# LOCALLY DIFFERENTIATED CONCRETE BY DIGITALLY CONTROLLED INJECTION

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**Abstract.** This paper presents a digital fabrication process for concrete which may be deployed for surface texturing, volumetric modification of material properties and 2D and 3D forming. We process concrete in its slurry state by locally injecting chemicals in solution which cause vigorous effervescent reaction to take place. By precise and controlled dispensing, using computer software and robotic hardware developed, we produce local differentiation in the finally set concrete artefacts. Our work contributes to additive and subtractive 3D manufacturing as well as functionally graded materials fabrication.

**Keywords.** Digital Fabrication; Additive Manufacturing; Functionally Graded Materials; Architectural Robotics.

## 1. Introduction

As Ordinary Portland Cement (OCP) cures, it undergoes an exothermic hydration reaction producing a highly alkaline chemical environment that reacts with locally injected aluminium particles to produce hydrogen gas. The immediate and vigorous formation of bubbles within the slurry results into the spectacular material transformation. The aluminium oxide which normally develops in the presence of atmospheric oxygen on the surface of the metal and prevents its corrosion, is attacked and converted by the lime in cement emitting hydrogen and building pressure within the concrete. Shortly after the reaction has completed all visual traces of the events that took place - including local discoloration, fumes exhausted and intense foaming - dissipates, leaving no immediate evidence of something different than a regular sloppy concrete pour. However, once the concrete has hardened, can be removed from the formwork and carefully examined, some quite remarkable properties can be observed which give rise to a spectrum of material effects.

### 1.1. SURFACE TEXTURE

Aluminium causes surface deterioration when directly dispensed on the still-wet concrete. The corrosive properties of wet concrete to metals has been long studied, generally considered undesirable (Portland Cement Association, 1969)

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and mitigated using protective surface coatings such as galvanization. However, visually it results in remarkable surface patterns reminiscent of conventional concrete texturing techniques produced by timber formworks, brushing and bead blasting. Illustrative examples include the use of tree trunks and hay bales as formwork in Bruder Klaus Field Chapel by Peter Zumthor and The Truffle by Ensamble Studio respectively, which create interior material finishes reflective of their original formwork. In these experiments, the result surface roughness nonetheless is high with a finish that resembles a natural patination due to ageing or erosion by weathering (Figure 1).

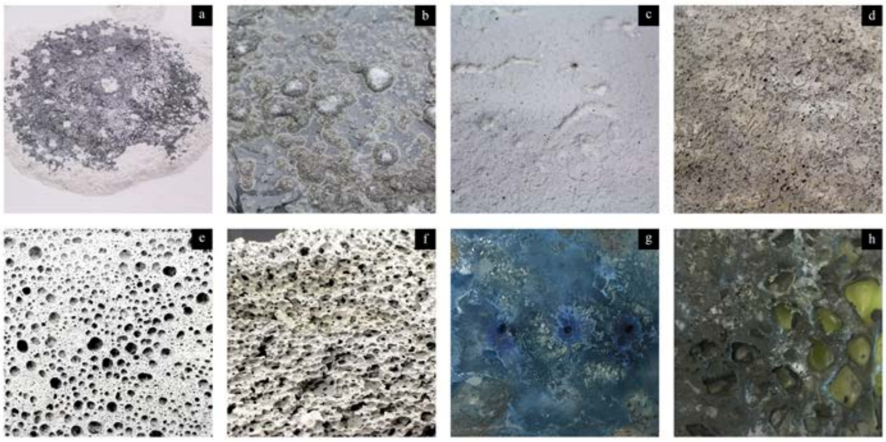


Figure 1. (a, b) White and regular Portland cement patterned by aluminium solution. (c, d) White and regular Portland cement after the surface has been washed off. (e) Cement mixed with hydrogen peroxide and yeast. (f) Cement mixed with detergents. (g) Cement injected with acrylic paint (h) Cement injected with wax after melting.

### 1.2. DENSITY MODULATION

Hydrogen trapped within the slurry produces volumetric porosity as minute pockets are formed after the concrete has set and all gasses have escaped. The presence of micro cavities affects the bulk density characteristics of the composite producing a result which belongs to the family of lightweight, autoclaved aerated or foamed concrete materials. Indicatively, the density of OCP is circa 3,150Kg/m3 (Lafarge, 2015), medium density concrete at circa 2,000Kg/m3 and thermal conductivity of 1.35W/mK, while aerated concrete can reach as low densities and thermal conductivities as 300Kg/m3 and 0.1W/mK respectively (ISO/DIS 10456, 2007). Nevertheless, permeability and often lower load-bearing performance characteristics are also associated with this material innovation dating back in the 1920's (Mathey and Rossiter, 1988).

