A robotically extruded sugar waste composite for a circular biomateriality in architecture

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ABSTRACT: To address the materiality of a post-waste scenario, a case study based on a calcium carbonate by-product from sugar refining was investigated. Here we demonstrate an interconnected workflow for fabrication scale up with a biopolymer-based composite material, Cal-x. Robotic 3D printing was employed as a method for construction, enabling customization to accommodate the material properties of Cal-x. A 4 x 2m prototype was assembled to explore the workflow and interface between material development, design, and robotic extrusion. The resulting output from this work, *Calcareous Arabesque*, was presented at the Design Museum London as part of the *Waste Age* exhibition, demonstrating a porous wall system that does not rely on continuous volumetric massing at an architectural scale. In future, implementation of advanced manufacturing to create architectural elements from industrial by-products has the potential to form the basis of a new circular biomateriality.

1 INTRODUCTION

1.1 *Context*

The materiality of a post-waste scenario has yet to be defined. To achieve net-zero in terms of waste and emissions, we have an urgent need to re-examine the extractive processes of manufacturing. Linear supply chains place pressure on our ecosystems, leading to anthropogenic mass exceeding all biomass on our planet (Elhacham et al., 2020). Industrial ecology is one potential route to enable a circular economy. By examining material flows within a city (Wachsmuth, 2012), designers may identify potential intervention points in order to create new urban metabolisms. Bio-integrated design (Cruz and Parker, 2021) strives to facilitate exchange between the technosphere and biosphere, with the aim to redress the unidirectional flow of materials and energy.

Carbon and calcium cycles are inextricably linked through biogeochemical cycles as well as industrial activity. Calcium carbonate in the form of limestone, marble and chalk is a familiar material in construction. In addition, ground calcium carbonate (GCC) is used extensively as an additive to plastics, paints, and adhesives. Another form, precipitated calcium carbonate (PCC) may be generated through an industrial process when calcium oxide reacts with carbon dioxide. While this may be produced as a by-product from the cement industry as a means of carbon offsetting, it also represents a major waste stream generated by a number of other manufacturing process. PCC possesses some significant differences from ground calcium carbonate. It has a fine particle size when dried, typically less than 10 microns, and contains less silica and lead than calcium carbonate obtained directly from mined mineral deposits (Echeverria and Holst, 2002). Depending on the source, it may also contain other organic compounds, which may impact the optical properties, as well as nitrogen and phosphorous.

Sugar refining, from either beet or cane, generates hundreds of thousands of tons of PCC each year. In London, one of the last remaining industrial operations on the Thames exists at Silvertown where Tate and Lyle Sugars processes sugarcane extracts as part of the American Sugar Refining operation. During the refining process, calcium oxide is added to affinated sugar in a step known as carbonatation. Carbon dioxide is bubbled through, resulting in the formation of calcium carbonate. This precipitates out impurities such as gums, amino acids and colour components that are not desired in the final product (EPA, 1997). PCC derived from sugar beet refining has been explored as a soil amendment (Hergert et al., 2017), or to lower the firing temperature of porous ceramics (Echeverria and Holst, 2002). At present, there are limited industrial uses for PCC formed in this way, although it has been tried as an additive in the formation of cementitious materials. However, the current applications do not fully explore the material properties or benefits of additional organic matter incorporated into calcium carbonate.

In this paper we develop a workflow that could support an urban metabolism seeking to prolong the existence of carbon and calcium as essential elements within construction. An industrial ecology based upon material development, fabrication and architectural design is presented, offering results that can be implemented in solutions with similar properties. A post-waste scenario is developed for by-products from sugar cane refining, PCC and bagasse through the application of advanced manufacturing techniques.

