DENSITY GRADIENT CONCRETE FABRICATION WITH INJECTION 3D GYPSUM PRINTING

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Abstract. Optimizing the material distribution of concrete elements has the potential to decrease concrete consumption and improve structural efficiency by reducing weight without altering the overall geometry. The challenge lies in making variable internal material densities of concrete elements. This study introduces the fabrication method of Injection 3D Gypsum Printing (IGP), which allows for creating functionally graded density of concrete elements. IGP removes concrete locally by injecting a gypsum-based temporary support material during the concrete casting. The water-soluble temporary support material injected into the liquid concrete is later removed by jetting water after the concrete cures. This system aims to fabricate topology-optimized structure designs while minimizing the additional construction steps and formwork requirements from the conventional casting construction system. This method combines effective material-saving digital fabrication strategies with conventional concrete construction's efficient reinforcement and casting processes. The study examines the material design and custom fabrication setup of IGP through initial feasibility experiments. Additionally, it presents IGP methods and applications through two proof-of-concept case studies. The digitally controlled material removal method introduced in this study holds potential as a material-saving strategy in future concrete construction.

Keywords. Injection 3D Gypsum Printing, Spatially Graded Concrete, Optimized Concrete Structure, Robotic Fabrication, Rapid 3D Printing

1. Introduction

With the increasing evidence of resource depletion and climate crisis, material efficiency holds importance in sustainable construction. The global consumption and environmental impact of cement for concrete construction are projected to increase continuously (Khaiyum et al., 2023). This tendency is particularly prominent in the Asia-Pacific region, where the most significant demand for cement is concentrated (Uwasu et al., 2014). Alternative approaches to designing and constructing material-efficient concrete structures become pivotal to reducing adverse environmental impacts.

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Conventionally, concrete structures such as hollow-core slabs and double-tee construction systems have been used to increase material efficiency and reduce the structure's dead load. The advent of recent generative design and digital simulation tools empowered designers to conceive non-standard, material-efficient shapes through structural analysis. One illustrative technique is topology optimization, which generates structural configurations within defined calculable boundaries based on force-flow simulation (Bendsøe & Sigmund, 2003).

Despite many effective optimized structure design methods and tools, the challenge lies in translating these unique designs into tangible structures. Considering cases such as the Unikabeton Prototype, structurally optimized concrete elements that achieved an average of 60-70 % weight reduction might involve irregular profiles (Glynn & Sheil, 2017). These complexities are difficult to achieve using traditional formwork fabrication methods, resulting in increased material wastage and labour demands during formwork fabrication (Antony et al., 2014).

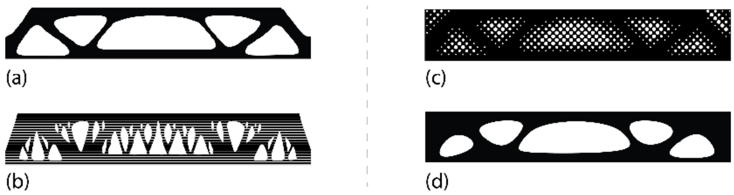

Figure 1. Various fabrication strategies for topology optimized beam. (a) Topology optimized beam geometry without constraint. (b) 3DPC method with 70° constraint. (c) Density gradient approach. (d) Geometry with IGP method with rapid material removal.

An alternative approach is making a material-efficient structure with functionally graded material. This material-based optimization offers advantages over fabricating intricate profiles for the entire optimized concrete structure (Sitnikov et al., 2022). Functionally graded concrete aims to design and fabricate the distribution of various material densities within an element in response to internal stresses. This approach allows for more effective structural performance with less material, all while preserving the simple geometry of the conventional structural component, as presented in Figure 1(c). Yet, fabricating complex internal geometries of the concrete elements is difficult to achieve with a conventional formwork construction system. In order to solve this problem, diverse alternative construction methods have been tested to make intricate shapes of optimized concrete structure design, such as 3D Printed Concrete (3DPC) and Digital Fabrication of Formwork (DFF).

