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Formation finding: exploring soft cast MICP fabrication in a Water Kiln

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Research Article

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Abstract

Microbially Induced Calcium Carbonate Precipitation (MICP) provides a biologically driven alternative to conventional cementitious processes, requiring fabrication methods responsive to the dynamics of living systems. This study introduces a submerged soft-casting approach, employing fabric mesh moulds to biocement sand aggregates through the biomineralisation activity of *Sporosarcina pasteurii*. Developed in 'Water Kiln' bioreactors, the process replaces high-temperature curing with controlled liquid-phase mineralisation, generating cemented components assembled into the prototype column *EmbryOme 1*.

Rather than targeting structural material outputs, the research emphasises exploratory, process-oriented 'formation finding', where microbial activity, substrates, media and moulds together shape macro form and microstructure. Fabric casts filled with sand and nutrient-rich bacterial suspensions were submerged in cementation solutions to induce calcium carbonate precipitation. Key variables, including mould design, calcium and nutrient concentrations and media replacement frequency, were systematically adjusted to assess their effect on formation quality.

Optimal outcomes occurred at 0.3 M calcium chloride and urea with daily medium replacement, and smaller mesh sizes produced denser, more uniform crusts. Cementation remained primarily superficial, though glazing treatments enhanced surface hardness. These results underscore the role of design in tuning biological–material interactions, framing biofabrication as a process of negotiation with material agency, variability and future architectural potential.

Introduction

This research explores the potential of Microbially Induced Calcium Carbonate Precipitation (MICP) as a fabrication method for creating structurally relevant, biofabricated building components. At its core, the study engages with the question: *Can we grow a building?* (Dade-Robertson 2023). By investigating the formation of 'hard' biological matter through biomineralisation, we examine how living processes can contribute to the development of scalable, architecturally viable materials. While MICP has been demonstrated in other studies as a means of producing solid, structurally capable forms (Smirnova et al. 2023). The experiments presented here were designed with a different objective. Rather than focusing on the optimisation of strength or load-bearing elements, this study seeks to understand how MICP forms under relatively unconstrained conditions, following a logic inspired by fabric-formwork and concrete casting. This work positions MICP as a material strategy that not only challenges traditional construction methods but also redefines the role of biological matter in engineered environments. Here, we have used the term '*formation finding*' to describe the core objective of the research. Formation finding differs from traditional '*form finding*' in both scale and approach. Whereas form finding often operates at a single scale, where the design negotiation occurs primarily between aggregated material and its formwork, formation finding engages across multiple scales simultaneously. Form in this case can be described at multiple scales from the form of the object itself to the form of the mineral crystals and their relationships to the substrate. Formation finding also leads to materials which are not heterogeneous. Formation is not delineated by the surface of the cast but rather gradients of more or less solid material and different material densities. These different material formations lead the cast materials to be more or less cemented, friable, susceptible to variable weathering or further work to reveal new form and structure. In our work, this involves exploring the interplay between microbial activity, granular substrate, liquid media concentration and spatial constraints of the mould, producing both a macro-scale form and a micro-scale structural fabric within that form. Formation finding positions microbial organisms not as tools to be controlled, but as collaborators whose biological behaviours, when tuned through design parameters, yield emergent structures. This multi-scalar

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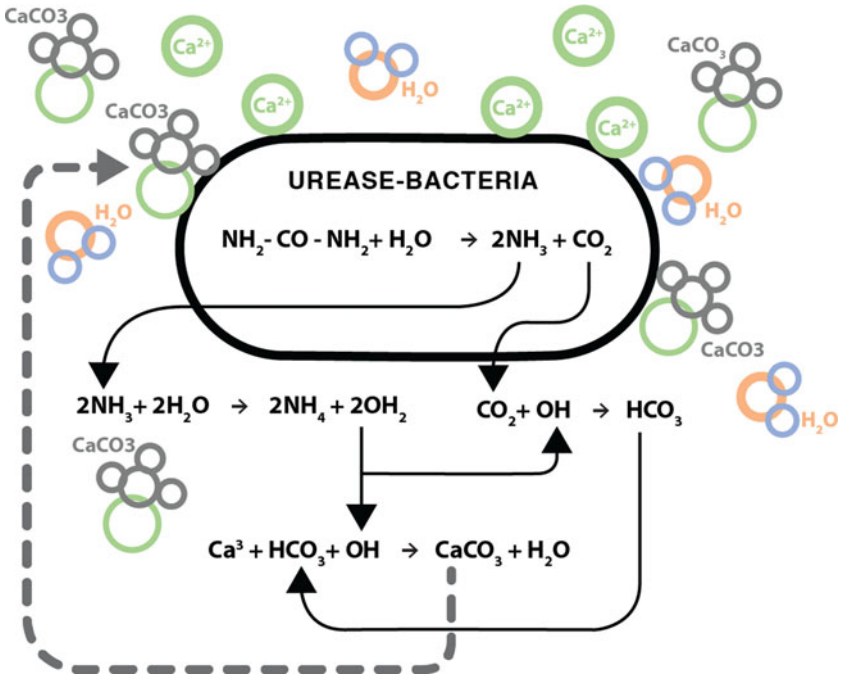


Figure 1. Schematic diagram of MICP through ureolytic bacteria.

engagement requires both scientific and design perspectives and expertise, aligning biological process understanding with material experimentation and spatial thinking. By working within this framework, formation finding reframes architectural biofabrication from a deterministic, control-centric practice toward a collaboration-centric paradigm one that accepts unpredictability, leverages the generative capacities of biological processes and opens new pathways for designing with matter in formation.

Biomineralisation involves complex processes that result in the formation of biogeological structures such as caves, soils, sediments and aquifers (Banks et al. 2010; Chou Chiung-Wen et al. 2011; Riding 2000). This phenomenon is evident in the calcium carbonate structures of corals and seashells and in calcium phosphate formations found in the bones and teeth of vertebrates. It plays a crucial role in both the development and structural integrity of organisms by forming durable materials through calcium deposition, which cements biological elements together (Mann 2001).

There are two primary forms of biomineralisation: biologically controlled and induced. Biologically controlled biomineralisation involves organisms precisely regulating mineral growth and nucleation to fulfil specific structural functions, as seen in bones and shells (Anbu et al. 2016). On the other hand, induced biomineralisation occurs extracellularly under favourable conditions, where microbes can precipitate calcium carbonate through chemical interactions that lead to environmental supersaturation (Anbu et al. 2016; Ghosh et al. 2019).

Microbial mineralisation

Microbially Induced Calcite Precipitation is a process that utilises ureolytic bacteria, such as *Sporosarcina pasteurii*, to induce the precipitation of calcium carbonate (Figure 1). Firstly, the ureolytic bacteria will catalyse the hydrolysis of urea to form carbon dioxide and ammonia, which diffuse out of the cell. The carbon dioxide forms carbonate and can react with calcium in the local environment to form calcium carbonate. Ammonia can react with water and form ammonium and hydroxide ions, which raises the environmental pH. The cell surface of ureolytic bacteria is negatively charged and can act as nucleation sites for the accumulation of calcium ions, leading to calcium carbonate supersaturation and precipitation (Zhang et al. 2018).

Sporosarcina pasteurii is known for its high urease activity, which is crucial for the MICP process, as urease catalyses the hydrolysis of urea, leading to the production of carbonate ions that react with calcium to form calcium carbonate (Konstantinou et al. 2021). This reaction serves as a binder for particulate matter, enhancing material properties like strength and filling voids in substrates (Smirnova et al. 2023).

MICP has been seen as environmentally friendly process as the biomineralisation process is able to occur at room temperature, which significantly reduces the high energy costs typically associated with conventional clay material manufacturing that requires intensive heating.

However, the most studied biocementation processes are through active pumping of nutrients and reactants which are energy intensive. Most applications of MICP focus on closed, hard casting moulds that are flushed to achieve biomineralisation from ground engineering (Whiffin et al. 2007), brick making (Henze and Randall 2018) and design applications (Gerlach 2023). This method presents several limitations, primarily the need for complex mould designs and an extensive setup involving peristaltic pumps, tubing and connections. These requirements not only increase the cost but also limit the accessibility of the technology outside of well-equipped research facilities. Furthermore, such systems can restrict the uniform distribution of the media, potentially leading to inconsistent biomineralisation. To achieve a more accessible fabrication process, therefore, this research looks at exploring and optimising a soft casting technique, using fabric mesh and acrylic scaffolds, for MICP in a submersion method. The introduction of a submerged casting system not only expands the fabrication approach of MICP in loose aggregates (Zhao et al. 2014) but could also enhance the access of liquid medium to the bacteria which could improve the biomineralisation process. This

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holds promising implications for design and form making, with potential scalability in the manufacturing for architectural applications (Mosse et al. 2024). Building upon prior investigations into MICP applications, such as liquid flow forming techniques (Arnardottir et al. 2021) and submerged strengthening methods (Horn et al. 2023), our focus lies in leveraging the biological constraints of ureolytic bacteria (*Sporosarcina pasteurii*) within a liquid environment. Our primary aim is to refine the submersed fabrication process to form and mass fabricate biomineralised pieces in static setups, where the media is not changed, which could significantly reduce labour and operational complexity in design settings and to suspend the cemented pieces into a non-load bearing, architectural column structure.

In this paper, we distinguish between biomineralisation and cementation. Biomineralisation refers to the microbial process, in this case, mediated by *Sporosarcina pasteurii*, that induces calcium carbonate precipitation through enzymatic urea hydrolysis. This process operates at the cellular and chemical level and can be influenced by parameters such as nutrient availability, pH and ion concentrations. Cementation, by contrast, describes the resultant material effect of this process: the bonding of granular particles, such as sand, into a cohesive structure. While biomineralisation is a biological phenomenon, cementation refers to its architectural and structural expression in the form of mineralised composites. In this project, we explore biocementation techniques that harness biomineralisation to produce form-stable components in a design-led development, exploring how the designer's influence shapes the process and outcomes of the biocemented material. By intervening in material and fabrication parameters, the research demonstrates how design decisions play an active role in mediating biological and material behaviours, expanding the potential for co-creative engagements with living systems.

