3D Concrete Printed Houses: Barriers to Adoption and Construction Practices

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Abstract

Home Innovation Research Labs (Home Innovation) was tasked by the U.S. Department of Housing and Urban Development (HUD) to explore the integration of 3D concrete printing (3DCP) technology in residential buildings. Most research in this area has focused on standardizing the equipment design, manufacturing process, and material formulation, which is critical to developing design techniques and performance criteria within the building code (Buswell et al., in press). To complement the current 3DCP research, this project investigates two key critical construction issues: (1) identify barriers to the adoption of 3DCP technology (such as the lack of building codes or standards, the lack of design and construction guidance, and the lack of technical expertise to implement the new technology) and (2) system integration—evaluate how 3DCP components (primarily walls) will be installed with conventional building product components. Home Innovation is conducting qualitative research among home builders and contractors to understand the challenges and opportunities to accelerate the adoption of 3DCP technology. In addition, Home Innovation has evaluated the construction of 3DCP residential buildings in the field with close attention to (1) installation of windows and doors, (2) wall penetration methods for installing utilities (primarily plumbing and electrical), (3) wall connections between the roof and foundation, and (4) interior and exterior wall finishing options. The project is in process, and the data presented in this article are preliminary.

Introduction: The Evolution of 3DCP Technology

3D concrete printing (3DCP) technology offers new opportunities for innovation in the building industry. Since concrete is the most widely used building material in the world, 3DCP technology has the potential to significantly change how buildings are delivered using new construction techniques (GCCA, 2020). With this technology, the concrete is formulated to achieve greater workability, setting, hardening time, and mechanical properties, which can be optimized for the specific requirements of the building. These attributes make innovative structural design possible using a 3D printer that extrudes concrete material layer by layer without any formwork support, as shown in exhibit 1 (ICON – 3D Tech, 2020).

Exhibit 1

PERI—Multifamily Building in Houston, Texas

Note: 3D Printed Wall by PERI.
Source: Home Innovation Research Labs

Several buildings around the world have been successfully erected using 3DCP technology in a wide range of applications—from affordable housing to structures for military applications.

3DCP technology was developed and first introduced in the late 1980s. The earliest applications were to manufacture solid objects using robots that deposited "stone-like materials" without formwork. Over the years, a variety of deposition strategies, robots, printer heads, and material formulations have been used.

Major developments in 3DCP technology started in California when Behrokh Khoshnevis introduced the "contour crafting" technique, which is the method of layering concrete extrudate through fused deposition modeling (FDM), which generally describes how the material is fused through heat and nozzle design (Khoshnevis, 2004; Khoshnevis and Dutton, 1998; Khoshnevis et al., 2006, 2001). The contour crafting technique is one example of FDM and involves layers of continuous concrete-like filament being deposited on top of each other using a single robot. With a few notable exceptions, most 3DCP devices around the globe operate using the FDM principle. In 2014, as an alternative to working with a single, large robot, the Institute of Advanced Architecture of Catalonia (IAAC) grouped together several small robots with sensing (or "swarm") technology to build a concrete printed structure (IAAC, 2014).

A more traditional, stereolithography 3D printing technology, named D-Shape, was adapted for concrete-like construction by Enrico Dini (Colla and Dini, 2013). Allouzi, Al-Azhari, and Allouzi (2020) built on the D-Shape concept using a binder-jetting procedure in which a powder deposition is hardened using a binder instead of being extruded like the FDM filament. Each layer of material is deposited in the required thickness and compacted; then, the printer deposits the binder where the material needs to be solid. Once the printing is completed, loose powder is cleaned from the finished component. In 2014, Universe Architecture and contractor Royal BAM Group used the D-Shape technique to develop the Landscape House in Amsterdam, the Netherlands (Adlughmin, 2014). This project was part of a competition; the technique was not broadly adopted like the FDM filament technique.

Disadvantages of Traditional Concrete Construction

Traditional concrete is made of cement, sand, aggregate, and water, which are combined to form a slurry that has no form of its own when wet. As a result, it has to cure (harden) in a formwork mold. Traditional formwork is fabricated using timber, but it can also be constructed from steel, glass fiber reinforced plastics, and other materials.

