Enhancing Concrete Formulations for Additive Manufacturing

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Capstone Design: Final Presentation

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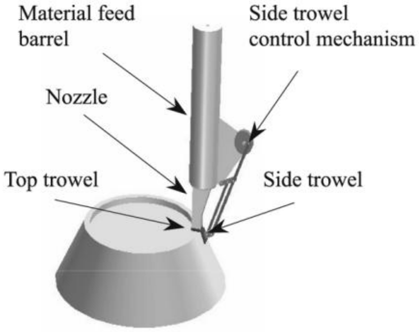
Introduction

Motivation

Additive Manufacturing (AM) is a process whereby material is deposited in layers to form a part.

Concrete is a prime candidate for AM applications, as a fluid mixture that cures into a high strength solid.

Several concrete AM technologies already exist, but a materials problem inhibits further acceptance and development.



Above: Contour crafting mechanism.[7]
Below: d-shape structure.[8]

Project Progression

1. Develop a 3D printer to study effect of concrete composition on bonding between layers.

2. Isolate extrusion process to focus on materials science, build on recently published model and extruder setup to study effect of air entraining admixture on fresh and hardened properties of extruded concrete paste.

3. Develop original simulation using material parameters obtained through small-batch extrusion as means for rapid scale-up of concrete AM systems.

Performance Goals

1. To produce an analytical simulation of flow through the nozzle of a concrete 3D printer, using material parameters obtained through extrusion testing.

2. To test the use of surfactant (an air-entraining admixture) on the fresh properties of extruded concrete.

Experimental Method

Technical Approach

Herschel-Bulkley fluid:

$\sigma = \sigma_0 + k(\varepsilon^{vp})^n$

$$P = -\sigma_{rr}(r_{\max}) = 2\sigma_0 \ln\frac{D_0}{D} + Ak\left(\frac{V}{D}\right)^n \left(1 - \left(\frac{D}{D_0}\right)^{3n}\right)$$

σ_0 - yield stress

k - consistency index

ε^{vp} - viscoplastic strain rate

n- flow index

Experimental Approach

1. Cleaning the apparatus
2. Attaching to the UTS
3. Mixing
4. Filling
5. Final preparations
6. Extrusion

Design of Experiments

- Control samples prepared with water, binder, aggregate, plasticizer, and retarder.
- Air entraining admixture added to remaining samples.
    - Percent composition held constant.
    - Mixing time varied to alter air bubble size.
- Sand and PVA fiber aggregates used.

