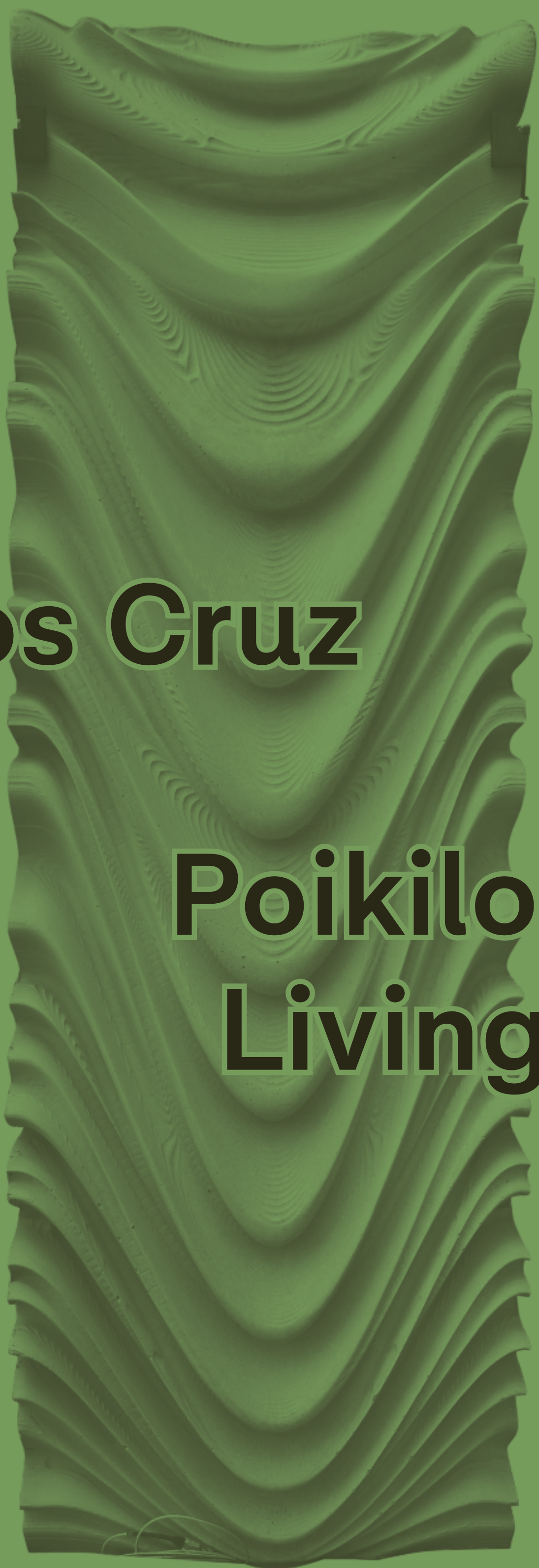
Bartlett Design Research Folios



Marcos Cruz

Poikilohydric Living Walls

BARTLETT DESIGN RESEARCH FOLIOS

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Poikilohydric Living Walls


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1 (previous) 18 MPC and OPC bioreceptive panels exposed in an outdoor trial, The Bartlett, UCL, 2016.

2 Poikilohydric living wall made for the exhibition, *La Fabrique du Vivant,* Centre Pompidou, Paris, 2019.

Project Details

Author	Marcos Cruz
Title	Poikilohydric Living Walls
Output Type	Design and built living walls
Research Dates	2014 to 2020
Phases and Practical Completion	1. EPSRC funding (2017) 2. St Anne's Catholic Primary School, London (August 2020); East Putney Underground Station, London (December 2020) 3. Merchiston Park, Edinburgh (December 2020)
Co-Researchers	Richard Beckett, Sandra Manso Blanco, Brenda Parker
Co-Investigator EPSRC Grant	Bill Watts
Research Associates	Chris Leung, Anete Salmane
Technical Assistants and	Nina Jotanovic (Merchiston Park), Javier Ruiz Computational Development
Research Assistants	Alexandra Lacatusu, Giovanna Lanius-Pascuzzi, Nina Jotanovic, Sarah Lever, Rushi Metha
Structural Engineering	Laing O'Rourke; Tim Lucas (EPSRC grant), Manja van der Worp (East Putney, St Anne's, Merchiston Park)
Architect	Andy Shaw (Merchiston Park)
CNC Milling	William Victor Camilleri, Alex McCann
Construction	Parker Steel (EPSRC grant)
Manufacturing of Panels	Pennine Stone Ltd, The Bartlett Manufacturing and Design Exchange (B-Made)
Academic Partnerships	Antonio Aguado de Ceo, Lurdes Belgas, Fernando Branco
Biological Studies	UCL Bio-Integrated Design, UCL Department of Biochemical Engineering

Material Studies	Amorim Cork Composites, Instituto Politécnico de Tomar, Universidade de Coimbra (Corkcrete); UCL Department of Civil, Environmental and Geomatic Engineering (Porous TecCast); Universitat Politècnica de Catalunya (MPC)
Wall Construction	Skanska (East Putney Underground Station); Solid Brickworks (St Anne's)
Legal Team	James McGilvray, UCL Innovation & Enterprise; June Campbell, UCL Insurance
EPSRC Advisory Board	Peter Bishop, Paolo Bombelli, Marc-Oliver Coppens, Johanna Gibbons, Elinor Huggett, Marco Lizzul, Andrew Minson, Mark Miodownik, Alan Penn, Stephen Ridell, Richard Sabin, Peter Scully, Nima Shokri
Sponsorship	Camley Street Natural Park/London Wildlife Trust, London Borough of Lambeth, Meanwhile Gardens/London Wildlife Trust, St Anne's Catholic Primary School, Transport for London (TfL)
Budget	£458,848.78
Funding	£7,997.80 Bartlett Faculty BDEF; £21,538.98 The Bartlett Architecture Research Fund (ARF); £299,972 Engineering and Physical Sciences Research Council (EPSRC) EP/N010108/1; £3,750 Erasmus; £13,625 Lambeth Council; £50,000 Pennine Stone Ltd; £61,965 TfL

Statement about the Research Content and Process

Description

Poikilohydric Living Walls responds to the urgency of the climate crisis by exploring ways to increase vegetative growth on architecture and improve the environmental quality of cities. It promotes the use of self-regulated biological systems on building façades and urban infrastructures by integrating poikilohydric species – algae, moss, lichen, etc. – that can switch their photosynthetic activity on and off without the need for additional irrigation and maintenance. Bioreceptive cementitious materials and novel fabrication processes were rigorously tested, to increase water absorption and retention in order to form bio-material substrata that feed this new type of living wall.

Questions

1. Can we create poikilohydric-responsive architecture by designing bioreceptive walls that promote the growth of microorganisms and cryptogams?

2. Which material scaffolds and substrates promote the biocolonisation of vertical surfaces?

3. Can bioreceptive façades be manufactured in a structurally sound and cost-efficient way, aiming for future widespread application in the built environment?

4. Can poikilohydric living walls create a new aesthetic that appeals to the general public?

Methodology

This six-year research project has advanced through three phases of design, material exploration (MPC, Porous TecCast, Corkcrete) and application (EPSRC-funded study, St Anne's, East Putney, Merchiston Park). Qualitative and quantitative results have been achieved via long-term indoor and outdoor observational studies of components and panels, multiple substrate and material tests, and bacteriological and plant growth in the lab. The commercial viability of these components has been developed in collaboration with industrial partners.

Dissemination

The 2015 Ecobuild fair provided an early opportunity to exhibit the research to a wide audience. It has since featured in 15 architecture journals, e.g. *Architectural Research Quarterly*, and in national newspapers such as *The Sunday Times*. It has been discussed in exhibition catalogues for the Cooper Hewitt in New York and the Centre Pompidou in Paris. Cruz has been interviewed on *BBC Earth* and *LBC Radio*. Long-term dissemination will be via built walls in the public realm.

Project Highlights

This research project is the first significant long-term investigation to establish the viability of poikilohydric living walls as a cost-efficient and appealing option for greening cities. It has consequently been cited by *The Sunday Times* as one of '11 great ideas from British universities that could change the world' (Kinchen and Forster 2020), see pp. 146–9.

Introduction

The most important concept that underpins this research is the phenomenon of ‘poikilohydry’, which defines the aptitude of certain plant species for long-term survival. The unique structural and physiological capacity of algae, moss and lichen enables them to resist lengthy drought periods and extreme temperatures. These species rehydrate by absorbing rainwater, vapour and dew, and switch on and off in a self-regulated manner. Cruz defines ‘poikilohydric design’ as a way to promote the growth of poikilohydric species on building surfaces without the need for additional irrigation and maintenance. To increase photosynthetic activity, material substrates were designed with specific surface morphologies that retain water for prolonged periods of time.

The research aims to develop designs for ageing buildings. Externally facing surfaces become biocolonised via exposure to climatic and biochemical factors, depending on the roughness of materials used and the intensity of particle depositions that trigger a biological succession. Bacteria, cyanobacteria, algae, mould, bryophytes, etc. gradually stain façades and make them look ‘old’. But rather than implying a sense of neglect and decay, biocolonised surfaces are alive and active contributors to the environment.

The research focused on material and morphological testing to evaluate the most suitable environment for poikilohydric plants to proliferate. This was done in three phases.

Phase One: EPSRC Funding

This 18-month research period departed from the investigations of Sandra Manso Blanco on bioreceptive MPC concrete and also a patent from the UPC in Barcelona, scaling up for the first time small samples to a building scale **(1)**. This was followed by an outdoor environmental trial in which two types of concrete panels – Magnesium Phosphate Concrete (MPC) and Ordinary Portland Cement (OPC) – were compared, while testing water run-off and thermal variability through a full annual cycle.

Phase Two: St Anne’s Catholic Primary School and East Putney Underground Station, London

This three-year phase focused on the design of two living walls. A new material mix was developed, Porous TecCast, based on an existing recipe by Pennine Stone but with better porosity. New designs and transplantation protocols were explored, which resulted in the construction of a wall for an exhibition at the Centre Pompidou, Paris. Following this, 32 panels were created for St Anne’s Catholic Primary School and 20 for East Putney Underground Station.

Phase Three: Merchiston Park, Edinburgh

This two-year phase focused on the development of a third living wall **(4)**, based on a new composite, Corkcrete, that was developed with academic partners in Portugal. Corkcrete is a mix of OPC and cork aggregates, the latter of which increases bioreceptivity. Testing was conducted for a variety of mixtures that retain more water and promote growth. Different moss types and additional organic substrates were also explored, as well as new design patterns.

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3 Poikilohydric living wall at St Anne's Catholic Primary School, London.

4 Rendering of poikilohydric living walls for Merchiston Park, Edinburgh.

Aims and Objectives

Poikilohydric Living Walls investigates ways to increase biological growth on building façades and urban infrastructures.
It responds to the urgency of the climate crisis by improving the environmental and aesthetic quality of our cities. It aims to:

1. Increase vertical greening in cities, creating new sustainable solutions to improve the environment and levels of urban wellbeing;

2. Design, fabricate and test living walls as an alternative to existing bolt-on vegetative façade systems;

3. Create new bioreceptive concrete composites that stimulate the proliferation of poikilohydric species without additional mechanical irrigation and maintenance;

4. Improve panel performance by increasing water retention to promote biocolonisation on building façades;

5. Combine interdisciplinary processes of computational design and material testing with advanced workflows to create knowledge for future commercial products;

6. Materialise the novel concept of an 'architectural bark': a layered biocolonised building façade that allows patchy growth to integrate with designed geometries.

Questions

1. Can we create poikilohydric-responsive architecture by designing bioreceptive walls that promote the growth of microorganisms and cryptogams?

A main aim of the research is to make environmentally responsive buildings that can switch on or off the photosynthetic activity of microorganisms and cryptogams – plants that use spores rather than seeds to propagate – on their façades, depending on rainfall and moisture levels in the air. Specific morphological surface patterns were designed and the porosity of bioreceptive materials was calibrated, allowing for increased absorption and retention to promote selected growth in certain areas of the façade.

2. Which material scaffolds and substrates promote the biocolonisation of vertical surfaces?

To promote biological growth, living walls require the complementary performance of material scaffolds and substrates. Porous materials act as scaffolds, creating a structural framework on which plants and substrates are fixed and moisture is retained. Organic substrates work as nutrient providers for the microbiota of small-scale plants to thrive. Most poikilohydric species are epiphytic, with rhizoids (proto roots) that need rough surface materials to hook onto. These species require small layers of organic matter from which they can feed. Substrates on building façades are commonly composed of dust and organic matter (mostly cyanobacteria and dead algae). In the first two phases, the research identified MPC and Porous TecCast composites as potential


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5 MPC panel with transplanted moss, *Cooper Hewitt Design Triennial*, New York, 2019.

structural scaffolds onto which substrates can accumulate. In the final phase, Corkcrete was developed to act as both scaffold and substrate.

3. Can bioreceptive façades be manufactured in a structurally sound and cost-efficient way, aiming for future widespread application in the built environment?

For the St Anne's and East Putney projects, a novel Porous TecCast system was developed that used glass-fibre reinforcement **(6)** Instead of expensive rubber moulds, CNC-milled polyurethane foam boards were used for the East Putney project, which allow for a higher degree of design variability and cost-efficiency.

4. Can poikilohydric living walls create a new aesthetic that appeals to the general public?

This research has been exhibited and published widely. The designed and manufactured panels have been acknowledged as 'ornamental' (Bufi 2019), 'attractive' (Hiesinger et al. 2019), 'elegant' (Coyne 2018), 'combin[ing] ecological, structural and aesthetic qualities' (Brayer and Zeitoun 2019), '[are] smart… more sustainable and beautiful' (Pagliacolo 2018) and 'enhance building aesthetics' (Thornton 2016). 150 visitor questionnaires were completed at Ecobuild in London that confirmed the strong visual and material appeal of the panels.

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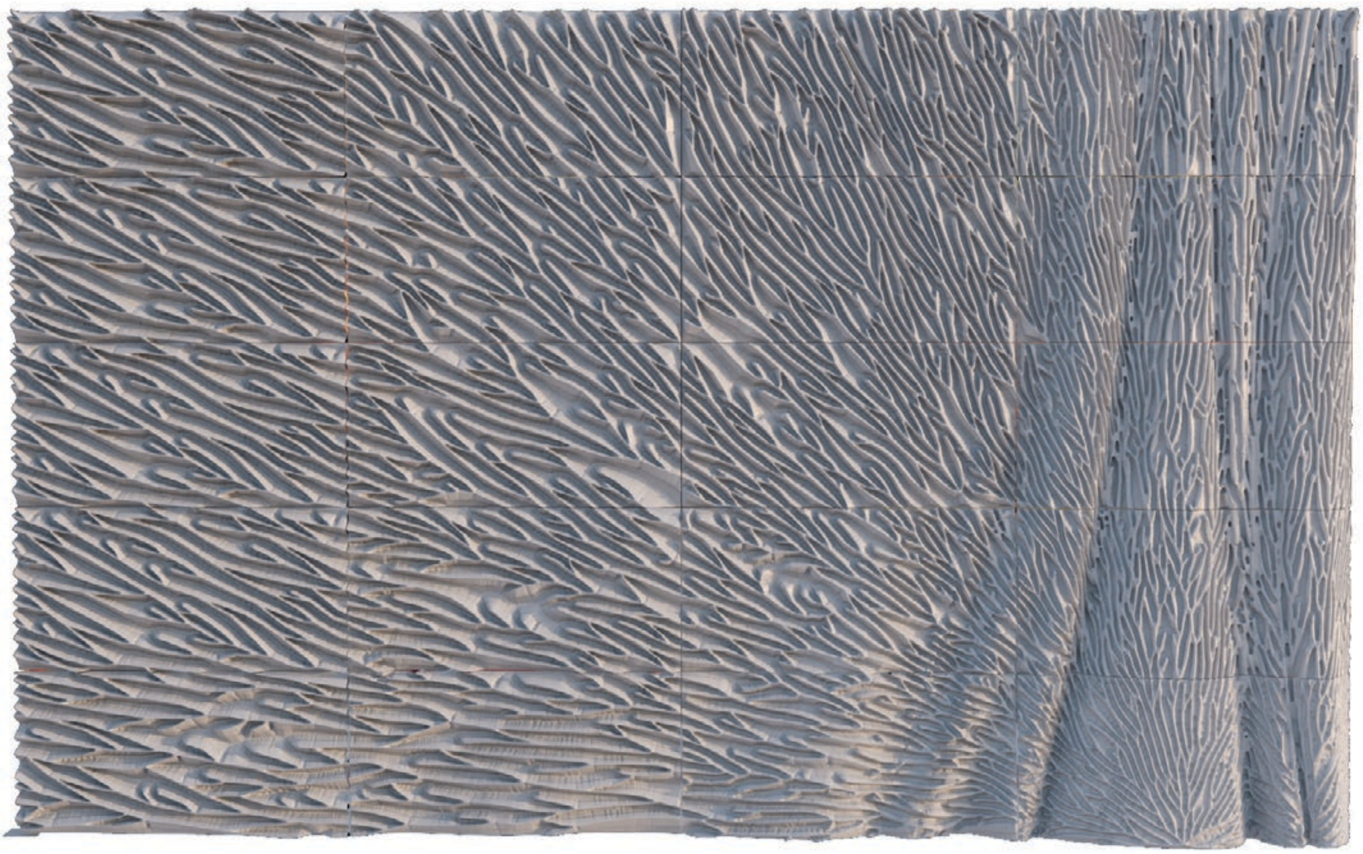
6 Porous TecCast panels being tested for structural strength at Pennine Stone.