Design concept

For this research we have entitled our prototype the '*EmbryOme 1*'. Much of the work in our lab is focused on fundamental material development and biological engineering; however, through the development of designed prototypes, we have been exploring the aesthetic design implication and the challenges of scaling up our biological materials and presenting them in public settings. The Embry, derived from embryo denotes these prototypes as at the early stage of their development, tentative in their form and structure. The ome denotes the many different levels of biological knowledge that has gone into their creation, which are often desired with terms using the suffix 'ome': genome, proteome, metabolome and biome. The *EmbryOme 1* is the first exploration of its type, and through it, we have looked at the implications of a scaled-up method of biocementation and the designer's role in mediating material behaviours and process outcomes.

The *EmbryOme 1* project introduces an approach to design with MICP, specifically focusing on mould design which plays a pivotal role in the MICP process. Drawing inspiration from the concept of ceramic kilning, this research introduces a bioreactor system termed the '*Water Kiln*'. Unlike traditional kilns, which rely on high-temperature firing to harden materials, the *Water Kiln* facilitates hardening through a submerged biotic liquid medium that supports and enables the activity of living bacteria (*Sporosarcina pasteurii*), providing a controlled environment for calcium carbonate deposition. This approach replaces thermal energy with biological activity, providing an energy-efficient alternative to conventional fabrication techniques.

Unlike hard moulds, which can limit accessibility to media and oxygen in the MICP process, this research explores a '*soft casting*' method that utilises flexible mesh fabrics to facilitate the casting process. This approach accommodates unique geometries and enhances liquid media flow and aeration to the bacteria. This study uses the '*submerged synthesis*' as a fabrication process where the interaction between bacteria, sand and media occurs entirely underwater in the cementation process. This simplifies the material-making process into a more passive forming, making it an accessible alternative to complex formwork and pumping methods for biomineralisation processes.

This project explores the integration of *soft casting*, *Water Kiln* systems and *submerged synthesis* to overcome limitations observed in traditional biocementation techniques. These design-led adaptations aim to improve the biomineralisation process while enabling scalable and architecturally relevant forms.

Materials and methods

Cultivation and inoculation

Sporosarcina pasteurii DSM33 were cultured from −80°C onto 2% agar plates with growth media, comprising of 13g/L of Nutrient broth *type E* and 5% urea. The NB media was autoclaved at 121 ° C for 15 min, and urea was sterilised separately, with a Büchner funnel and filter paper (Whatman Grade 1) and a Laboport N86 vacuum pump for the stock solution. The plates were incubated at 30°C to promote bacterial growth before being transferred to refrigeration to pause growth, ensuring viability for subsequent experiments.

Fresh colonies of *S. pasteurii* were streaked from the plates into 50 mL falcon tubes with 10mL of liquid growth media each and grown in a shaking incubator overnight at 30°C and 180 rpm.

Sand with the particle size ranging from 100 to 300 microns was used and 120 g of the and was autoclaved at 121 ° C for 15 min in 250 mL beakers. Once autoclaved 50 mL of growth media was poured into the beakers with 0.5 mL of overnight culture of *S. Pasteurii.* Cultivation of sand beakers with liquid culture bacteria in the shaking incubator at 30°C and 180 rpm for 16–24 hours (Arnardottir 2024).

The optical density of the bacteria was measured before beginning the experiment of placing the media into moulds, providing insights into microbial activity at the time.

Mould design

The mould design's primary function is to support the biocementation process by providing a controlled environment for calcium carbonate deposition through the interaction of the bacteria, sand and media within the fabric cast. Key biological considerations for the mould design included the nutrient media diffusion and oxygen accessibility, all of which directly influence the efficiency and uniformity of the biomineralisation process and set up the design parameters. These looked at the optimum size and shape of the mould frame, as well as the tightness of the fabric tensioned within that frame that would allow for easy packing of the aggregate material, as well as extraction from the mould, and increase access to nutrients and oxygen during the mineralisation.

The mould design (Figure 2) uses fabric mesh and acrylic structures to facilitate the MICP process from mould fabrication explored in Wang's (2024) master's project, *Bactoware*. The forms of the mould were developed further in this study to address limitations in the biomineralisation fabrication process,

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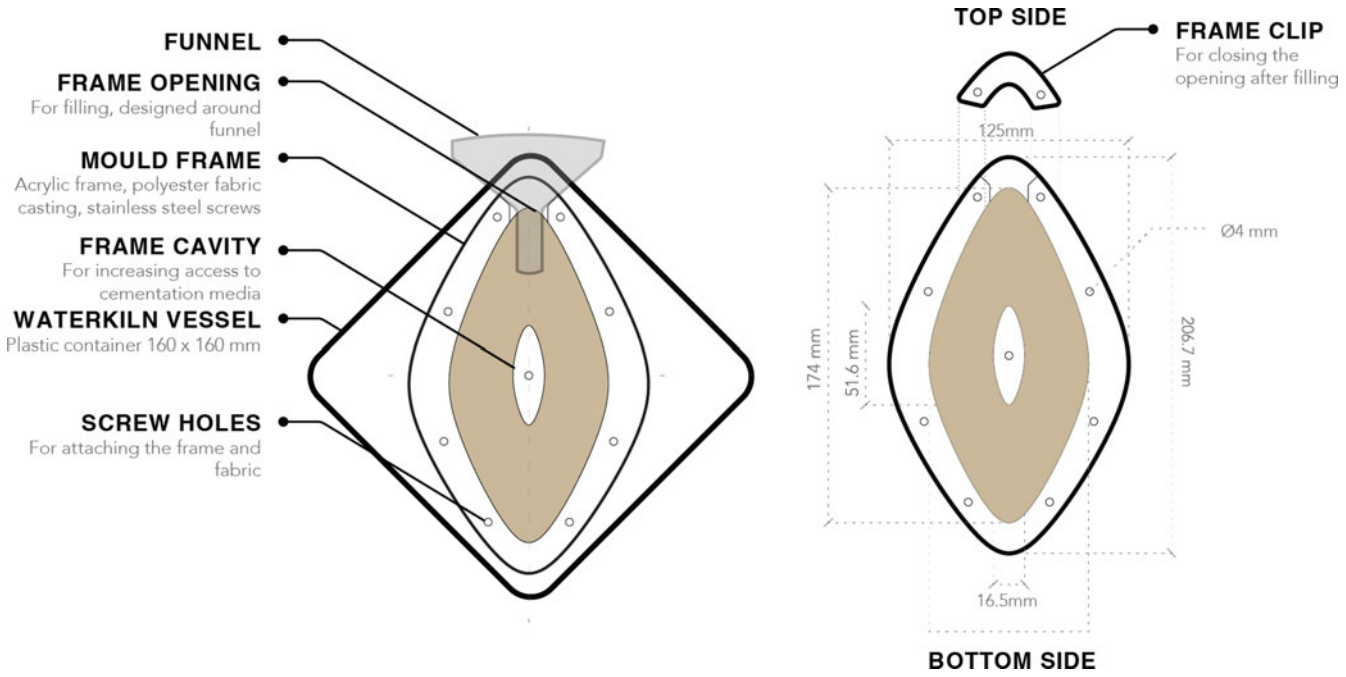


Figure 2. Diagram of the mould design and specifications.

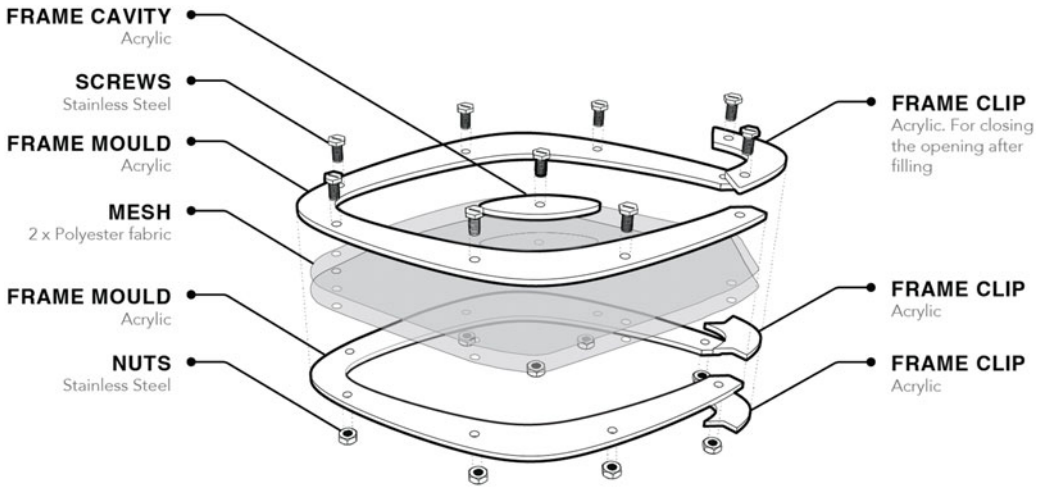


Figure 3. Exploded diagram of the mould.

particularly regarding minimal diffusion pathways for key nutrient reactant and oxygen accessibility. A central hole was introduced to enhance the permeability of the cementation media, ensuring more surface area for biomineralisation to occur by allowing nutrients to flow through the fabric and into the sand mixture. Additionally, the overall geometry in the acrylic was developed to maintain the mould's shape, providing a stable outer and inner form and securing a polyester mesh that contains the bacterial-infused sand-media mixture and to optimise the packing efficiency of the material, while maintaining ease of extracting the mineralised form from the mould once hardened sufficiently (Figure 3).

This method takes inspiration from fabric formwork in concrete casting in challenging the assumption that the matter being cast must conform to rectilinear, predetermined structures. Instead, it allows gravity and material properties to shape the final outcome (Lloyd Thomas 2007), producing forms that are more organic, efficient and structurally responsive. This dynamic relationship between material and form-giver is central to both fabric-cast concrete and the biocementation casting process explored in this study.

The acrylic frames are tailored to snugly fit within the containers specified in our *Water Kiln* setup. Specifically, the frame dimensions are designed at 125 × 206.7 mm to accommodate the scale of the experiments.

