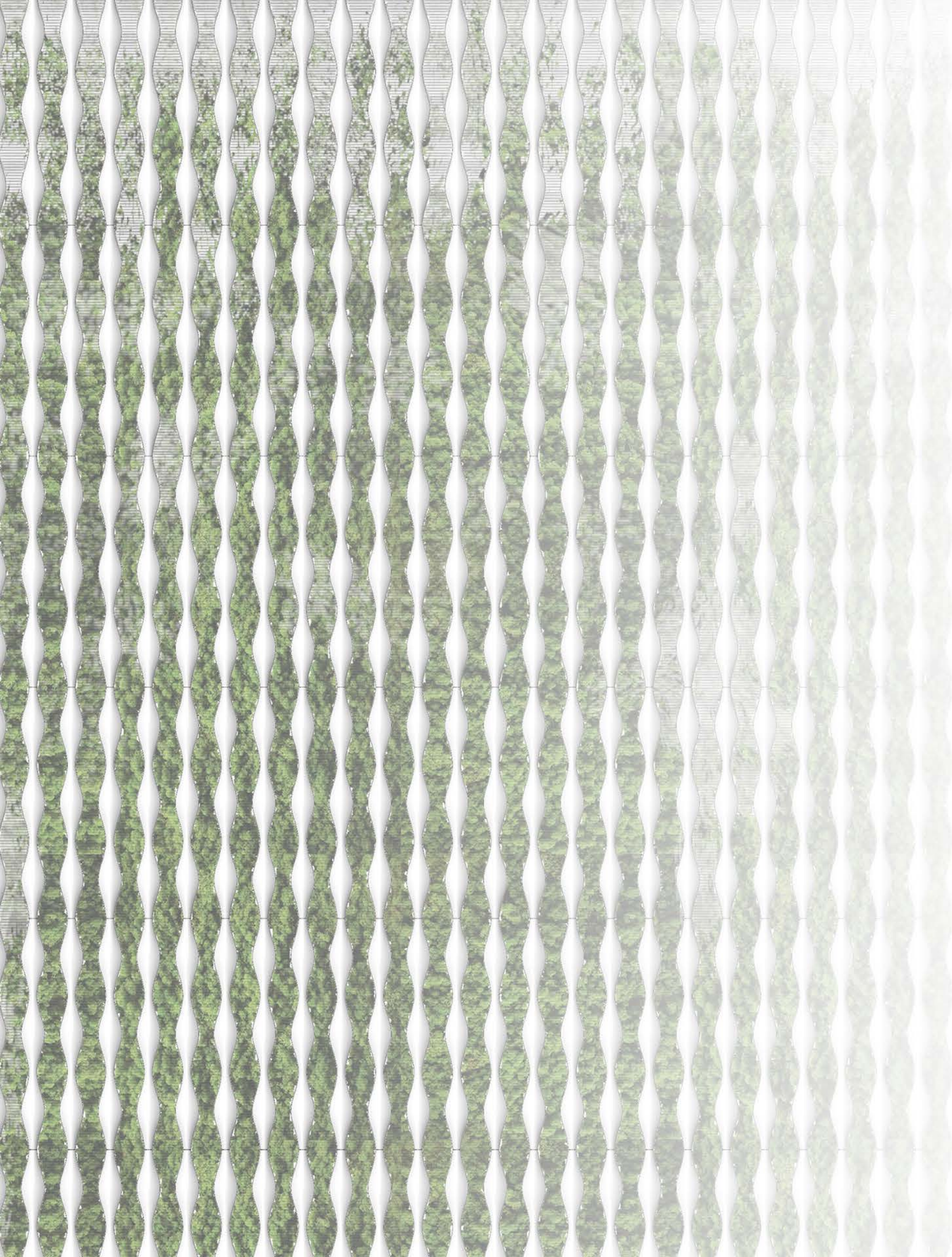

Geometrically articulated
Bio-receptive concrete facades

p5 presentation

26/06/2020

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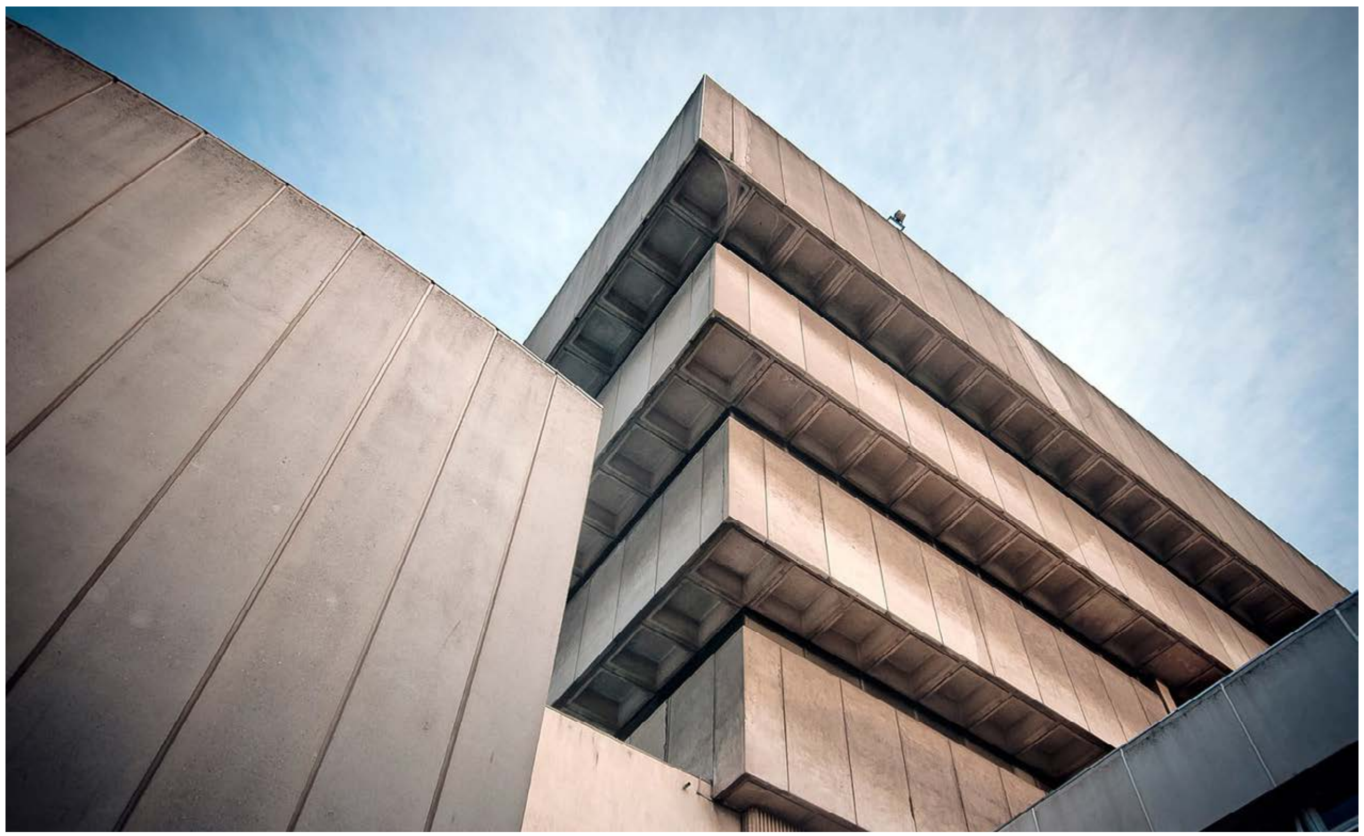
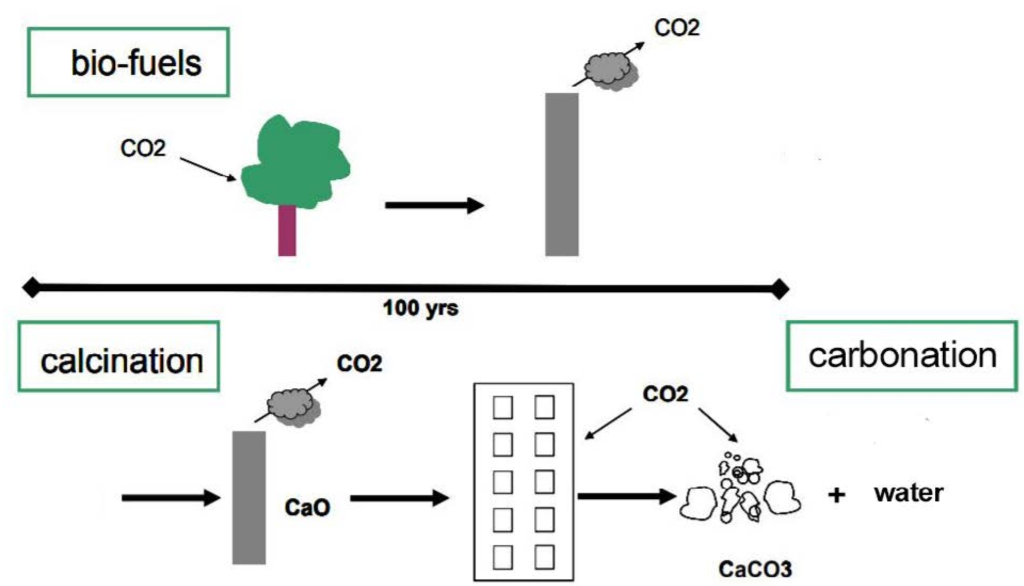
1. Background

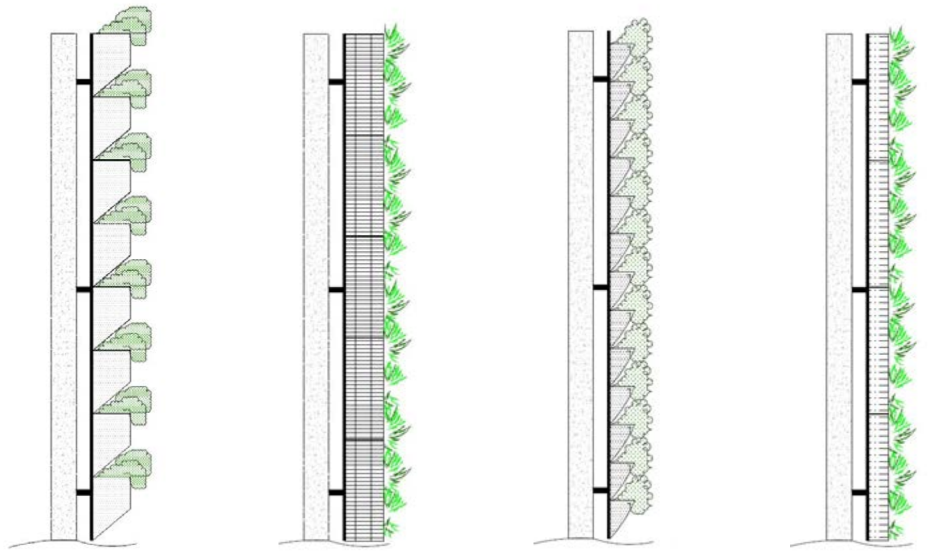


Concrete construction
8% of the total CO_2 emissions worldwide

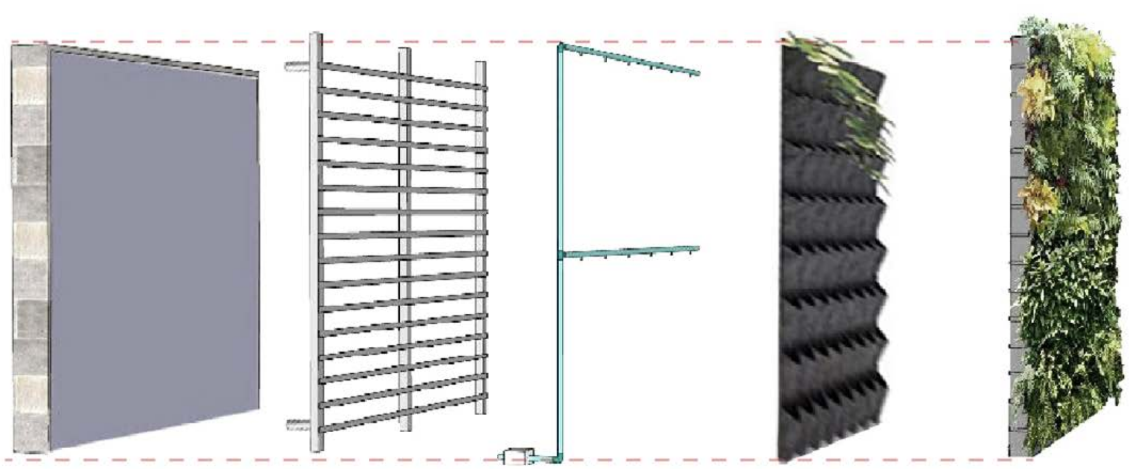
57% CO_2 uptake
by concrete structures



GREEN WALLS IN PRACTICE

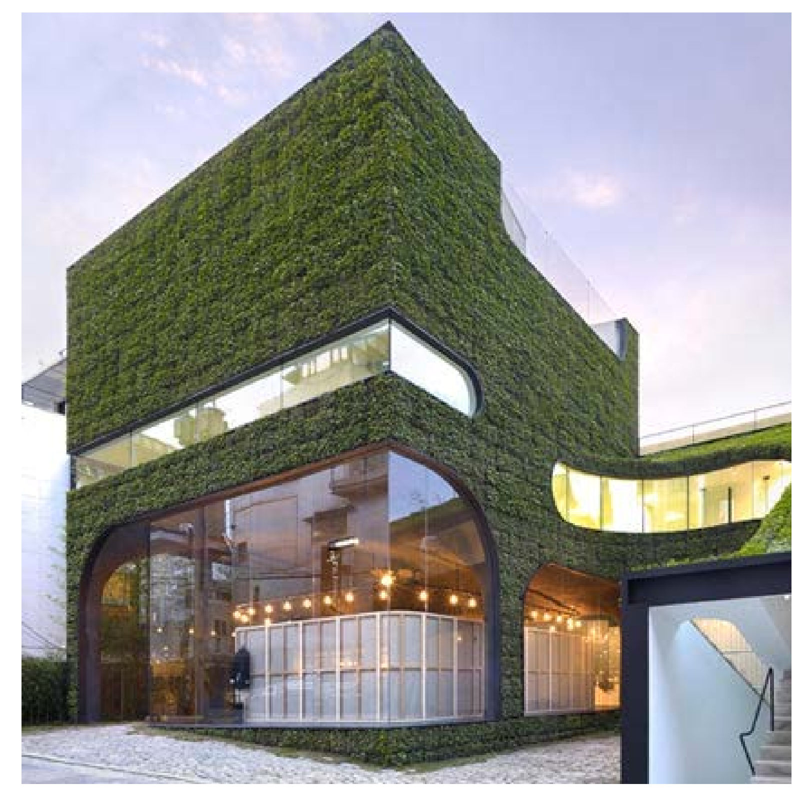


Planter boxes | Foams | Layer of Geotextile | Mineral wool



Waterproof layer | Steel frame | Irrigation | Geotextile layer | Plants

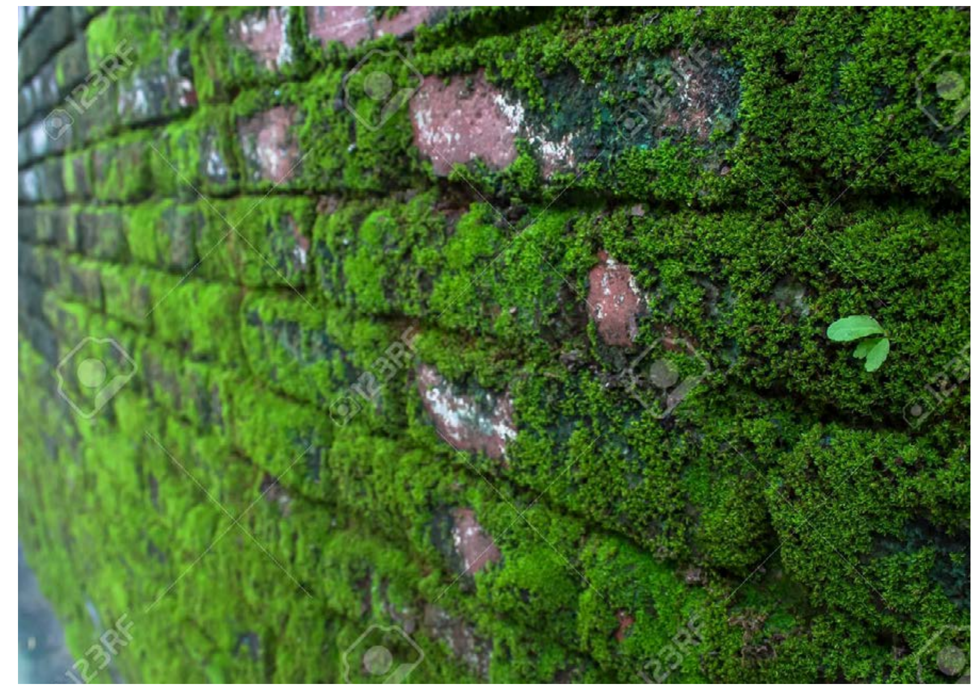
USA Pavilion - Milan Expo 2015 by Biber Architects



Ann Demeulemeester Shop in Seoul by Mass Studies

As defined by Guillitte in 1995

'The aptitude of a material (or any other inanimate object) to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration.'

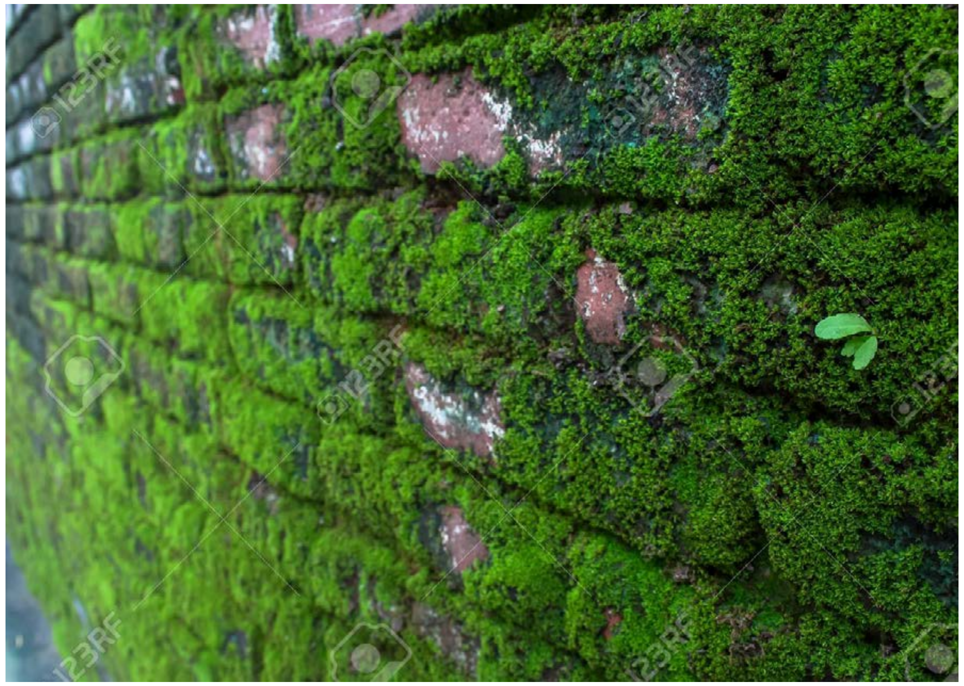


An alternative term to Bio-Receptivity is Bio-colonization (Cruz & Beckett, 2016)

'Surface growth of plants upon a material is known as biological colonization.'

As defined by Guillitte in 1995

'The aptitude of a material (or any other inanimate object) to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration.'



An alternative term to Bio-Receptivity is Bio-colonization (Cruz & Beckett, 2016)

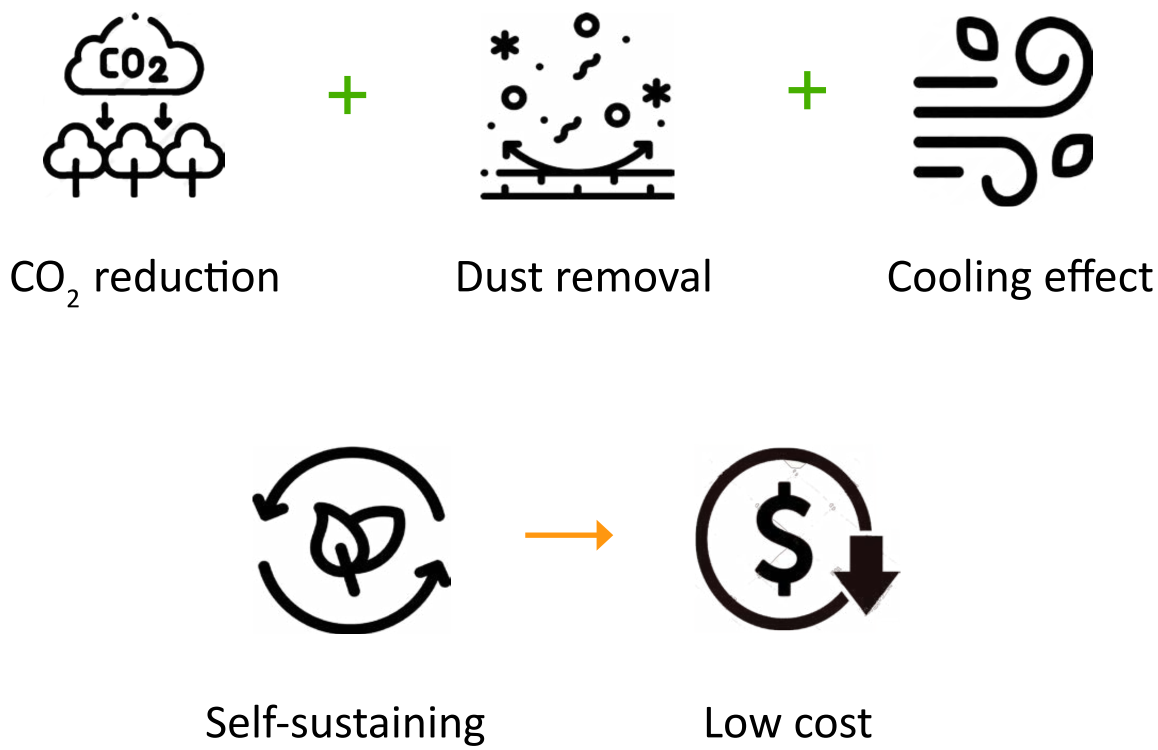
'Surface growth of plants upon a material is known as biological colonization.'

a

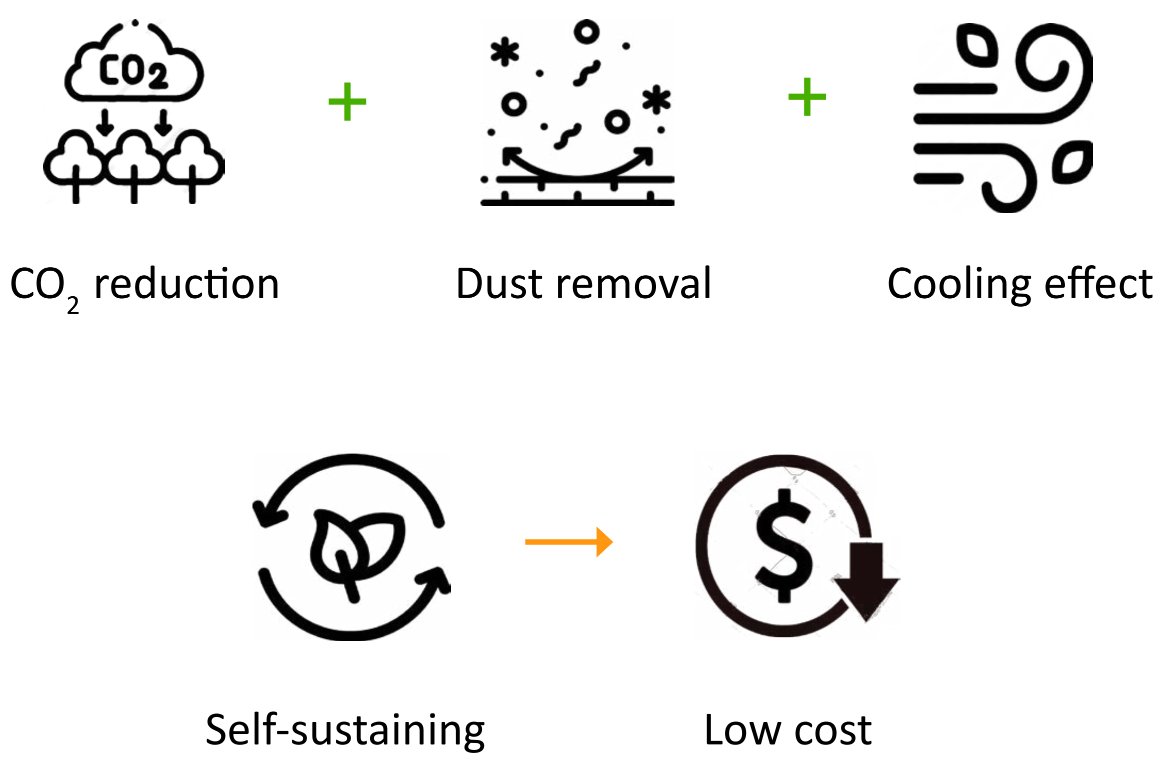
b

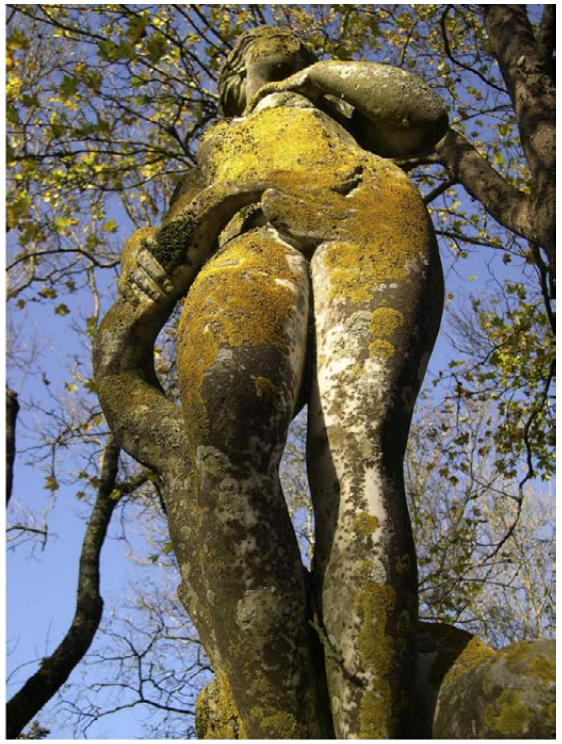
a. Facade of San Telmo Museum Spain, 2011

b. GRC limestone concrete panels UCL Bartlett, 2017


CO_2 reduction
Dust removal
Cooling effect
Self-sustaining
Low cost

BENEFITS OF BIO-RECEPTIVITY




Moss and algae on sculpture


Moss on brick wall

Problem statement

Despite the benefits of a Bio receptive façade, it is often viewed as a deteriorating factor in building envelopes. Hence, an ordered and systematic approach to moss growth could help change the perception of people and designers, promoting its widespread use.

Objectives

- Create order & balance in moss growth
- Test the role of geometry
- Engineer an optimized facade system

Main research question

What is the role/impact of surface geometry on an engineered/systematic growth of mosses on concrete facade panels?

Sub research questions

Background Research:

1. What are mosses? What is the biological growth pattern of mosses?

2. What factors influence the growth of mosses on stony materials (mainly concrete)?

Validation of Design:

5. How to measure the workability of a geometrically articulated bio-receptive concrete façade?

6. What is the impact of the micro and macro elements of geometry on water relations of the surface?

Design by Research:

3. What are the different geometry types and their possible applications in façade design?

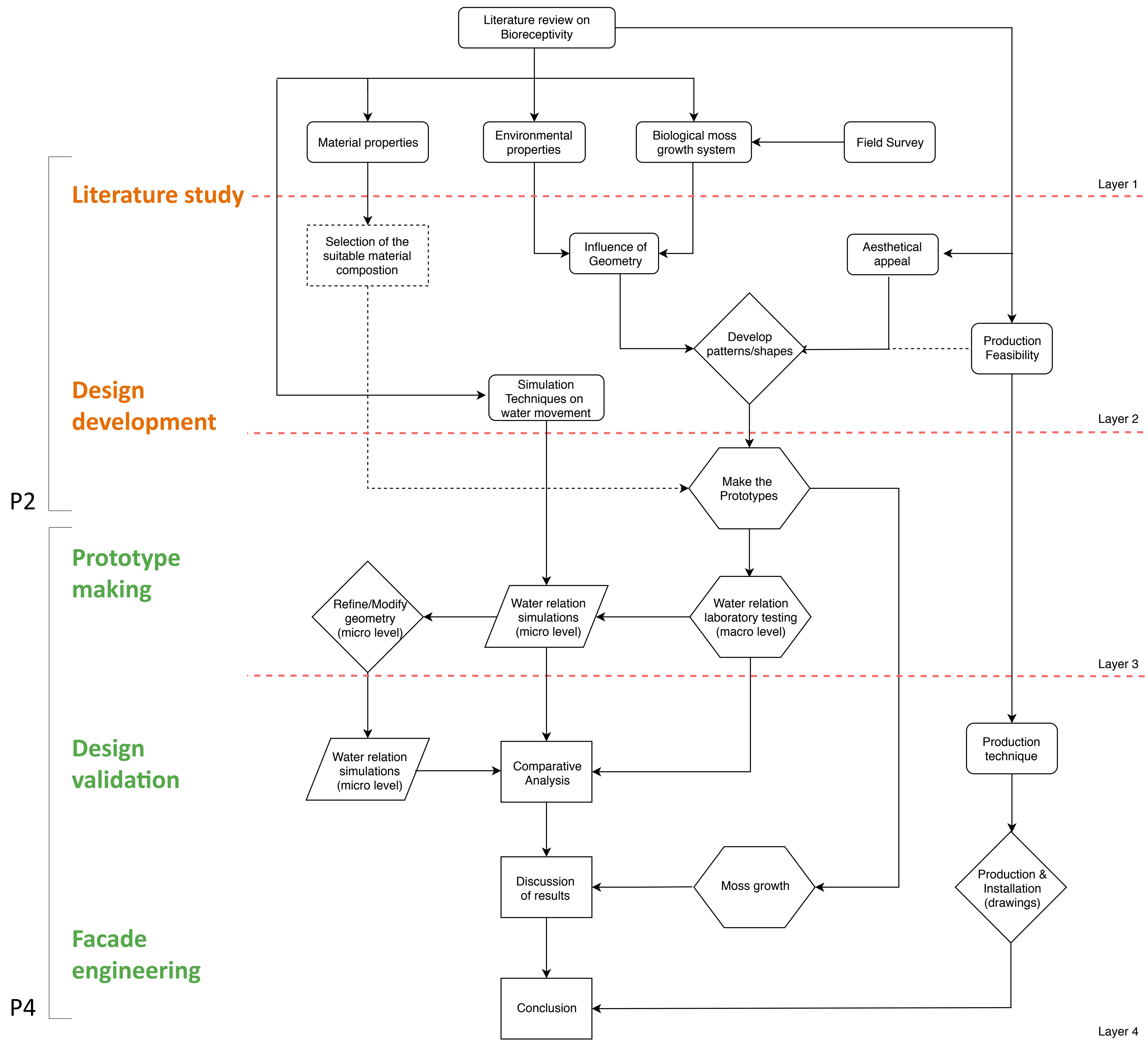
4. How can geometry be used to engineer a self-sustaining moss growth system on concrete panels?