7 Final design of the poikilohydric living wall for East Putney Underground Station, London.



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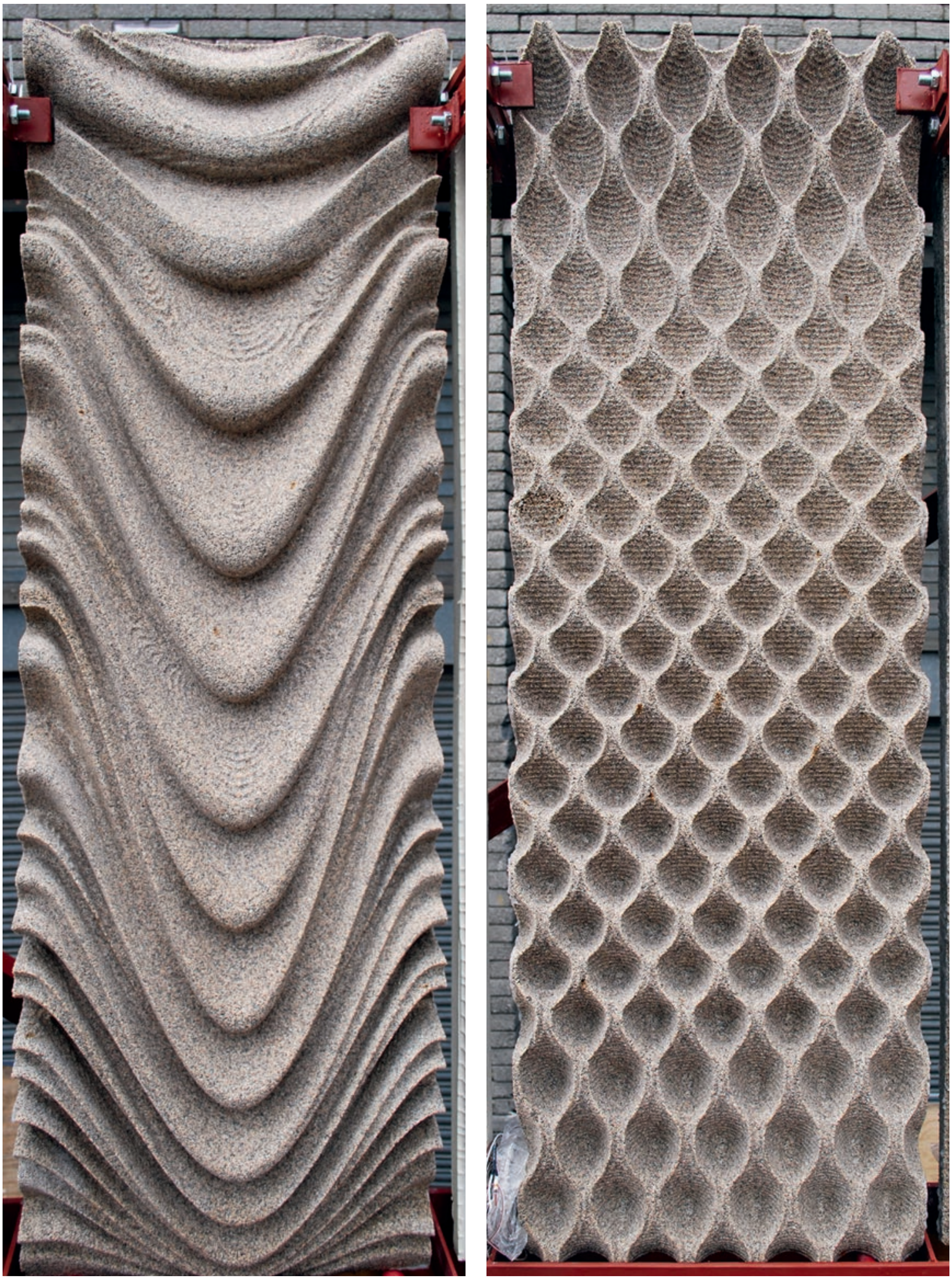
8 (overleaf) Initial outdoor exposure of MPC concrete panels.

9 (overleaf) Initial outdoor exposure of OPC concrete panels.



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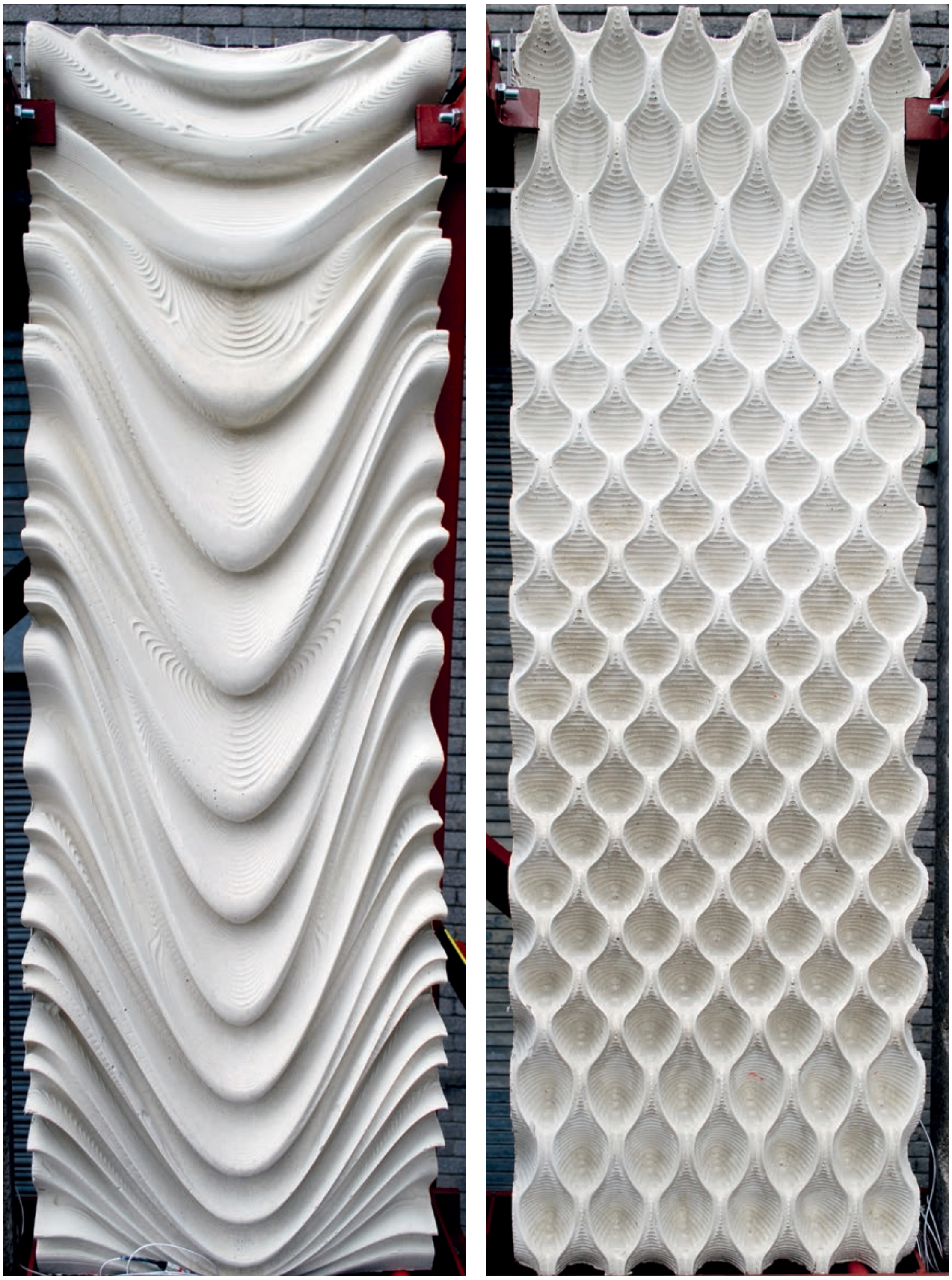

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Context

Cities are characterised by the hard and vertical surfaces of building façades, which from an evolutionary point of view 'have many of the same macro- and micro-habitats, and many of the same plants, as natural cliff faces'. According to the urban cliff hypothesis, 'cliffs, talus and other rock outcrops represent a marginal, unproductive refuge habitat that gave rise to … humans and their commensals and mutualists' (Larson et al. 2004).

At the same time, urban 'cliffs' share characteristics with deserts: very low-nutrient conditions, extreme surface temperatures, desiccation through evaporation or rainwater run-off, and material alkalinity. Plants occupying such surfaces share features with desert species: '(1) shallow roots and a high root:shoot ratio; (2) higher water stress and heat tolerances; (3) small leaves that closely track air temperature; … (5) low photosynthetic and growth rates; (6) opportunistic phenologies; and (7) a regular spatial pattern' (Smith et al. 1996).

Façades are therefore extreme environments of which morphological variance is of huge importance: they define a micro-environmental heterogeneity that influences the deposition of organic matter and the accretion of micro-substrates upon which islands of species can thrive (Smith et al. 1996). They also offer micro- and meso-concavities in which new 'urban habitat templates' (Lundholm 2006) for cryptogamic growth can emerge.

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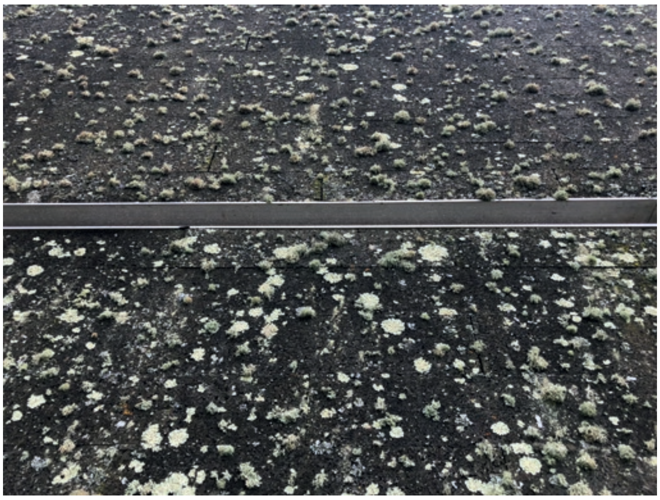
10 Clockwise from top left: cryptogamic surface cover on tree bark, Regent's Park, London; bioreceptive wall in Lisbon; and two bioreceptive walls in London.

In the 1990s, Belgian biochemical engineer, Olivier Guillitte, defined 'bioreceptivity' as the phenomenon of materials being biocolonised without biodeterioration (Guillitte 1995). He categorised four types, all of which enhance cryptogamic growth on walls:

- 'primary or intrinsic': the initial phase of material biocolonisation;
- 'secondary': biocolonisation that changes over time due to external factors;
- 'tertiary': biocolonisation that is promoted due to human activity;
- 'extrinsic': biocolonisation due to the external deposits of dust and organic particles upon which plants thrive.

11 Clockwise from top left: three details of an expanded cork agglomerate north-facing façade with evidence of at least six different lichen types, Pavilhão Centro de Portugal, Coimbra; ornamental concrete sculpture, Giardini della Biennale, Venice; two details of an ornamental sandstone wall, Convento de Cristo, Tomar.



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Researchers from the Max Planck Society and University of Kaiserslautern found that cryptogamic cover amounts to 7% of net global primary production of carbon uptake by terrestrial vegetation, while accounting for nearly half of biological nitrogen fixation on land (Elbert et al. 2012). Algae and moss absorb large amounts of pollution as they lack protective cuticles on their surfaces and leaves.

Designing façades to accommodate cryptogams is challenging as irregularity and unpredictability of growth contradicts a sense of order and clarity of geometric form; an 'aesthetic of cleanliness' (Vigarello 1988) and 'purity' (Forty 2000) still remains the ideal in design. The scattered occurrence of growth patches resembles blotching in human skin. It is regarded as potentially pathological, 'matter out of place' as defined by the anthropologist Mary Douglas (1966), and promotes impure aesthetics. Meanwhile, biophilic design establishes new aesthetic criteria in terms of scale and gradient of pattern, tectonic readability, transition between material and biology, visual response to living and dead biomass, chromatic value, depth and shading.

12

12 Transplanted moss on bioreceptive components and panels installed at The Bartlett, UCL.

13 Spontaneous algae and moss growth on bioreceptive components.

13

Methodology

1. Scaffold Material Development, Testing and Manufacturing

<u>Phase One</u>

Initial tests were conducted with MPC due to its hardiness, low alkalinity and water-retention capability **(19)**. Selected composites were made of magnesium oxide, ammonium dihydrogen phosphate, borax and two types of aggregate – 1–2 mm of sand for a fine layer and 2–4 mm for a course layer – mixed with a minimum of water to increase material porosity. The coexistence of two MPC mixes allowed for water to be absorbed quickly through the coarser back, before being sucked into the finer front **(16)**. Additional porosimetry tests were conducted on the surface roughness and capillary action of the panels **(17)**.

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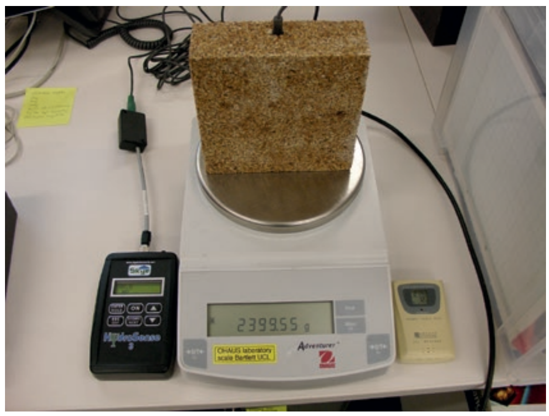

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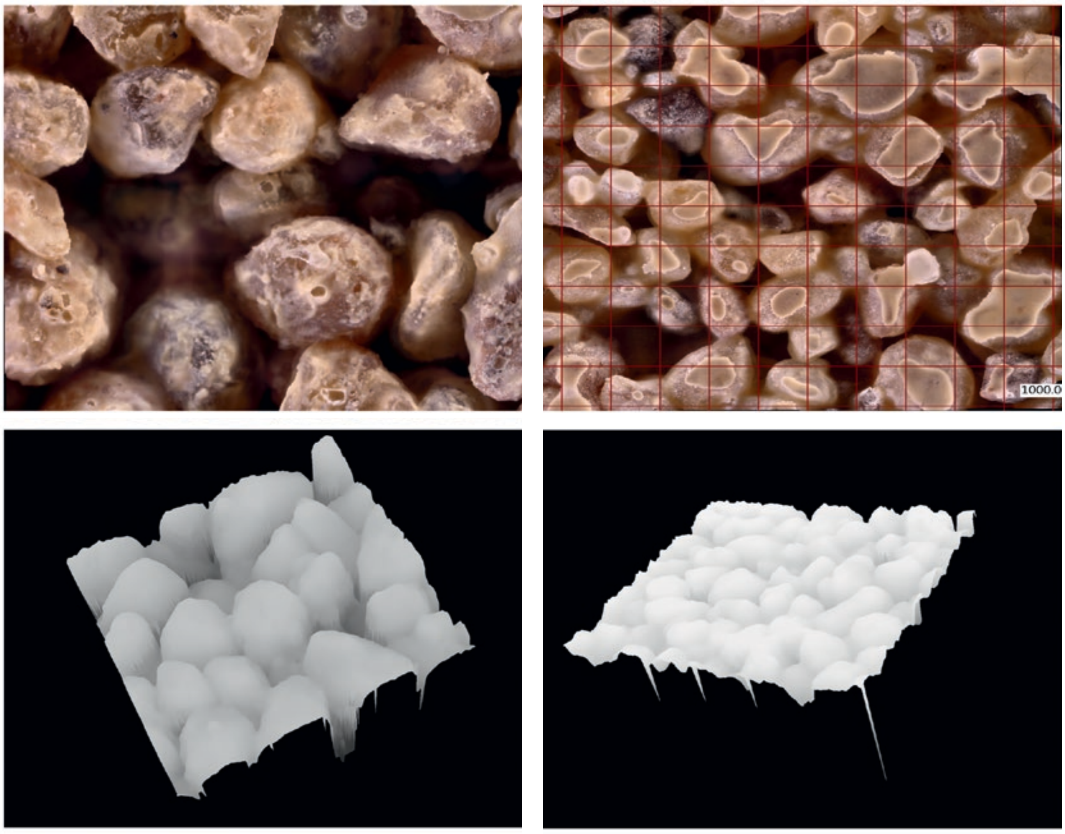
14 Capillary suction test on MPC sample.

15 Micro-hygrometry sensors.

16 Water absorption test.

17 Porosimetry tests to define surface roughness.

18 Table of MPC material characterisation.



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	Baroque			Poché			Vertical		
	Fine	Coarse	Fluid	Fine	Coarse	Fluid	Fine	Coarse	Fluid
Volume	0.041	0.011	0.0045	0.037	0.012	0.0045	0.04	0.011	0.0045
Aggregates	77.10	19.73	8.72	69.58	21.52	8.72	75.22	19.73	8.72
MgO	9.36	1.70	1.08	8.45	1.85	1.08	9.13	1.70	1.08
Phosphates	5.35	0.97	0.62	4.83	1.06	0.62	5.22	0.97	0.62
Borax	0.88	0.16	0.10	0.80	0.17	0.10	0.86	0.16	0.10
Water	2.34	0.42	0.45	2.11	0.46	0.45	2.28	0.42	0.45
M:P	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
% Borax	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
W/C	0.15	0.15	0.25	0.15	0.15	0.25	0.15	0.15	0.25

