VARIABLE AGGREGATE IMPACT PRINTING OF COB

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Abstract. In this article, we present Variable Aggregate Impact Printing (VAIP), a novel additive manufacturing methodology for the automated assembly of traditional cob using a six-axis robotic arm and custom tool. This methodology enables the aggregation of discrete particles composed of soft heterogeneous material containing aggregates of multiple sizes. Single-particle experiments were conducted to optimize particle geometry and study the behaviour of individual soft particles under compression. Multiple particle prototypes were produced to understand the behaviour of soft particle aggregation under sequential compression. Variation in individual block size and aggregate content are accommodated due to the tolerances afforded by the malleability of the blocks. A model for the tolerance of soft particle aggregations is developed for particle positioning and orientation in relation to particle deformation. Finally, a large-scale installation was fabricated as a proof-of-concept prototype for the scalability of natural earth-based materials using computational design and robotic manufacturing technologies.

Keywords. Variable Aggregate Impact Printing, Earth-based Materials, Impact Printing, Automation, Robotic Fabrication.

1. Introduction

1.1. COB CONSTRUCTION

Earth-based materials are regaining traction as a sustainable alternative to conventional modern construction methods. This has led to a renewed interest in vernacular processes that have low-environmental impact, require minimally processed low-cost locally sourced materials, and possess carbon capture capabilities (Ben-Alon et al., 2019). Cob is a wet mixed earth construction technique that uses a clay-based subsoil in a plastic state, mixed with aggregates to build load-bearing monolithic walls. A Cob mixture typically comprises 4 components– a clay subsoil, aggregates, long natural fibres, and water. Cob construction often uses materials found onsite resulting in geographical variations in mixture techniques, components, and ratios. Traditional cob

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construction consists of the manual aggregation and compaction of small portions of material. Layer adhesion and lateral interface bonding between particles emerges from the plastic deformation of hydrated material. Large-scale structures are built in increments called ‘lifts’, where a section of the wall is built and then allowed to dry before being further built up vertically. As a result, traditional methods of cob construction are slow and labour-intensive, often relying on the experience and tacit knowledge of specialised workers (Hamard et al., 2016).

Digital fabrication processes reduce cost and time of construction while offering a high degree of process optimization, such as minimized waste and precise local material distribution (Paolini et al., 2019). Additive manufacturing (AM) methods based on continuous material deposition such as 3D printing require a highly homogenous material composition therefore present significant challenges with Cob. Fibrous and granular aggregates have been shown to lead to clogging and damage equipment (Gomaa et al., 2019). Water content, structural integrity and design geometry must be negotiated to enable layer-by-layer deposition (Reyes et al., 2018).

1.2. VARIABLE AGGREGATE IMPACT PRINTING

Inspired by traditional cob construction practices, Impact Printing is an assembly AM methodology consisting of a robotic pick and place and subsequent compaction of soft particles. Bonding strength results from the interlocking of individual adjacent particles upon sequential compaction. As a result, no use of additional binders is necessary. This method challenges conventional continuous material deposition through sequencing fabrication into discrete steps. Impact Printing precedents include the use of a ‘shooting’ apparatus to aggregate soft particles (Ming et al., n.d.). ‘Clay Rotunda’ used a lance technique to pick and the force of the robot to place and compact particles (Jenny et al., 2022). Current methods support the use of homogeneous material mixes but are incompatible with aggregates and fibres which can lead to clogging or collisions in the tooling.

In this publication we introduce Variable Aggregate Impact Printing (VAIP) as a novel Impact Printing method to enable the assembly of soft particles of heterogeneous materials containing fibrous and stone aggregates of varying sizes. The inclusion of aggregates severely effects the manufacturing process both in material behaviour and production logic. The material composition needs to be optimized to achieve a specific particle cohesion balancing malleability, to achieve bonding strength, and firmness to ensure repeatability and structural integrity. The use of a six-axis robotic setup allows VAIP to build complex design structures or onto existing structures and thus opens new opportunities for earth-based construction. The direct correlation between the mechanical compaction force and the material deformation enables functionally and structurally graded architectural elements, ranging from load-bearing masses to porous aggregations. Key parameters including material composition, particle geometry, compaction pressure, tool geometry and toolpath logic were investigated for the design of an integrative robotic process.