Robotic 3D printing in construction offers a platform for bespoke and customized large-scale fabrication of building elements, which has benefits when dealing with heterogenous or variable materials such as waste. With the aim of creating continuous volumetric massing of walls, concrete 3D printing using robotics has been widely explored in construction for large scale printing (Xiao et al., 2021). Recently, Wasp, an industrial manufacturer of 3D printers demonstrated large scale 3D printing of locally sourced materials through the Tecla house project (Russo and Moretti, 2020). For more porous systems, responsive spatial printing of clay has been tested in form of spatial lattices that use real-time model recalibration (Im et al., 2018). These extrusion-based processes integrate a number of complex and non-linear interactions such as the rheological properties of the material, curing and shrinkage behaviour and structural performance. These may be influenced by the pump speed and flow rate, extruder and nozzle geometry and nature of the substrate for deposition. Negotiating these intricate relationships for new materials where there is little to no tacit knowledge is challenging, but essential to allow for new applications in the built environment. Here we investigate how a novel material, Cal-x, derived from waste can be designed and scaled-up via robotic fabrication processes to attain a porous wall system with a maximum printing depth, while achieving a high-quality finish.

1.2 *Research agenda*

This research aims to contribute to more sustainable practices in material utilization through the application of industrial residues as potential low-cost and carbon-negative resources for future construction materials. The result is a circular biomateriality in architecture that has the dual benefit of mitigating waste and potentially reducing embodied carbon footprints within the built environment.

The following sections map out the pathway of fabricating large-scale customized wall panels made using a novel composite material developed in the Bio-ID lab and sponsored by Tate & Lyle Sugars.

2 MATERIAL DEVELOPMENT

2.1 *Development of Cal-x*

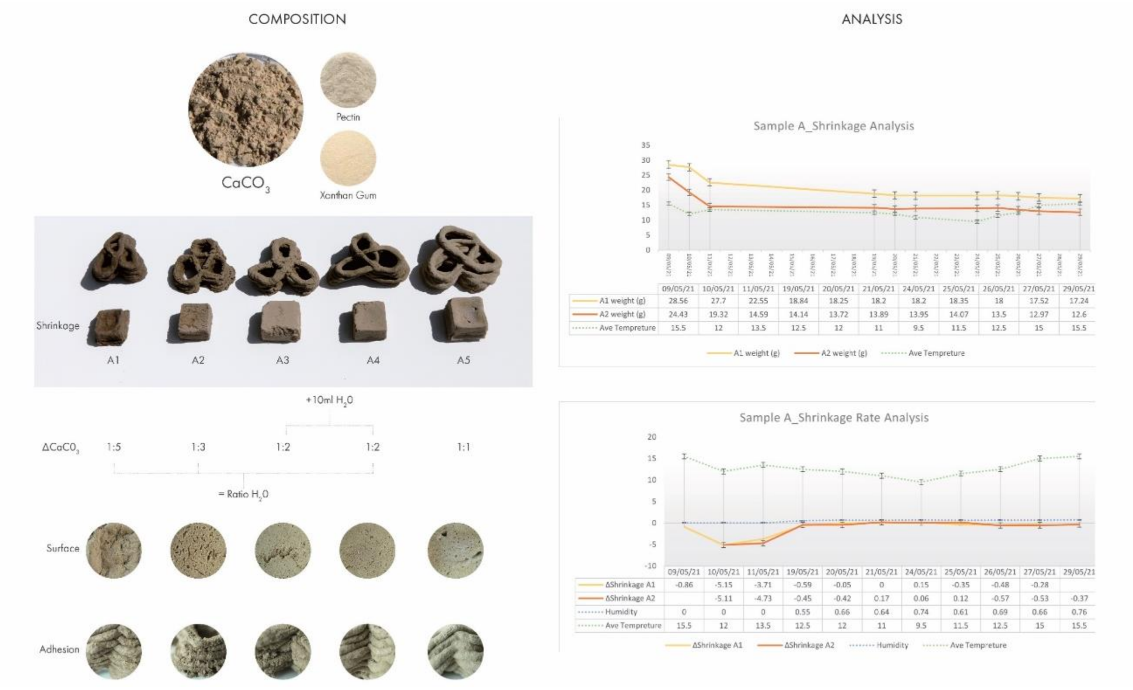
Cal-x is a biopolymer-based composite material, reinforced by PCC derived from sugar cane refining. The choice of binders was made to comply with the desire to minimize environmental impact. Biopolymers were considered as they can be sourced from renewable feedstocks and potentially offer performative characteristics compatible with robotic extrusion. Pectin and xanthan gum are commonly used in the food manufacturing industry. Pectin is a naturally occurring substance derived from fruits such as apple and citrus. It has properties such as gelation and emulsion stabilization (Sakai and Okushima, 1980). In this context, pectin was used as a gelling agent that binds the reinforcement particles together. Xanthan gum is a polysaccharide produced by a microorganism and purified from a fermentation bioprocess. It is highly viscous, even in low concentrations, and has a particularly strong shear-thinning characteristic that is fundamental for producing fluids. In commercial food use, xanthan gum is utilized as a thickening additive, acting as a stabilizer that assists in keeping ingredients from separating. In order to improve the water resistance, pectin nanofibers were crosslinked using calcium ions (Ca^{2+}). Ethanol in the form of Surgical Spirit BP was used at the early stage to prevent mould activities and to provide a rapidly evaporating solvent post-printing. This contains Wintergreen oil which has a characteristic odour.