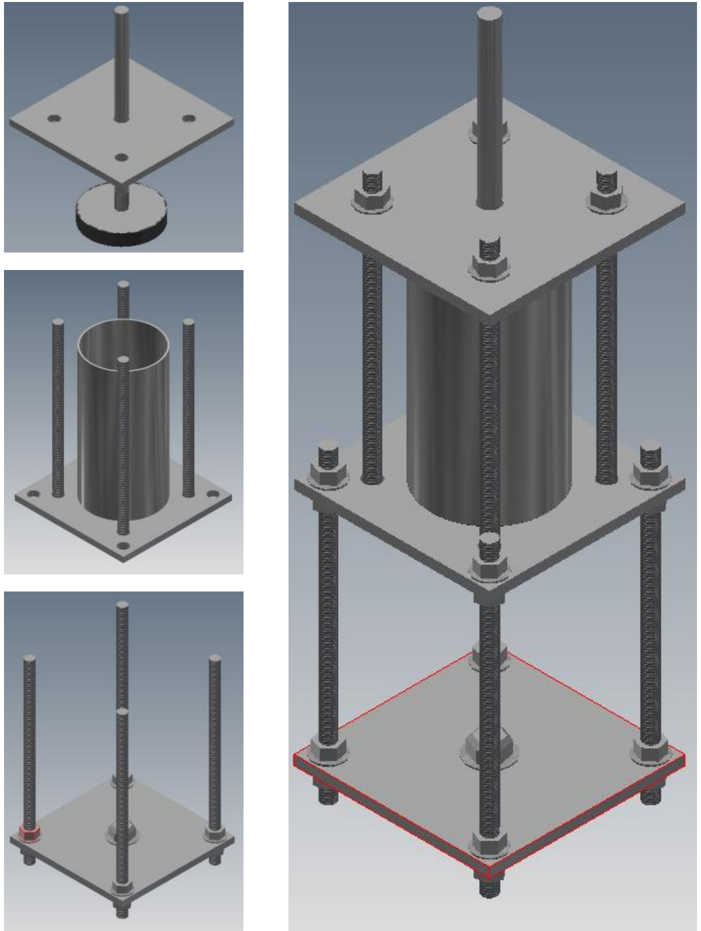
Prototype Fabrication

- Parts were purchased through online venders and machined to our specifications
- Modifications were made to the ram, bottom plate, top plate and support bars
- Material selections were made to either lower costs or improve wear resistance

Prototype Assembly

Made up of 3 subassemblies

- A: Bottom Base with Rods
- B: Central Base with Rods & Cylinder
- C: Upper Lid with Plunger



Facilities

- Utilized the Modern Engineering Materials Instructional Laboratory (MEMIL)
- MEMIL has everything we needed
- MEMIL is free to use for students
- Dr. Robert Bonenberger was available both days that we worked in MEMIL

Prototype Testing

- Made several mixtures that all were all the same
- Added sand into samples, mixed and extruded
- Added fiber into samples, mixed and extruded
- Used fiber mixtures and then added air entraining surfactant, mixed at different times and extruded

Cement	Slag	SS1	SS2	PVA	Methocel	ADVA	W/B
0.5	0.5	0.2	0.125	2%	1%	0.25%	0.25

Zhou et al.

ANSYS Fluent Simulation

- Herschel-Bulkley Fluid Model
  - Non-Newtonian fluid model
    - Behaves as rigid solid until yield stress is met, where the fluid begins to flow as a viscous liquid
  - Shown in literature to accurately model cement mixed with fiber aggregate
  - FLUENT does not allow for modeling both a H-B fluid and discrete phases simultaneously

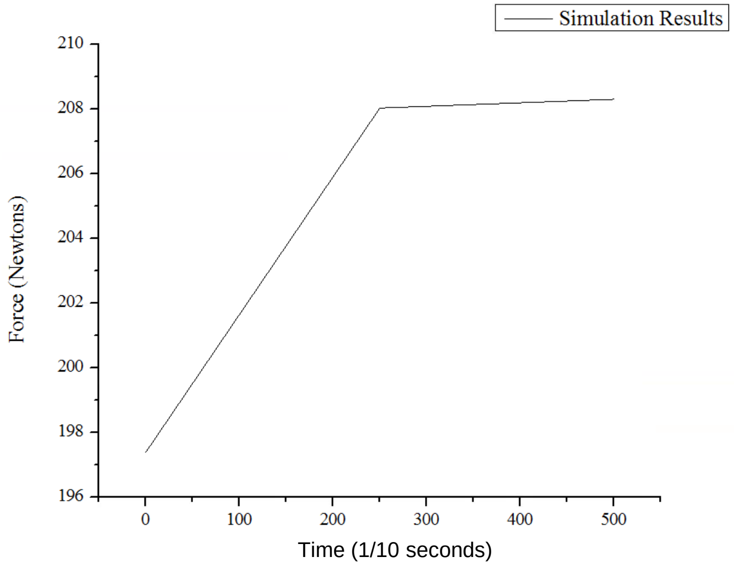
ANSYS Fluent Simulation (cont.)

