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RESEARCH PROJECT TITLE

Feasibility Study of 3D Printing of Concrete for Transportation Infrastructure

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Feasibility Study of 3D Printing of Concrete for Transportation Infrastructure

tech transfer summary

This project developed 3D printable concrete mixtures to better understand the effects of properties and proportions of materials and of the printer parameters on the printing qualities to evaluate the potential of 3D printing technology for the field of transportation engineering.

Goal and Objectives

The goal of the project was to apply three-dimensional (3D) concrete printing technology to transportation-related infrastructure. The specific objectives were as follows:

- Develop a printable and functional 3D printing concrete mixture using materials commonly available in Iowa
- Characterize the 3D printed concrete properties and better understand the requirements of 3D printing technology to develop concrete mixtures
- Explore the potential applications of 3D printed concrete in the field of transportation engineering, realize the challenges and future perspectives, and lay a foundation for extended studies and applications of 3D printed concrete in Iowa

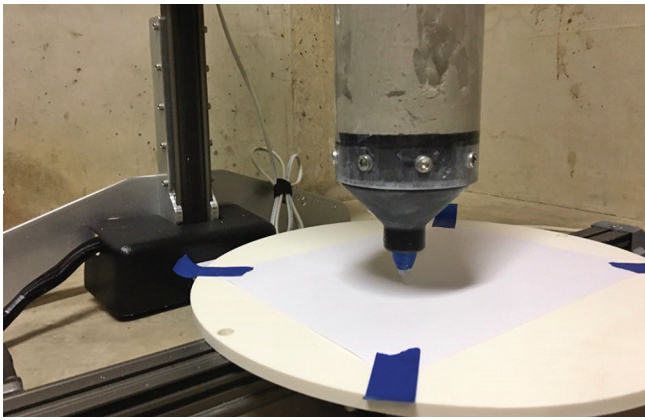
Problem Statement

In spite of exploratory structural applications, 3D concrete printing technology remains fragmentary, and its full-scale uses in transportation infrastructure are still rarely seen. In order to bring the full benefits of this technology to the construction industry, it requires a much better understanding of the relationships among digital design, operation/processing, mechanisms of building materials, formulation of printing materials, and performance of printed products.

Background

The interest in the use of 3D printing technology in concrete manufacturing has grown. Instead of placing, leveling, consolidating, and finishing concrete directly on the jobsite, 3D concrete printing technology has the potential to bring all the traditional manufacturing steps into one process by designing and building full-scale concrete objects in the laboratory with automation and digitalization.

3D concrete printing technology also permits the creation of concrete structures having complex geometry (e.g., various shapes and cross sections) with high precision. It enables concrete construction under extreme conditions that are difficult and/or very costly for conventional concrete construction to accomplish with traditional formwork setup, placement, and/or consolidation.



3D printer with mounting extruder

Using such an innovative technology can significantly alter the way society constructs today, facilitating immense time and cost savings in construction, and opening a new door for innovation in structural concrete design and construction.

Project Description

1. *Printing procedure and parameter study* – The research team selected a commercial 3D clay printer to print small-scale clay and concrete objects and investigated the printer setup (selections of nozzle size and shape, stand-off distance, etc.), different printing parameters (printing and extrusion speed), and printing procedures (material preparation, loading time, and printing time).
2. *Design of 3D printable mortar mixtures* – The team then selected different types of materials, including cement, silica fume, viscosity modifying agents (VMAs), superplasticizer, and grout, and different water-to-binder (w/b) ratios for the design of 3D printing mixtures. The researchers then conducted tests to identify paste and mortar mixtures with proper printing flowability and extrusion, capable of 3D printing into well-shaped objects, and with proper thixotropic behavior for holding the shape of the printed objects.
3. *3D printable mix optimization* – The team investigated the effects of materials, mix proportions, and printing parameters on the fresh printable concrete properties, such as flowability, extrudability, printability, and open time. Based on the easiness of the printing processes and the quality of the printed objects, the optimal mortar mix was identified.