The frame of the mould consists of top and bottom side, where one side is equipped with an opening at the top and a frame clip to close, designed to facilitate easy filling of the fabric mesh mould (Figure 4). This feature is critical for introducing the sand-media mixture uniformly, aided by a funnel that fits snugly into the opening, directing material flow and preventing displacement. A frame cavity was designed to create a central hole in the mould and increases the surface area in direct contact with the cementation media, enhancing biomineralisation throughout the structure.

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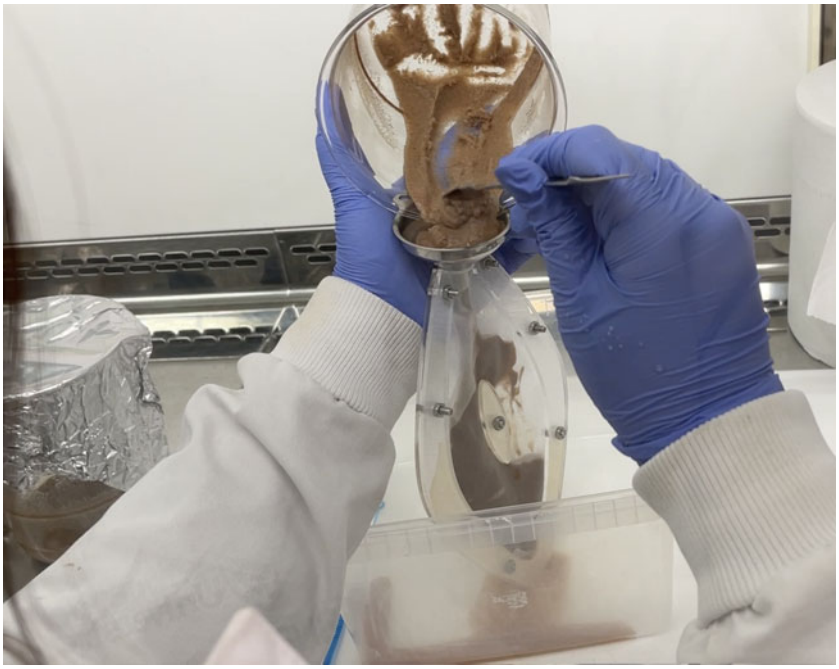


Figure 4. Filling mould with sand inoculated overnight with bacteria.



Figure 5. Mould filled and closed.

Screw holes are positioned around the edges of both the frame and mesh. These allow for the attachment of the two frame halves, securing the mesh fabric in place. An additional screw hole in the centre holds a cavity blocker piece to prevent sand from entering the central hole, ensuring even distribution of material and media. The frame and mesh are held together with 4 mm stainless steel screw and nut, allowing for tight sealing of the mould. This feature is crucial for holding the mesh in place and ensuring that the mould remains closed during the filling and casting process, avoiding any leakage of the sand-media mixture (Figure 5).

Mould fabrication

In these experiments, two types of polyester fabrics were used: a fine polyester mesh with openings smaller than 100 microns, ideal for retaining finer sand particles and ensuring detailed casting fidelity (supplied from *https://bestscreenprintingink.com/product/screen-printing-mesh-64t/)* and a polyester voile, selected for its larger opening mesh size (supplied from *https://www.amazon.co.uk Megachest wedding Voile Fabric 58 Inches Wide 50 meters long*). Both fabrics were tested to determine their impact on calcium carbonate deposition which influences the permeability, texture and extraction of the casting process.

The acrylic frames were designed in Rhinoceros 3D (version 7, McNeel, USA) and the files exported for fabrication in 3 mm acrylic sheets, that were laser cut by Cad Cam Technology FB 7100. The mesh fabrics were cut using an acrylic guide and a soldering iron (Tabiger) to melt the edges to prevent fraying. This method melts the edges, creating a clean, fray-resistant finish.

Optimisation for Water Kiln technique

This study explored 16 experimental conditions across multiple sets of biomineralisation trials, as summarised in Table 1. These experiments evaluated the effects of media amounts, composition and the effects of different urea and $CaCl_2$ concentrations ratio (0.3M vs. 0.5M), fabric mesh opening size, media cycles and sample extraction timing on the MICP process. Each condition was systematically varied to identify the optimal parameters for efficient biomineralisation and robust sample quality.

The cementation media consisted of a mixture of urea and calcium chloride ($CaCl_2$), with concentrations adjusted to either

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Table 1. Experimental overview

Ex. No.	Set no.	Replicates	Mesh opening	Growth time	Media cycles	Media volume	Urea	$CaCl_2$	NB	$MgCl_2$	Aeration	Flip	Extraction	Glazing
W1	**1**	3	88 microns	16–24 hours	5	1L	0.33M	0.33M	13 g/L	–	Constant	Daily	Dried in mould	–
	2	3	88 microns	16–24 hours	5	1L	0.5 M	0.5 M	13 g/L	–	Constant	Daily	Dried in mould	–
	3	3	88 microns	16–24 hours	2	1L	0.5 M	0.5 M	13 g/L	–	Constant	Daily	Dried in mould	–
	4	2	88 microns	24 hours	–	2L	0.5 M	0.5 M	–	0.5M	Constant	–	Dried in mould	–
	5	2	88 microns	4 hours	–	2L	0.5 M	0.5 M	–	0.5M	Constant	–	Dried in mould	–
	6	2	88 microns	24 hours	–	2L	0.5 M	0.5 M	–	–	Constant	–	Dried in mould	–
W2	**1**	3	88 microns	16–24 hours	5	2L	0.3 M	0.3 M	13 g/L	–	Constant	Daily	*Dried in mould*	–
	2	3	> 88 microns	16–24 hours	5	2L	0.3 M	0.3 M	13 g/L	–	Constant	Daily	*Dried in mould*	–
	3	3	> 88 microns	16–24 hours	–	2L	0.5 M	0.5 M	–	–	Constant	–	*Dried in mould*	–
	4	3	> 88 microns	16–24 hours	–	2L	0.5 M	0.5 M	–	0.5M	Constant	–	*Dried in mould*	–
W3	**1**	3	88 microns	16–24 hours	5	2L	0.3 M	0.3 M	13 g/L	–	Constant	Daily	Day 7 (wet)	–
	2	3	88 microns	16–24 hours	4	2L	0.3 M	0.3 M	13 g/L	–	Constant	Daily	Day 7 (wet)	–
	3	3	88 microns	16–24 hours	5	2L	0.3 M	0.3 M	13 g/L	–	Constant	–	Day 6 (wet)	2 days
	4	3	88 microns	16–24 hours	4	2L	0.3 M	0.3 M	13 g/L	–	Constant	–	Day 6 (wet)	2 days
W4	**1**	9	88 microns	20 hours	4	2L	0.3 M	0.3 M	13 g/L	–	Constant	Daily	Day 8 (wet)	0.3M – 1 day
	2	9	88 microns	20 hours	1	2L	0.5 M	0.5 M	–	–	Constant	–	Day 8 (wet)	0.3M – 1 day

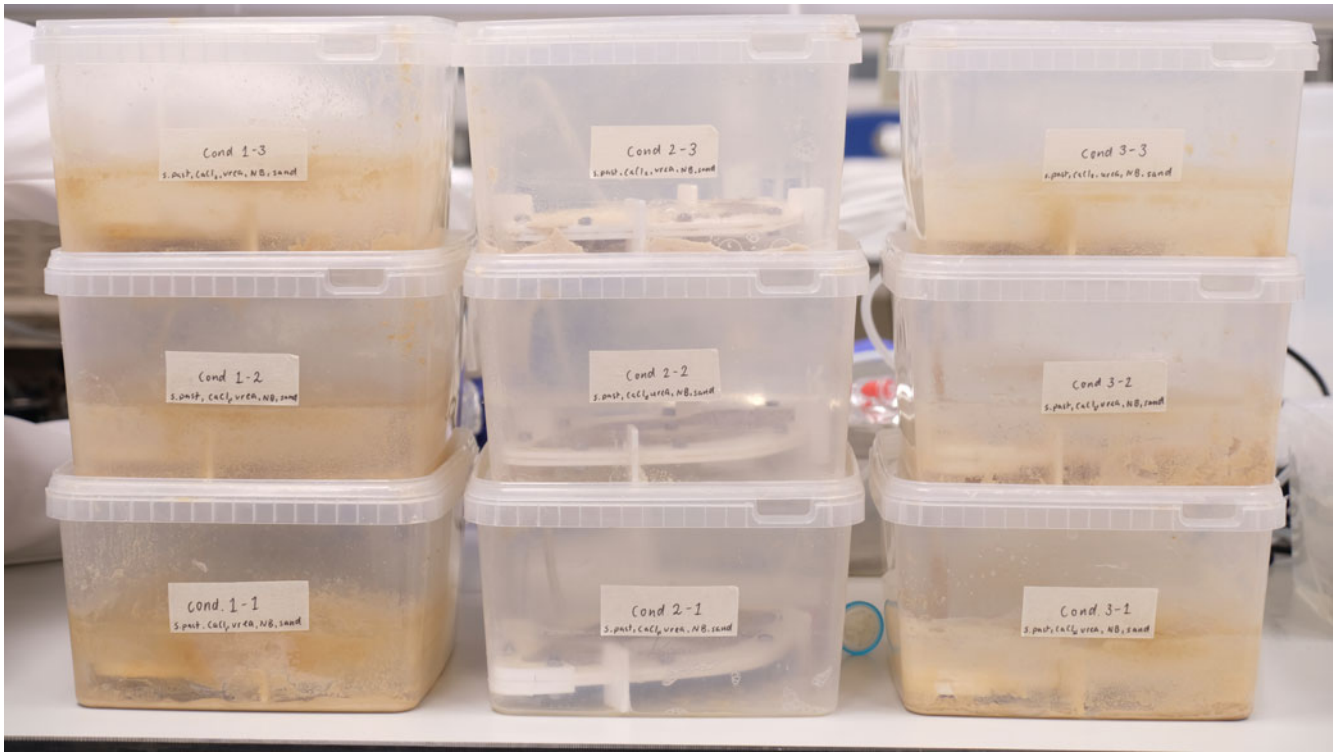


Figure 6. Water Kilns setup in the lab (W1) exploring 3 conditions.