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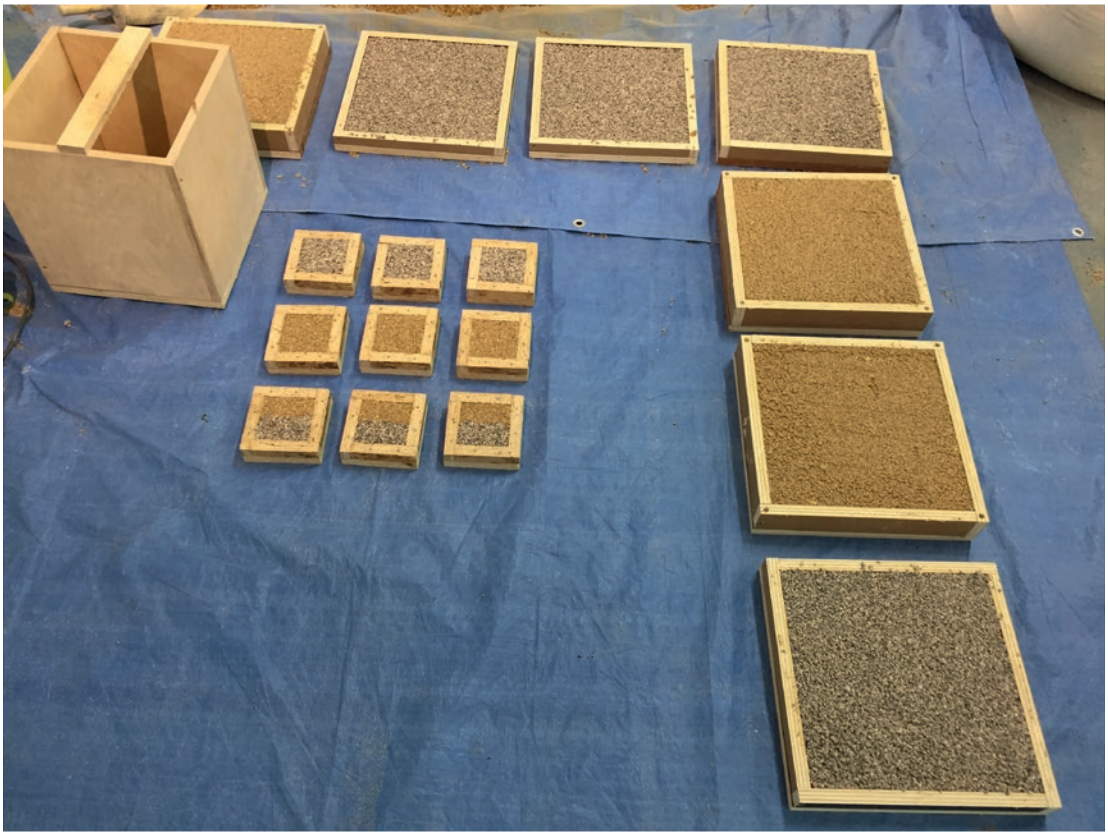
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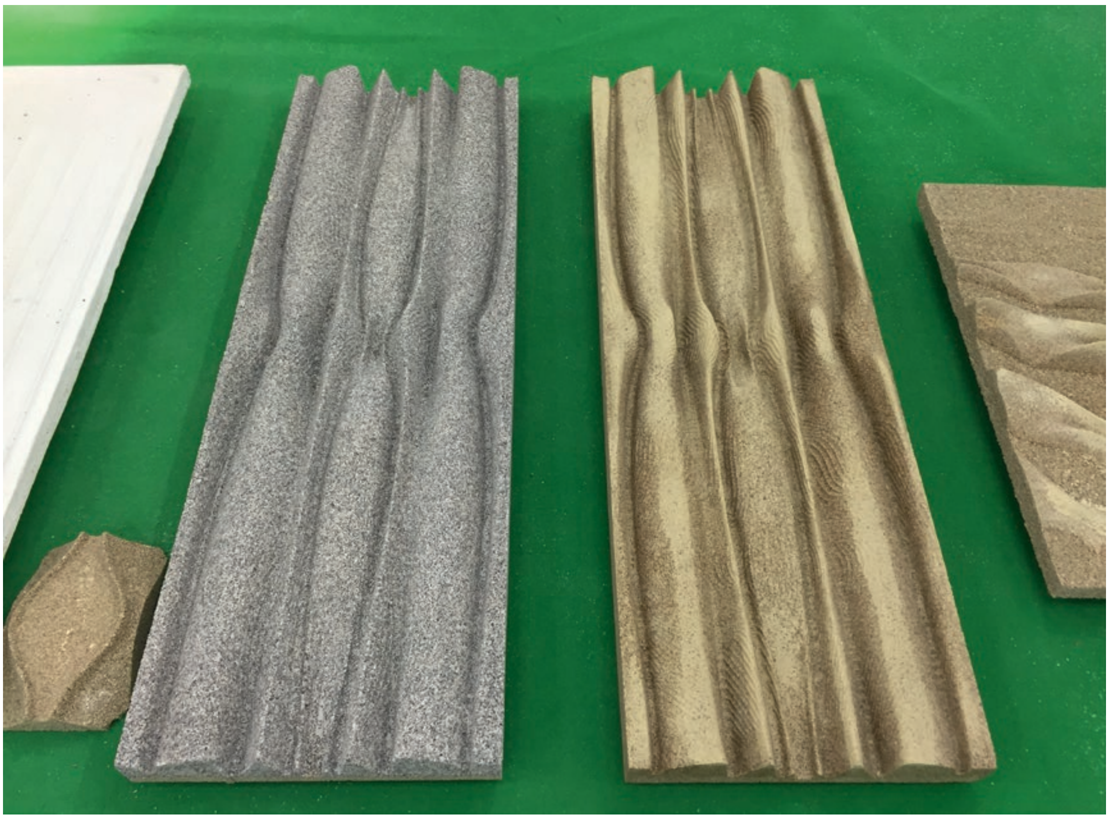
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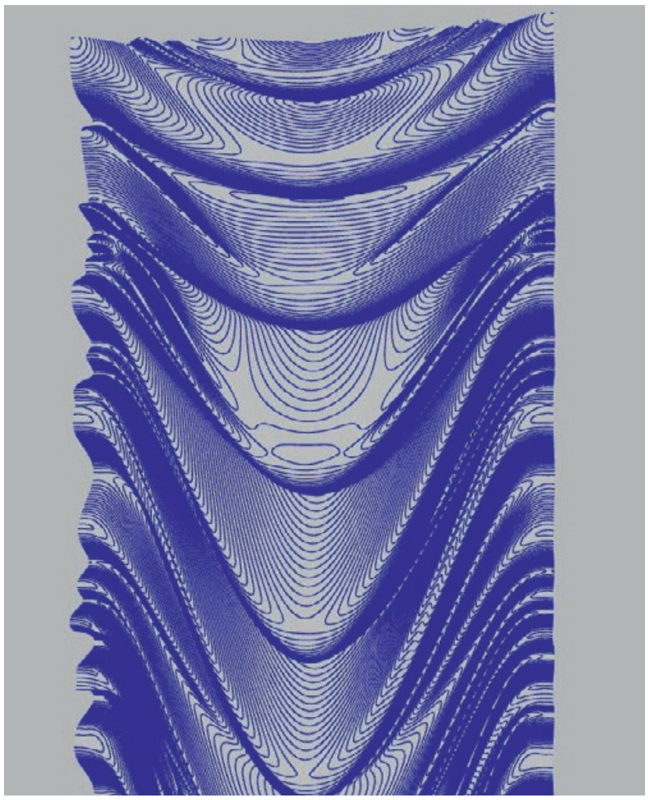

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21 Detail of MPC casts with variable surface textures. Bespoke toolpath definitions defined smaller-scale textural surface variance to slow water run-off.

22 Design of toolpaths to create texture on panels.

19 MPC material tests were conducted on small casts (100 × 100 mm and 300 × 300 mm) with different aggregate sizes to create multi-material porous composites that promote water absorption in specific areas of the panels.

20 Initial MPC casts with different levels of porosity.

Age (days)	Sample Number	Length (mm)	Width (mm)	Height (mm)	Weight (g)	Density (kg/m3)
1	1.1	160.01	39.61	40.07	454.15	1788.2
	1.2	160.16	39.73	40.09	452.61	1774.3
	1.3	160.14	39.87	40.09	455.52	1779.6
2	2.1	160.10	39.30	40.07	445.78	1768.1
	2.2	160.35	39.09	40.04	449.28	1790.1
	2.3	160.14	39.05	40.13	441.75	1760.3
7	7.1	160.18	39.24	40.03	444.89	1768.2
	7.2	160.19	39.35	40.14	445.36	1760.2
	7.3	160.33	39.28	40.06	459.38	1820.9
28	28.1	160.52	39.06	40.04	448.71	1787.4
	28.2	160.14	39.33	40.10	454.74	1800.5
	28.3	160.26	38.89	40.06	447.14	1790.9

23

Age (days)	Sample Number	Flexural failure load (N)	Flexural Strength (MPa)	Average Flexural Strength (MPa)
1	1.1	935.17	2.21	3.06
	1.2	1467.93	3.45	
	1.3	1507.99	3.53	
2	2.1	1955.55	4.65	4.17
	2.2	1689.73	4.04	
	2.3	1595.13	3.80	
7	7.1	1876.81	4.48	4.79
	7.2	1968.04	4.66	
	7.3	2197.47	5.23	
28	28.1	2099.69	5.03	4.91
	28.2	2118.90	5.03	
	28.3	1940.87	4.66	

24

23 Dimension, weight and density of 12 prism specimens used for flexural and compressive strength tests, carried out by the Building Research Establishment, 2017.

24 Results of flexural strength tests carried out by the Building Research Establishment, 2017.

Age (days)	Sample Number	Test Number	Compressive Failure Load (N)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
1	1.1	1	25392.27	16.03	15.54
		2	24294.34	15.33	
	1.2	1	24367.78	15.33	
		2	24872.94	15.65	
	1.3	1	24744.50	15.52	
		2	24494.48	15.36	
2	2.1	1	30118.71	19.16	18.72
		2	30979.44	19.71	
	2.2	1	***15746.11***	***10.07***	
		2	29214.64	18.68	
	2.3	1	***17563.52***	***11.24***	
		2	27067.69	17.33	
7	7.1	1	31510.93	20.08	21.77
		2	31729.60	20.22	
	7.2	1	31958.04	20.30	
		2	31335.25	19.91	
	7.3	1	40004.40	25.46	
		2	38745.04	24.66	
28	28.1	1	37570.98	23.48	23.35
		2	35785.57	22.37	
	28.2	1	42078.79	26.30	
		2	37628.35	23.52	
	28.3	1	35499.82	22.19	
		2	35606.54	22.25	

25

25 Results of compressive strength tests on 24 ends of 12 prism specimens, carried out by the Building Research Establishment, 2017.

The material bioreceptivity of MPC and OPC was tested outdoors over a 12-month period, using panels of three different geometry types to compare surface morphologies. Three replicas of each type were produced, resulting in 18 medium-scale façade prototypes. Material tests were carried out during the exposure study, including testing of flexural and compressive strength – three specimens tested at one, two, seven and 28 days – freeze-thaw resistance and fixing pull-out resistance **(26)**. These tests established that the MPC panels, even though very porous, had good structural integrity but they did not perform well when exposed to the action of freeze-thaw. This suggests that the mix was potentially inappropriate for long-term outdoor exposure in the UK's climate.

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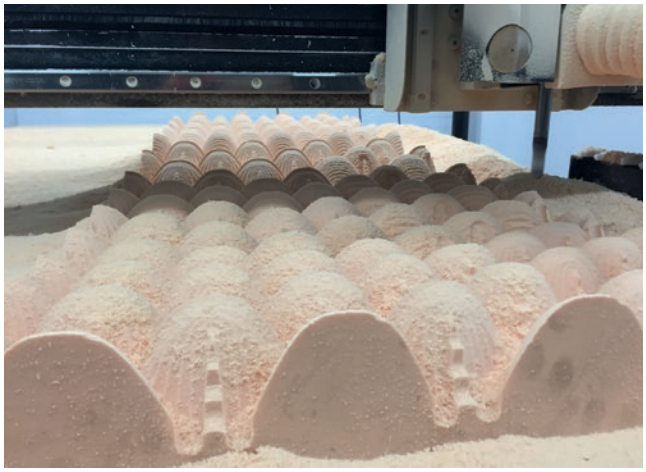

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26 Flexural and compressive strength test being performed on an MPC sample at the Building Research Establishment.

27 Three-axis milling of SikaBlock® Foam on a PACER 615 HDs using Delcam software.

28 MPC cast in GRC Fleximould – a rubber type that is suitably durable for multi-concrete casts.

Phase Two

Panels for the St Anne's and East Putney projects were built from OPC due to problems affecting biocolonisation during the curing process of MPC **(29)**. Observations in urban environments showed that certain moss types are perfectly capable of growing on OPC. Despite initial high alkalinity, OPC has a gradual decrease of pH when carbonised over time, which makes it gradually more bioreceptive. The goal was to offset the carbon footprint of OPC, which is the cheapest and most available material in the construction industry. A preliminary design featuring complex three-layered panels was not pursued beyond the testing phase, as it did not retain more water as hoped and transplanted moss did not establish. The casting of such panels was also very laborious, which made it a commercially unavailable process.

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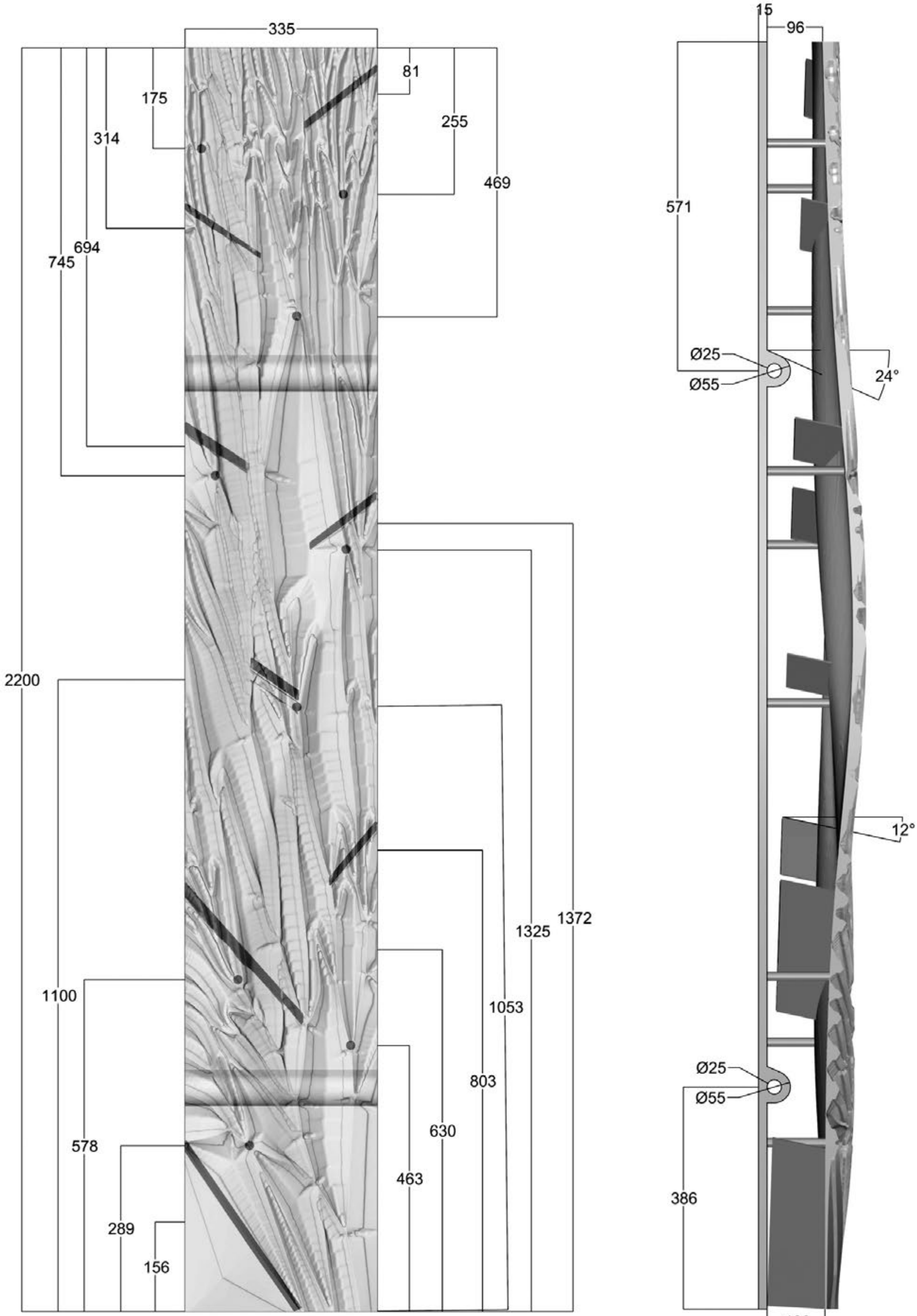
29 Rubber moulds and multi-material OPC casts with lightweight aggregates, produced for St Anne's Catholic Primary School, London.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30 Drawings of multi-layered panels.

31 A multi-material OPC cast with lightweight aggregates and a closed front layer.

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32 Installation of poikilohydric living wall at St Anne's Catholic Primary School by Solid Brickworks.

33 Collage of poikilohydric living wall at East Putney Underground Station, London.

34 Preliminary moss transplantation on a multi-material OPC cast with lightweight aggregates.

Ultimately, all panels were made from single-layer OPC. TecCast – a recipe by Pennine Stone Ltd composed of cement, sand, lime dust, water, admixtures, yellow dye and glass fibres for higher tensile and flexural strength – was calibrated for increased porosity, showing a high level of water-absorption capability. Compressive strength tests averaged 26.12 N/m^2; a density of 120 kg/m^3; and an average weight of 80 kg for St Anne's and 70–100 kg for East Putney **(38)**.

The resulting glass fibre reinforced concrete (GRC) panels were fabricated by Pennine Stone Ltd, who employed state-of-the-art CNC milling of moulds and industrial casting systems **(35)**.

35

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35 Final production of TecCast concrete panels for St Anne's Catholic Primary School, London.

36 Test casting of TecCast concrete panels for East Putney Underground Station, London.

37 Structural testing of TecCast concrete panels for the Centre Pompidou, Paris.

38 Structural testing of TecCast concrete panels for St Anne's, London.

37

38

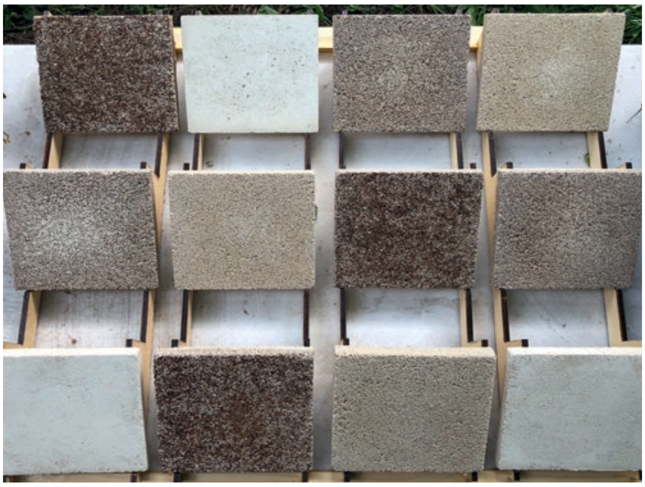
Phase Three

Cork was used as an aggregate due to several advantages when compared with previous studies: it is a natural material that is highly bioreceptive, especially for the development of lichens that are slow to proliferate on urban surfaces; it is very light, minimising the overall weight of panels; and it provides good thermal and acoustic insulation. Corkcrete components were developed in collaboration with the University of Coimbra for Merchiston Park. A variety of porous mortar mixtures of OPC and natural and expanded cork were tested to minimise the evaporative loss of water while keeping structural integrity **(40–2)**.

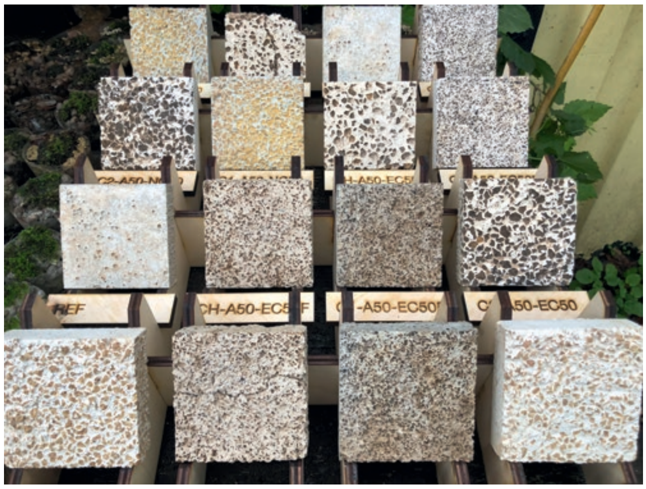
Material mix	**Cement: aggregate ratio**	**Water: cement ratio**	**Cement (g)**	**Sand (g)**	**Cork (g)**	**Water (g)**	**Top layer (yes / no)**
Non-porous cement	1 to 2	1 to 0.5	1200	3000	0	680	n
Porous cement	1 to 2	1 to 0.3	1200	3000	0	430	n
Porous Corkcrete	1 to 2	1 to 0.55	1200	0	440	660	n
Porous Corkcrete with exposed cork layer	1 to 2	1 to 0.55	1200	0	440	660	y

39

39 Composition of each set of material samples fabricated for the study.



40



41

42

40 Four preliminary types of Corkcrete samples installed in random order, to test bioreceptivity, at Meanwhile Wildlife Gardens in London.