Nematollahi, Xia, and Sanjayan (2017) highlighted formwork as a significant source of waste in concrete construction. On average, formwork is used five times before being discarded into a landfill, which contributes to a growing amount of waste in the construction industry. Llatas (2011) estimated that 80 percent of the world's waste is generated by the construction industry. In addition to waste concerns with formwork, approximately one-half the total cost of traditional concrete construction is related to the labor-intensive and time-consuming installation and deconstruction of formwork.

Beyond the issue of waste, there are worker safety concerns related to traditional concrete construction. The Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor lists the following potential hazards for workers in the concrete industry: (1) eye, skin, and respiratory tract irritation from exposure to cement dust; (2) inadequate safety guards on equipment; (3) inadequate lockout/tagout systems on machinery; (4) overexertion and awkward postures; (5) slips, trips, and falls; and (6) chemical burns from wet concrete (OSHA, 2004). Bos et al. (2016) also analyzed the physical labor involved during traditional concrete manufacturing, noting that the erection of molds and the placement of steel reinforcement is physically demanding labor, particularly when custom-made geometries are required.

3D Concrete Printing Techniques and Equipment

Nematollahi, Xia, and Sanjayan (2017) explored the two major techniques used in 3DCP technologies: extrusion-based and powder-based. They stated that the extrusion-based technique, analogous to the FDM method, extrudes cementitious material from a nozzle mounted on a gantry, crane, and/or robotic arm to print a structure layer by layer. This technique has been specified mostly for onsite construction applications, such as large-scale building components with complex geometries, and it has the potential to make a significant and positive contribution to the construction industry by saving time and eliminating the need for formwork. They explain that the powder-based technique creates accurate structures with complex geometries by depositing binder liquid ("ink") selectively into a powder bed to bind powder where it impacts the bed. This technique is an offsite process designed for manufacturing precast components. The authors suggest the powder-based technique is highly suitable for small-scale building components, such as partition walls or panels, and interior structures such as benches or furniture that can then be assembled or installed on site.

Materials Used in 3D Concrete Printing

3DCP material formulations differ compositionally from traditional concrete by adding three ingredients to the basic concrete formulation: (1) a reinforcing material; (2) an adhesive; and (3) a hydrator. This formulation gives 3D concrete special attributes, including the ability to maintain its shape when wet, eliminating the need for formwork.

Allouzi, Al-Azhari, and Allouzi (2020) explored the composition of cement used in both traditional concrete construction and 3DCP. The authors noted that traditional types of concrete formulations are not suitable for 3D printing because the aggregate of materials jams and damages the printing nozzle. Most current research studies are focused on developing new concrete material formulations for 3D printing to obtain the appropriate material performance properties and extrudability that enables the material to be printed continuously and stacked in layers.

One developing printing technology that uses the new mortars is called Shotcrete 3D Printing (SC3DP) by Raatz et al. (2019). The SC3DP technology is significantly more complex than the conventional 3D concrete printing processes because several closed-loop online control routines are required to drive the robotics.

The Ting et al. study (2019) considered the use of recycled glass as the fine aggregate for 3DCP applications. While the mechanical strength of concrete with sand aggregates was better than the concrete formulations using recycled glass, the concrete with the recycled glass was more flowable in 3DCP technology than the concrete with sand aggregates. Further study has been recommended to develop a mix of sand and recycled glass aggregate that will result in the optimum mechanical and flowability properties for new 3DCP mortars.

Hambach and Volkmer (2017) evaluated fiber-reinforced mortars to determine their flexural and compressive strength. Fibers will align with the flow direction of the 3DCP process, which makes some control of fiber orientation possible within the printed structures. The fiber alignment can be used to tailor the material properties of 3DCP components.

In 2018, the American Concrete Institute (ACI) established Committee 564 on 3D Printing with Cementitious Materials.[1] The mission of the committee is to develop and report information on three-dimensional printing (3-D) printing, or additive manufacturing with inorganic cementitious materials. The work is conducted through three subcommittees that are focused on (1) reporting on technical developments in the area of 3DCP, (2) developing guidance documents for structural design and testing, and (3) developing guidance documents for material formulation and testing.

Concurrent with the work of ACI, the National Institute of Standards and Technology (NIST) established a program focused on the premise that "Additive Manufacturing (AM) with concrete, also known as 3-D concrete printing (3DCP), is an emerging technology in the construction industry."[2] In this program, NIST addresses the need for basic standardization of the material and technology.