Façade Engineering:

7. What is the most feasible production technique to make the designed geometries?

8. How to design an optimized façade panel to facilitate a simple and efficient installation process?

Top down approach
flow chart



Literature study

Design

Experimentation

Simulations

Results

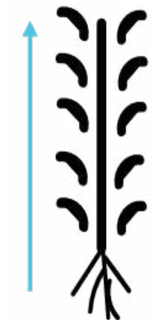
Plant Biology- Moss

Types

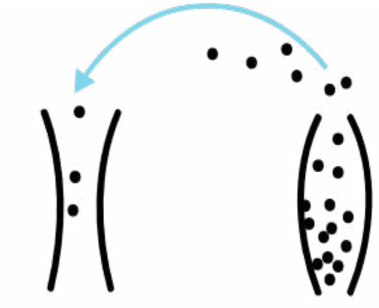
Tortula muralis

Grimma pulvinata

Water essential



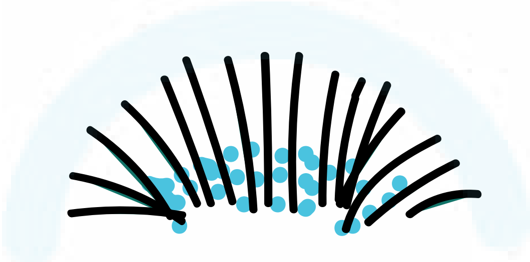
Photosynthesis



Fertilization

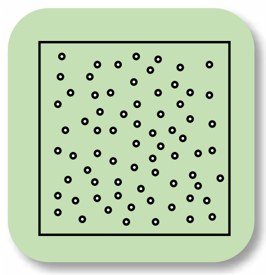
Cushion growth

laminar layer

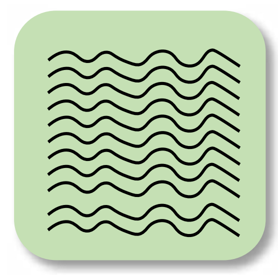


- Prevent evaporative loss
- water storage

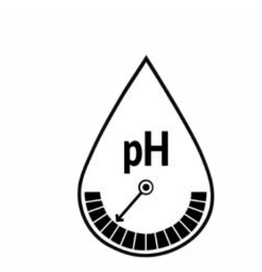
Material properties



High porosity
and permeability



High surface
roughness



Low pH 8-10

Blast furnace
slag cement

Environmental properties

Adequate rainfall

RH 70% ±

10-20 ^{O}C

Scattered sunlight

Low wind

Exploring order and balance in nature


Symmetry


Spirals


Chaos/meanders

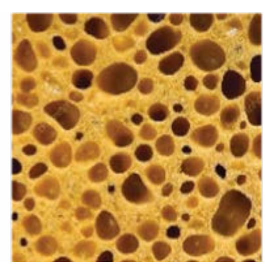

Waves/dunes


Trees/Fractals


Cracks

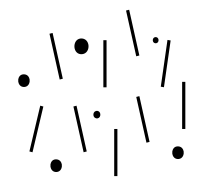

Tessellations

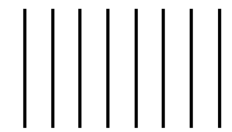

Spots/strips

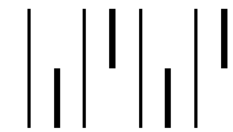

Foam/bubbles

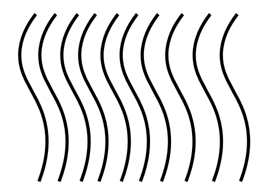
Methods to create surface motifs

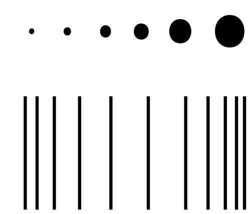
- Repetition
- Pattern
- Rhythm


Random rhythm


Regular rhythm


Alternating rhythm


Flowing rhythm


Progessive rhythm

Exploring order and balance in nature


Symmetry


Spirals


Chaos/meanders

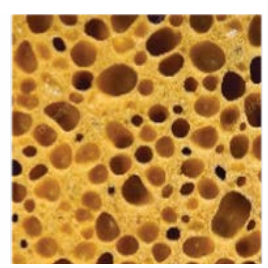

Waves/dunes


Trees/Fractals


Cracks


Tessellations


Spots/strips


Foam/bubbles

Methods to create surface motifs

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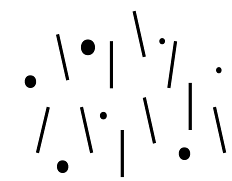
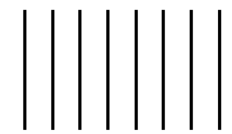
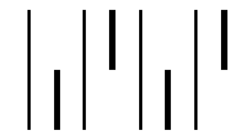
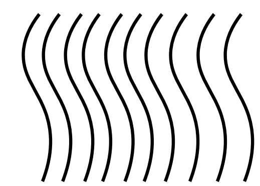
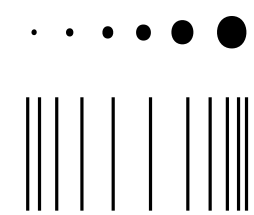

Random rhythm


Regular rhythm


Alternating rhythm


Flowing rhythm

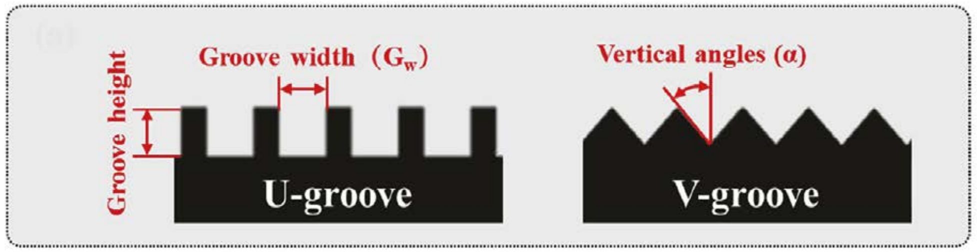

Progessive rhythm

Free-form deformations

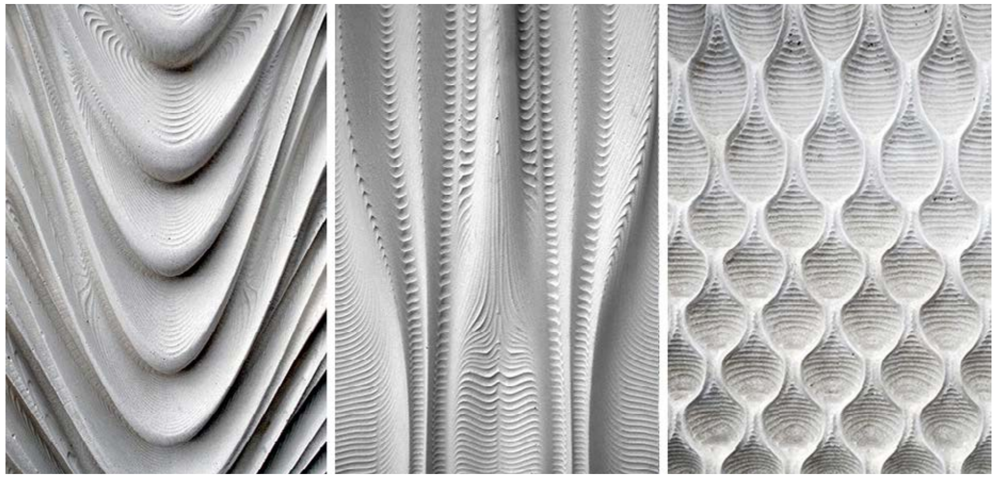
Spatial deformations

Geometry on facade design

Case studies on
geometry influenced Bio-receptivity



1 Microalgae biofilm formation and growth
(Huang et al., 2018)



2 Computational Seeding of Bio-receptive Materials
Marcos Cruz & Richard Beckett, 2016

3 Concrete as a multifunctional material
Ottele et al., 2010

Experimentation

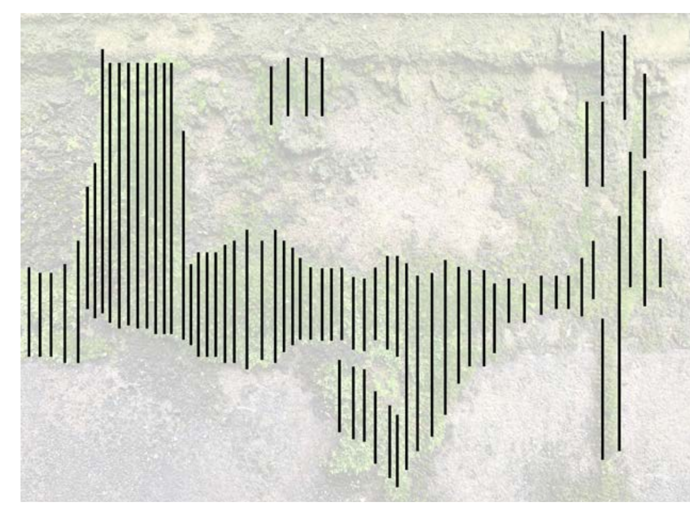
Moss slurry preparation

Application

Outcome

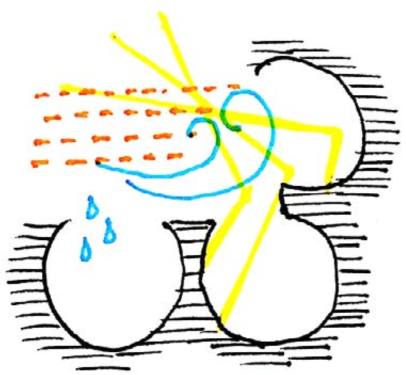
Field survey

- Trail growth
- Imbalance in growth
- Cushion growth
- Deep penetration
- Affinity to rough surfaces
- Shaded and moist areas
- Dependent on material property



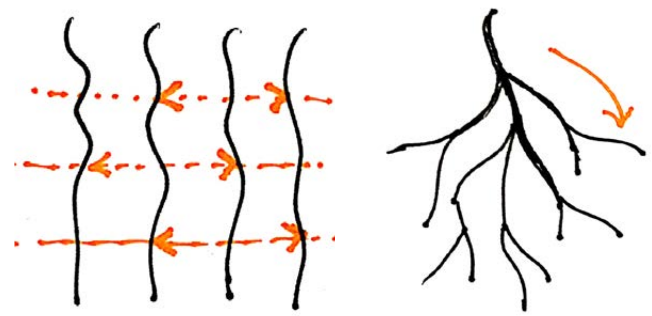
2. Design development

MICROCLIMATE



- Water retention
- Indirect sunlight
- Wind buffer
- Nutrient accumulation

DIRECT ROUTE for growth



- Slow water movement
- Rainwater channeling
- Cushion growth
- Anchorage

PRODUCTION FEASIBILITY

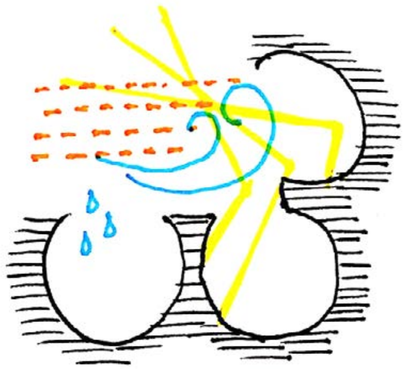
 Net cost

 Material use

 Production process

 Installation

MICROCLIMATE



- Water retention
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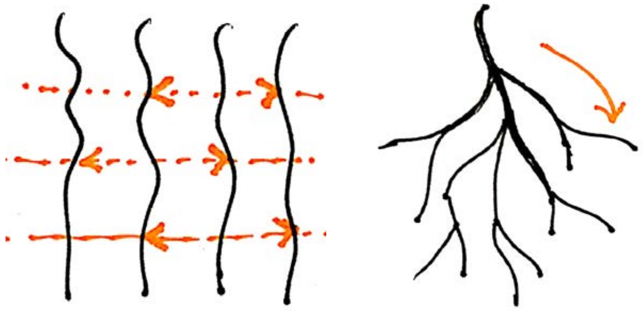
DIRECT ROUTE for growth



- Slow water movement
- Rainwater channeling
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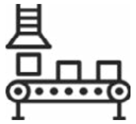
PRODUCTION FEASIBILITY

 Net cost

 Material use

 Production process

 Installation

FACADE
Layer 1 (structural)
Layer 2 (protective)
Layer 3 (Growth)
Layer 4 (No Growth)

ENVIRONMENTAL
Rain
Temperature (10-20 C)
Low light
Low wind speed
High RH (moisture)
North orientation

MOSS TYPE
Saxicolous Moss
Acrocarp
Thrive in exposed surfaces

MOSS STRUCTURE
Dense packing (cushions)
Greater depth of canopy
Self shading

SURFACE MORPHOLOGY/ROUGHNESS
Macro level
Slow water movement
Cushion growth
Shading
Wind buffer

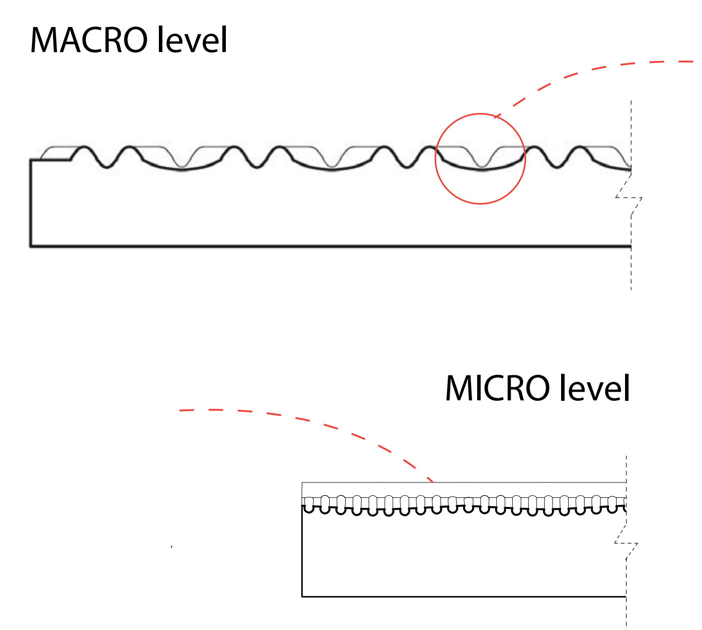
Micro level
Water retention/catchment
Nutrient accumulation
Anchor facility

Macro+Micro level
Rainwater channeling

POROSITY
Microporosity - water retention
Macroporosity - water absorption
Permeability - interconnected pores

CHEMICAL COMPOSITION
Blast furnace cement
Sand (0-4mm)
Gravels/stones (4-8mm)
Water/cement ratio (0.6-0.7)
No curing needed
Setting time: 24hrs

Natural process:
Carbonation
Formation of gypsum

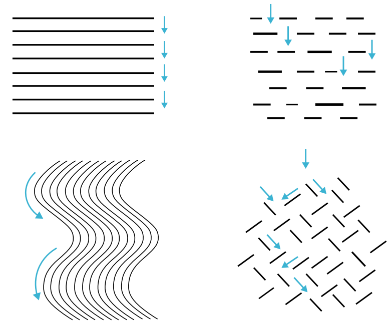


MACRO LEVEL GEOMETRY

also:

Shading
Wind buffer

Slow water movement



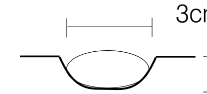
Continuous   Discontinuous

against the flow

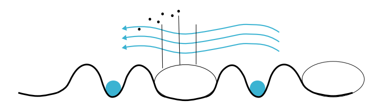
along the flow

Cushion growth

3-5cm (small moss, min. area 3cm2 approx)



1 - 2cm cushion height/ macro depth



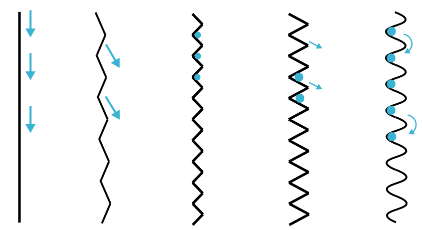
the depth creates a wind buffer

MICRO LEVEL GEOMETRY

also:

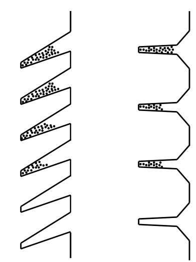
Anchorage facility

Water retention/catchment



Micro-depths (2 - 5mm) increase the duration of water holding

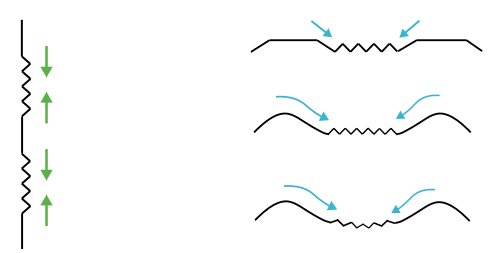
Nutrient accumulation



Deep micro-depths allow dust particles and other nutrients to accumulate ~> 5mm

MACRO LEVEL + MICRO LEVEL GEOMETRY

Channel water to growth areas

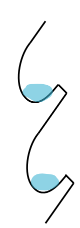


combination of smooth and rough to define growth areas

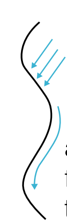
growth areas should always be lower in height

** No water clogging

Macro geometry must not cause water clogging which may result to unhealthy conditions for saxicolous mosses and the surrounding.

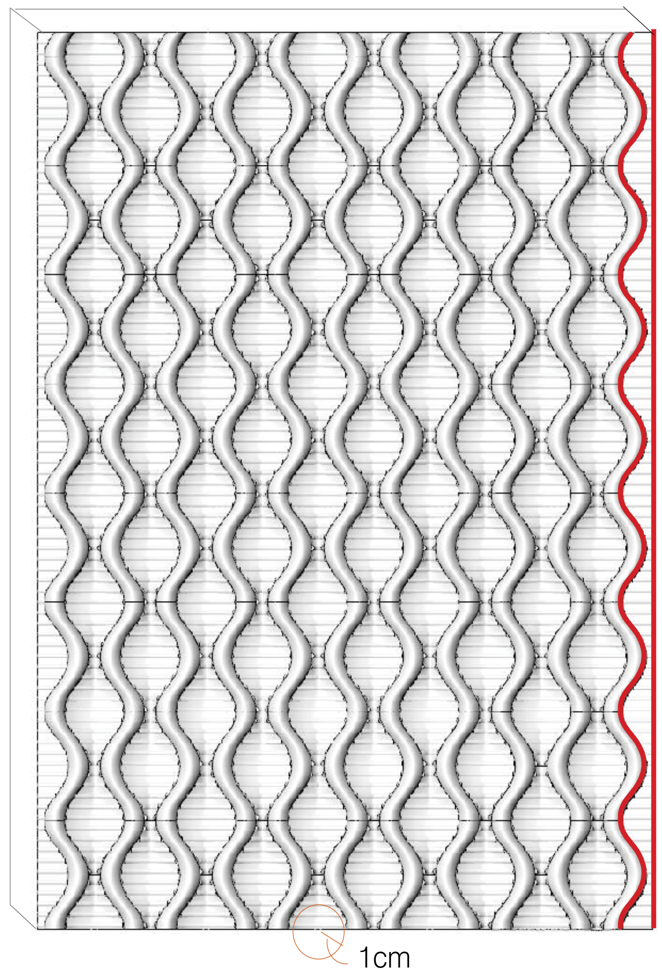


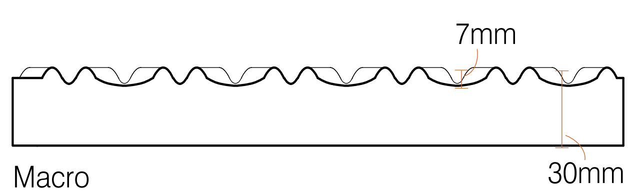
excess of water ceases the growth



an uniform flow through the surface

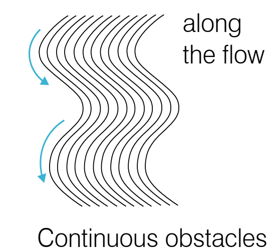
Panel 1



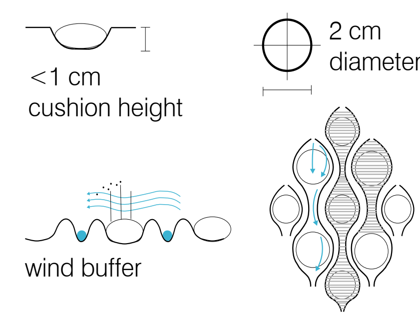


Geometric features applied in alternating rhythm

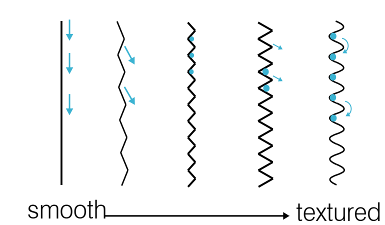
Slow water movement



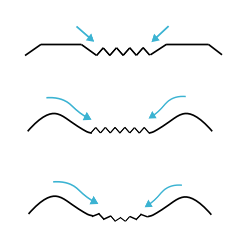
Cushion growth + radial form



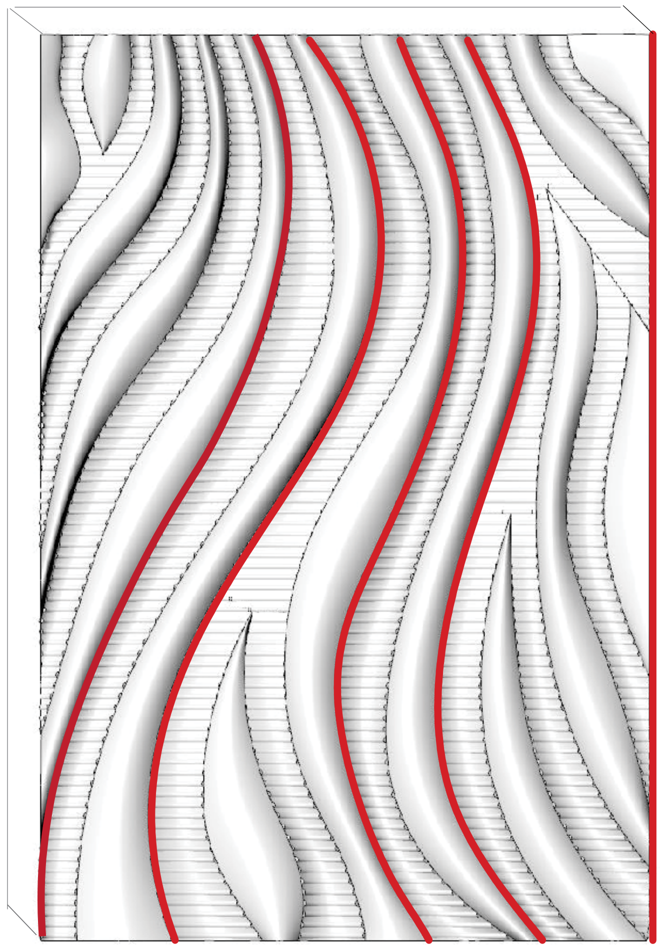
Water retention / catchment areas

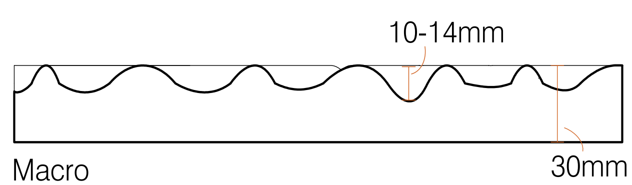


Channel water to growth areas



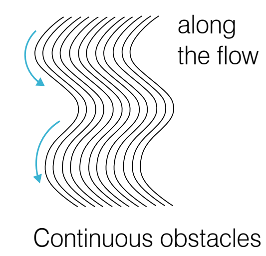
Panel 2



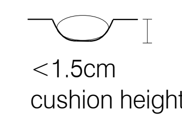


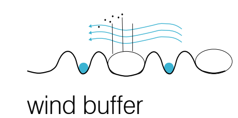
Geometric features applied in flowing rhythm

Slow water movement

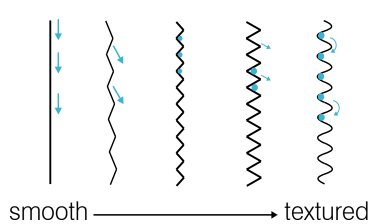


Cushion growth

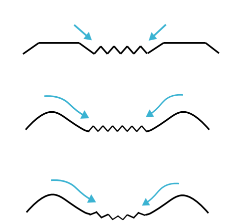




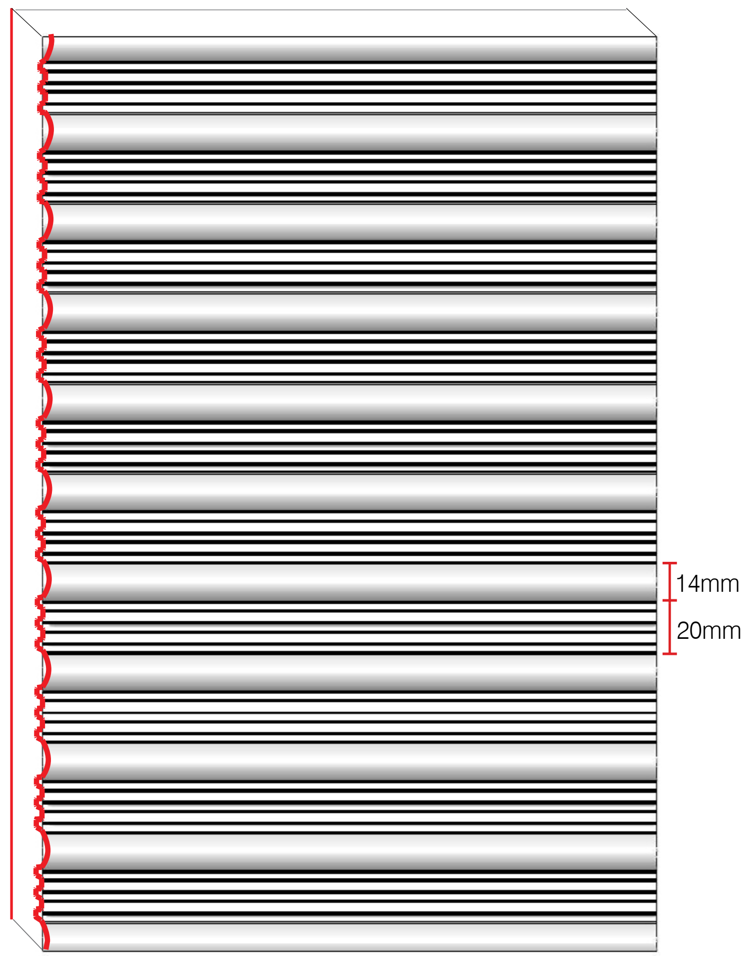
Water retention / catchment areas

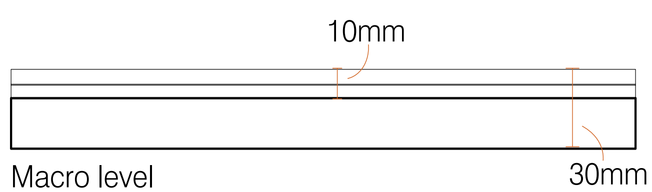


Channel water to growth areas



Panel 3

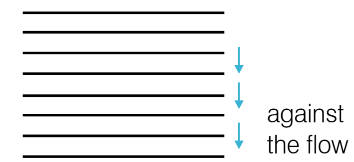




Macro level

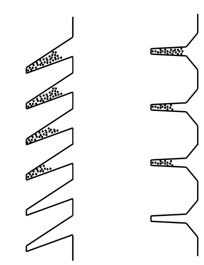
Geometric features applied in regular rhythm