- Discrete Phase Model (DPM)
  - Allows for multiple fluid and particulate phases
  - Fluid phase (i.e. the cement) is modeled as a Newtonian fluid
  - Aggregate (sand) and entrained air bubbles both modeled as inert particle injections
    - Sand - 500µm diameter
    - Air bubbles - 1mm diameter

Results

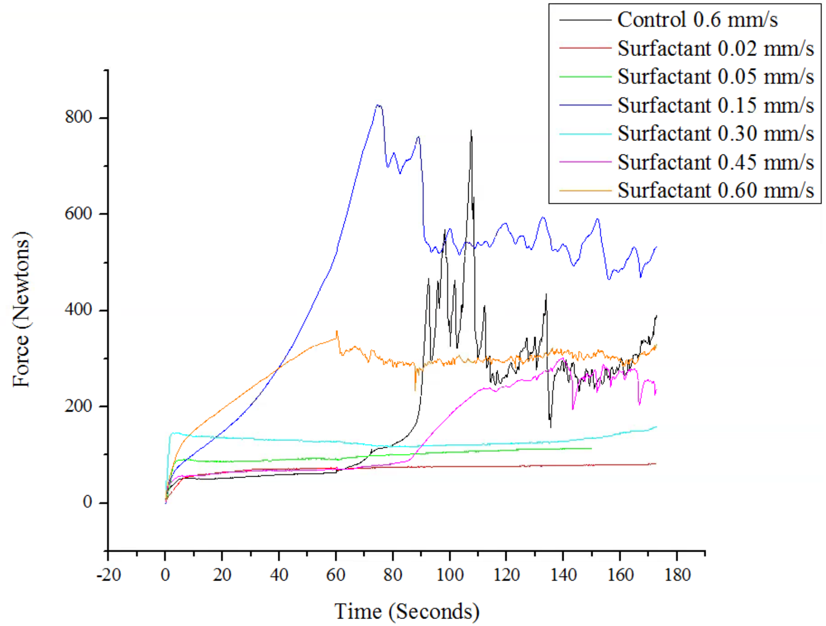
ANSYS Fluent Simulation

- H-B Model
  - Pressure measured at orifice exit surface
  - 1 mm/s flow rate
  - Force increases linearly until yield stress is exceeded and flow begins