2.2 *Materials*

Dried PPC powders were supplied by Tate &Lyle sugars. Pectin and xanthan gum were purchased from Special Ingredients, UK. Anhydrous calcium chloride was purchased from Mistral Industrial Chemicals Ltd. Surgical Spirit BP+ was purchased from APC Pure.

2.3 *Method*

Material was prepared as follows per 100g of the dry calcium carbonate. Powdered materials pectin, xanthan gum and PCC 40g, 20g and 100g respectively were mixed until evenly distributed. For liquid components 200ml 95% ethanol containing 2 wt% calcium chloride was added to homogenously incorporate the ethanol insoluble polymers in the material. After twenty minutes in ambient conditions crosslinking was performed using 120ml of 40 wt% aqueous calcium chloride solution. At this stage additional water can be added for further rheology modification. The paste was mixed mechanically until homogenous and loaded into the extrusion vessel. After extrusion following air drying, an additional step of neutralization by immersion was explored. Prints were submersed in 0.5M sodium hydroxide for 3 minutes, then cross washed with DI water until pH=7 (Fig. 1).



	09/05/21	10/05/21	11/05/21	19/05/21	20/05/21	21/05/21	24/05/21	25/05/21	26/05/21	27/05/21	29/05/21
A1 weight (g)	28.56	27.7	22.55	18.84	18.25	18.2	18.2	18.35	18	17.52	17.24
A2 weight (g)	24.43	19.32	14.59	14.14	13.72	13.89	13.95	14.07	13.5	12.97	12.6
Ave Tempreture	15.5	12	13.5	12.5	12	11	9.5	11.5	12.5	15	15.5

	09/05/21	10/05/21	11/05/21	19/05/21	20/05/21	21/05/21	24/05/21	25/05/21	26/05/21	27/05/21	29/05/21
ΔShrinkage A1	-0.86	-5.15	-3.71	-0.59	-0.05	0	0.15	-0.35	-0.48	-0.28	
ΔShrinkage A2		-5.11	-4.73	-0.45	-0.42	0.17	0.06	0.12	-0.57	-0.53	-0.37
Humidity	0	0	0	0.55	0.66	0.64	0.74	0.61	0.69	0.66	0.76
Ave Tempreture	15.5	12	13.5	12.5	12	11	9.5	11.5	12.5	15	15.5

Figure 1. PCC reinforced composite material samples (left); shrinkage analysis (right).

2.4 *Result*

Control of shrinking and cracking was necessary for print integrity. The evaporation of water content caused dynamic shrinkage during the drying process, and cracks on the surface were caused by the low tensile strength within the material structure (Fig. 1). There is a mutual influence between the two issues, as simply decreasing the water usage lowered the mixture's viscosity due to the properties of xanthan gum. This in turn impacted the binding strength between the PCC particles at the micro-scale, cause cracks, and reduced adhesive strength between printed layers at the macro-scale. Hence, instead of changing water content in the mixture, the ratio of PCC particles was the key variable for control of material properties while maintaining the same viscosity.