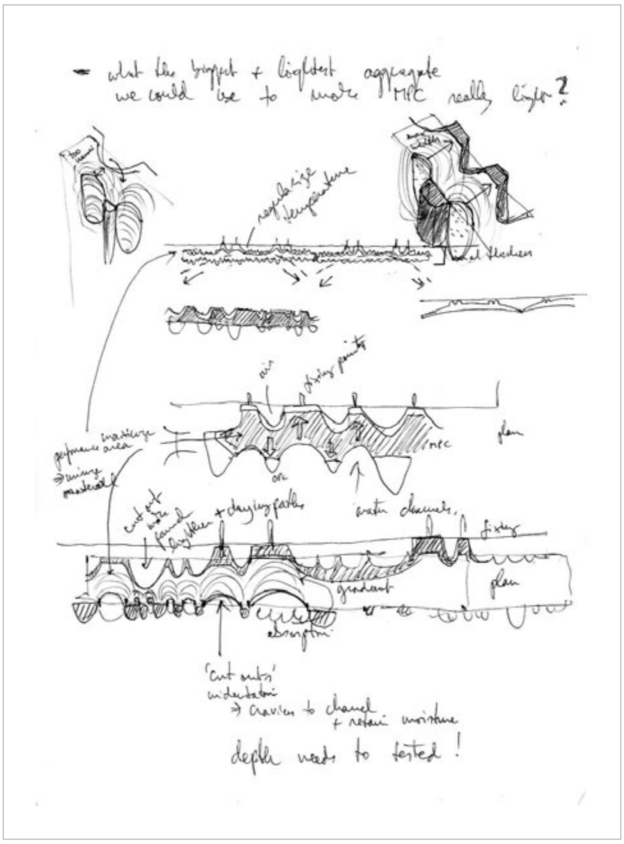
41 Eight further types of Corkcrete sample installed in random order to test bioreceptivity at Meanwhile Wildlife Gardens in London.

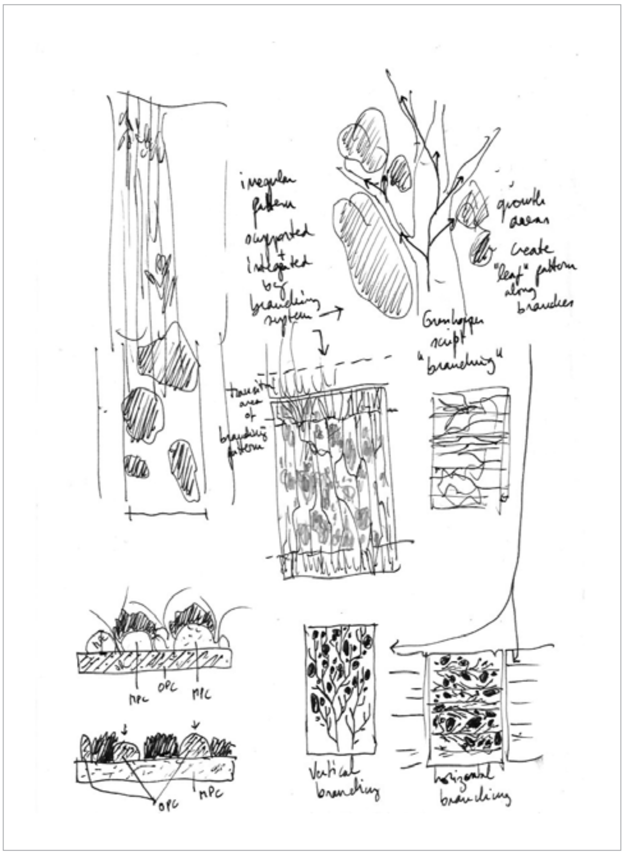
42 Comparative study of different size and intensity of cork aggregate in the material composite.

2. Design and Computational Modelling

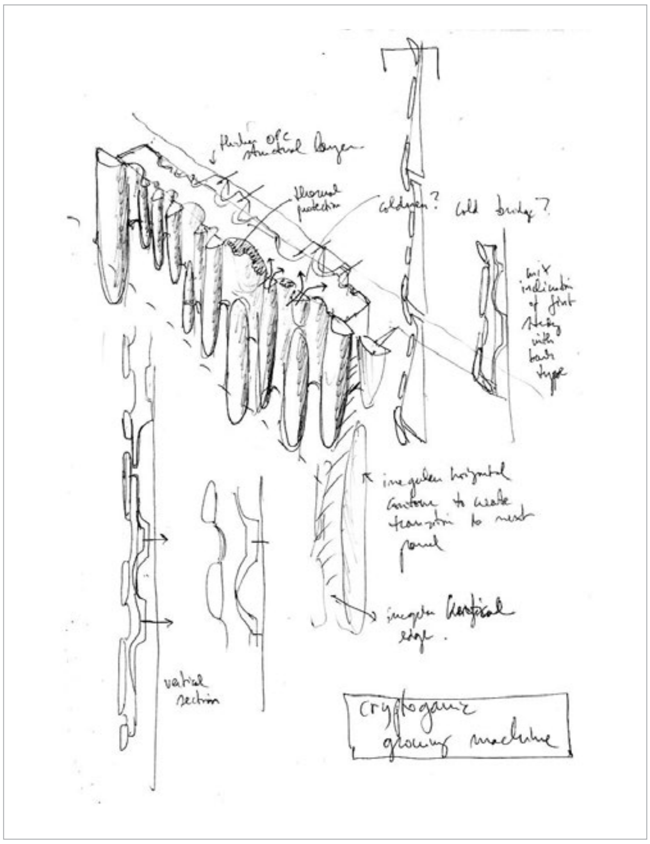
Phase One

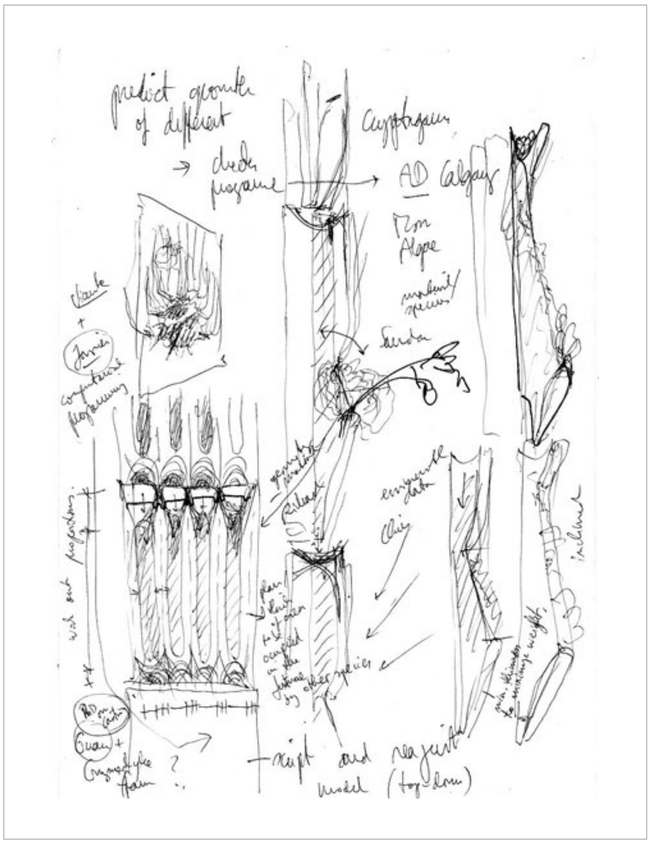
The classification of different tree barks and intense sketching led to the creation of over 30 3D Rhino and Houdini models, organised into a 'taxonomy' of morphological surface patterns. From those, 15 small models were 3D printed and categorised into six geometric families: vertical curtain system, diagonal baroque, scattered poché, horizontal striations, bulging and branching. The first three were selected for the fabrication of three panel types (1500 × 1000 mm) based on their surface water run-off capability.

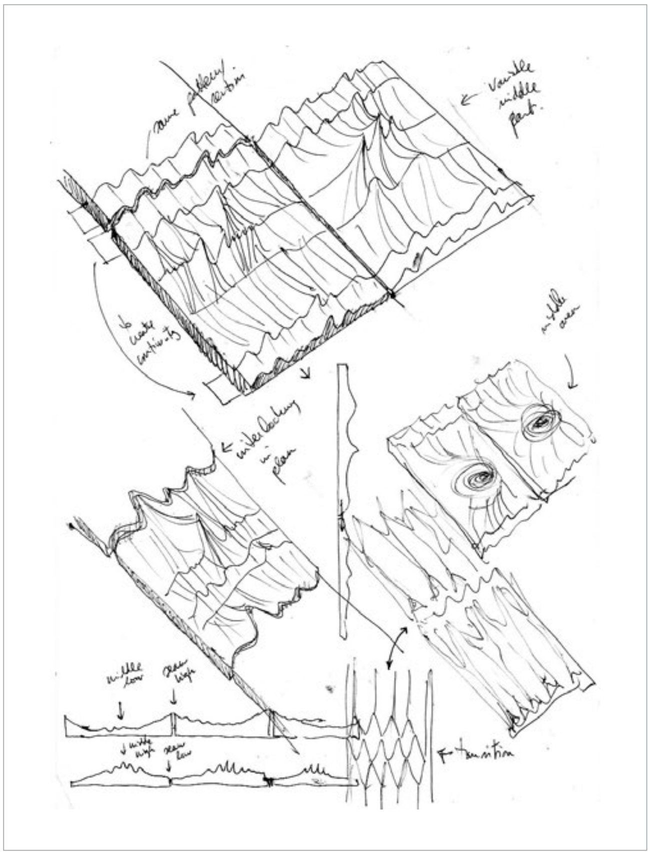


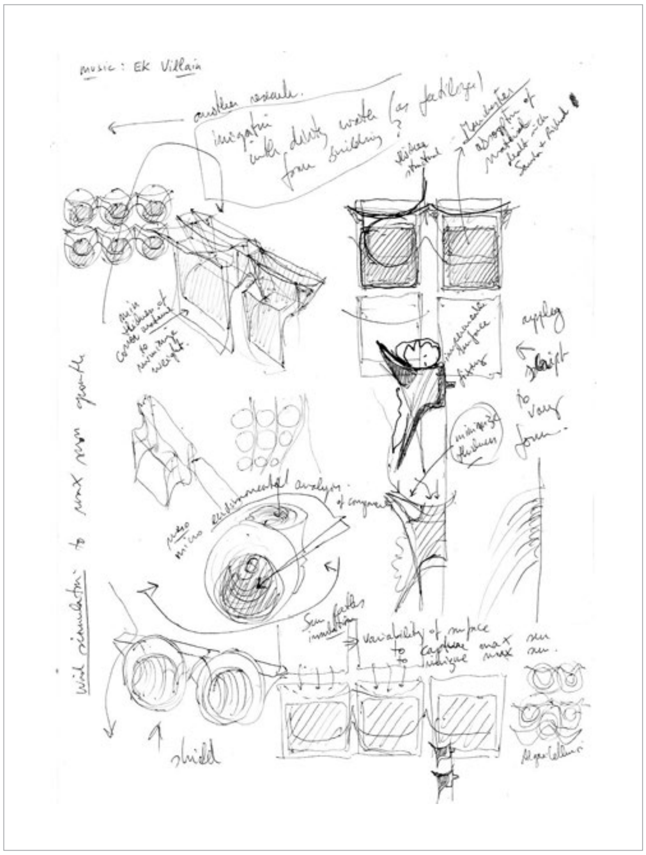


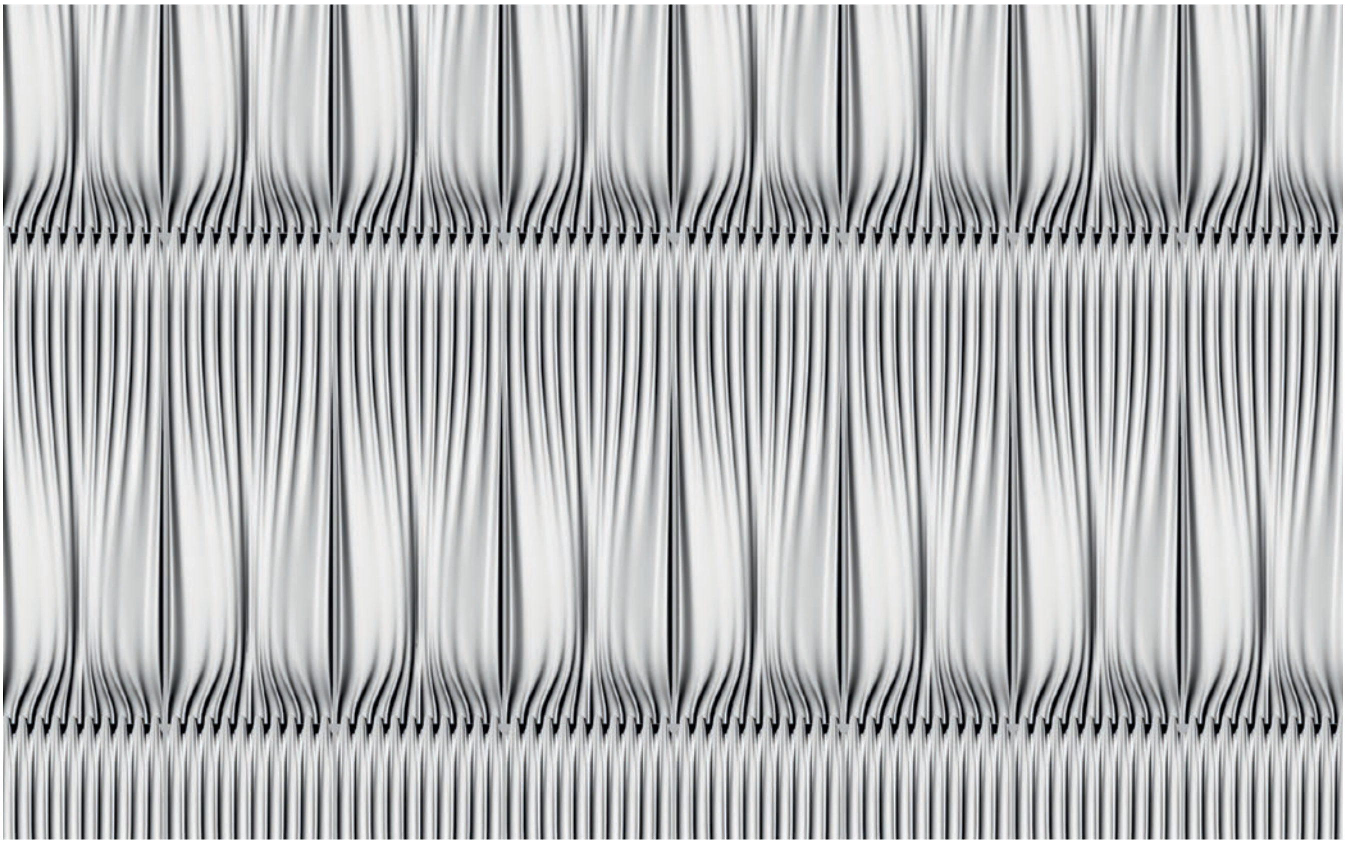
43 Preliminary sketches outlining key concepts and systems for components and panels.


cold bridge?
vertical section
cryptogamic growing machine


predict growth of different
Cryptogams
script and rasp model (top down)