Recent emphasis in sustainable development and the circular economy has resurged interest in aerated concrete for reducing bulk usage of cement and while recycling dross by-products of industrial manufacturing for ceramic materials additives (Studart et al, 2005; Maziah, 2001; Kinoshita et al, 2013; Liu et al, 2017). Relevant to this is research in controlled density modulation of material properties for functionally graded materials (FGM), originating from the fields of mechanical engineering and material science (Mahamood and Akinlabi, 2017). Examples of influential architectural work include gravity and formwork induced variable porosity in aluminium-based aerated concrete (Cooke, 2012) and functionally graded rapid prototyping (Oxman, Keating and Tsai, 2011; Duro-Royo, Mogas-Soldevila and Oxman, 2015). Further development in the controlled modulation of material properties at the scale of construction fabrication could lead to architectural innovations such as pre-cast concrete panels that have high structural and thermal performance in the same domain, removing the need for material assemblies such as concrete sandwich walls.

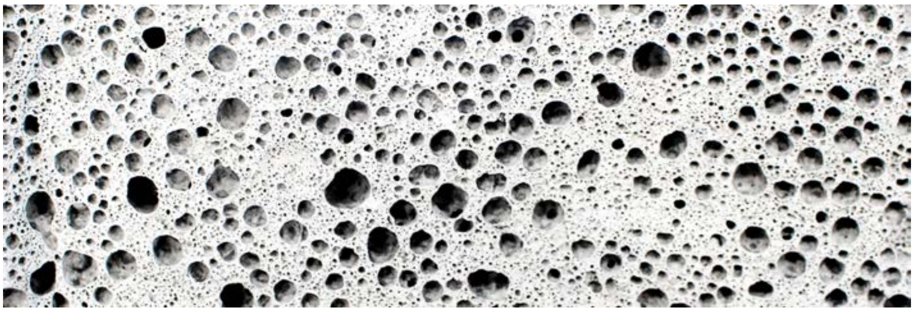

Figure 2. Detail of porosity characteristics.

### 1.3. FORMING DISCONTINUITIES

If the solution is carefully injected by continuous volumetric dispensing in the form or liquid beads, it is not only possible to texture or aerate concrete but also simultaneously create severe and permanent discontinuities which emerge as large volume of gases travel vertically, puncture the top surface and escape the material. To achieve full perforation the aluminium solution must be injected at high flow rates at the base of the mould. 3D sculpting can be also achieved by depth control of continuous injection producing height-field surfaces of the f(x,y)=z type. The proposed method offers the opportunity to perforate and even sculpt concrete unlike any other conventional method. When considered against the difficulty of cutting and shaping concrete after it has hardened, which requires significant investment in specialty impact equipment and expensive consumables such as diamond grade abrasives, this feature provides an insight for the potential of the presented method.

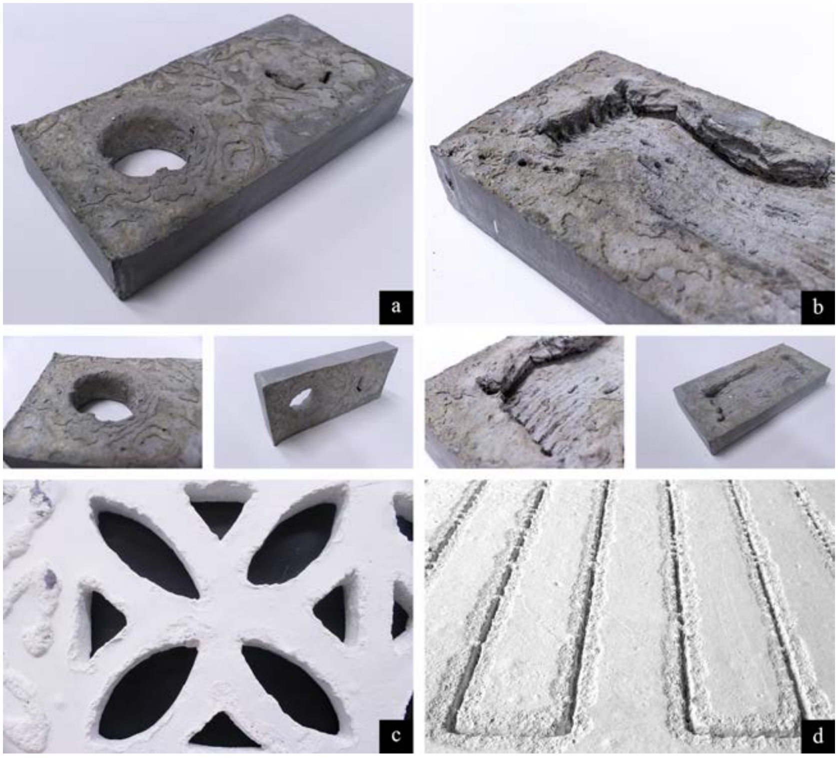


Figure 3. (a) Circular cut-out sample (b) 3D shaping by wave patterned motion (c) Cut-out of vernacular ventilation brick panel (d) Segmentation by continuous variable injection experiment.