3 FABRICATION

3.1 *Material calibration for scale-up*

3D printing of biopolymers has been widely explored at the lab scale for biomedical applications, achieving complex geometries and three-dimensional matrices (Arrabito et al., 2020). They also may be printed in large surface area but low in height (Malik et al., 2019) due to their low compressive strength. Hence, there is a significant challenge in achieving three dimensional constructs with viscous materials where the design aims to produce a porous wall system that does not rely on continuous volumetric massing at an architectural scale. To understand and overcome the material limitations, prototyping experiments at different scales were conducted: pilot scale test (small scale using a 3D printer) and full-scale test (large scale using industrial robotic arm).

3.2 *Pilot scale test*

Pilot scale material tests were carried out to understand the composition ratio of Cal-x to biopolymers, aimed to achieve the following: slow curing process, reduce shrinkage, avoid deformation during the extrusion and prevent cracking during the curing period. Pilot scale printing utilized a fused deposition modelling (FDM) technique, also known as the slicing-in-layers printing technique, which relies on the lamination between layers during and after extrusion. Therefore, top layers relied on the structural stability of layers below. The two fundamental requirements for achieving taller prints within the material perspective using FDM technique were to avoid deformation of the structural layers and improve adhesion between the layers.

Previous material tests demonstrated that increased ratio of PCC could avoid deformation and increased water content can increase viscosity of the material. However, changing the water ratio resulted in altering the performance of the material. Table 1 summarises the impact of water content on material behaviour.

Table 1. Relationship between water content and material behaviour for Cal-x.

Water content	Shrinkage	Cracking	Curing time	Performance (strength)
High	High	No	Slower	Tensile
Low	Low	Yes	Faster	Compressive

Hence, further material experiments focused on modifying the ratio of PCC while the ratio of the water content to Cal-x remained consistent (Fig. 2). By optimizing the PPC ratio, overall shrinkage was reduced to a maximum of 10% and augmented the use of sugar by-products to up to 85% of total dry mass. PCC particles in the mixture formed a more rigid material with better performance under compression, which could support more weight and allow higher extrusions.

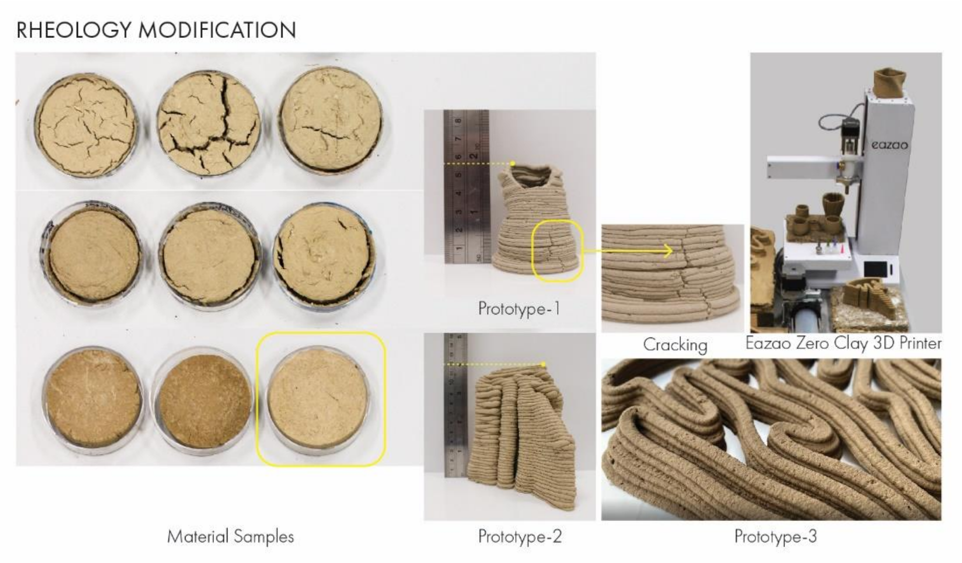


Figure 2. Modified material samples of Cal-x (left); Prototypes of printed Cal-x (right).