2. Materials and Methods

2.1. MATERIAL PREPARATION

Material selection and grading for the development of aggregated mix recipes meant that initial material sourcing would need to be from standardised sources to ensure repeatability and reliable quantification of results. Powdered earthenware and fireclay were sourced from Potclays. Sharp Sand, 10mm and 20mm gravel were purchased from Travis Perkins Building supplies. Straw was donated by EBUKI (Earth Building UK and Ireland). Cob was prepared by mixing 7 litre dry volumes of equal parts clay, sand, 10mm gravel and 20mm gravel before mixing thoroughly. Once the dry materials were evenly mixed, 3 litres of water were added stepwise in 1 litre increments. 1 equal part of straw is then added. This mixture was homogenized using a Soroto forced action mixer. A brick-forming jig was made to facilitate the process of soft-brick formation.

To assess the readiness of the material and set a standard mix, traditional 'drop tests' were performed (Weismann Adam & Bryce Katy, 2006).

2.2. ROBOTIC MANUFACTURING AND VAIP TOOLING SET-UP

The fabrication set-up was devised to sequentially pick, orient, place and compact blocks of heterogeneous material. A UR10 six-axis collaborative robot arm is mounted on a pedestal with an integrated custom impact printing end effector. Figure 1 shows the impact printing apparatus that consists of a double-acting pneumatic gripper Destaco DPG-10M-4 operated by a digitally controlled multi-block solenoid valve integrated with the robot controller I/O. The gripper jaws were customised to match the particle size and are equipped with a textured surface to enhance the grip. The distance between the jaws was 80mm in the closed state and 120mm in the open state suitable for particles of 100x100 mm. The jaws were made from a flexible acrylic material which enabled a soft grip to accommodate slight variations in particle size. The compacting operation is performed with a pneumatic piston customised with a textured flange. The textured piston imprints a textured surface on the soft particles which enhances the surface area of the compressed particle and facilitates bonding with the subsequent layer.

Figure 1 : CAD model of VAIP apparatus. (1) Pneumatic piston (2) Pneumatic gripper (3) Textured piston (4) Textured Jaw (Left). Photograph of tool mounted on robot during build (Right).

2.3. CAM SET-UP

A script for the robot motion and tool commands was developed with the 'Robots' plugin in Grasshopper3D in the Rhinoceros 7 environment. The script consists of a conventional pick and place algorithm. Particle deformation experimental data was incorporated into the script to accommodate tolerances. The layer height is determined by the experimental data of particle height deformation upon sequential compaction. Contours are subsequently subdivided by distance that accommodates for lateral deformation. The pneumatic piston and the pneumatic parallel gripper are operated by commands within the code. Furthermore, prototype geometries were optimized to fit within the robot working envelope.

2.4. EXPERIMENTAL METHODOLOGY

Using the standardised material mix, initial experiments were conducted to characterise key fabrication parameters. To analyse behaviour under compression in relation to particle size, particles of varying heights were compressed at varying pressures. Particles were prepared for testing by packing material to heights of 50mm, 75mm and 100mm into pre-made wooden formers (width 100mm x length 100mm) and compressed using the VAIP apparatus at pressures of 1, 2, 3 and 4 bars respectively. The lateral and vertical deformation of particles was then quantified. Particles were weighed before and after drying to understand shrinkage and cracking.

Next, behaviour under sequential compression steps was tested to optimize bonding strength through particle interlocking. Experiments were carried with a single, double and triple impact including a 5mm stepdown to the robot motion between impacts.

Behaviour of multiple particles under sequential compression using varying pressures was investigated. Stacks of 3 particles were compressed using 2 and 3 bar.

These samples were then tested on a Zwick Roell AllroundLine Universal Testing Machine (UTM).

A subsequent series of prototypes were constructed to understand geometric possibilities of the cob material using VAIP. This was necessary to create a scalable fabrication strategy and ensure the structural integrity of a larger structure.

Finally, a large-scale prototype was constructed displaying non-planar slicing, double curved walls and overhangs. The prototype was built over 4 days with 4-6 layers built each day with 19 layers in total. Each day, the top layer from the previous day was wetted with a water spray until moist to continue printing. The material was prepared using the method described above in multiple batches over the build period. The robot was mounted in the centre of a 1.8m x 1.2m platform on a custom steel plinth that did not exceed the footprint of the robot enabling maximum reach across the platform. Three pick points were located directly in front of the robot that were manually loaded with premade blocks.

3. Results

3.1. PARTICLE DEFORMATION

Particles were determined to be in a cuboid block with a footprint of 100mm (length) x 100mm (width). A cuboid form offered greater surface contact between particles than cylindrical particles for adhesion under compression. Weight was a key consideration in the particle size as the manipulator used (UR10) had a maximum payload of 10kg.

