STEREOLITHOGRAPHY WITH RANDOMIZED AGGREGATES

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Abstract. The paper documents the design and development of an additive manufacturing process based on stone aggregates. Unlike conventional 3D printing technologies which target miniaturization of the material grain and deposition layers to achieve as high resolution as possible, our process deploys sizeable and randomized grains of stone. The objective of this is to leverage between physical scale of the particulate and time it takes to produce large enough artefacts, fast enough to potentially evoke spatial qualities. Perhaps unavoidably, due to its materiality, the process revisits one of the most archaic methods of building technology, namely masonry, and suggests for a unique digital perspective for structures and landscapes made from stone.

Keywords. Digital Fabrication; Additive Manufacturing; Aggregate Assemblies.

1. Introduction

The progress of cultural development is often associated with the materials that dominate technological applications of an era. Stone is the most archaic material used through history, while today we may associate our age with silicon. The study investigates digital fabrication with one of the oldest materials for design and construction of architecture. The method used is additive manufacturing which has been a topic of active research in the past decades (Tofail et al, 2018). The objective of the work is to explore contemporary modes of approaching masonry, create a process that can produce larger objects than those capable by common rapid prototyping 3D printers and produce a range of suggestive design objects.

Perhaps the most striking characteristic of additive manufacturing is in its geometric freedom and resource efficiency afforded by precise localized spatial arrangement of materials. Its enabling concept is in the assembly of coherent objects from microscopic grains of material which once fused together we can no longer discern them apart. Miniaturization of material grain is directly associated with the resolution of 3D printing and its ability to assign complex geometric features within a quantized space indexed by the underlying mechanical positioning system. However, resolution is inversely proportional to time required
for producing 3D objects from fine layers or filaments; thus, a compromise is
required if we aim to move towards architectural applications. Here we take the
approach of increasing the size of material particle to enable faster production
of larger objects and exploit the randomness of natural materials to achieve end
product coherence. We use stone aggregates because of their abundance in almost
every part of the world, their low cost, embodied energy, high compression
strength and association with architecture and landscape design (Figure 1).

Figure 1. Randomised stone aggregate prototypes.

2. Background
The project was inspired by traditional East Asian dry landscapes, also known
as rock gardens, and gravel sculptures such as the Kogetsudai located within the
garden of Ginkaku-ji in Kyoto, Japan (1482). The Dominus Winery by Herzog
and de Meuron in Napa Valley California, USA (1995-1998), where use of coarse
stone aggregates encased within steel cages suggested for a unique perspective to
drywall masonry. Additive manufacturing already spans over 30 years of research
and development (Huang et al, 2015) with early applications targeting rapid
prototyping using thermoplastic and thermoset polymers, with fused deposition
modelling (FDM) and stereolithography (SLA) being respective examples thereof.
One of the earliest relevant methods, commercially available by Z-Corp, used a
plaster-like material which was fused by inkjet printing of a binder. Applications
of 3D printing in architecture and construction generally pivot about material
extrusion of concrete (Khoshnevis, 1998; 2004; Lim et al 2012; Bos et al 2016)
while some of the earliest applications of robotics targeted additive assembly of
masonry structures (Andres, Bock and Gebhart, 1994; Gambao, Balaguer and
Gebhart, 2000; Gramazio and Kohler 2008). Experimental methods of additive
manufacturing progressively incorporated a wide range of materials including clay
(Friedman, Heamin and Mesa, 2014), silicone (Snooks, and Gwyllim, 2016), wax
(Gardiner and Janssen, 2014) and wood composites (Tan et al, 2017). Stone, a material which is generally considered difficult to use because of its high density and hardness, has been part of digital fabrication methods including subtractive processes (Ariza et al, 2016; Block et al, 2016; Burry, 2016). Relevant research here includes 3d printing of stone-like materials (Morgante, 2011; Lowke et al 2018), additive manufacturing with sand particles (Gramazio and Kohler, 2011; Dillenburger and Hansmeyer, 2014), additive assembly with large spherical particles (Kurilla and Svoboda), friction-based randomized aggregations (Dierichs and Menges, 2010; Dierichs, Schwinn and Menges, 2012) as well as cord reinforced aggregate assemblies (Aejmelaeus-Lindström, 2016; 2018).