## 2. Background

Our project is situated within the domain of digital design and fabrication. It investigates creative material transformation processes (Lefteri, 2007). It is informed by conventional waterjet cutting, the Direct Ink Writing (DIW) 3D printing for FDM (Lewis, 2006) and research work in suspended matter within viscous media (Johns, Kilian and Foley, 2014). Studies performed include: (a) Decorative surface patterning by erosion, (b) FDM fabrication via spatial density modification, and (c) Fusing additive and subtractive manufacturing by injection. The paper is organized by the following research tasks: (a) Material Studies: investigation of chemical reactions between OPC and additives, (b) Software and Hardware: development of servo-motor controlled syringe injection system, integration of micro-controller dispensing logic with industrial Programmable Logic Control, translation of design geometry to robotic motion, (c) Fabrication and prototyping: design and development of artefacts demonstrating the capabilities of injection fabrication process.

## 2.1. MATERIAL STUDIES

The project developed as an exploration of a controlled volumetric injection process. Portland cement was selected as the base substrate because it is a common construction material. The material allows for producing large-scale artefacts with mechanical properties favourable to architectural applications, and it has a low bulk cost. Initial experiments, involving the injection of inert solutions such as pigments, produced visually interesting results (Figure 1). However, they were evaluated as rather exclusively decorative and abandoned in favour of injections that begun to alter the base material properties.

Introducing hydrophobic agents such as surfactants and detergents, offered the first positive results where concrete transformed into a fragile sponge-like substance, extremely prone to crumbling as the internal bonding was locally suppressed (Figure 1). This approach was also abandoned, yet the notion of localized material disruption was a concept carried forward. Experiments with organic and inorganic additives such as common yeast, paraffin wax and hydrogen peroxide were attempted to induce cavitation and enable density modification and volumetric anisotropy. The industrial method of aluminium for aerated concrete production was adopted due to availability of materials and its rapid reaction. Use of finely powdered aluminium suspended in water, increased the metal's surface area in contact with the slurry, amplified the foaming and accelerated the fabrication time. Unlike previous experiments where externally introduced chemicals were absorbed and homogenized past curing, aluminium caused separation as surface interfaces developed. This was a critical property that enabled the retention of voids internally and parting surfaces as opposed to post-reaction fusion.


Figure 4. (a) Initial manually produced prototypes with various additives, (b) Prototypes produced with robotic injection of aluminium, (c) Experiments with image transfer by injection, (d) Medium scale panel experiments, (e) Large scale variably perforated white cement panel.

### 2.2. SOFTWARE AND HARDWARE

The instrumentation of our experiments progressively transformed from lab testing using hand tools to the development of a specialized digital design and fabrication process for precise injection. We deployed an ABB IRB1200 series industrial articulated six-axis robot as a programmable and accurate positioning mechanism. Nevertheless, a three-axis cartesian system would have also sufficed as the spatial orientation capabilities of the machine were not required or perhaps not thoroughly explored.

We developed a purpose-built syringe dispenser to control the volumetric injection of the aluminium solution. The end-effector was fabricated using laser-cut acrylic sheets, its mechanical components were standard hardware such as threaded rods and metric nuts and miscellaneous bespoke parts such as reduction gears were 3D print. The actuator is powered by a RhinoRMCS high-torque servo motor with integrated encoder and controller electronics. Assembly of these components forms a linear actuator which mechanically depresses and retracts a 10ml medical syringe's piston. Associated speeds of rotation (RPM) with volume dispensed were measured using the gradations of the syringe to derive the flow-rate formulation.

Figure 5. Robot integrated with an actuator that injects controlled amounts of aluminium. Injected aluminium is initially grey, however once the aluminium has successfully reacted with the cement, the colour changes to white as seen at the left side of the cement mould.