3DPC and DFF also have several challenges. 3DPC is limited in its printable geometries without support, fabrication speed, and strength due to the layering construction sequence (Jipa & Dillenburger, 2022). Figure 1(b) shows an overly complex 3DPC geometry subject to a 70-degree angle constraint, aiming to achieve the optimized beam shape depicted in Figure 1(a). Additionally, integrating continuous reinforcement during the construction process is limited in 3DPC (Bos et al., 2016). However, DFF poses issues such as generating additional waste and requiring extended assembly time, particularly in the case of complex formwork construction using digital fabrication tools like computer numerically controlled (CNC) milling, CNC wire cutting, and 3D printing.

This paper proposes an alternative fabrication method, Injection 3D Gypsum Printing (IGP), that removes concrete material locally by injecting gypsum-based temporary support during the casting process instead of prefabricating formwork. This method aims to fabricate topology-optimized structure designs while minimizing the additional construction stages and formwork requirements from a conventional casting system. IGP leverages injection 3D printing (I3DP) technology to selectively control the densities and shape of cast concrete structures (Chee et al., 2019). IGP intervenes in the casting process after the concrete is poured into the formwork. While the concrete is in a liquid state, a long nozzle goes into the slurry concrete and injects gypsum-based temporary support to remove concrete from desired areas. The proposed method enables the creation of cast concrete structures with localized density variations, enhancing material efficiency.

The research includes laboratory-scale fabrication experiments on the injection printing of gypsum-based water-soluble support materials into liquid concrete. These processes are guided by robotic control, with a custom-built tool that injects gypsum mixture into the liquid concrete during the casting process. This robotic fabrication procedure seamlessly integrates with generative design tools to enable density control over the concrete structure.

The contribution of this study lies in presenting an alternative fabrication methodology that enables localized manipulation and programming of concrete's material characteristics. Moreover, this research proposes to unify the realms of generative digital design and material fabrication of concrete casting into a cohesive and streamlined process. This integration can potentially reduce design and construction timelines, material consumption, and labour requirements in non-standard concrete construction projects.

2. State of the Art

Various techniques for fabricating density gradient concrete have been investigated. These strategies can be classified into two distinct groups. The first group employs a chemical approach. The Mediated Matter Group at MIT Media Lab created a radial density gradient in concrete by manipulating density through hydrogen gas bubbles generated in the chemical reaction between aluminium powder and lime (Bártolo et al., 2011). Timothy Cooke adopted a similar approach, crafting a gradient aerated concrete resembling bone structure by controlling hydrostatic pressure in a cementitious foam casting (Cooke, 2012).

The second group employs a mechanical approach, including 3DPC, DFF, and I3DP. Tay et al. made density-graded concrete beams through direct 3D printing, manipulating parameters such as material mix, printing speed, and printing geometry (Tay et al., 2022). The DFF method was tested by various projects to achieve the same goal. In Vasily Sitnikov's ice formwork project, various scales of ice aggregates were used as temporary spacers to generate spatially graded

concrete elements (Sitnikov et al., 2022). The advantage of ice aggregate formwork is that temporary support melts away without an additional formwork removal process. The powder-bed-based formwork fabrication method achieved more accurate geometry control of spatially graded concrete structures. Water soluble formwork was 3D printed using the binder jetting method to bind sand particles with dextrin, a soluble industrial starch, and water (Kovaleva et al., 2022). While offering precise geometry control and easy removal of the formwork material, this method has limitations in scaling up to building size and has a prolonged assembly time.
I3DP technology addresses the challenges DFF poses. Interacting in the concrete curing process eliminates the need for prefabricated formwork, resulting in faster construction. This method involves injecting an aluminium solution into the concrete to generate local low-density parts by capturing hydrogen gas within the slurry (Chee et al., 2019). A non-hardening suspension such as sand-gel can also be injected to create temporary support, forming void spaces within the concrete element (Hack et al., 2020).