Experiments of single particle compression with particles of various heights showed that particle height appeared to affect the uniformity of particle deformation. Particles of 100mm in height did not display the effects of compression throughout the whole block with just the top section experiencing deformation resulting in a tapered form. 50mm was determined to be an appropriate particle height due to uniformity of deformation. It was observed that upon impact, all particles maintained structural cohesion and did not disintegrate within the pressure range tested. 4 bar was the maximum amount of pressure exerted by the piston on the particle without triggering the robot manipulators' emergency stop due to maximum torque violation.

Lateral and vertical deformation of particles under varying pressure was quantified. Figure 2B shows the mean depth of vertical compression achieved for each block height with varying degrees of pressure. The graph demonstrates a positive correlation between increased pressure and depth of compression. Block height did not seem to significantly impact the compression of an individual block. For example, with 4 bars of pressure a 50mm block would compact an average of 8% whereas a 100mm block would compact 9%. Lateral deformation showed no clear trends due to the irregular contour of each particle.

Understanding the effect of drying on particle adhesion and structural integrity was an important parameter. Blocks of 50x50mm weighed approximately 1000g when wet. Upon drying, blocks lost around 7-10% of their weight. The large quantity of large and fibrous aggregates in the material mix gave an already clumpy or cracked texture when wet. On drying the texture was visually similar with no noticeable additional cracks. Figure 2D shows the difference in material texture on drying in a stack of 3 blocks.

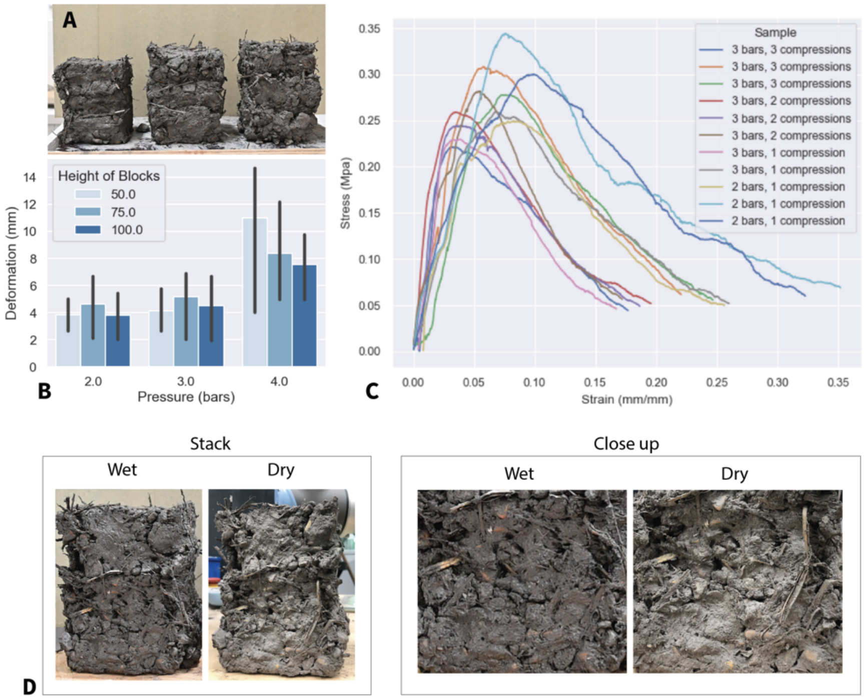

Figure 2: A: Effect of multiple compactions on particles with 1 compaction per block, 2 compactions per block and 3 compactions per block (left to right). B: Graph showing depth of vertical compression on varying individual blocks. C: Stress-strain curve of compacted particles. D: Effect of drying on material texture in a particle stack and close up section.

3.2. MULTIPLE PARTICLE BEHAVIOUR

Experiments of multiple particle compaction explored the effect of sequential compression on multiple layers (Figure 2A). Previously compacted particles appeared susceptible to further compaction upon the deposition of additional layers. To enhance the adhesive properties of the material, an additional step of spraying water between layers and roughing the surface was added to the process. The roughing increased the surface area at the contact point between blocks and the water increased the adhesiveness of the surface.

The force and number of compressions directly affects the formal characteristics of the particle assembly. Small-scale particle aggregations retained a distinctive discretized morphology, where every individual particle is distinguishable. This morphology reflects the robotic manufacturing process in a similar way to a running brick bond and offers a contrast with continuous material deposition processes (Figure 3). Multiple compressions led to greater merging between layers with greater load bearing ability. Less compression results in porous layers with more distinctive particles. Better adhesion between particles was also observed with increased pressure.