Today, research continues in the area of material development. In June 2022, Texas A&M University announced a new research project to develop hempcrete for 3DCP technology. The research, led by Dr. Petro Sideris, is novel because "using hempcrete has the potential to lower the environmental impact of traditional construction methods and make housing more affordable and available" (Chapman, 2022).

Adoption of 3DCP Technology for Residential Construction

HUD has studied the diffusion of innovation in the residential building industry for decades. The process of accepting and adopting new technology is generally slow, and "no single path exists for housing industry adoption of new technologies" (Koebel et al., 2004). Furthermore, Koebel et al. (2004) stated that "acceptance of new technologies and materials ultimately depends on whether they meet the needs of the consumer and the builder better than existing technologies and materials. The needs for high- and low-end markets, or for large and small builders, are not always the same. Additionally, geographic differences also help shape the needs of both builder and buyer."

Some generalizations, however, have emerged from this review of diffusion trends from 1995 to 2001 that warrant further research. Further quoting Koebel et al. (2004): "Large builders seem to be first to adopt new materials that offer a cost savings, improvement in production process, reduction in call-backs or exposure to liability. Smaller builders are often first to adopt technologies where high consumer awareness of a material exists, the price of the new technology is significantly higher than what it replaces, or if the home construction process must be substantially altered. Homes in geographic areas where homebuyers and builders have an increased awareness of a new technology or find a technology most useful are likely to be first to adopt."

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[1] For more information, see ACI's Committee 564: 3D Printing with Cementitious Materials at: https://www.concrete.org/committees/directoryofcommittees/acommitteehome.aspx?Committee_Code=C005640B.

[2] NIST. "Additive Manufacturing with Cement-based Materials." https://www.nist.gov/programs-projects/additive-manufacturing-cement-based-materials#:~:text=Additive%20Manufacturing%20(AM)%20with%20concrete,used%20to%20create%20infrastructure%20components.

Market Research Findings

Home Innovation identified construction industry stakeholders, including builders, contractors (such as plumbers and electricians), architects, developers, and homeowners to understand the barriers to adoption and the opportunities for 3DCP technology to become commonplace within the construction industry. Since 3DCP technology is highly automated, it can be a solution for those areas of the country where there is a permanent labor shortage for construction. Since the technology can be used to quickly build a single-story small home (i.e., 350 to 500 square feet), it may become a perfect option for the tiny home enthusiast, and it may also be a cost-effective option for those living in poverty, as demonstrated by the first 3DCP housing community built in Mexico (Young and McMahon, 2020).

Home Innovation observed qualified construction professionals at the jobsite in Austin, Texas, and documented how 3DCP changes the design and construction process. Home Innovation is currently conducting a national survey to validate the market need for 3DCP and to understand the construction process barriers that currently exist to widespread commercialization of 3DCP technology.

Methodology

Home Innovation conducted a two-phase primary qualitative market research study in 2021 to better understand builder, architect, and trade perspectives of construction considerations when using 3D concrete printing (3DCP) technology. The objectives of the primary qualitative market research were to: (1) understand construction considerations from the perspectives of the builders, architects, plumbers, and electricians; (2) better understand considerations, potential benefits, and potential challenges of 3DCP construction in comparison to traditional construction methods; and (3) identify opportunities and challenges that may influence the adoption of 3DCP in residential construction.

Phase 1: Home Innovation partnered with one 3DCP company for the primary market research, which consisted of nine onsite interviews in Austin, Texas, with builders, general contractors, architects, plumbers, and electricians at homes under construction that incorporated 3DCP technology to print the first story of the homes. Each interview lasted approximately 60 minutes. The interviews were conducted from April 20–22, 2021, after the walls had been printed, but still during the rough-in stage of construction. The four homes were designed by an architect and were either already under contract or on the market for sale.

Exhibit 2

Example of an Onsite Individual In-Depth Interview Location in Austin, Texas

Note: 3D Printed House by ICON.
Source: Home Innovation Research Labs

Phase 2: This phase consisted of nine videoconference interviews with a geographic mix of builders, plumbers, and electricians. The stimuli for those interviews included a slightly revised 3DCP technology overview description from what was presented in Austin, Texas, including photographs of the homes under construction and additional photos of homes completed using 3DCP technology in a community built to house the homeless in Mexico. The interviews were designed to build on learning from the in-person interviews conducted during Phase 1.