3. Methods

3.1. IGP - INJECTION GYPSUM PRINTING

IGP was developed based on earlier I3DP studies. IGP follows the principles of injection 3D printing, which is to intrude one material into another with a computer-controlled path (Xiao et al., 2022). The IGP procedure starts with a standard concrete casting. Place reinforcement bars in the plywood formwork and pour concrete. While the concrete is still in its liquid state, a robotically controlled long nozzle on a paste extruder injects the gypsum mixture into the concrete. The injection process requires to be finished before the concrete starts to solidify. Once the concrete is cured, the temporary gypsum support is removed by applying high-pressure water. One notable advantage of using IGP for creating density-graded concrete structures is the ease of integrating continuous rigid reinforcement elements. This is possible because the fabrication process is based on the conventional reinforced concrete casting system.

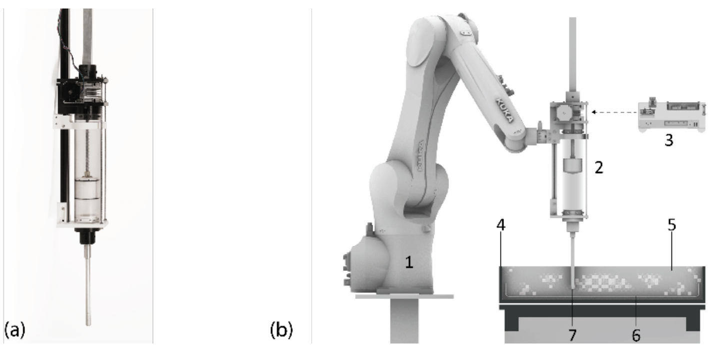

Figure 2. (a) Custom made plunger paste extruder. (b) IGP fabrication setting. 1 KR10R1100. 2 Paste extruder. 3 Extrusion controller. 4 Formwork. 5 Poured concrete. 6 Reinforcement. 7 Injected gypsum-based support.

3.2. MATERIAL DESIGN

The objective of injecting material into the concrete is to provide support during the curing process and enable easy post-curing removal. For several reasons, the gypsum and sand mixture (G1, Table 1) was chosen as the supporting material. Firstly, gypsum's water solubility (2.531 g/L in 20°C pure water) allows it to be washed away easily. Secondly, the density of G1 gypsum paste (2.29 g/cm3) closely matches that of the C1 concrete mix (2.30 g/cm3). This similarity prevents the injected gypsum mixture from sinking or floating. Furthermore, replacing an equivalent volume of concrete with gypsum can maximize environmental benefits as the greenhouse gas emissions associated with processing natural gypsum are 15% of cement (Fořt & Černý, 2018).

Through an empirical 3D printing test and erosion test of many different mixes, materials outlined in Table 1 were used to fabricate case studies in this paper. G1 is the gypsum paste that is designed to have suitable viscosity for extrusion using a custom-made plunger through a long nozzle (Figure 2(a)). C1 is the concrete mix designed to undergo a retard curing process, allowing sufficient time to inject and print gypsum within the poured concrete. While this study excludes coarse aggregate in concrete, future research may explore injection printing into concrete with aggregates for broader applications.

Material \ Ratio in weight	G1	C1
Gypsum: solution grade gypsum_Calcium Sulfate Dihydrate ($CaSO_4 \cdot 2H_2O$) 97%	2	0
Cement: Portland cement type I	0	1
Coarse sand: 0.5 - 1.0mm (Sieve No. 35)	2	2
Water	0.9	0.3
Superplasticizer: Basf, Melflux 2651F, concrete additive water reducer	0	0.01
Deflocculant: darvan #7	0.001	0

Table 1. Material ratio

3.3. ROBOTIC FABRICATION

The IGP uses the robotically controlled fabrication with a custom-made ram extruder directly mounted to the 6-axis robot arm (KR10R1100). Toolpaths are generated through the Grasshopper plugin KUKA|prc (Braumann & Brell-Cokcan, 2015). A custom-made controller manages the extruder operation, including plunging speed, pause, and stop. Gypsum paste plunges from the cartridge to the concrete through the long, narrow aluminium nozzle. The long-proportion nozzle design enables deep penetration into the concrete during injection-3D printing. Two different nozzle sizes, 5mm inner diameter with 210.8 mm length and 9mm inner diameter with 241.8mm length, allow the 3D printing of gypsum in various resolutions (Figure 2).