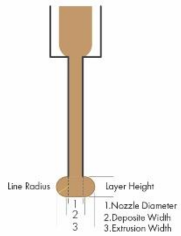
Each modified sample was tested on an electric puttered 3D printer Eazao Zero and using Cura as the G-code generation tool. Pilot scale prototypes were using a 6mm diameter nozzle, printing at 20mm/s speed, with 2mm as layer height. Various prototypes were tested using the optimized material mixture, and a maximum of 120mm in height was achieved (Fig. 2: Prototype 2). The small-scale tests informed the full-scale prototyping stage through the realization of the various printing parameters. A successful lamination was achieved by finding an optimal rate of extrusion, thickness of layer height, feed rate or speed of the manipulator (3D printer or robot).

3.3 *Full-scale test*

The full-scale prototype was printed on a vacuum compressed bagasse panel. Due to the large cross-sectional area of the print base, it deformed during the compression process, and the height differentiation of the four corners exceeded 5cm, which is approximately six times more than the print layer height. This reduced the bonding strength to the base and decreased the deposition area for higher layers, which caused failure of the print. Hence, an industrial robotic arm, rather than a 3D printer, was used to overcome the non-planar nature of the base in order to achieve a high precision outcome for full-scale fabrication. The printing parameters in terms of layer height, print speed and flow rate were optimized and a comparative study of various extrusions was done at a pilot scale and later on a bigger robot scale until it reached the desired resolution as shown in Table 2.

Table 2. Extrusion parameters in relations to the print scale.

Parameters	Method	Lab Scale	Prototype scale
Nozzle diameter	D	6 mm	7.4 mm
Layer height	L	2 mm	2.5 mm
Extrusion width	Y > D+L	12 mm	15 mm
Total height	=	120 mm	150 mm
Robot speed	=	20 mm/s	20 mm/s
Flow rate	=	=	800 mm^3/s



The hardware setup for the large-scale fabrication process included a 6 -axis industrial robot, KUKA KR60, a Netzsch NBE20 barrel emptying unit connected to a customized pneumatic extruder with a 7.4mm diameter nozzle. The pneumatic extruder was actuated by a solenoid valve. The nozzle was custom machined to 200mm in length to avoid collisions while printing deep ridges and valleys of the proposed design. Both barrel emptying unit and pneumatic solenoid valve were wired into the robot controller via standard digital IO (Input/ Output) to start and stop the extrusion synchronizing with the robot motion. Although, the robot used has a max reach of 2033mm, the sheer scale of the final prototype required optimization of workpiece location.

A custom algorithm created within Grasshopper3D was used to generate the 3D printing toolpath. KUKAprc Plugin for Grasshopper3D was used to translate the toolpath into robotic simulation (Inverse Kinematic solver) and generate the robotic codes for the controller. The custom algorithm utilized a fused deposition modelling (FDM) technique where the printed geometry was sliced to generate contour curves (Kontovourkis and Tryfonos, 2018) that in turn created a complex pattern of Cal-x extruded 'lamallae'.

Two methods for tool path generation were tested during the calibration period: a planar and non-planar printing process with the aim to test the quality of the print. Non-planar printing offers a continuous tool path with a better finishing quality unlike planar printing toolpath which offers a stepped pattern. At the same time, planar toolpaths result in equal layer height between layers, while non-planar toolpaths generate layers with a varying height. This variation needed to range between 2 and 5mm for the existing material and fabrication setup. But this was not possible with the intended design since the non-planar layer height ranged between 0.5 and 10mm. It resulted in a variable deposition of material in different segments of the toolpath. Remapping the robot velocity to the layer height failed as the current setup using the pneumatic extruder allowed only to start or stop, while the variable flow rate of extrusion could not be controlled parametrically. In addition, a further test of combining two types of tool paths as a hybrid tool path was examined. It used the planar tool path as the base to fill the volumes and the non-planar ones as the finishing layer to cover the tip formed at the end of each breaking line. However, it also failed due to the collision with the surroundings extruded lamellae as non-planar toolpath required 6DOF (degrees of freedom) orientation of the robot (Fig. 3).