3. Digital Fabrication

The operating principle of our method is classified as binder jetting (Figure 2). Powdered material is deposited layer by layer within a fixed-size printing volume and it is locally fused together by dispensing a liquid binder. The container supports progressive accumulation of material vertically and retains loose particles until the adhesive hardens. This simplifies machinery programming as there is no requirement for provision of 3D printing scaffold structures. However, printed parts are extracted from the build volume by a characteristically laborious excavation type of process. Nevertheless, material that has not been fused in the solid body or contaminated by the binder can be reused.

![Figure 2. Binder jetting additive manufacturing process as per ISO/ASTM 52900:2015.](image)

3.1. SYSTEM OVERVIEW

Implementation of binder jetting here is based on an industrial articulated 6-axis robotic arm with 5 kg payload and 0.9 m horizontal reach used as a positioner. The robot is employed as a flexible programmable space indexer as its full breath of motion on 6-axes is not required; a three-axis or even two-axis cartesian robot would have sufficed. The binding material is transported from a stationary container next to the robot via hose using a pump and directly dispensed from a 3D printed coupler mount on the robot’s flange. The pump operation is synchronized with the robot’s motion using a programmable logic controller (PLC). Its firmware binds the robot’s controller digital outputs to an analog pulse width modulated (PWM) signal controlling the DC motor-based pump’s speed via voltage changes.
3.2. MATERIAL PROPERTIES

The aggregate material is a coarse stone with diameter circa 3-5 mm and weight 2-3 g/cm³. It is commonly used for gardening, landscaping and construction. It is available in multiple colours and costs approximately 0.4 USD/kg. Unlike rough surface aggregates used for concrete fabrication, its texture is smooth, and shape rounded. It is pleasant to touch and in appearance it resembles sea or river pebbles. The binder used is a commercial off the shelf two-part epoxy adhesive with 20 min open time. Typical viscosity of thermoset polymer adhesives, such as epoxies is circa 10,000 cP, even though low viscosity 200 cP and ultra-high 1,500,000 cP formulations exist. Compared to familiar liquids such as water’s 1 cP and other common adhesives such as low and medium cyanoacrylates ranging about 5-100 cP, the rheological properties of epoxies are challenging for binder jetting processes being too viscous.

While it is not impossible to dispense high-viscosity liquids, it often requires high-pressure mechanical units such as those used for clay or concrete extrusion. High viscosity is also associated low flow rate, by Hagen-Poiseuille law, and consequently dispensing needs to slow down substantially such that motion speed can track material flow. In addition, strong universal material adhesives such as epoxies are very difficult to handle because their open time window is often limited and once it closes the system requires laborious purging and disposal of consumable components. Finally, while the cost of aggregates is low, the cost of epoxies is rather high, particularly in small quantities, while in large batches one needs to consider its limited shelf-life.

To overcome dispensing challenges and accelerate printing we diluted the epoxy binder with an acetone-based product and lowered its viscosity such that it could flow through a 2 mm internal diameter hose. Diluting epoxy with thinners is generally not advised by manufacturers because it compromises its
adhesive strength and overall mechanical properties. Ratios of acetone to resin experimentally tested were 1:2, 1:4, 1:8 and 1:12 by weight, with 1:8 determined as sufficient for transport and layer penetration. A collateral effect of acetone to resin mixture was in widening the curing time window from its advertised 20 to 40 min. Binding material transport could then be performed using a low power and cost peristaltic pump driven by a 6 V DC motor. To prevent clogging and disposal of consumables we used silicone hosing and utensils.

![Material samples and preliminary experiments.](image)

**3.3. PRINTING PROCESS**

The process requires a bounding envelope where coarse aggregates are placed in 10-15 mm high layers. We built a cabinet with 0.4 by 0.4 by 1 m featuring detachable walls to reduce part extraction time. Currently aggregate layer layout is performed manually unlike commercial 3D printers which often use two mechanically actuated containers transferring material from one another using an additional mechanically actuated wiper. While manual material layering is far from ideal, for experimental purposes it allowed testing different materials and thickness per layer. In addition, as the aggregates used are large in diameter it takes only 50 layers to print a 0.5 m high artefact. After each layer of aggregates is placed, the contours extracted from a 3D shape are traced by the epoxy dispenser. Thinned epoxy resin is dispensed from 700 mm above the pebble layer and on impact infiltrates the porous pebble layers and binds them horizontally and vertically. Contour extraction, translation to machine paths, compilation to robot programing language and communication with the controllers were performed.
through a digital fabrication library within Rhinoceros and Grasshopper.