variable middle part.
transition

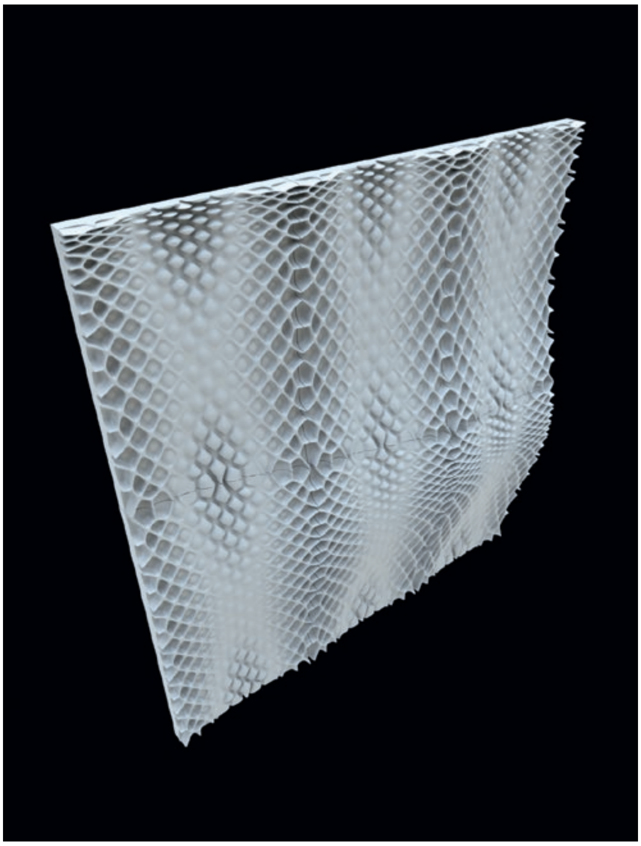

music: EK Villain
shield



44

44 Morphological study of vertical surface pattern ‘Fins’.

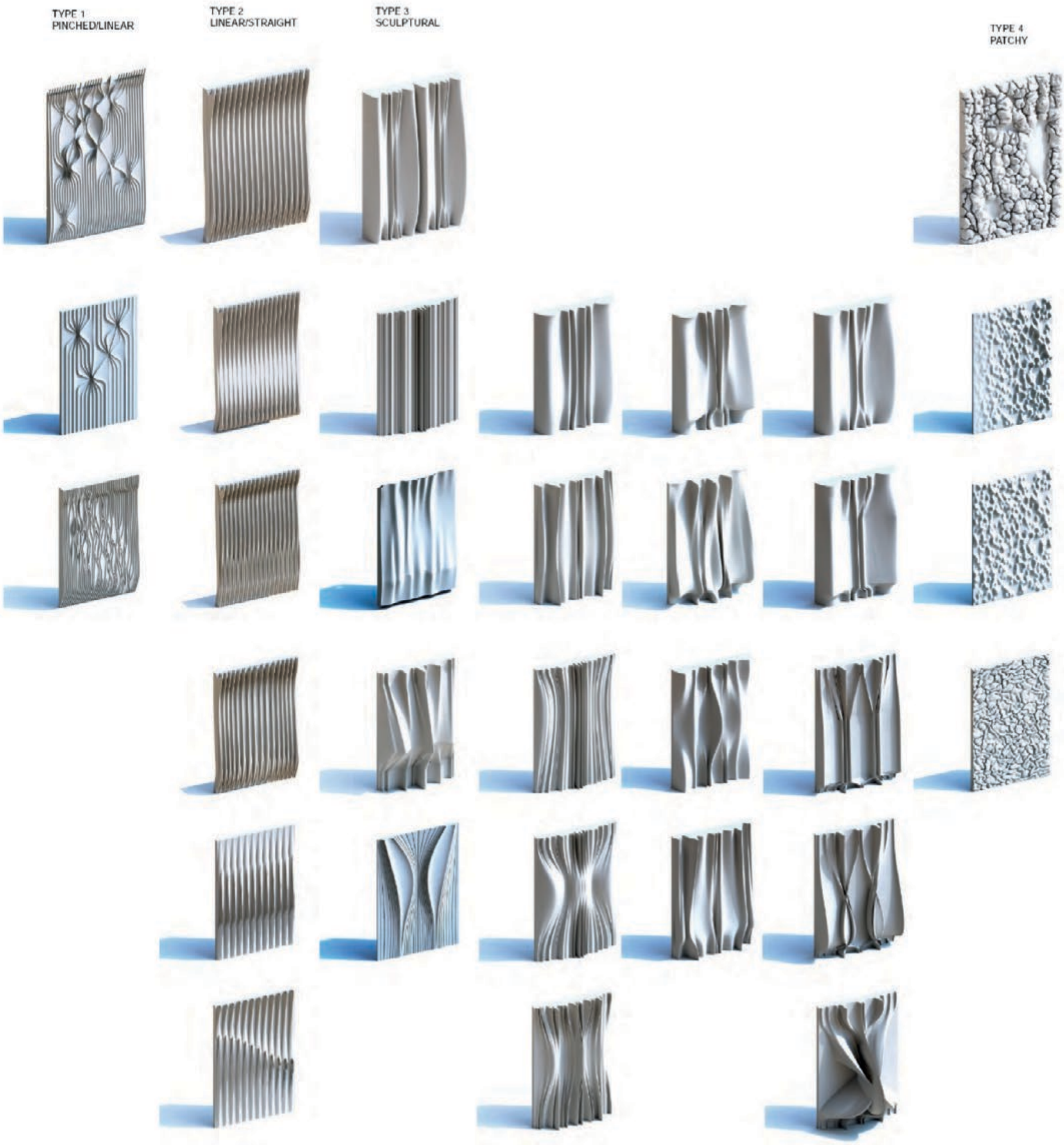

45

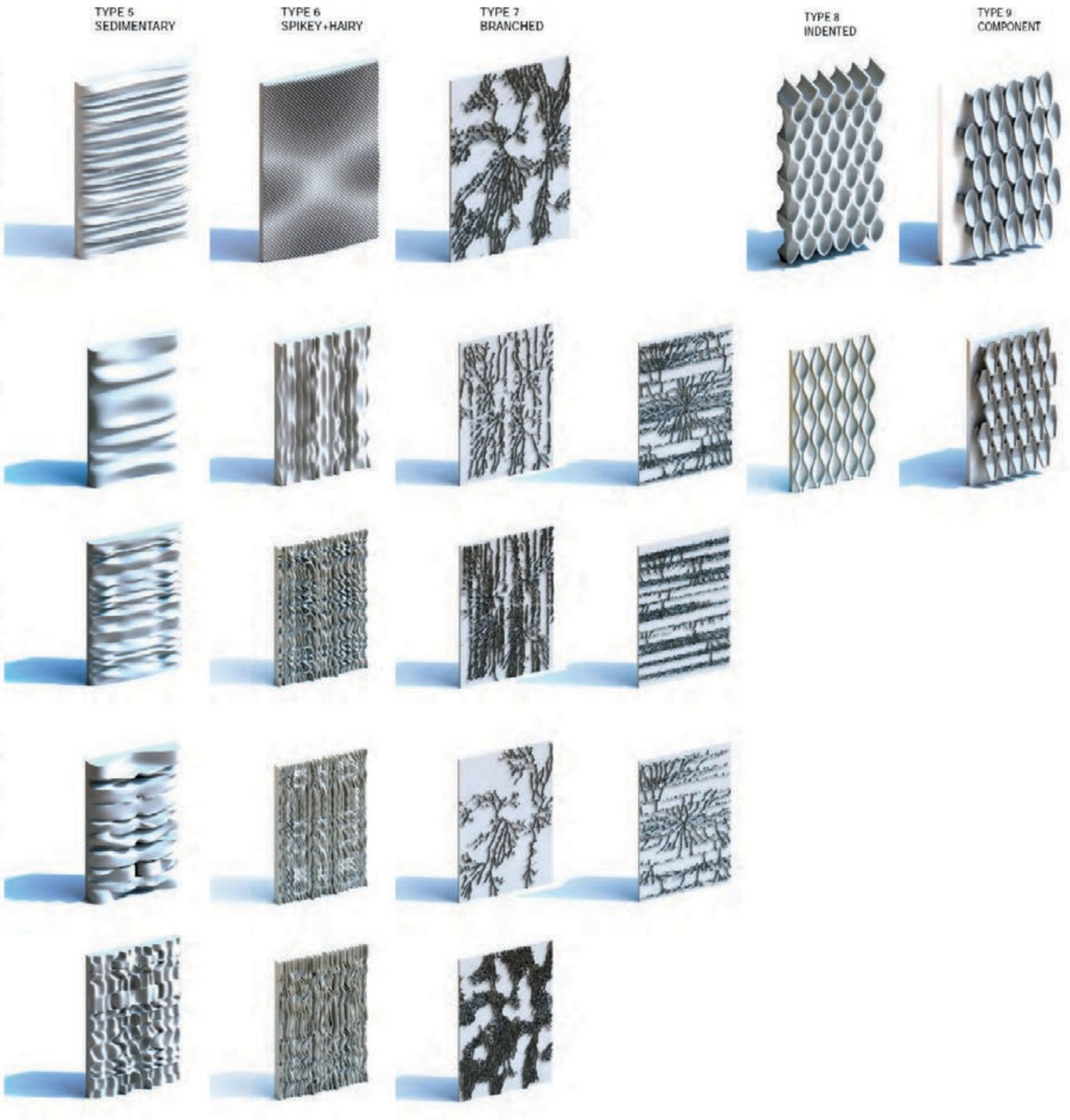

46

45 Morphological study of vertical surface pattern 'Longitudinal Striations'.

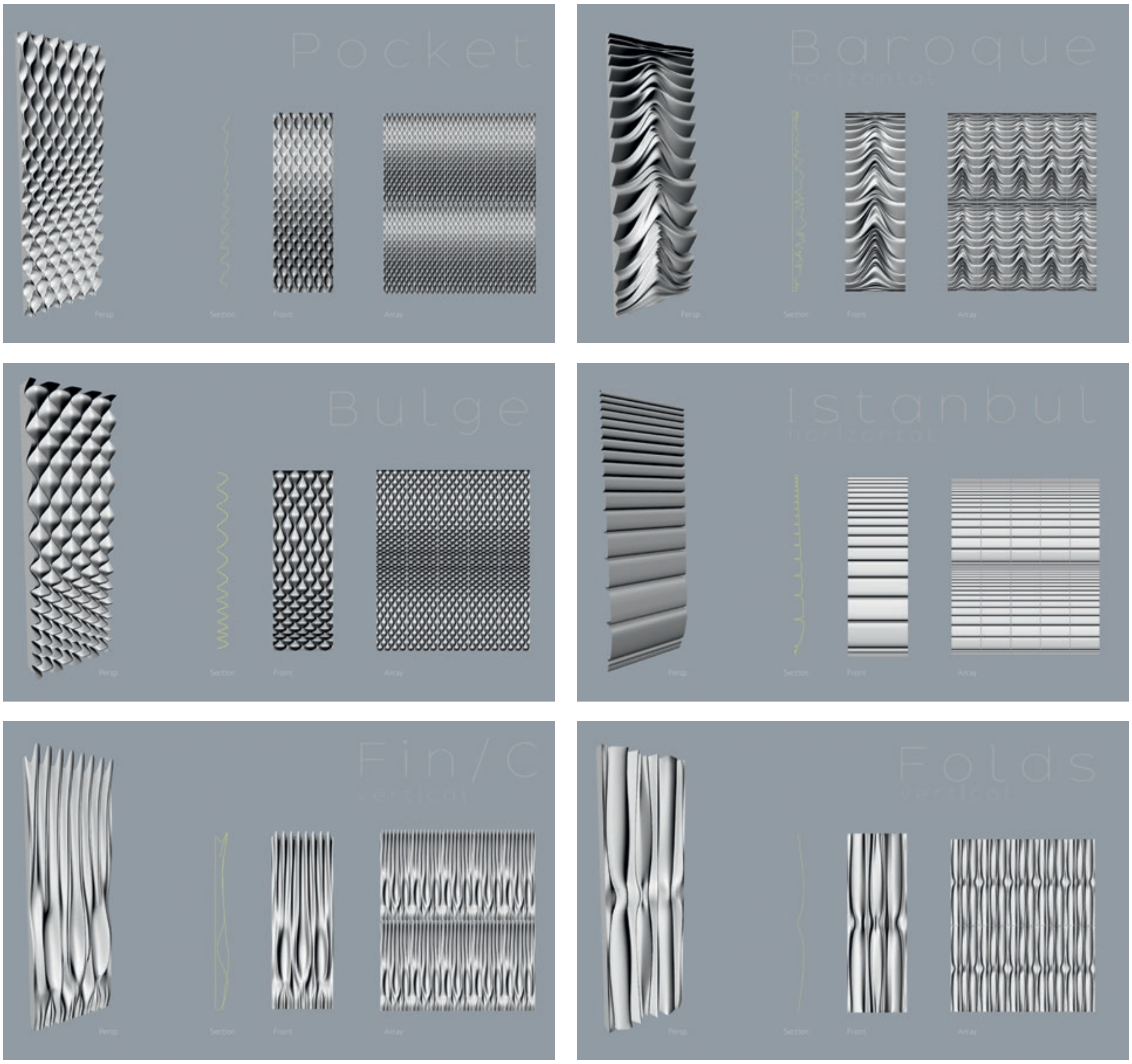
46 Morphological study of vertical surface pattern 'Snake Skin'.

47 (overleaf) Taxonomy of 13 types of surface morphology for bioreceptive façade panels.


TYPE 1
PINCHED/LINEAR
TYPE 2
LINEAR/STRAIGHT
TYPE 3
SCULPTURAL
TYPE 4
PATCHY

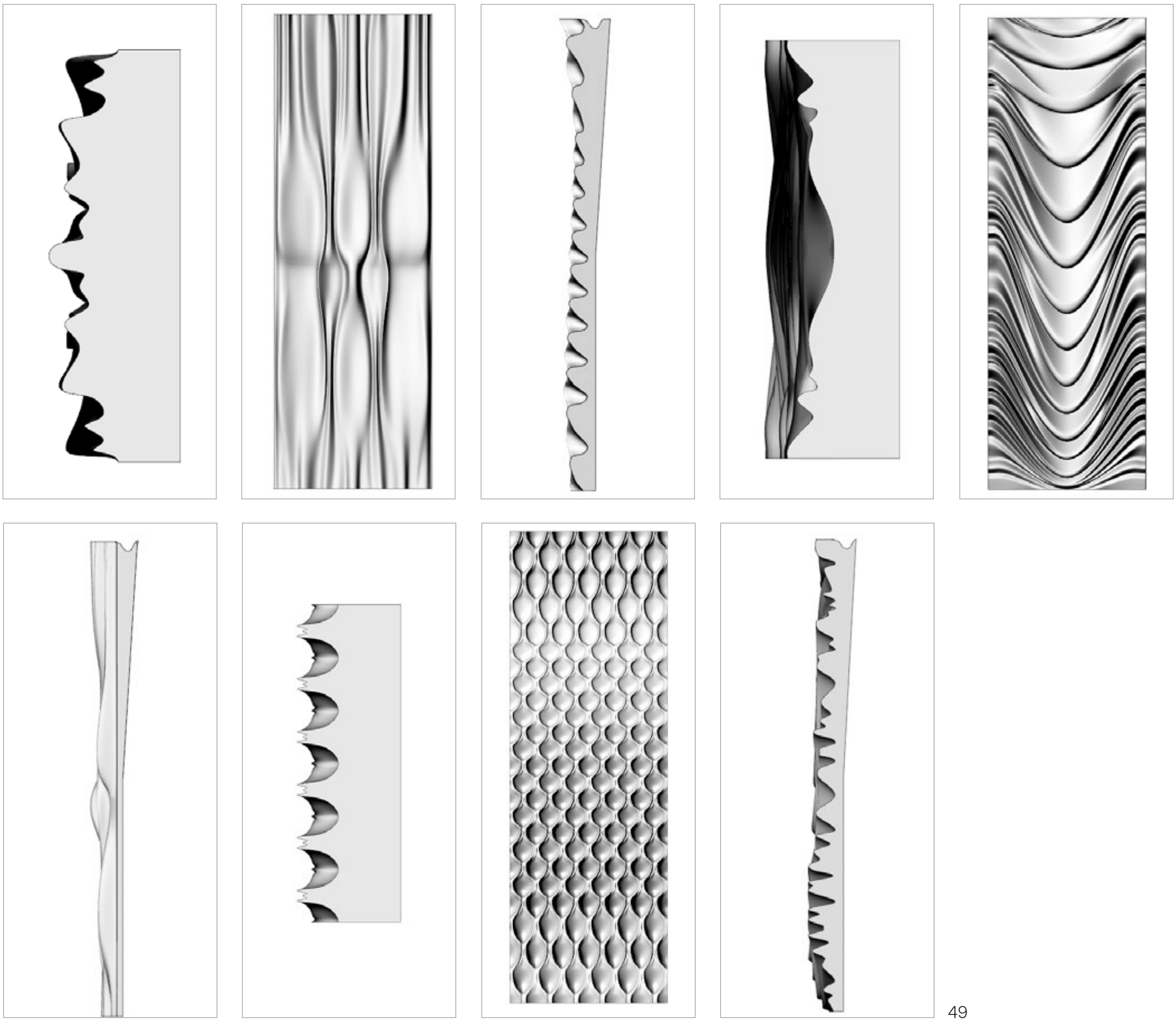

TYPE 5
SEDIMENTARY
TYPE 6
SPIKEY+HAIRY
TYPE 7
BRANCHED
TYPE 8
INDENTED
TYPE 9
COMPONENT

47



48

48 First selection of morphological surface patterns.



49

49 Final selection of three key surface patterns: curtain, poché, baroque.

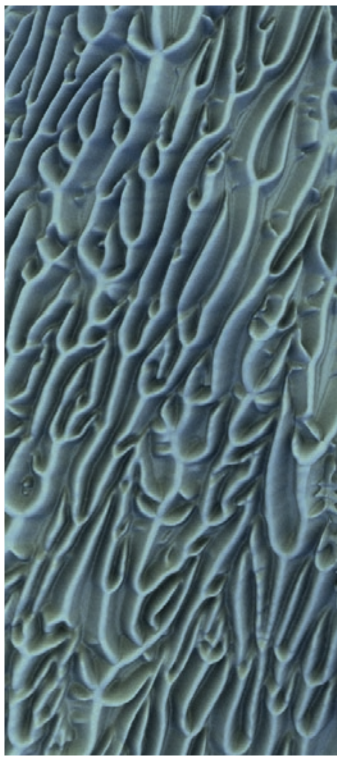
50

51

Phase Two

Another series of geometric studies with a vertical branching system was carried out in Houdini for St Anne's **(51–2)**. The chosen patterns were mirrored, creating a repetitious yet diverse design for the wall, with calibrated spacing between branches to prevent children from trying to climb up it.