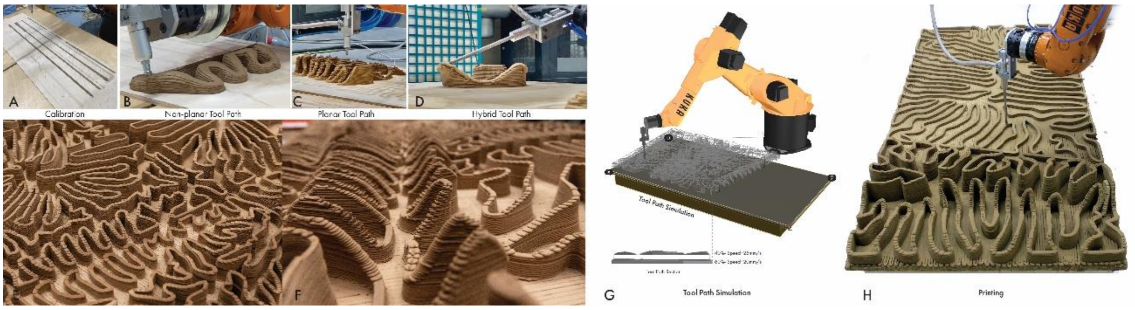


Figure 3. Left: A. Speed calibration; B. Non-planar extrusion; C. Planar extrusion; D. Hybrid tool path extrusion; E. zoomed view of panel; F. Detail view of panel; G. Tool path simulation; H. Physical printing.

To address the structural stability of the design and take in account the material shrinkage, the generated contour curves or layers were split into two groups. The bottom 60% layers were printed at 20% lower speed than the top 40% curves. Lowering the speed to increase deposition led to more thickness at the bottom, thereby providing better stability.

3.4 *Demonstration – Calcareous Arabesque*

Calcareous Arabesque is a 4m high, 2m wide and 15cm deep interior wall designed for the *Waste Age* exhibition at the Design Museum in London. Hereby the compressive strength of Cal-x and the robotic extrusion process to achieve maximum print height was demonstrated at scale. The wall rested on the floor and was constructed in three juxtaposed strata (Fig. 4). A timber-framed cassette formed a structural back layer for each panel. Bagasse, lignocellulosic material, which is also a byproduct from sugarcane processing, was vacuum pressed to bond to the cassette creating a homogeneous middle layer with a high-level surface roughness. This textural bagasse layer provided a robust mechanical bond to the third and most exposed part of the wall in form of a highly intricate robotically extruded Cal-x ornamental lamellae pattern – an arabesque. The wall was ultimately divided into four one-meter-high and two-meter-wide smaller panels due to limitations of reach of the robot arm. Each panel was assembled and extruded horizontally and after curing installed vertically in the exhibition space.