Slow water movement

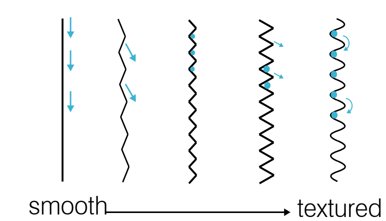


Continuous obstacles

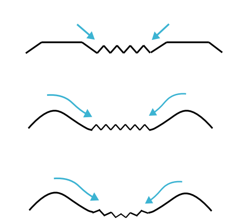
Nutrient accumulation



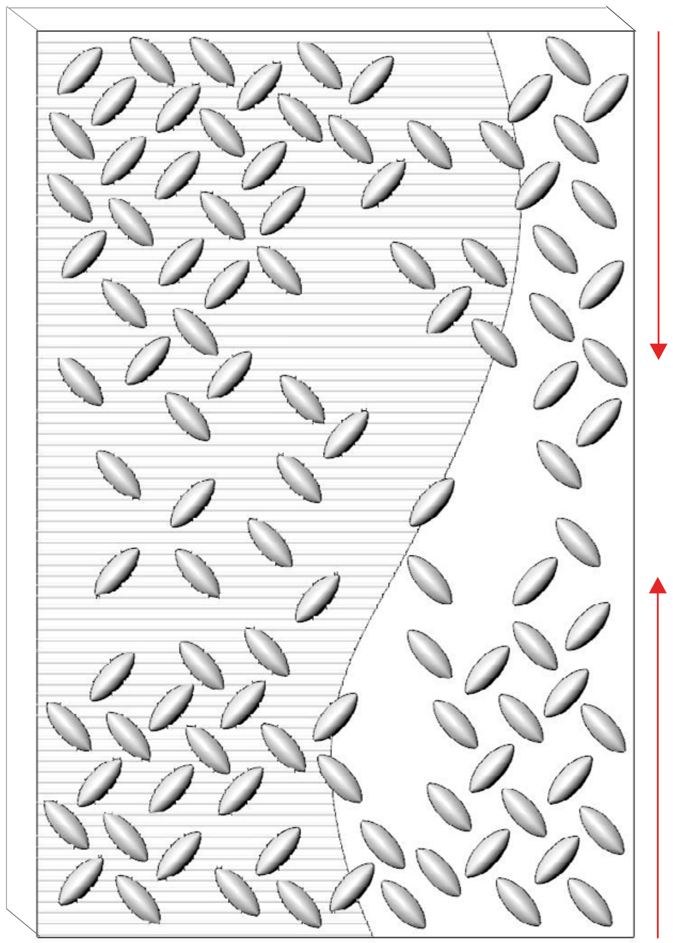
Water retention / catchment areas

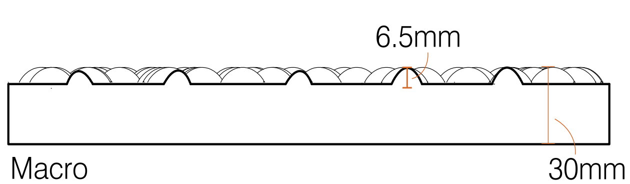


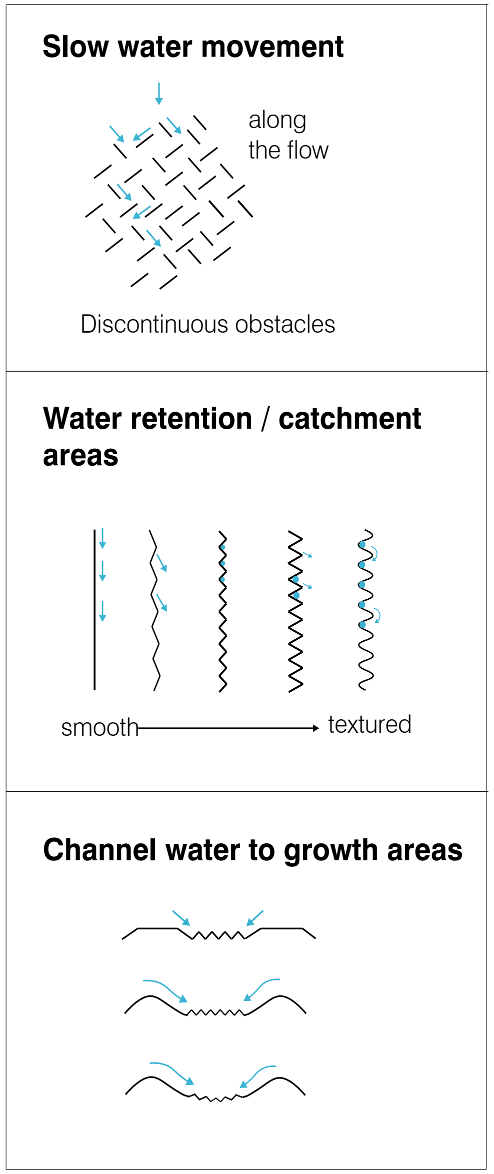
Channel water to growth areas



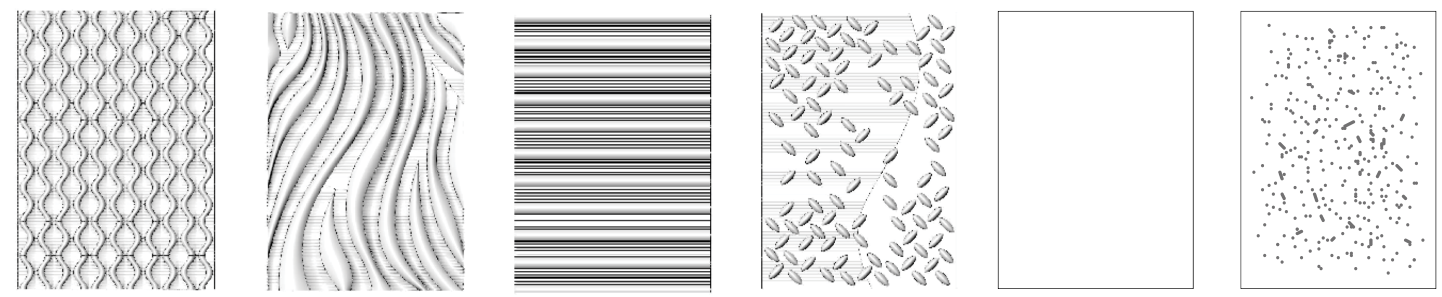
Panel 4





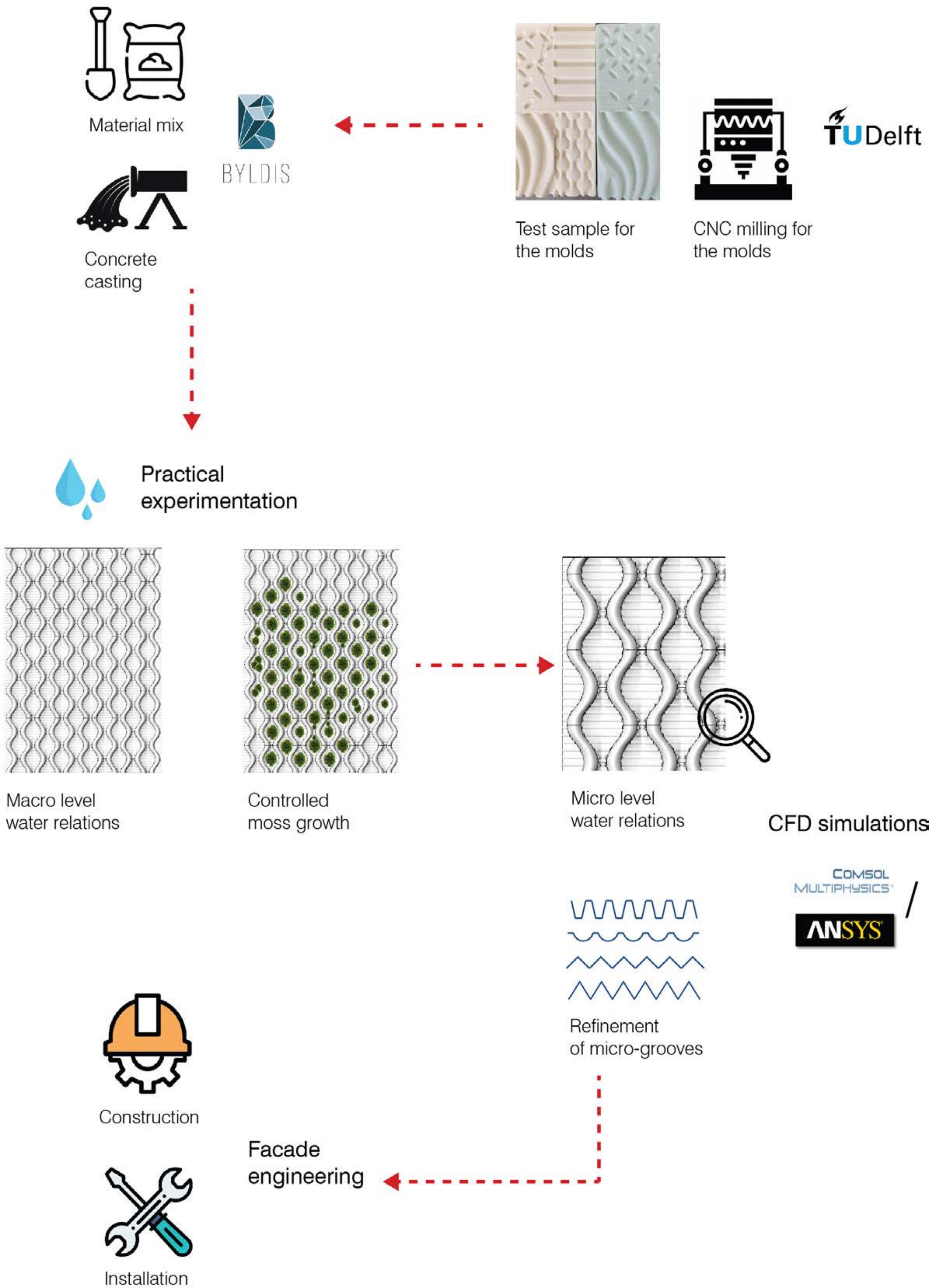


Geometric features applied in random rhythm



Features	Geometry (rhythm)	Level	Panel 1 (alternating)	Panel 2 (flowing)	Panel 3 (regular)	Panel 4 (random)	Panel 5 (n/a)	Panel 6 (n/a)
Slow water movement	Continuous obstacles	Macro geometry	✓	✓	✓			
	Discontinuous obstacles					✓		
	Along the flow		✓	✓		✓		
	Against the flow				✓			
Cushion growth	Macro depth		✓	✓				
	Radial form		✓					
Water retention & Anchorage facility	Micro depth	Micro geometry	✓	✓	✓	✓		✓
Nutrient accumulation	Deep Micro depth				✓			✓
Channel water to growth areas	Height and texture variation	Macro+ Micro geometry	✓	✓	✓	✓		

FOLLOWING RESEARCH PLAN

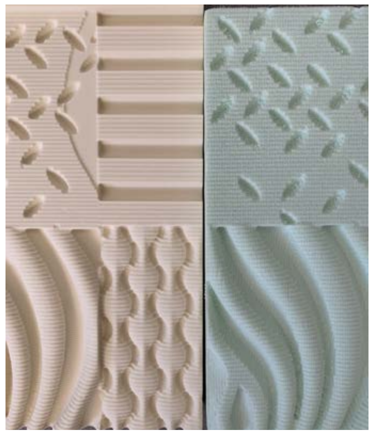


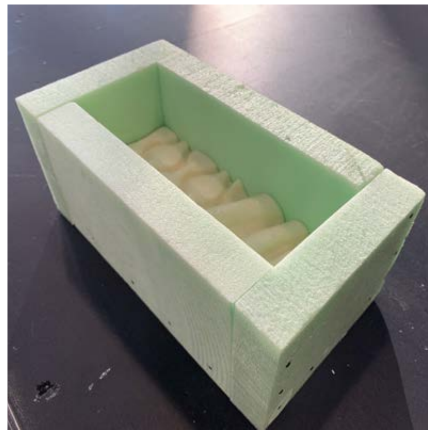
- Prototype making
- Practical experimentation
  - Moss growth
  - Water relations
- CFD simulations
- General guidelines
- Façade engineering
- Visualization

3. Prototype making

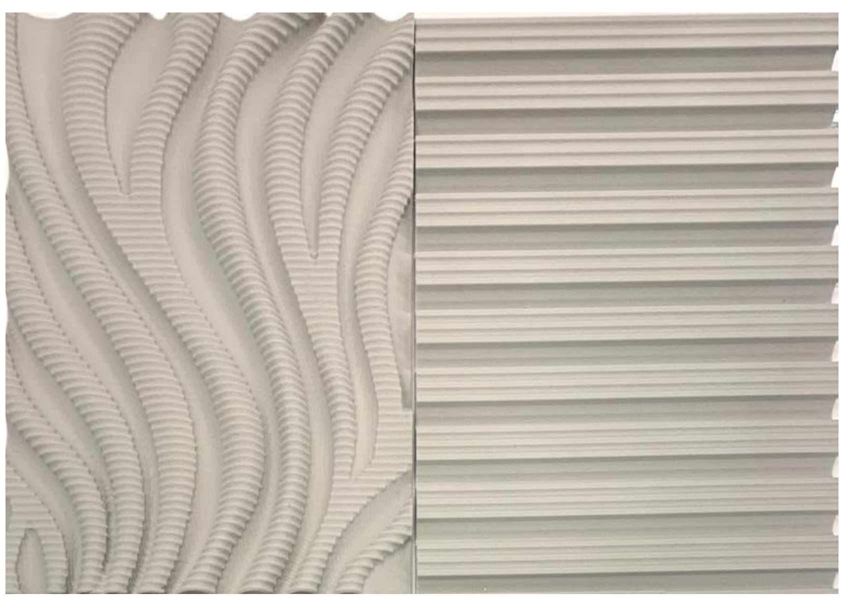
MOLD PREPARATION

Step 1: Material testing for CNC milling of molds

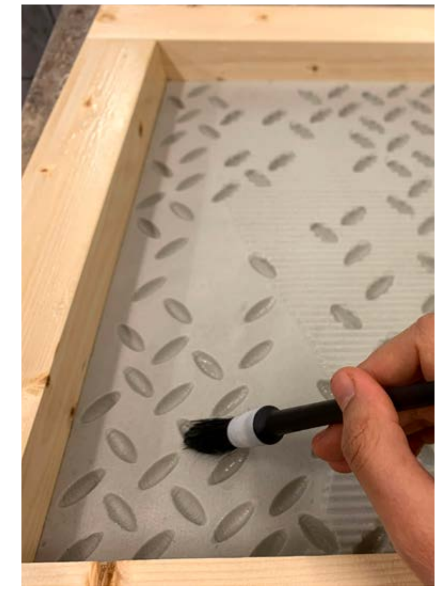




Step 2: CNC milling of final foam molds



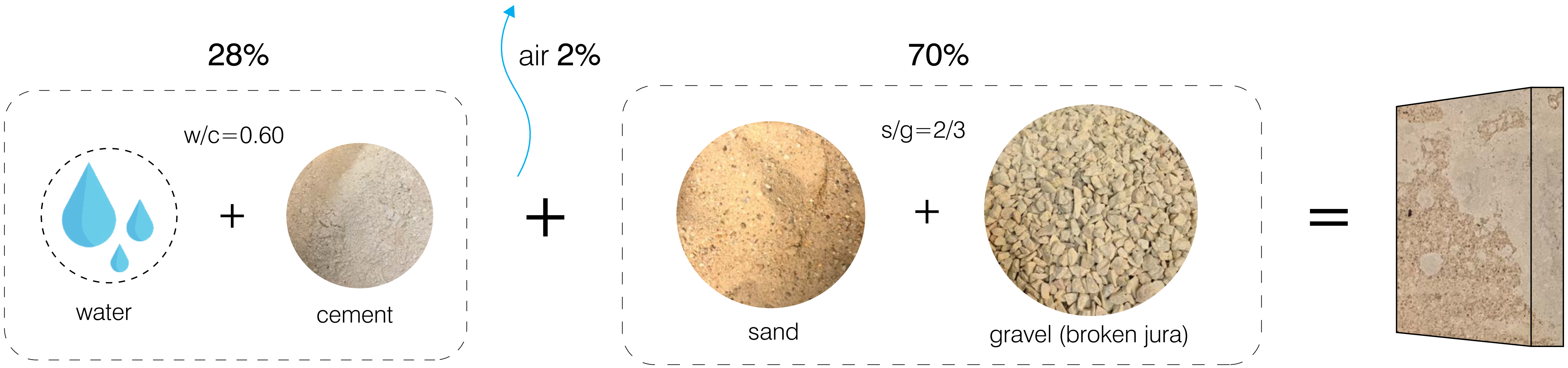
Step 3: Coating applied on molds



designed panels

plain panel

sand-layered panel



For 1 m3 of concrete:

Material	Specification	Amount (in 1m3)
CEM III/B 32.5 N	75% slag	300 kg
Dry sand	0-4mm	740 kg
Yellow jura gravels	5-8mm	1142 kg
Water		180 liters

1 tile (350 x 250 x 40)mm = 3.25 litres

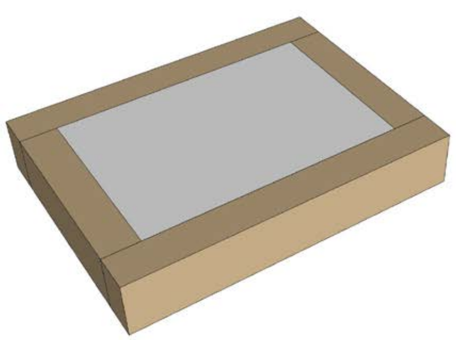
BYLDIS

Step 1: Weighing

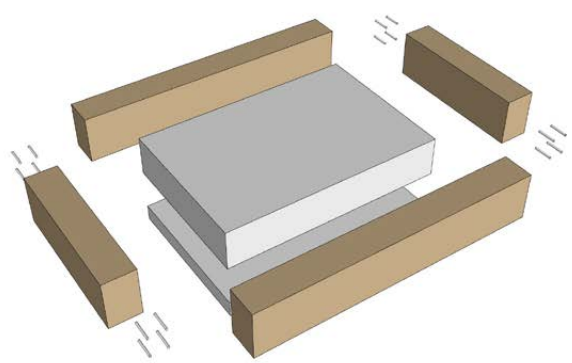
Step 2: Mixing

Step 3: Pouring

Step 4: Vibration

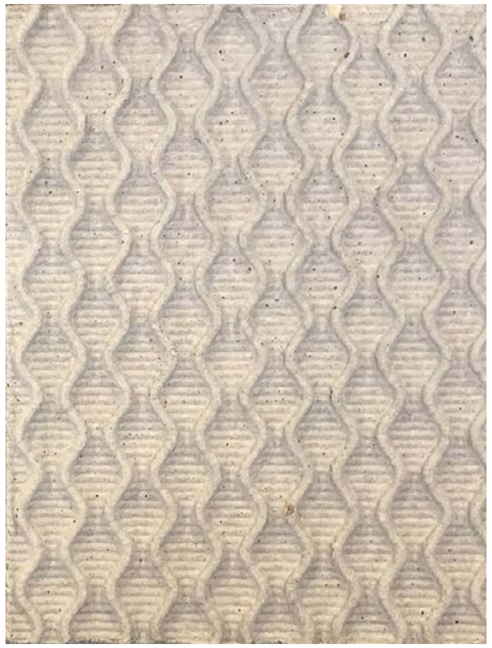


Step 5: Setting



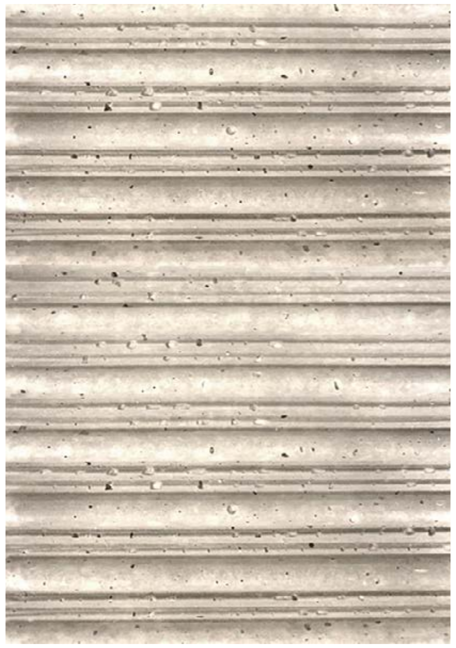
Step 6: Demolding

BYLDIS



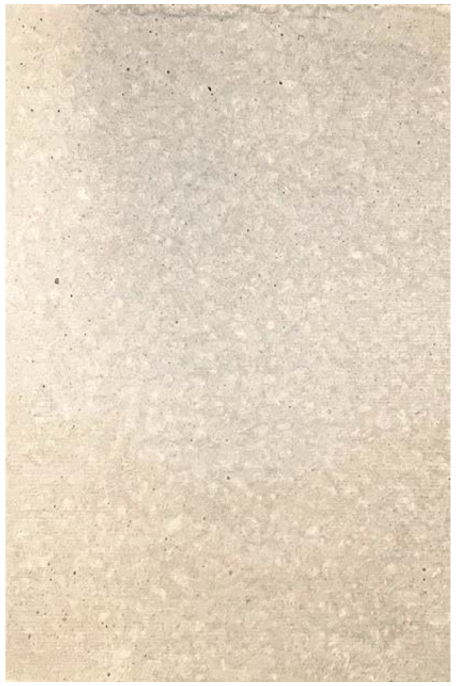
Panel 1

Panel 2



Panel 3

Panel 4



Panel 5

Panel 6

Two sets (12 nos.)

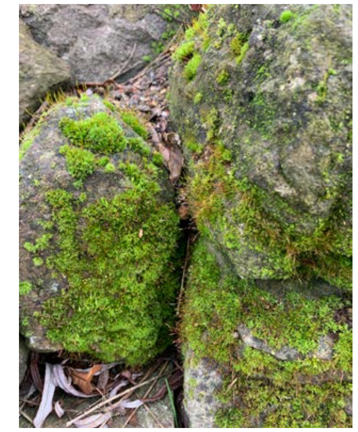
Each weigh 7.5-8 kg

Size: 350 x 250 x 40 mm

4. Design validation

- Moss growing experiment
- Water relations experiment
- CFD simulations

Tropical green house



Saxicolous moss

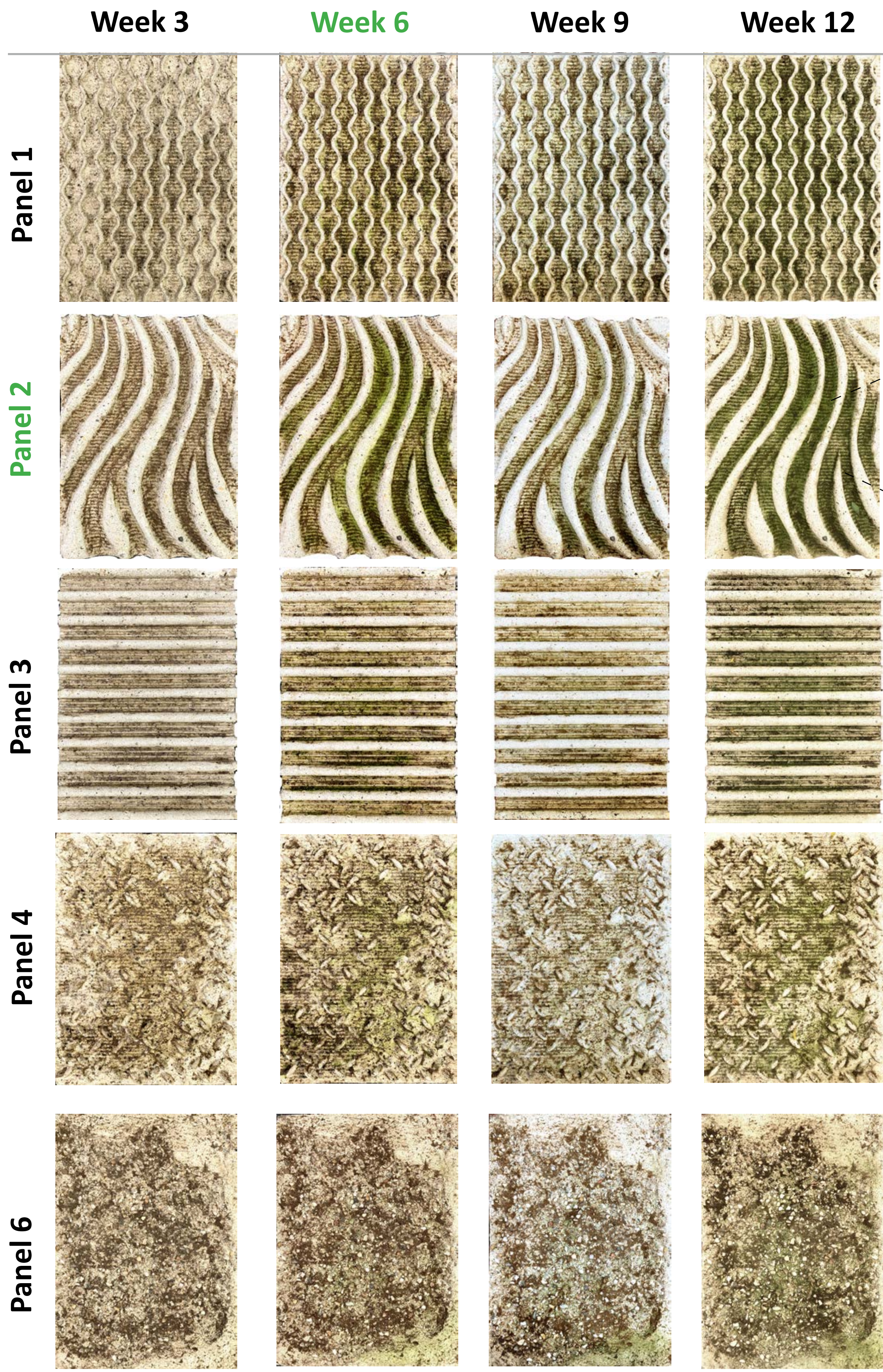
Moss slurry

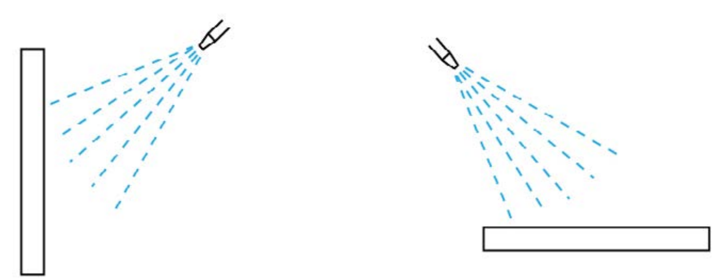
White fungus growth

Location: TU Delft Tropical Green house
Tempertare: 20 - 24^{o}C
Humidity: 65-85%
Watering: Rainwater 2-3 times daily
Growth period: 12-weeks
Placement: **1st 6 weeks horizontal**
2nd 6 weeks upright

MOSS GROWING EXPERIMENT

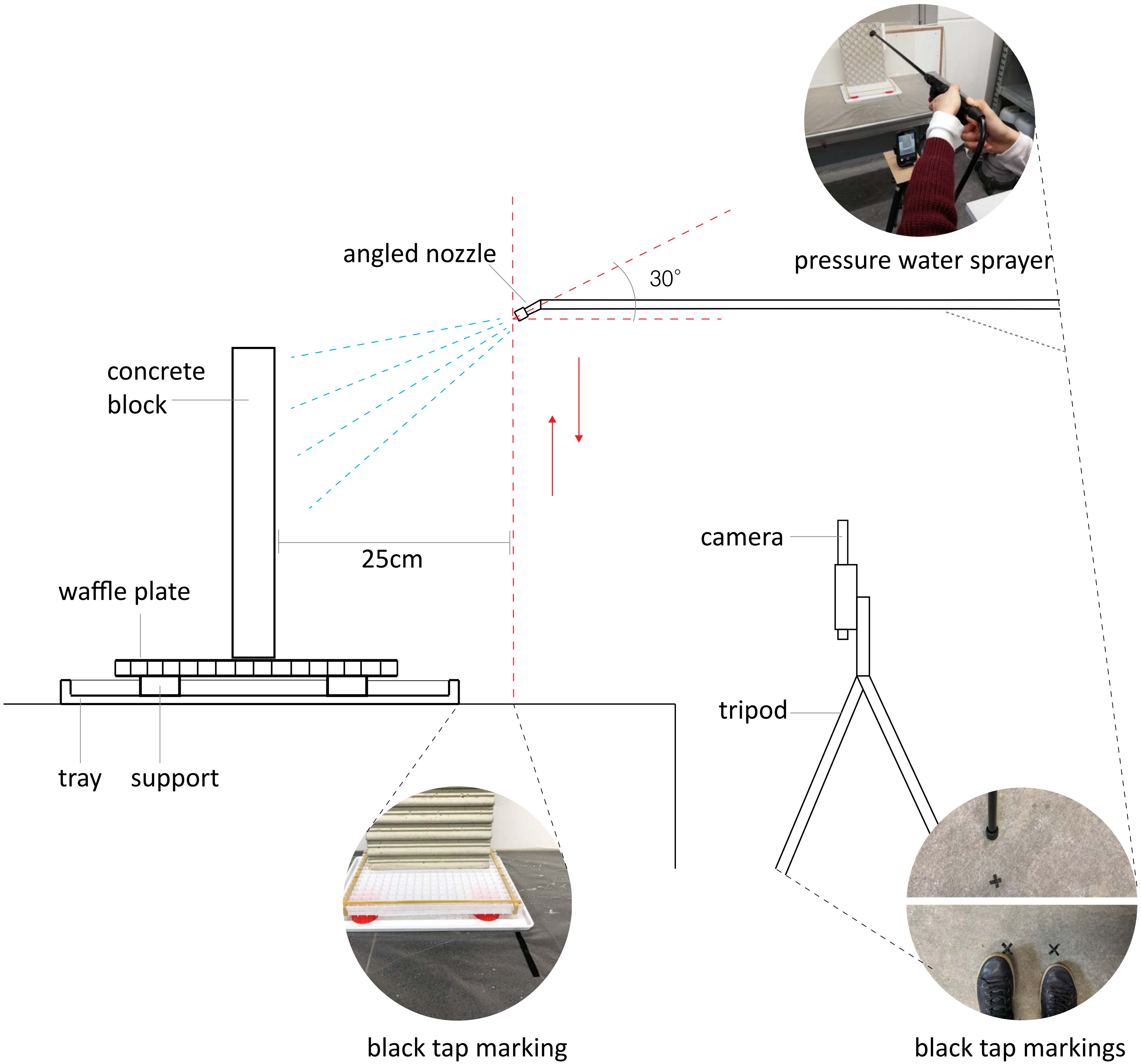
Results





Upright position
week 7 - 9

Horizontal position
week 1 - 6
week 10 - 12



spraying time: 30sec

spraying amount: 150ml
(coloured water)

Initial preparation:

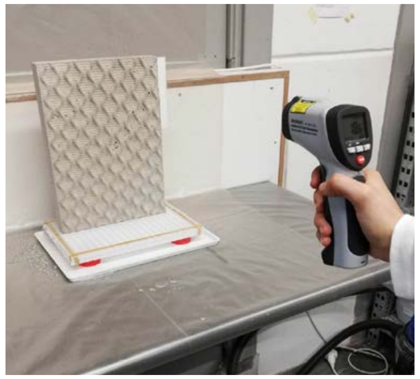

Sanding


Oven drying

The measurements:


Relative humidity


Weight


Temperature

Measurements taken:

2mins, 10mins and 20mins after spraying.

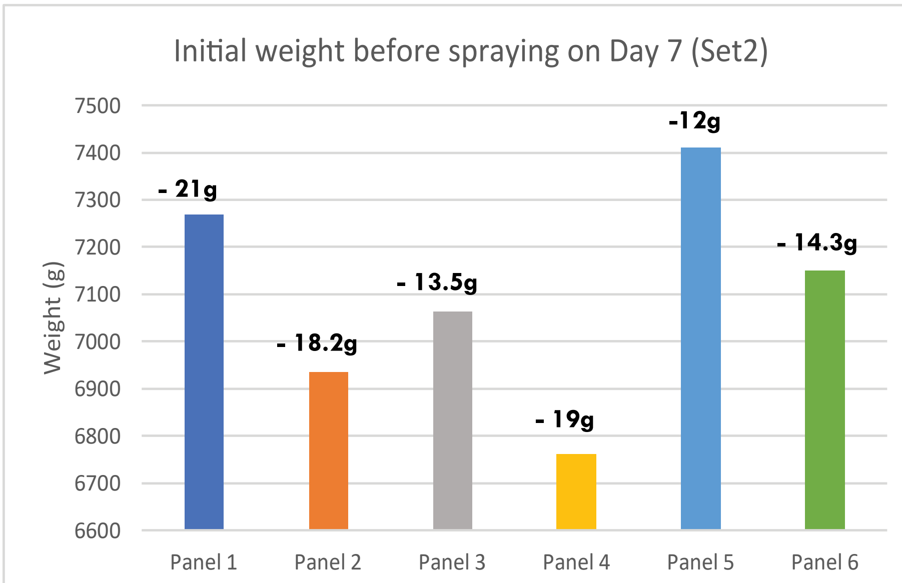
Frequency of experiment:

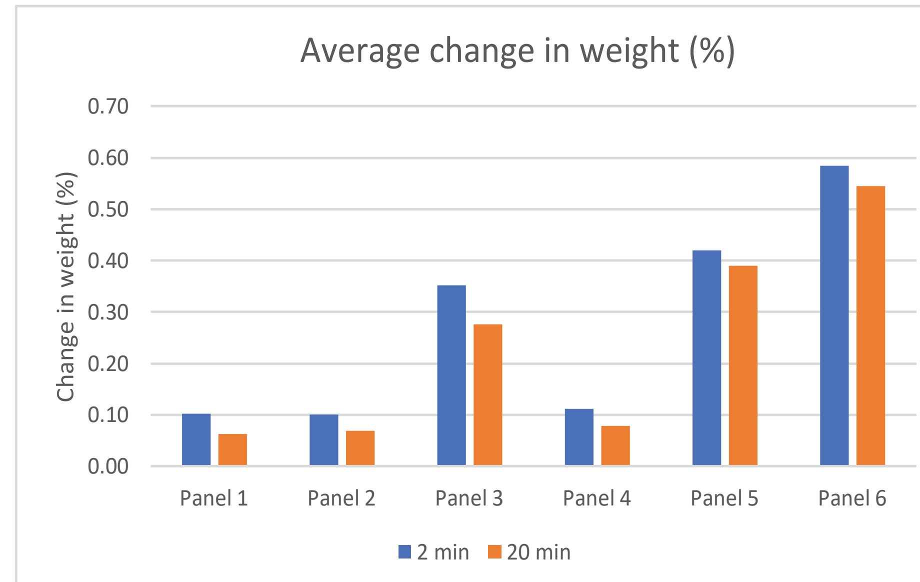
Day 1, Day 3, Day 7

Panel 1 Panel 2 Panel 3 Panel 4 Panel 5 Panel 6

WATER RELATIONS EXPERIMENT

Results for change in weight





Initial weight loss

Highest Panel 1
Panel 4
Panel 2

Lowest Panel 5
Panel 3 ✓
Panel 6

Reasons:
Fragility of the designed patterns
Breaking of corners/parts
Internal moisture evaporation

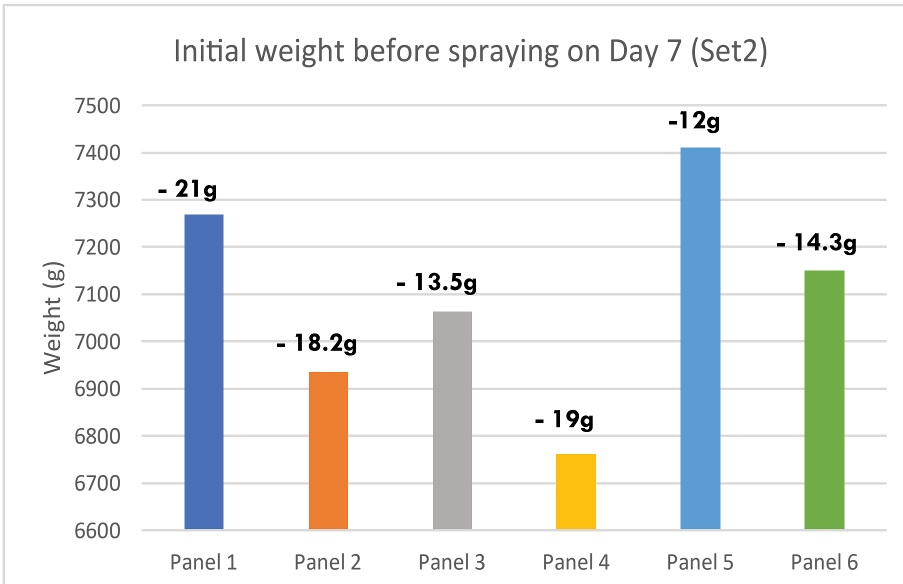
Weight gain in relation to initial weight

