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3D Concrete Printing; The Material Point

Frank Marquette[1]

[1] Troy University, Troy, AL,
fmarquette@troy.edu

Abstract
The growing application of automation in manufacturing and construction processes, leveraged by advances in computer aided design, presents a growing opportunity for 3D Concrete Printing technology (3DCP). This sector of additive manufacturing is receiving considerable attention with social and traditional media references to projects by companies achieving certain levels of efficacy generating a high level of public awareness of its potential. Our estimation is there's an emphasis on projects and equipment over 3DCP material science, and at this time open collaboration in research will support the development of the material science central to this technology.

Keywords
3DCP, 3D Concrete Printing, 3DCP Mix Design, 3DCP Mortar Mix Design, Open Source 3DCP, Mortar Rehology, Mortar Pumpability, Mortar Extrudability, Mortar Printability, Portland Cement, CSA Cement.

1. Introduction
3DCP technology remains at relatively early stages of development in all aspects of design and implementation. The ambition of designers utilizing CAD and parametric software outpaces the present deposition technology for automated 3DCP manufacturing. The additive manufacturing slogan "complexity is free" is yet to be realized in 3DCP without significant investment in proprietary equipment and material; even with these constraints are limiting.

Much of 3DCP focus to date has been on large format 3D concrete printing machines over a greater understanding of the printing material. This paper posits the industry will benefit from an emphasis on the material science of 3DCP first, and how this offers the greatest potential for advancing this manufacturing and construction technology.

Additive Manufacturing has its origins and growth in "open source" sharing of R&D, and we envision 3DCP benefiting from the same. Outstanding research has been completed and made available addressing several aspects of 3DCP mix designs including:

- Rehology Characteristics
- Structural Performance
- Interlayer Bonding
- Effective Extrusion
- Structural Stability
- Cement Hydration
- Fiber Reinforcement
- Polymer Admixtures

Still, those approaching the industry anew find that 3DCP mix designs are not readily shared, and companies that have developed designs for proprietary use are understandably protective of their intellectual property.

3DCP starting point scratch mix designs supported by an open source collaboration between industry and education will accelerate the range, advancement, and uptake of concrete printing. Examples and learnings gained will be shared from research in our university lab setting and working with industry.

2.1. What Comes First?
Usually, a machine. A machine that can print a house as a solution to the housing supply and construction labor shortages. This prospect has been a primary fuel for early investment in equipment and industry positioning.

It’s understandable, someone sees a large printer extruding the walls of a house. The machine is printing a house, we need a machine. The machine is printing an engineered mortar, that may or may not be available or ultimately effective. With an effective and readily available 3DCP mortar mix a printer can manufacture house walls and a lot more, not before.

What if the first question when witnessing a machine print concrete was: “What mortar mix can we obtain to achieve our 3DCP vision”?

Concrete is among the most common, inexpensive, tested, and understood building materials in modern history. The assumption that a typical concrete mortar could be effectively printed is a blindside and gross oversimplification.

Performance criteria of 3D printed concrete is perhaps one of the least common, tested, inexpensive, and understood applications of concrete or mortar to date.

Can we effectively batch and mix an available 3DCP mortar? Do we have a pump and extrusion system to deposit this? Can the material perform to our production and design needs? Our research informed us the material comes first.

3DCP technical nomenclature is emerging and beginning to articulate the fundamental aspects of mix design performances. The following constitute the primary characteristics, challenges, and needs discovered in our experiments.

2.3.1. Lack of mix Designs and Sources

The ability to source materials is clearly essential, yet often over looked. Proprietary mixes are evolving and often difficult to obtain, and in many cases have exclusive distribution. Identifying supply chains and the required logistics is essential and often carries hidden expenses and other practical challenges.

2.3.2. Material Mixability

The ability to mix and hydrate the material, especially in instances of continuous supply on large scale projects, is often underestimated. Proprietary mixes may have particular needs, i.e. high-shear mixing, and may or may not be compatible with automated mixing equipment commonly utilized. An understanding of the chemistry of admixtures and their activation needs is also central to workflow of the mixing process.

2.3.3. Mix Pot-Life and Open-Time

These reference the amount of time available after mixing and before deposition; how long an activated mix can be effectively pumped or extruded. Pot-life and open-time are affected by atmospheric conditions, mixing procedure, and pumping technology. The ability to work within or adjust pot-life and open-time requires material chemistry understanding and dynamic management options.

2.3.4. Pumpability

The ability to pump and convey the mortar to an extruder is fundamental to the printing process. Precise control of over delivery rates and integration into the printer control system is required. Concrete and mortar pumps can induce surging of material supply and/or shearing and heating that are not favorable in most 3DCP applications. Pump, mortar, extruder, and control system alignment is critical.

