3D Printing: A New Promising Avenue for Concrete and the Construction Industry?

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www.Printingcementin3d.com
NSF 1239979 and NSF 1563389

NSF Workshop on Additive Manufacturing for Civil Infrastructure Design and Construction, Arlington – July 13-14, 2017
World’s Most Ubiquitous Material
World’s Most Ubiquitous Material
A Complex, Random, Multiscale Material

Length
- meter
- millimeter
- micrometer
- nanometer

Engineering
- Mechanics
- Chemistry
- Physics

Discipline

Minutes/Hours/Days
- Powder
- Fluid
- Paste

Days/Decades/Centuries
- Solid
- Pieces

A Multi-disciplinary Approach

Time
A Complex Multiscale Porous Composite Material with a Complex Nanoscale Structure

Macroscale (m)  Mesoscale ($10^{-2} – 10^{-3}$ m)  Microscale ($10^{-6}$ m)  Nanoscale ($10^{-9}$ m)  Length

Continuum Methods  Atomistic and Molecular Scale Methods
Complex Multiscale Interactions with the Environment

Weathering Forces \[\rightarrow\] Internal Chemical Changes \[\rightarrow\] Internal Stresses \[\rightarrow\] Material Damage

Chemical $\leftrightarrow$ Mechanical

Feedback Loop: Increase in Deterioration

- Weathering Forces
- Internal Chemical Changes
- Internal Stresses
- Material Damage

Stress

Nano-Reinforcement

Pores

Salts $\rightarrow$ Acid $\rightarrow$ Water

Feedback Loop: Increase in Deterioration
Cement-based Materials
Increasingly Complex... Yet, Empirically Designed

- Need for high-performance infrastructure materials with superior and multifunctional properties
- Need for more sustainable, “green” concrete
  - Innovative alternative cementitious materials
  - Use of a wide range of supplementary cementitious materials
- Need to increase the design life of structures
- Need for repair strategies
Computational Materials Science

- Opportunity to simulate complex behavior and to model systems over many length and time scales

NSF 1239979: US-Poland Workshop on Multiscale Computational Modeling of Cementitious Materials

Need for new modeling and experimental strategies to bridge length and time scales
Nano-Engineering of Concrete

Has emerged as a promising technology in the construction industry over the past decade

Steel rebar
A main cause of concrete degradation

“Nano-rebar” made of carbon nanofibers

Need for new design paradigms and innovative approaches to accelerate the introduction of new materials
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3D Printing Cement Workshop: Exploring the promising potential of additive manufacturing

Experts address promises and problems of 3D printing large structures

Every month or so an article comes out reporting that some new object has been made using 3D printing: Everything from jewelry to prosthetic devices to electronic circuit boards to住宅 offers to automobiles has now been printed in

Solid processes—ACerS members lead workshop on 3-D printing of cement-based materials
3D Printing Concrete: The Next Revolution?

- Make your own
  - From a digital design to a 3D object through a computer-controlled printer head
- 3D printing is revolutionizing several areas
  - Biomedical, automotive, aerospace, food
- First houses are now being 3D printed
- NASA's 3D Printed Habitat Challenge
  - Create sustainable housing for deep space exploration
3D Printing Concrete Technologies

- Hatchek method - 1890’s
  - Production of fiber cement boards
- Extrusion-based techniques
  - Contour Crafting – Univ. of S. California
  - Concrete Printing – Loughborough Univ.
- Powder jetting/bonding techniques
  - D-Shape Printing - Monolite UK Ltd
- 3D printing technologies have been to date primarily attractive to architects and designers
  - Create structures in new shapes and with exotic architectural features
Opportunities in the Construction Industry

- Reduction in construction cost and time by eliminating the need for formwork
  - Molding and formwork are 35 to 60% of the cost of a concrete structure
- Increase in productivity and safety
  - Eliminate time spent on rebar placement, mold construction and inspection
  - Construction industry has one of the highest fatal injury rates of all industries
- Increase in construction flexibility and adaptability
  - Ability to accommodate change
Opportunities in Concrete

- New opportunity to optimize the binder
- Use of local materials, non-portland binders
  - Powder-based inks made of construction waste materials
  - Iron oxide-free portland cement polymer formulation, magnesium oxide mixes, and sulfur-based concrete
- Enabling inclusion of all manner of co-printed reinforcements and control of reinforcement-matrix interfaces
- Enabling localized control of chemistry, process conditions (temperature and shear rate, etc.) and microstructure
- Enabling the designer to utilize a hierarchy of structures and patterns
3D Printing of Concrete: Challenges

- **Large to mega scale infrastructure**
  - Limitation of the size of the 3D printer
  - Modular approach used: prefabricated blocks - "Legos" - assembled on site

- **Material characteristics**
  - Extrusion-based 3D printers
    - Flowability, extrudability, buildability
    - Shape stable after being deposited
  - Powder deposition-based 3D printers
    - Cement *ink* must set rapidly and have high adhesive resistance
  - Rapid rigidity to withstand load of subsequent layers

- **Structural behavior and durability**
  - Structural capacity and effect of successive layer deposition is unknown
  - Long-term durability to environmental exposure is unknown
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3D Printing of Civil Infrastructure Materials with Controlled Microstructural Architectures

Ink Formulation and Printing

Computational Modeling

Hydration and Rheology

Ink Development

Printing Parameters

3D Printing Process

Layer Solidification

Chemistry

Printed Layer Interfaces and Bonding Mechanisms

Filaments

Inter Filament Region

Intra Filament Layer

3D Printer Nozzle

Printing parameters
Processing conditions
Interfacial interactions
Filament layer thickness
Printing orientation
Setting process

Intra-Filament Tobermorite-Graphite Interface

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Does 3D Printing Have a Concrete Future in Our World and Beyond?

- Clearly an emerging technology
- Disruptive or decades away from viability?
- Poised to have a dramatic impact on how architects, engineers, and designers are using concrete
- Provides materials scientists and engineers with the ability to create materials that exhibit paradigm-shifting properties
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