Highest Panel 6 ✓ — Natural roughness
Panel 5 — Material porosity
Panel 3 ✓ — Deep micro-grooves

Lowest Panel 1
Panel 2
Panel 4
— Shallow micro-grooves
Surface repellence

WATER RELATIONS EXPERIMENT
Results for change in weight

Panel 1 Panel 2 Panel 3 Panel 4 Panel 5 Panel 6



Initial weight loss

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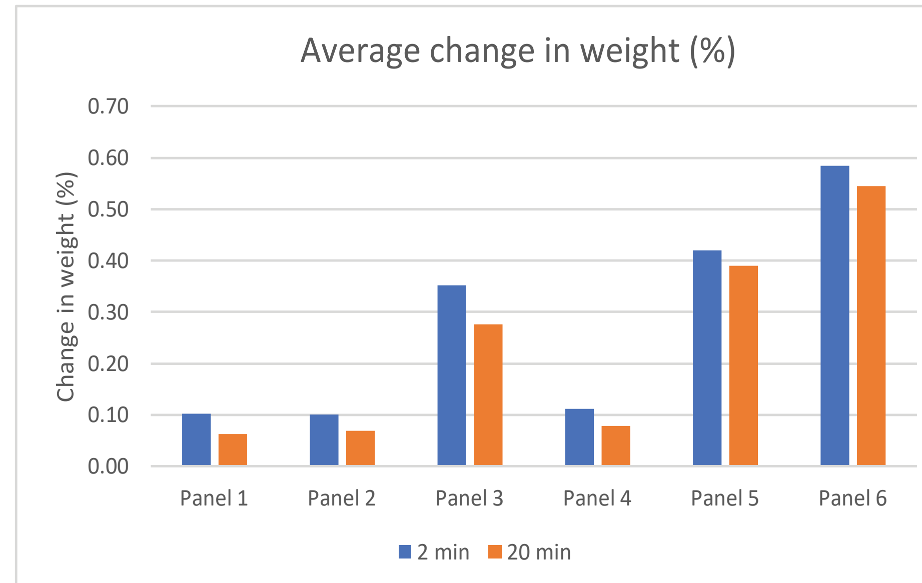

Weight gain in relation to initial weight

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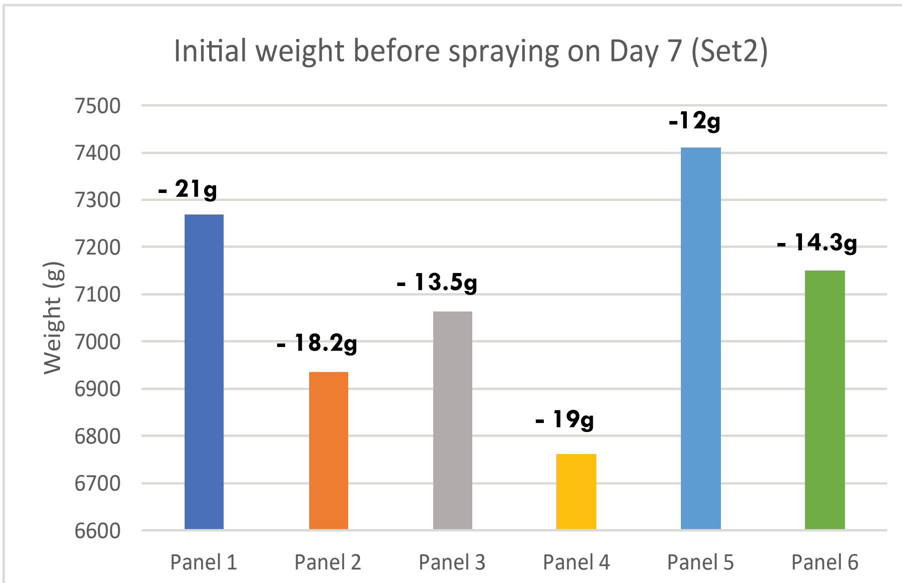
Panel 5 — Material porosity
Panel 3 ✓ — Deep micro-grooves

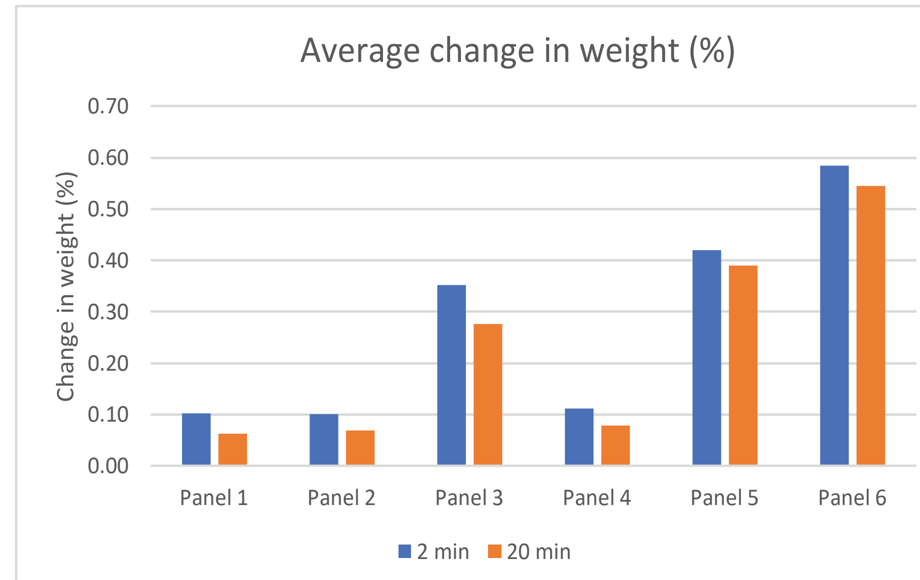
Lowest Panel 1
Panel 2 — Shallow micro-grooves, Surface repellence
Panel 4

WATER RELATIONS EXPERIMENT

Results for change in weight

Panel 1 Panel 2 Panel 3 Panel 4 Panel 5 Panel 6





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Panel 2

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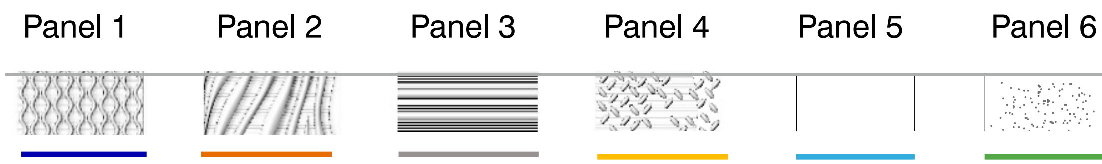
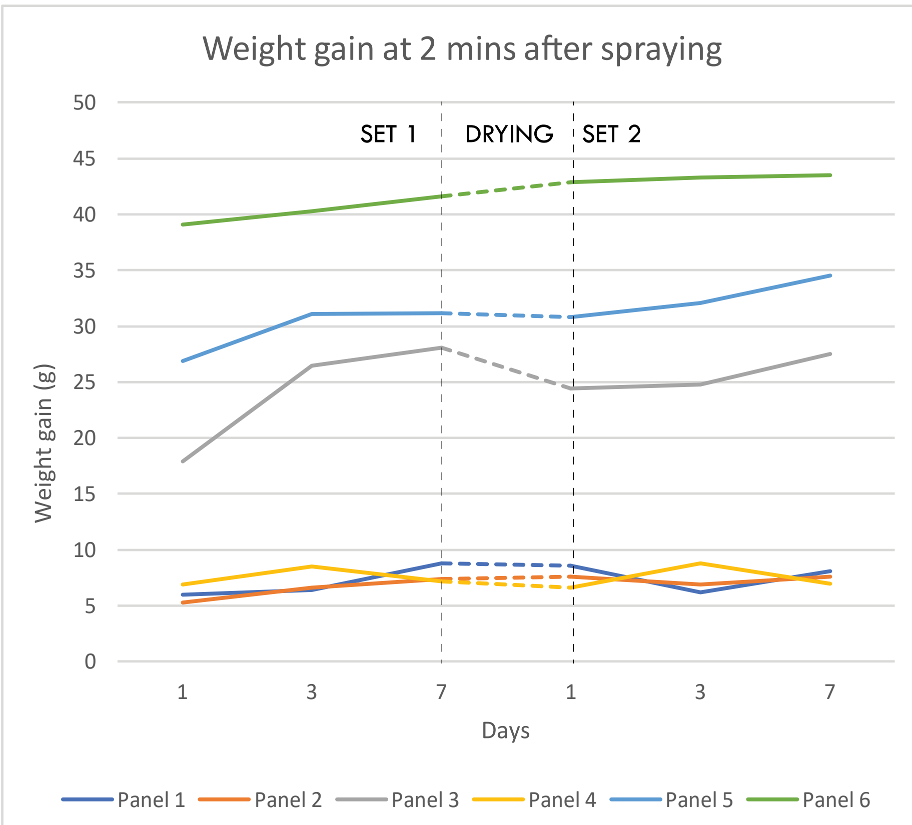
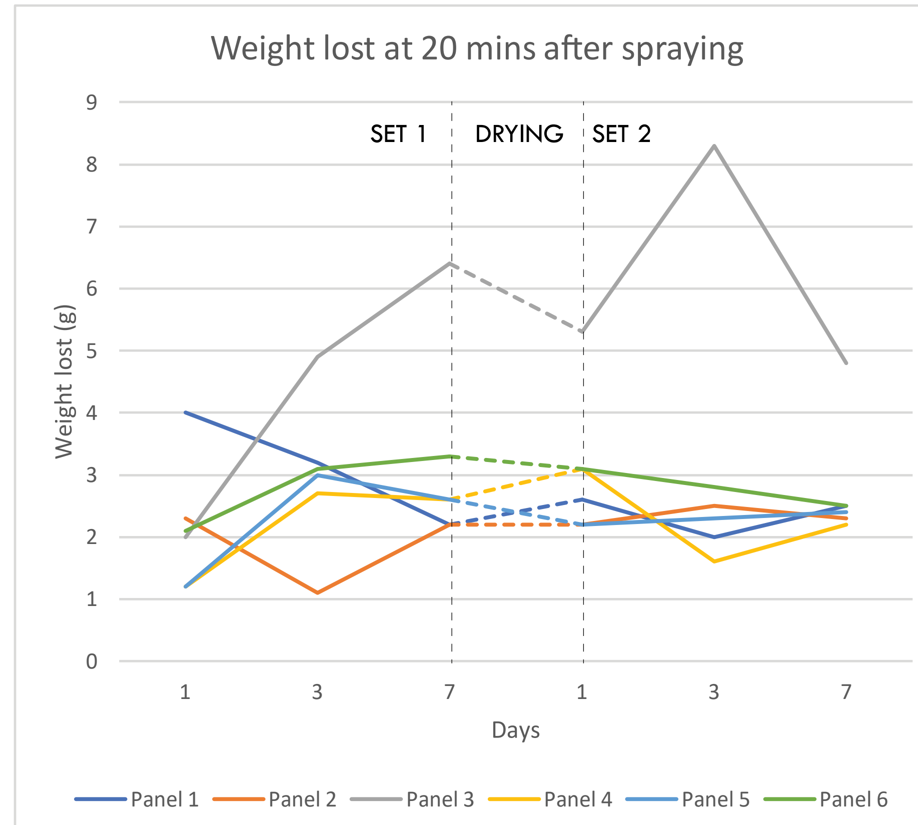


WATER RELATIONS EXPERIMENT

Results for change in weight





Weight gain at 2 mins after spraying

Highest Panel 6 Range (39-44g) ✓

Lowest Panel 2 Range (5-7g)

Panel 3- Maximum fluctuation
Panel 2- Minimum fluctuation

Exception: Panel 5 high water absorption

Weight lost at 20 mins after spraying

Highest Panel 3 Range (2-8g)

Lowest Panel 2 Range (1-2.5g) ✓

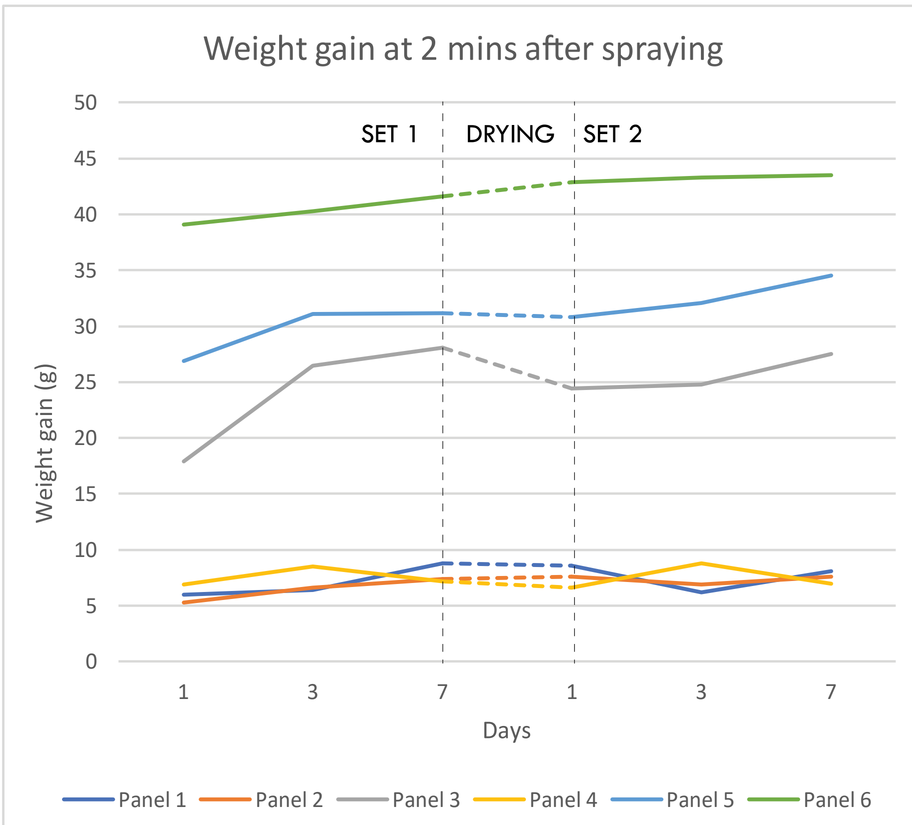
Panel 3- Maximum fluctuation
Panel 2- Lowest weight loss

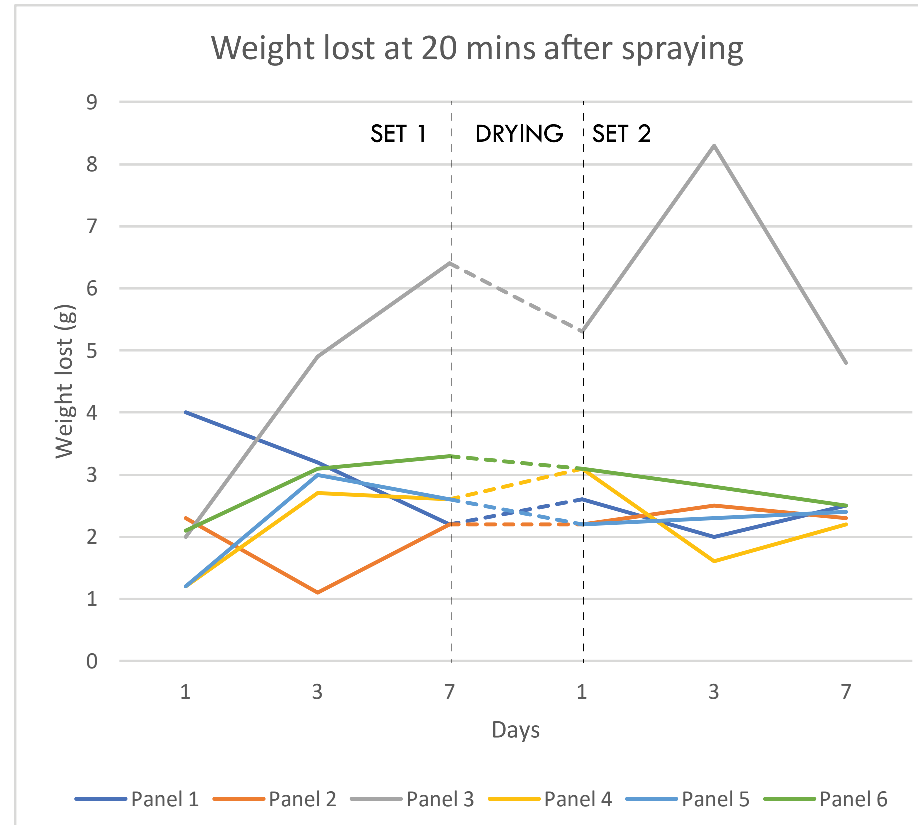
Note: Panel 6 high weight gain

Panel 1 Panel 2 Panel 3 Panel 4 Panel 5 Panel 6

WATER RELATIONS EXPERIMENT

Results for change in weight





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Lowest Panel 2 Range (1-2.5g) ✓

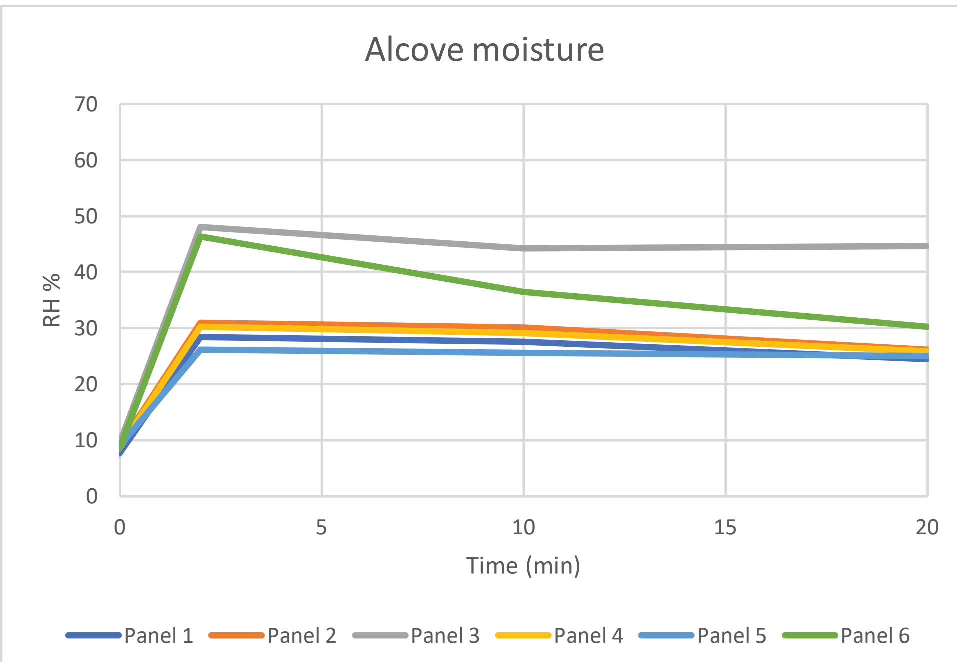
Panel 3- Maximum fluctuation
Panel 2- Lowest weight loss

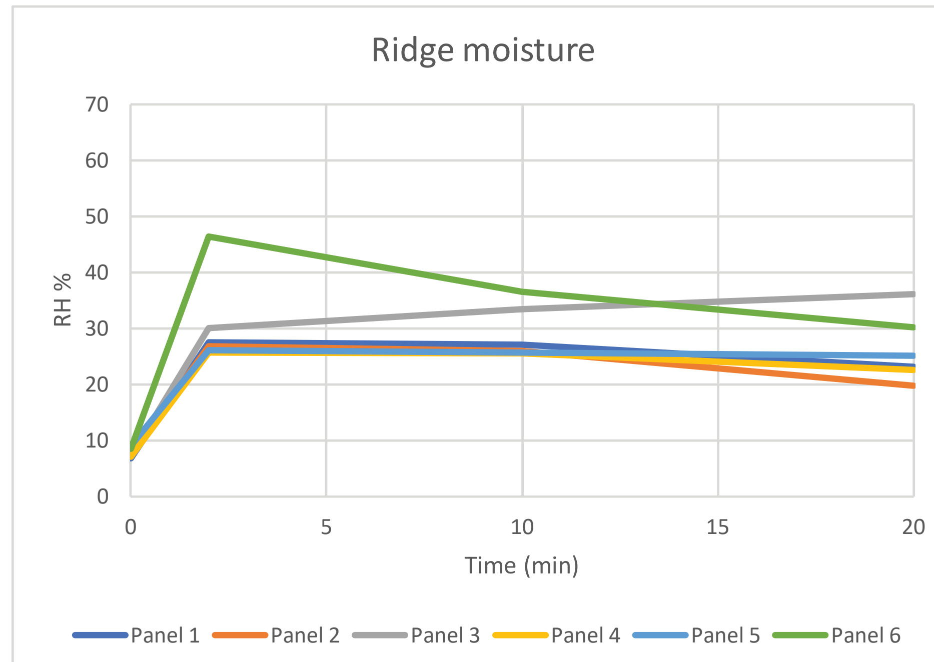
Note: Panel 6 high weight gain

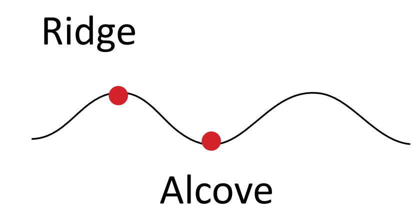
Panel 1 Panel 2 Panel 3 Panel 4 Panel 5 Panel 6

WATER RELATIONS EXPERIMENT

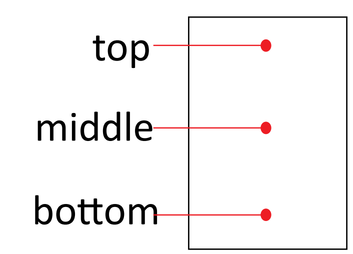
Results for relative humidity







Points of measurement



Alcove moisture after 2 min

Highest Panel 3 Rg. (RH 26.8 - 61.2%)

Lowest Panel 5 (RH 23 - 30%)

Alcove moisture after 20 min

Highest Panel 3 Rg. (RH 34.3 - 58.4%) ✓ Deep micro-grooves

Lowest Panel 1 (RH 17.3 - 29.6%) Shallow micro-grooves

Highest loss in surface mositure: Panel 6

Ridge moisture after 2 min

Highest Panel 6 Rg. (RH 33.5 - 55.6%)

Lowest Panel 4 (RH 20.7 - 29%)

Ridge moisture after 20 min

Highest Panel 3 Rg. (RH 29 - 43.5%) Against the flow macro-grooves

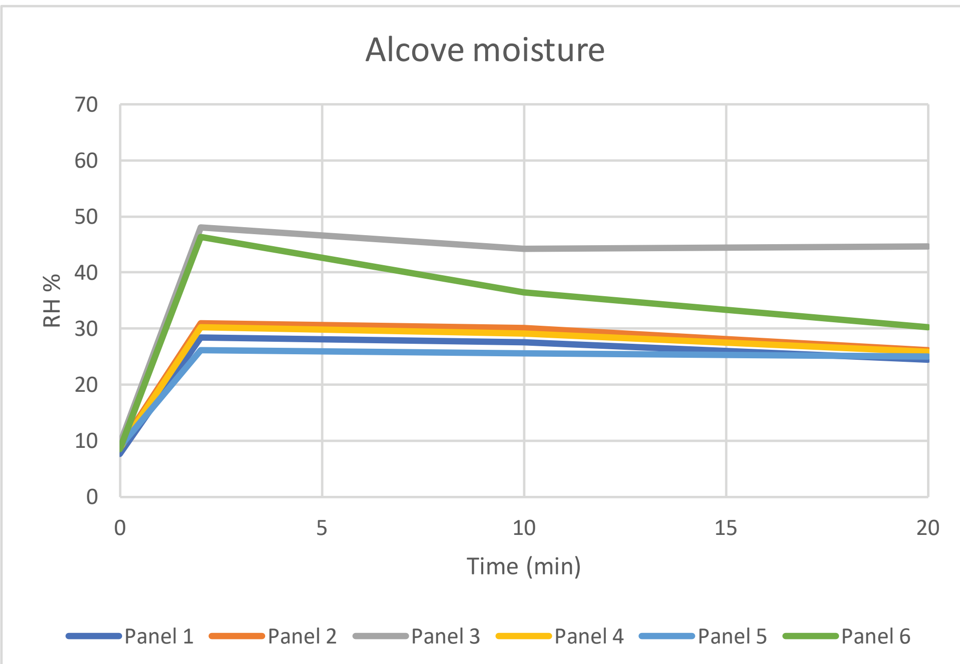
Lowest Panel 2 (RH 11 - 29.5%) ✓ Wider and higher macro-grooves

Highest loss in ridge moisture: Panel 6 & Panel 2

Panel 1 Panel 2 Panel 3 Panel 4 Panel 5 Panel 6

WATER RELATIONS EXPERIMENT

Results for relative humidity



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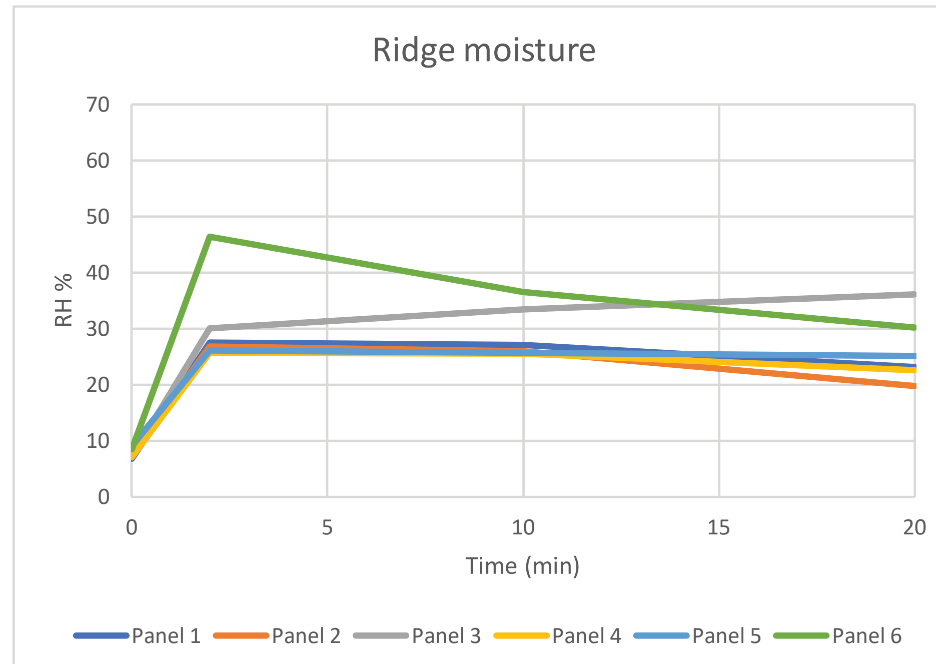

Ridge moisture after 2 min

Highest Panel 6 Rg. (RH 33.5 - 55.6%)

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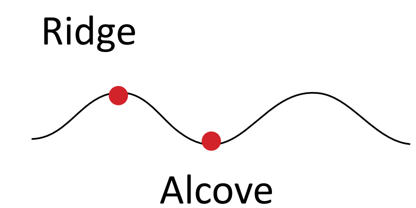
Ridge moisture after 20 min

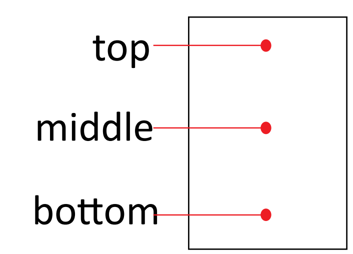
Highest Panel 3 Rg. (RH 29 - 43.5%) Against the flow macro-grooves

Lowest Panel 2 (RH 11 - 29.5%) ✓ Wider and higher macro-grooves

Highest loss in ridge moisture: Panel 6 & Panel 2



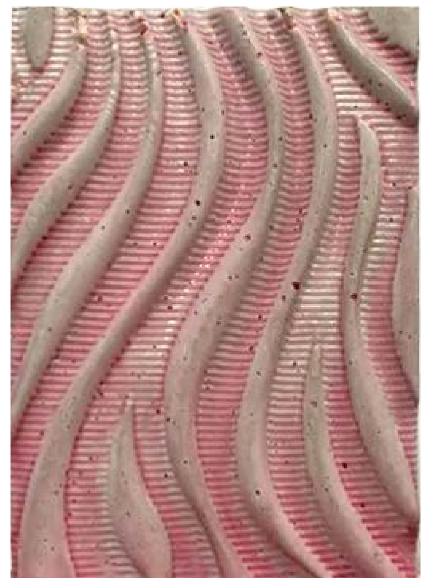
Points of measurement



Visual analysis

Panel 1

Minimum distinction between growth and no growth areas



Panel 2

Clear distinction be-tween growth and no growth areas

Panel 3

No distinction between growth and no growth areas

Panel 4

Clear distinction on surface texture

Panel 5

No flow obstruction

Panel 6

No directed growth

Panel 2:

- Lower ridge moisture
- Low water retention
- Low absorption capacity

Panel 3:

- Higher surface moisture
- Increased ridge moisture

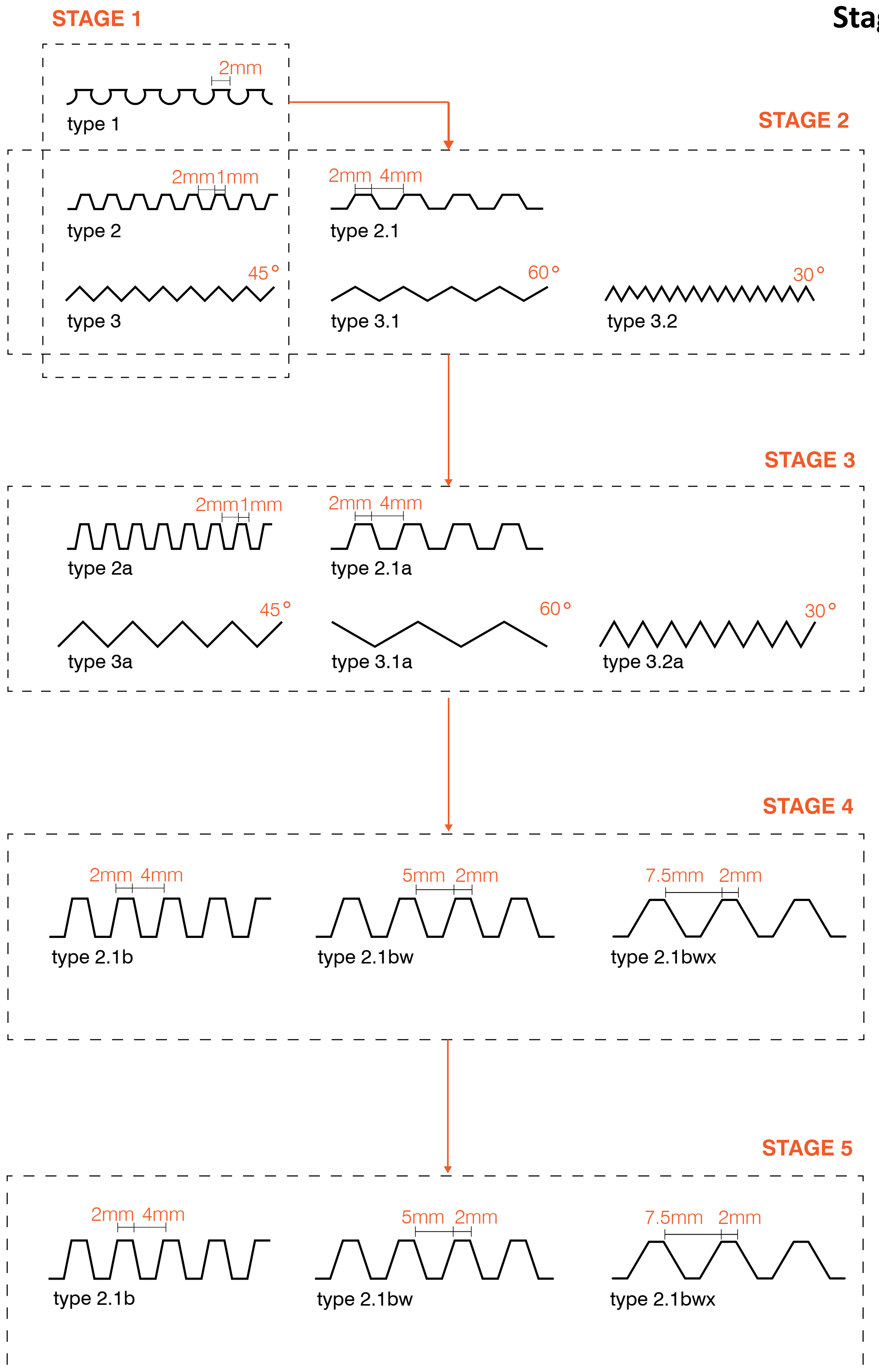
Panel 6:

- Higher surface moisture
- High absorption capacity
- Quick drying

CFD SIMULATIONS

The setup

Stages of testing



PARAMETERS

Height 1.5 mm
Inlet velocity 5m/s

Height 3 mm
Inlet velocity 5m/s

Height 5 mm
Inlet velocity 5m/s

Height 5 mm

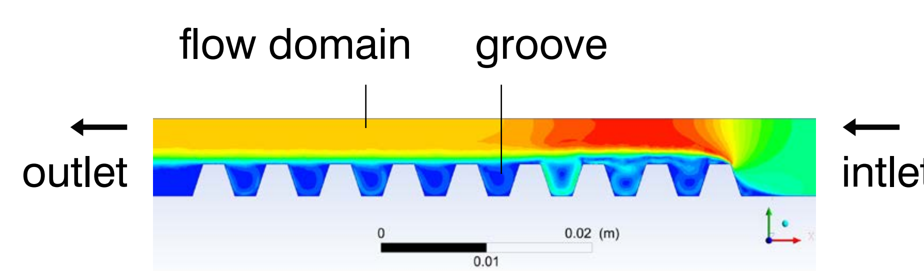
Compare by
Inlet velocity 2m/s
5m/s
9m/s

Triangular Meshing

Transient state

Laminar model

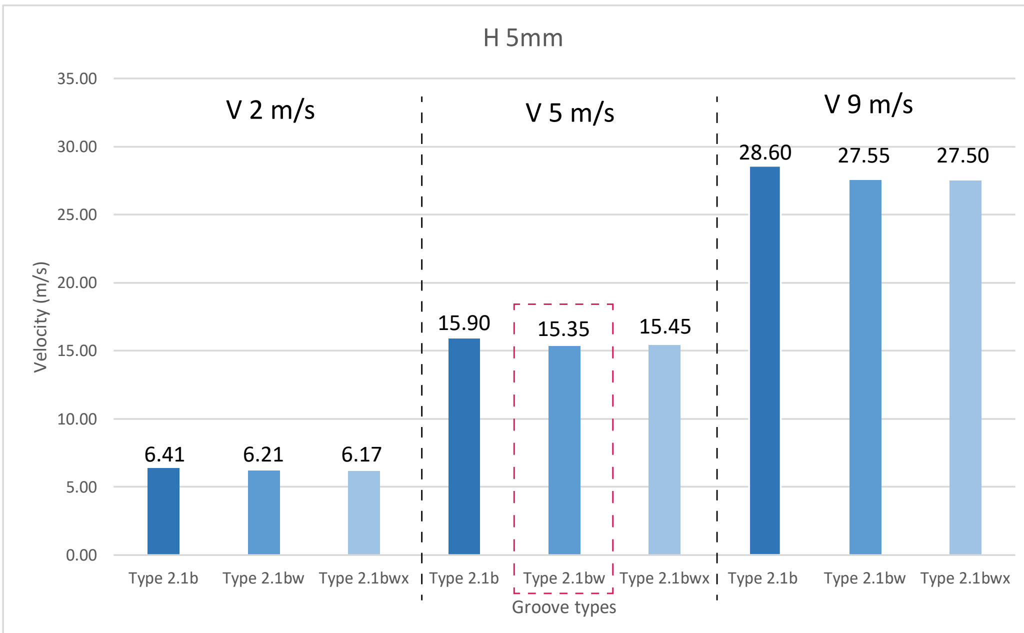
No. of iterations: 300
Results at 30sec



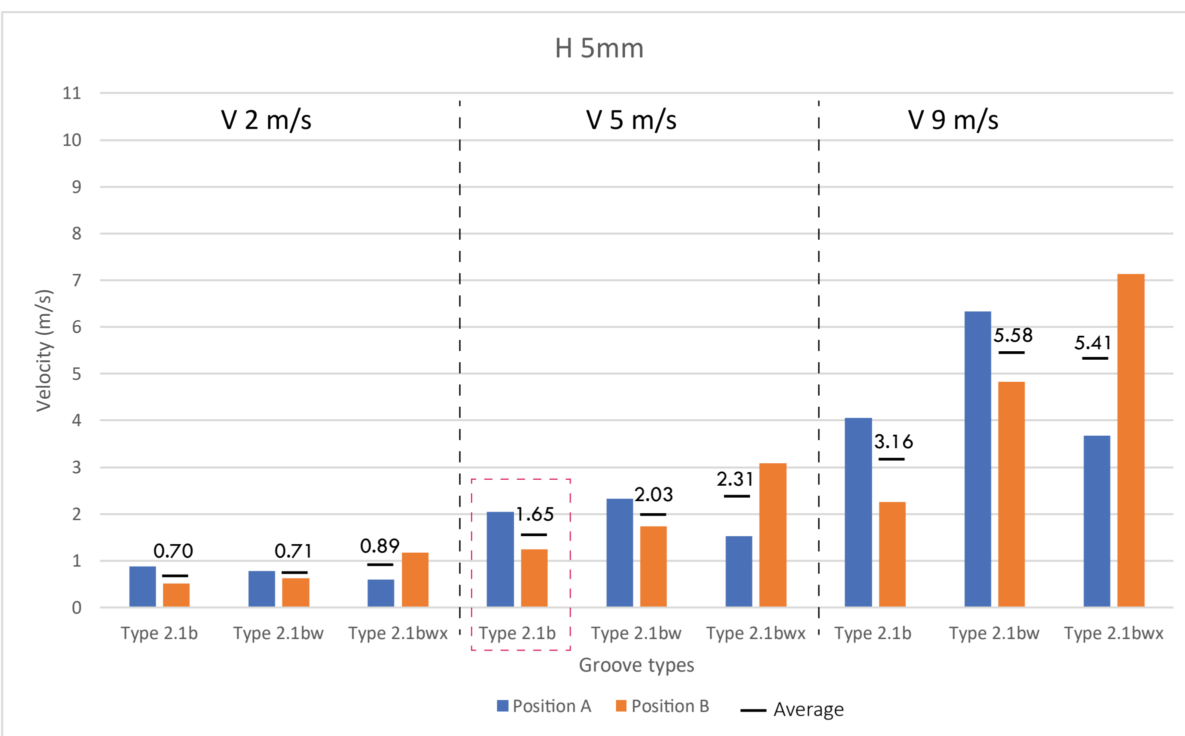
CFD model for Ansys Fluent

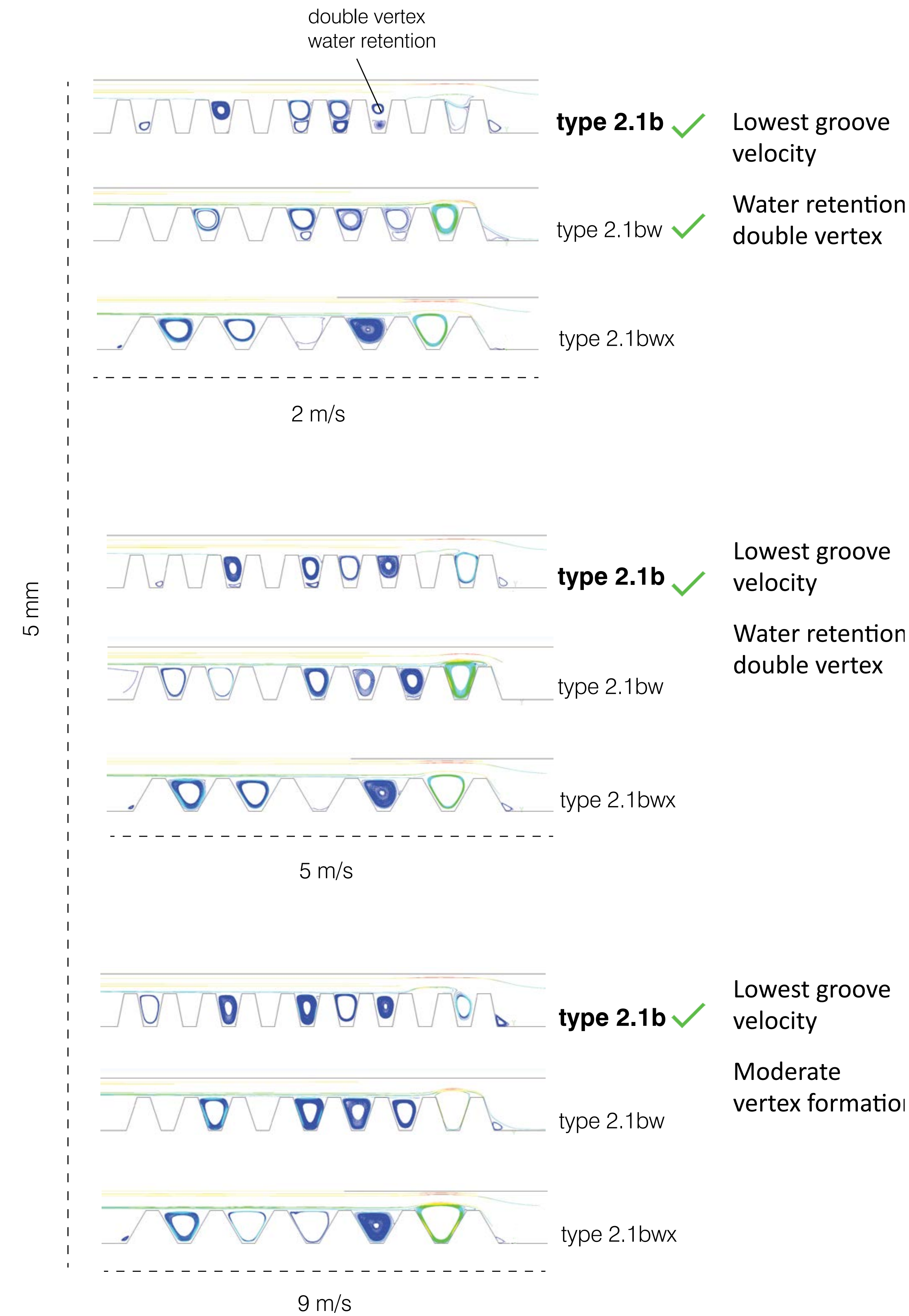
STAGE 4 & STAGE 5

Highest velocity in flow domain



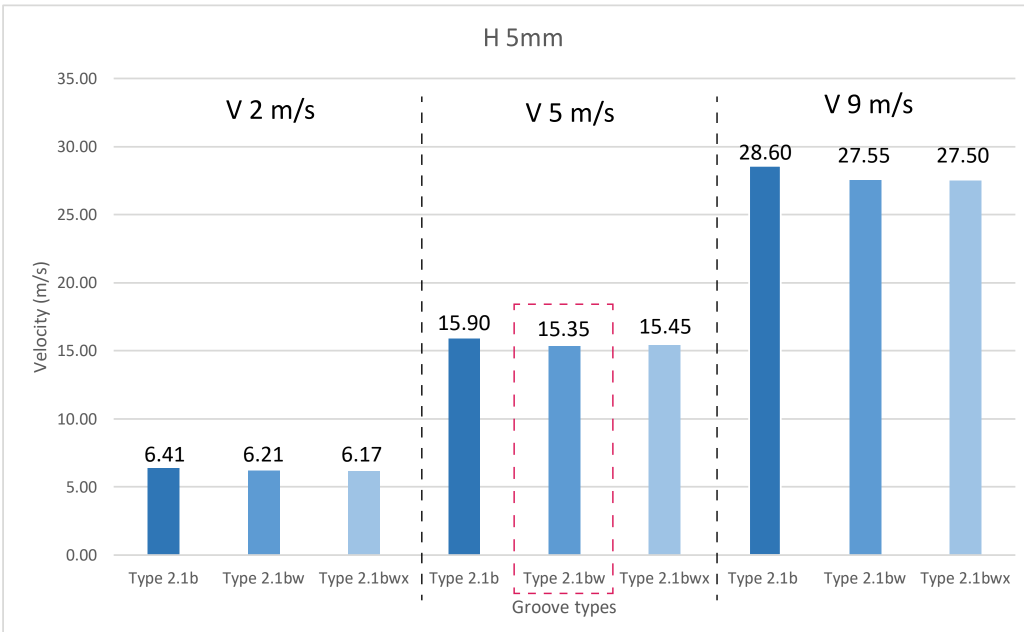
Highest velocity in grooves



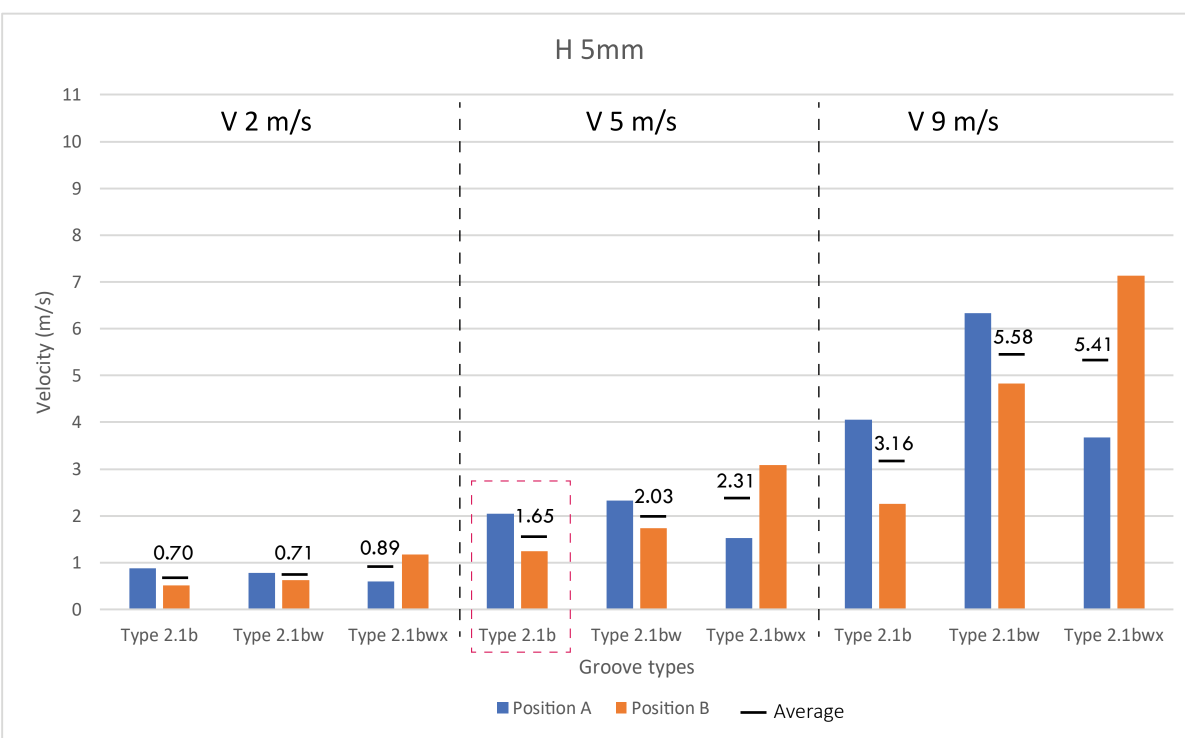


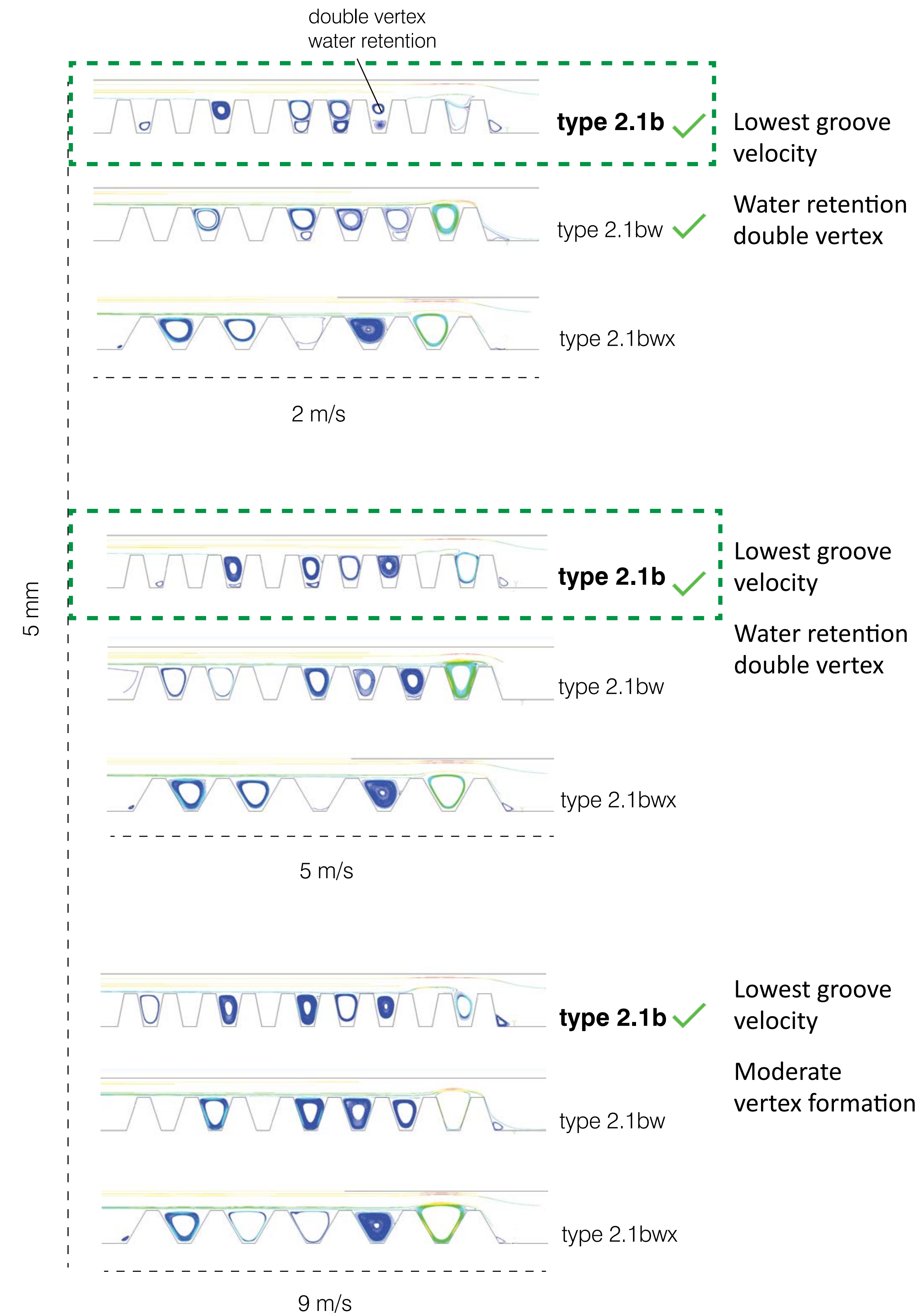
STAGE 4 & STAGE 5

Highest velocity in flow domain

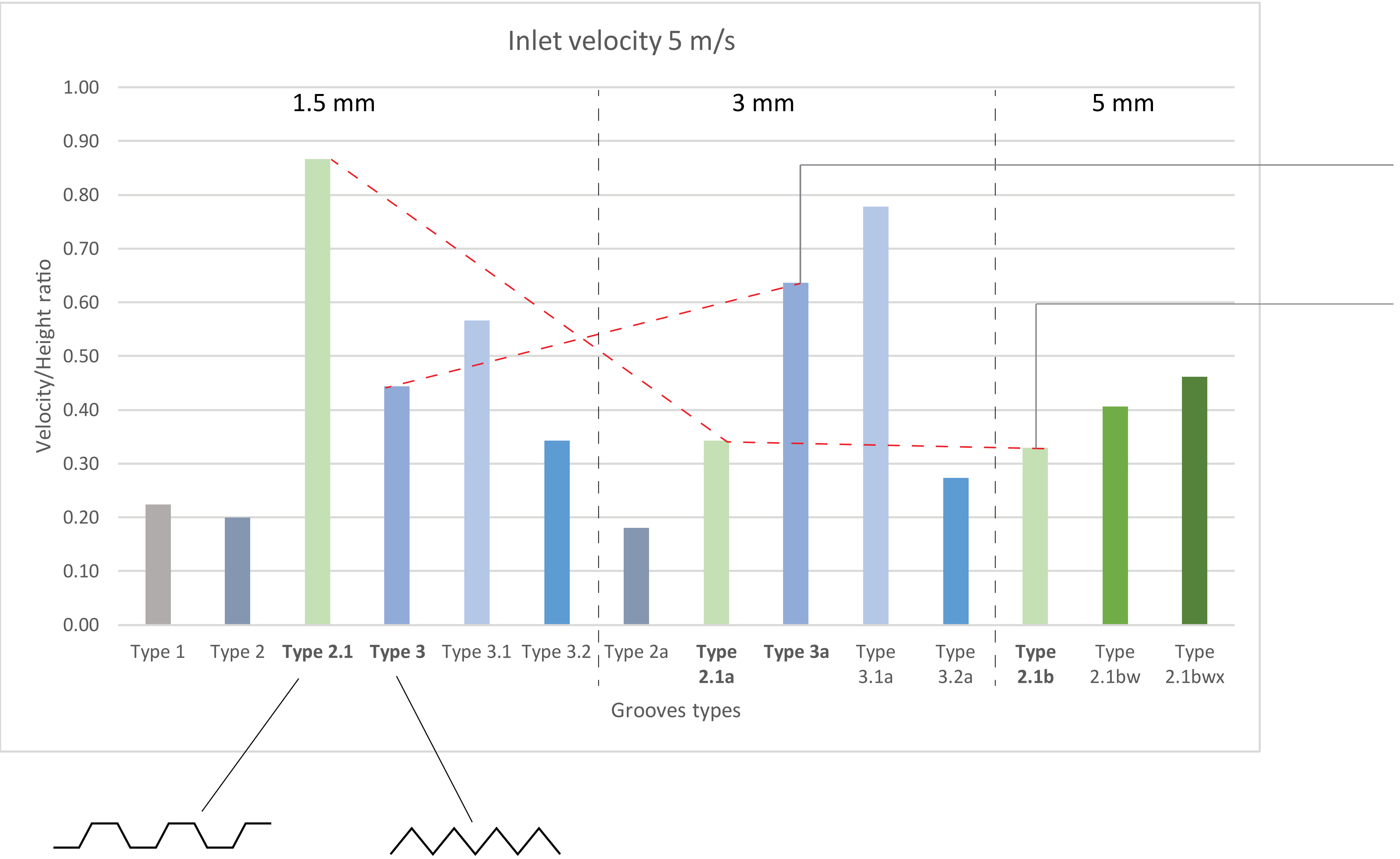


Highest velocity in grooves





Groove velocity in relation to height for an inlet velocity of 5m/s



Increase in depth, higher wash away effect.

Increase in depth, higher water retention

Wedge shaped

V- shaped

A summary table for the vertex formation in different groove types

Inlet velocity	Groove type	w/h	Low speed	High speed	Water retention	Wash away	No vertex
	1.5 mm						
5 m/s	Type 1	1.33					
	Type 2	1.33					
	Type 2.1	2.67					
	Type 3	2					
	Type 3.1	4					
	Type 3.2	1.33					
	3 mm						
	Type 2a	0.67					
	Type 2.1a	1.33					
	Type 3a	2					
	Type 3.1a	3.33					
	Type 3.2a	1					
	5mm						
	Type 2.1b	0.8					
	Type 2.1bw	1					
	Type 2.1bwx	1.5					
2 m/s	Type 2.1b	0.8					
	Type 2.1bw	1					
	Type 2.1bwx	1.5					
9 m/s	Type 2.1b	0.8					
	Type 2.1bw	1					
	Type 2.1bwx	1.5					

For 1.5mm groove height
Shallow w/h > 2
Congested w/h <2

For 3mm groove height
Shallow w/h > 1.33
Too Deep w/h <1

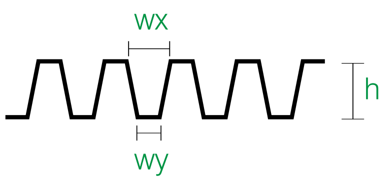
For 5mm groove height
Shallow w/h > 1

Groove height ↑
Weight(w)/Height (h) ↓ ~ 1

For ideal vertex formation

CHOSEN GROOVE

Type 2.1b

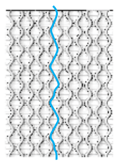
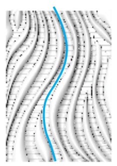
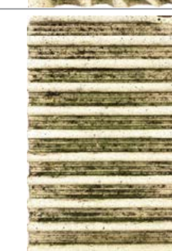
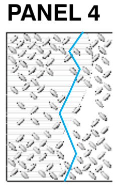
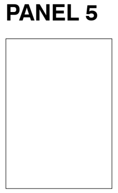
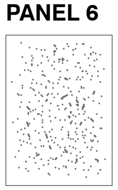


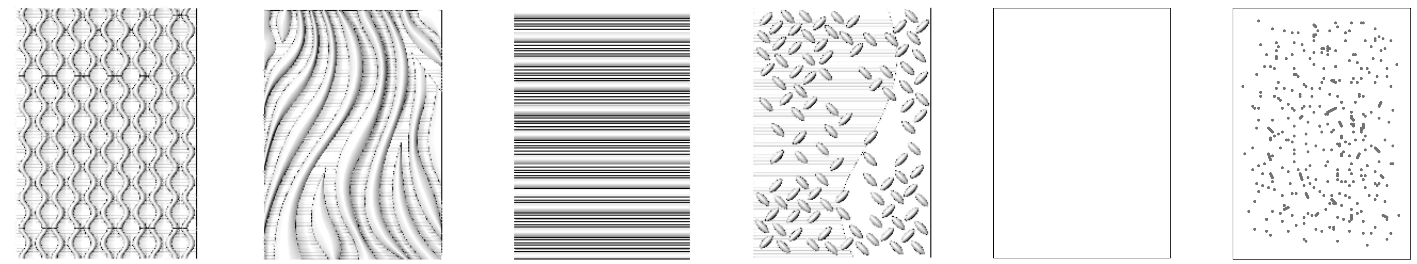
Desired height (h): 5mm (from literature & practical experimemt)
Adjusted width (wx): 4mm
wx/h= 0.8
wy/wx= 0.4

Moderate to low vertex velocity
Water retention

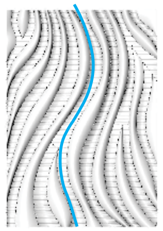
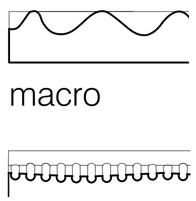
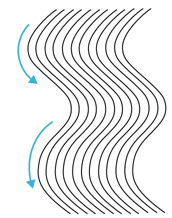
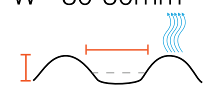
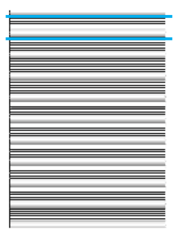
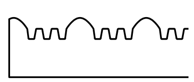
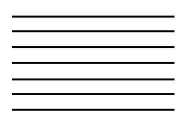
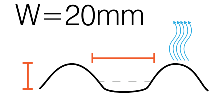
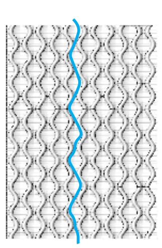
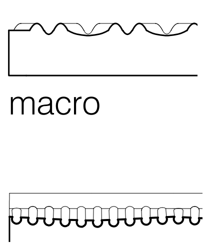
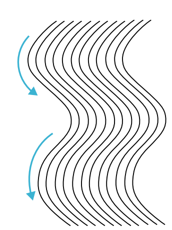
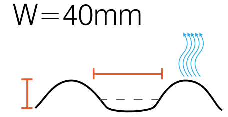
5. Design guidelines

RE-EVALUATION OF ORDERED SYSTEM IN MOSS GROWTH

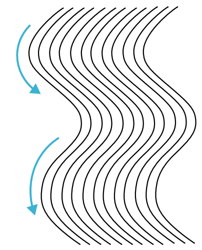
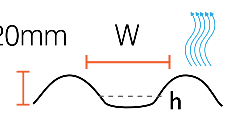
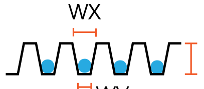
OBSTACLE DIRECTION	GROOVE DEPTH	AVG.WEIGHT GAIN (%) (at 20 min)	WEIGHT LOSS (%) (from 2 - 20 min)	ALCOVE MOISTURE (RH %) (at 20 min)	ALCOVE MOISTURE LOSS (%) (from 2 - 20 min)	RIDGE MOISTURE (RH %) (at 20 min)	RIDGE MOISTURE LOSS (%) (from 2 - 20 min)	MOSS GROWTH (week 12)	REMARKS + -
PANEL 1 	along the flow; macro; micro	+0.06	-0.04	24.4	-4	23.1	-4.4		- cushion growth with macro depth - moderate growth - low absorption & retention - low micro depth
PANEL 2 	along the flow; macro; micro	+0.07	-0.03	26.1	-4.8	19.7	-7.1		- wider & deeper macro depth - lower ridge moisture - good growth - low absorption & retention - low micro depth
PANEL 3 	against the flow; macro + micro	+0.28	-0.07	44.6	-3.4	36.1	+6.1		- moderate micro depth - higher alcove moisture - high ridge moisture - lesser growth area - low growth
PANEL 4 	along the flow; macro; micro	+0.08	-0.03	25.9	-4.4	22.6	-3		- low absorption & retention - low macro & micro depth - low and random growth
PANEL 5 	no obstacle; no depth	+0.39	-0.03	25.1	-1	25.1	-1		- high absorption - quick drying - no growth
PANEL 6 	random; micro	+0.55	-0.04	30.2	-16.1	30.2	-16.1		- high absorption - low and random growth

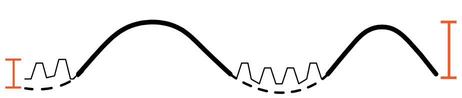


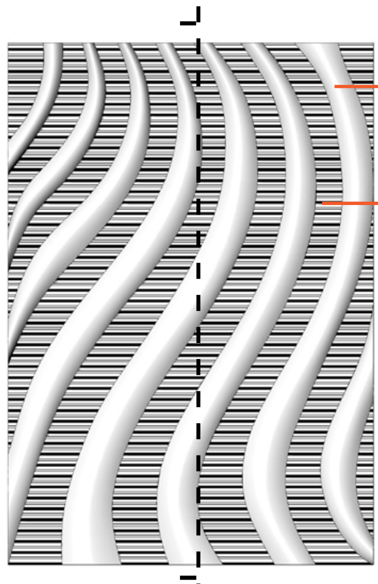
Features	Geometry (rhythm)	Level	Panel 1 (alternating)	Panel 2 (flowing)	Panel 3 (regular)	Panel 4 (random)	Panel 5 (n/a)	Panel 6 (n/a)
Slow water movement	Continuous obstacles	Macro geometry	✓	✓	✓			
	Discontinuous obstacles					✓		
	Along the flow		✓	✓		✓		
	Against the flow				✓			
Cushion growth	Macro depth		✓	✓				
	Radial form		✓					
Water retention & Anchorage facility	Micro depth	Micro geometry	✓	✓	✓	✓		✓
Nutrient accumulation	Deep Micro depth				✓			✓
Channel water to growth areas	Height and texture variation	Macro+ Micro geometry	✓	✓	✓	✓		