4. Experiments and Case Studies

4.1. INITIAL IGP FEASIBILITY TESTS

The initial phase of the research involves assessing the feasibility of the IGP method and testing potential printing techniques. The objective of the first test was to find a correlation between 3D printing speed and sectional diameters of printed elements. This test utilizes a 9 mm inner diameter nozzle to 3D print a straight line of gypsum within the concrete while adjusting the printing speed. Figure 3 illustrates the cross-sectional view of the concrete object from the first test. The extrusion process starts by consistently depositing gypsum from the base, moving upward with gradually decreasing retraction speeds. Initially, the nozzle moves at a speed of 20mm/s until reaching a final tool path speed of 6mm/s. The outcome reveals the gradual cross-section cavity, 44mm top diameter, 9mm bottom diameter with 150mm height truncated cone, formed by adjusting the nozzle speed.

Figure 3. Cavity size according to the gradual printing speed change.

The second test, illustrated in Figure 4, aims to demonstrate that IGP can create complex shapes of cavities within concrete. This test uses a 5 mm inner diameter nozzle to print a helix cavity inside a 52 mm diameter and 100 mm height concrete cylinder. The result demonstrates that complex geometries can be accurately printed inside the concrete using the IGP method. However, due to their small contact point with water, these complex geometries require more time for the gypsum mixture to dissolve. Applying high-pressure water directly to the support material also becomes challenging in such cases.

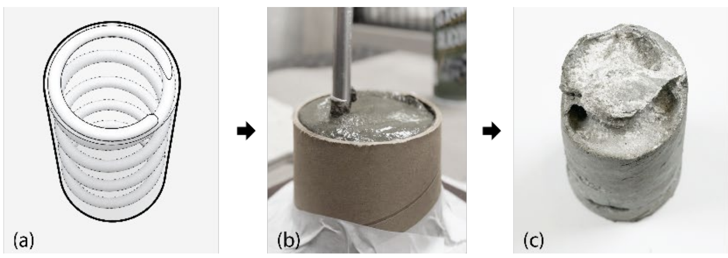

Figure 4. Helix cavity printing within concrete. (a) Cavity geometry design. (b) Robotic IGP fabrication. (c) Result after gypsum support is removed.

4.2. CASE STUDY 1 - GRADIENT COLUMN

The density-gradient column is designed to have the highest density at the bottom, gradually decreasing as it ascends. As illustrated in Figure 5(d), scattered sphere-shaped voids are generated inside of the concrete element. These void spaces are made through the spot-extruding method, injecting gypsum mixture for two seconds in one spot and moving the nozzle at a speed of 12mm/s between injection spots to minimize cavities while creating channels for removing gypsum materials post-curing.

The fabrication starts with pouring the C1 concrete mix (detailed in Table 1) into a cylindrical formwork with a 100 mm inner diameter. Following this, a 5 mm inner diameter nozzle descends to the formwork's bottom, initiating the injection of gypsum paste according to the predetermined toolpath. After 48 hours, the formwork is removed, and the water is jetted to wash away the gypsum paste from the cavities. As depicted in Figure 5, the sections of the column show the controlled density achieved through the digitally designed and controlled IGP fabrication.

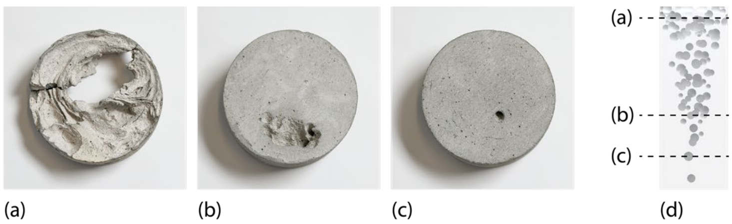

Figure 5. Sections of case study1 column.

4.3. CASE STUDY 2 - MATERIAL REDUCED BEAM

The second case study examines a concrete beam fabricated through the IGP method. The experiment employs a topology-optimized beam design with a 6:1 length-to-height ratio (420 mm length, 70 mm width, 35 mm height). The beam is supported on rollers at one point and fixed support at another, with a uniform load applied. The primary goal of the topology-optimized beam design, in this case, is to minimize global compliance, testing the fabrication of a globally optimal design rather than a specific one. The Grasshopper plugin TopOpt is utilized for beam design (Maier, 2013).

