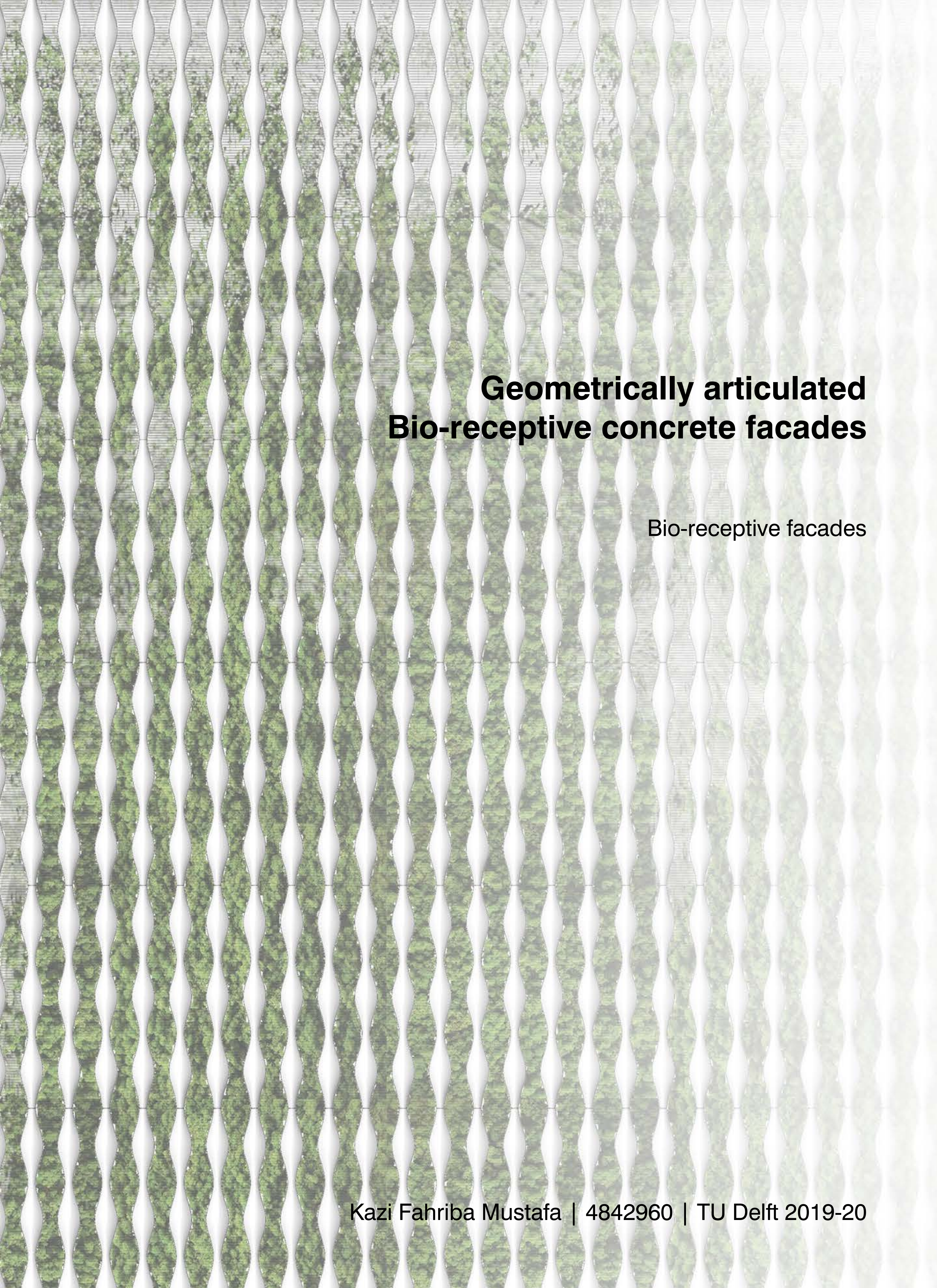

Geometrically articulated Bio-receptive concrete facades

Bio-receptive facades

Kazi Fahriba Mustafa | 4842960 | TU Delft 2019-20

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"The first rule of sustainability is to align with natural forces, or at least not try to defy them."
– Paul Hawken

Acknowledgement

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Abstract

Key words: bio-receptive facades, self-sustaining facades, green concrete, geometrical articulation, moss biology, surface water relations, facade systems

Bio-receptivity is a natural growth of small plant species on stony surfaces with minimum external influence. It is commonly found around us on old buildings, crevices and corners, damp and moist areas. Bio-receptivity has always been viewed as a negative phenomenon in the public eye due to its random and shabby growth conditions. However, this phenomenon co-exists on building surfaces establishing a hybrid relationship, which poses several advantages on the building lifecycle. Apart from being a protective coating, its environmental benefits, like CO2 reduction in air, air purification through dust removal and cooling effect through evapotranspiration, has been known and researched through decades, but has not been brought into practice in the building industry. This research chooses to use geometry as a design variable to engineer self-sustaining moss growth on concrete panels in an ordered and systematic manner. The exercise is an attempt to not only address the functional aspect of Bio-receptivity but also its aesthetic quality which is vital to influence the perception of people and promote mass use of this new type of sustainable concrete material.

The primary intend of the research is to gain a thorough understanding into the concept of Bio-receptivity and identify the governing factors responsible for the relationship between the small plant species and stony materials. Saxicolous moss like Tortula muralis and Grimmia Pulvinata are found to be the most common moss types growing on limestone base stony materials and is further utilized in the practical experiment. The research is conducted in a top-down approach, where first the designs are developed in an ordered system taking into consideration the growth structure of moss in nature and the influencing environmental characteristics, next the designs are fabricated into prototypes exhibiting the appropriate material properties and then validated through series of practical experimentations and CFD simulations to justify the influence of geometry; based on the comparative analysis of the results a general design guideline is provided for a self-sustaining Bio-receptive concrete facade panel. A real-time visual representation of Bio-receptive panel is presented as per the guidelines and an economically viable and technically feasible facade system is proposed to facilitate its commercial use on buildings/facades.

0. Content

1. Introduction

In the time of climate change, Architects and Engineers are trying several new materials and construction techniques to minimize the negative environmental impact caused by the building industry. According to the report of the World Green building council (2019), the building industry is responsible for 39% of CO_2 emissions worldwide, of which 28% contributes from the heating and cooling load on the building and the rest 11% comes from the material and construction process. Concrete is one of the most popular construction materials in the world due to its strength and durability, however it is responsible for 8% of the total CO_2 emissions due to its production process (Lehne & Preston, 2018).

1.1. Bio-receptivity

On a building level, concrete can take in up to 57% of CO_2 during its service years through a process called Carbonation (NRMCA, 2012, Kjellsen, et al., 2005). Being a natural phenomenon, the compensation rate is very slow. Researchers have come up with a new way to speed up the return. A literal way is to grow plants on concrete to facilitate CO_2 uptake (Cruz & Beckett 2016, Manso, 2014, Ottele 2010, Guillitte, 1995). Designing a concrete material that can be host to small plant species and micro-organsism without any superficial layer is termed as Bio-receptivity. In 1995, Guillitte was the first person to define and recognize Bio-receptivity,

'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.'

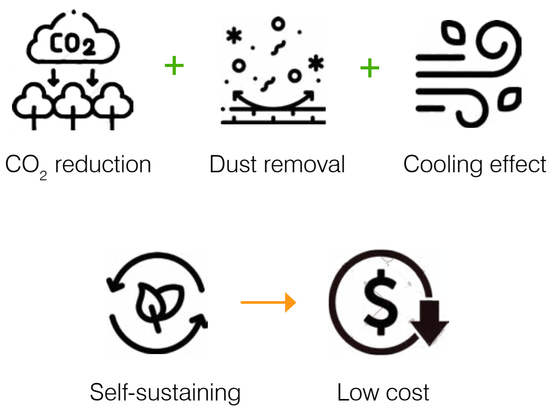
An alternative term to Bio-Receptivity is Bio-colonization, as mentioned by Cruz & Beckett in 2016, *'Surface growth of plants upon a material is known as biological colonization.'*

The natural process of carbonation can further facilitate Bio-receptivity. The presence of $CaCO_3$ and water in the concrete together with other relevant properties, make it an attractive substrate for the colonizing plants(Guillitte & Dreesen, 1995).

1.2. Benefits of Bio-receptivity

Bio-receptive concrete material can be an answer to create a green sustainable construction for the future of net-zero buildings. The growth of these small non-vascular plants helps to create a protective layer for the façade as well as contribute to cleaner, fresher and cooler air (Cruz & Beckett, 2016). The green layer can protect the exposed material from harsh weather, provide thermal and sound insulation (Ottele, 2011). These plants can take in up to 3.9 billion metric tons of carbon per year through the process of photosynthesis (Elbert et al., 2012). The presence and the movement of water through the plant body contribute to cool down the surrounding air by evapotranspiration (Glime, 2017), thus reducing the cooling load on the building. The structure of these plants is such that they can trap dust and other impurities cleaning up the air to breathe (Haynes et al., 2019).

Bio-receptive facades being a result of the material property of the main building fabric is viewed as a self-sustaining system. The facade system requires no external irrigation or maintenance facilities unlike the typical green walls. When provided the appropriate combination of material, environmental and plant properties, Bio-receptive façade can prove to be an economically feasible greening medium.



1.3. Green walls in practice

To achieve all the mentioned environmental benefits, in the last decade, several types of vertical green walls with vascular plants have been developed and installed (Fig 1.3a). These living wall systems (LWS) work as a secondary skin on the building envelope, comprising of several layers of installation (Fig 1.3b). The LWS needs regular watering and grooming for the vascular plants to function, demanding an integrated irrigation system. The high installation and maintenance cost (e.g. irrigation systems) of these green walls have proved them to be more of a burden than beneficial, reducing its use (Ottelé, 2011).

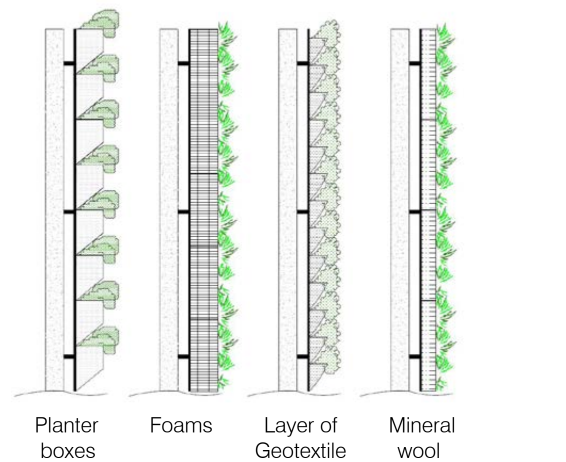


Fig 1.3a: Types of Living wall system (LWS) (Ottele, 2011)

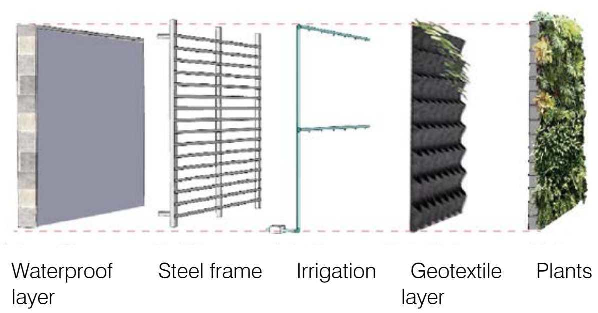


Fig 1.3b: LWS facade system (retrieved from internet and modified)

Fig 1.3c: USA Pavilion - Milan Expo 2015 by Biber Architects (archdaily)

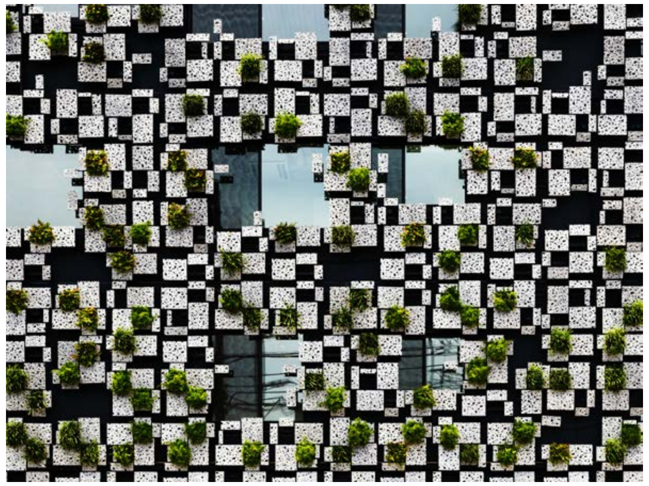


Fig 1.3d: Green Cast in Japan by Kengo Kuma & Associates (archdaily)

Fig 1.3e: Ann Demeulemeester Shop in Seoul by Mass Studies (dezeen)

1.4. Bio-receptivity in practice

The concept of Bio-receptivity is a natural phenomenon that exits in the built environment without any external effort. Mosses and other smaller plants species are attracted to cementous surfaces or any damp and shaded surface (Miller et al., 2012). The natural growth of these green layers is mostly seen on old buildings, monuments, statues, sidewalks and even damp and rusted metal surfaces (Fig 1.4a).

This natural process of moss growth on different surfaces has been adapted by graffiti artists and interior designers to create green walls within the living spaces. Graffiti Artist Anna Garforth has used moss transplants on rough surfaces to create different patterns, figures and calligraphy (Fig 1.4b). The unaided growing process of the mosses into the carved designs create an evolving and live form of art. Several interior designers are replacing the living green walls with preserved moss or lichen walls owing to its long-lasting character with little or no maintenance (Riley, 2019).

In recent years architects aiming for a greener built environment are experimenting new ways to integrate Bio-receptivity on the building facade. The perforated cast aluminum envelope of the extension building of San Telmo Museum in San Sebastian, Spain is an interesting example of a growing facade (Fig 1.4d). The varied perforations on the rusted aluminum surface captures moisture from air facilitating moss growth (Nieto Sobejano, 2011). In a more recent example, UCL Bartlett professor Marcos Cruz and his team from the Biolab are testing different material compositions to create growable concrete blocks fostering small plant species (Fig 1.4c).

Fig 1.4a: Natural moss growth on walls (retrieved from internet)

Fig 1.4b: Moss graffiti on walls (Anna Garforth, 2014)

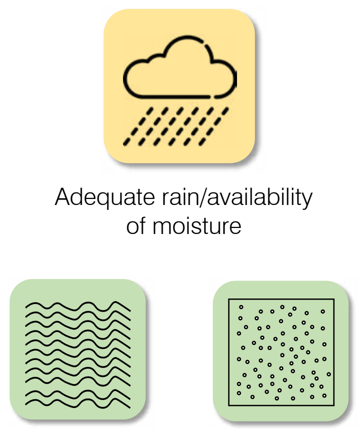
Fig 1.4c & d: Bio-receptivity in Architecture:

c Digitally fabricated GRC limestone concrete panels transplanted with moss (Marcos Cruz and team, 2017)

d Facade of San Telmo Museum Extension by Nieto Sobejano Arquitectos in San Sebastian, Spain, 2011 (archdaily).

1.5. Main factors for Bio-receptivity

The presence of water is the most crucial criteria in the growth and development of bio-colonization (Miller et al., 2012, Dubosc et al., 2001, Bates, 1998). The physical characteristics of the material such as roughness and surface undulations should be such that it can absorb and retention water from the rain, dew and other natural phenomenon. The ability of the material to absorb and store the water inside the material for a longer time depends on its porosity (D'Orazio et al., 2014). A network of interconnected pores allow the permeability of water through the material providing the moisture for survival of the micro-organisms. These physical properties together with a low pH value create the suitable chemical composition to make the material Bio-receptive ready (Guillitte, 1995). Thus, the combination of appropriate material properties and the environmental factors like rain, moisture, dust, temperature, exposure to sunlight and diaspores propagation through wind are important contributors to promote bio-receptivity (Miller et al., 2009a, Guillitte, 1995).



1.6. Types of Bio-receptivity

As defined by Guillitte in 1995, Bio-receptivity on a material can be primary, secondary or tertiary (Fig 1.6a). When the initial composition of the material can promote the growth of micro-organisms, without any external influence, it is termed as Primary or Intrinsic Bio-receptivity (Cruz & Beckett 2016). When material characteristics suitable for Bio-receptivity are developed over time, by the influence of external factors like carbonation or by the action of the colonizing vegetation, it is termed as Secondary Bio-receptivity. Secondary Bio-receptivity is a common phenomenon observed in old stony buildings and are often viewed as an effect of surface weathering. Tertiary Bio-receptivity occurs when the primary or secondary character of the material is changed by human inference like application of biocides, surface polishing etc.

