



ENGINEERING
MECHANICS
INSTITUTE

Research Group Profile Mechanics of Materials and Structures Research Group at M.I.T. Nanomechanics of Concrete

Problem

More concrete is produced than any other synthetic material on Earth. The current worldwide cement production stands at 2.3 billion tons, enough to produce more than 20 billion tons or one cubic meter of concrete per capita per year. There is no other material that can replace concrete in the foreseeable future to meet our societies' legitimate needs for housing, shelter, infrastructure, and so on. But concrete faces an uncertain future, due to a non-negligible ecological footprint that amounts to 5-10% of the worldwide CO₂ production. It now appears that mechanics can be the discipline that enables the development of a sustainable green concrete future.

Approach

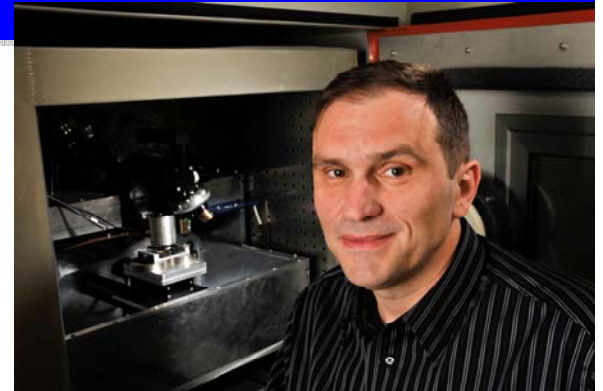
The approach we have taken at MIT originates from Galileo's Strength of Materials Theory, which recognizes that weight, and thus CO₂-emission, increases with the volume of the produced material, while strength of structural members increases with the section. Hence, as one increases the strength of a material by a factor of x , one reduces the environmental footprint by $1/x$ for columns, and $1/x^{0.66}$ for beams in bending. In contrast to the classical top-down empirical approaches, we have chosen a bottom-up approach that starts at the electron and atomic scale to nanoengineer the fundamental building block of concrete; to assess the properties by nanoindentation; and upscale strength, fracture and stiffness properties from nanoscales to macroscales of day-to-day concrete engineering applications. The key to all this is mechanics at the interface of physics and engineering.

Recent Findings

One of our key findings is that five-nanometer sized Calcium-Silicate-Hydrates (C-S-H), the binding phase of

Core Competencies

- **Nanomechanics and nanoengineering of hydrated composites: concrete, bone and shale.**
- **Statistical nanoindentation techniques: strength, stiffness and creep properties.**
- **Sustainable development of materials and structures for construction, oil and gas, energy industry, CO₂ sequestration.**



Franz-Josef Ulm

Photo / L. Barry Hetherington

all concretes, exhibit a unique nano- granular mechanical signature characterized by limit packing densities of spherical objects: 64% for a Low-Density phase, 74% for a High-Density phase, and 87% for a Ultra-High-Density C-S-H phase. From a mechanical point of view, this means that



Department of
Civil & Environmental Engineering
Massachusetts Institute of Technology

Contact: Prof. Franz-Josef Ulm

ulm@mit.edu

On the web at <http://cee.mit.edu>

stiffness, strength and creep properties of concrete are driven by two key quantities: constituent properties and limit packing density of nano-sized particles. The constituent properties can be nanoengineered ab initio, by modifying the fundamental molecular structure of C-S-H, while volume fractions of LD, HD and UHD phases can be nanoengineered by concrete mix design, and manufacturing conditions.

The nanomechanics approach developed for concrete has been successfully applied to other hydrated composites, like bone and shale and bricks.

Impact

Thanks to progress in nanomechanics and nanoengineering, concrete has re-emerged as a high-tech bulk material at the forefront of materials science and engineering that can be fine-tailored not only to meet the classical strength, stiffness and durability requirements; but also to contribute to reducing the environmental footprint of our concrete consumption; thus adding a new “green concrete value” to the development of our society in terms of both economic growth and social progress. These three components—economic growth, social development and environmental protection—are the definition of sustainable development as set forth in the Rio Declaration on Environment.

Selected Publications

1. Constantinides G, Ulm F-J., “The nanogranular nature of C-S-H”, *J. Mech. Phys. Solids* 55(1), 64-90, 2007.
2. Ulm F-J., Vandamme M., Bobko C., Ortega J.A. Tai K., Ortiz C., “Statistical indentation techniques for hydrated nanocomposites: Concrete, bone, and shale”, *J. Amer. Ceram. Soc.* 90(9), 2677-2692, 2007.
3. Cariou S., Ulm F-J., Dormieux L., “Hardness-packing density scaling relations for cohesive-frictional porous materials”, *J. Mech. Phys. Solids* 56(3), 924-952, 2008.

Current Research Team Members:

- J. Alberto Ortega (Ph.D. Candidate)
- Rouzbeh Shahsavari (Ph.D. Candidate)
- James Vanzo (S.M. Candidate)
- Zenzile Brooks (S.M. Candidate)
- Romain Bard (S.M. Candidate)

Recent Graduates:

- Dr. Georgios Constandinides (Ph.D. 2006), now at Cyprus Univ. of Technology.
- Dr. Matthieu Vandamme (Ph.D. 2008), now at Ecole des Ponts, France.
- Dr. Christopher P. Bobko (Ph.D. 2008), now at North Carolina State University.

Current Research Collaborations:

- GeoGenome Project: Prof. Younane Abousleiman, PMI Oklahoma University at Norman.
- Liquid Stone Project: Prof. Roland

4. Tai K., Ulm F-J., Ortiz C., “Nanogranular origins of the strength of bone”, *Nanoletters* 6(11), 2520-2525, 2006.
5. Bobko C., Ulm F-J., “The nano-mechanical morphology of shale”, *Mech. Mater.* 40(4-5), 318-337, 2008.
6. Ortega J.A., Ulm F-J., Abousleiman Y., “The effect of the nanogranular nature of shale on their poroelastic behavior”, *Acta Geotech.* 2, 155-182, 2007.
7. Dormieux L., Kondo D., Ulm F-J., *Microvoromechanics*. I. Wiley & Sons. 2006.