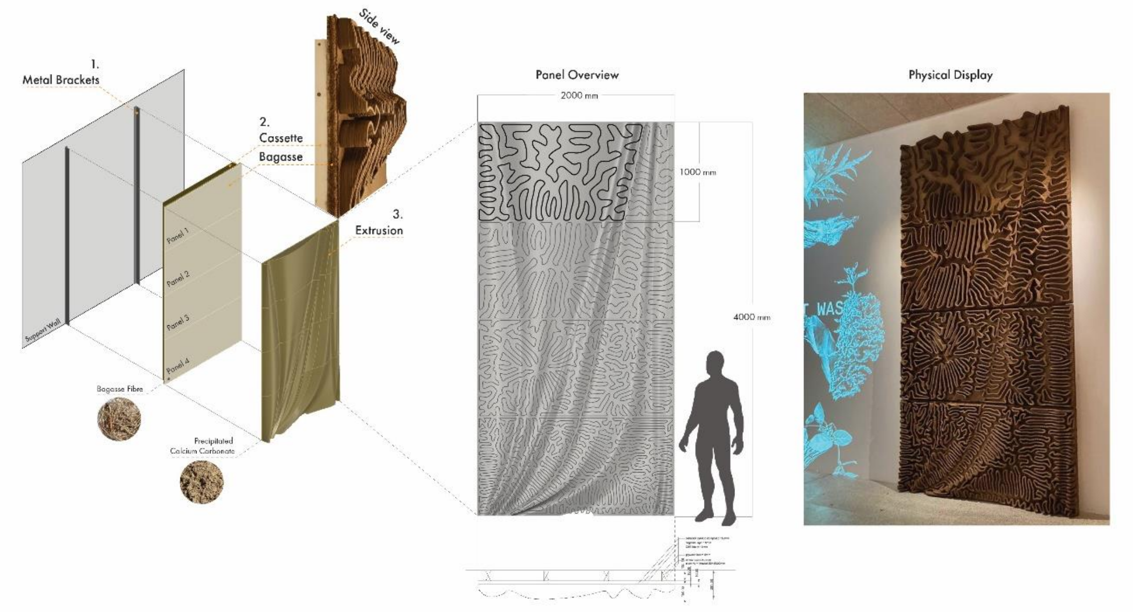


Figure 4. Panel Structure diagram (left); and photo of elevation (right).

The three-dimensional pattern was produced by a self-generative computer design algorism ‘differential growth’ (Fig. 4) contained within a lofted variable surface topology that invoked the idea of a curtain with multiple folds. This enabled a perspectival variation depending on the viewer’s distance and point of view. The pattern density was designed following a gradient of less spacing between extruded lamellae on the bottom and more spacing at the top. This reduction of the printed density towards the top enhanced the structural stability by gradually reducing the weight on the upper panels, while preventing the tilting and overhang of the entire wall arabesque towards the front. In addition, the lamellae pattern was divided into two planar sections on each panel for splitting the print load during the extrusion process.

4 CONCLUSIONS

The project has demonstrated the interconnected workflow for fabrication scale up with a biopolymer-based composite material, Cal-x. To examine the potential of this material for architectural applications, a full-scale wall prototype was assembled to explore the workflow and interface between material development, design, and robotic extrusion. The ability of customization and bespoke settings enabled the use of post-industrial waste.

Within the circular economy there is a lack of truly transformational processes. Work typically examines reformation rather than upgrading. It has been discussed previously that how our management of waste streams could be enriched by engaging with “how material flows are shaped by, and interact with, nonmaterial flows, that is, the different forms of social embeddedness” (Blomsma and Brennan, 2017). *Calcareous Arabesque*, the resulting output from this work, was presented at the Design Museum in London as part of the *Waste Age* exhibition. Sensory elements, odour, biological action, and ornamental porous features were all vital elements of the resulting installation, yet these characteristics are seldom explored in design as inherent properties of organic materials.

In terms of application, *Calcareous Arabesque* has potential to provide acoustic and thermal properties for an indoor environment, exploring the material porosity and variable three-dimensional depth of the extruded lamella. The additive manufacturing process enables precise and customized control over the geometry which can be designed and adjusted to different spatial acoustic requirements. These features can be of high value in high-traffic space, e.g. flight terminals, trains stations and shopping centres. Furthermore, hydrophilic properties of Cal-x allow such ornamental wall to absorb moisture from the air, which in busy public spaces can be of great significance. Future work on Cal-x may also investigate the bioreceptive qualities offered by the material for outdoor environments. The subsequent colonisation of microorganisms on such a structure may be speculated through data acquired on other calcareous materials (Crispim et al., 2003). Ecological data on plants adapted for growth on limestone, but also higher plants that are able to use industrial waste such as this as a habitat (Ash et al., 1994) are promising departure points to investigate how Cal-x may be used as a new type of poikilohydric living wall system (Cruz, 2021). This approach could create a new circular economy paradigm that could break the apparent disconnect between the biological and technical cycles presented in Cradle to Cradle or McArthur foundation models (Blomsma and Brennan, 2017). In this way we may foresee architectural elements bridging the technosphere and the biosphere through a new material ecology supported by advanced manufacturing techniques.