When the secondary material characteristics together with the external deposits like soil, dust or nutrients results in bio-colonization, it is termed as Semi-extrinsic Bio-receptivity. Lastly a type of bio-receptivity that occurs due to external deposits without any influence of material property, it is called Extrinsic Bio-receptivity. In this research, the primary characteristics of the material together will other relevant external factors will be studied to develop a Bio-receptive façade system.

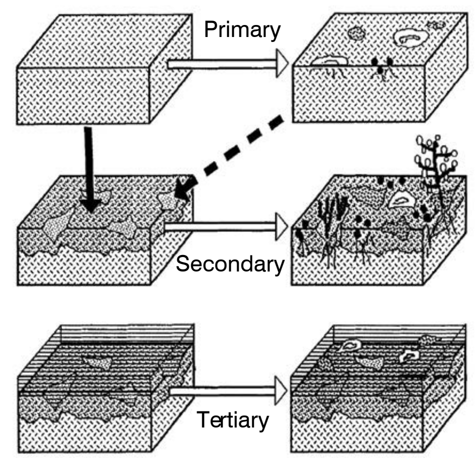


Fig 1.6a: Types of Bio-receptivity (Guillitte, 1995)

2. Research framework

2.1. 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.

As defined by Hueck in 1965 'Biodeterioration is any undesirable change in the properties of a material caused by the vital activities of living organisms.' The effect of bio-colonization on the building surface has been viewed as a negative phenomenon since way back. Due to the lack of study on this topic, the growth of the spontaneous vegetative layer was thought to deteriorate the physical and chemical properties of the material resulting to significant colour change on the surface.

In the late 70s, few researches were done, which concluded that the colonization by the organisms only contributed in changing the surface quality of the material, with no internal chemical or physical damage. Instead the vegetative layer created a protective cover against any natural or artificial interventions (Guillitte 1995). Despite the numerous positive impacts of Bio-colonization discussed so far, the use of Bio-receptive concept is still very limited. In the eyes of the common people, the impression of aesthetics is a 'clean and untouched' surface (Cruz & Beckett, 2016). The random growth of moss or lichens observed in nature are often found in old buildings, shaded and damp areas. The lack of order creates an impression of a dirty and damaged surface (Miller et al., 2012).

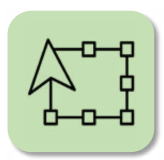
In recent times researchers are trying different way to redefine Bio-receptivity and promote its benefits. By creating different surface textures and undulations and consequential micro climates within the surface, bio-colonization can be propagated or inhibited in areas as desired (Cruz & Beckett, 2016, Ottele et al., 2010). Thus, as stated by Marcos Cruz (2016), 'an inherently time-based, yet self-regulating condition in sustainable design' can be created through geometrically articulated surfaces. Going with the quote, in this research project a humble attempt is being made to test and analyze the significance of geometry on an ordered moss growth system resulting to an aesthetically pleasing and functional surface layer.

2.2. Objectives

Based on the problem statement, the following lists the main objectives that will be addressed in the course of this research work.

- Understand the concept of Bio-receptivity, its role and relevance in façade design.
- Create order and balance in the spontaneous growth of mosses due to its random and unpleasing appearance.
- Understand the role of geometry to engineer a self-sustaining moss growth system.
- Create an optimized façade panel in terms of production and installation using the knowledge of façade design.

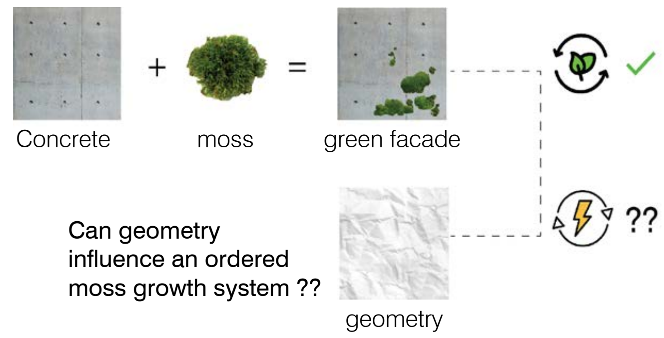
Create order & balance in moss growth



Engineer a self-sustaining facade system

2.3. Research Question

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



2.4. 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)?

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?

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?

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?

2.5. Research Methodology

As shown in Fig 2.5a, this research project is conducted in a top-down approach, which means first some prototype designs are made and moss is grown on them. Based on the moss propagation on the prototypes the influence of geometry on moss growth is validated and the best geometrical articulation is presented. The research begins with a thorough literature study on moss biology, material properties, environmental properties, influence of geometry on Bio-receptivity and field survey. Based on the literature review and practical knowledge, concrete panels are designed and fabricated. The created designs are then validated in three steps, macro and micro level water relations on the geometry and intensity of moss propagation.

First through a practical experimentation the macro level influence of geometry on water relations are tested. Next the designs are further refined, and the influence of different micro level geometries are checked through CFD simulations. In the meantime, moss is grown on the prototypes in an outdoor environment under proper care. A comparative analysis is drawn from all the practical experiments and computational simulations. Based on the results the influence of geometry on Bio-receptivity is validated and a geometrical guideline is provided. The last segment of the research investigates the production feasibility of an concrete façade panel and suggests the most efficient construction technique and installation method to create an optimized façade panel.

The research is divided into three main focuses:

1. Design by research (Primary focus)

- Geometry designed based on literature and practical research
- Prototype making
- Micro level geometry modification in terms of water relations on surface

2. Design Validation (Key indicator)

- Moss growth on panels
- Water movement relations of the geometries
  - Practical Experiments
  - Simulations

3. Outcome (Secondary focus)

- Production feasibility
- Construction and installation technique

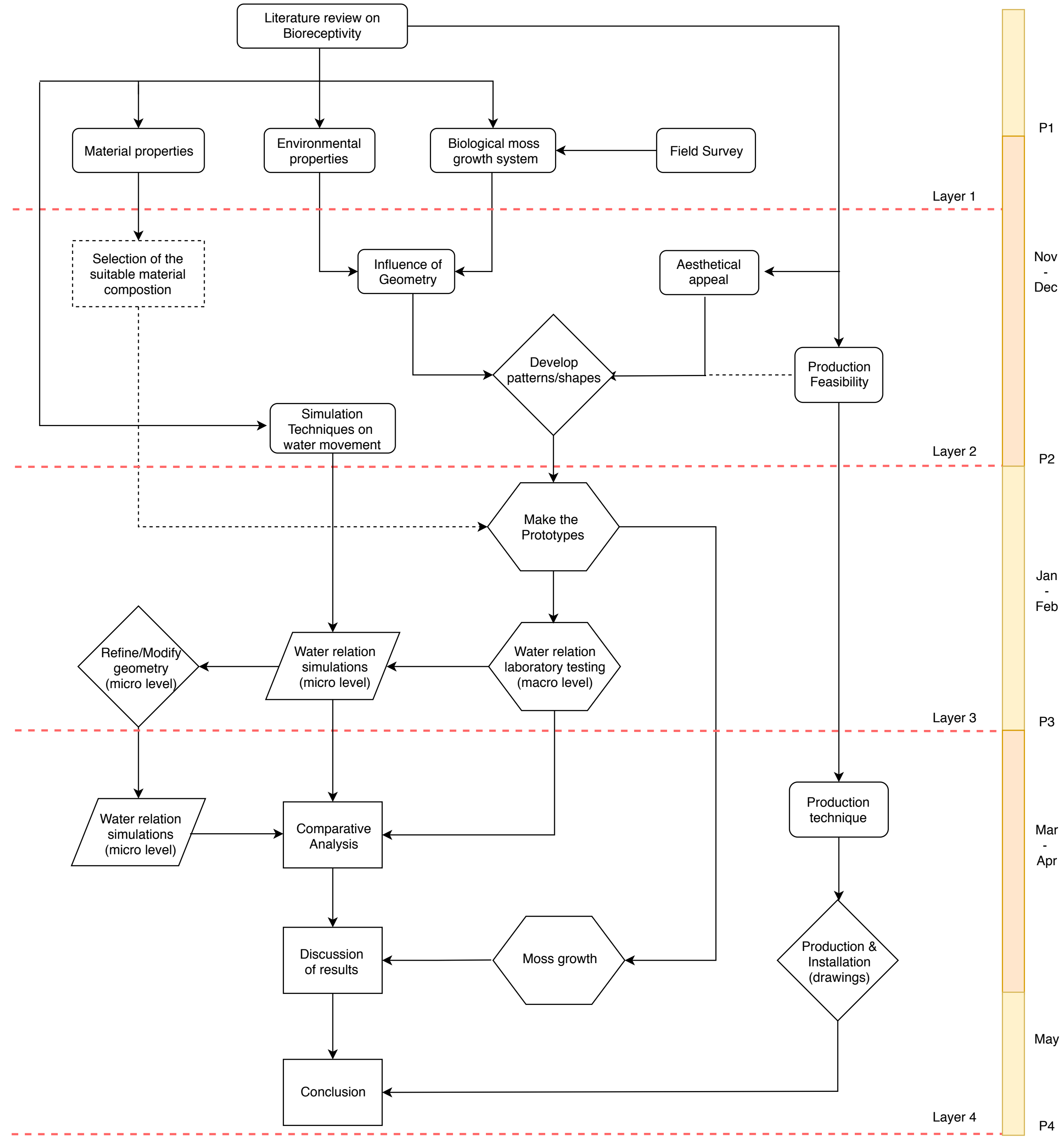
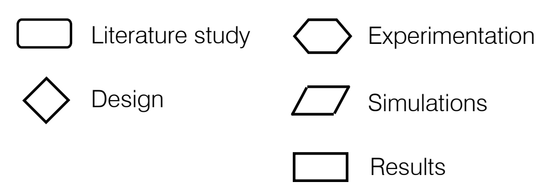


Fig 2.5a: Top-down approach



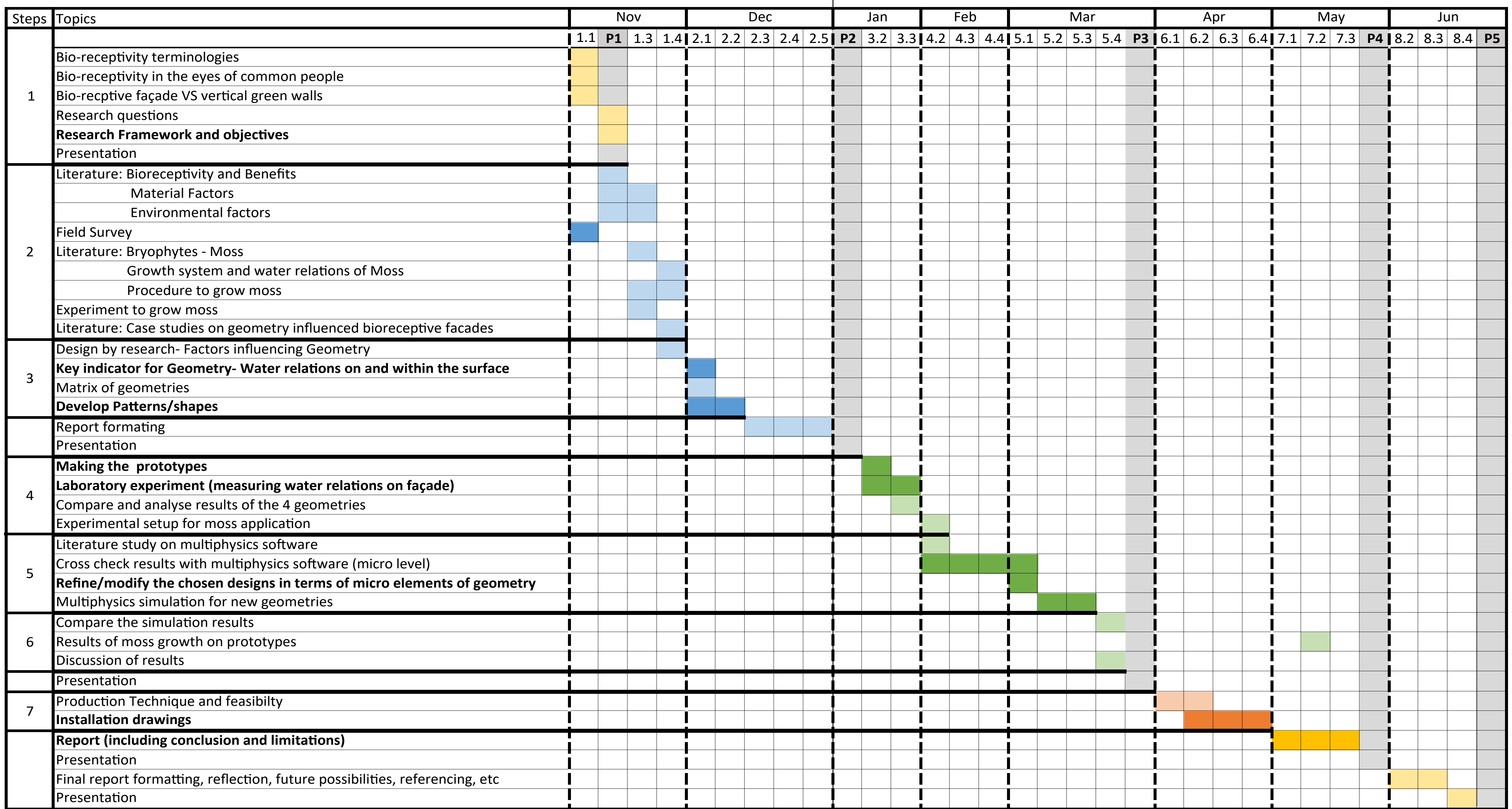
2.6. Relevance

In the era of climate change, developing a material that is environmentally responsive is of extreme importance. Bio-receptivity is a phenomenon which aids in greening the environment with minimal cost and maintenance unlike the living wall system. Despite the benefits of Bio-receptivity, the concept is still not widely celebrated. The lack of previous research into the topic and limited practical use, has made it a challenging topic to research into.

The research focuses on creating geometrical possibilities to facilitate moss growth on concrete panels in an ordered and systematic manner. This is an attempt to influence the perception of people on Bio-receptivity and promote mass use of this new type of concrete material. This research will involve a detailed investigation into the branches of material science, plant biology, geometrical articulation, fluid dynamics and facade construction to develop a comprehensive facade design solution.

2.7. Time planning

The research is divided mainly into seven steps within the time period of seven months. In the first step, a research framework is prepared by the beginning of November. In the second step, based on the framework, a detailed literature research and field survey is done till the 1st week of December. In the 3rd step, the 2nd and 3rd week of December are spent on designing geometries based on literature review and field survey. After the P2 presentation, in the 4th step the prototypes are made, and the practical experimentation regarding water relation test and moss growth are carried out. In the 5th step, from the beginning of February till mid-March, the geometries are further refined and tested through several rounds of CFD simulations. In the 6th step, a comparative analysis of the geometries is done based on the practical and simulation results and a conclusion is drawn. In the final step, the month of April is spent on finalizing the design for an optimized façade panel in terms of production feasibility and efficient installation method.



Work plan

3. Literature research

3.1. Plant Biology- Mosses

Cryptogams are the group of lower plant species which reproduce by spores and have no seeds or flowers. Cryptogams are divided into three sub-groups, Thallophytes, Bryophytes and Pteridophytes (Fig 3.1a). This chapter will look in detail into Moss species which belong to the sub-category of Bryophytes (CRYPTOGAMS [Video file], 2015). The study of moss ecology, structure, water relations and types of mosses growing in stony materials will provide the basis for the suitable vegetation for the development of Bio-receptive façade.