CHOOSEN PANELS	MACRO GEOMETRY/ OBSTACLE DIRECTION	MACRO DEPTH	MICRO DEPTH
  macro micro **PANEL 2**	Along the flow  Continuous obstacles	W=30-50mm H=10-15mm  H/W=0.2~0.3 Higher, wider, smoother ridges	 shallow micro-grooves 1-1.5mm depth
	-direct water to growth areas	-quick drying of ridges -direct growth areas	-no water circulation
  macro + micro **PANEL 3**	Against the flow  Continuous obstacles	W=20mm H=10 mm  H/W=0.5 Higher, wider, smoother ridges	 deep micro-grooves 3mm depth
	-cannot direct water to growth areas	-high moisture in ridges -limited growth area	-water circulation -vertex created
  macro micro **PANEL 1**	Along the flow  Continuous obstacles	W=40mm H=7 mm  H/W=0.15 low, thin ridges	 shallow micro-grooves 1-1.5mm depth
	-direct water to growth areas	-shallow ridges -limit directed growth	-no water circulation

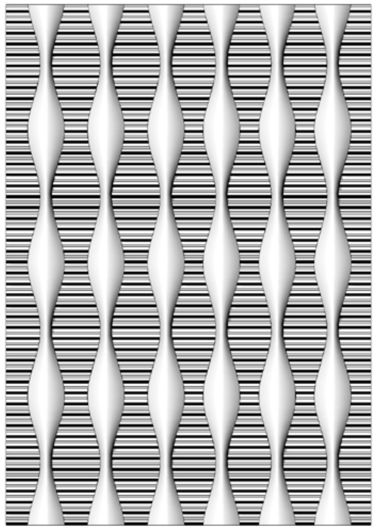
remarks + -

	MACRO GEOMETRY/ OBSTACLE DIRECTION	MACRO DEPTH	MICRO DEPTH
GENERAL GUIDELINES	Along the flow  Continuous obstacles (flowing/alternating rhythm)	H<= 20mm W  h H/W=0.2~0.3 Higher, wider, smoother ridges	verified with CFD simulation wx  h wy deep micro-grooves 5mm depth wx/h= 0.8 wy/wx= 0.4





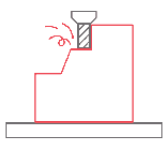
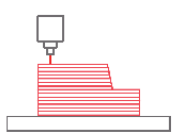
Flowing rhythm
W= 60-70mm
H= 15mm

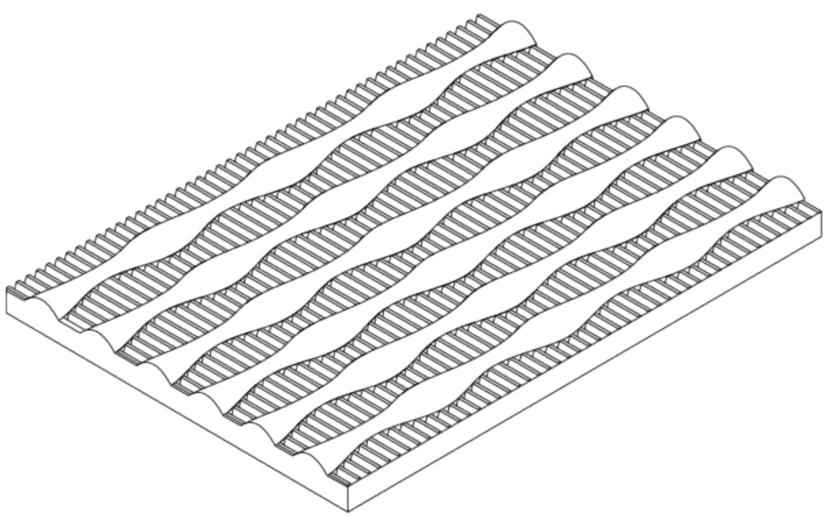


Alternating rhythm
W= 75mm
H= 15mm

6. Production to assembly

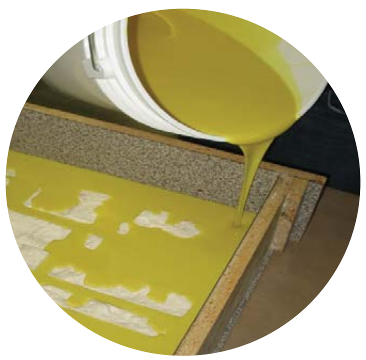
CNC milling vs 3D printing:

Type	Method	Remarks + -
CNC milling	Substractive manufacturing 	- high precision - variety material - smooth finish
3D printing Fused diffusion modeling(FDM) - Industrial	Additive manufacturing 	- less precise - limited work volume - layer imprints - high post processing

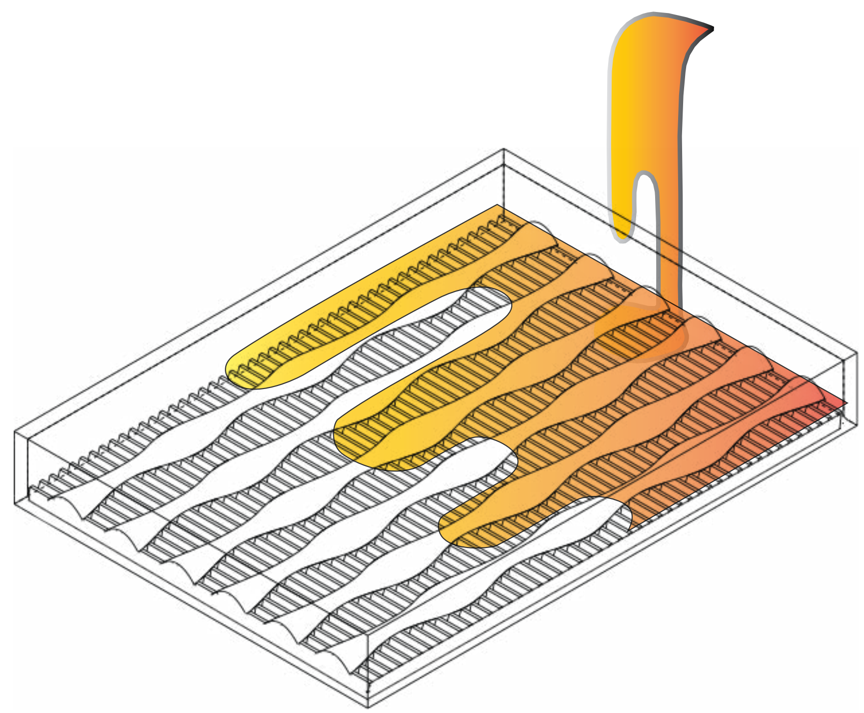


Step 1: CNC milling of sample design

Polyurethane rubber:


1. Pouring

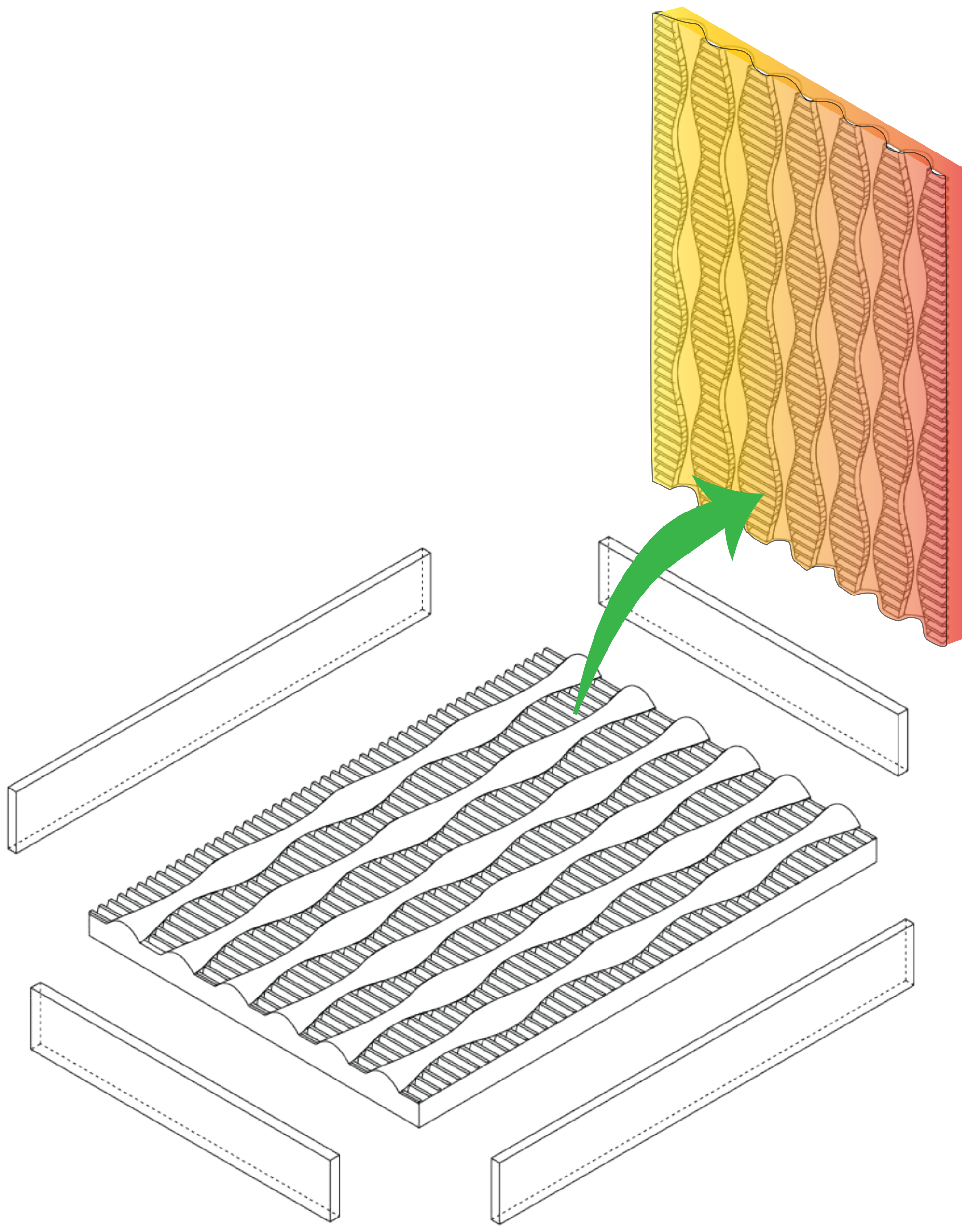

2. Demolding



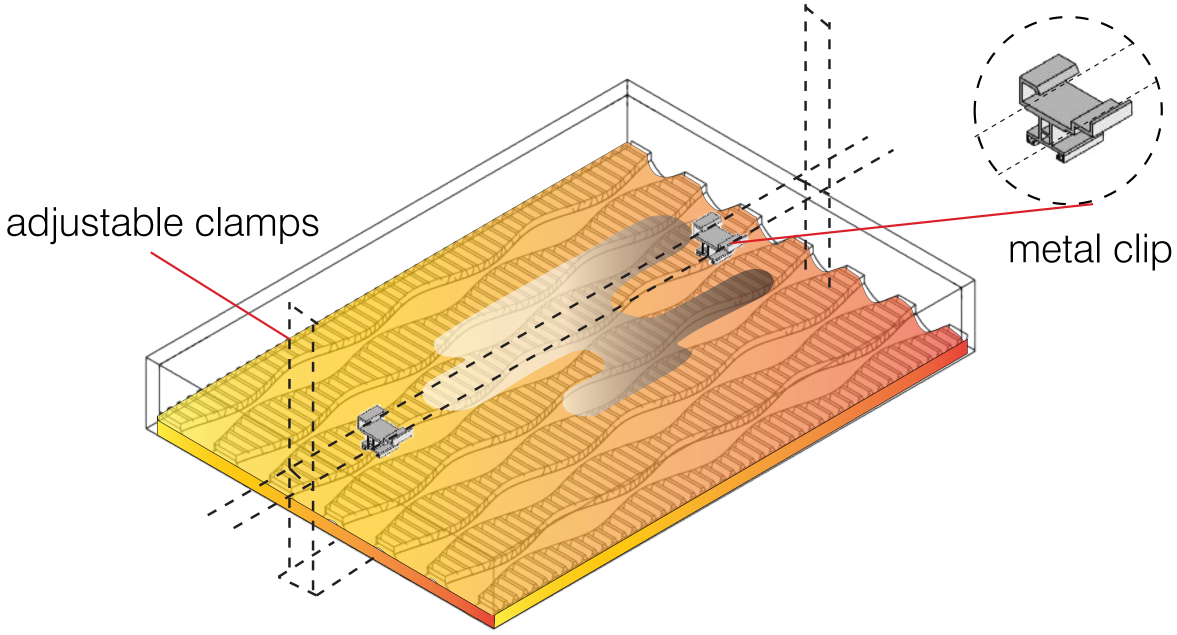
Step 2: Casting of negative elastic mold

Advantages:

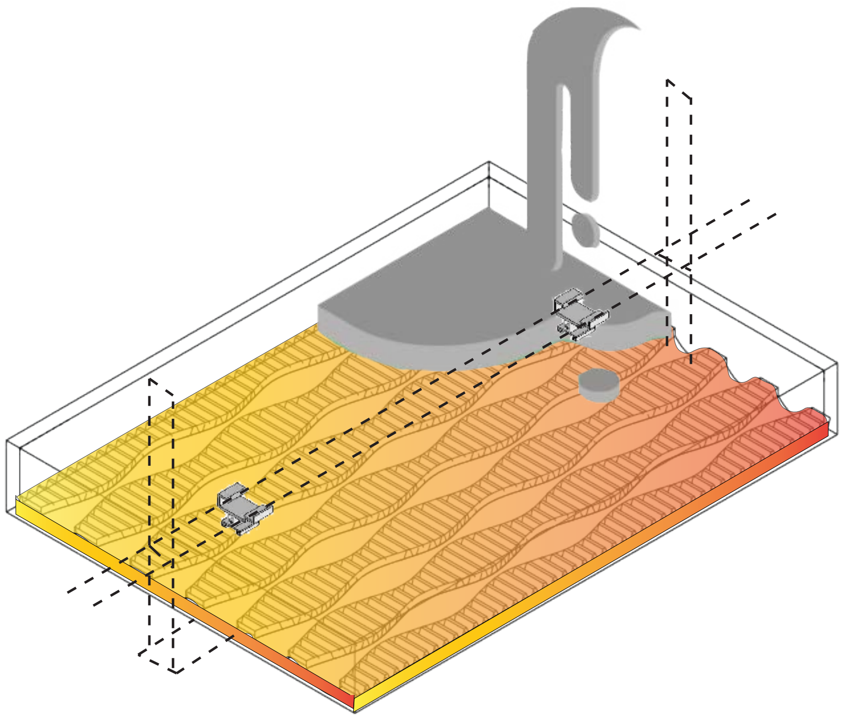
- Reusable about 100 times
- No shrinkage
- Good abrasion resistance
- High strength
- Economic



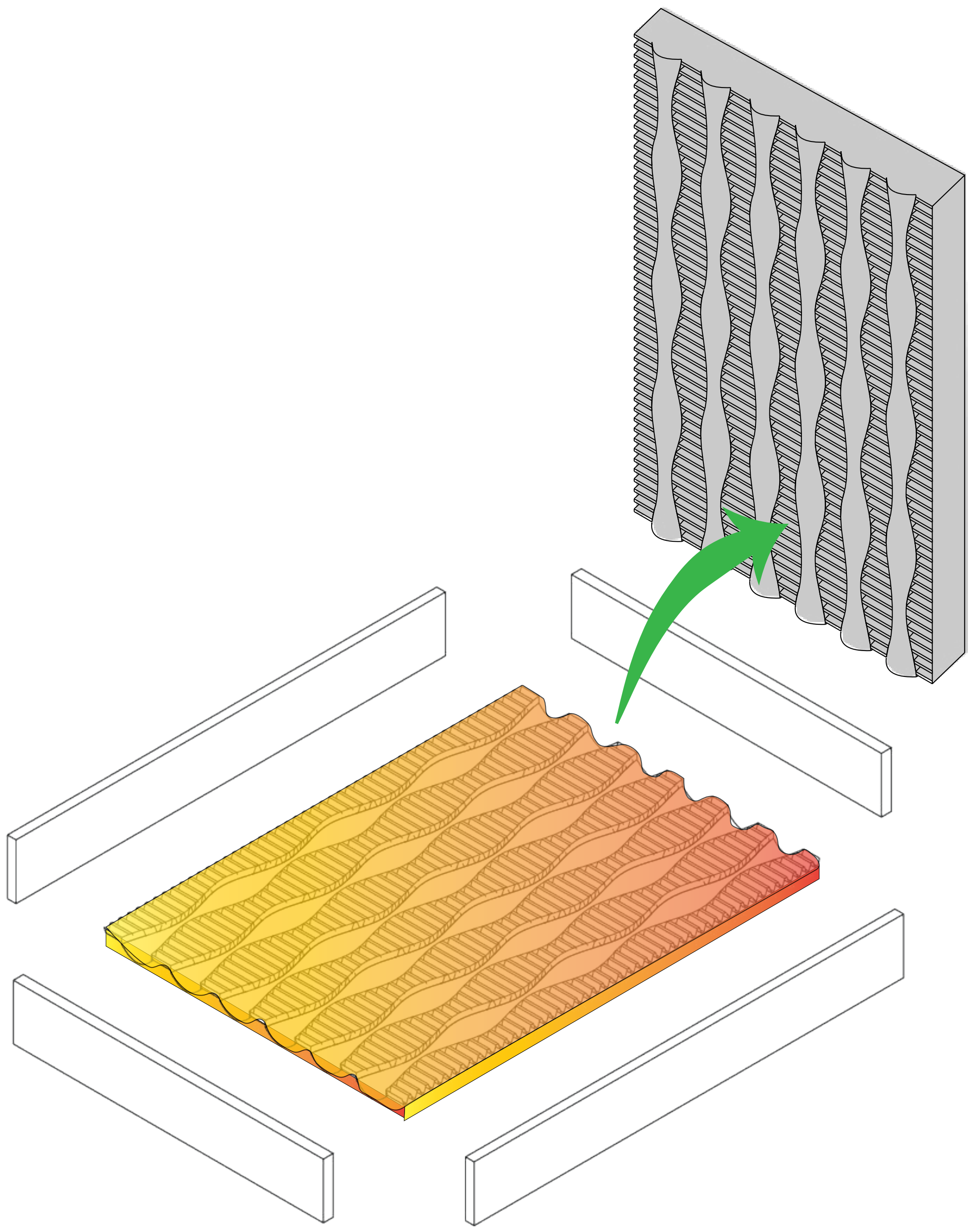
Step 3: Demolding of negative elastic mold
Resuable over 100 times



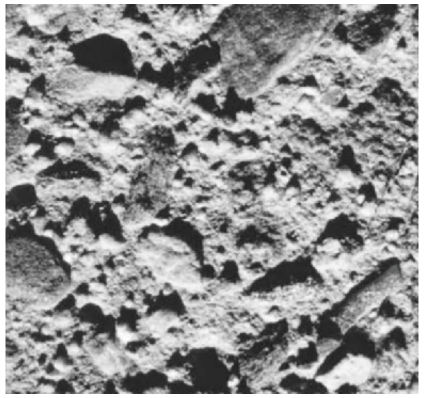
Step 4: Embedded metal clip



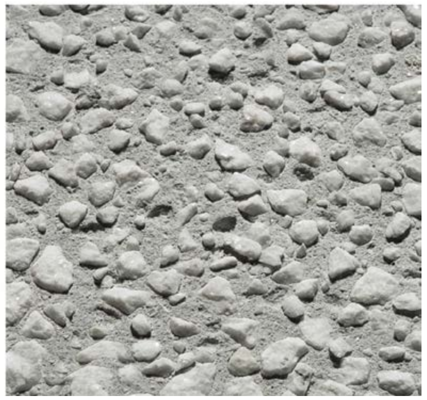
Step 5: Casting of concrete panel



Step 6: Demolding of concrete panel



Grit blasting

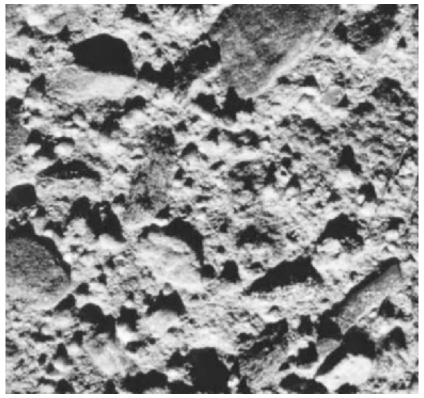


Washing

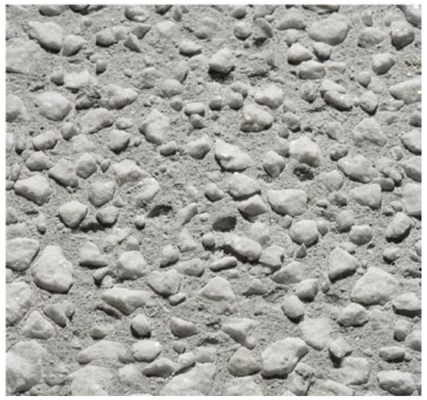
Acidification

Bush Hammering

Sanding/Chiseling
(sand+gravel layer)



Grit blasting



Washing

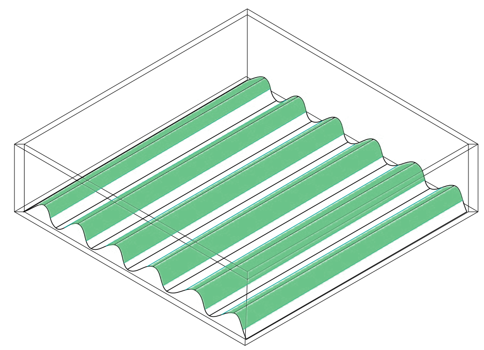
Acidification

Bush Hammering

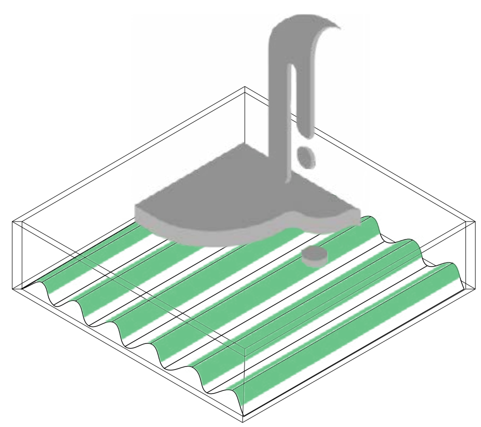
Sanding/Chiseling
(sand+gravel layer)

WASH (SURFACE RETARDER)

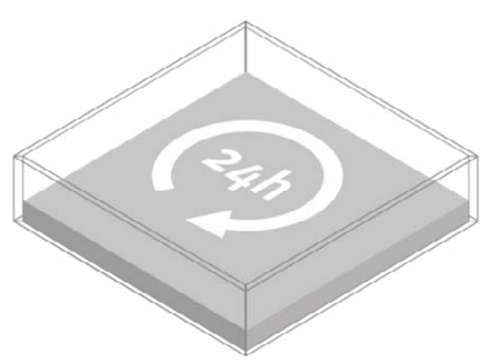
Negative process (N)



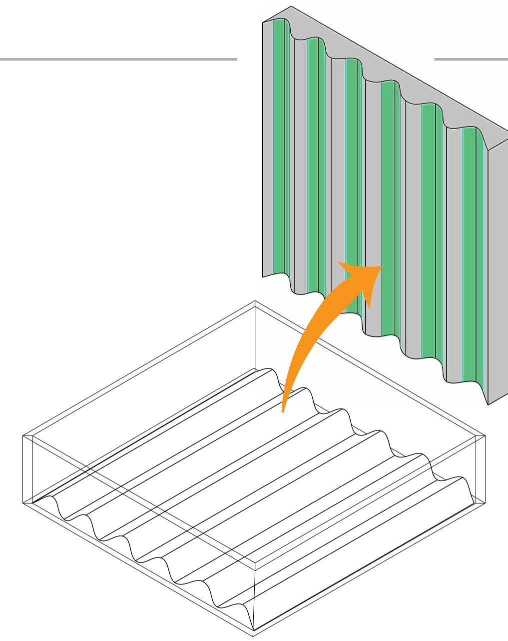
Step 1 - Surface retarder applied on the mold



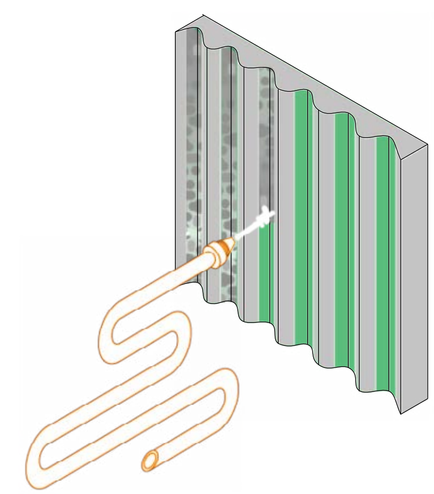
Step 2 - Casting of concrete



Step 3 - Setting time 24hrs, more than 48hrs may require sandblasting.



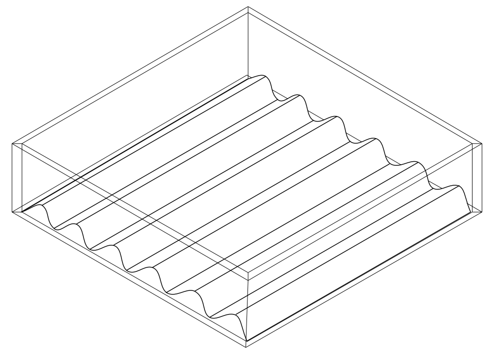
Step 4 - Demolding of the concrete panel



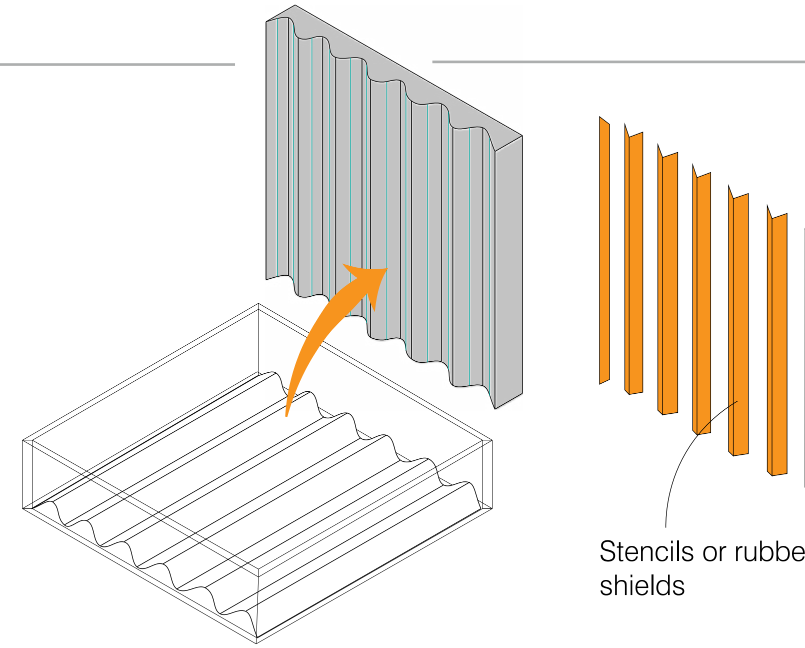
Step 5 - High pressure water wash

Note: Affect of surface retarder on the Bio-receptive character of concrete.