52

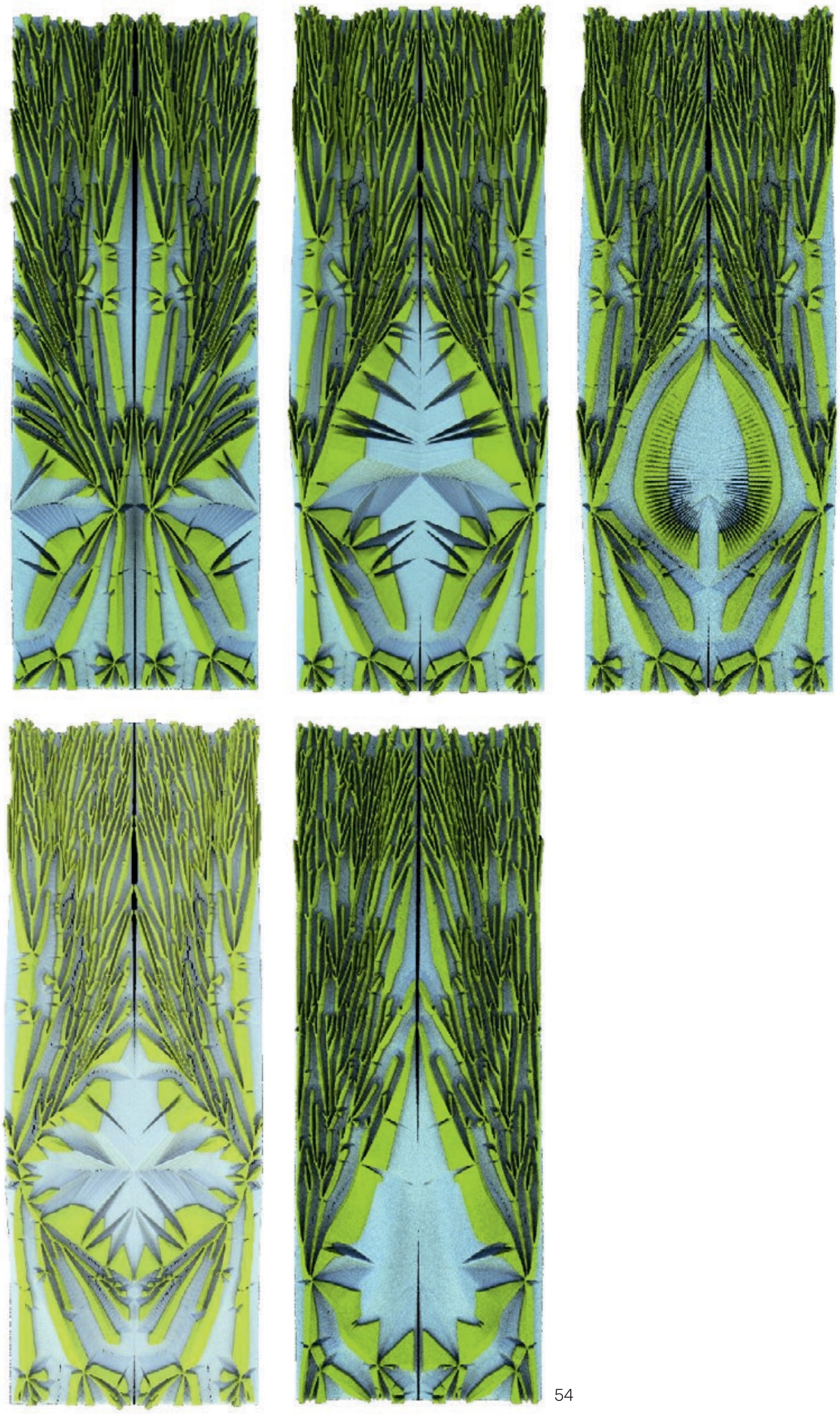


53

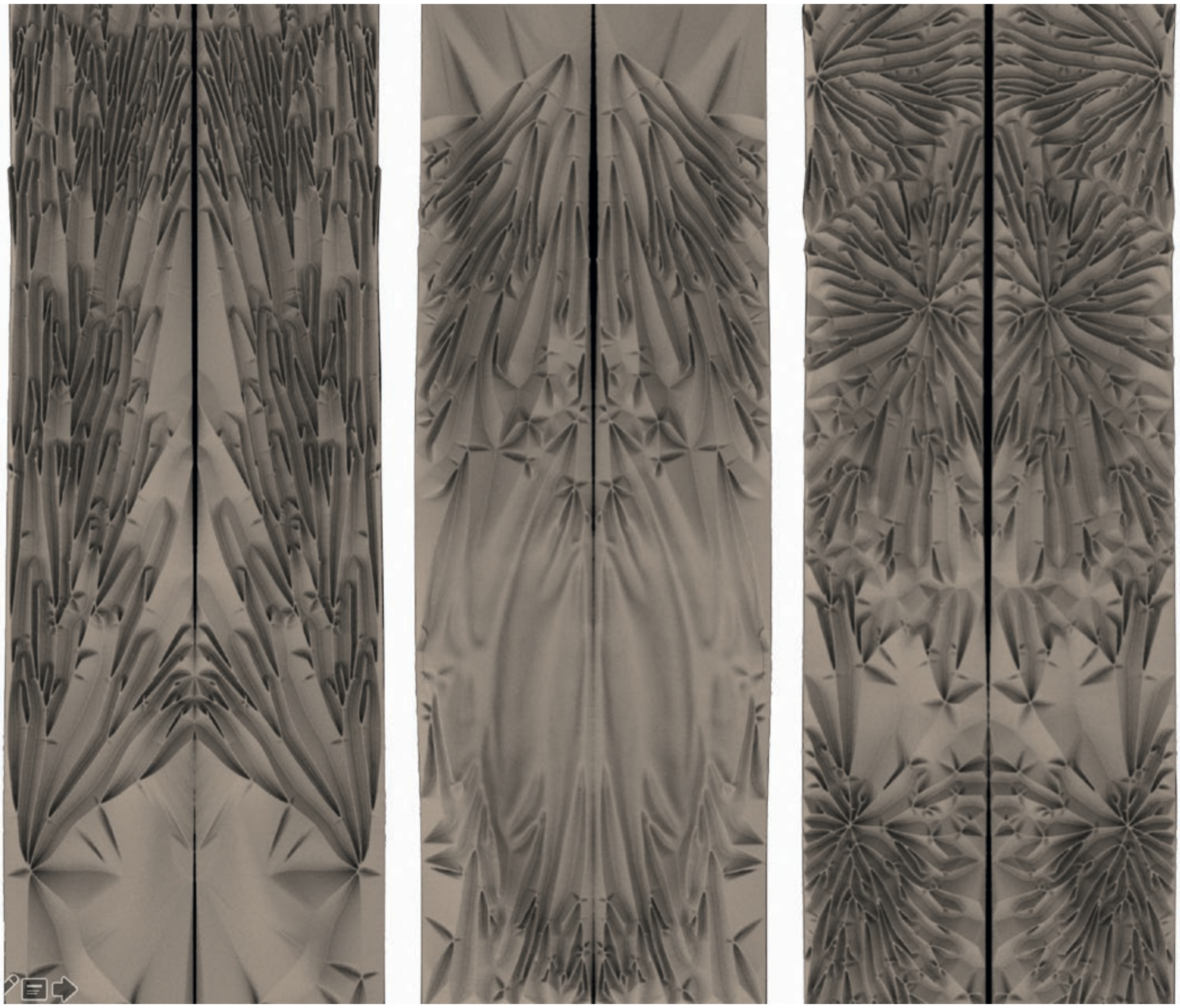
50 MPC panels with three selected surface patterns: curtain, poché, baroque.

51–2 New generation of surface morphologies developed in Houdini for St Anne's, London.

53 Branching geometry developed in Houdini.

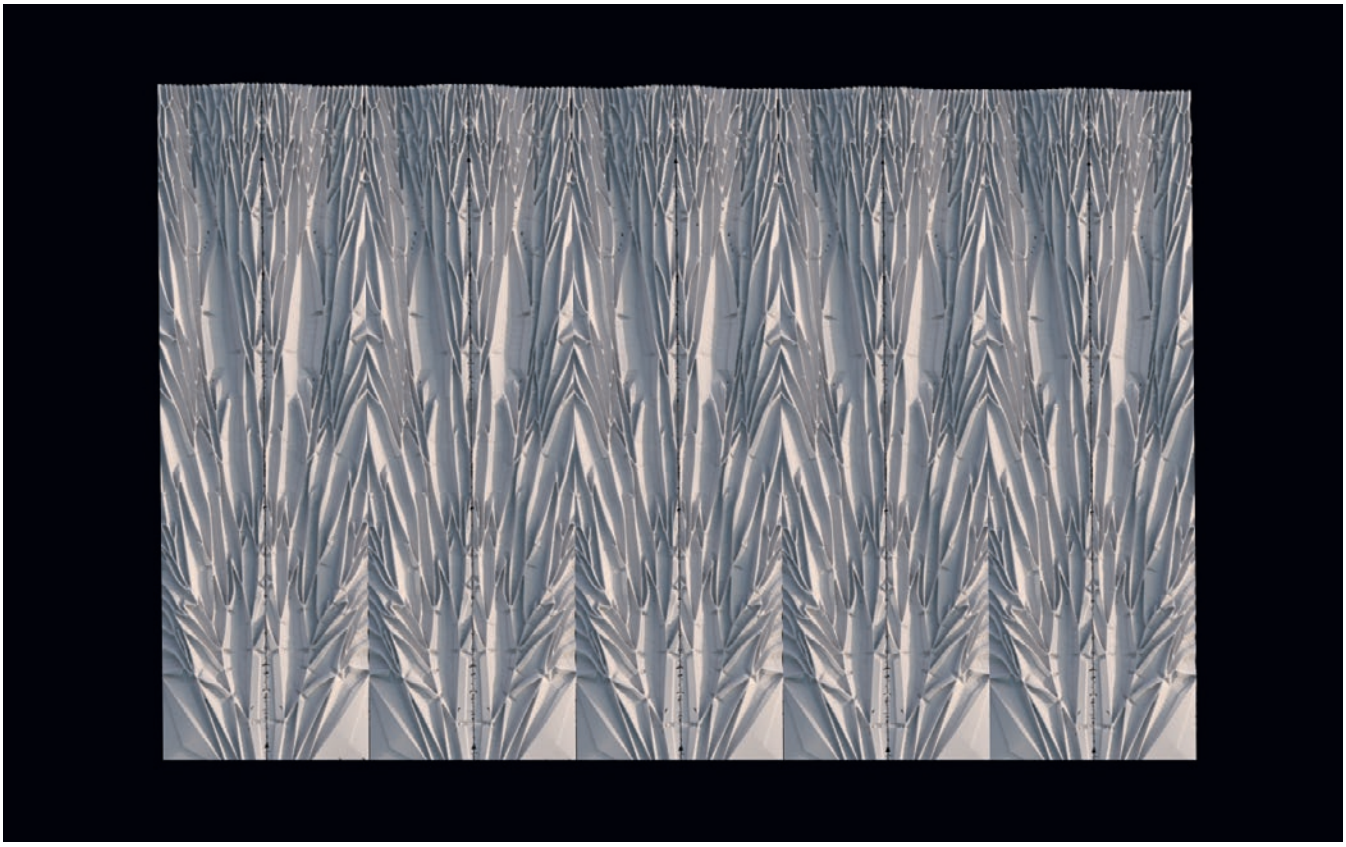


54



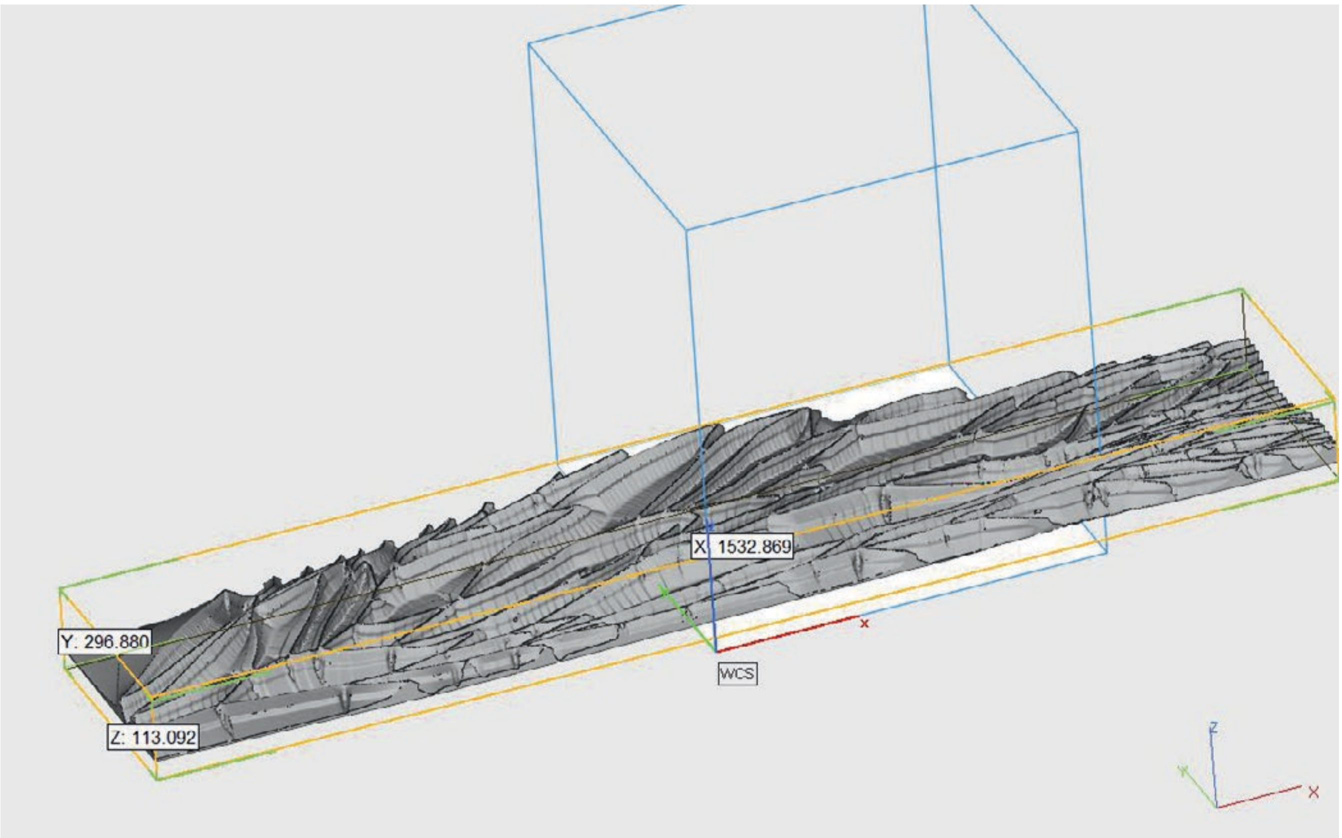
55

54-5 Branching geometry.



56

56-7 Preparation of files with final branching geometry for the manufacture of moulds.



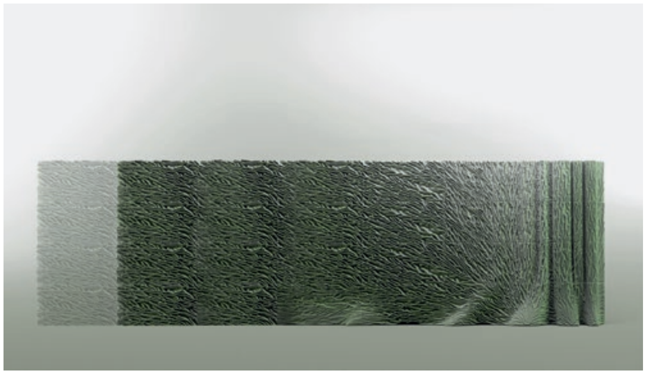
57

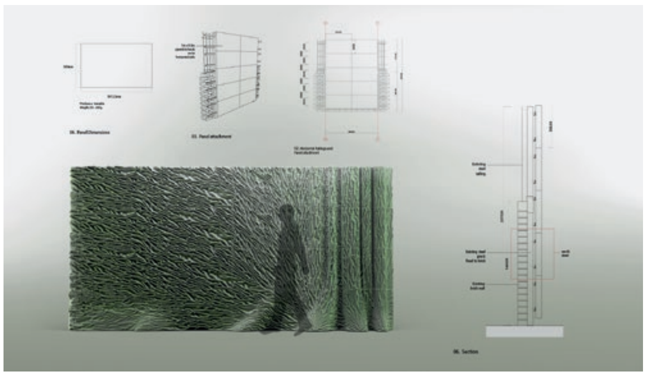
A new series of branching patterns was designed for East Putney Underground Station, creating a wall with few repeated panels. A curtain theme was chosen to enhance the legibility of the wall from a distance and to maximise the surface depth for increased shading **(58, 60)**. A branching pattern was then imposed over the curtain folds, creating an ornamental pattern on the wall **(59, 61–2)**. The size of the branches was calibrated with a gradient that ranged from flat vertical indentations where curtain folds are deep to horizontal crevices where they are shallow.

Phase Three

A set of new differential growth patterns was created for Merchiston Park. The aim was to augment the surface area of panels and slow down water run-off. This allows the material to absorb and retain moisture **(63–4)**.

58



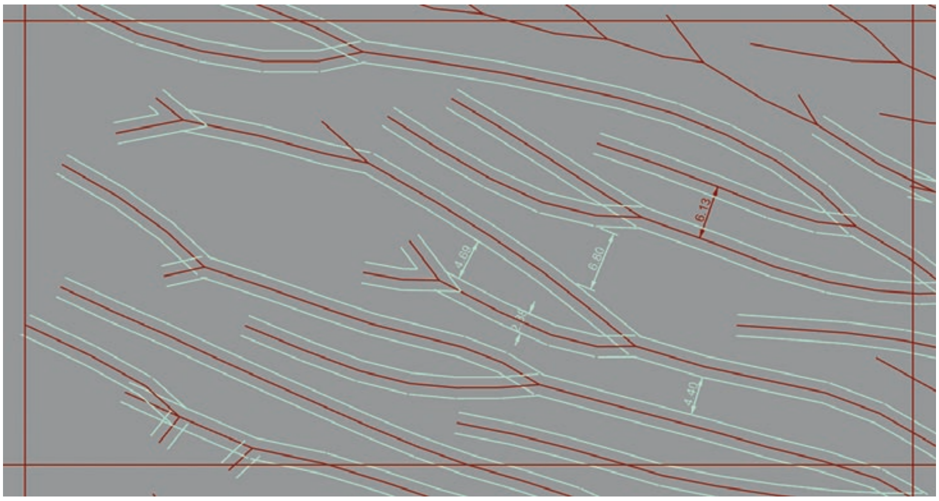


59

58 Preliminary curtain tectonic for East Putney Underground Station, London.

59 Bioreceptive wall for East Putney.

60



61

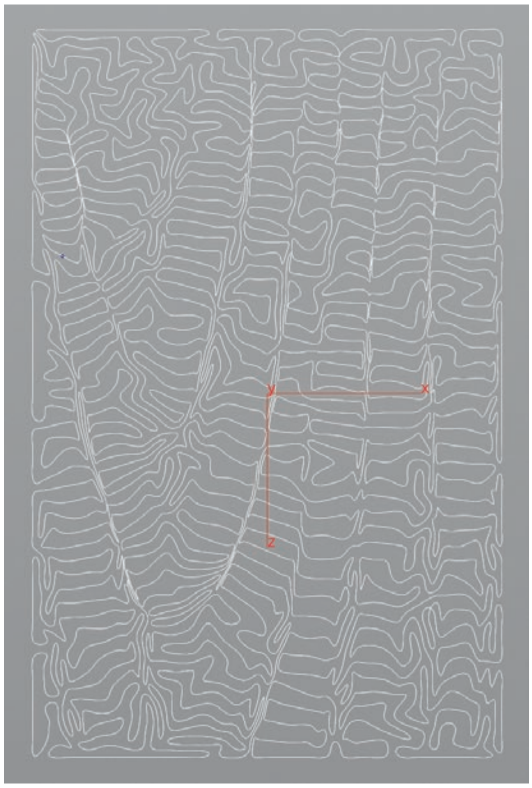
62

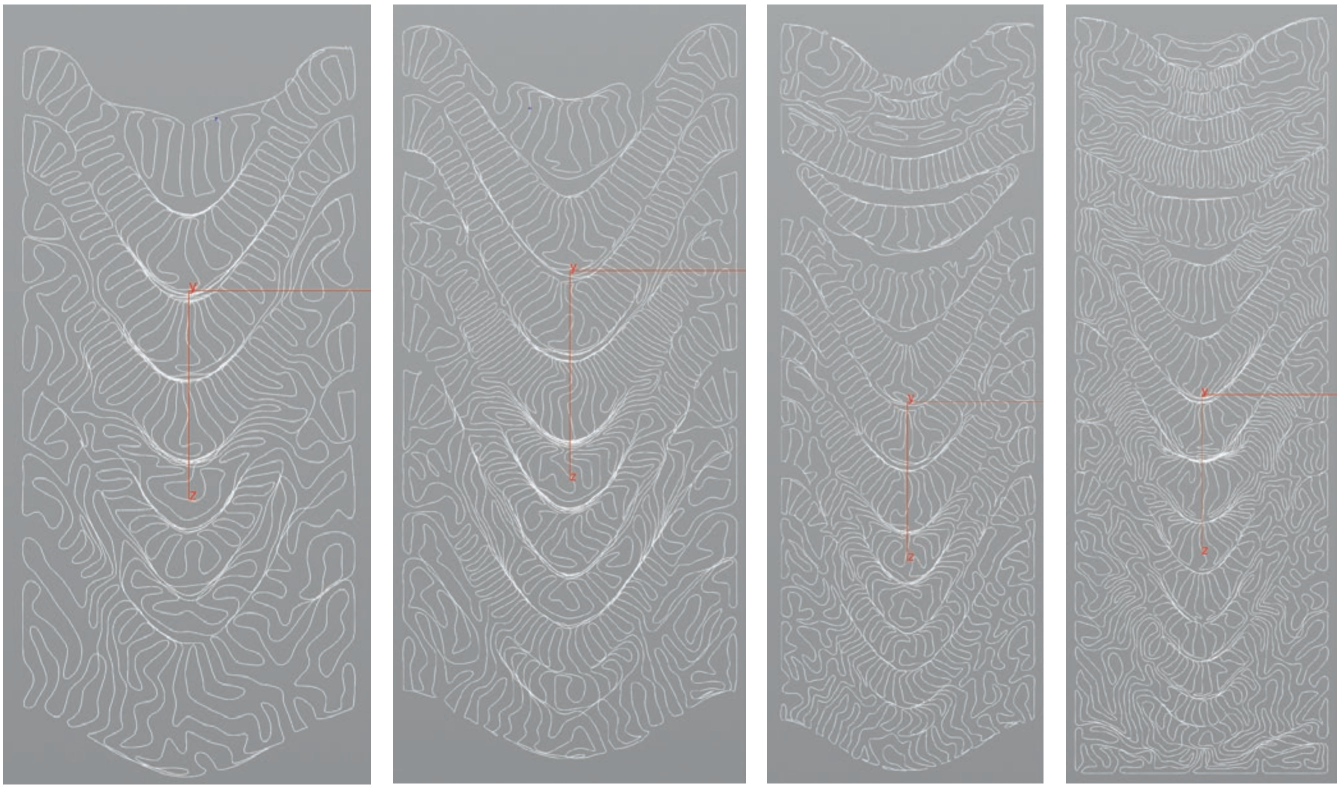
60 Final curtain tectonic for East Putney.