2.3.5. Extrudability

Two types of extrusion are commonly used presently: Continuous Feed and Controlled Feed systems. Continuous feed, wherein the material is extruded through and aperture with little control over placement at the nozzle. With Controlled feed the material is pumped into a hopper that feeds an extruder with the ability to control the speed and pausing at the nozzle. Different extruder and nozzle designs require different mix designs for optimum performance.

2.3.6. Buildability

This is the ability of the material to develop sufficient yield strength to support subsequent layer deposition while maintaining layer bond. Time required between each layer deposition, the nature of the hydration or other reactive properties of the mix design, sufficient open-time to maintain effective bond between layers, and the level of complexity of forms that can be printed define good buildability.

2.4. Fundamental and Practical Requirements

Mix design affects and governs the efficacy of all phases of 3DCP production. Access to formulations, accurate and consistent batching of materials, effective and consistent mixability, material delivery and pumpability, material extrudability, material deposition and buildability, material durability and structural performance - all of these are inherent in the mix design.

3DCP mix designs require rigorous consistency and often paradoxical performance parameters, i.e. pumpability of mix and controlled hydration of set has effectively the opposite performance needs of buildability and early strength. All of these factors and how they respond in an applied environment are central to the effective placement of 3DCP concrete and mortar.

The utility of portland, calcium sulphoaluminate, geopolymer, and other cement binders have revealed unique strengths and weaknesses striving to address these demanding requirements. In the lab, several mix formulations have demonstrated efficacy in small batches and experiments. Applying the same formulas in the field at larger scales reveal other fundamental and practical needs.

Material availability, logistics, and general material handling during implementation are other fundamentals required for application success. Extrinsic factors affecting the utility and placement of mixes include atmospheric, mechanical handling, and human skills sets. Failure in any of these areas will be expressed in the product appearance, production rates, and final mechanical properties.

2.5. Rehology and Accelerated Reaction

The buildability of 3DCP mortar is delivered by the rehology and acceleration of early set in the mix. Rehology and Acceleration work in concert to make a buildable mix while meeting the other needs of successful 3DCP deposition.

Though these two work together to achieve buildablilty, at present mix designs emphasize one of these as primary. We will describe these as Rheology Build Mortar and Accelerated Build Mortar.

Rehology Build Mortar is a mix design activated by water, or another type of reagent, to create a homogenous mix that delivers a limited degree of buildability through integral yield stress for successive layer deposition. However, this is limiting to build speed and draft or incline of vertical surfaces. These mixes are relatively simple formulations and can be batched with commonly available materials.

Accelerated Build Mortars are typically proprietary mixes that have evolved through significant investment in development that allows for high levels of control over deposition rate and material set time. This technology typically injects and mixes a secondary catalyst to the mix at the print nozzle immediately preceding extrusion. This can be one or a combination of accelerators of different chemistry that are adjustable to realize the most complex and rapid build in 3DCP to date.

CSA cement can be utilized as a binder for Accelerated Build Mortar as this material offers high early strength, typically with minutes, developing enough yield stress resistance to build as high as the printer build volume allows. This is a less forgiving approach as the reaction of the mix originates at the first stage of mixing and dynamic control of reaction is limited compared to multi-part designs that can be accelerated at different rates to service a range of buildability needs.

The range of hybrids of rehology and reaction blends is effectively innumerable. We will share the hybrid formulation we have developed in our lab and an indication of the performance of this mix design.

2.6. Material Delivery: Controlled or Continuous

Continuous material feed is effectively an extrusion through the print nozzle that is controlled by the pump delivering the material. The ability to pause and restart the print is compromised due to pressures in the pump line and any control over the material at the nozzle. These mixes generally begin extruding before beginning the print profile and continue after the print is completed. This lack of material feed control limits the deposition and design of the layer geometry. Continuous feed works best with “spiral” printing geometry as the extrusion is continual and does not require the ability to pause for Z height or point to point nozzle position changes.

Controlled material feed utilizes an extruder immediately preceding the print nozzle. This is a combination of a hopper to accumulate material and an auger to extrude and control the flow of material. The extruder allows good control of the volume of material delivery and has the ability to pause or even retract material to allow the print nozzle to be repositioned either on Z axis or to other locations.

Both material delivery systems have application advantages, however the controlled method is most commonly utilized especially in large format 3DCP.

3. 3DCP Lab Results

Here we share the results of our lab experiments with 3DCP mix designs and deposition techniques.

3.1. 3DCP Experiment Goal

Our project goal was to learn more about 3DCP at small to medium scale application. The students decided upon printing a vase of approximately 400mm diameter as high as possible with the given equipment and material performance constraints.