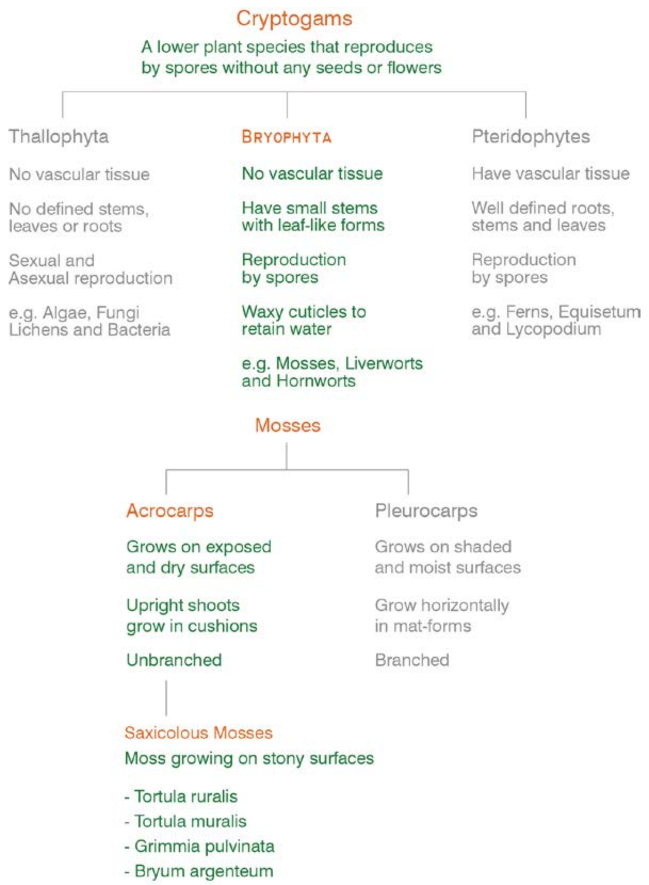


Fig 3.1a: Tree diagrams explaining the origin of mosses

3.1.1. Moss ecology

Mosses are non-vascular plant species, with stems and leaf-like forms of one cell thickness. Mosses have no roots instead they have rhizoids which help them to get attached to the substrate on which it grows. Being non-vascular plants with no root system, mosses do not have any mechanism to transport water within the body. The moss structure works like a sponge, seeping in water by capillary action. Mosses are autotrophs who can produce their own food by photosynthesis in presence of water (Haynes et al., 2019). Photosynthesis occurs in the green body of the plant called gametophyte.

Mosses are Poikilohydric, which means they lack the ability to store water within the plant body. Their water level is directly proportional to water content of the surrounding environment. In dry weather, mosses lose all their water content without dying unlike vascular plants. While again in presence of water, within a short period of time they get back to their complete metabolic activity with a positive carbon intake. This adaptive nature of mosses is termed as Desiccation tolerance (Marschall, 2017, Charron & Quatrano, 2009, Proctor et al., 2007, ZOTZ et al., 2000).

3.1.2. Reproduction in Mosses

The reproduction of moss is asexual through the disperse of spores via the wind. The spores under suitable growth conditions develop into green thread-like filaments called protonema. The protonema grows horizontally staying close to the substrate surface. The protonema than produces several buds along its length which further grows into bodies of stems and leaves called gametophores. The gametophores further mature to form male or female sex organs on its tip. In the presence of water, fertilization occurs, where the sperms of the male gametophyte swim into the egg of the female gametophyte. Next a thin long stem called seta grows out of the gametophyte, this part of the plant body is called sporophyte. Lastly through a process called meiosis spores are produced within the sporophyte and the life-cycle is repeated (Fig 3.1b) (Charron

& Quatrano, 2009). In exposed areas the sporophyte grows long enough from the gametophyte body to access the wind for better spores' dispersal while the gametophytes forms into a compact cluster close to the substrate to minimize water loss (Bates, 1998).

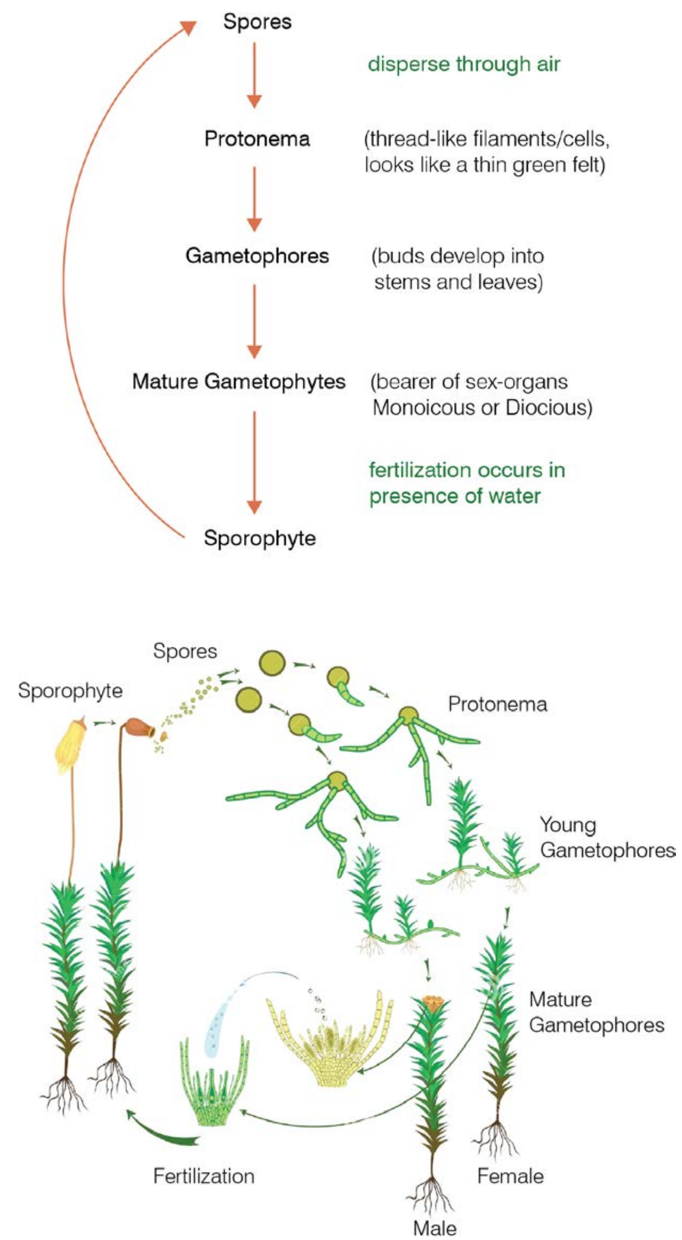


Fig 3.1b: Moss Life cycle, by Luayana (retrieved from Dreamstime.com)

3.1.3. Saxicolous Mosses

According to the webpage by the Department of Natural sciences, WNMU, Mosses are largely classified into two groups Acrocarps and Pleurocarps. Acrocarps prefer to grow in dry and exposed areas whereas Pleurocarps need enough shade and moisture to thrive. In Acrocarpous mosses, individual shoots grow upright arranging into dense cushions, in smooth hemispherical shapes or scattered patches. Pleurocarpous mosses grows in a creeping manner, expanding horizontally into tangled branch forming mats (Burk, 2018, David, 2015). Mosses that grows on stony surfaces are called Saxicolous mosses (David, 2015). Saxicolous moss types of the Acrocarp classification is further studied due to its abundance in exposed surfaces.

The most common type of mosses found in Urban areas are Tortula muralis, Bryum agenteum, Grimmia pulvinate and Tortula ruralis (Fig 3.1c). Tortula muralis and Bryum agenteum are more pollution resistant compared to Grimmia pulvinate. The presence of Grimmia pulvinate is a good indicator to endorse the freshness of the surrounding air. All these type of mosses prefer growing on base-rich substrate, like limestone, concrete, bricks and other calcareous rocks(Fletcher, 1995).

Tortula muralis (Wall-screw moss)
Grows in tufts, cushion, or patches
Height <1 cm, Seta length 1-2cm,
Tongue shaped leaves 2-3.5mm long
Family: Pottiaceae (Mark Lawley, n.d.)

Grimmia pulvinata (Grey-cushioned)
Grows in tufts, cushion, or patches
Height 1-2 cm, arching seta,
Thin narrow leaves 3-4 mm long
Family: Grimmiaceae (Ron Porley, n.d.)

Bryum agenteum (Silver-moss)
Grows in tufts or patches
Height <1 cm, Seta length 1cm,
Egg shaped leaves 0.75-1.25mm long
Family: Bryaceae (Mark Lawley, n.d.)

Tortula ruralis (Great Hairy Screw-moss)
Grows in tufts, cushion, or patches
Height 1-2 cm, capsules are rare,
Tongue shaped leaves 4-6 mm long
Family: Pottiaceae (Martin Godfrey, n.d.)

Fig 3.1c: Different Saxicolous mosses (Images retrieved from interrnet)

3.1.4. Moss structure

As mosses are Poikilohydric, mosses that are found in exposed surfaces often grows in tufts or cushion form to minimize water lose (Dilks & Proctor 1979). The dense packing of a group of mosses into a cushion-like form are brilliant adaption to maintain a positive metabolic function. These kind of life forms possess several advantages (Bates, 1998):

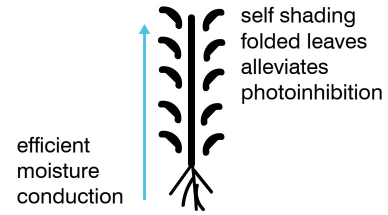


Fig 3.1e: Individual shoot of a moss

1. The colony of mosses growing into a cushion, can maintain a storage of water within their form. This storage capacity helps the mosses to carry out photosynthesis during periods of dryness (Fig 3.1d).
2. The smooth form of cushions create a layer of water vapour above its surface, termed as laminar layer as quoted by Bates from the 1981 journal by MCF Proctor. This laminar layer contributes to protect against evaporative water loss (Fig 3.1d).
3. Due to the endohydric nature of the mosses, the individual shoots within the cushion has a vertical growth to allow an efficient conduction of water from the base to the tip to accelerate photosynthesis (Bates, 1998, Anderson & Bourdeau, 1955)(Fig 3.1e).
4. The folding mechanism of the leaves from the individual shoots help to create self-shading. The leaves curl outward to provide shading to reduce evaporative water loss. In times of extreme dry weather, the leaves curl inward to protect cell damage (Bates, 1998, Anderson & Bourdeau, 1955) (Fig 3.1e).

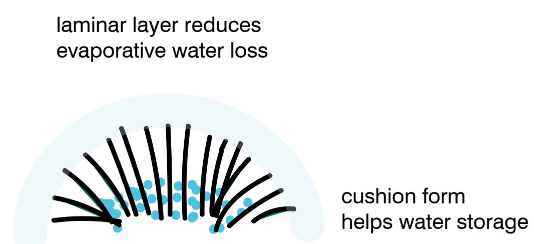


Fig 3.1d: Cushion structure of Saxicolous mosses

Development of colony

The leafy shoots of mosses commonly growing into colonies rather than individual shoots for the reasons explained above. The development of colony can occur in three ways (Bates, 1998):

1. The simultaneous growth of gametophores from the buds of a single protonema or several adjacent protonemas expanding radially. This results into a quick formation of a densely packed colony. However, in dry exposed surfaces, the protonemas cannot expand much in length due to the lack of moisture.

2. The second mode of colony formation is through the production of offspring from a single shoot and further from the mature products of the mother plant. Thus, resulting to a gradual radial growth of colony.

3. The third mode of colony formation is by the production of offspring from multiple mature shoots. This results into several overlapping radial colonies of mosses.

3.1.5. Water relations

The maximum water content, WCmax of mosses can be expressed as percentage of its dry weight DW, mosses cushions can hold as much as 108 to 2070% water of its DW, as quoted by Wang & Bader (2018) from the 1998 journal paper by MCF Proctor. With the increase in diameter of the moss cushion, it tends to flatten out from its hemispherical shape into a smoother surface, causing the thickness of the laminar layer over the surface to increase by the square root of the diameter, as quoted by (Zotz et al., 2000) from the 1991 book Plant physiology by JS Nobel. The thicker laminar layer helps to reduce evaporative water loss and the larger size of the moss provides a greater surface area for water storage (Sand-Jensen & Hammer, 2012).

However excess of external water content may also reduce efficient photosynthesis activity. The thick water vapor layer tends to hinder the CO_2 diffusion from the air to the plant body. Therefore, the optimum photosynthesis occurs at a moderate water content of the moss dry weight (Wang & Bader, 2018, Green & Lange, 1995), e.g. for Tortula ruralis water content of 120-200% of its DW facilitates maximum photosynthesis (Tuba et al., 1996).

The water content in the moss does not need to reach its full turgor, for active photosynthesis to begin. The splash of water from rain or dew, first fall on the leaves before it continues down into the plant body. These water droplets can help resume the metabolic activity within few minutes of rehydration (Csintalan et al., 2000). The lower water content requirement and quick recovery rates are common in most desiccation tolerant mosses making them highly suitable for exposed areas (Table 1).

Tortula ruralis, Grimmia pulvinata can survive with only 5-10% water of its DW, with low RH values ranging between 20-50% at around a temperature of 20^{O}C (Vitt et al., 2014, Proctor et al., 2007, Alpert, 2000).Tortula ruralis takes less than 2mins to recover from its dry state and achieves a net CO_2 uptake within 15-20mins (Oliver et al., 2005, Tuba et al., 1996, Rundel & Lange, 1980). Desiccation tolerant mosses can remain dry for 10 months or more without dying but abrupt and extreme weather changes prove to be detrimental for such mosses (Schonbeck & Bewley, 1981).

Table 1: Water relations in desiccation tolerant plants (Alpert, 2000)

	Time required to		Can rehydrate with		
	Dehydrate	Rehydrate	Rain	Dew	Water vapor
Lichens	Hours	Minutes	×	×	×[a]
Bryophytes	Hours	Minutes	×	×	
Pteridophytes	Days	Hours	×		
Angiosperms	Days	Hours	×		

[a]Lichens with green algal phycobionts.

Small mosses take a surface cover of 3-26cm2 and its dry mass ranges between 0.02-3.6 g (Zotz et al., 2000). The height of the mosses is found to be 0.56 times of its radius, maintaining a constant density irrespective of change in size. The maximum amount of water holding capacity also remains constant at an average value of ±720% of its DW (Sand-Jensen & Hammer, 2012). In an experimental study carried out by Gerhard Zotz and his team (2000) with Grimmia pulvinate, it was found that 0.1g DW of moss took around 12hrs to lose all its water within a controlled lab environment, as shown in Fig 3.1f. The same 0.1g moss when exposed to an outdoor hot and dry environment in late June, lost all its water within 4hrs of hydration. Thus it can be seen that the ability to retention water and the rate of evaporative water loss from the moss body depends on both the structure of the moss and its surrounding environmental conditions.

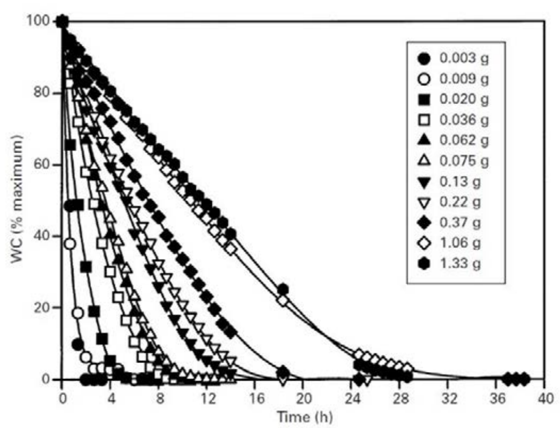


Fig 3.1f: Decline in cushion water content during a drying cycle in a climate chamber (temperature 16°C, relative air humidity 70%, Dw 0.5 kPa, wind speed 1.4 m s−2) as a function of cushion dry weight (Zotz et al., 2000).

3.1.6. Moss Propagation:

According to Marie Lannotti from How to Grow Moss (2019), the best time to propagate moss growth is during early spring when the sun is low in the sky and the surface conditions are wet due to winter rain or snow. During the initial growing period of the mosses (around first 6 weeks), the surface on which it grows should be placed horizontally to benefit from the gravity for better moisture and nutrients uptake. In the early stages' regular irrigation of the young mosses is essential. Once the mosses gain their adult form, the watering should be done as required. To water the mosses only rainwater or distilled water should be used as mosses cannot tolerate the chemicals present in tap water. During extreme hot dry seasons, the moss should be kept dry as mosses can tolerate long dry periods better than short cycles of wetting (Ónody et al., 2016).

The following presents few ways/methods for growing mosses:

Growing moss on soil: The experiment is carried out at a temperature of 20^{O}C with an 8hr lighting period. In this method a layer of sawdust soil is covered with cotton fabric with moss fragments spread over it. The moss fragments are sprayed with a mixture of milk and water (in the ratio 1:7) twice daily for a period of 2 weeks. After 2 weeks the moss fragments are periodically sprayed with distilled water and are covered with an aluminum foil to avoid drying of the mosses (in case of high temperatures, the aluminum coil should be replaced with black cloth to avoid overheating [Vila, n.d.]). After about 4.5 months mosses are completely grown and are ready to be planted on the garden soil outdoors (Glime, 2017).