Compaction and lateral deformation need to be optimized to afford the maximum lateral bonding through deformation while maintaining a consistent layer height. Disregard of lateral deformation in the toolpath resulted in increasing overlap of particles as seen in Figure 3. Varying compression rates were compensated for with subsequent layers owing to the material tolerances.

Figure 3: Overlapping particles as a result of lateral extension (Left). Particle aggregation in curved, running brick bond formation (Right).

3.3. COMPRESSION TESTING

As mentioned above, through testing on a UTM, the material has a load bearing range of 0.24 - 0.34 MPa (0.24 – 0.34N/mm2) as shown in Figure 2C, based on 100mm particle size. The data suggests the number of compressions is directly proportional to load bearing ability. Samples with fewer compressions also appeared to be more brittle overall than samples with more compressions. Samples compressed with a lower pressure also appeared to have greater ductility than particles compressed at higher pressure. In contrast to this, the compressive strength of a rammed earth wall for single storey dwelling must bear 1.5N/mm2 (1.5MPa) where wall thickness is 400mm thick (Keable & Keable, 2011). This indicates that the material compaction using VAIP would need to be scaled up using greater pressures or larger blocks of material.

3.4. FINAL PROTOTYPE

The outcome of research was demonstrated in a 1:1 scale doubled curved wall of 1200mm high and 5000mm long. The structure was exhibited at the London Architecture Festival. Using the results derived in the material deformation and compaction experiments, the large-scale prototype was produced with the dimensions of 1.5m (w) x 1.5m (l) x 1m (h). The prototype was optimised to fit within the maximum reach radius of the robot (1300mm). The overall height of the prototype was over 1m and achieved 19 vertical layers of printed particles. The final prototype achieved a non-planar height difference in the top layer of (250mm). Images of the final prototype can be found in Figure 4.

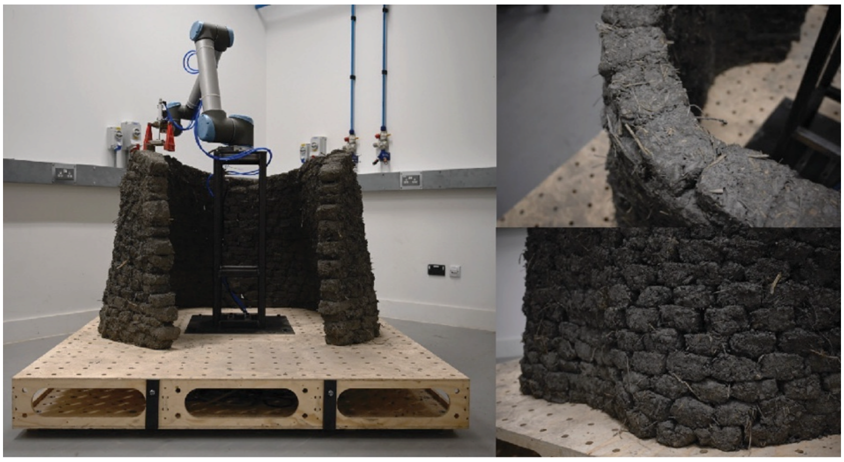

Figure 4 : Final scaled prototype and fabrication set up.

4. Discussion

The project demonstrates the viability and scalability of earth-based construction through a method of soft particle assembly with heterogenous aggregate distribution using a six-axis robotic process. Balancing cohesion and malleability, soft particles can sustain sequential compression steps and enable a layer-by-layer compression process. The process is affected directly by the relationship between the material consistency and the impacting force. The final structure was designed to demonstrate the geometrical possibilities of VAIP and included double curved walls, non-planar slicing and overhangs.

We developed a VAIP apparatus that enables iterative pick, orient and place of particles of heterogeneous materials. A pick and place approach was desirable for a material containing both particulate and fibrous aggregates. Other, more rigid methods of soft particle gripping such as cylinder-based stamping pick, or lance-based pick were assessed to be incompatible with heterogeneous material mixtures. The former led to collisions and entrapment of the robot manipulator with large solid aggregates, and the latter to disruption of the particle cohesion. Compliant acrylic soft jaws allowed for a soft grip which maintained particle cohesion during the pick and travel process. To increase the friction between the block and acrylic jaw, PLA 3D printed textured pads were added.