For integrating and coordinating the all mechanical sub-systems, from the robot itself to the injector, we developed a simple Programmable Logic Control (PLC) system. The driver logic was integrated in an ArdBox PLC, a low-cost industrial interface device using Arduino as its microcontroller unit. The benefit of this system is that it can be programmed using standard C/C++ and it mediates 5VDC logic-level signal shifting to the industrial standard of 24VDC required to communicate between the servo motor driver and robot controller. A firmware was developed to convert a digital array of bits from the robot controller to signed speed instructions for the servo drive. As such the dispenser could be controlled by ABB RAPID programming without need for external control and synchronization logic.

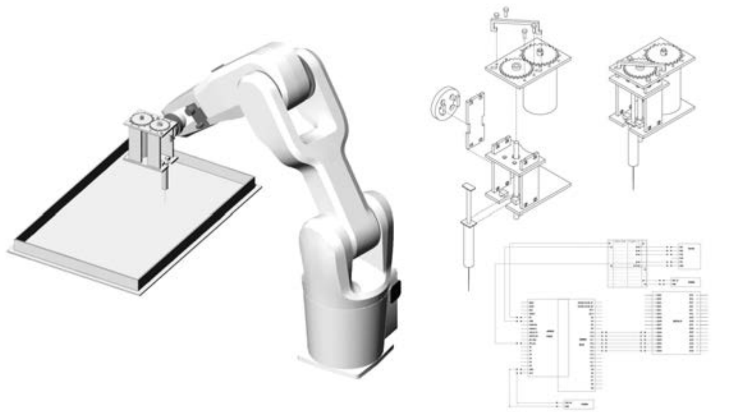

Figure 6. Left-to-Right: Robot setup, exploded diagram of end effector and electronic logic.

Workspace calibration, motion planning, simulation, off-line programming and communications with the robot were performed using the Jeneratiff Digital Design and Fabrication library for the Rhino/Grasshopper visual programming environment. Using parametric modeling techniques enabled rapid experimentation and fine-tuning of critical for the process settings such as motion speed and injection feed-rate and eventually automating the production of prototypes.

## 2.3. LARGE PANEL DESIGN

We designed and fabricated a large prototype comprised of three white cement panels with dimensions of 1,650mm by 850mm and 35mm thick in total. The objective of the prototype was to evaluate the process parameters beyond the previously created small and medium-size prototypes. The design is comprised of 335 perforations derived from an algorithmic process blending imagery data from multiple sources. The combined weighted sums of overlapped raster image intensities were converted to an abstract perforation pattern artwork.

The range of diameters used, spans between 5mm and 30mm, with minimum distance between circle perimeters at least 5mm. The constraint was derived experimentally, where below this nominal tolerance the concrete became too brittle for further processing. The syringe needle of 0.75mm internal diameter was ground flat and depth-set at the very bottom of the acrylic mould. Linear motion speed was 75mm/sec and injection flow rate at 0.375ml/sec. Those settings ensured full penetration of the solution with enough material available to reach the top surface.