Growing moss on stony surfaces: According to Bob Vila from the website How to: Grow Moss (n.d.), the method to grow moss on stony materials is different than that on soil. To begin with, a moss slurry is prepared with plain yogurt/buttermilk and moss fragments in the ratio 2:1.5 and left to settle for a day or two. The slurry should have a moderate consistency, so that it can be applied with a paint brush over the surface. After application, the stone is kept moist under optimum conditions until the moss sprouts appear. After that the surface is sprayed with distilled water once or twice a day for the next few weeks. Within a period of about 6 weeks, mature moss plants should be visible.

Key points:

Moss ecology

- Mosses are non-vascular plants, with no root system, takes in water through capillary action.
- Moss are Poikilohydric, have no ability to store water within the plant body
- Mosses require water to carry out the fertilization process and wind for spores dispersal.

Moss structure

- Mosses grow in cushion form to store water within its structure.
- A laminar layer over the smooth cushion protects from evaporative water loss
- Mosses are endohydric, conducts water from base to its tip.

Water relations

- Excess of external water content may hinder CO_2 diffusion, ceasing photosynthesis activity.
- Desiccation tolerant mosses like Tortula muralis, Grimmia pulvinata can function in 5-10% water of its dry weight in exposed areas.
- Desiccation tolerant mosses can regain its metabolic activity within 90 sec of hydration.
- Mosses prefer to remain dry during prolonged hot dry seasons rather than short cycles of wetting.

Moss propagation

- A slurry with butter milk and moss fragments can be applied to stony surfaces to propagate moss growth

3.2. Material Properties

Material property is by far the most important factor to create a bio receptive concrete façade. Normally the concrete used for building construction are designed to be highly dense with minimum water penetration. To achieve bio-receptive property, high surface roughness with high porosity and a neutral ph level is desired (Cruz & Beckett, 2016). Physical property like roughness and porosity is often valued over the chemical compostion of the material, being the contributing factors for the presence of water on and within the surface (Tomaselli et al. 2000 and Miller et al. 2009a). To create a bio-receptive concrete with the desired roughness, porosity and chemical composition, factors like the type of binder to be used, the aggregate sizes, the water/cement ratio and the amount of cement paste needs to be tried and tested (Manso, 2014).

3.2.1. Chemical composition

The pH value is the main element of the chemical composition which contributes to bio-receptivity. The pH value determines the alkalinity of the material which can be tested using a surface electrode (Tran & Hoang, 2017). A lower pH value around 8-10 is desirable to promote bio-colonization. A fresh new concrete used in construction has a very high ph value around 12-13. With time naturally through a process called carbonation the surface ph of the material can drop. The Ca(OH) from the cement in concrete reacts with CO_2 in air to form calcium carbonate and water (Manso, 2014, Guillitte & Dreesen, 1995). The presence of SO_2 in polluted urban areas produces sulphuric acid by reacting with oxygen and moisture in air. The sulphuric acid can create a gypsum layer over the concrete surface thus fostering a localized habitat for micro-organisms or Bryophytes (Saiz-Jimenez, 1997). All these processes requires time and so mostly secondary bio-receptivity is observed in older facades.

To design a primary bio-receptive concrete the binding material needs to be addressed. The most common hydralic binder used in concrete making is Ordinary Portland cement (OPC). In order to produce Portland cement, Alite (Ca_3SiO_5) has to be heated to around 1500ºC to form clinkers, this process emits huge amount of CO_2 (Amato, 2013). Researches to replace the clinker with slag, fly ash, silica fumes have proved to be more sustainable being by-products from other industries like iron, steel, thermoelectric etc (Kim & Lee, 2012). The use of fly ash, slag or silica fumes can also reduce the ph level due to the presence of lesser hydroxl ions making them suitable binder material to make bio-receptive concrete (Manso et al., 2015). Another suitable alternative with a much lower ph value than OPC is Magnesium Phosphate cement (MPC) recently used by Marc Cruz from the UCL Biolab for making Bio-receptive concrete panels (Cruz & Beckett, 2016). Lastly plain mortars mixtures of sand or pozzolana with limestone are also found to be highly bio-receptive to lime loving small plant species (Urzì and De Leo (2007).

Hydralic binder
Slag or Fly ash (by-product)
lower pH

3.2.2. Porosity and Permeability

Water is essential for Bio-receptivity. The amount of water that can be absorbed and retained in a material is decided by the level of porosity of the material. As defined by Tran & Hoang (2017), 'Porosity is the ratio of open pore volume to the total volume of materials' and it can be measured using a mercury intrusion porosimetry. Porosity can be of two types macro porosity and micro porosity. Macro porosity plays the role of absorbing the water on the surface while micro porosity helps to retain the water maintaining a local humid environment within the material (Manso, 2014). The macro pores provide the anchor points for the different colonizing organisms and once anchored the development of the organisms depend on the amount of water available in the micro pores to be soaked in by capillary action (Guillitte & Dreesen, 1995).

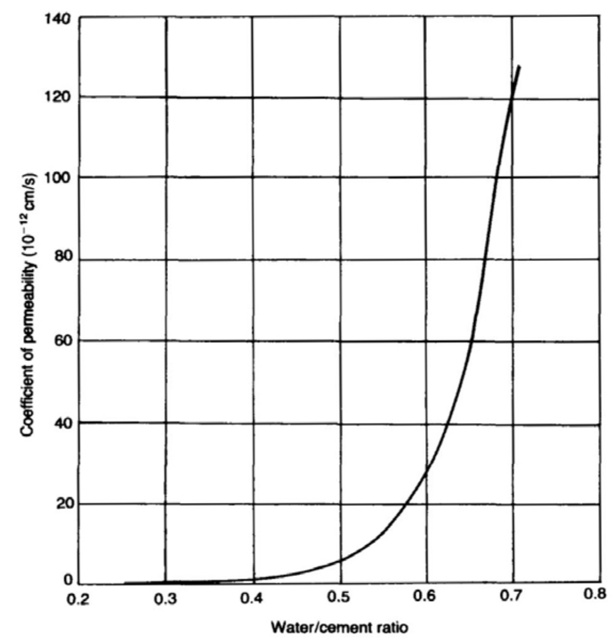


Fig 3.2b: Relation between w/c ratio and permeability (Day, 1999)

The formation of micro porosity of the material depend on the water cement ratio (w/c). Higher the water content in the cement mixture, higher will be the percentage of micro pores formed. Macro porosity can be achieved by using aggregates of varied sizes (0/2 and 2/4 mm) and an appropriate amount of cement paste necessary for holding the aggregates together. The combination of different sized aggregates, a moderate cement paste content and a relatively high percentage of water can create a permeable concrete with networks of connected pores (Manso, 2014, Miller et al., 2012).

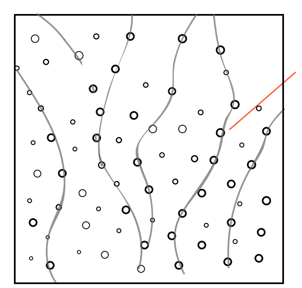


Fig 3.2a: Network of interconnected pores within a concrete block

Above a w/c ratio of 0.38, the excess water cannot be used in the hydration process of concrete formation. This excess water then evaporates leaving scattered void spaces during the curing process. The formation of these scattered pores is not enough to allow the movement of water within the concrete. To achieve the permeable character of the concrete, a connected network of different sized pores needs to be created. When the w/c is higher than 0.60, bleeding occurs during the curing process. As the cement particles slowly settle down in the liquid mixture, water bubbles are created below the coarse and fine aggregates (Fig 3.2a). The excess water draws up the water bubbles creating a channel of connected pores (Day, 1999). The higher the w/c ratio, lesser the compactness of the mixtures resulting to increased bleeding effect (Fig 3.2b).

3.2.3. Surface Roughness

Surface roughness can be defined as the topographic profile of the surface (Tran & Hoang, 2017). The variations in height creating curvilinear or angular bumps defined the degree of roughness or irregularities on the surface. The exposed top layer of the material is the first contact point between the substrate and the surrounding environment to promote bio-colonization. With higher concentration of varying rough bumps on the surface, the surface area available for the attachment of micro-organisms also increases. This degree of roughness also helps to create a micro-climate essential for the growth and development of the micro-organisms, by trapping in moisture, accumulation of dust and providing the necessary shading from harsh environment (Miller et al., 2012).

The topographic variation can be achieved in two ways. One way can be by varying aggregate sizes and cement paste content to produce different degrees of roughness. A pronounced rough surface can be achieved by creating a concrete mixture with larger sizes of coarse aggregates (2/4 mm) and a minimum amount of cement paste only to bind the aggregates together (Manso, 2014, Ottele, 2011). This kind of rough concrete surfaces promote a more random pattern of bio-receptive growth. Another way can be, introducing patterns on the surface by creating depression, surface extrusions or crevices with customized formworks or digital fabrication techniques. With this technique the surface roughness can be designed to direct the areas of growth for the micro-organisms (Cruz & Beckett, 2016).

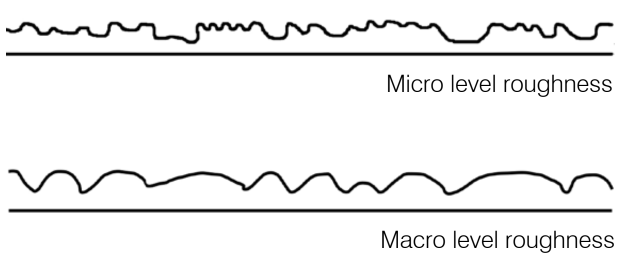
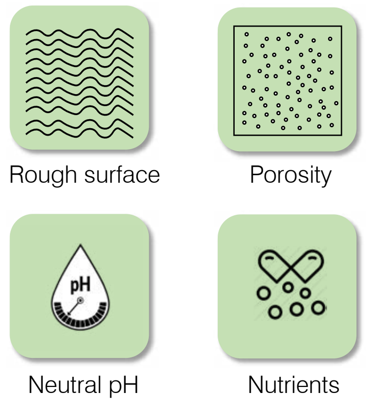


Fig 3.2c: Surface morphology (Reckli, n.d)



Key points:

Chemical composition

- The pH value between 8-10 is desired for Bio-receptivity.
- Industrial by-products like fly ash, slag cement can be used as binding material in place of OPC.

Porosity and Permeability

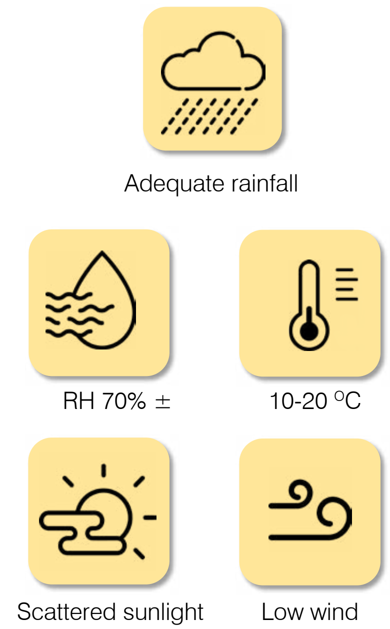
- Macro pores absorb water on the surface.
- Macro pore is created by varying the aggregate sizes (0-4mm) and the cement paste content.
- Micro pores retain the water within the surface.
- A water/cement ratio of 0.60-0.70 can result in a network of connected pores.

Surface roughness

- Surface roughness can create a micro-climate and provide more anchorage point for micro-organisms
- Surface morphology can be achieved by altering the concrete mixture composition or by creating artificial patterns/grooves on the surface.

3.3. Environmental Properties

As bio-receptivity is a natural process, environment plays a very important role in promoting the development and flourishment of biological colonies. The desired intensity of rain, moisture, sunlight, temperature and wind together with suitable orientation and shading are the environmental parameters responsible for bio-receptivity (Miller et al., 2012). Rain and low speed winds can help to carry spores, dust and other nutrients to the growth site. Rain or the presence of water droplets are very essential in the fertilization and photosynthesis processes of Bryophytes. Higher relative humidity values can help to maintain an adequate moisture content in air to promote growth (Manso et al., 2015). A cooler temperature prevents drying out and an orientation away from the direct sun can provide the shading to reduce evaporative water loss.



Mosses operate best in wet seasons at a lower temperature range within 10-20°C, with <20% intensity of sunlight. In bright sunny weather above a temperature of 25°C, mosses remain dry and cannot photosynthesis (Ónody et al., 2016). They can tolerate sudden large fluctuations in temperature (extreme hot or cold) in dry state than in wet state. Therefore, mosses that prefer to grow in moist and shady environment are more prone to sudden temperature changes and are often not tolerant to desiccation (Glime, 2017, Marschall, 2017).

Key points:

- Rainwater is essential for fertilization and photosynthesis.
- Low wind speed is required for spore dispersal.
- Low intensity sunlight <20% is desired to avoid photoinhibition
- Cooler temperature (10-20°C) is ideal to prevent drying
- High relative humidity can maintain an adequate moisture level to promote micro-climate.

3.4. Geometry

3.4.1. Exploring order and balance in nature

The patterns studied in nature are often the starting point of the façade geometry (Fig 3.4a). The patterns are free-flowing and organic forms found in nature. The possible occurrence of these patterns has been explained in different levels by branches of physics. chemistry and mathematics. They are created according to certain functional needs under natural phenomenon (Wikipedia, 2019). These patterns translated into surface morphologies for the facades often stick to the direct functional translations as in Biomimicry or are modified according to the design requirements.

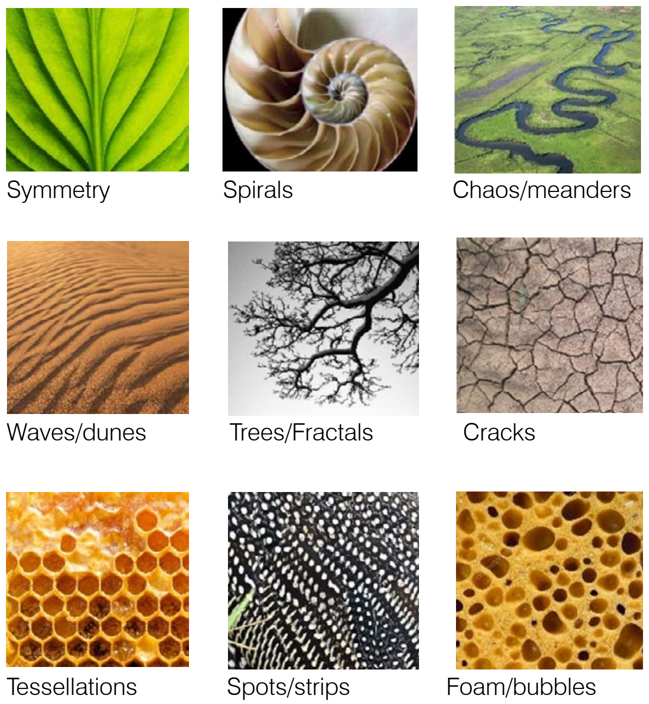
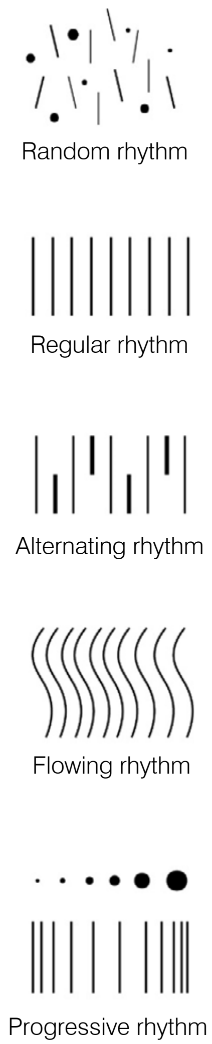


Fig 3.4a: Classes of patterns (Wikipedia, 2019)

These patterns can be translated into surface motifs in three repetition methods: repetition, patterns, and rhythm, addressing order and balance in varied degrees. 'Repetition is simply repeating a single element many times in a design. Patterns are a repetition of more than one design element working in coherence with each other. Rhythm involves using intervals or spaces between elements to give the user an impression of rhythm or movement,' creating an aesthetically pleasing composition (Soegaard, 2018).