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6 REFERENCES

Acosta Echeverria, A., Ruiz Holst, M., 2002. Use of a Precipitated Calcium Carbonate (PCC) originating from sugr as a raw material in the ceramic industry. EP1498399.

Arrabito, G., Ferrara, V., Bonasera, A., Pignataro, B., 2020. Artificial Biosystems by Printing Biology. Small 16.

Ash, H.J., Gemmell, R.P., Bradshaw, A.D., 1994. The Introduction of Native Plant Species on Industrial Waste Heaps: A Test of Immigration and Other Factors Affecting Primary Succession. J. Appl. Ecol. 31, 74.

Blomsma, F., Brennan, G., 2017. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. J. Ind. Ecol. 21, 603–614.

Crispim, C.A., Gaylarde, P.M., Gaylarde, C.C., 2003. Algal and Cyanobacterial Biofilms on Calcareous Historic Buildings. Curr. Microbiol. 2003 462 46, 0079–0082.

Cruz, M., 2021. Poikilohydric Living Walls. Bartlett Design Research Folios.

Cruz, M., Parker, B., 2021. From the Anthropocene to the Biocene - novel bio-integrated design as a means to respond to the current biodiversity and climate crisis. In: Harriss, H., House, N. (Eds.), Intersectional Space- Architecture of the Post Anthropocene. RIBA Publications, London.

Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y.M., Milo, R., 2020. Global human-made mass exceeds all living biomass. Nat. 2020 5887838 588, 442–444.

EPA, 1997. Sugarcane Processing. In: AP-42 Compilation of Emissions Factors.

Hergert, G., Darapuneni, M., Aqeel, A., Wilson, R., Harveson, R., Bradshaw, J., Nielsen, R., 2017. Agronomic Potential of Using Precipitated Calcium Carbonate on Early Plant Growth and Soil Quality in the Intermountain West - Greenhouse Studies. J. Sugar Beet Res.

Im, H.C., Alothman, S., García, J.L., Castillo, D., 2018. Responsive Spatial Print: Clay 3D Printing of Spatial Lattices Using Real-Time Model Recalibration. In: Acadia.

Kontovourkis, O., Tryfonos, G., 2018. Integrating parametric design with robotic additive manufacturing for 3D clay printing: An experimental study. ISARC 2018 - 35th Int. Symp. Autom. Robot. Constr. Int. AEC/FM Hackathon Futur. Build. Things.

Malik, S., Hagopian, J., Mohite, S., Lintong, C., Stoffels, L., Giannakopoulos, S., Beckett, R., Leung, C., Ruiz, J., Cruz, M., Parker, B., 2019. Robotic Extrusion of Algae-Laden Hydrogels for Large-Scale Applications. Glob. Challenges 1900064.

Russo, D., Moretti, M., 2020. Shamballa, Heaven can wait. How 3D printing will sustain the future. AGATHÓN | Int. J. Archit. Art Des. 8, 32–43.

Sakai, T., Okushima, M., 1980. Microbial Production of Pectin from Citrus Peel. Appl. Environ. Microbiol. 39, 908–912.

Wachsmuth, D., 2012. Three Ecologies: Urban Metabolism and the Society-Nature Opposition. Sociol. Q. 53, 506–523.

Xiao, J., Ji, G., Zhang, Y., Ma, G., Mechtcherine, V., Pan, J., Wang, L., Ding, T., Duan, Z., Du, S., 2021. Large-scale 3D printing concrete technology: Current status and future opportunities. Cem. Concr. Compos. 122, 104115.