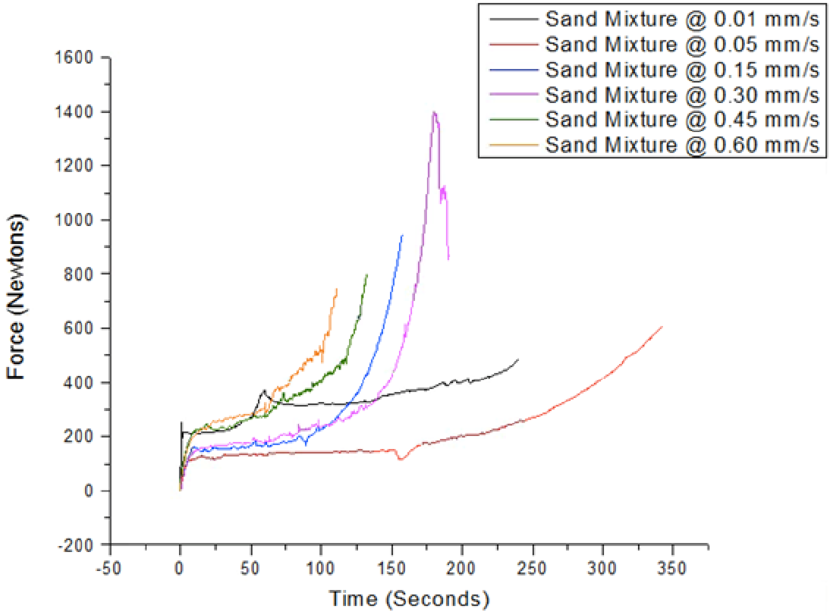


Prototype Results

Fiber Aggregate Results

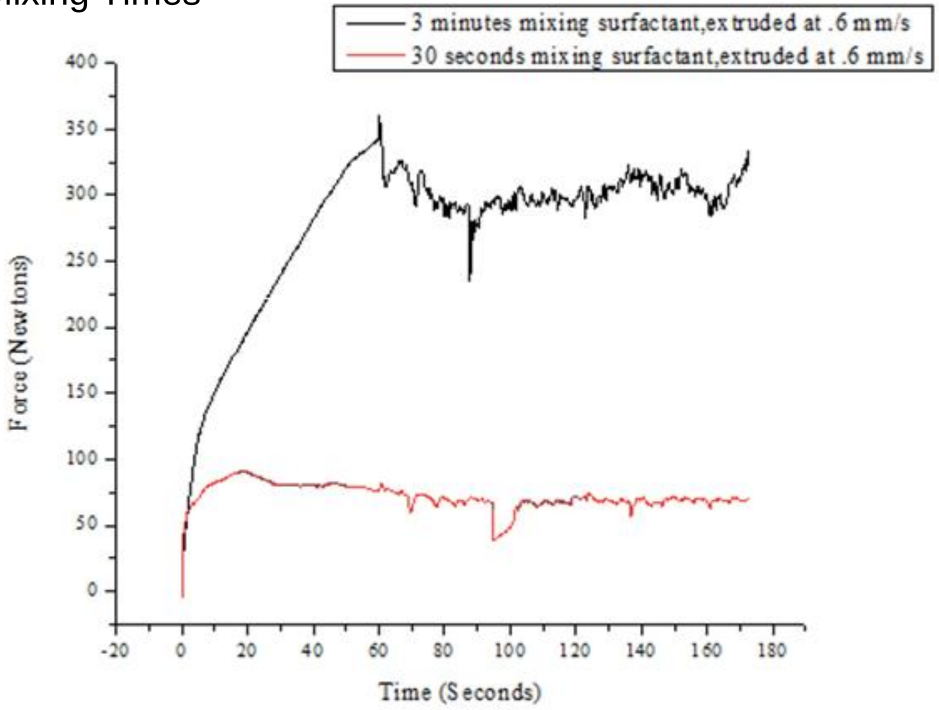


Sand Aggregate Results



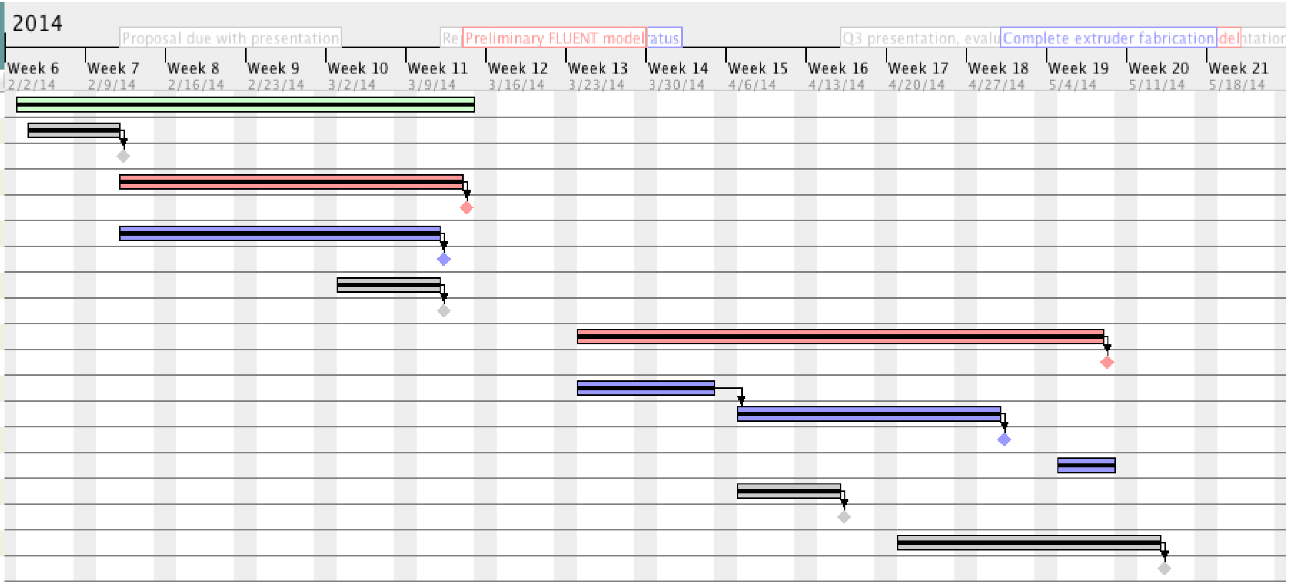
Prototype Results (cont.)