Rhythm is further divided into five types:



3.4.2. Geometry in façade design

Geometrical Articulation (of a façade) is defined as changes in the depth of the surface of a building face with geometrical or organic shapes/patterns to create morphological variations. Articulation also provides textured variation to the façade surface (Appendix D, n.d.). In architecture, surface motifs are essentially created not only for aesthetical purposes addressing order and balance but also to fulfill certain environmental qualities, like shading, solar control, wind deviation, rainwater collection, air-purification, vertical greening etc.

According to Brzezicki Marcin (2018), this surface morphology on façade are broadly divide into two types. They are Spatial deformations and Segmented iterations:

Spatial deformations are the surface undulations created out of a continuous surface with no sharp edges or corners. The surface undulations comprise of regular or irregular shapes. The regular shapes include single curved surface variations like cylindrical, conical, elliptical and rotational geometry, while the latter comprise of double curved surfaces (synclastic and anticlastic shapes) like hyperbolic paraboloid. These irregular surface variations are more organic, with twisting, bending, tapering and free-form features (Fig.3.4b).

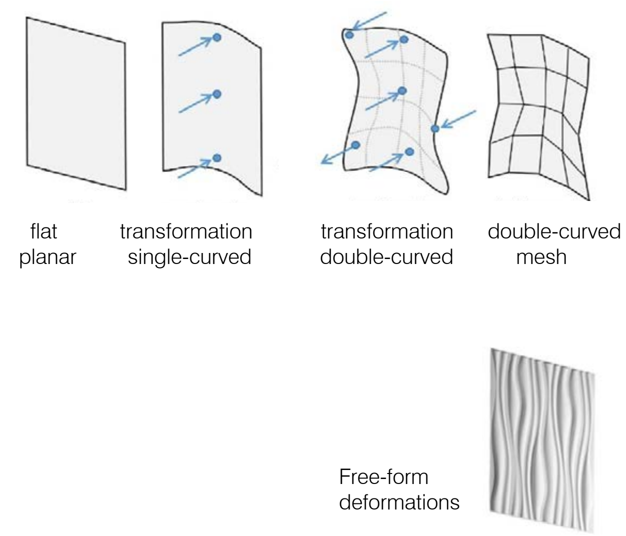


Fig 3.4b: Spatial deformation (Brzezicki, 2018)

Segmented iterations are surface undulations created in two steps. First the whole surface is divided into regular or irregular segments. The segments are then individually changed in shape, scale and orientation resulting to varied surface morphology. The transition between each segment create sharp angles or edges with each other. The individual segments can be rotated around its horizontal or vertical axis to create recessed or protruded surfaces. They can also be bend in different directions to achieve desired folded surfaces (Fig.3.4c).

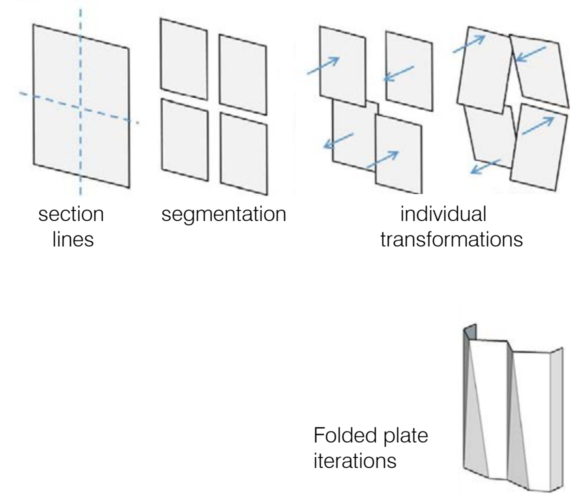


Fig 3.4c: Segmented iterations (Brzezicki, 2018)

3.4.3. Geometry influenced Bio-receptivity

The following presents three case studies where topological variations/surface geometries have been employed in different ways to promoto Bio-receptivity.

Case study 1:

Microalgae biofilm formation and growth by fabricating microgrooves onto the substrate surface

Author: Huang et al., Date: 2018

Objective: The change in the rate and the strength of microalgae attachment due to different types of microgrooves was tested.

Geometry: The microgrooves were designed in U and V shapes in different sizes (100µm-200µm in height, 200µm-500µm in width and the V-grooves in vertical angles of 20°, 30°, 45° and 60°)(Fig 3.4d). The micro-grooves were 3d-printed on polydimethylsiloxane (PDMS) to make microphotobioreactors (MPBRs).

Experiments: The attachment process of the microbial were first tested through an experimental setup by passing the microbial solution at different flow rates over the MPBRs. The results of the attachment concentration were viewed through an optical microscope and the flow velocity was calculated by using the analytic formula, Vin = Qin/wh, in which, Qin (m s−1) is the inlet flow rate, w is the MPBR width and h is the B-MPBR height.
In order to cross-check the flow velocity and determine the dynamic shear stresses on the MPBRs, a CFD simulation was done. For the ease of the modeling and to simplify the computational process, 2d section of the micro-grooves were modelled. The boundary conditions were set as inlet velocity, outlet pressure and no slip condition.

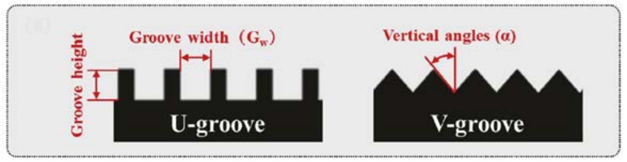


Fig 3.4d: Groove details (Huang, 2018)

Results: The shear stress was less over V-grooves than over U-grooves. The lower shear stress increased both the rate and the strength of attachment of the microbial on the V-grooves. Next the 45º V-grooves showed better anchorage rate than 60º V-grooves. Due to higher resistance created by the 45º V- grooves, the velocity of flow over the 45º V-grooves were lower than over the 60º V-grooves. The higher resistance allowed for more time for the microbial attachment and thus resulting to higher concentration of microbial. The 45º V-grooves also created a vortex or a dead zone inside the groove space, protecting the attached microbial from getting washed away by the flow forces. Lastly the microbial attachment on the 45º V-grooves were also compared with that on the flat surface. The concentration of microbial was about 14.29% higher on the 45º V-groove requiring about half the attachment time as compared to the flat surface.

Conclusion: The role of the grooves has a significant effect on the concentration of microbial attachment on the substrate. The type of grooves used is also a deciding factor on the rate and strength of attachment on the substrate.

Case study 2:

Computational Seeding of Bioreceptive Materials

Authors: Marcos Cruz & Richard Beckett, Date: 2016

Objective: Design of a concrete facade as an architectural bark, inheriting the natural bio-colonization features of a tree bark. Instead of creating a secondary skin on the surface of the building, the building material has been chemically and physically modified to foster a natural breeding surface for microorganisms.

Design Process: The material characteristics, the environmental factors and the plant features have been considered as parameters to develop a self-generative computational design. The generated designs were simultaneously cross-checked through simulations to validate the performance of the facade panels. The validated designs were than fabricated in CNC-milled molds (Fig 3.4e). The chemical composition of the concrete mixture, with the required pH, porosity and permeability to inherit the bio-receptive qualities were prepared. The concrete mixture was casted in layers into the molds to create the desired geometry. Thus, several geometries were constructed with varied surface morphological and roughness conferring to a bio-receptive ability of the panels.

Fig 3.4e: Prototype designs (Cruz & Beckett, 2016)

Experiments: The constructed concrete panels were than inoculated with algae and moss spores through a robotic seeding process, to ensure the same quantity of microbial sprayed onto all the surfaces. The panels were than placed outdoor with a northwest orientation to monitor the effects of natural environment (Fig 3.4f). The quantitative data of the amount of biomass produced, the moisture level and the thermal conditions around the panels were recorded at regular intervals. A photographic image analysis process was also used to observe the growth journey of the panels.

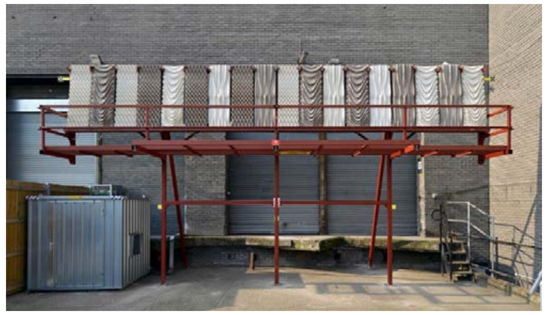


Fig 3.4f: Experiment setup (Cruz & Beckett, 2016)

Results: Not known yet

Case study 3:

Concrete as a multifunctional ecological building material

Author: Ottele et al., Date: 2010

Objective: A new approach to green facades by creating a multifunctional concrete material. The concrete has been such designed to provide both structural strength as well as be a host to small plant species.

Construction: For the experiment Blast furnace slag cement was used as the base material. The concrete panel consists of two layers (Fig 3.4g). The base layer was made of densely compacted concrete to provide the required structural strength and the front layer was made of lava stones (32mm granulates) stuck together with cement mortar. The front layer of the panel was made to have a lot of air gaps between the lava stones to be filled in with fertilized soil. The soil provided the ground to plant in 7 different species of plants. A total of 20 panels were made in the size 500X500mm with a thickness of 160mm (80mm back layer and 80 mm front layer).

Fig 3.4g: Two-layered concrete block (Ottele, 2010)

Experiment: The prepared concrete panels were left outdoors at a suitable location. At the beginning of the experiment, the pH level of the soil (7.2), the lava stones (12.2) and of the cement layer (12.4) were tested. After 3 months the pH level of the soil was found to have increased from 7.2 to 9.2. Due to rain and artificial irrigation of the panels Na^+, K^+, and Ca-bearing chemical compounds diffused from the cement layer into the surrounding soil, hence causing an increase in ph.

Fig 3.4h: Plants within the concrete geometry (Ottele, 2010)

Results: After a total 4-month period, only two plant species, Cymbalaria muralis and Sedum survived the alkaline condition of the soil (Fig 3.4h). As the plant rely for nutrients on the soil and generally prefer a more neutral pH value for growth, all the plants were not able to survive the pH change.

Conclusion: The geometry of the top layer of the concrete panel showed an innovative way to foster plant growth on its surface, providing a multifunctional characteristic to a regular construction material. The experiment also provided a clear relationship between the properties of the material and the growth of vegetation on the surface. The pH value is an important chemical property of the material which should be checked while designing a bio-receptive material.

Summary

Based on the above case-studies, it can be concluded that surface variation plays an important role in Bio-receptivity. Geometry can be used to promote bio-colonization by creating a micro-climate on the surface. The geometry can provide higher surface area for anchorage and nutrient accumulation (Huang et al., 2018, Ottele, 2010). It can also be used to create a network of channels to direct water to growth areas, provide protection from detachment by high wind and shading from harsh solar radiation (Cruz & Beckett, 2016).

A combination of smooth and rough surfaces and morphological variation can be used to define areas of growth and inhibition (Cruz & Beckett, 2016). Variations in the sizes, shapes and depth of surface geometry can be used to define the different intensity of growth (Huang et al., 2018). The structure of bryophytes colonies can be mirrored to design the desired shape for the mosses to grow in and further facilitate their water storage strategy (Cruz & Beckett, 2016, Bates, 1998). The material composition of the substrate can also be altered to create a rough surface suitable for Bio-receptivity (Ottele, 2010).

Key points:

Geometry in general

- Patterns in nature are translated into surface motifs in three repetition techniques; repetition, patterns and rhythm.
- Facade geometry can be created through spatial deformation or segmented iterations. Spatial deformations results in nature inspired organic free-flowing motifs.

Geometry in Bio-receptivity

- Geometry can be used to promote Bio-receptivity by creating a micro-climate on the substrate surface.
- Macro geometry can aid in an ordered moss growth system by directing water flows into the desired growth areas.
- The geometry should create areas of water catchment on the surface to prolong availability of water for the mosses.
- Variations in size, shape and depth of micro-grooves on the surface can influence the intensity of moss growth.

4. Practical research

4.1. Field Survey

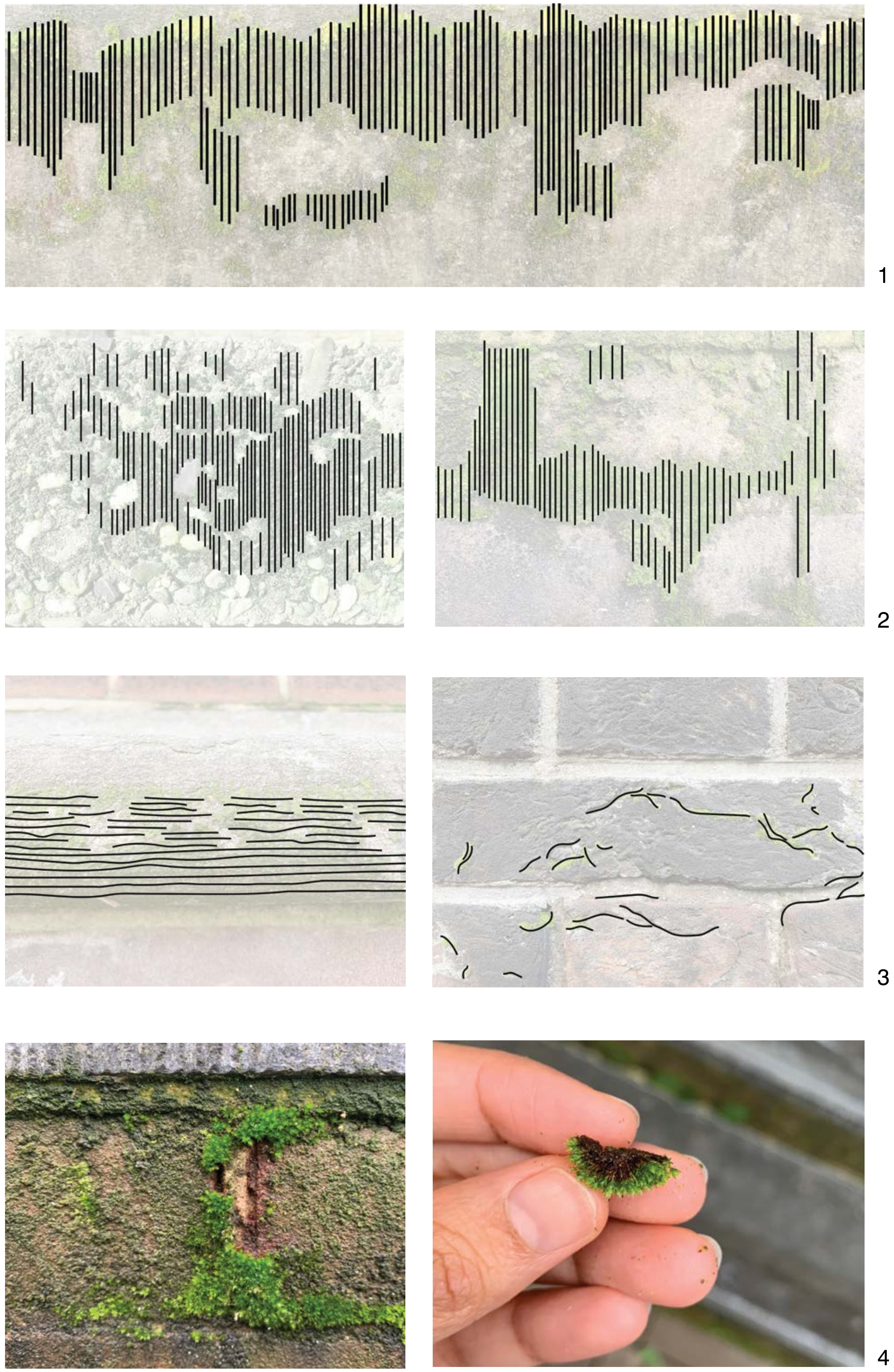
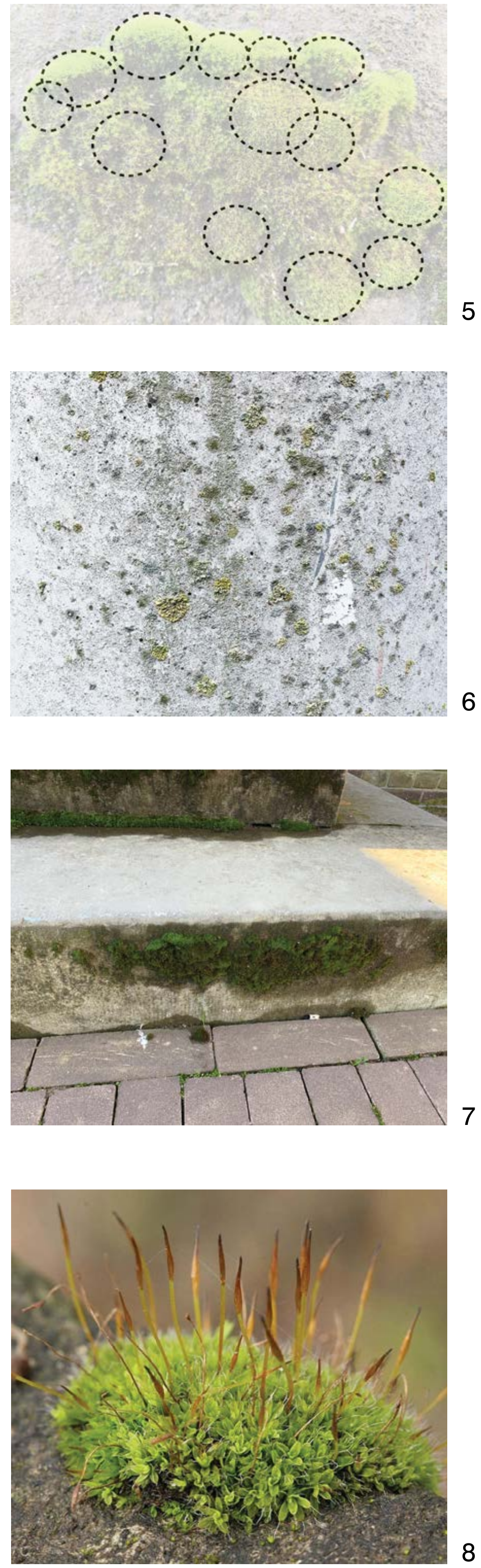


Fig 4.1a: Photo analysis of field survey data



As shown in Fig 4.1a, the following observations are presented.