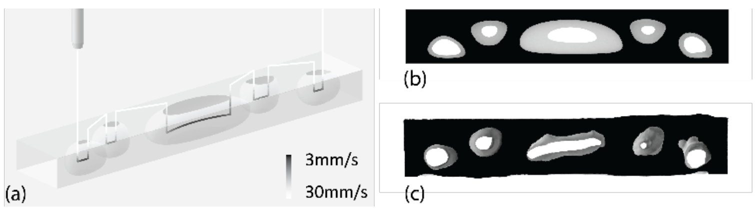

Figure 6. (a) Toolpath diagram with gradient nozzle speed. (b) Section image of case study2 beam design. (c) Section image of fabricated result.

The IGP method has a time constraint due to the necessity of completing the gypsum 3D printing process while the concrete is in a liquid state. Thus, reducing the 3D printing time becomes crucial for effectively applying the IGP method in fabrication. For this reason, the toolpath design in this case study aims to minimize complex nozzle movement and fabrication time. The toolpath is designed with variable nozzle speeds to control the size and shape of the cavity, building on knowledge gained from the initial feasibility test. This toolpath design approach facilitates rapid concrete removal compared to the layered extrusion 3D printing toolpath by minimizing the nozzle movement inside the concrete. Figure 6(a) illustrates the robotic fabrication toolpath, designed with a continuous nozzle path featuring gradual nozzle speed. Controlling printing speed creates various void sizes within the concrete structure with minimal nozzle movement. The nozzle operates at a speed of 30 mm/s for plunge and retraction. During gypsum 3D printing, the nozzle transitions from 30 mm/s to 3 mm/s to generate a streamlined shape print. The injection printing toolpath is designed to take 73.5 seconds for the entire fabrication. Following 48 hours, the concrete and gypsum-based support material are cured(Figure 7(a)). By spraying water to remove the gypsum support, the final shape of the beam appears with internal voids (Figure 7(b)). The comparison between the section of beam design(Figure 6(b)) and the 3D scanned model of the final result(Figure 6(c)) presents that the IGP method can locally remove concrete material rapidly within the low resolution. The weight of the resulting beam is 1295.08 g, which is 79.2 % of the weight of the same dimensioned concrete beam.

Figure 7. Case study 2 result. (a) Before gypsum support is removed. (b) After gypsum support is removed.

5. Conclusion

The experiments detailed in this paper demonstrate the viability of using IGP to create complex void geometries within concrete elements. A preliminary feasibility study indicates that intricate geometries with variable sectional diameters can be 3D printed inside the concrete elements. The first case study shows the creation of density gradient concrete by incorporating spherical void spaces within a concrete column. The second case study establishes the IGP method for rapid material removal. One notable advantage of IGP is its avoidance of additional steps and intricate formwork fabrication, as it intervenes during the concrete curing process.

Furthermore, this method facilitates the integration of continuous reinforcement into highly customized density-gradient concrete elements by generating voids by injecting slurry gypsum paste via a fine nozzle. With the reinforcement, the horizontal movement of the nozzle would be limited, but the point-extrusion method demonstrated in case study 1 can be utilized to make a density gradient structure. While proof of concept case studies in this paper demonstrates the potential and feasibility of IGP, further studies are needed to apply IGP to building components.

Key areas for future development include the creation of a toolpath and simulation tool tailored to extrusion rates and printing speeds to enhance the 3D print quality within concrete. Additionally, material design must be refined for improved printability and versatile applications, such as the development of easier removable paste and stay-in-place materials. The current robotic fabrication setting is not suitable for building components. The fabrication setting needs to be developed on a larger scale and at a faster speed. Finally, broader applications need to be explored, such as stay-in-gypsum injection printing for gradient-density structures with added functions such as insulation and soundproofing. Addressing these aspects will contribute to the broader utilization of IGP in the construction industry.

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