3.2. Binder

Resources limited our choice to hybrid rehology build mortar mix designs. We began with OPC binder, and due to the scale and limited time between layer deposition we could not achieve more than 6” of Z height on our prints. This was affected by the small scale of our prints, typically shapes less than 500mm in diameter, which resulted in successive layers being placed within 20- 40 seconds. This did not allow enough time for OPC mixes to develop yieldstrength.

We began formulations blending CSA and OPC binders to create a hybrid mix that offered both pot-life and different degrees of early strength.

3.3. CSA/OPC 3DCP Mix Design

This table defines our scratch mix design that utilizes CSA binder, polymer, VMA, fiber, and pH adjusted potable water.

Material	**Parts by batch weight**
Washed and graded 30-120 mesh silica sand	1.0
Ordinary Portland cement	0.9
CSA Cement	0.3
Dry Polymer Admix	0.2
Hydroxyethylcellulose	0.03
PVA Fiber, 6mm	0.05
Water	0.3
Citric Acid	As needed to achieve 2.5 pH in batching water

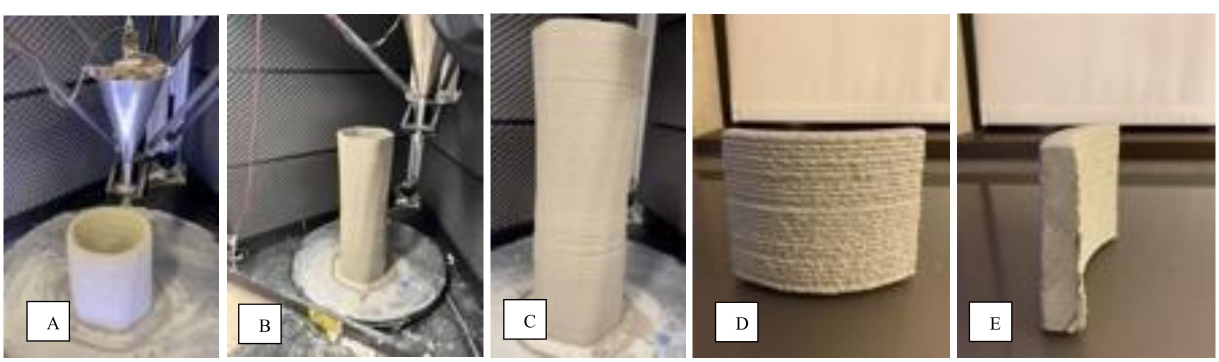
The consistency of the mix will vary and the water content adjusted to achieve the desired viscosity.

3.4. Mix Deposition

We experimented with both continuous-feed pumping the material and with controlled deposition utilizing an auger extruder and manual feed material hopper.

3.5. Print Results

With the formula and deposition described above we achieved a build of 400mm diameter at 900mm high. The layer height was 4mm. The nominal print speed was 40mm/sec. The extruder rate was adjusted to deliver a wall thickness of nominally 20mm.



A: First attempts to achieve 300mm Z height. B: Achievement of 900mm Z height with more complex shape geometry. C: Completed 900mm Z height print at specs defined above. D: Detail of layer heights. E: Cross section showing interlayer adhesion and integration.

4. Discussion

The recent growth in awareness of 3DCP, especially in large format for printing walls for residential applications, we were inspired to begin the journey of experimenting with this technology. We found proprietary material supply companies supportive and continue in these relationships sharing outcomes and general learnings of 3DCP technology. However, we also found that other proprietary 3DCP companies remain protective of their material innovations, and understandably so. However, our intention was to develop and share starting point mix designs as perhaps the most central element for successful 3DCP.

This is clearly a much broader technology than can be addressed in this paper. However, in our estimation, all progress and success in 3DCP will revolve around more effective 3DCP mix designs. Material science first, product design and electromechanical engineering second.

5. Conclusions

It is possible to create a scratch mix for 3DCP that meets all of the primary performance criteria with readily available materials. With access to starting point mix designs locally available materials and regionally available admixtures can yield a mix design with predictable results.

Open sharing and collaboration of mix designs will accelerate the adoption of 3DCP and make possible applications and utility of design and deposition technology accessible. Industry-wide adoption of 3D Printing was greatly accelerated when open source sharing was facilitated and the same is possible for this sector, 3DCP.

Going forward our research will continue to enhance the performance of 3DCP mix designs with an emphasis on buildability and form complexity, making these findings available open source. This will include:

- R&D modifying and controlling hydration rates
- R&D of dynamically adjusting mix designs to compensate for environmental changes
- Flexural and compression testing of 3DCP mix designs for small scale structural elements
- Exploration of “1.5K” mix designs for greater complexity of print designs and increased printing speed
- Development of an open source library of design files for 3DCP that align with scratch mix design performance criteria.

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