Observations

1. Random growth pattern is observed, with no particular order followed. However, a continuous trail like character is also seen.

2. There is an imbalance in coverage with higher concentration in certain areas compared to others with the same material composition.

3. The affinity to grow in rough surfaces like cracks, creek lines, corners and grooves is found, and often irrespective of the material property.

4. The rhizoids of the mosses are found to penetrate about 2-5mm into the material creating a protection layer and higher water retention ability. Similar observations were also mentioned by Guillitte & Dreesen, in their 1995 article and by Wolfhart Pohl and Jürgen Schneider from the Geology society, London in 2002 (Miller et al., 2012).

5. In spite of the random growth pattern, the mosses are found to grow in small clusters in cushion forms, creating a moist environment within its layers.

6. A porous material with water retention ability, showed a degree of Bio-receptivity, suggesting the dependence on material property.

7. The mosses prefer to grow in damp and shaded areas. However, moss growth is also observed in dry textured surfaces.

8. The most common mosses observed on brick walls, and mortar surfaces are Tortula muralis and Grimmia pulvinata.

Please find the survey pictures in appendix 14.1

4.2. Experimentation

Procedure:

As shown in Fig 4.2a, the moss growing experiment is carried out based on some literature study. The material used is regular dense concrete block to mainly test the validity of the method for growing moss.

Step 1:
Some abundant concrete blocks were gathered from nearby construction site. The concrete blocks were initially used for making pavements.

Step 2:
Three types of wall mosses were collected for the experiment. Tortula muralis and Grimmia pulvinata. The moss surfaces were cleaned of any external dirt or dust.

Step 3:
The collected stones were thoroughly cleaned with water to remove the dirt layer from the surface. The cleaning was essentially done to eliminate any external influence other than material property for bio-receptivity.

Step 4:
The moss slurry was prepared (as instructed in the literature) in the proportion 1 cup moss and 1.5 cups of plain yogurt. Some water was added to get the right consistency.

Step 5:
The slurry was blended into a rough paste using an electric hand-blender. The prepared slurry was then left to set for a period of 24hours before application

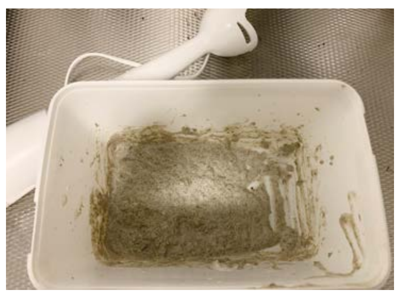
Step 6:
The slurry was applied using a paint brush on areas desired to be covered in mosses. The areas which were intended to be kept moss free was not applied with the slurry


Step 1


Step 2


Step 3


Step 4


Step 5


Step 6

Fig 4.2a: Steps for application of moss slury on concrete blocks

Application 16/11/12019 | Growth Outcome 21/12/12019

Fig 4.2b: Comparative results for growth outcome after 6 weeks of application

Setup:

Location: Indoor
Temperature: 23-25^{o}C
Light: approx.12-14hrs (sunlight + artificial)
Water sprayed: 1-2 days interval for approx. 1-2 min duration
Wind: nil
Growing period: 6 weeks

Results according to Fig 4.2b:

Face 1 and face 2 showed moss growth in areas where slurry was applied. The rough character of the surface helped the rhizoids to anchor to the surface. However, browning of the mosses was evident.

Face 3 showed almost no moss growth on the surface due to its smooth finish.

Face 4 being an adjacent face to surface 3 of the same block showed higher amount of moss growth owing to its rough surface quality.

Face 5 showed moss grown within its deeper regions on the surface owing to better anchorage area and moisture holding capacity.

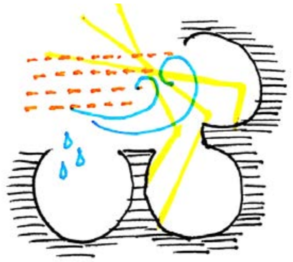
The results were not adequate to what was expected. The reasons for the poor growth and browning of the mosses might be due to the following:

- The use of dense compact concrete, with no water retention ability.
- The smooth surface character of the concrete blocks reduced possible anchorage.
- The unsuitable pH level for Bio-receptivity.
- The inadequate watering and high temperature values caused rapid drying of the mosses.
- The absence of proper sunlight ceased photosynthesis which resulted to browning of the mosses.

5. Design development

5.1. Factors influencing Surface geometry

Environmental - Microclimate

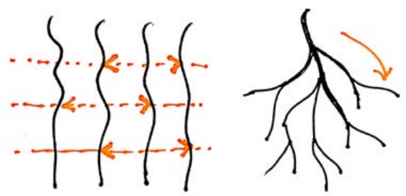


- Water retention
- Indirect sunlight
- Wind buffer
- Nutrient accumulation

According to the literature study, the mosses require certain environmental parameters to thrive. Mosses being small plant spices need to have a micro-climate on and above the surface. The micro-climate can help to maintain the required moisture level, a cooler temperature and a low wind speed.

The role of geometry is vital to create the desired micro-climate for plant growth. Rough surfaces with certain height to surface area ratio can hold moisture and gather nutrients onto its surface. The surface morphology can also help to create areas of shading to protect plants from direct sunlight and provide buffers to high wind speed causing detachment.

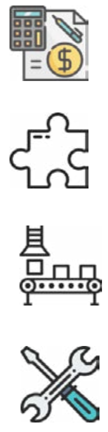
Direct route for growth



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

One of the main objectives of this research is to create order and balance in the random growth of mosses observed in nature. Surface undulations and the combination of rough and smooth textures can be used to define areas of growth and inhibition. By creating slow water movement and channeling rainwater to desired areas moss growth can be engineered. Further by replicating the cushion structure of moss in nature and creating adequate anchorage facility moss growth can also be enhanced. These geometries can contribute to the aesthetic aspect of the facade by creating an ordered and systematic growth through the desired pattern.

Economic feasibility

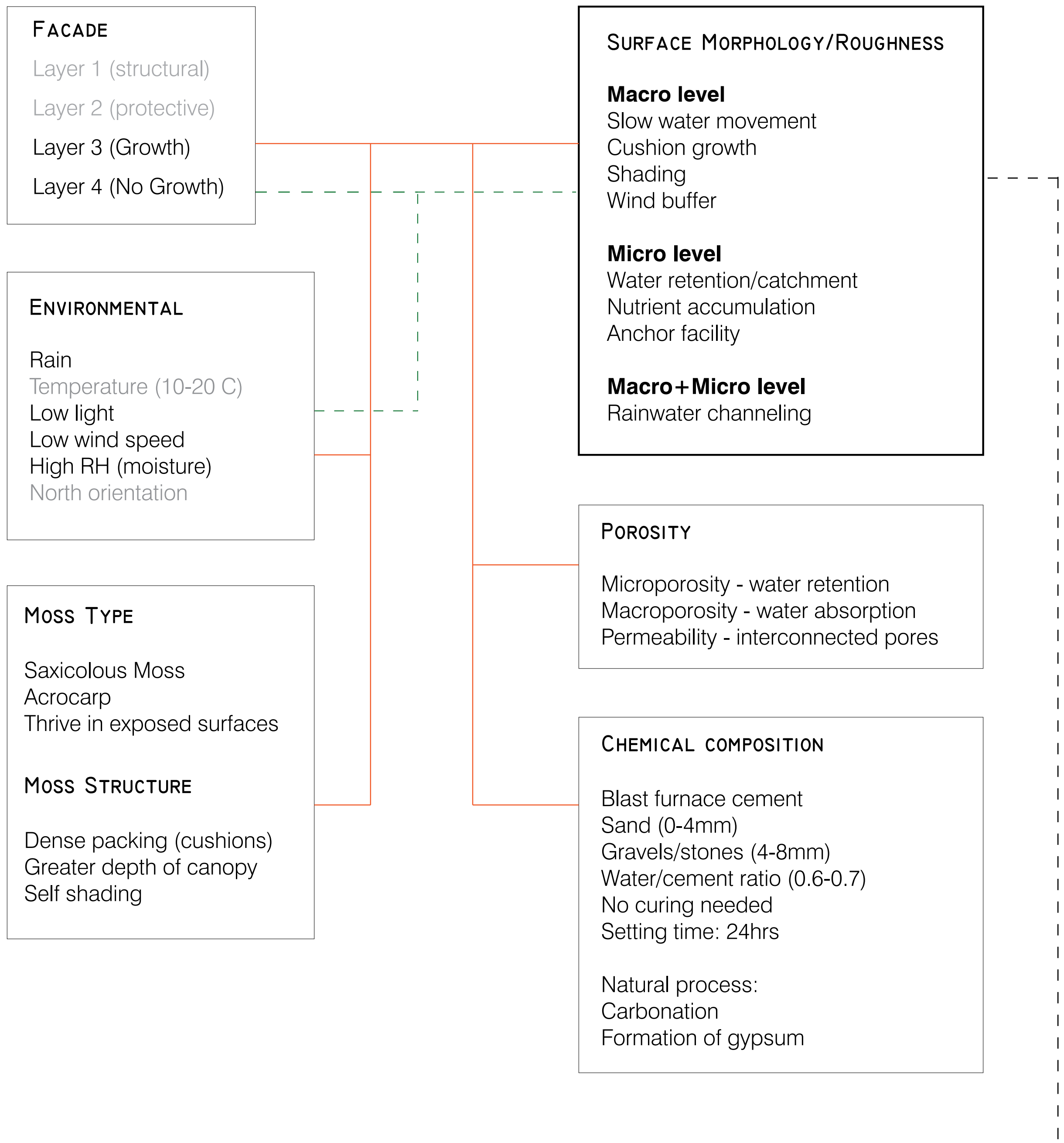


- Net cost
- Material use
- Production process
- Installation

To promote the use of Bio-receptive facade panels as a commercial product, the economic feasibility of the product must be considered. In terms of material use, the use of least amount of material to create the desired geometry as a lightweight yet rigid panel is essential. The geometry should be complex to meet its functional role yet simple enough to be produced by an efficient as well as economic production process. The panels created should be within weighing limits and carriable size to have easy transportation and installation process.

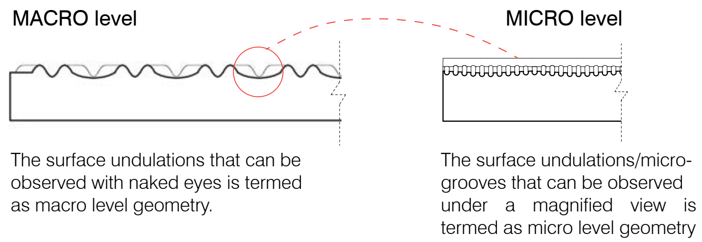
Automatic and non-labour intensive techniques, like CNC-milling and use of reusable molds can reduce the production cost to a great extent and also accelerate the production process. Thus, an overall low net cost to produce and install the facade panels must be considered to encourage mass use.

Fig 5.1a : Design Schematic



In order to design a bio-receptive concrete, the above features are determined as the influencing factors. These features can be translated into design by two types of geometrical level, macro and micro. Individually and in combination the macro and micro level geometries can create the desired micro-climate and direct growth route.

5.2 Essential features for growth



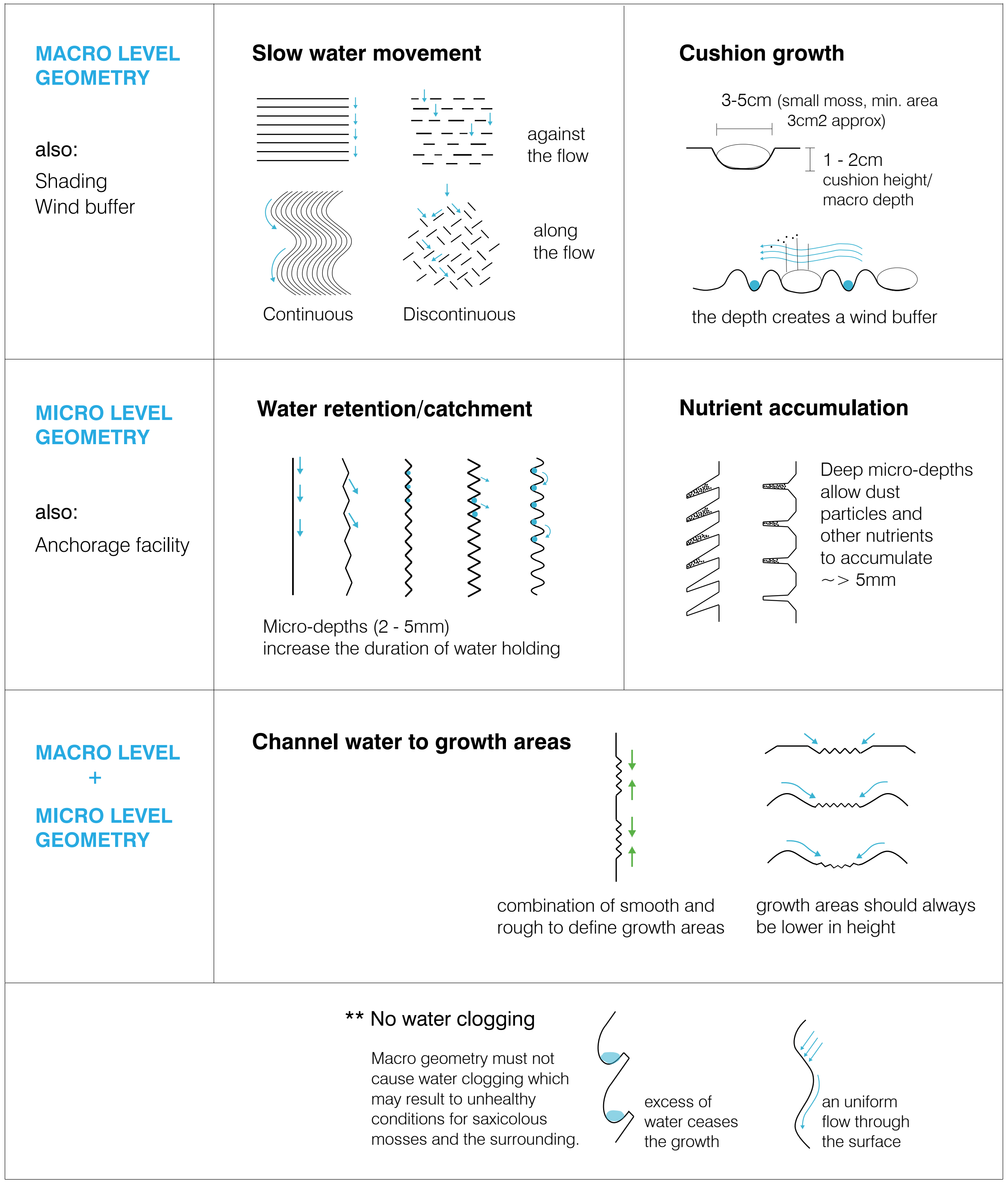


Table 2: Matrix of geomtries or elements to design a bio-receptive concrete facade panel

As can be seen in Table 2, the matrix of geometries are divided into three sub-categories, individually or in combination they can result in surface morphologies through different rhythm methods to promote an aesthetically pleasing and ordered system of moss growth on concrete surfaces.