Different Mixing Times



Timeline

Name	Begin date	End date
Resarch	2/3/14	3/14/14
Proposal writing	2/4/14	2/11/14
Proposal due with presentation	2/12/14	2/12/14
Develop FLUENT model	2/12/14	3/13/14
Preliminary FLUENT model	3/14/14	3/14/14
Design extrusion apparatus	2/12/14	3/11/14
Finish CAD of extrusion apparatus	3/12/14	3/12/14
Q2 presentation, evaluations	3/3/14	3/11/14
Report due with presentation	3/12/14	3/12/14
Refine FLUENT model	3/24/14	5/8/14
Final FLUENT model	5/9/14	5/9/14
Revise CAD of extrusion apparatus	3/24/14	4/4/14
Fabriacte prototype	4/7/14	4/29/14
Complete extruder fabrication	4/30/14	4/30/14
Extrusion testing in MEMIL	5/5/14	5/9/14
Q3 report writing	4/7/14	4/15/14
Q3 presentation, evaluations	4/16/14	4/16/14
Develop final video, poster, report	4/21/14	5/13/14
Final presentation, evaluations	5/14/14	5/14/14



Budget

CATEGORY	ITEM	UNIT COST	TOTAL COST
FACILITIES	MEMIL lab usage	---	---
APPARATUS	Hopper	---	$73
	Piston	---	$80
	Plates	$24	$72
	Extruder dies	$10	$30
	Connection hardware	---	$50
	Machinist labor	---	$500
CONCRETE	Portland cement	---	---
	Sand	---	---
	Water	---	---
	Surfactant, 8 oz.†	---	---
	Fibers, 1 lb.†.	---	---
	Superplasticizer, 2.5 lb.	---	$17
	Silica fume, 10 oz.†	---	---
	Fly ash†	---	---
	Retarder	$3	$9
MISC.	Mixing paddle	---	$12
	Drop cloth	---	$11
PRESENTATION	Poster	---	$70
SHIPPING	Total shipping costs	---	$73
		TOTAL	$997

† Indicates that samples were procured for free through suppliers.

Scale-Up Cost Analysis

- Difficult to assess given our circumstances
- Advantages over traditional construction methods
    - Diminished labor/risk
    - Longer lifetime
    - Energy-efficient
    - Less waste

Table 1. SINGLE-FAMILY PRICE AND COST BREAKDOWNS
2009 National Results

Average Lot Size: 21,879 sq ft
Average Finished Area: 2,716 sq ft

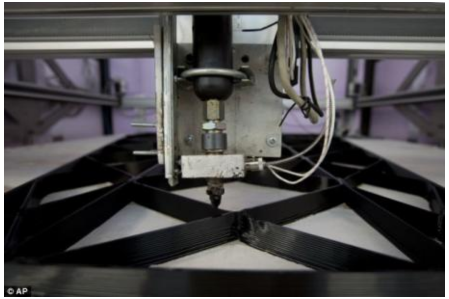
Sales Price Breakdown	Average	Share of Price
A. Finished Lot Cost (including financing cost)*	$76,591	20.3%
B. Total Construction Cost	222,511	58.9
C. Financing Cost	6,375	1.7
D. Overhead and General Expenses	20,377	5.4
E. Marketing Cost	5,297	1.4
F. Sales Commission	12,815	3.4
G. Profit	33,658	8.9
Total Sales Price	**$377,624**	**100.0%**