4. *Design of 3D printing objects* – Small-scale samples with simple geometries, such as circular columns, cubes, and prisms, with different infill rates (0%, 60%, and 80%), were printed with clay, pastes, and mortar.
5. *3D printed concrete performance evaluation* – The team determined the performance of printed objects made with various mortar mixtures by measuring their mechanical properties (compressive and flexural strength) and evaluating their printing qualities through image analysis. In addition, samples were 3D printed with different printing paths and tested under different loading directions to understand the anisotropic behavior of the printed objects.

Key Findings

- Materials and mix proportions had significant effects on key printing properties, including flowability, extrudability, buildability, and open time (i.e., the period during which the mixture is printable), of 3D printing mortar. Paste and mortar mixtures made with cement, silica fume, a rapid-set grout powder, VMAs, and superplasticizer can be engineered to have the desirable properties for 3D printing.

- Mix 0.32-G20, made with a binder containing portland cement, silica fume (2.5% by weight of binder), and 20% grout, and a w/b ratio of 0.32, was the best mortar mixture among all mixtures studied. This mixture was easily placed into the printer, extruded out smoothly and consistently, and was able to hold the shape of the designed objects during and after printing.

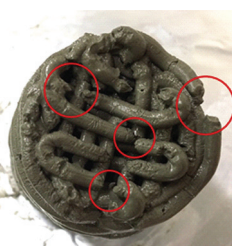


Printed sample of Mix 0.32-G20

- The 3D printed samples displayed different compressive and flexural strength values when loaded in different directions. The compressive strength of the 3D printed samples loaded parallel to the filaments was much lower than that of corresponding samples loaded perpendicular to the filaments. The difference in flexural strength of the 3D printed samples loaded in the two different directions was much smaller.



(a) Air bubble pop outs



(b) Discontinuity



(c) Slump



(d) Cracks

Typical problems during concrete printing process

- Mold-cast samples had a higher compressive strength compared to the 3D printed samples regardless of loading direction. However, under flexural loading, the printed samples had a higher flexural strength than the mold-cast sample regardless of loading direction.
- Printing qualities, such as geometric accuracy, distortion, and surface roughness, of printed objects can be well evaluated using image analysis.
- All the printed samples exhibited certain differences between their measured and designed values, even for those that appeared well-printed. Compared with the designed object, the printed samples generally had reduced total height, diameter, and layer thickness but increased layer width, mainly due to slump.

Conclusions and Recommendations

- 3D printable concrete mixtures should have suitable flowability to be easily transported from a mixer to a printer, proper extrudability to be extruded out smoothly and consistently, and develop sufficient stiffness to hold the object's shape or resist the weight of the subsequently deposited filaments without distortion or collapse.
- The study results suggest that the use of a highly flowable, rapid-setting grout that is commercially available to replace cement can simplify the 3D printing mortar mix design and achieve proper extrudability and buildability very effectively.
- 3D printable concrete mixtures should be designed and adjusted to fit the features, parameters, and procedures of the 3D printer to meet key printing properties.
- In addition to printing materials (concrete mixtures), various printing parameters, including printing speed, extrusion speed, nozzle size and shape, and stand-off distance could affect the printing qualities of the 3D printed objects.
- Prompt and proper curing is essential for 3D printable concrete to reduce slump and plastic shrinkage cracking.

Recommendations for Future Research

- Printing parameters, including printing speed, extrusion speed, nozzle size and shape, and stand-off distance, which affect the printing qualities of the 3D printed objects, should be further studied to improve the 3D printing quality.
- The research team gained good experience in the design of 3D printed objects, development of 3D printable mortar mixtures, and operation of the 3D concrete printing process. The next steps are to transfer the knowledge learned from this project to a scaled-up study, including using a larger 3D printer, developing additional mortar or concrete mixtures made with various materials, printing intermediate-sized objects such as columns and beams with dimensions around 3 ft, and testing 3D printed components for structural performance.

Implementation Readiness and Benefits

The project successfully demonstrated the feasibility of using a 3D printer to create small-scale objects using a concrete mixture after determining appropriate mix materials and proportions and key printing properties.

Continued study on this subject should lead to the development of the scalability that links the behaviors of the small-scale 3D printing objects used in this study with an intermediate (pilot) scale and ultimately provide a solid foundation for transferring the research results to full-scale production.