The goal, purpose, and intent of the qualitative research were to understand builder, architect, and trade perspectives and to identify key questions, considerations, and potential challenges, not to evaluate a specific 3DCP technology.

3DCP Technology

Overall, the 3DCP technology is considered to offer multiple benefits to construction as summarized in exhibit 3.

Exhibit 3

Perceived Benefits of 3DCP Technology
Speed of construction
Cost of construction (less labor)
Elimination of finishing materials (exterior and interior)
Strength of the “double” layer wall (improved resiliency)
Fire resistance
No formwork needed (less cost)
Able to build curved or irregular floorplans (which are difficult to do now)

3DCP = 3D Concrete Printing.
Source: Home Innovation Research Labs

Builders wanted to understand how the wall performed with respect to meeting energy code requirements, which is an important consideration, as shown in exhibit 4.

Exhibit 4

Questions from Builders About 3DCP Exterior Wall Thermal Performance
What is the R-Value of a 3DCP exterior wall without insulation?
How can insulation be integrated into a 3DCP exterior wall?
How can R-25 or greater insulation be achieved in 3DCP exterior walls?
How difficult is it to air-seal a 3DCP exterior wall? Can a tight building envelope be achieved?
Can an air gap within the wall cavity improve the R-Value of the 3DCP exterior wall?
Will thermal bridging occur even if spray foam is used inside the 3DCP exterior wall?
Can continuous insulation be integrated into 3DCP exterior wall?

3DCP = 3D Concrete Printing.
Source: Home Innovation Research Labs

Builders wanted to understand how moisture management would be addressed, especially in hot, humid climates. They wanted to know the perm ratings of the concrete material and understand more about the vapor transmission and potential for water penetration. There was some concern about not using a moisture barrier; more information is needed about how the wall design protects against moisture and potential mold growth. Since the windows at the residential house in Texas were installed without a weather-resistant barrier (WRB) or flashing, water penetration was a concern for the participants in the market research study, as shown in exhibit 5.

Exhibit 5

Questions from Builders About 3DCP Exterior Wall Moisture Management
How are windows and doors sealed to prevent water infiltration?
How are walls treated to prevent water penetration (i.e., damp proofing or water proofing)?
Is the bond agent between layers enough to prevent water penetration or water infiltration?
How difficult is it to air-seal a 3DCP exterior wall? Can a tight building envelope be achieved?

3DCP = 3D Concrete Printing.
Source: Home Innovation Research Labs

Builders thought the foundation and roof connections were well designed because there was a threaded anchor extending from the foundation, through the walls, and then connecting to the top plate. Nonetheless, additional guidance was requested, as shown in exhibit 6.

Exhibit 6

Questions from Builders About 3DCP Foundation and Roof Connections
What design options are available when connecting the foundation to the wall?
What design options are available when connecting the roof to the wall?
What are the structural considerations when building a 2-story structure?
What are the structural considerations when considering soil type and potential settling issues?

3DCP = 3D Concrete Printing.
Source: Home Innovation Research Labs

Builders wanted more information about how to install windows and doors, including if standard installation instructions would be developed for 3DCP walls (exhibit 7).

Exhibit 7

Comments and Questions from Builders About 3DCP Window and Door Installation
Flashing and sealing details are needed for both windows and doors.
Will windows and doors be developed by manufacturers specifically for 3DCP walls?
Can any best practices be adopted from similar masonry walls for 3DCP walls?
How should cracks between windows, doors, and 3DCP walls be sealed if walls are not straight?
Aesthetically, how should window and door trim be installed on 3DCP walls?
How should windows and doors be replaced in 3DCP walls?
How should the 3DCP walls be supported above the windows and doors (can this be standardized)?
Will air and water infiltration be an issue for curved edges when installing straight windows and doors?
How can ADA compliant doors be installed if doorways are not printed wide enough?

3DCP = 3D Concrete Printing. ADA = Americans with Disabilities Act.
Source: Home Innovation Research Labs

Builders and electricians wanted more information about how to install electrical conduit and receptacles, including if standard installation instructions would be developed for 3DCP walls (exhibit 8).