3.4. PROCESS PARAMETERS

Achieving consistent results with binder infiltration is not an easy task: Insufficient adhesion due to resin starvation resulted to numerous parts being fractured during extraction. Excessive use of epoxy produced undesired effects such as over penetration and pooling at the bottom of the container. In addition, use of a peristaltic pump for dispensing was not ideal as its reciprocating action overlayed a harmonic on binder flow which resulted in uneven penetration along linear motions. This can be observed by the formation of undesired, but otherwise beautiful, stalactites suspended from the surface of the 3d prints. To approach this problem methodically we performed a series of experiments and measured the results of single linear stone beads (Figure 5).

![Figure 5. Experimental design tests aiming to control binder flow and penetration.](image)

The objective of this study was to achieve approximately 15 mm depth of penetration consistently, to ensure subsequent layer adhesion, while reducing the amount epoxy used to prevent it from appearing on the exterior surface of parts or worse causing the formation of stalactites. Controllable parameters include: the material flow rate ($f$) for which we measure via the voltage applied on the pump, the motion speed of the robot ($v$) measured in mm/sec, the acetone to resin ratio ($r$) and distance of dispensing ($d$) in mm. We performed a two-level combinatorial set of experiments using 5 and 5.5 V flow rate, 15 and 35 mm/sec motion speed, 1:8 and 1:12 ratio; and 70 and 130 cm dispensing distance. We measured the average penetration depth at three points along each bead and number of stalactites
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generated. While attempt to fit a regression model to allow for prediction of an optimal operating point was not statistically fruitful, perhaps because of innate non-linearity of material dosing, we did identify useful parameter configurations. Prototypes created using those parameters resulted to coherent exterior surface without gaps seen in earlier prints.

4. Prototyping

During project development we produced a large number of prototypes. Early experiments focused on variations of materials including adhesives and grain sizes such as soil, sand, gravel and pebbles. Once the use of pebble aggregates was determined as most effective, experiments focused on investigating visual, morphological, material and structural capabilities of the produced artefacts. Visually a unique characteristic of aggregate assemblies is in their ability to read simultaneously randomized and noisy but coherent from distance, while their granularity can be appreciated from closer proximity. The ability to locally inject the binder, produced stone-like artifacts with counterintuitively thin walls and low overall mass. The unexpected property of harmonic pump pulsation and early inability to control it sufficiently was reflected on some of the parts as a rhythmic introduction of surface perforations, localized erosion or stone lattice-like structures. Experiments with material variations include mixture of colored pebbles, at progressive interpolating ratios between thereof, producing a material gradient vertically.

![Figure 6. Prototypes developed exploring the material and geometry interactions.](image-url)

Working near the starvation bound of resin-to-pebble ratio was effective as the adhesive remains hidden internally within 3D printed surface walls. This results in a sense of ambiguity for the creation process behind the artefacts. They appear to be formed by natural forces, such as conglomerate sedimentary rocks, as it is unclear how pebbles are fused together. The dichotomy between the source of origin of the artefacts was exaggerated, or perhaps resolved, by structurally
counterintuitive geometric features such as tapering walls, cantilevering edges and low spanning arches achieved. The rather broad range of unique aesthetic attributes enabled by the pebble binding method, some of them discovered by accident and/or lack of process control, demonstrates that often there are interesting tangential design opportunities beyond achieving initially planned conventional targets.

![Figure 7. Randomized pebble aggregate prototypes with various color combinations.](image)

5. Conclusions

We presented the development of an additive manufacturing process using coarse randomized assemblies of pebble aggregates. The motivation that guided the development of the project was driven by the desire to produce large artefacts by accelerating additive manufacturing. Using large grained, ubiquitous and low cost materials directed us towards the use of stone. Use of not particularly environmentally-benign nor cost-affordable adhesives, directed development efforts towards minimizing its use. Prototypes created demonstrate some unique characteristics of a process that can produce artefacts that fuse natural, machine and man-made aspects. This could have not been possible without integration of materials and fabrication: if the pebbles were not coarse while smooth and convex enough to allow binder flow through their interstitial spaces and cavities; or if objects were structurally not primarily working in compression this method would not have worked. In terms of scaling this process to create larger objects closer to architectural scale, our perspective is that we do not need to scale the machine to
the size of the building. Instead we believe that reducing the time and effort for producing transportable components is more meaningful. An interesting aspect of randomized aggregate assemblies is that tectonics are baked-in the material and fabrication logic. Placing components next or on top of one another is often sufficient to blend them together due to randomization which at broader view homogenizes the visual and mechanical properties of the whole. We envision that the process developed and presented, can be used for both architectural as well as dry landscape design applications.

Figure 8. Rock garden feature prototype.

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References