0.3M or 0.5M for both chemicals depending on the experiment, with the addition of 13 g/L NB media and 0.5M magnesium chloride ($MgCl_2$) dissolved into deionised water. Each component was sterilised using filter sterilisation separately, besides NB, to prevent degradation and mixed depending on the experiment.

The impact of the frequency of the media change on the uptalking of $CaCl_2$ and sequential physical properties of the MICP were also investigated. As well as incorporating or excluding nutrient broth and $MgCl_2$ to determine their necessity and effectiveness in enhancing the MICP process and the quality of the final biocemented products.

Each experiment was conducted within a series of standard autoclavable plastic vessels (Figure 6) 185 mm x 185 mm by 78 mm height *SAC02 Microbox from Maya Mushrooms*, each covered with aluminium foil during the Water Kiln submersion.

Aeration was maintained consistently across all experiments, and moulds were flipped daily in certain trials to ensure uniform calcium carbonate deposition. In the first set of experiments (W1), the moulds were positioned just above the base of the container with laser-cut clips that the moulds were suspended in. Air was supplied to the box using an air pump *Uniclife Quiet Aquarium Pump*, a 5 mm outer diameter thick silicon air tube, connected to a filter with a pore size of 0.22 µm, was positioned into the vessel to provide oxygen and circulation of liquid media. In the later W2–W4 set of experiments, each mould was supported with an aeration stand and silicone tubing fastened within the stand see in Figure 7A. This feature raised the mould slightly above the base of the box, facilitating a better air circulation and distribution of media in the liquid beneath the mould.

Starting amount of cementation media was 1L per vessel (Figure 7B) then increased to 2L (Figure 7C). Exchange of media occurred in different treatment cycles ranging from none to five times during the experiments. Experiments ran for 7–8 days.

Different methods of extraction were explored that varied from immediate extraction from mould to allowing samples to dry within the mould (Figure 7D). Wet extraction was conducted at defined intervals (e.g., Day 6–8), while some samples underwent a glazing process to enhance surface durability.

'Glazing' was introduced which mimic the traditional ceramic glazing for the final touch of the cementation piece where samples were taken out earlier from the fabric mould. This step was investigated to enhance the surface characteristics and binding of the biocemented samples. For conditions involving glazing, the extracted samples were placed to a glazing solution which consisted of 0.3M urea and 0.3M $CaCI_2$ for 1–2 days. The introduction of a glazing step was aimed at exploring the potential for enhancing the structural and aesthetic qualities of the samples.

pH

Left over cementation media was measured for pH using a FE20 FiveEasy™ Benchtop pH meter (Mettler-Toledo, Leicester). The calibration of the electrode was performed using certified pH buffer solutions (precision = ±0.01 pH units). To avoid $CaCO_3$ precipitation occurring on electrode surfaces for samples containing $CaCl_2$, the electrode was washed in an acidic solution followed by 18.2 MΩ·cm H_2O between measurements.

Calcium uptake measurements

Left over cementation media (1 mL) was collected throughout the experiments and stored at −20 °C until further analysis to measure Ca^{2+}. The Patton-Reeder method (Patton and Reeder 1956) was used to measure Ca^{2+} concentration in left over cementation media, which indicates the concentration of $CaCO_3$ formed. Patton-Reeder indicator (10 mg) was dissolved in 0.1 mL of

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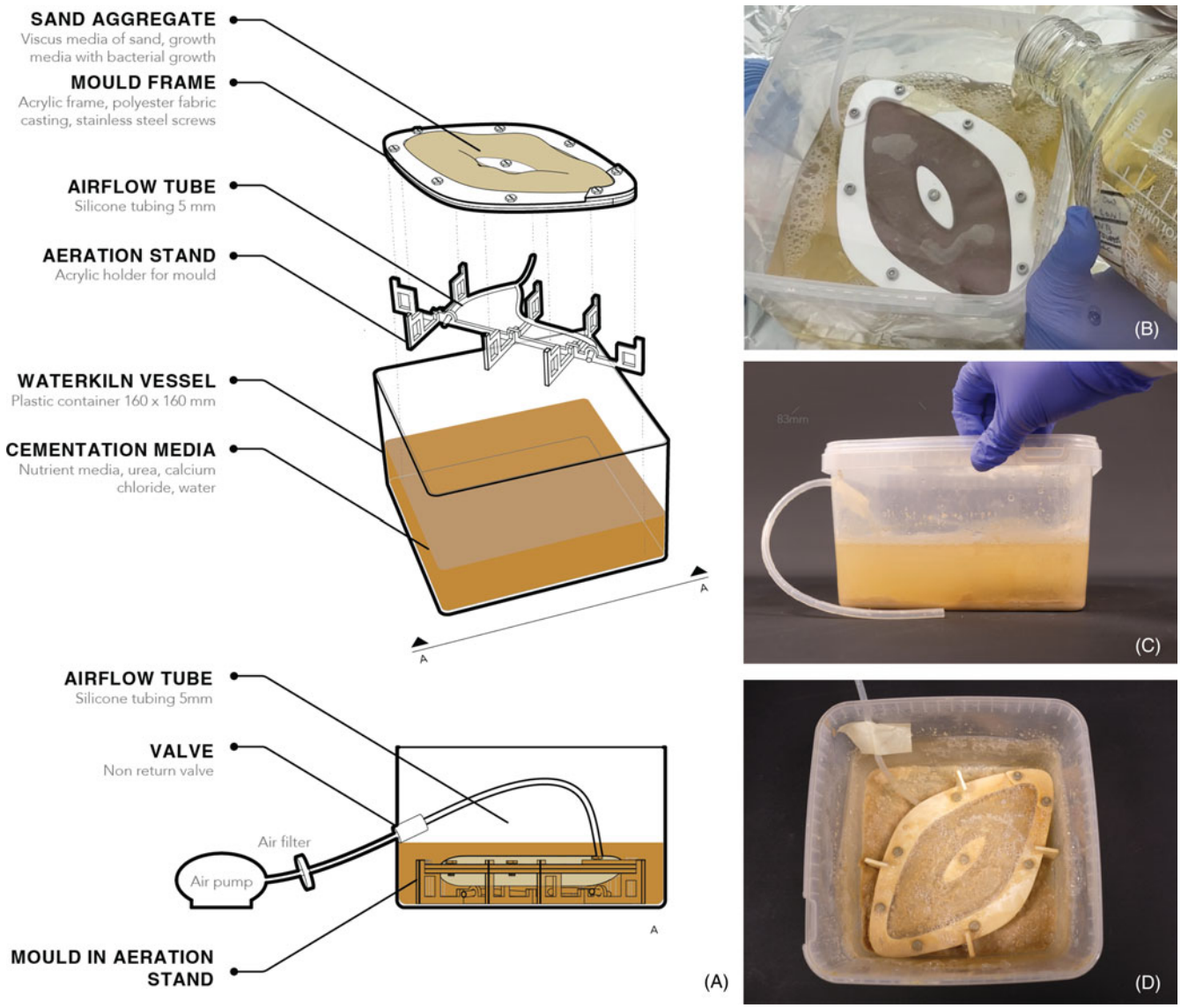


Figure 7. Water Kiln set up diagram (A). Moulds placed in container and liquid media poured in (B), before running for 7–8 days in Water Kiln method (C) and drained for extraction (D).

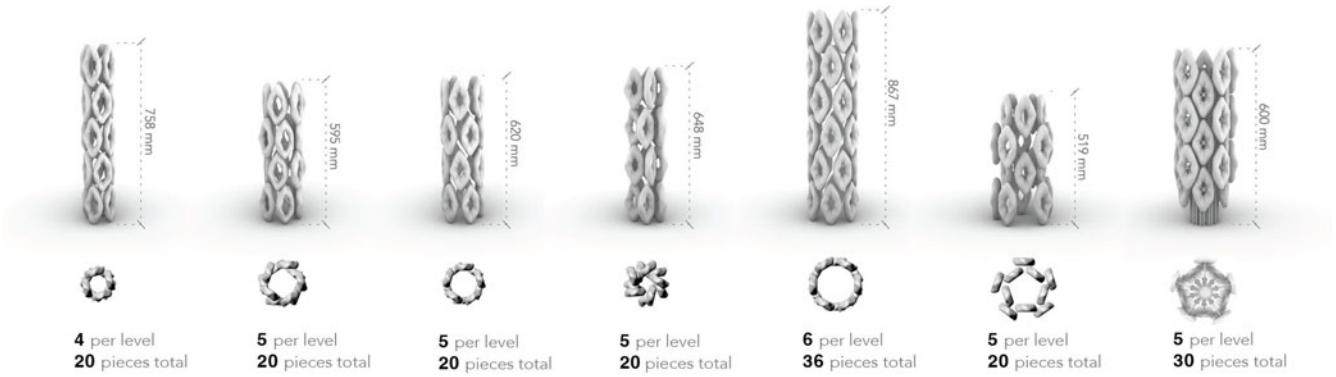


Figure 8. Development of column arrangement, height and number of pieces.

sample, 20 mL of 18.2 MΩ·cm H2O and 2 mL of 8 M NaOH. The Patton-Reeder indicator used consisted of a 1:100 ratio of calconcarboxylic acid and sodium sulfate. This solution was titrated with 0.6–5 mM EDTA until the colour changed from pink/red to blue. The concentration of calcium was calculated using the equation:

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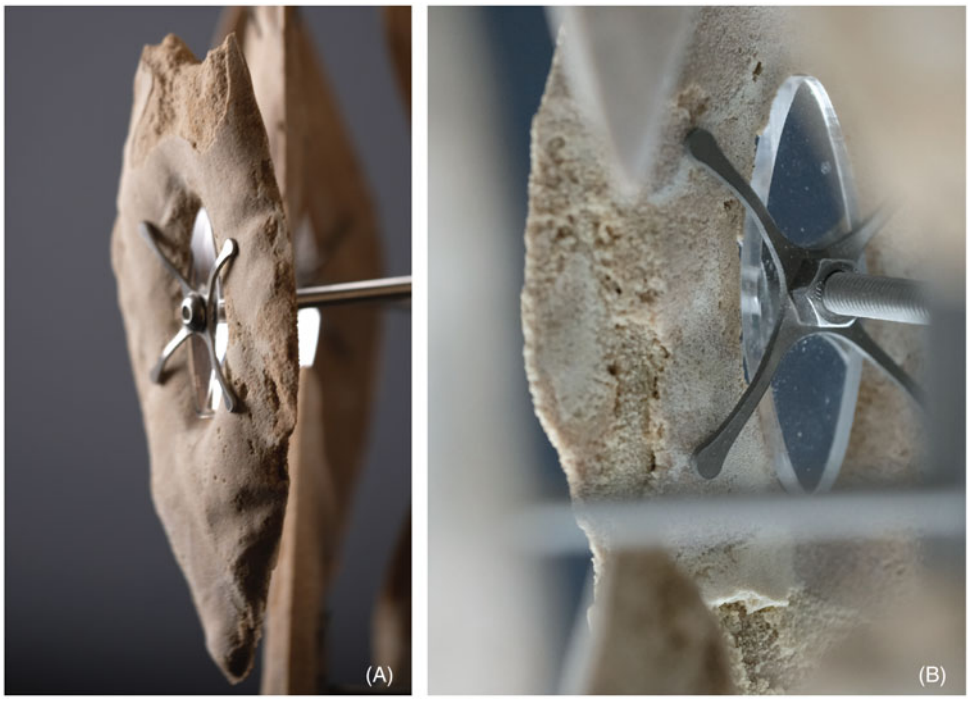


Figure 9. Bracket assembly securing a biomineralised piece: (A) Front bracket connected via a stainless-steel bolt passing through an acrylic spacer, and (B) back bracket fastened with a nut to hold the structure in place.

Calcium = final titre (mL) × sample volume (mL)/EDTA concentration

Cementation thickness evaluation

To evaluate the distribution and penetration of calcium carbonate precipitation within the samples, cementation thickness was systematically measured on samples that exhibited structural failures during the Water Kiln process or post-handling degradation. These measurements aimed to ascertain the uniformity and depth of biocementation across different experimental conditions. To measure the crust thickness, any loose sand was brushed away, and the remaining crust was measured using a digital calliper (Mitutoyo Absolute Digimatic). For each sample, up to eight points of reference were used across the samples. These included the two corner ends of the sample and additional four to six points evenly distributed around the central opening of the cast. This arrangement was chosen to cover both peripheral and central areas, providing a comprehensive profile of crust formation and its distribution.

EmbryOme design

The design of the *EmbryOme 1* project culminated in the fabrication of 30 robust biocemented pieces that were suspended and arranged into a modular scaffold system. It was designed with a layering strategy that aimed to emphasise the materiality of the cemented forms while reducing the visual presence of the aluminium frame. This interwoven arrangement created a denser, continuous surface, reinforcing the impression of a unified structure rather than an assembly of discrete components. The design of the column allowed for variations in the height, number and arrangement of the pieces, as shown in Figure 8. The overlapping configuration also helped accentuate the variations in surface texture across the pieces, bringing forward differences in colour, mineralisation texture and formation patterns.

To highlight the precision of the moulding process, each piece was fabricated with a defined inner and outer geometry. The inner geometry was strategically designed to accommodate support brackets, ensuring secure suspension within the scaffold. The brackets (Figure 9) were designed to adapt to the unique forms of each of the pieces, while embodying the conceptual tension between precision engineering and the organic unpredictability of their formation. Individually hand-bent into place, these brackets provide a minimal, gentle touch to secure the pieces, allowing the natural irregularities of the biological process to remain a central feature of the design. This highly engineered bracket system contrasts with the more organic and imprecise final castings.

The minimal design of the brackets ensures that the human intervention does not overshadow the natural characteristics and emergent qualities in the biomineralised forms. Instead, it highlights the mutual dependence between the engineered structures and biological processes.

The arrangement of the pieces use V-slot frames to suspend and align the pieces in a radial configuration (Figure 10A). This system provides a stable framework, enabling the pieces to be securely attached while allowing for flexibility in their placement and orientation. A key factor in achieving this flexibility was the adjustable fastening system. By using custom brackets that could slide within the V-slot frame, the system provided fine control over positioning, allowing pieces to be raised or lowered to optimise coverage and overall composition. This flexibility ensured that the final assembly remained adaptable, accommodating the natural variations in shape and mineralisation of each of the pieces. The top view of the design (Figure 10B) reveals a symmetrical radial pattern, highlighting the modularity and repetition of the biocemented elements. This arrangement emphasises the structural and visual cohesion of the column.

Overall structural design

The *EmbryOme 1* structure is made from the combination on microbially mineralised pieces and engineered supports. Each part

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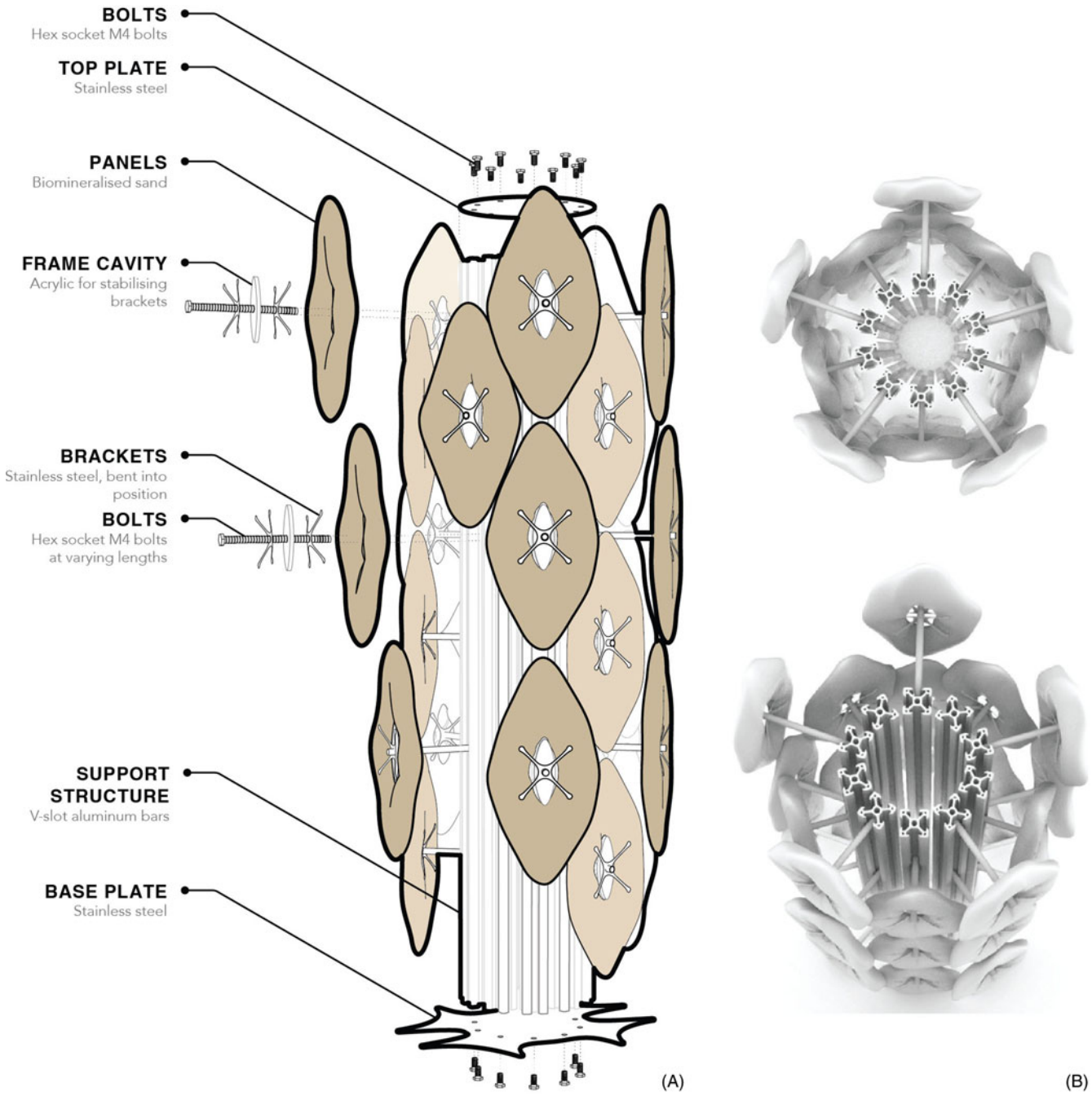


Figure 10. (A) Diagram of EmbryOme 1 structure, (B) renders of top views without top plate, showing arrangement of pieces into V-slot frames.

of the supporting structure was designed in Rhinoceros 3D (version 7, McNeel, USA) and the files exported for fabrication. The scaffold supporting the pieces is made of 20 × 20 mm v-slot aluminium profiles at 600 mm length, chosen for their robustness and versatility in modular construction. The pieces are held in place by two 1 mm thick stainless-steel brackets, fabricated using the ProtoMAX Waterjet cutter. These brackets are designed to accommodate the unique geometrical configuration of each of the biocemented pieces, ensuring secure attachment and uniform load distribution. Each piece is secured to the frame with M4 stainless steel bolts of interchanging lengths of 45 mm and 60 mm, strategically placed to highlight the varying cementation experimentation and variety. Acrylic frame cavity inserts are laser-cut with Cad Cam Technology FB 7100 to exact dimensions as the mould design cavities and form part of the bracket assembly. These provide central stability as well as a visual translucent interface between the metallic components and the biocemented pieces. The top and bottom of the frame are reinforced with 1 mm stainless steel plates, fabricated using the ProtoMAX Waterjet cutter, which serve as anchor points for the v-slots, ensuring that the vertical alignment is maintained throughout the structure. The top plate, in particular, is critical for maintaining the alignment and spacing of the pieces, while the bottom plate provides a solid foundation that distributes the weight evenly across the base of the assembly.