MACRO LEVEL GEOMETRY

Slow water movement

Geometry can play an important role to retain water on the substrate surface for a longer period of time. Continuous and discontinuous obstacles with its orientation along or against the flow of rain can contribute to control the flow velocity on the surface. Continuous/discontinuous against the flow bumpers can obstruct the linear flow of water down a surface, increasing the time for water to stay into the alcoves. Discontinuous obstacles at diagonals can help to divert the direction of water flows on the surface, reducing the flow speed along the growth areas. Curvilinear flow paths can prolong the route of water movement, creating a more continuous channel for growth.

Cushion growth

Through literature study it is found that mosses on exposed surfaces prefer to grow in cushion form. The radial arrangement of moss colonies helps them to store water within the depth of the moss structure. In order to utilize this quality of the mosses, circular spaces with a certain depth can mirror the mosses structure in nature and promote water retention ability. The depth of the surfaces helps to create a wind buffer and shading protecting the moss structure from evaporative water loss. A depth of 1-2 cm is desired according to the height of the gametophyte of the moss leaving the sporophyte exposed to the wind to disperse the spores.

MICRO LEVEL GEOMETRY

Water retention/catchment

Micro textures on the surface can promote growth in several ways. The higher the depth of micro-grooves, the higher the roughness of the surface. Rough surfaces can provide greater surface area for anchorage of micro-organisms. They can increase the duration of holding the water into the alcove spaces, which facilitate water absorption into the surface through capillary action. Along with the depth, the geometry of the micro-grooves can also vary the water movement and water retention ability on the surface.

Nutrient accumulation

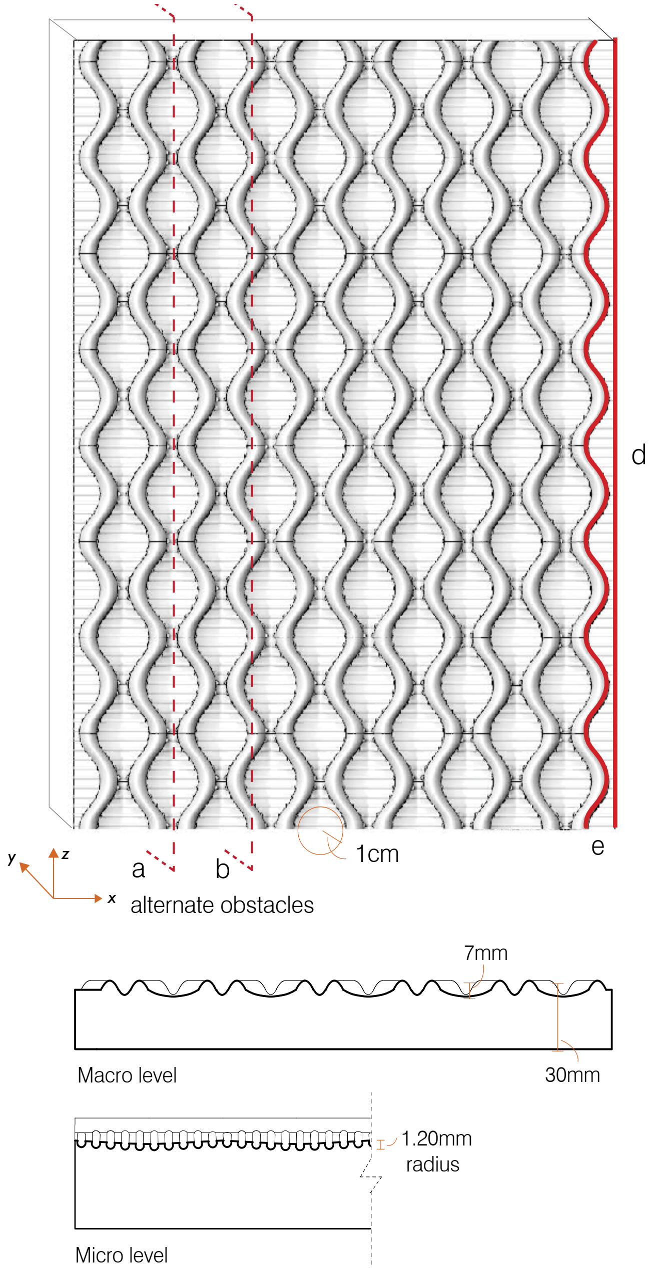
Secondary Bio-receptivity often occurs in old building facades due to the process of carbonation, gypsum formation and accumulation of dust particles into cracks, fissures and creek lines. Geometry can be used to create deeper grooves to accelerate such natural process and promote the growth of bio-colonization. Groove shape and depth can vary according to the material property and thickness of the facade panel.

MACRO + MICRO LEVEL GEOMETRY

Rainwater channeling

Surface roughness is one of the crucial criteria to promote bio-receptivity on a substrate. In order to facilitate moss growth in certain areas on a surface while not in others, a combination of smooth and rough surface quality at different heights is required. Growth areas with textured surface at a relatively lower height than the no growth smooth surface can help to channel rainwater and nutrients into the growth areas and enhance moss proliferation.

5.3. Prototype designs



Surface area	obstacle ratio (x)=e/d	obstacle ratio (y)=[(a+b)/2]/d
1314 cm2	1.17	1.29

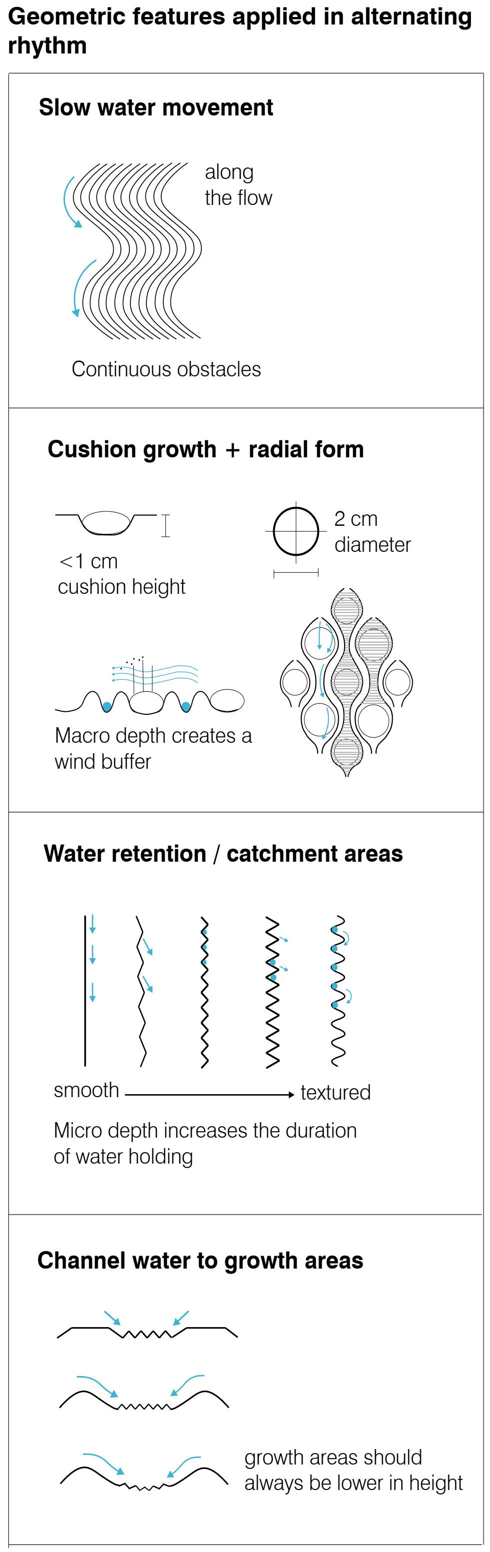
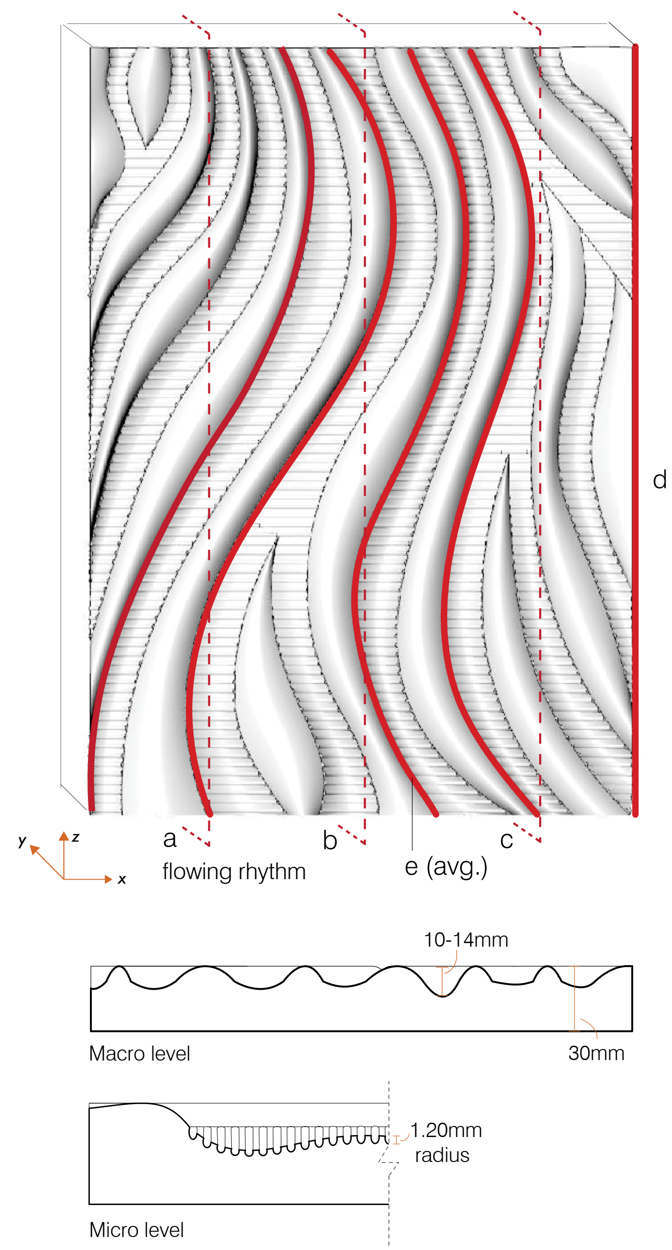


Fig 5.3a:Panel 1 designed in alternating rhythm



Surface area	obstacle ratio (x)=e (avg.)/d	obstacle ratio (y)=[(a+b+c)/3]/d
1261 cm2	1.07	1.26

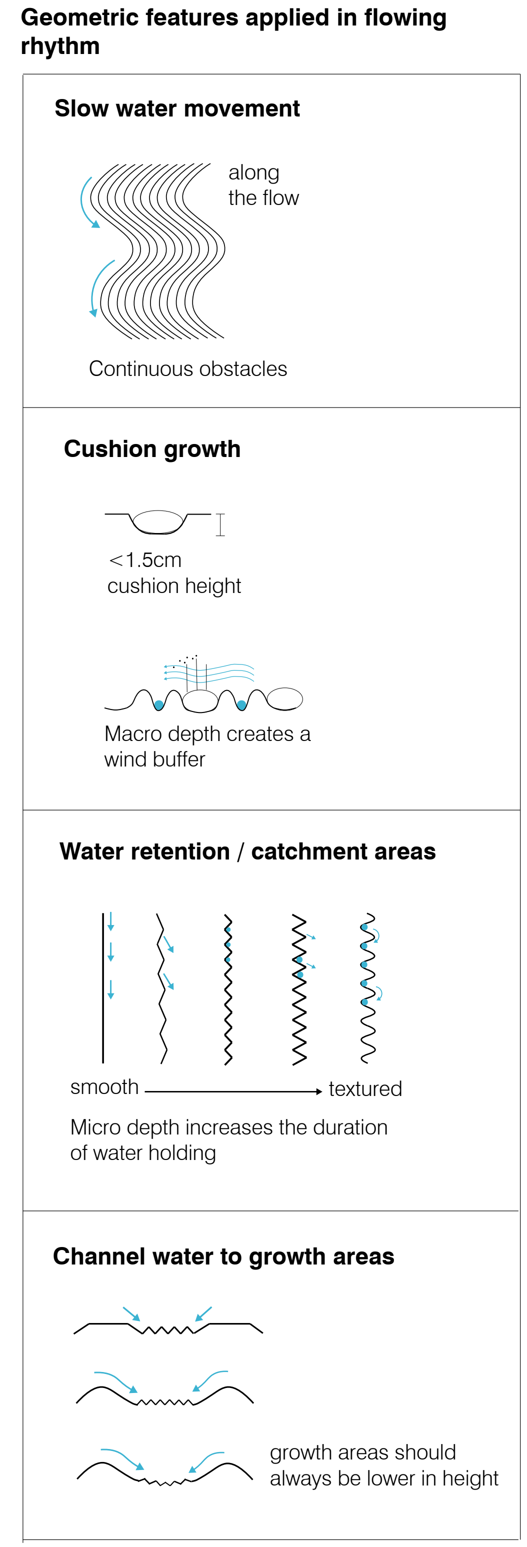
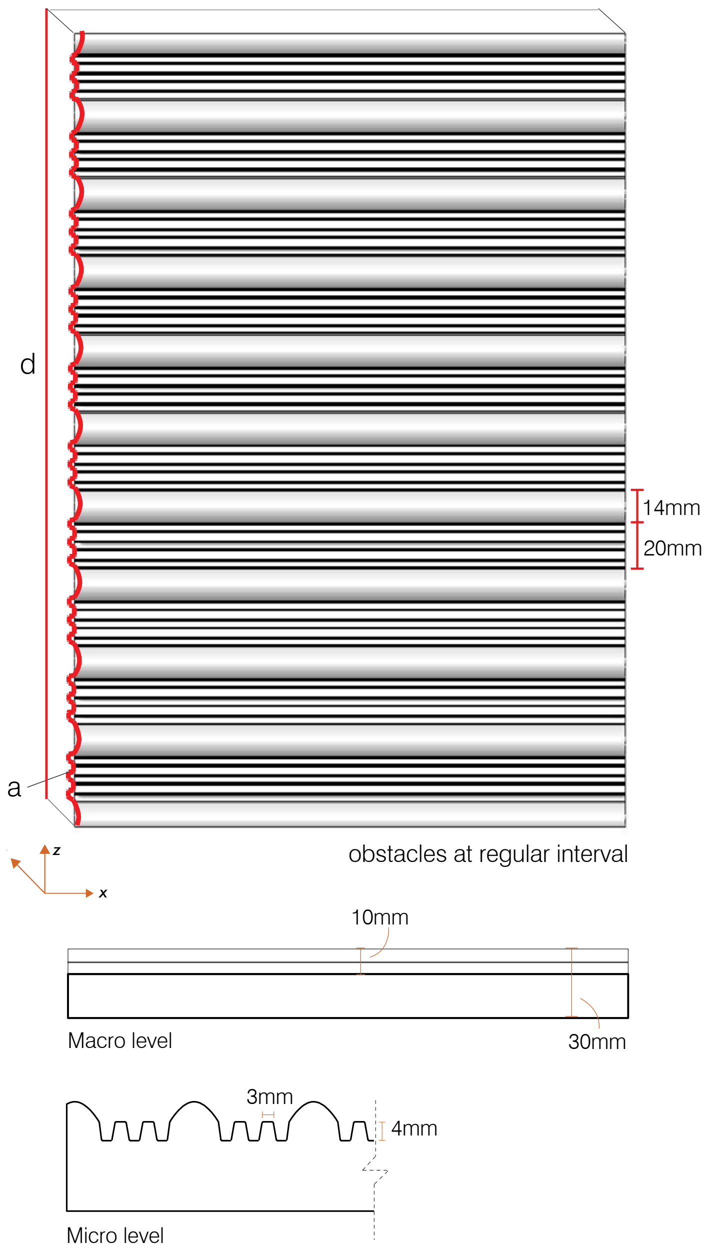
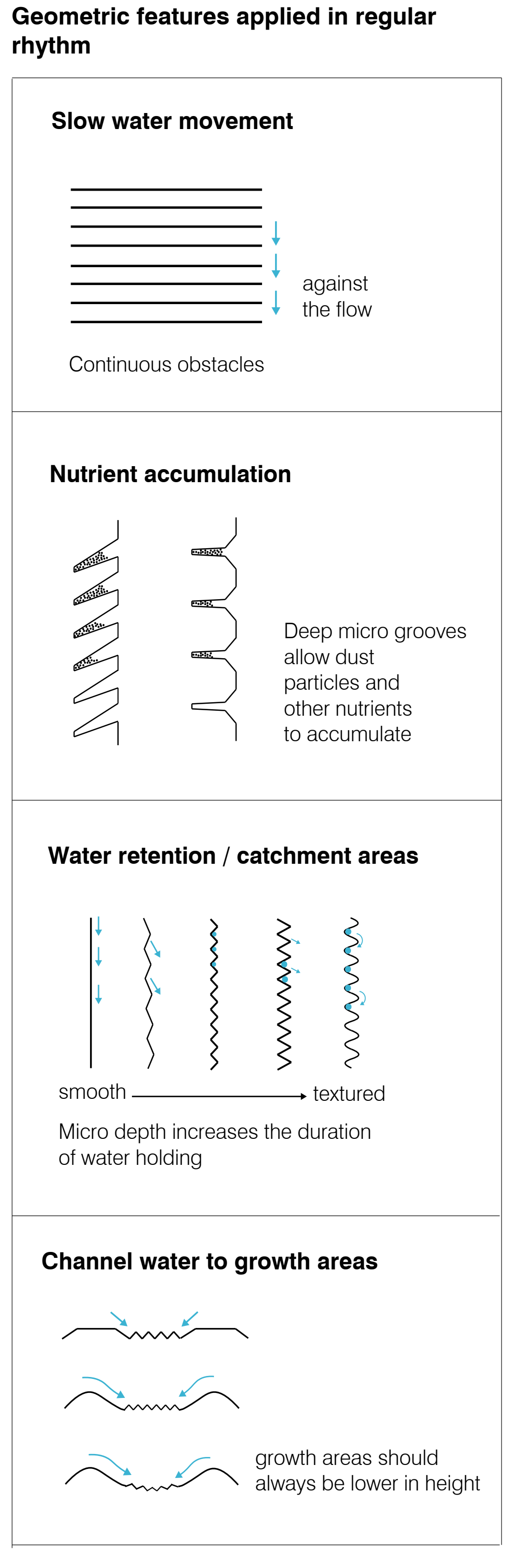