61 Adjustment of crevice width in the branching system.

62 Final wall morphology for East Putney, which is divided into 20 horizontally juxtaposed panels of 500 × 1,000 mm.

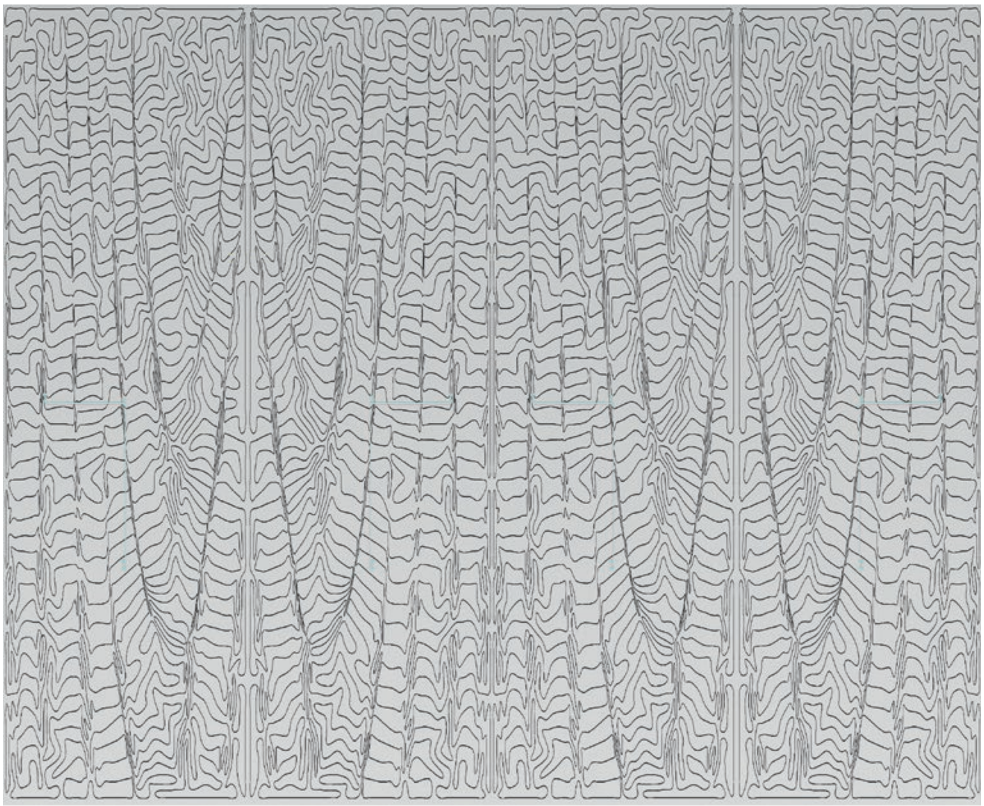

y
x
z

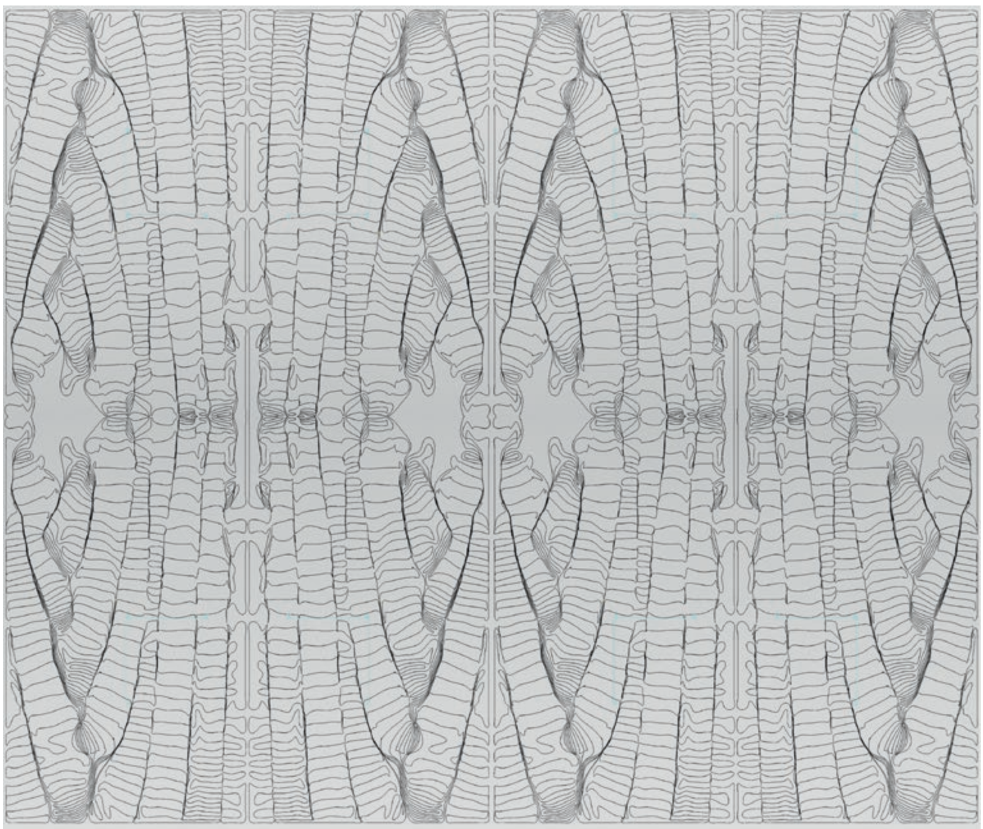

y
x
z



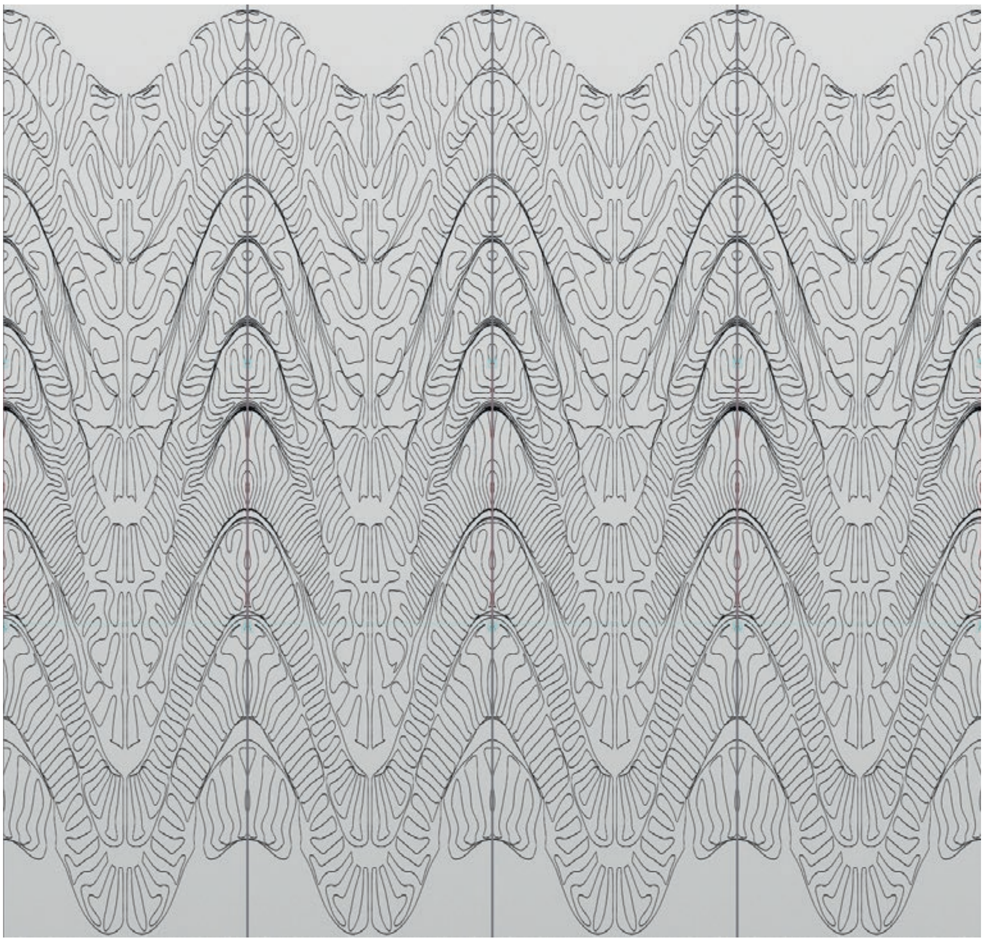
63

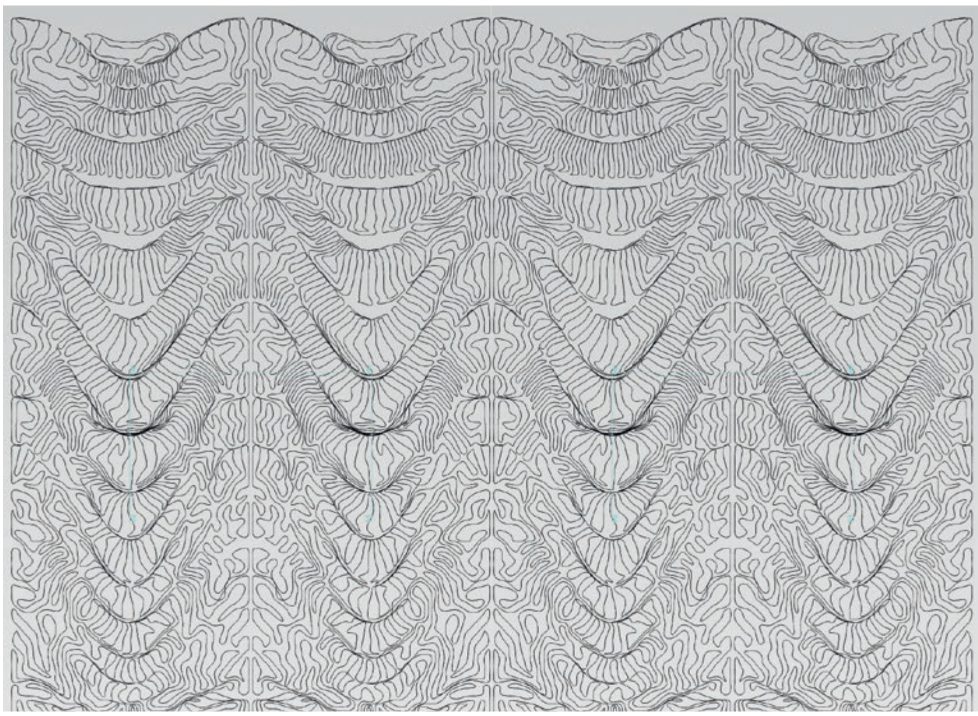
63 Pattern study for
Merchiston Park, Edinburgh.





64 Wall study for Merchiston Park, Edinburgh.





64

3. Biological/Environmental Tests and Observational Studies

Phase One

A community dynamics test was conducted to compare the evolution of microbial and algae communities on different panel sizes, both indoors and outdoors, and in varying conditions of humidity and irrigation. Metagenomics tests were carried out with samples collected at four different times. Molecular data was then analysed using bioinformatics, allowing for the characterisation of microbial biodiversity in 14 points/samples after one year of exposure. Three further tests were conducted on samples that were then compared with small outdoor panels as part of an observation study to monitor water content with three volumetric water sensors (VWS).

Different species of algae and moss were tested on 18 large-scale OPC and MPC panels in an outdoor exposure study, over a period of a year, to understand the viability of motile, non-motile and filamentous species **(71, 73)**. Later, a selection of moss species was collected from the local area and mixed into a shake; this was applied to the right side of each panel to allow for comparison with the left **(72)**. All studies considered the complementary relationship between the seeding process, the nursery period with controlled irrigation and the growth period dependent on climate.

A series of environmental studies was carried out to track growth on the panels. This included:

- Collecting climatic data from an automatic weather station (AWS) measuring wind speed and direction compared to the prevailing norms for London;
- Measuring sub-surface temperature using incorporated sensors in both the MPC and OPC panels to show diurnal and seasonal fluctuations **(68)**;
- Collecting and measuring water run-off in a tray underneath the mounted panels
- Chemically analysing coloured water collected from the MPC panels **(66–7)**.

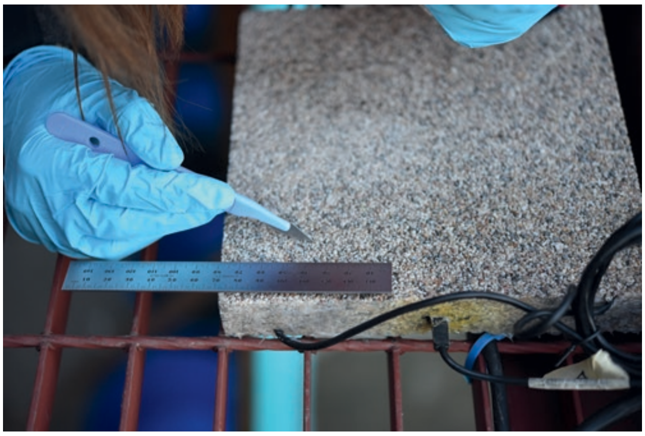
36 measurement channels, including volumetric water sensors and a water run-off instrument logger fed into a database that was analysed using MatLab software. A robotic photographic survey of panels was carried out from a fixed vantage point in regular intervals of two weeks **(69, 74–5)**. Two 3D LiDAR surveys were also carried out. The point clouds were coordinated with the photographic survey and were analysed for vertical rain catchment.

	Units	Lab. Sample Code No. H11048-1	Lab. Sample Code No. H11048-2
Magnesium, Dissolved	mg/l	1.3	21
Phosphorus, Total	mg/l	5.8	5000
Suspended Solids	mg/l	6	710
Ammoniacal Nitrogen as N	mg/l	<0.015	32
Nitrate as N	mg/l	1.1	0.88
Nitrate as N	mg/l	0.046	0.20
Ortho Phosphate as P	mg/l	4.9	5900
Silicate as Si02	mg/l	<0.10	<0.10

65


66


67


68


69

65 Analysis of rainwater run-off from MPC and OPC panels.

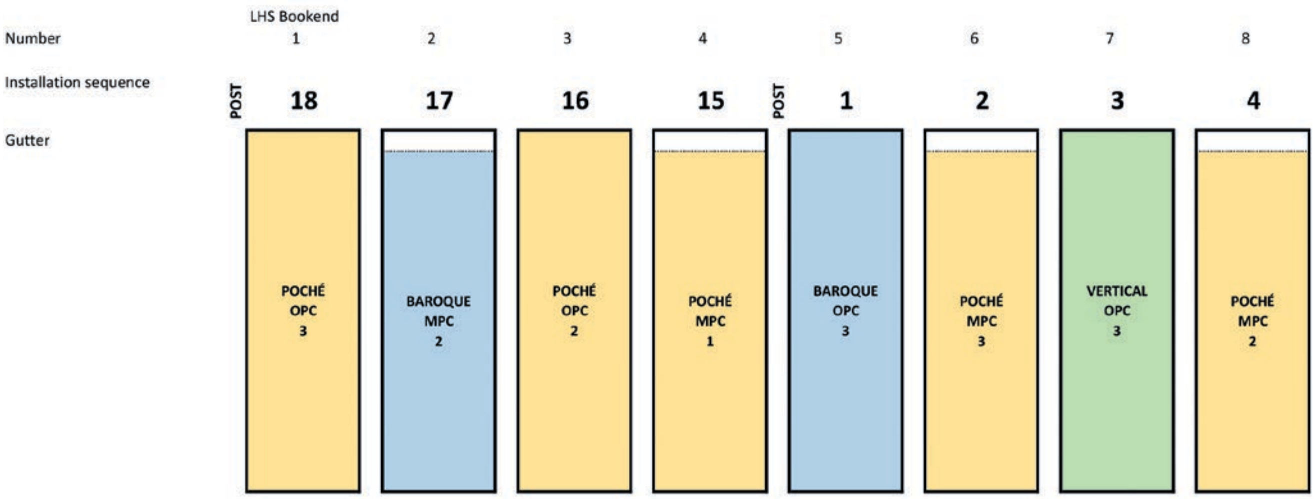
66 Sample of rainwater run-off from OPC panels.