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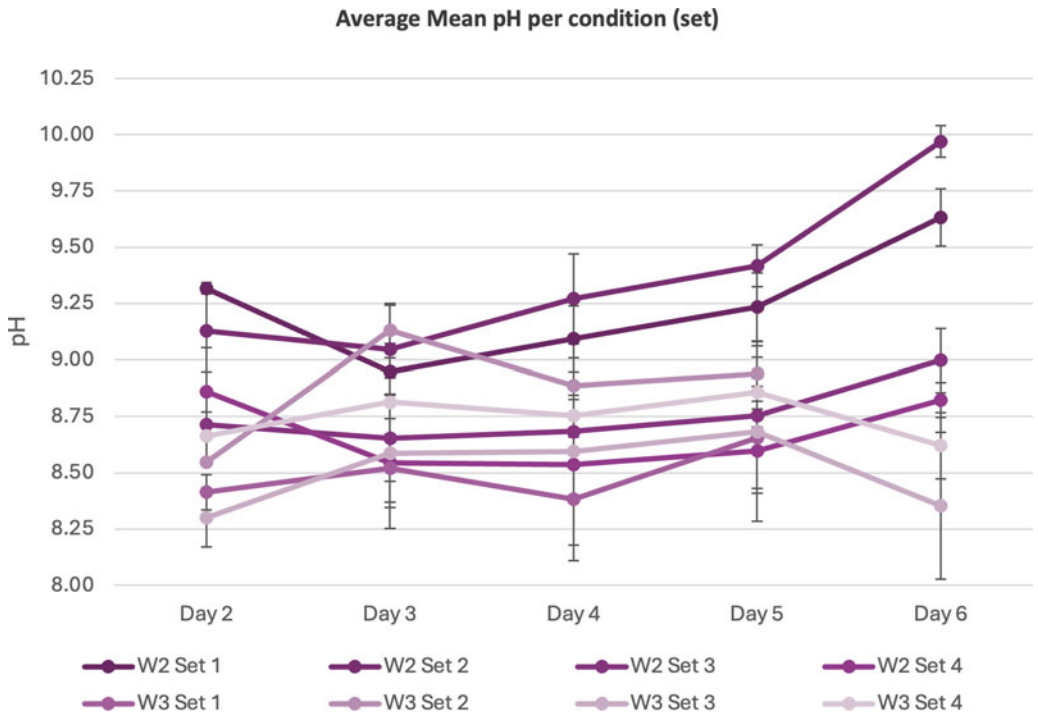


Figure 11. pH variation across W2 and W3 experimental sets over six days.

Results and discussion

In this research, we created sixteen different experimental setups, in replicates, to identify the most effective conditions. Variables included the concentration of the cementation solution, the frequency of medium replacement and the introduction of various additives to enhance protocol efficiency and maximise the cementation bond.

pH monitoring

Daily pH measurements over six days revealed clear distinctions between W2 and W3 experimental sets, with W2 maintaining consistently higher pH values throughout the experiment (Figure 11). Notably, W2 in sets 1 and 2 exhibited a steady increase in pH, suggesting sustained ureolytic activity and ongoing biomineralisation. In contrast, W3 sets displayed lower overall pH values, with set 3 showing the lowest pH by Day 6, indicating potential limitations in bacterial activity or reactant diffusion.

A trend observed in W2 was the influence of media cycling and nutrient composition on pH evolution. W2 sets 3 and 4, which did not receive media changes and lacked nutrient broth (NB), exhibited lower pH values. These conditions, which initially contained higher urea and $CaCl_2$ concentrations, may have led to rapid early shifts but a lower sustained pH, due to nutrient depletion or localised carbonate precipitation buffering the pH increase. These findings highlight the critical role of nutrient availability and media replenishment in maintaining optimal biomineralisation conditions, with higher pH values correlating to improved ureolytic activity and likely enhanced calcium carbonate precipitation.

Calcium ion monitoring

Calcium measurements were taken for experiment W1, W2 and W3. Results from W1 demonstrate that calcium was utilised much higher for condition in set 1 compared to conditions in set 4–6 (Figure 12A–D). This difference is due to the absence of nutrient broth in set 4–6, which evidences the importance of including nutrient broth in the cementation media. Similarly, calcium measurements taken for W2 show higher calcium utilisation for conditions in set 1–2 compared to in set 3–4 which again occurs due to the absence of nutrient broth in set 3–4 (Figure 12E–H). W3 calcium measurements show higher calcium utilisation for conditions in set 2 and 4 compared to set 1 and 3 (Figure 12J–L). These differences occur from the initial media change frequency, which is 1 day for set 1 and 3 and 3 days for set 2 and 4. The longer incubation in the initial media allows for bacteria to grow to higher numbers and promotes the survival and activity of the bacteria, which is important to induce $CaCO_3$ precipitation. Overall, calcium measurements show that the best conditions include nutrients for bacterial growth and survival, as well as sufficient incubation time in the initial media for bacterial growth.

Material homogeneity and coloration

A total of 57 biocemented samples were produced using the Water Kiln method. Out of these, 38 samples were deemed successful, while 19 were classified as unsuccessful. Among the unsuccessful samples, 8 pieces either failed to cement entirely or formed bonds that were too fragile to handle. These fragile or uncemented pieces were primarily observed in W1 (sets 5.1 and 5.2) and W2 (sets 3.1, 3.2, 3.3, 4.1, 4.2 and 4.3). These samples also exhibited a darker colour compared to the successful ones, indicating potential inconsistencies in the biomineralisation process.

The remaining broken pieces resulted from issues during the extraction process. Some pieces experienced breakage, particularly at the ends, likely due to excessive force applied while removing them from the fabric mesh. This highlights the importance of careful handling during extraction to preserve the integrity of the biomineralised samples.

The unsuccessful sets in W1 (5.1, 5.2), W2 (3.1–3.3, 4.1–4.3) and W4 (2.5) highlighted several key factors affecting the integrity

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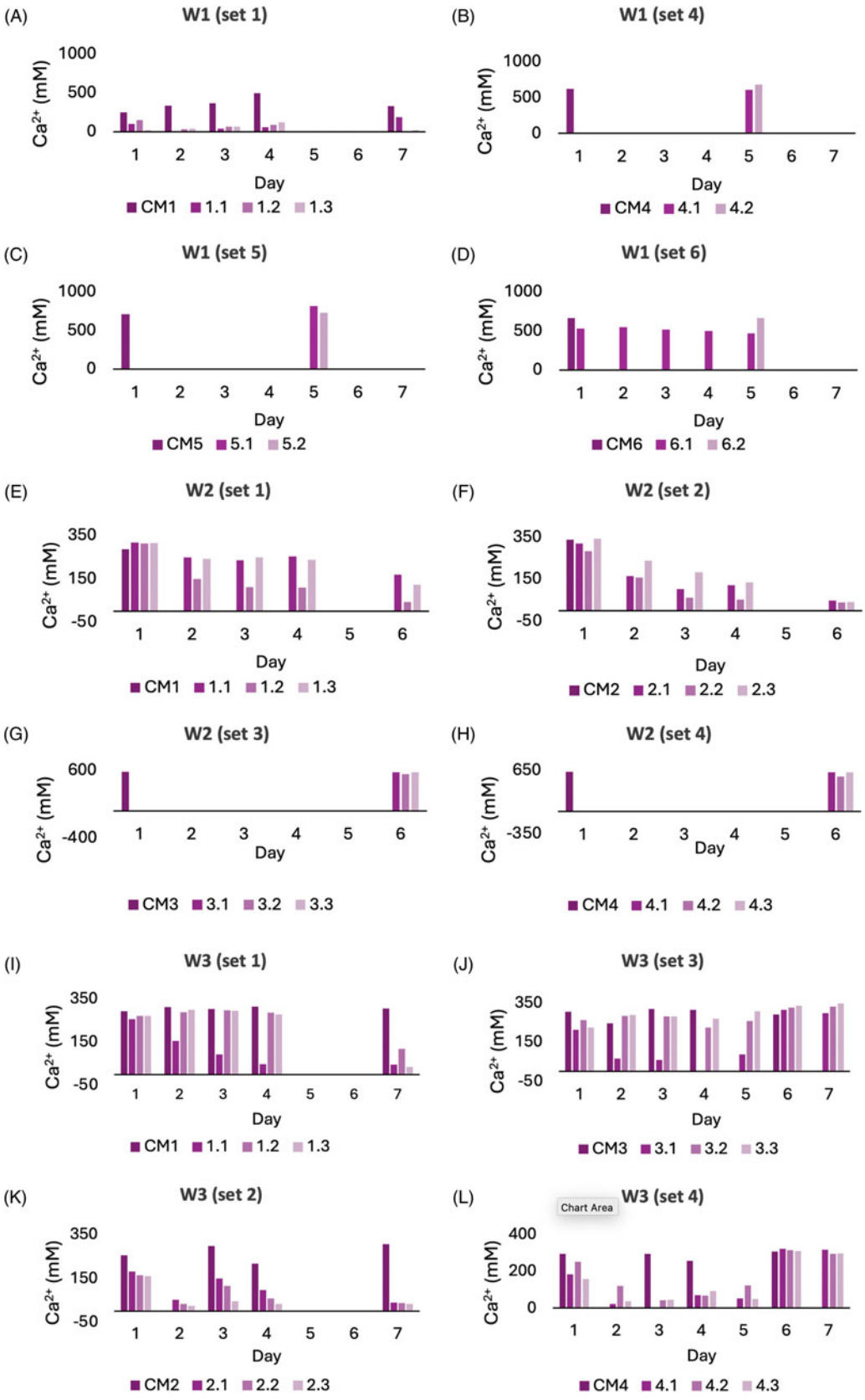


Figure 12. Utilisation of calcium chloride for W1. (A) set 1. (B) set 4. (C) set 5. (D) Set 6. Utilisation of calcium chloride for W2. (E) set 1. (F) set 2. (G) set 3. (H) set 4. Utilisation of calcium chloride for W3. (I) set 1. (J) set 2. (K) set 3. (L) set 4. CM represents the cementation media control in all samples.

of the samples. The absence of daily mould flipping likely caused uneven nutrient and cementation media distribution, which contributed to inconsistent mineralisation. Additionally, the lack of media replenishment limited the availability of nutrients and calcium ions, further restricting uniform calcium carbonate deposition and resulting in weaker sample bonds.