The irregularity in aggregate distribution in individual particles resulted in variability in behaviour under compression. Particle deformation upon impact was investigated to develop a model to predict and compensate for material and particle size irregularities. The data recorded was inconsistent due to the variability in aggregate distribution and cannot be used to create an accurate model for the precise prediction of particle behaviour under compression. However, qualitative data could be derived to establish a range of deformations.

A key function of compaction is to bond the blocks together in layers. On the microscale, the clay and water content of cob regulate the bonding between adjacent particles upon drying. On the mesoscale, through local deformation, compacted particles interlock with neighbouring particles to form bonds. While increased pressure was desirable for increased levels of particle adhesion, too much lateral deformation caused overlapping and inconsistent layer height.

The plastic material properties allow for the construction of highly complex geometries such as non-planar deposition and orienting blocks to produce curved prototypes without adaptive scanning toolpath optimisation. Despite irregularities being gradually compensated through sequential impacting it would be desirable to incorporate sensing feedback to accomplish a fully automated, closed-loop system. Thus, static models derived from experimental data for deformation could be further optimised through the implementation of real time scanning protocols to create dynamic models of fabrication.

The use of a collaborative robot enabled material handling inside the robots working envelope allowing simultaneous manual block production and robotic block assembly. Future possibilities with this set-up could include VAIP fabrication being implemented onsite with human-robot and multiple robot interactions (Burden et al., 2022). However, the reach of the UR10 represented the major limitation of our set up which could be overcome by the introduction of a mobile robot.

5. Conclusion

The research presented here demonstrates the viability of automated VAIP for large scale construction. Further, a novel methodology is established for the aggregation of soft particles of heterogenous materials, creating opportunities to expand the material choices within additive manufacturing. With minimal material optimisation, other highly viscous and heterogenous materials such as, hempcrete, limecrete or light earth can be implemented in AM using VAIP widening the palette of carbon-negative materials that alternatives to working with concrete.

Architecturally, the introduction of digital design and fabrication methodologies radically broadens the scope of application of vernacular materials such as Cob. This methodology expands on the geometrical and textural vocabulary of AM with earth-based materials, by which a complex structure with curved and non-planar particle assembly was achieved. The building morphology manifests through the interplay of particle geometry, malleability, aggregation logic, and impacting force, culminating in a synthesis of material development and materially informed automation methodology. Cob not only offers excellent sustainable credentials in eliminating environmental costs of sourcing materials, but also contextualises the material within its environment allowing for unique architectural identity.

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References

Ben-Alon, L., Loftness, V., Harries, K. A., DiPietro, G., & Hameen, E. C. (2019). Cradle to site Life Cycle Assessment (LCA) of natural vs conventional building materials: A case study on cob earthen material. Building and Environment, 160, 106150. https://doi.org/10.1016/J.BUILDENV.2019.05.028

Burden, A. G., Caldwell, G. A., & Guertler, M. R. (2022). Towards human–robot collaboration in construction: current cobot trends and forecasts. Construction Robotics. https://doi.org/10.1007/s41693-022-00085-0

Gomaa, M., Carfrae, J., Goodhew, S., Jabi, W., & Veliz Reyes, A. (2019). Thermal performance exploration of 3D printed cob. Https://Doi.Org/10.1080/00038628.2019.1606776, 62(3), 230–237. https://doi.org/10.1080/00038628.2019.1606776

Hamard, E., Cazacliu, B., Razakamanantsoa, A., & Morel, J. C. (2016). Cob, a vernacular earth construction process in the context of modern sustainable building. Building and Environment, 106, 103–119. https://doi.org/10.1016/J.BUILDENV.2016.06.009

Keable, J., & Keable, R. (2011). Rammed Earth Structures: A Code of Practice (2nd ed., Vol. 1). Practical Action Publishing.

Paolini, A., Kollmannsberger, S., & Rank, E. (2019). Additive manufacturing in construction: A review on processes, applications, and digital planning methods. Additive Manufacturing, 30, 100894. https://doi.org/10.1016/J.ADDMA.2019.100894

Reyes, A. V., Gomaa, M., Chatzivasileiadi, A., Jabi, W., & Wardhana, N. M. (2018). Computing Craft Early stage development of a robotically-supported 3D printing system for cob structures. Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe, 1, 791–800. https://doi.org/10.52842/CONF.ECAADE.2018.1.791

Weismann Adam, & Bryce Katy. (2006). Building with Cob: A Step-by-step Guide (Sustainable Building) (1st ed., Vol. 1). Green Books.