67 Sample of rainwater run-off from MPC panels.

68 Outdoor testing of MPC samples (200 × 200 mm).

69 Apparatus for the photographic survey.

Front north-facing elevation of panels for observation study (2016 to 2017)



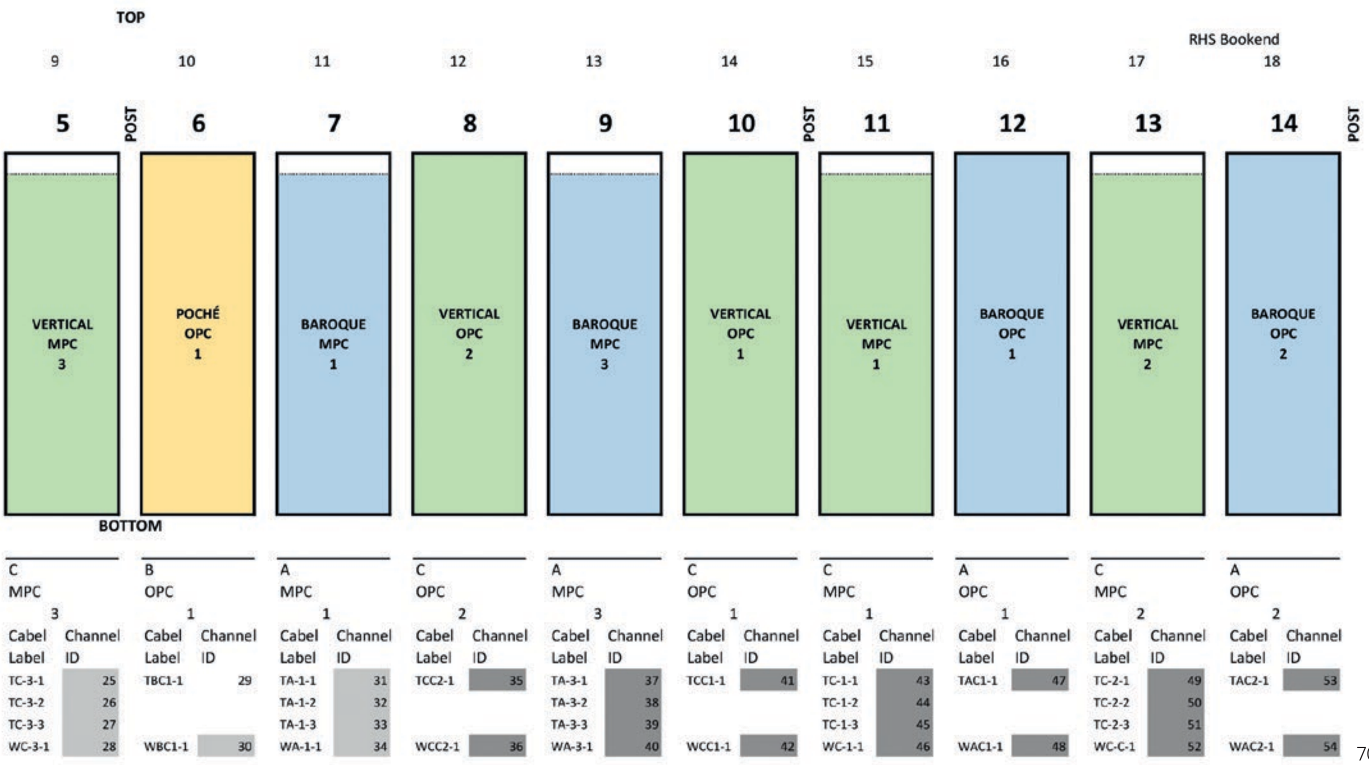
Design		B		A		B		B		A		B		C		B	
Type		OPC		MPC		OPC		MPC		OPC		MPC		OPC		MPC	
Number		3		2		2		1		3		3		3		2	
	Panel location	Cabel Label	Channel ID	Cabel Label	Channel ID	Cabel Label	Channel ID	Cabel Label	Channel ID	Cabel Label	Channel ID	Cabel Label	Channel ID	Cabel Label	Channel ID	Cabel Label	Channel ID
Temp	EXPOSED	TBC3-1	1	TA-2-1	3	TBC2-1	7	TB-1-1	9	TAC3-1	13	TB-3-1	15	TCC3-1	19	TB-2-1	21
sensor	INTERMEDIATE			TA-2-2	4			TB-1-2	10			TB-3-2	16			TB-2-2	22
ID	SHELTERED			TA-2-3	5			TB-1-3	11			TB-3-3	17			TB-2-3	23
Run-off Water sensor ID		WBC3-1	2	WA-2-1	6	WBC2-1	8	WB-1-1	12	WAC3-1	14	WB-3-1	18	WCC3-1	20	WB-2-1	24

Key

Design A	BAROQUE
Design B	POCHE
Design C	VERTICAL

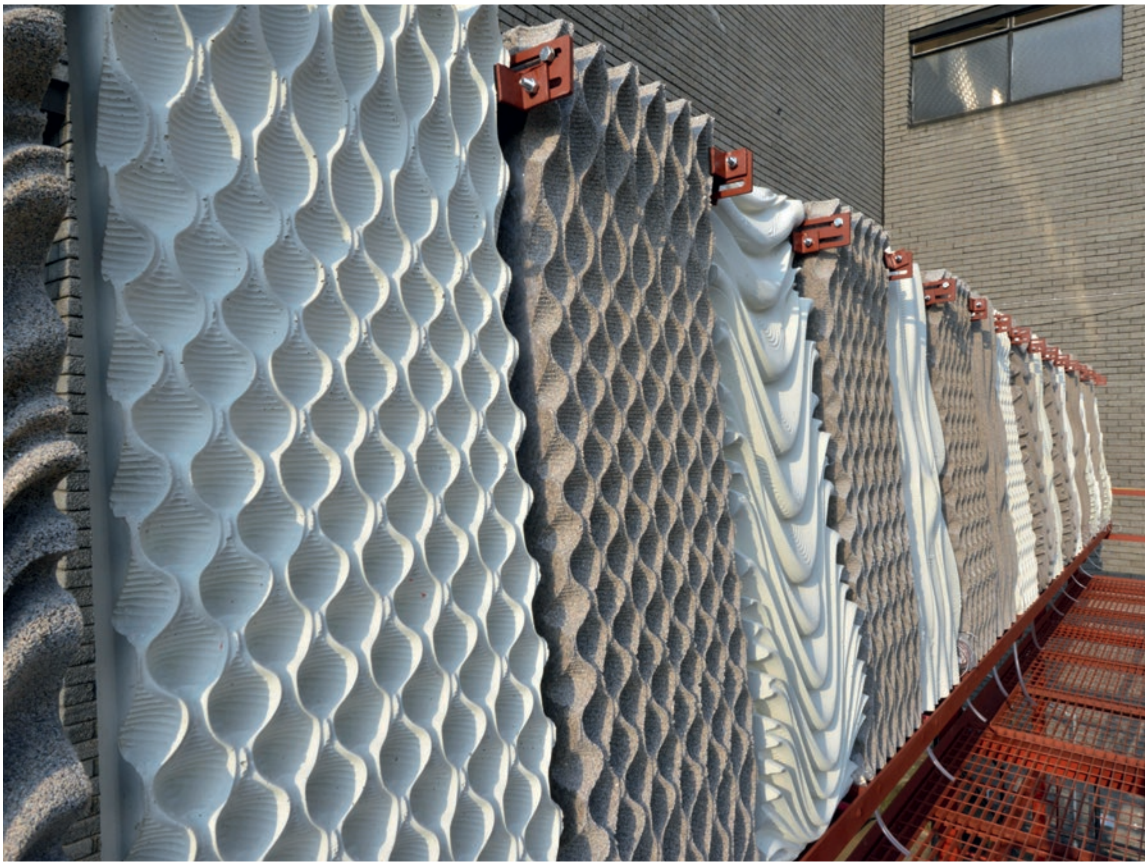
Logger module

CEM20/106700
D80
CEM20/?



70

70 Drawing of sensor logger to measure the thermal variance of the surface and interior of the panels.



71

71 18 MPC and OPC bioreceptive panels exposed outdoors at The Bartlett, UCL, 2016.

72

72 A moss shake was applied to half of each panel, consisting of: *Bryum Capillare, Tortula Muralis, Grimmia Pulvinata, Hypnum Cupressiforme, Trichostomum sp*. and *Homalotecium Sericeum*.

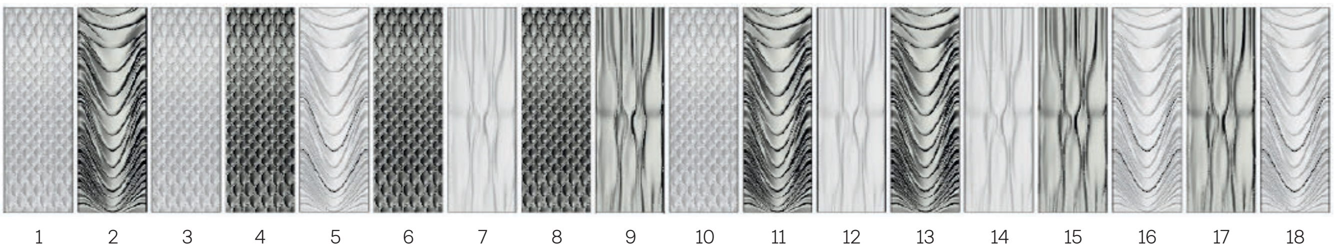
73

73 18 bioreceptive concrete panels as part of a 12-month outdoor exposure trial at The Bartlett, UCL, 2016.

74

74–5 (overleaf)
Photographic survey of the
18 MPC and OPC panels.

75



76

76 The panels are mounted at first-storey height and are arranged in a random order. They represent a north-facing façade with partial sheltering to the south and west.

4. Conclusions

1. Colour variations on MPC panel surface, from brown to white, resulted from: (a) intense evaporation activity and (b) chemical leaching from within the panels after rainfall **(78)**;

2. There was no sign of biological growth on the MPC panels. There was also no evidence that the possible cooling effects from surface evapotranspiration affected superficial growth. In order to test biological growth in optimal conditions, a further two-week algae-fouling test was carried out, which still did not show growth;

3. All tests confirmed that both residual chemical surface properties and porosity created an unexpected inhibitor for growth in a single annual cycle;

4. Algae and moss growth were evident in specific areas of OPC panels that had no porosity and, therefore, offered water catchment areas in horizontal crevices **(79)**. This was significant proof that the surface morphology on its own – independent of its material chemistry, pH and porosity – has a vital role in creating bioreceptivity on concrete panels.


77


78

77 Detail images of MPC panels with struvite formation on the material's surface.

78 Leaching effect of boric acid on the porous surface of an MPC panel.

79

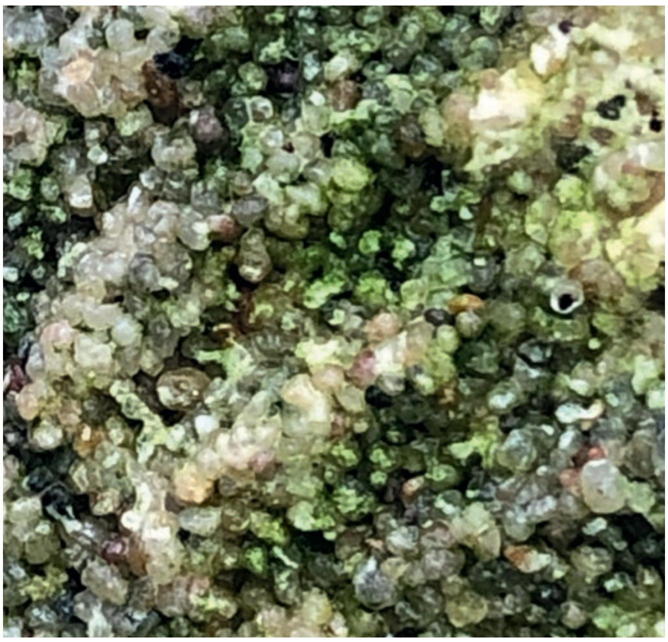
79 Evidence of moss growth on an OPC panel after 12 months of outdoor exposure.

Phase One

An EPSRC observation study was conducted with an MPC panel for two additional years in other locations in London, finally showing a mild presence of algae in selected areas. The panel was first exposed at Camley Street Natural Park in an inclined manner for over a year. Following this, it was relocated to Meanwhile Gardens and was positioned in a vertical manner with a slight inclination **(81)**. Another set of multi-material bioreceptive MPC panels was exposed at Camley Street Natural Park and showed evidence of algae growth after two years **(80)**. These studies demonstrated that more time was necessary for porous MPC panels to become bioreceptive, possibly to allow uncured chemicals in the material to be washed out. The studies also showed that vegetation in the surrounding parks created an inducive context for bioreceptive growth, due to heightened moisture and shading of trees as well as the release of algae and spores from adjacent plants.

Phase Two

Different types of moss were considered for transplantation onto the St Anne's and East Putney projects. Three were chosen – *Bryum Capillare, Tortula Muralis, Grimmia Pulvinata* – according to their resilience during the grafting process, speed of establishment, occurrence on vertical and concrete surfaces, dehydration tolerance and aesthetic qualities. In parallel, hydrogels were deployed to promote initial adhesion of moss to the TecCast panel and protect it in the early stages of growth. A variety of cross-linked hydrogel materials were tested.



80

80 Selective algae growth on a multi-material MPC prototype after 24 months of outdoor exposure at Camley Street Natural Park, London.

81 Algae growth on an MPC baroque panel after 12 months of outdoor exposure at Camley Street Natural Park and 12 months at Meanwhile Gardens, London.

81

Phase Three

Colonisation-rate tests were carried out on different substrates, assessing the compatibility between these materials and the species of moss. An ongoing study considers other bacteriological factors that could enhance moss propagation, informed by in-situ observations of bryophyte colonies and lab experiments. These include:

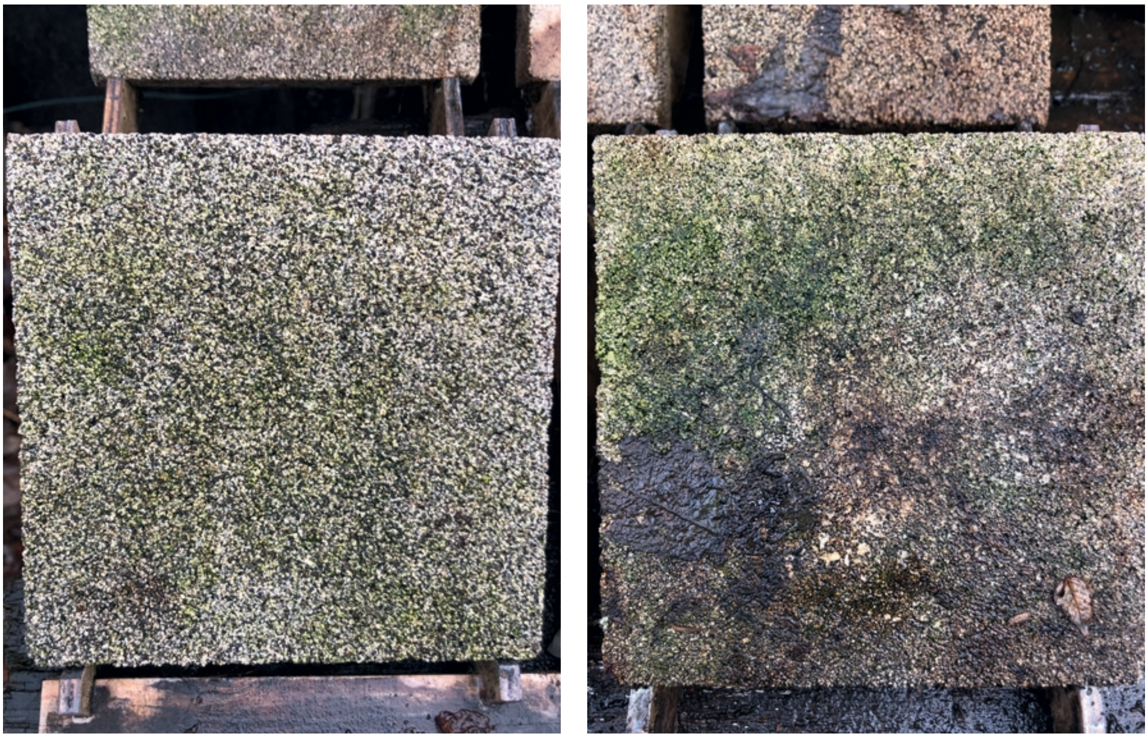
- Isolation of methylobacterium, cyanobacteria, nitrogen-fixing bacteria and other epiphytic microorganisms to understand the functional diversity of the moss microbiome;
- Cultivation of epiphytic microbial species in a liquid medium for the development of probiotic biogenic binder and liquid probiotic consortia to promote the establishment of moss;
- Impact assessment of specific probiotic treatments on in-vitro growth of three moss species;
- In-situ growth-rate documentation of different moss species according to specific concrete substrate compositions.

Corkcrete samples exposed for 12 months in various London locations showed that those with larger-scale cork aggregates and a higher presence of cork on the surface became biocolonised with algae **(83–4)**. When compared with the slow growth on MPC panels, the selected Corkcrete samples proved to be more bioresponsive, even hosting moss and lichen after a single winter cycle.

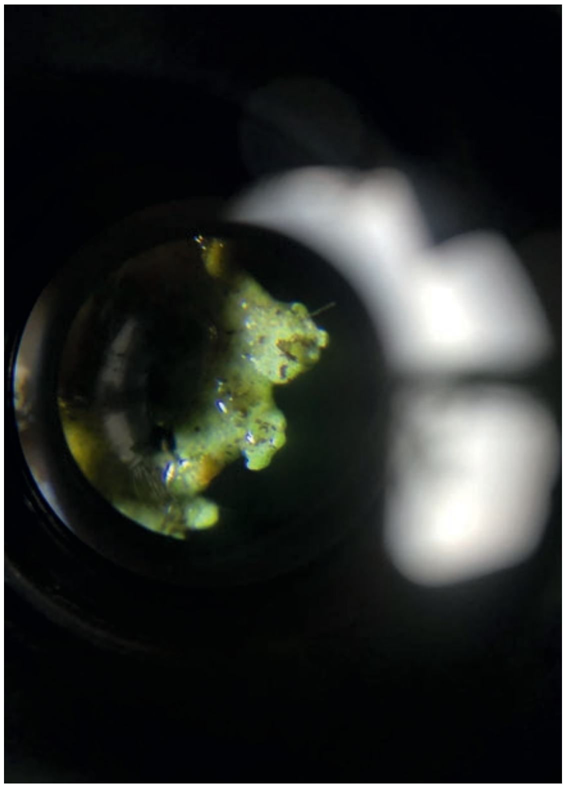
83

82 (previous) Poikilohydric living wall installed on a north-facing wall in the playground of St Anne's Catholic Primary School.

83 Weathering of Corkcrete samples after 12 months of outdoor exposure. There is evidence of algae and moss growth on those with a higher percentage of cork.



84



85

84 Algae, moss and lichen growth on Corkcrete samples after 12 months of exposure at Meanwhile Gardens, London.

85 Microscopic image of lichen.

Dissemination

Publications and Interviews

The research has been disseminated in one peer-reviewed journal article written by Cruz published in *Architectural Research Quarterly* (2016), and two chapters in the books *Meeting Nature Halfway* (2018) and *Design with Life* (2020) – all included in the Appendix, see pp. 85–112. It has been discussed in a range of diverse publications, e.g. *Étapes Magazine* (2019) and *The Sunday Times* (2019), and has featured in exhibition catalogues for the *Cooper Hewitt Design Triennial* (2019) and *La Fabrique du Vivant* at Centre Pompidou, Paris (2019). Cruz has been interviewed in *IaaC Bits/Black Ecologies* (2019), *Arredamento MIMARLIK* (2019) and on *BBC Earth* (2016).

Films

- *10 Great Inventions* (2020). Directed by Jim Turner. London: OfftheFence
- *Virtual Pavilion SuperCity* (2019). Directed by Tom Kovac

Exhibitions

- *Design Future*, Philadelphia Museum of Art (2019)
- *Cooper Hewitt Design Triennial*, Cube Design Museum, Kerkrade (2019)
- *Cooper Hewitt Design Triennial*, New York (2019)
- *La Fabrique du Vivant*, Centre Pompidou, Paris (2019)
- *New Forms of Practice / Drivers of Change*, The Arup Gallery, London (2019)
- *Futurebuild: The Shape of Things to Come*, ExCeL, London (2019)
- *Bio-ID*, London Design Festival (2018)
- *Ecobuild*, ExCeL, London (2018)
- Norman Foster Foundation, Madrid (2017)
- *Ecobuild*, ExCeL, London (2017)
- *Super Materials*, Building Centre, London (2017)
- *Biofabricate*, Ecobuild ExCeL, London and Microsoft and Parsons School of Design, New York (2016)

Built Living Walls

An important form of dissemination has been the installation of materials and designs in public spaces. First, bioreceptive materials have been installed in various gardens across London; second, two bioreceptive walls have been designed: one installed at St Anne's Primary School, the other due to be installed at East Putney Underground Station (late 2020).

Project Highlights

This research is one of the first attempts to systematically explore the potential for bioreceptive building façades. Its significance must be considered within the context of the current climate crisis. Its potential to address environmental challenges connected to urban life was first recognised by UK Research and Innovation (with an EPSRC grant). Further phases of the research have been sponsored by governmental organisations, such as Transport for London, and have been advanced through collaborations with commercial companies, such as Laing O'Rourke. Manufacturing feasibility has been developed in collaboration with Pennine Stone, making the panels cost-efficient in terms of structure, material and casting techniques, and potentially viable for mass production.

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