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Figure 13. Photo overview of results across different experimental setups (see Table 1 for details). 'W' represents Water Kiln setup with numbers indicating replicates in that setup with within the different conditions, i.e., W1 1.3 representing Water Kiln setup 1 and the 3rd replicate of condition/set 1.
* Colour variation in W4 appear lighter in colour due to photography setting.

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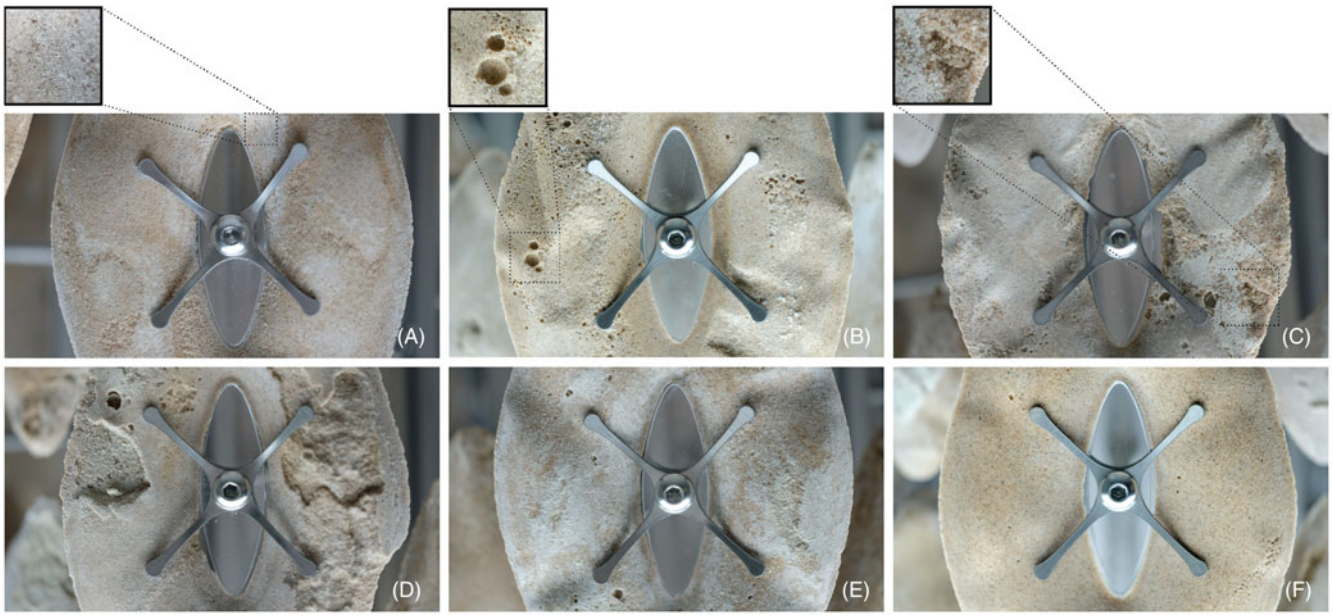


Figure 14. The variations in the biomineralisation of the pieces seen in (A) where a mesh pattern is cemented into the outer layer, (B) trapped air appear as bubbles, (C) lack of crust causing friability, (D) missing parts as the crust cemented into the fabric, (E) patches of calcite deposits and (F) homogonous cementation and smooth surface.



Figure 15. Crystal precipitation forming on top of the mesh in (A) experiment W1 set 1.1 (top) and 2.3 (bottom). Growing crystal morphology after 1 day in W1 set 3.3 (left) and after 2-3 days in sample W1 set 1.2 on right. Extracting W1 1.2 piece (C) out of the mesh by hand.

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Figure 16. Photograph of more crystalline area of the piece (A), and observation of crystal spheres with 1.0x higher magnification lense (Fujifilm XF 80mm f2.8 LM OIS WR) (B).

Variations in the presence or absence of $MgCl_2$ appeared to influence calcium carbonate deposition, suggesting that this component may play a role in modulating the biomineralisation process.

The examination of each of the pieces created through MICP in submerged conditions yielded significant insights into the effects of varying experimental conditions (Figure 13). These results highlight the critical role of environmental controls and formulation strategies in achieving desired biocementation outcomes. Initial observations indicated significant variations in the texture and structural integrity of the pieces. In experiments where higher concentrations of $CaCl_2$ were used (in experiments number: W1 (set 2,3,4,5,6), W2 (set 3,4) and W4 (set 2)), pieces exhibited a denser and more crystalline surface, enhancing their aesthetic appeal and surface durability (Figure 14). However, these conditions also resulted in increased rigidity, which complicated the extraction process from the moulds due to the enhanced adherence of the biocemented sand to the mesh fabric.

The pieces subjected to conditions with NB consistently showed more effective cementation, as evidenced by denser and more uniformly distributed calcium carbonate formations. This was particularly visible in setups where NB was included (in experiments number: W1 (set 1,2,3), W2 (set 1,2), W3 and W4 (set 1)), highlighting its importance in supporting bacterial activity and calcium carbonate deposition. Conversely, samples without NB were easier to extract but showed less durability and a higher propensity for surface abrasions and irregularities, underscoring the necessity of nutrients in sustaining microbial life and activity.

The addition of $MgCl_2$, contrary to findings by Horn et al.. (2023), did not seem to enhance biomineralisation in the experimental conditions tested, suggesting that its efficacy may be dependent on specific environmental conditions or bacterial OD. Samples with $MgCl_2$ appeared brittle and not well cemented externally.

The air scaffold design prevented the formation of air pockets with inconsistent calcium carbonate precipitation, which appeared to lead to uneven biocementation as seen in samples W1 (set 2.1 and 2.3). To accommodate the elevated position of the moulds within the scaffold, the volume of the nutrient broth-based cementation media was increased from 1 litre to 2 litres per container.

Extraction

The moulds were extracted from the Water Kilns at varying times, as summarised in Table 1, with extraction occurring between **Day 6 and Day 8**, depending on the experimental setup. Before disassembling the frame, it was necessary to remove excess crust formations from the mould (Figure 15A). These crusts, primarily composed of calcium carbonate precipitates, bonded strongly to the fabric mesh and frame, particularly after prolonged exposure to the cementation media. Samples were carefully removed by hand to minimise potential damage (Figure 15C). However, an excessive amount of calcium carbonate precipitation frequently occurred on the mesh and the acrylic frame during the cementation process, presenting challenges in achieving clean and intact extractions.

The morphology of these crusts varied with the experimental timeline and conditions. Finer crystal structures were typically observed after one day of exposure (Figure 15B, left), while larger, more developed crystals formed after 2–3 days (Figure 15B, right). Overall, where there were less developed crusts, it was easier to detach from the mesh, resulting in cleaner extractions. In contrast, thicker crusts required additional care during removal, as the bond between the crystals and the mesh fabric was significantly stronger. This was observed in W2 samples, where a larger mesh grid size >88 micron was used, which appeared to exacerbate the integration of the crust into the sample.

Extraction of the cast pieces presented practical challenges, highlighting opportunities for future improvement. These could include mesh designs with larger openings or alternative textures to reduce adhesion, the use of sacrificial or flexible moulds and integration of 3D-printed biodegradable components (Pakkanen et al. 2017), to enhance scalability and accommodate more complex geometries.

Glazing

Pieces subjected to glazing treatments (W3 and W4) exhibited a crystalline texture (Figure 16) more uniform appearance, suggesting a more hardened or mineralised surface finish. This was particularly evident in the setup, where a notable sheen on the pieces highlighted the effectiveness of the glazing process in the material making.

Experiments W3 and W4 that allowed pieces to be extracted while still wet from the Water Kiln showed a marked improvement in the ease of handling and overall quality of the pieces. This method helped mitigate the challenges associated with crust formation, which had previously led to difficulties during extraction and potential damage to the structure of the pieces.

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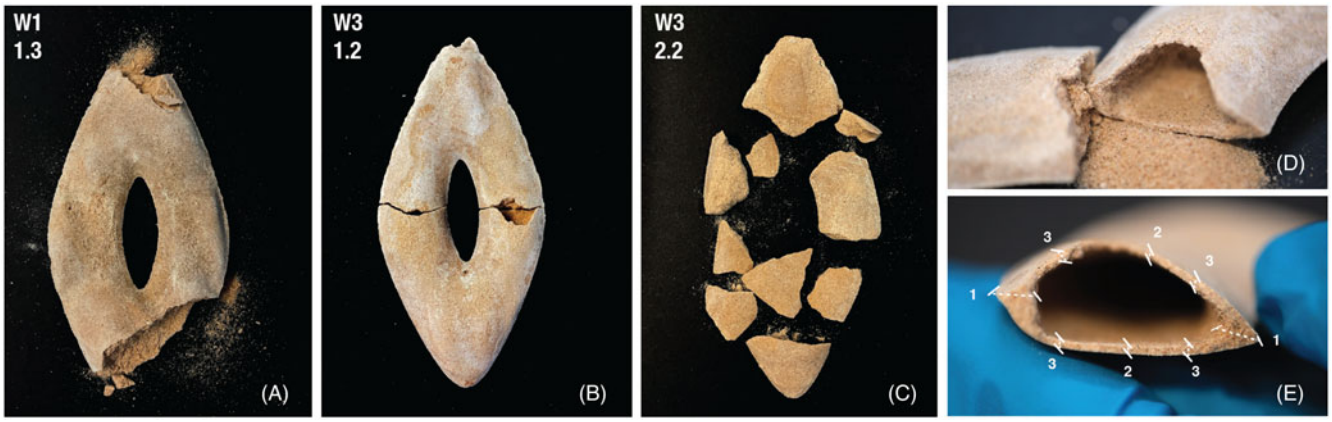


Figure 17. The examined samples that exhibited failure post-assembly. Highlighting details top and bottom fragmentation of a piece (A), a piece bisected (B) and a piece fragmented into multiple parts (C). Loose sand was removed to better assess the crust (D), and sectional measurements were recorded from fragments at corner (E-1), centres (E-2) and sides (E-3) points.