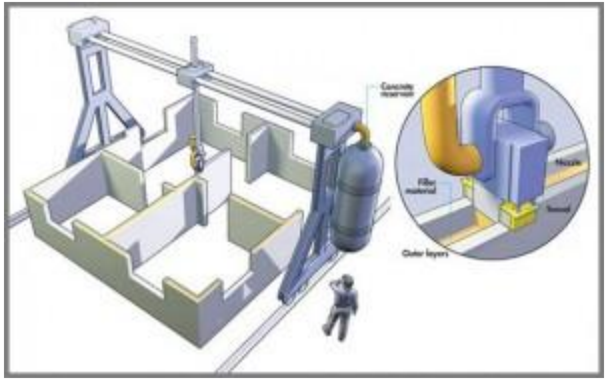
Construction Cost Breakdown	Average	Share of Constr. Cost
Building Permit Fees	$4,264	1.9%
Impact Fee	3,165	1.4
Water and Sewer Inspection	3,761	1.7
Excavation, Foundation, and Backfill	15,878	7.1
Steel	1,637	0.7
Framing and Trusses	34,805	15.6
Sheathing	3,869	1.7
Windows	6,236	2.8
Exterior Doors	1,930	0.9
Interior Doors and Hardware	3,356	1.5
Stairs	1,676	0.8
Roof Shingles	8,472	3.8
Siding	12,858	5.8
Gutters and Downspouts	949	0.4
Plumbing	11,753	5.3
Electrical Wiring	8,309	3.7
Lighting Fixtures	2,372	1.1
HVAC	8,860	4.0
Insulation	3,332	1.5
Drywall	11,332	5.1
Painting	7,638	3.4
Cabinets and Countertops	12,444	5.6
Appliances	3,583	1.6
Tiles and Carpet	11,436	5.1
Trim Material	7,394	3.3
Landscaping and Sodding	7,088	3.2
Wood Deck or Patio	1,948	0.9
Asphalt Driveway	3,083	1.4
Other	19,085	8.6
Total	**$222,511**	**100.0%**

Source: NAHB 2009 Construction Cost Survey, based on a national sample of 54 home builders

Current 3D Concrete Printers

- Amsterdam Canal House
- China Recycled House
- USC Contour Crafting





Future Work

- ANSYS Simulation
  - Herschel-Bulkley model seems most promising
    - ANSYS Polyflow, another CFD program, allows for H-B fluid models with discrete particle phases
    - More accurate material properties (e.g. viscosity, sand particle size, air bubble size)
    - Model air-air interactions (i.e. bubbles merging into one)
- Extrusion Testing
  - Exact water-to-binder ratios, larger batches
  - Hardened properties testing (void content, freeze-thaw)
  - Investigate effect of aggregate size and composition on extrudability

Questions?

References

[1] National Academy of Engineering, "Restore and improve urban infrastructure - Engineering Challenges," 2014. [Online]. Available: http://www.engineeringchallenges.org/cms/8996/9136.aspx. [Accessed: 01-Feb-2014].

[2] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibb, and T. Thorpe, "Mix design and fresh properties for high-performance printing concrete," *Mater. Struct.*, vol. 45, no. 8, pp. 1221–1232, Jan. 2012.

[3] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, R. Law, A. G. F. Gibb, and T. Thorpe, "Hardened properties of high-performance printing concrete," *Cem. Concr. Res.*, vol. 42, no. 3, pp. 558–566, 2012.

[4] G. Gibbons, "3D Printing of cement composites," *Adv. Appl. Ceram.*, vol. 109, no. 5, p. 4, 2010.

[5] X. Zhou, Z. Li, M. Fan, and H. Chen, "Rheology of semi-solid fresh cement pastes and mortars in orifice extrusion," *Cem. Concr. Compos.*, vol. 37, pp. 304–311, Mar. 2013.

[6] Khoshnevis, B. Automated construction by contour crafting—related robotics and information technologies. *Autom. Constr.* **13,** 5–19 (2004).

[7] <http://static.squarespace.com/static/5111abfde4b0abbcce9df169/519219c0e4b01bf9287dec52/519219c0e4b00cc73119750a/1368529345838/radiolariapav5.jpg>

[8] A. Roussel, Nicolas, Gram, Ed., "Simulation of Fresh Concrete Flow: State-of-the Art Report of the RILEM Technical Committee 222-SCF," Springer, 2014.