Exhibit 8

Comments and Questions from Builders and Electricians About 3DCP Electrical Installation
Electricians did not believe there would be any savings in terms of labor or time.
Builders believed there would be some marginal time savings during installation of electrical.
Builders believed that electrical conduit and receptacles should be installed just like CMU walls.
Does the installation of electrical conduit or receptacles save labor or time?
Electricians insisted that they should be on site when electrical is installed in 3DCP walls.
Will the building code allow a non-electrician to install electrical conduit and receptacles?
The electrical inspection protocol will likely differ from traditional construction.

3DCP = 3D Concrete Printing. CMU = Concrete Masonry Unit.
Source: Home Innovation Research Labs

Builders and plumbers wanted more information about how to install piping and plumbing fixtures, including if standard installation instructions would be developed for 3DCP walls (exhibit 9).

Exhibit 9

Comments and Questions from Builders and Plumbers About 3DCP Plumbing Installation
Plumbers believed that the labor and time required would be like CMU walls.
Plumbers believed that planning and layout would be critical since it will be hard to relocate pipe.
Builders and plumbers believed that pipe chases on the interior or exterior wall would be needed.
Pipe vents would need to be located during the planning period.
Will 3DCP manufacturers provide some general guidance for plumbing installation?

3DCP = 3D Concrete Printing. CMU = Concrete Masonry Unit.
Source: Home Innovation Research Labs

Builders wanted more information about finishing options for the interior and exterior walls, including if standard installation instructions would be developed for 3DCP walls (exhibit 10).

Exhibit 10

Comments and Questions from Builders About Finishing Exterior and Interior Walls
What are the finishing options for exterior and interior walls?
Will customers like the appearance of the 3DCP wall?
Eliminating the cost of drywall and exterior cladding is significant cost and time of construction savings.
What paint can be used on the interior and exterior 3DCP Walls?
Without drywall in the interior of the house, how would one hang objects on the wall (masonry screws)?
Cracks in concrete was considered a major issue for 3DCP Walls. How can this be minimized?
Builders believed that surface textures and finishes should be offered.

3DCP = 3D Concrete Printing.
Source: Home Innovation Research Labs

Builders had additional comments and questions for 3DCP technology manufacturers concerning barriers to the adoption of the 3DCP walls (exhibit 11).

Exhibit 11

Questions from Builders for 3DCP Manufacturers
Does the 3DCP concrete material “breathe”? Is it permeable?
How much space does the 3D concrete printer require on the jobsite?
Will it be a challenge to use the technology on small lots?
Are there weather limitations to running the 3D concrete printer (i.e., rain or temperature)?
What is the typical cure time for 3DCP walls?
How should 3DCP walls be cleaned (if they do not have a finish)?
Is the material recyclable?
How can one do alterations or modifications to the floor plan in the future?

3DCP = 3D Concrete Printing.
Source: Home Innovation Research Labs

Integrating 3DCP Technology into Traditional Construction

3DCP technology manufacturers have worked with the International Code Council Evaluation Services (ICC-ES) to develop new acceptance criteria (AC509) for evaluating 3D automated construction technology for 3D concrete (Ekenel and Sanchez, 2019). Acceptance criteria define the performance of new building materials, products, and technology. The criteria are precursors to formally defining new construction technologies and building products for inclusion in the building code. Manufacturers that produce 3DCP products in accordance with AC509 will have to demonstrate consistent product performance using a quality-controlled process. This is a very important step when ensuring the safety of any building product and defining expected performance (including the mode of failure). This step can take many years because when a technology is new to the industry, “know-how” can be proprietary and a competitive edge, which often makes codifying standard construction practices difficult. The primer document will highlight findings from the market research study along with other instructional guidance, which is considered a vital first step in the adoption of 3DCP technology. Both the 3DCP industry and home builders interested in the technology will benefit from this educational information.

Conclusion

Home Innovation has convened an advisory group of key stakeholders to review the technical findings and discuss ways to expedite the widespread adoption of 3DCP technology. The study indicates 3DCP technology is expected to significantly change the homebuilding process in terms of labor requirements (different skill sets and fewer people), aesthetic wall exterior (how to install conventional cladding products if they are preferred), the construction process itself (no more 2 x 4 framing for the walls), and how best to demonstrate code-compliance when the technology is not yet recognized by the building code, to name a few. Since the construction industry is often slow to adopt new technology, there will need to be education and instruction about how best to integrate 3DCP technology with builders that are used to building the conventional way.

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