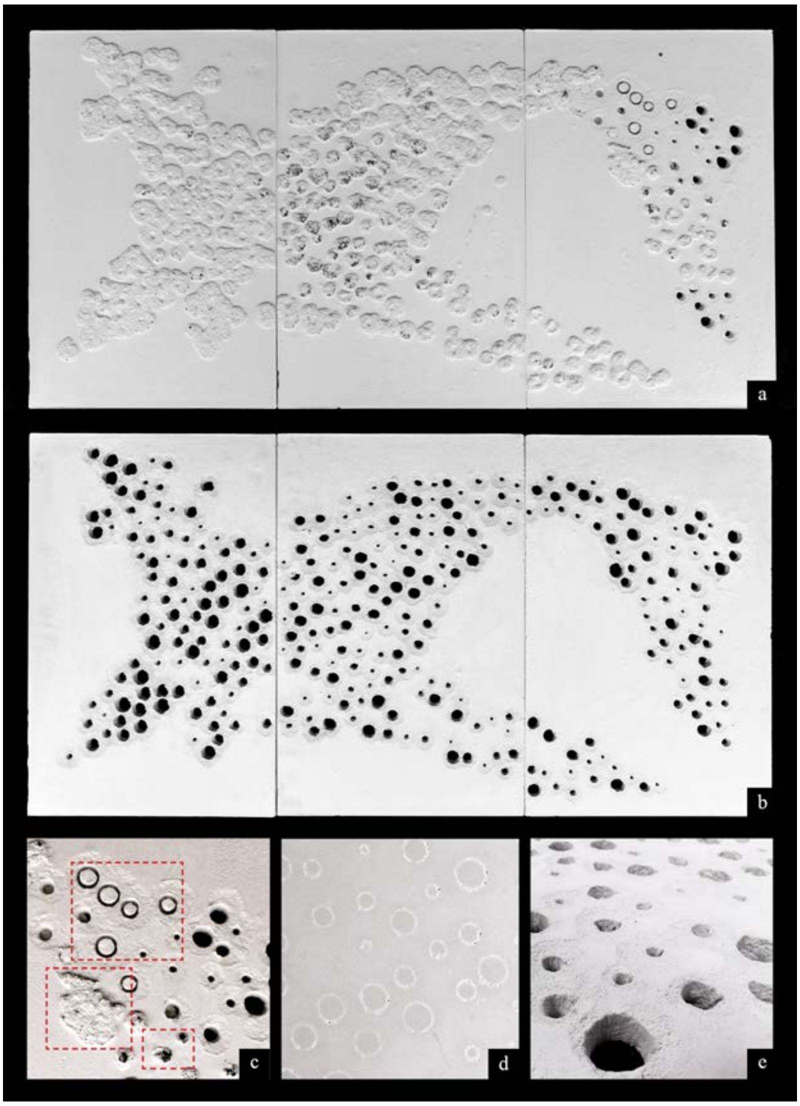


Figure 7. (a) Top view of panels after the cement has cured (b) Top view of panels after water blasting, (c) Top detail view of aluminium not reaching the mold's bottom hence some areas were not fully cut. Grey areas indicate excess unreacted aluminium whereas white areas indicate concrete of high porosity. (d) Bottom detail view of highly smooth surface finish due to acrylic mold. (e) Top detail view of the textured perforations with approximately square draft angle.

Nevertheless, due to the low rigidity of the acrylic injector, scrapping of the bottom mould's surface due to leveling calibration and induced vibrations, the finished front-facing/bottom-of-mould surface was irregularly punctured. To dislodge the non-fully disconnected concrete plugs from the panels we used a power washing system for ejection. Nevertheless, the hole diameters were surprisingly consistent, with an average error of ±1.2mm or approximately between 0.2mm to 3mm with respect to largest and smallest programmed hole sizes. In addition, due to the upward direction of escaping gasses, the interior wall finish of perforations was rough including a nominal draft angle similar to waterjet cutting edge-tapers but with inverse orientation. The prototype panels weight 16kg each, required approximately 20mins of the injection process, at least 24hrs of curing and 5mins of high-pressure water blasting. Each panel used in total 30ml of equal aluminium to water solution by weight. The excess aluminium solution that reached the top and pooled around the perforation produced a highly patterned, unforeseen and beautiful result which combines both the cutting and texturing features of the process.

## 3. Conclusions

The experiments performed and documented herein, demonstrate that from the three trajectories investigated, our approach offers the most interesting contributions to digital fabrication. In functionally graded materials we offer a case study beyond the popular approach of multi-material rapid prototyping to simulate FGM manufacturing. Local material differentiation by injection affects density, mechanical and thermal insulation characteristics and enables creating varied material properties within the same component. At this phase, we have not exploited the capability towards a concrete functional objective, such as modulation of structural or environmental performance, but focused on developing experience and understanding the process parameters. This requires additional work in Design of Experiment models to enable prediction of composite properties parametrically.

The second aspect of the proposed process, namely a 2D/3D hybrid casting and forming, holds the potential for a unique approach to fabrication with concrete. In-situ and even pre-cast concrete in controlled environments using molds are often laborious, inaccurate and time-consuming. Perforating or generally sculpting cured concrete is labour-, time- and cost-intensive. By controlling the depth, motion, and injection flow rate, we can produce direct cuts and even surface contours similar to those created by milling machines. While the fabricated 35mm-thick prototype panels - due to limited lengths of injection needles used - pale in comparison to actual pre-fabricated walls that are upwards of 100mm thick, injection shafts of extended lengths may be specially fabricated and used in industrial concrete casting tables. The escaping gases partition the material locally in a similar fashion to an end-mill subtracting material by mechanical forces. Experiments with the injection of inert compounds explored may also become fruitful for accommodating embedded components, such as creating conduit channels in the slurry for later routing electrical and mechanical installations.

The surface finish of the gas-cement interface leaves a lot to be desired and ample more room for future work. Additional challenges include the control of curing time, precise dispensing and volume diffusion study and inclusion of aggregates, fillers and reinforcement. Nevertheless, the ease and speed of forming 2D and 3D concrete surfaces by chemical injection is still remarkable when contrasted to casting, depositing and machining methods. In conclusion, our wet injection method suggests for an alternative approach to concrete fabrication for some applications potentially may be a faster and more cost-effective, or just purely aesthetically and creatively interesting.

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