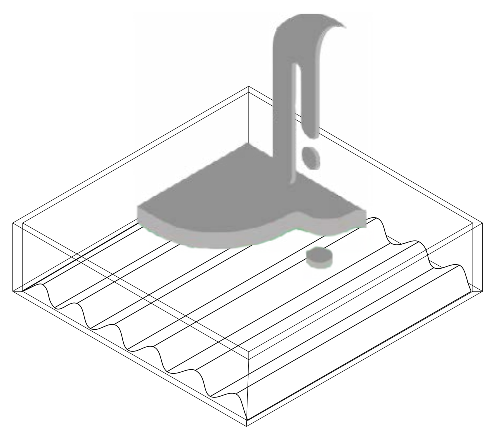
GRIT BLASTING



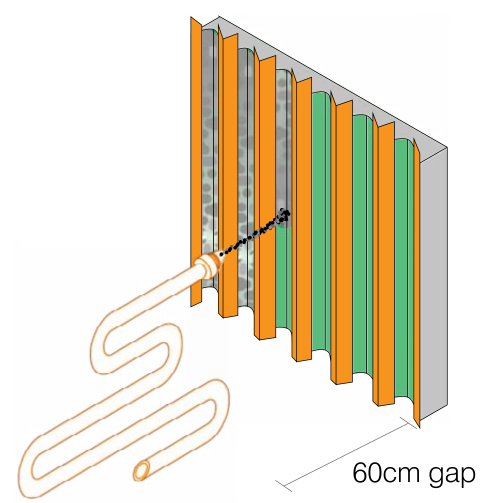
Step 1 - Surface retarder applied on the mold



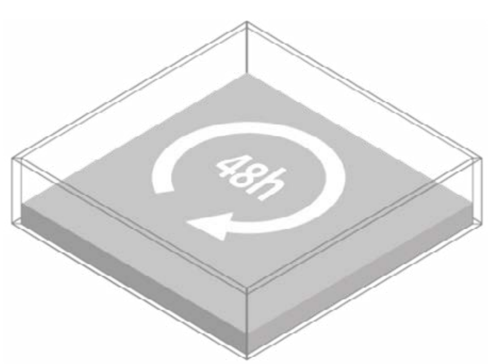
Step 4 - Demolding of the concrete panel



Step 2 - Casting of concrete

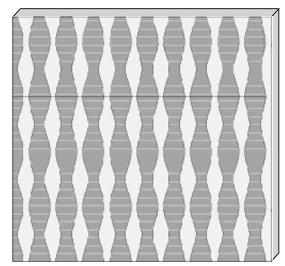


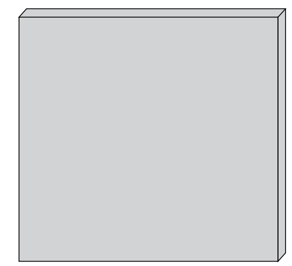
Step 5 - Micro-abrasive blasting, stencils protect non-blasted surface



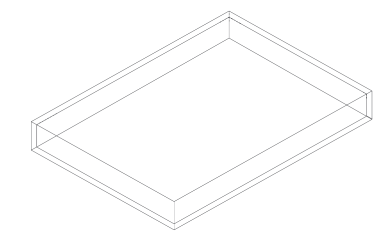
Step 3 - Setting time 48hrs

Note: Mostly suitable for concrete with low w/c ratio

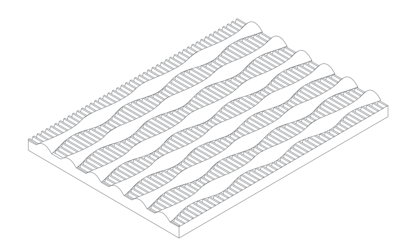




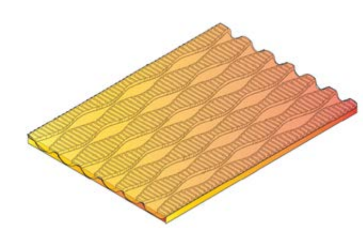
	Designed bio-receptive panel (euro)	**Plain concrete panel (unpolished)** (euro)
Concrete mix cost	6.0	6.0
Wooden frame	3.2	3.2
CNC milling cost	0.8	
Polyurethane rubber mold	2.83	
Casting time (labour wage)	87.5 (2.5 hr)	52.5 (1.5 hr)
Estimated total cost for a (1x1x0.04m) panel	~100 euro	~62 euro



Wooden frame



CNC milled sample



Polyurethane mold

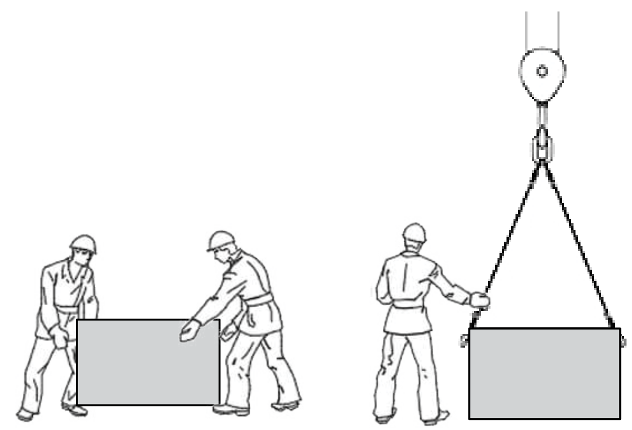
Cost can be reduced through mass production:

Multiple elastic mold

- production time
- per hr labour cost
- miscellaneous factory cost

Panel size:

- Weight limitations
- **Production limitations**
- Transportation weight and dimension limitations
- Erection feasibility and access
- **Stress limitations**

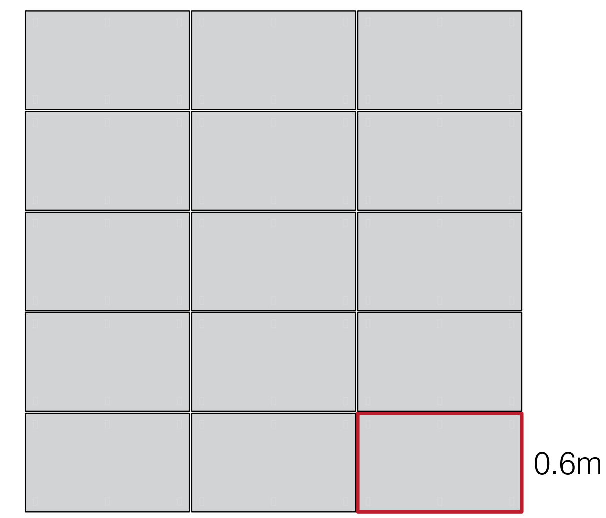


Handling weight per person = 25kg (elbow height)

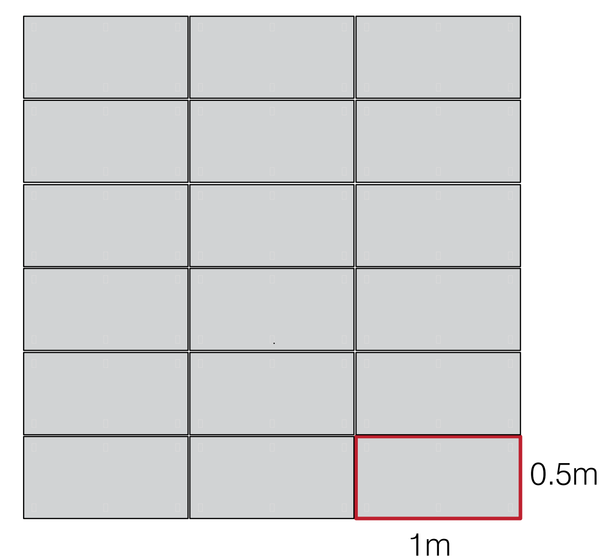
Actual Panel sizes:

1m x 0.5m x 0.04m (35kg)
or
1m x 0.6m x 0.04mm (42kg)

Panel arrangement for a 3m x 3m wall area:



Type 1

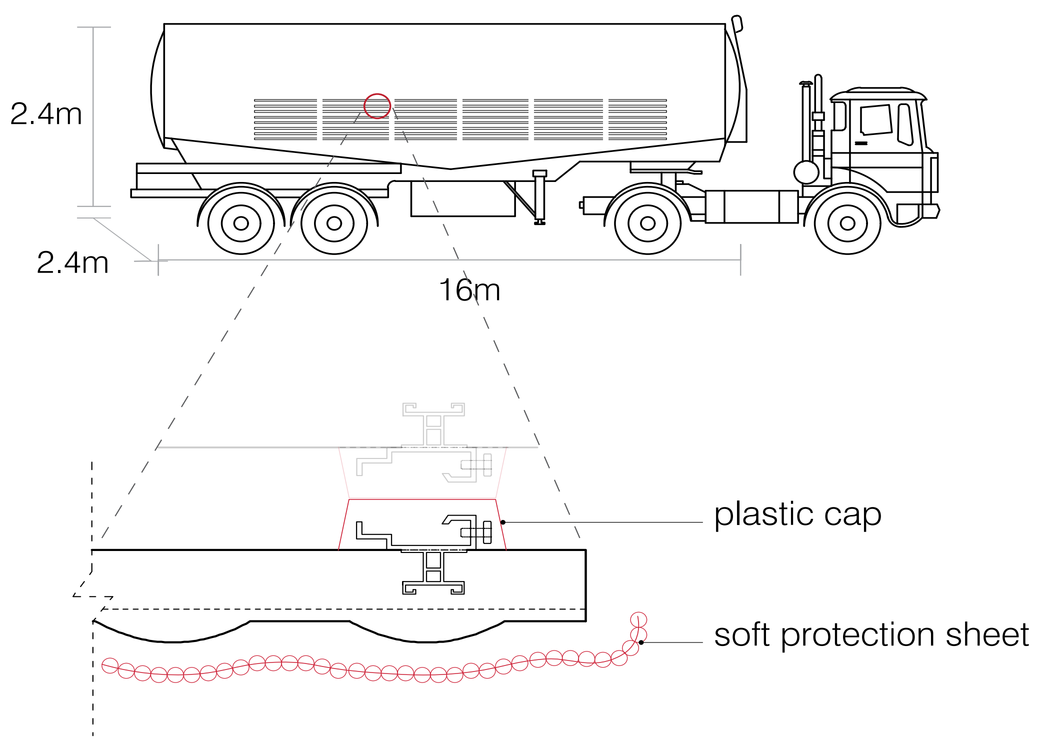


Type 2

Packing and Transportation:

Max. load carried 18-20 tons (20,000kg)

Max. number of panels per trip 450 (approx.)



Maintenance:

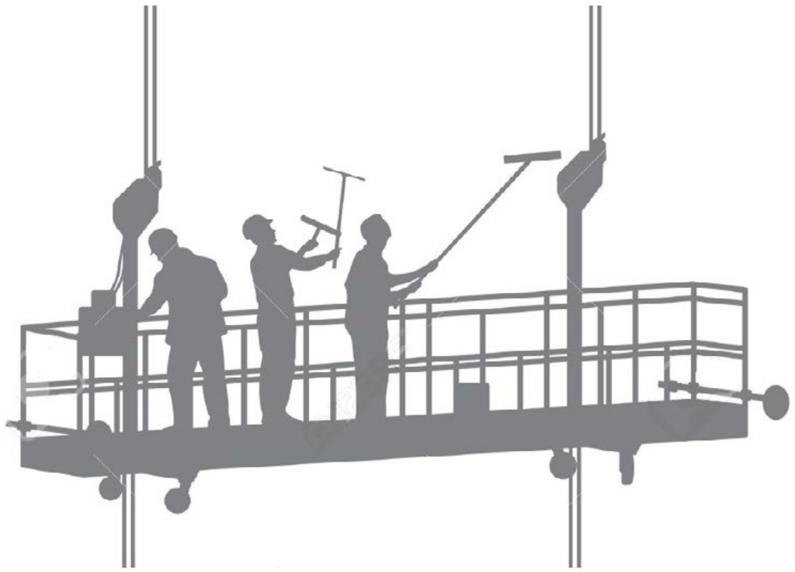
Panels require periodic inspection **once every 6 months:**

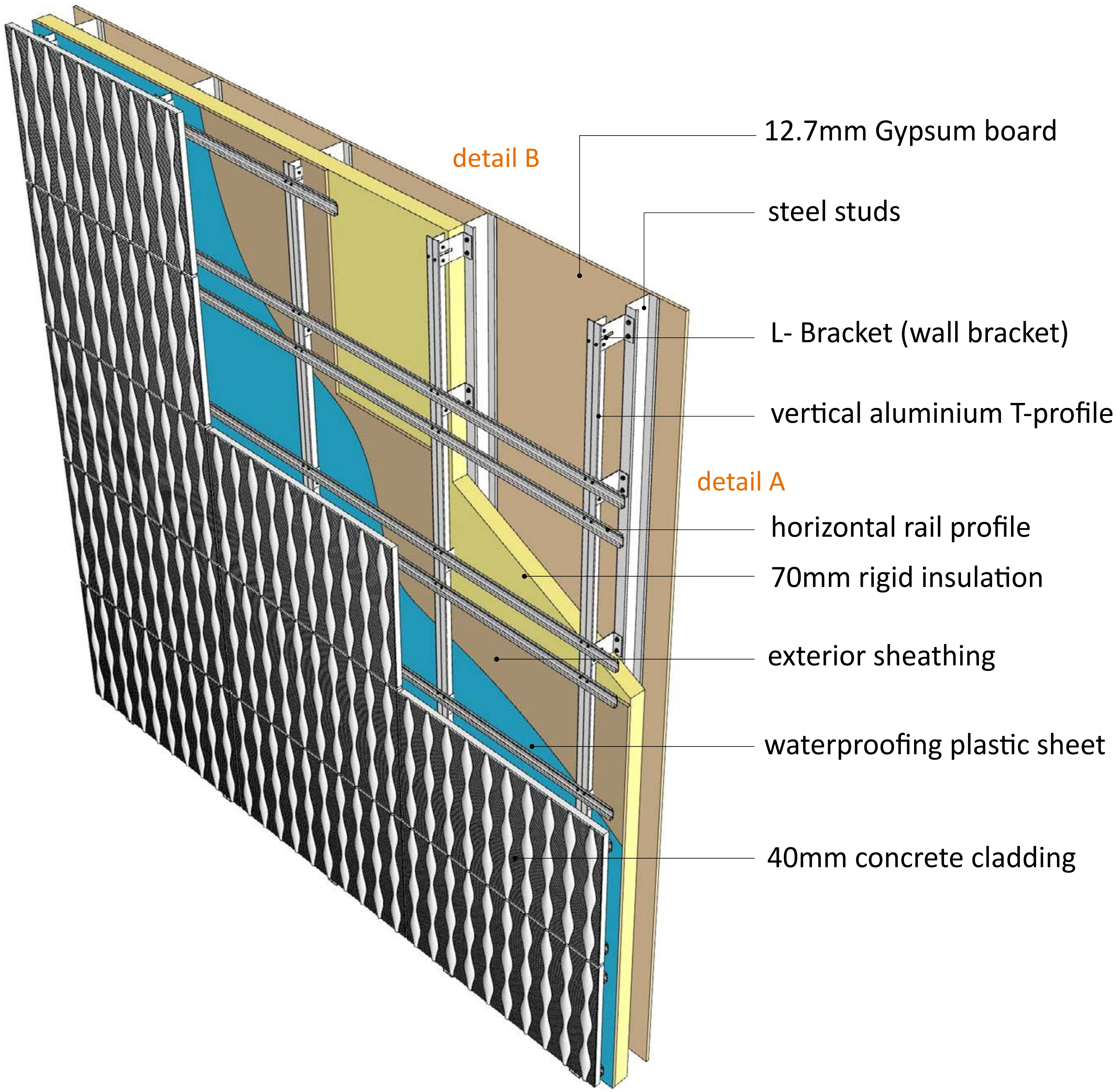
- Remove any unhealthy moss patches
- Re-inoculate with moss spores
- Remove external surface contaninants

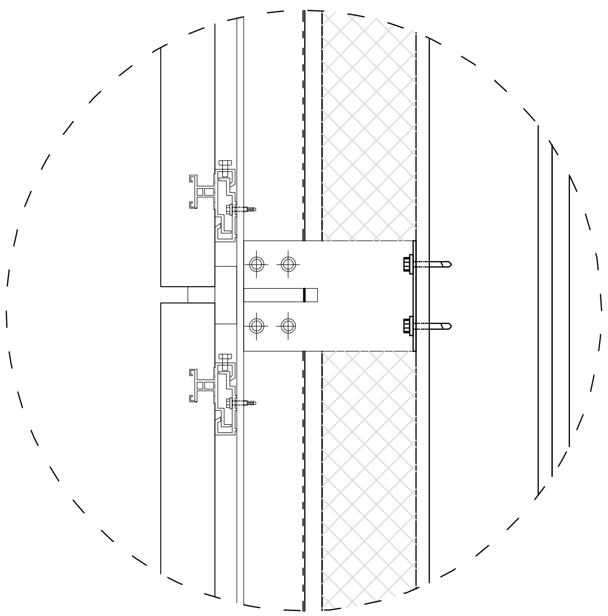
Note:

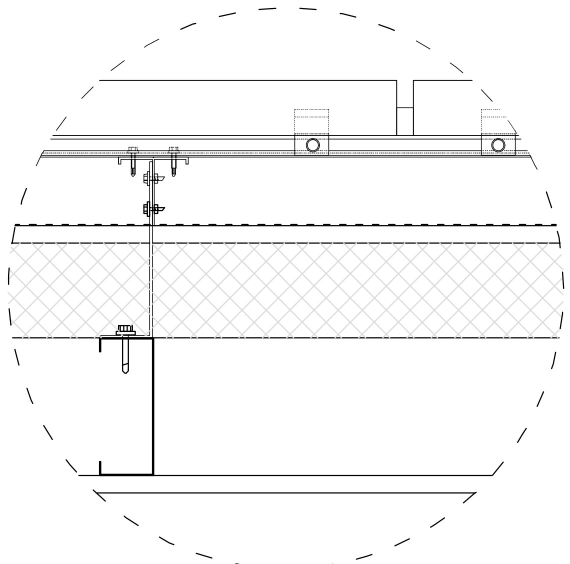
Drought longer than 3 months external watering required

Suitable for mild temperate to tropical climates

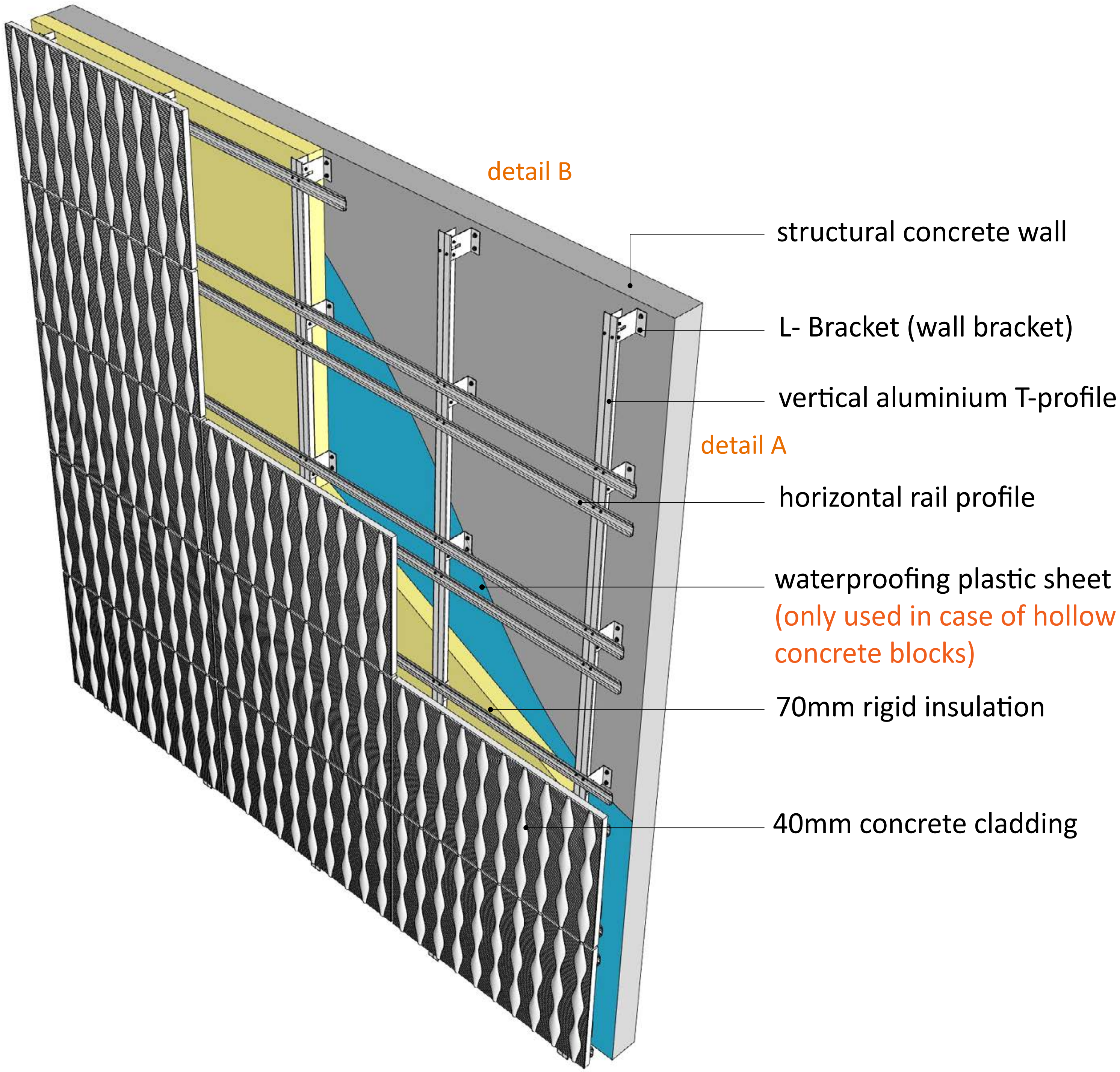


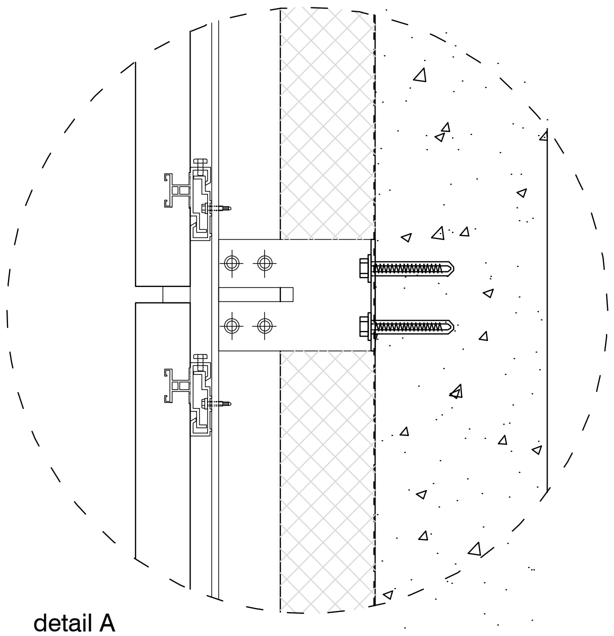



detail A

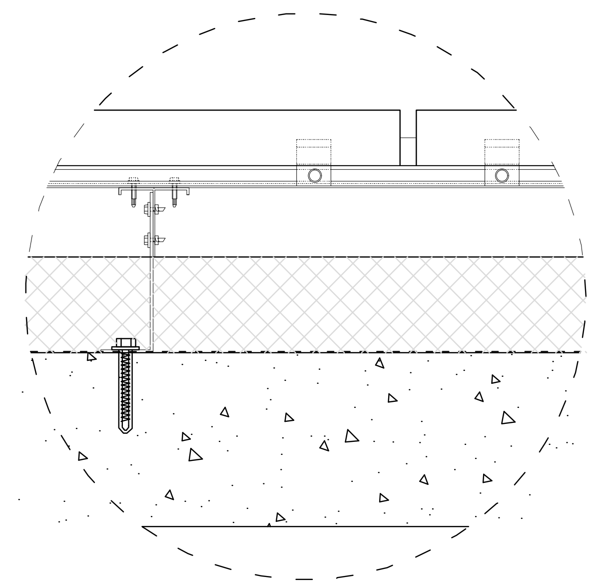

detail B

Concrete cladding on steel frame structure



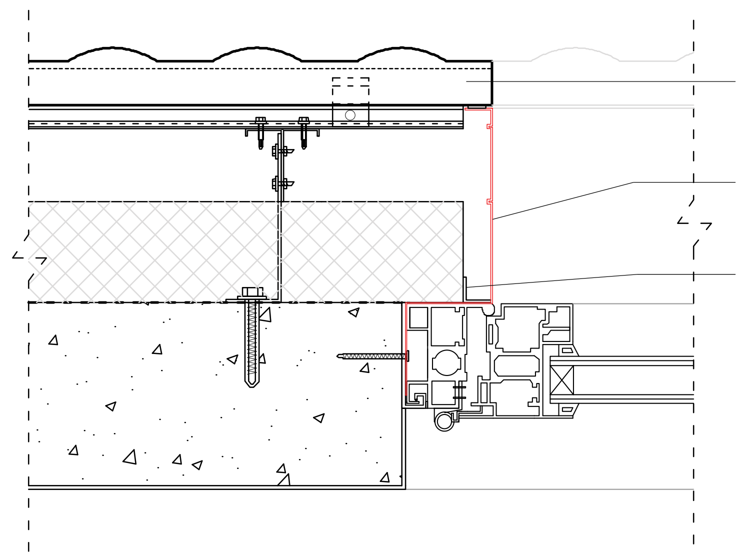


detail A

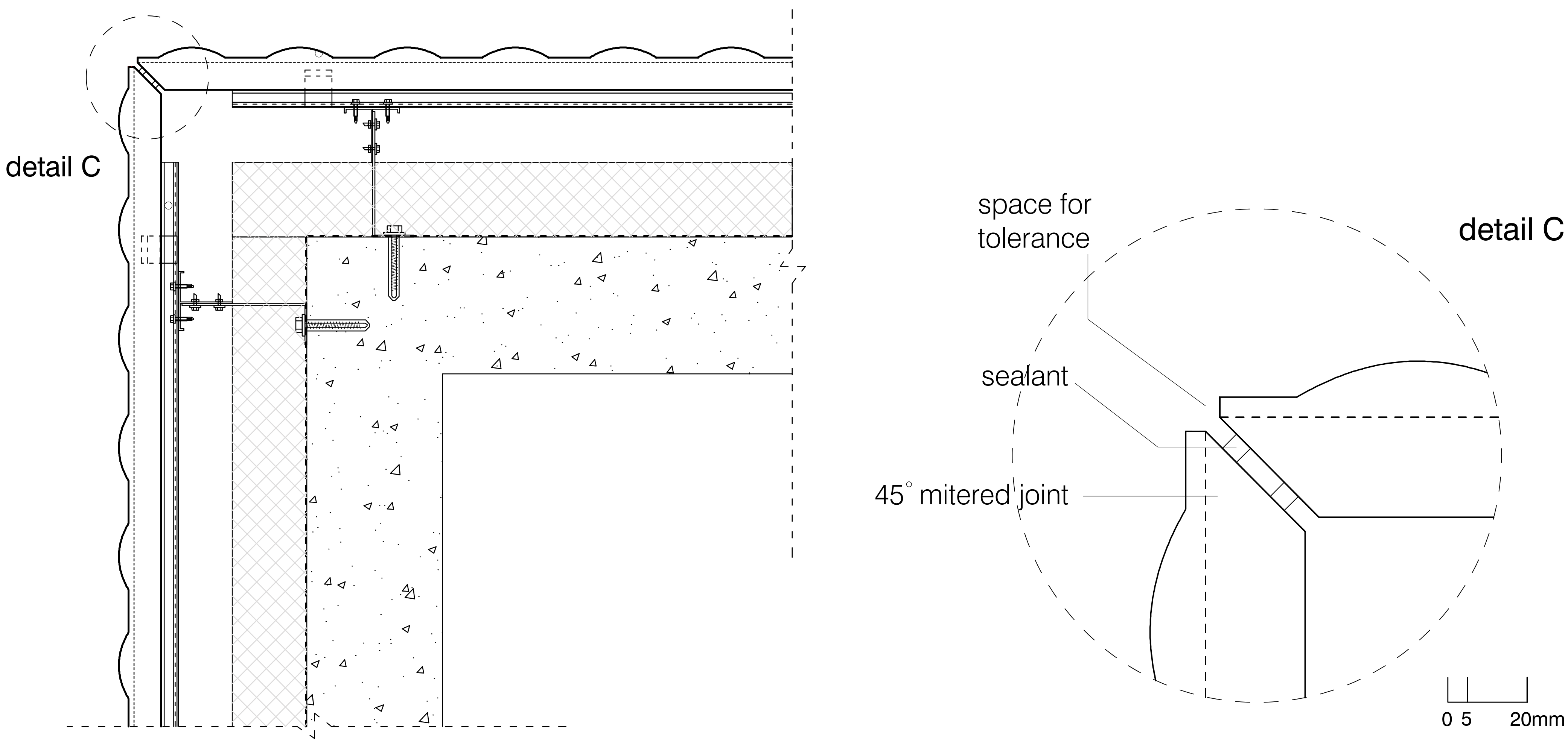


detail B

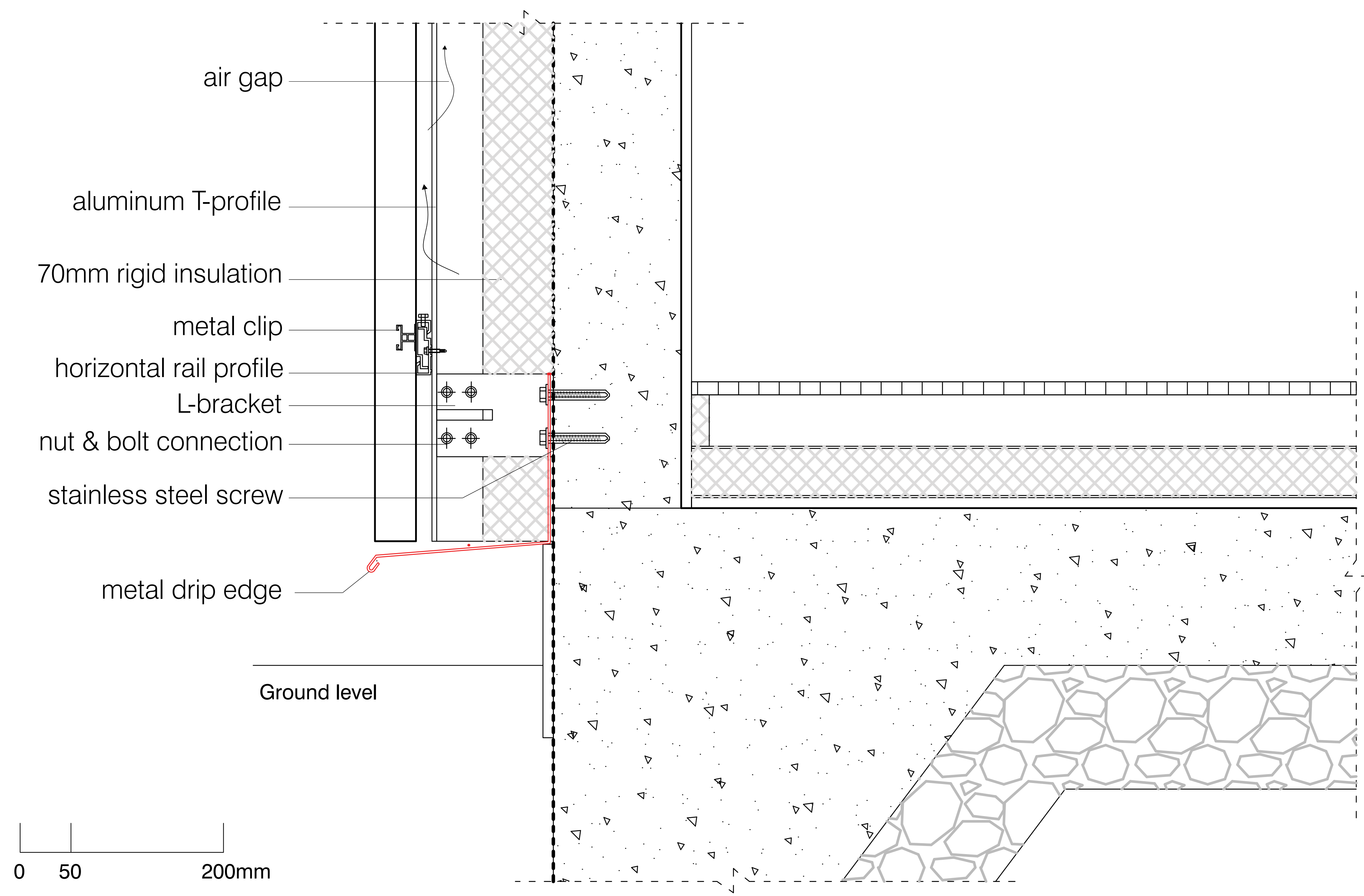
Concrete cladding
on structural concrete wall



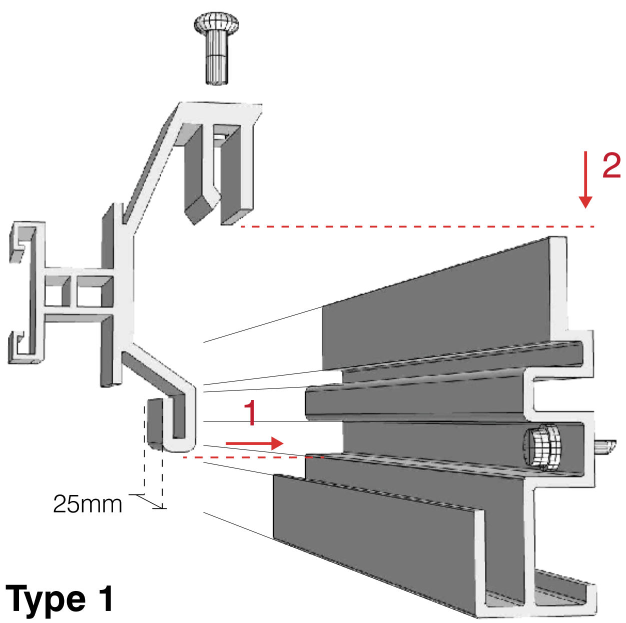
Window edge detail (plan view)



Corner detail (plan view)

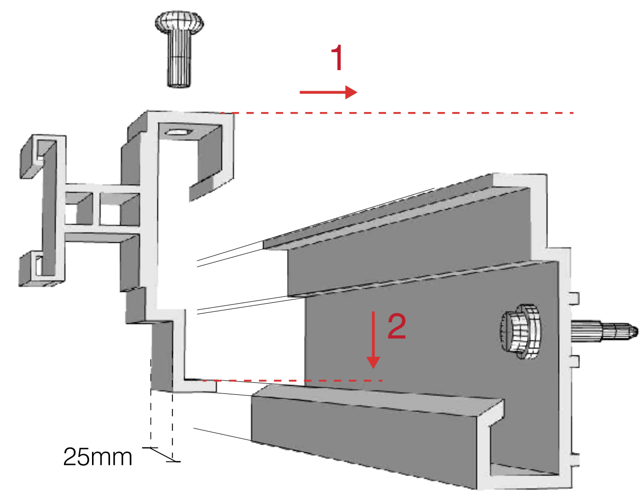


Base detail (plan view)