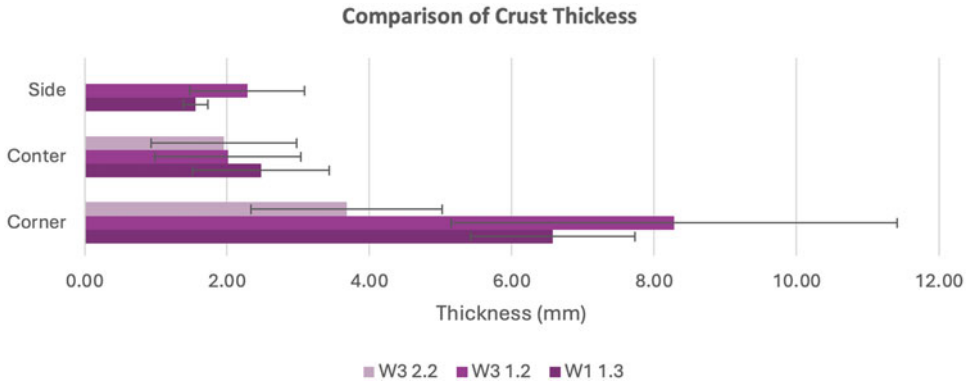


Figure 18. A comparative analysis of the three pieces that sustained damage, highlighting differences in crust thickness and structural integrity across the varying experimental conditions.

Cementation thickness

Through three biocemented pieces, W1 set 1.3, W3 set 1.2 and W3 set 2.2, we analysed the crust thickness and structural integrity (Figure 17) and present the results in a statistical analysis (Figure 18) that was performed to compare the mean crust thickness between the pieces. Over time, signs of structural deterioration were observed, suggesting variability in mineralisation stability and effectiveness across these samples. W1 set 1.3 showed consistency in thickness with lower variability. This piece remained structurally intact longer than the other two pieces, suggesting a more uniform biomineralisation process compared to W3 set 1.2 and W3 set 2.2 which showed higher variability in the crust formation. W3 set 1.2, which underwent five media changes, showed greater variability in crust thickness, especially at the corners, suggesting uneven cementation. W3 set 2.2, with four media changes, presented a generally thinner and more uniform crust across all measured points, which translated into a worse structural integrity.

In general, the pieces may have been subject to various stresses in its handling and fitting to the column, which could have affected the stability of the mineralisation. The mean thickness indicated that the corners generally have a significantly thicker crust compared to the centre and sides of the pieces. This might suggest a greater access to aeration and cementation media leading to better cementation conditions at the corners.

None of the samples achieved complete biocementation throughout the sand aggregate as the mineralisation was only observed within a few millimetres from the surface. A similar observation has been reported in other studies, where cementation depths were limited to 1–1.8 mm (Dutto et al. 2025), likely due to the formation of a dense carbonate skin that inhibited further ion diffusion. From a structural perspective, these results indicate that the current process would not be viable for direct load-bearing architectural applications due to insufficient cementation depth and overall material fragility. However, observations from Figure 17E highlight a new potential fabrication strategy, casting a pre-defined mineral shell. This approach could lead to novel composite material strategies where biomineralisation contributes to surface durability while an embedded material provides internal filling supporting the outer cemented shell.

Conclusion

EmbryOme 1 leverages biological processes and design intention to highlight the critical role of the designer in mediating biological and material behaviours, demonstrating how thoughtful interventions in material and fabrication parameters can influence process outcomes. The project emphasises the potential of combining biological processes with innovative design strategies to expand the possibilities of form-making and scalability in

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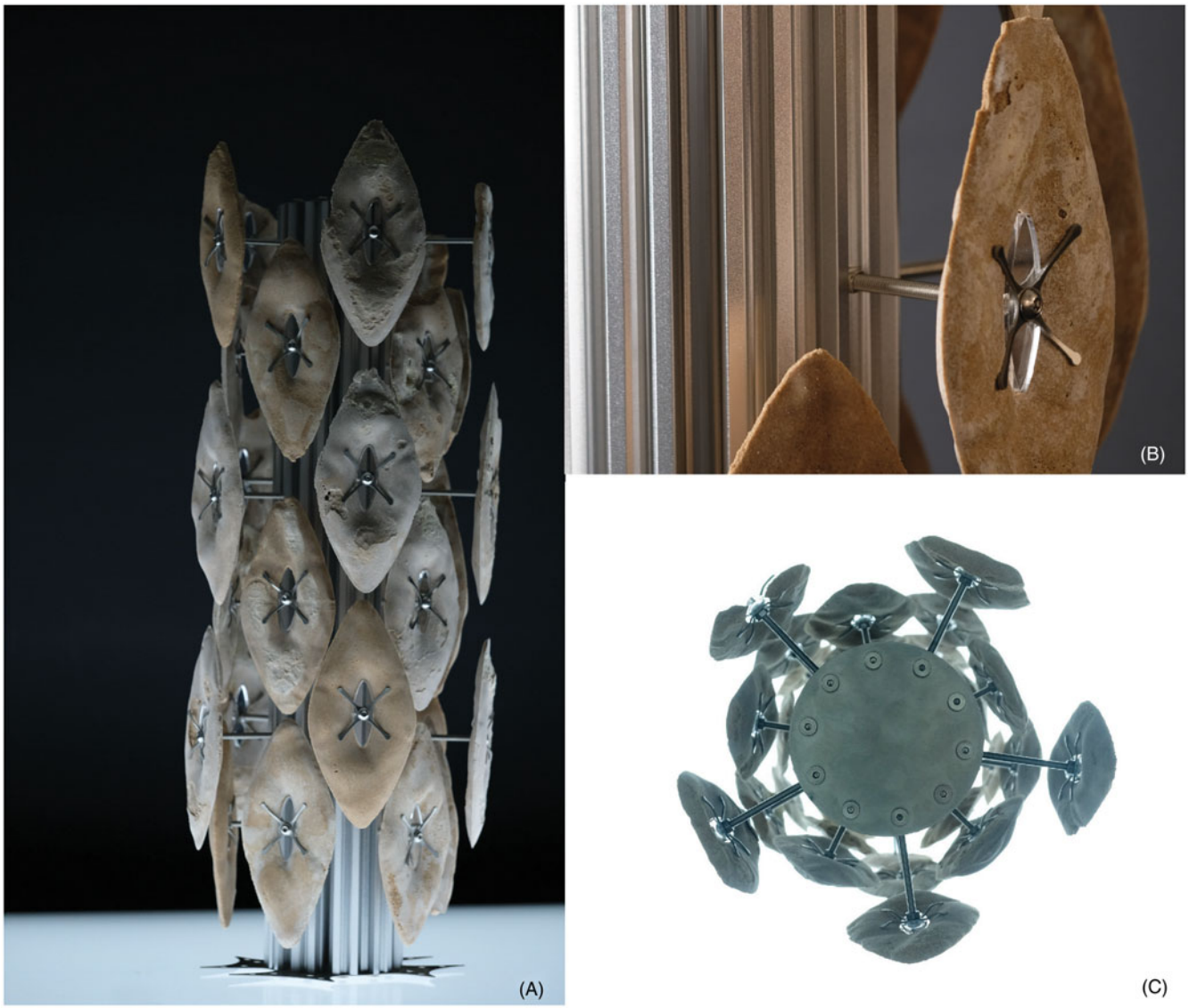


Figure 19. EmbryOme 1 column assembled. Biomineralised pieces covering the aluminium frame (A), bolted and suspended in the v-slot structure (B). Top view (C) showing the undulating distribution pattern of the pieces.

architectural applications. By designing the setup of the *Water Kiln* and the mould in this way, the project aligns the physical requirements of MICP with scalable and more accessible fabrication processes.

From the trials across these experimental conditions, several key parameters emerged as critical to a successful submerged fabrication method with biomineralisation. Early evidence suggest that calcium ion depletion and elevated pH levels may serve as useful indicators for assessing the success of biomineralisation in the submerged fabrication. The most effective formation occurred under 0.3 M calcium chloride and urea concentrations when combined with nutrient broth and media replacement every 24 hours. Consistent aeration and smaller mesh sizes supported more uniform and denser outer mineral layers. Conversely, the absence of nutrients or media cycling led to poor calcium uptake and brittle or friable outcomes.

While cementation remained largely superficial, conditions involving glazing enhanced surface hardness and texture uniformity, pointing toward the possibility of multi-phase mineral treatments. These findings suggest that biofabrication outcomes are not merely biologically determined but are the result of careful design and parameter orchestration, a process where form, materiality and microbial behaviour are co-authored. The aesthetic that emerges from the process, with imperfections in colour and texture the result of the complex interplay between many sensitive variables in the making process.

The biocemented pieces are arranged to form a seamless flow of interconnected elements, showcasing the organic yet structured potential of the MICP fabrication process. The design balances functionality with a strong visual statement, illustrating how biological processes can inform architectural aesthetics (Figure 19). The resulting structure symbolises the synergy between human engineering ingenuity and nature's resilience, leading to functional and expressive forms deeply rooted in the process of their biological fabrication. It also demonstrates how designers can be embedded in the material innovation process at an early stage, collaborating with scientists around tangible objects and developing new craft processes.

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This study did not produce fully structural materials; rather, it established a conceptual framework of formation finding, a multi-scalar process in which microbial activity, granular substrate and formwork constraints co-produced both macro form and microstructure. The Water Kiln method demonstrated the potential of this approach, producing biocemented pieces with varying degrees of structural integrity, while revealing opportunities to refine fabrication control, enhance predictability and integrate biological processes within architectural tolerances. Formation finding offers a bridge between design experimentation and biological fabrication, treating variability and material agency as productive forces in shaping new modes of making with living systems.

Data availability statement. Data availability is not applicable to this article as no new data were created or analysed in this study.

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Crystal Wang: Conceptualisation, Methodology, Investigation, Data Curation, Visualisation

Jamie Haystead: Data Curation, Validation, Formal Analysis, Writing – Review & Editing

Soley Sara Eiriksdottir: Investigation, Data Curation

Martyn Dade-Robertson: Conceptualisation, Methodology, Resources, Supervision, Writing – Review & Editing

Meng Zhang: Methodology, Resources, Supervision, Writing – Review & Editing

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