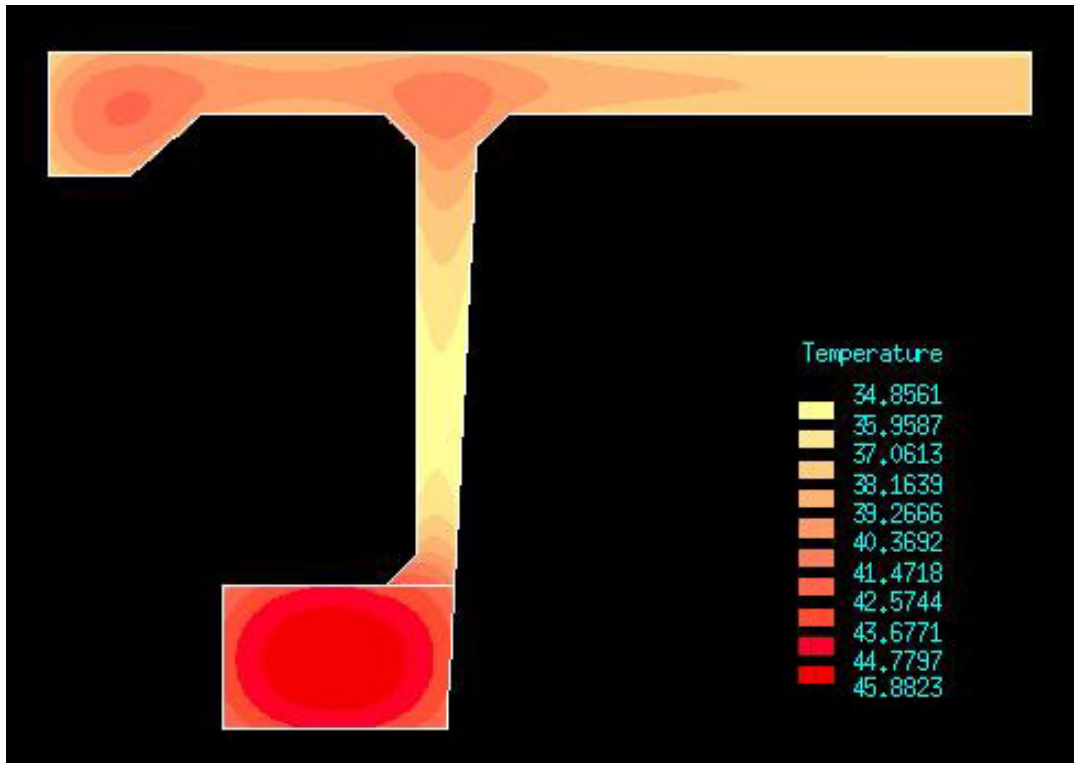




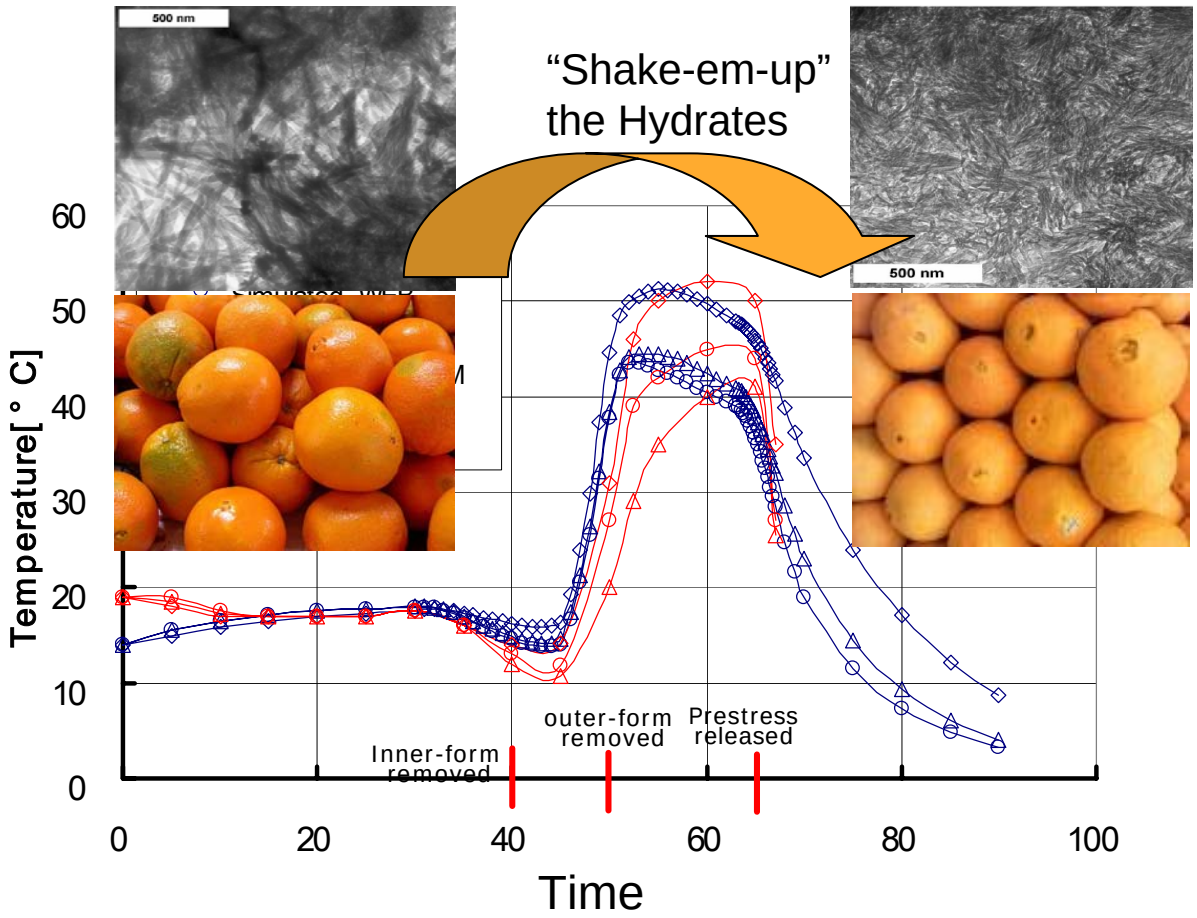
5 cm Web
(no reinforcement)

Monitoring the Temperature during Hydration



Results with
CESAR-LCPC

Nano Engineer the Performance



Prototype Development

- Failure as designed

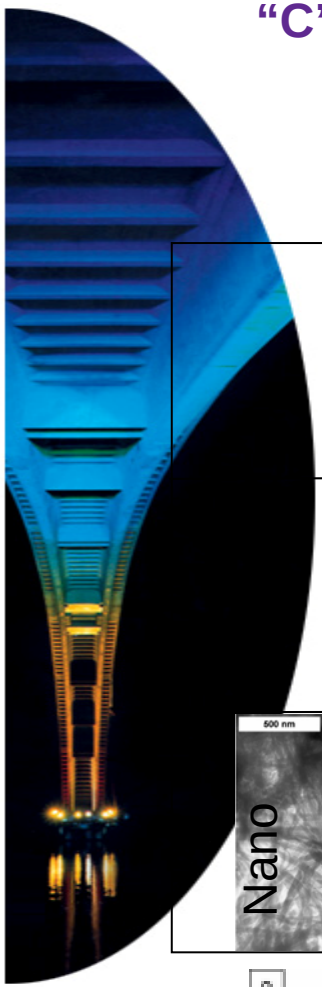
- Tested in May 2005 by FHWA (Virginia)

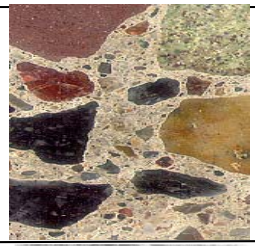
From Nano-to-Structures:
Nano Engineering of Concrete

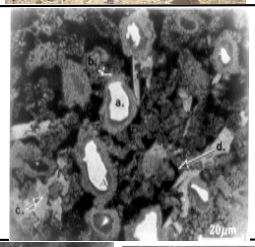
1st Implementation Iowa 2007

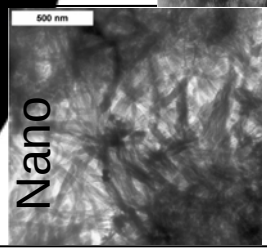
…and what is your “ C-crete “?

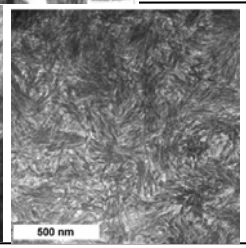
“C” like… CO_2 Reduction

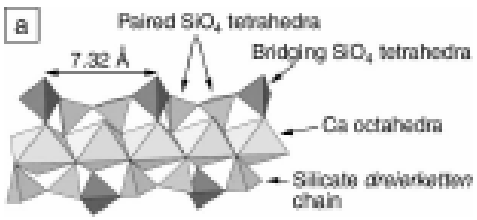












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