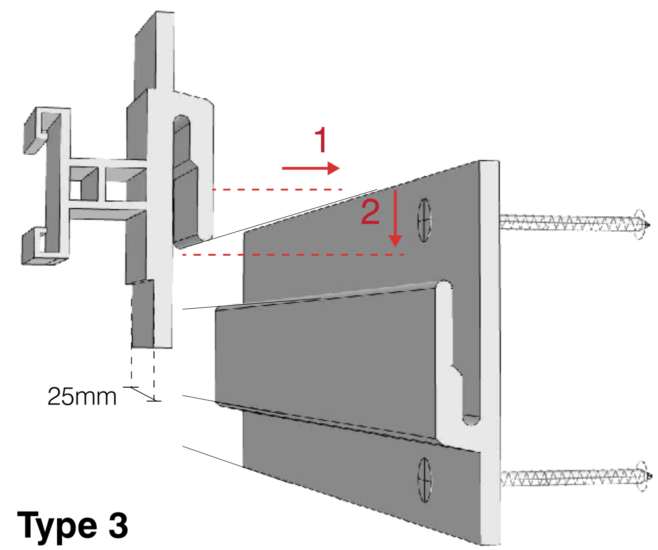
Type 1

Heavy weight
Panel length ±100cm



Type 2

Medium weight
Panel length ±70cm

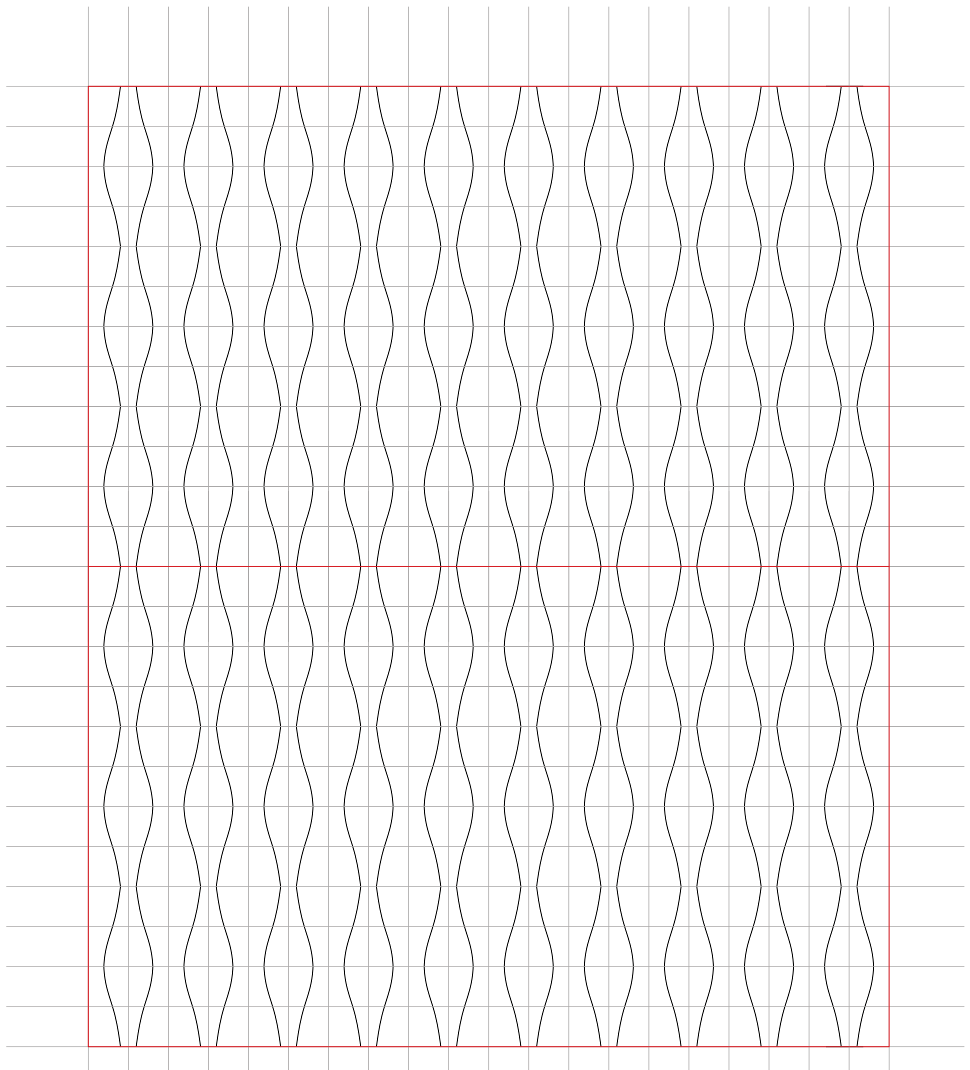


Type 3

Light weight
Panel length ±50cm

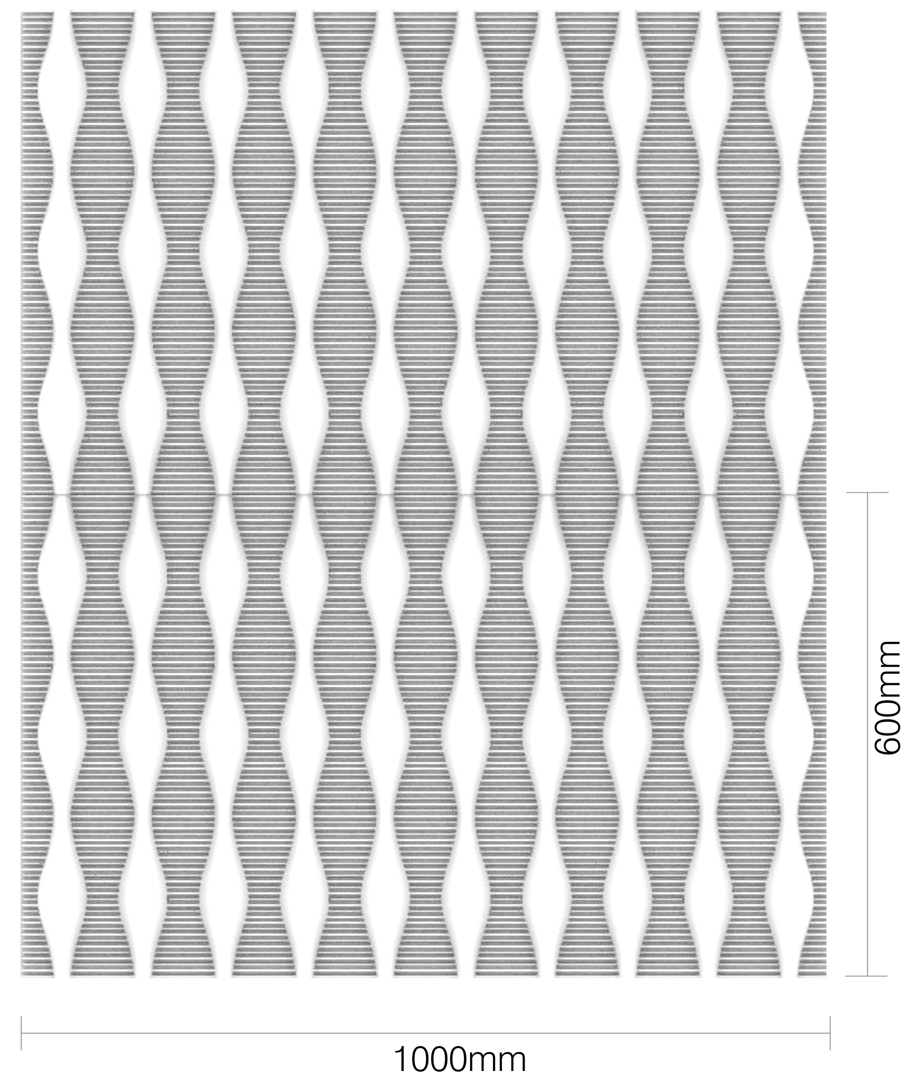
Types of connector/clip

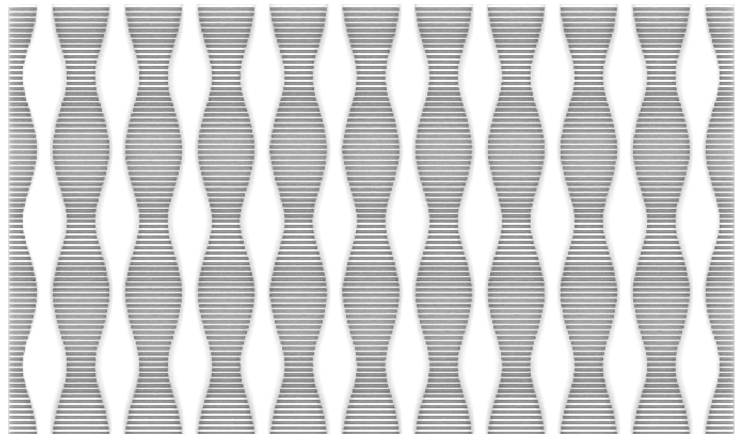
7. Visualization



Design Grid (unit size 50mm)

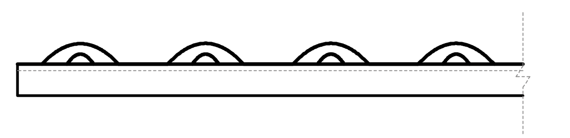
Example 1

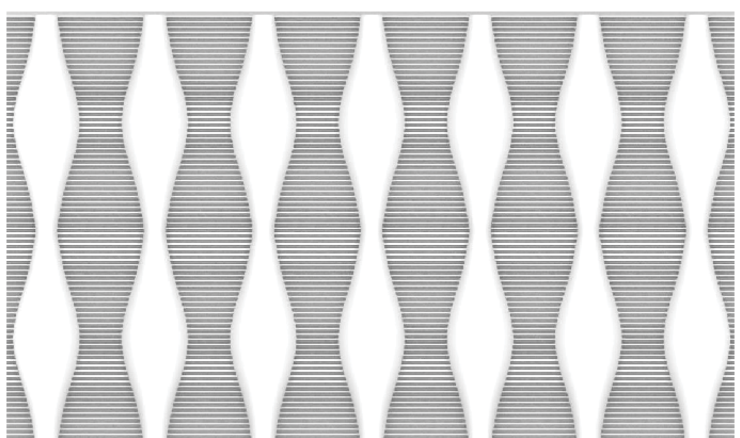




Type A (IDEAL estimated 100% coverage)

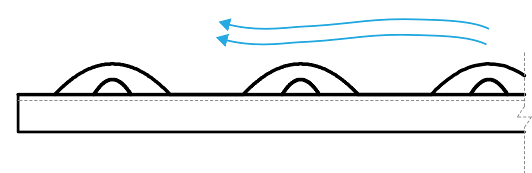
Groove depth, H=20mm
Groove width, W= 60-85mm
H/W=0.2~0.3



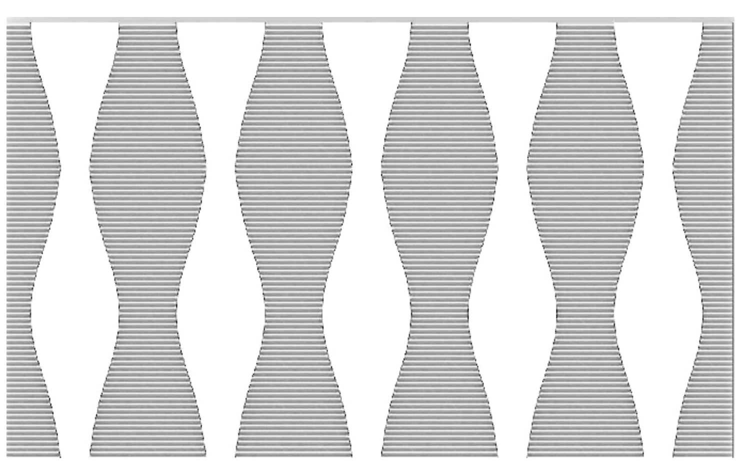


Type B (Scale up:1.5 estimated 70% coverage)

Groove depth, H=30mm
Groove width, W= 85-120mm
H/W=0.2~0.3

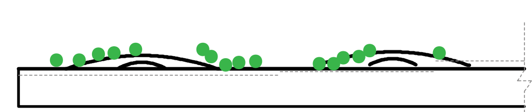


Depth > 20mm
wind barrier
hamper spores dispersal



Type C (Scale up:2 no ordered growth)

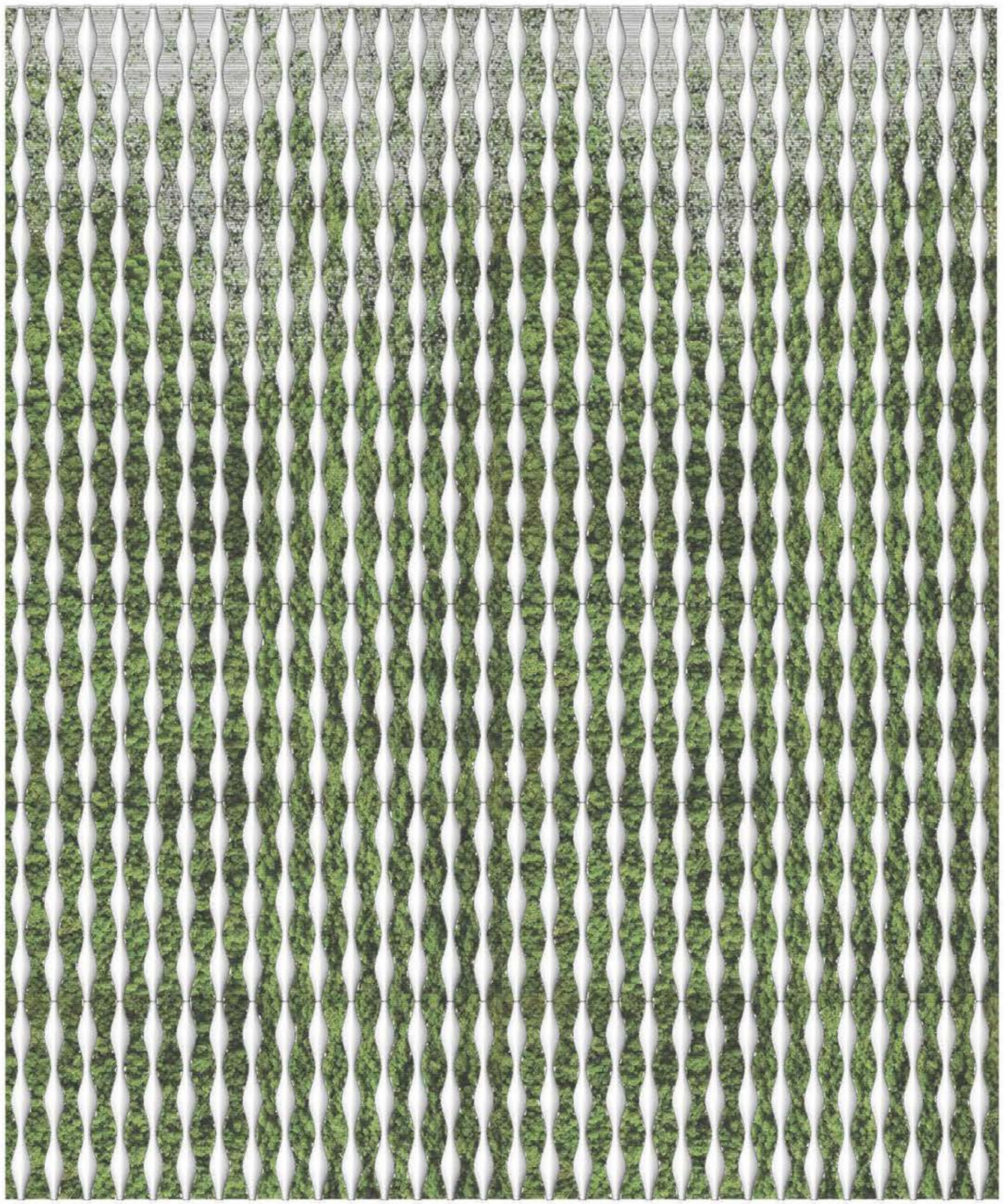
Groove depth, H=15mm
Groove width, W= 125-160mm
H/W=0.09~0.12



Width >~
a flattened surface,
random moss coverage

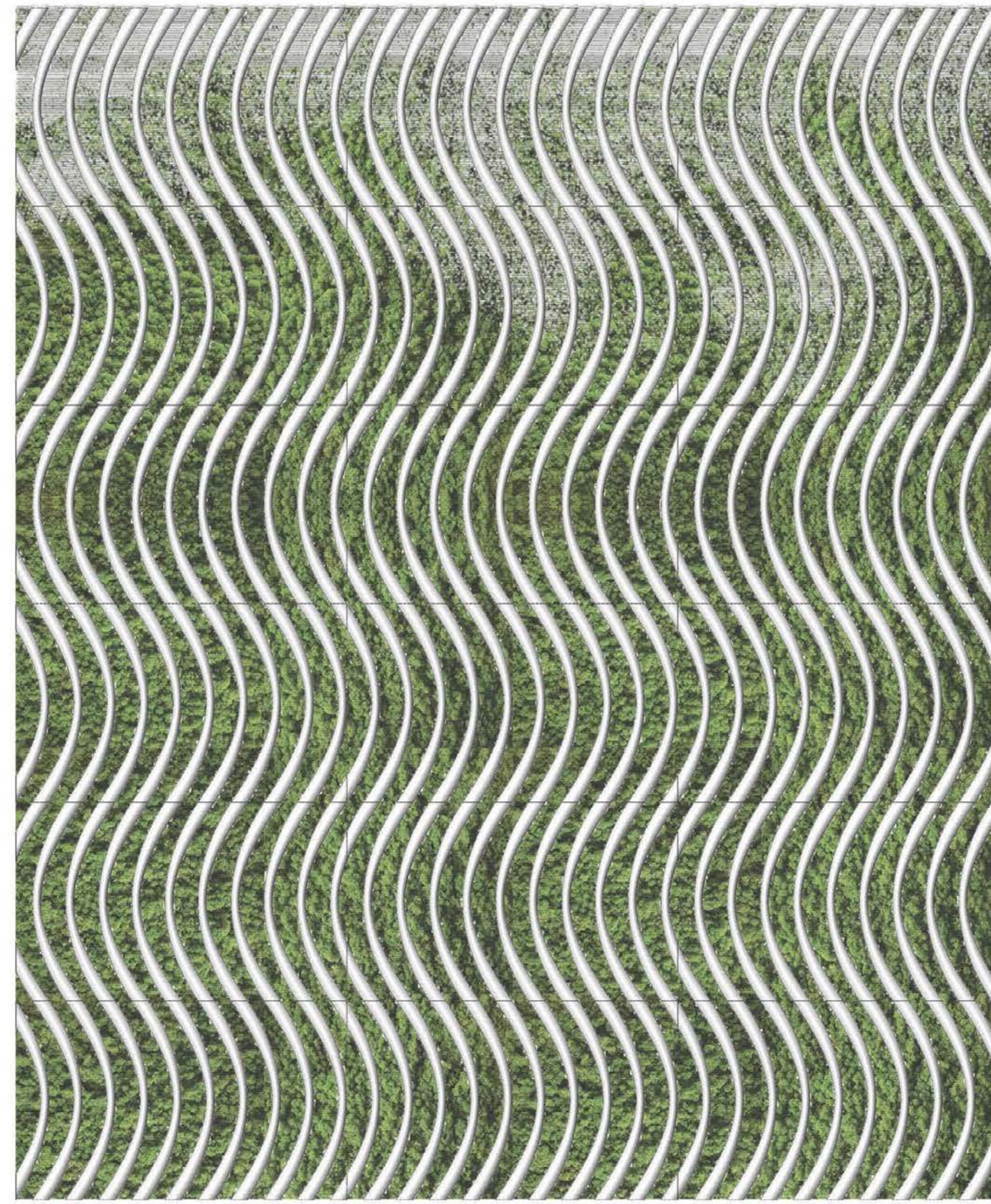
Example 1

Type A



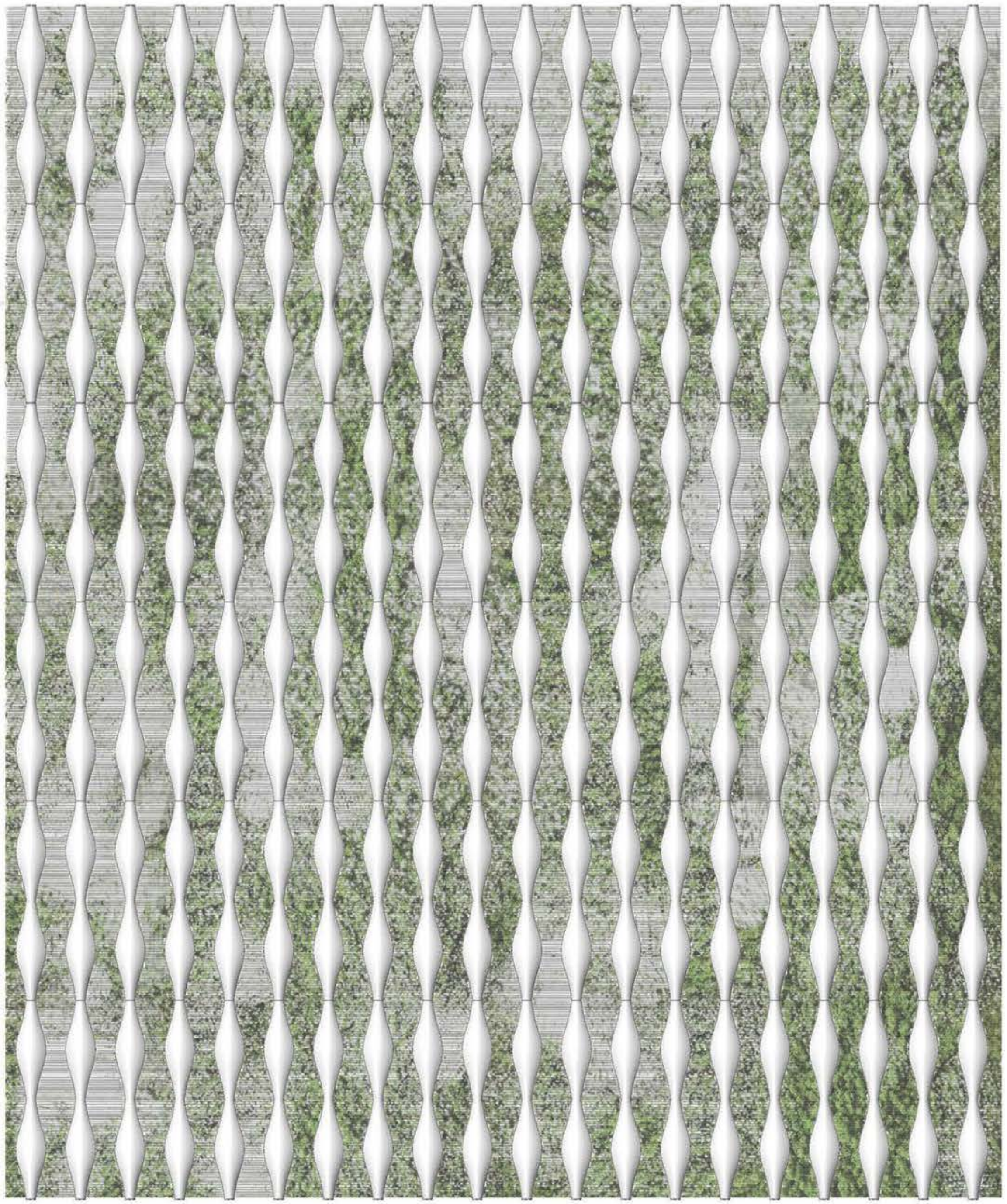
Example 2

Type A



Example 1

Type B



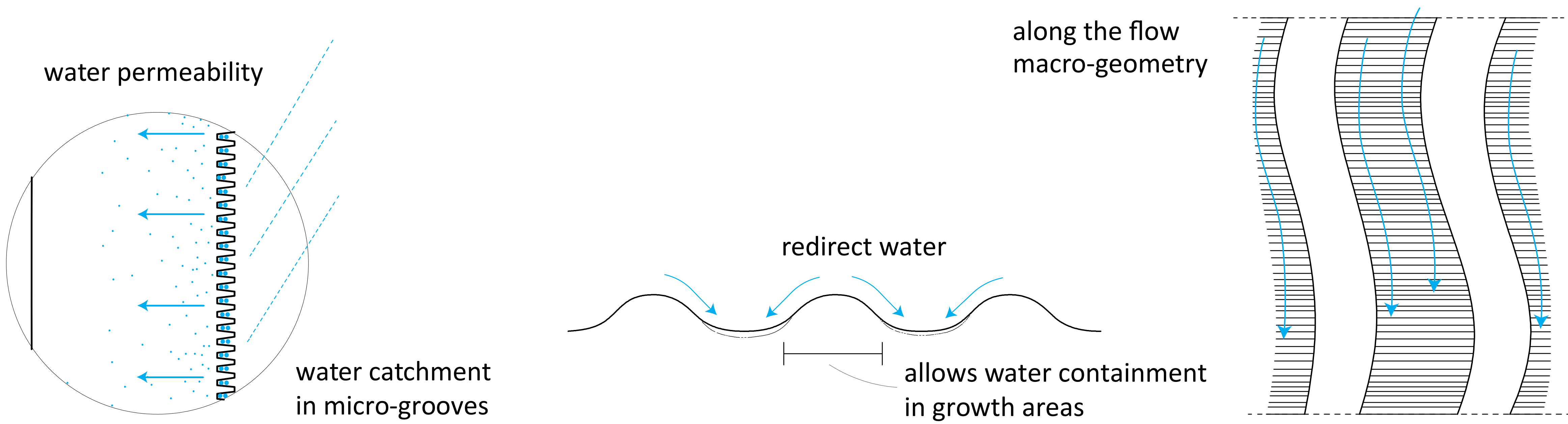
Example 2

Type B

8. Conclusion and discussion

What is the role/impact of surface geometry on an engineered/systematic growth of mosses on concrete facade panels?

A self-sustaining system:

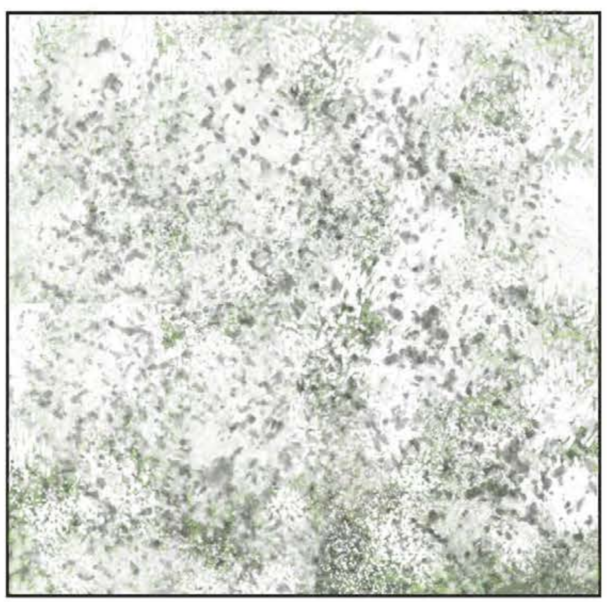


MICRO LEVEL GEOMETRY

MACRO LEVEL GEOMETRY

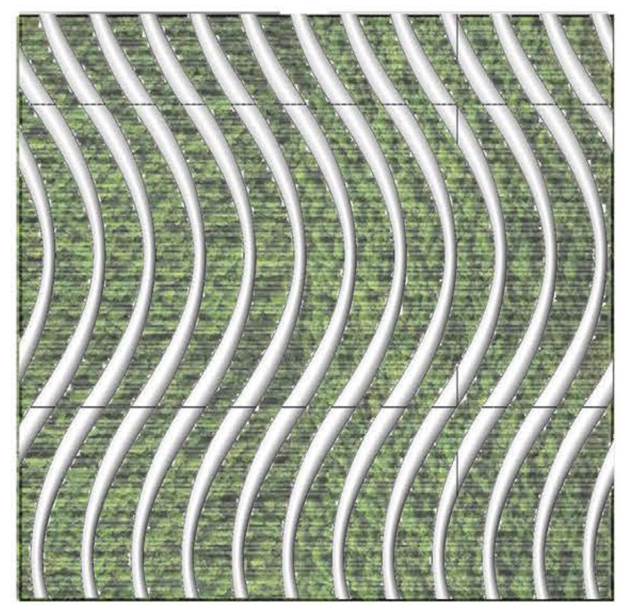
What is the role/impact of surface geometry on an engineered/systematic growth of mosses on concrete facade panels?

An ordered and balanced growth:



Natural rough/grit blasted

Micro-grooves only



Micro & macro-geometry

Flowing rhythm

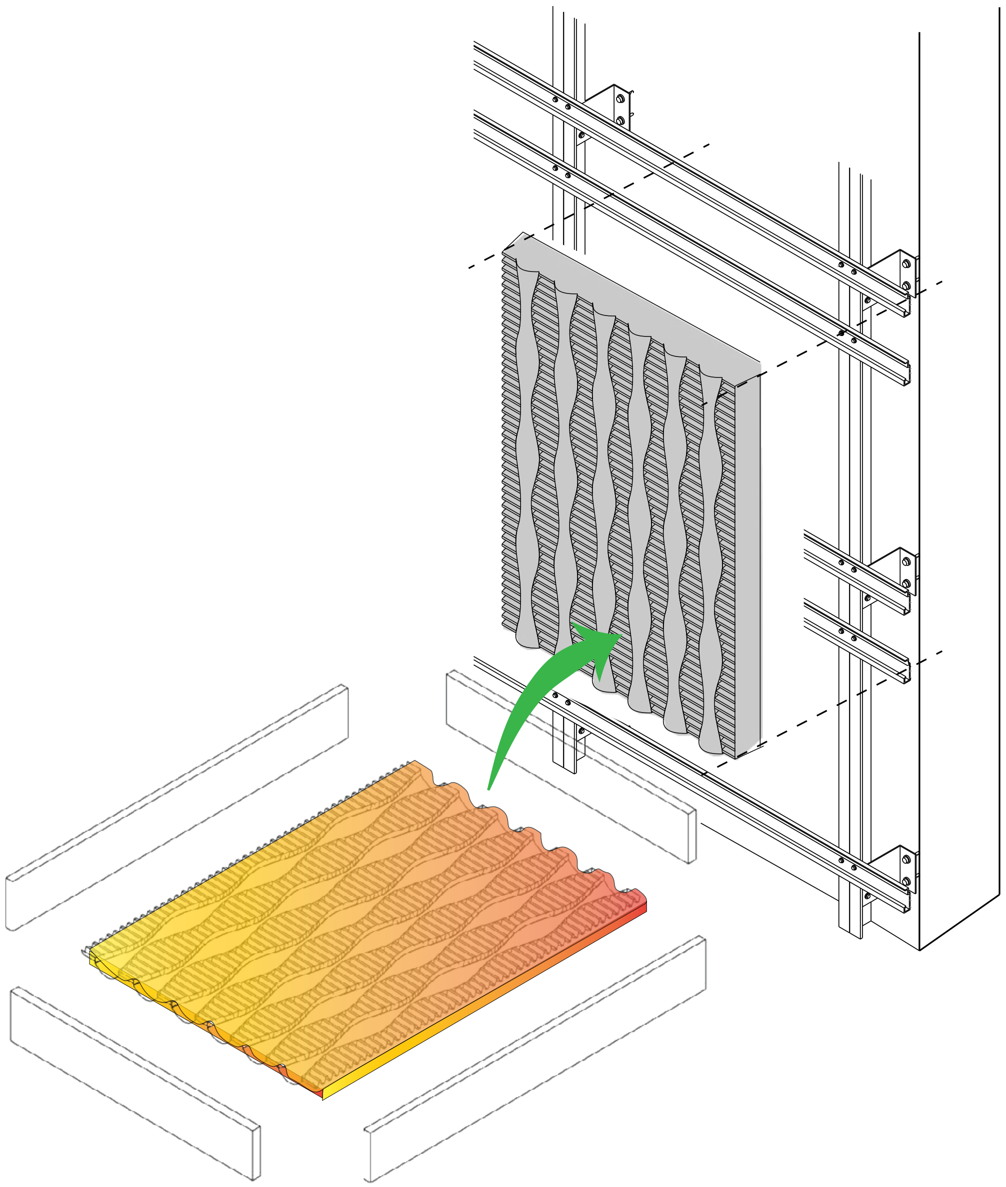
Alternating rhythm

NO ORDER & BALANCE

ORDER & BALANCE

What is the role/impact of surface geometry on an engineered/systematic growth of mosses on concrete facade panels?

An optimized facade system:



- simple designs
- resuable molds
- mass production
- efficient installation method

What is the role/impact of surface geometry on an engineered/systematic growth of mosses on concrete facade panels?

Limitations:

- Testing in natural environment
- Testing of the modified panels

Future recommendations

- Assign into parametric platform
- Quantify through environmental parameters
- Bio-receptive quality of other materials.

THANK YOU