Fig 5.3b: Panel 2 designed in flowing rhythm

As shown in Fig 5.3a, the geometry has been designed in alternating rhythm method (Soegaard, 2018) to mirror the cushion form of moss structures. According to the literature study and field survey, small mosses are found to have a radial dimension of 2-5cm2. Based on this knowledge a series of connected circular spaces have been designed to facilitate the cushion growth of mosses. To create a rough texture for the overall surface 2mm circular micro-grooves have been introduced.

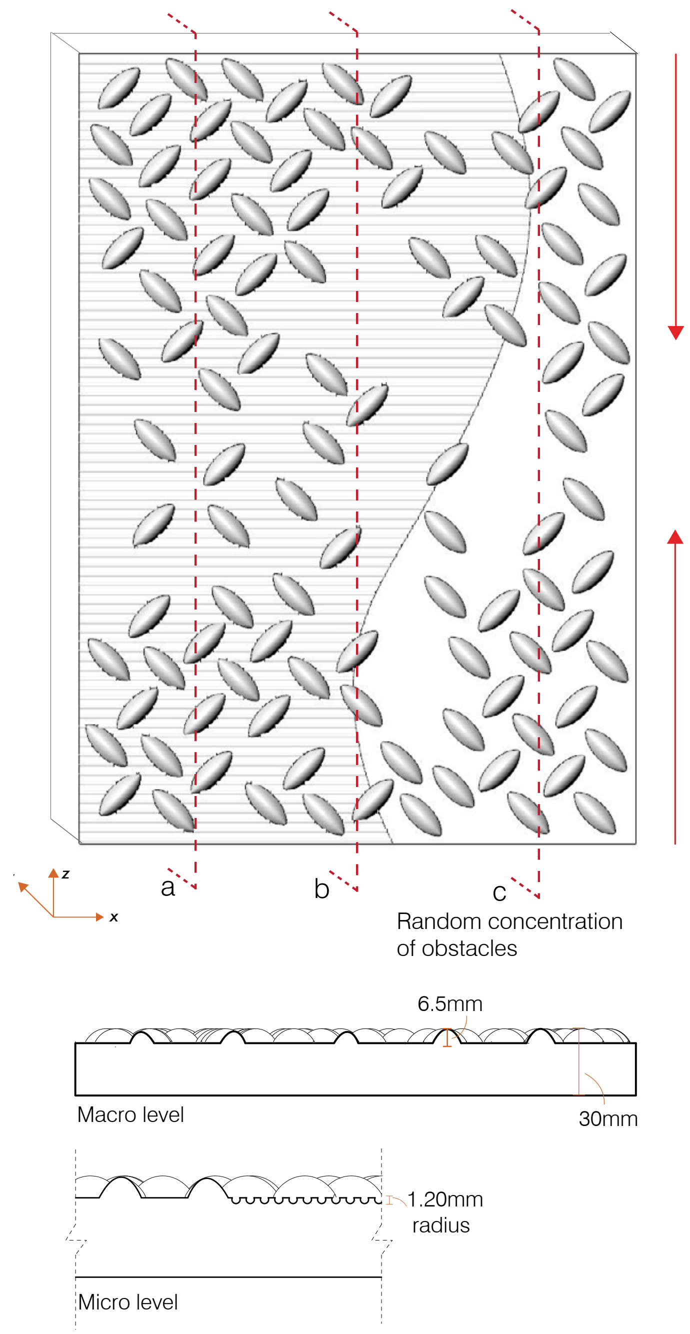
As shown in Fig 5.3b, the geometry is inspired by the structure of a tree bark. The organic curved geometry is designed in a flowing rhythm method (Soegaard, 2018) to direct the flow of water on the surface. The curved shapes with the increased depth can prolong the duration of water movement. The geometry alternatively contains rough and smooth areas to define the growth areas. Circular micro-grooves of 2mm diameter creates the surface roughness.

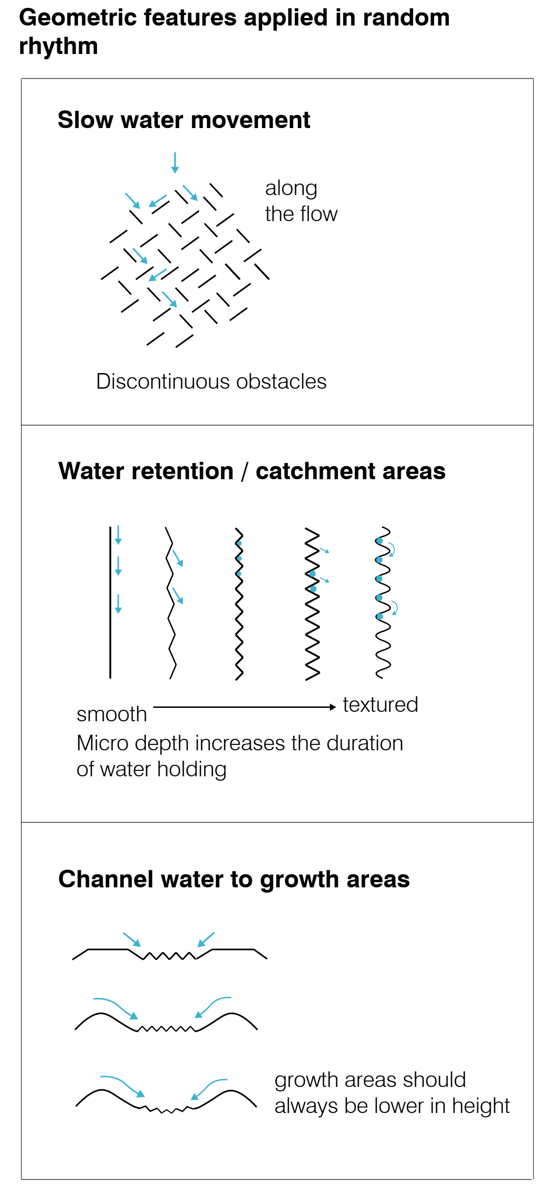




Surface area	obstacle ratio (x)=e/d	obstacle ratio (y)=a/d
1680 cm2	0	1.92

Fig 5.3c: Panel 3 designed in regular rhythm



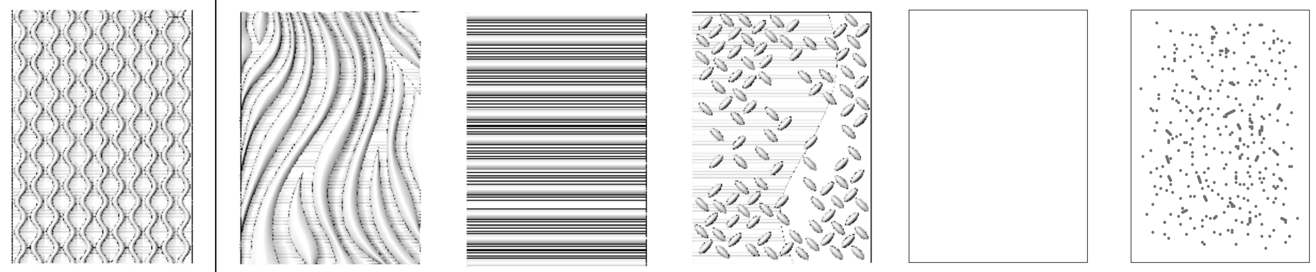


Surface area	obstacle ratio x=y=[(a+b+c)/3]/d
1182 cm2	1.25

Fig 5.3d: Panel 4 designed in random rhythm

As shown in Fig 5.3c, the geometry is designed as simple horizontal grills with curved bumpers at 20mm intervals, in a regular rhythm (Soegaard, 2018). The grills are made with deep grooves of 4mm. The grooves have a wedge shape to suck in dust and other nutrients into its deeper space. The deep grooves can also provide greater anchorage space for the moss rhizoids to create a strong grip. The curved bumpers create breaks between the grill spaces to hinder the flow of rainwater.

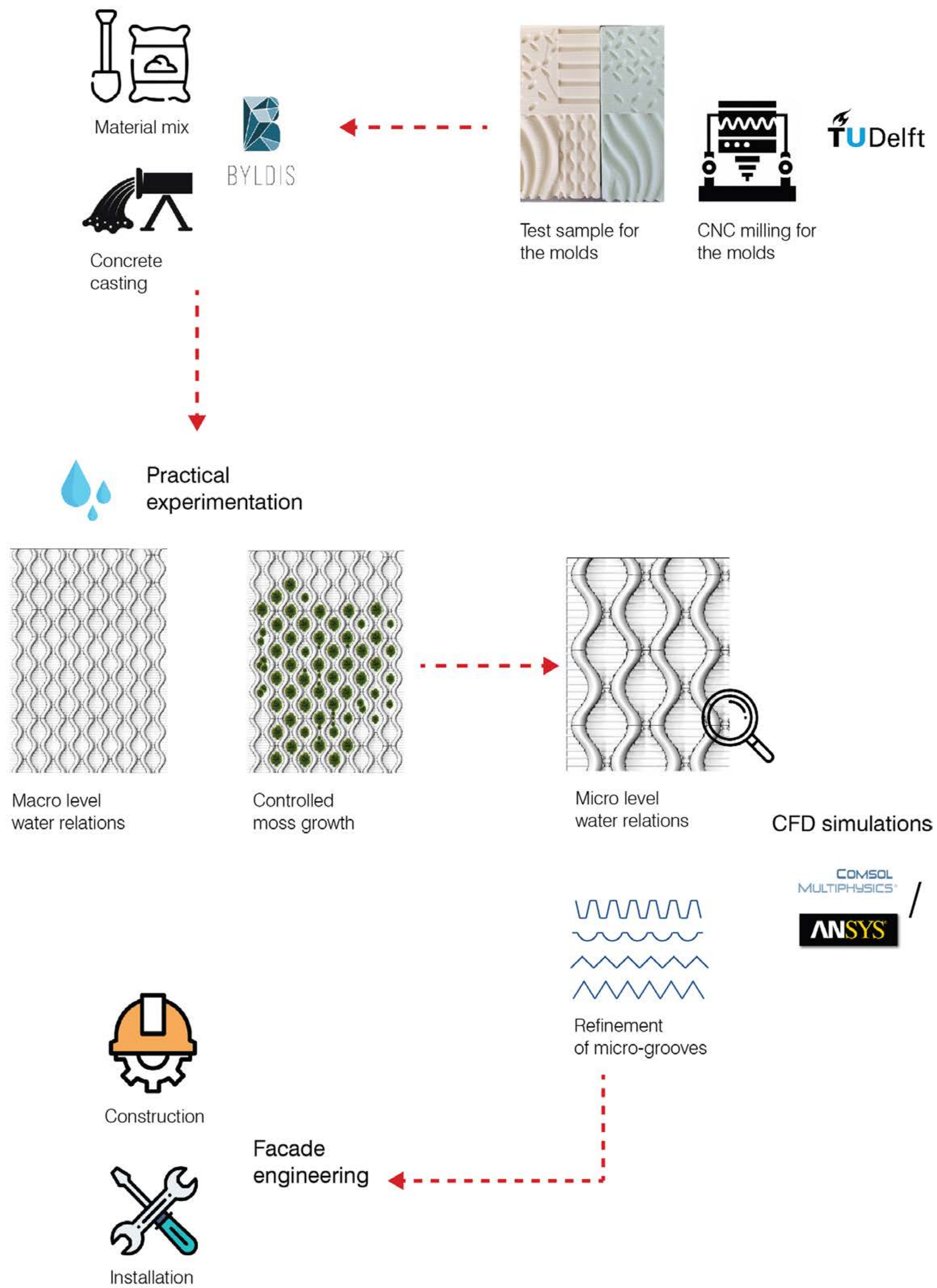
As shown in Fig 5.3d, the macro level geometry is created with capsule forms at diagonal angles. The capsules work as obstacles to rainwater, slowing down its flow rate on the surface. The capsules are distributed in varying concentrations through the surface in a random rhythm (Soegaard, 2018) to check the variations in water retention in different areas. The overall surface is divided into smooth and rough areas to further check the affect of surface roughness on moss 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	✓	✓	✓	✓		

Table 3: A comparative summary table with geometry features of the designed and undesigned concrete panels

Table 3 creates a comparative summary of the geometry features of the 4 designed panels. Two extra panels, panel 5 which is a plain concrete panel and panel 6, a natural rough concrete panel with exposed sand and gravels layer are introduced to create a more vivid comparative analysis between the ordered and random surface geometries. In the following chapters several experiments will be carried out in the 6 panels to test and validate the role of geometry on water retention and absorption ability which is vital for moss growth.



The second part of this research involves the validation of the created designs for Bio-receptivity. First the design prototypes (6 panels) are cast in concrete in the chosen material composition. Two sets of concrete panels are cast where one set is used for the controlled moss growth experiment and the other set is used for the macro level water relation laboratory testing. Next CFD simulation using Ansys software is carried out for the water relation on the micro-grooves of the geometry. Based on the comparative analysis of all the results a design guideline is provided, and modified design proposed. Lastly the research investigates the production feasibility of a concrete façade panel and suggests the most efficient construction technique and installation method to create an optimized façade panel.

6. Prototype making

6.1. Mold making

The designs are created using the 3d modeling software rhinoceros. To translate the designs into prototypes, the negative of the designs are fabricated through the process of CNC milling. The entire process is carried out with assistance from Bob de Boer at the model hall at BK city, TU Delft.

To ensure milling precision, initially small sample of the designs are CNC milled in two types of foam material, styrofoam and Necuron(hardfoam) (Fig 6.1a). Necuron showed more clean cut then styrofoam, thus the former is further tested by casting concrete with a vaseline coating, for easy demolding (Fig 6.1b, c). On successful testing, Necuron (hardfoam) is chosen for the final product. Due to the limitation of the needle size of the CNC milling machine, the micro-grooves is placed at gaps of 4mm for better grooving depths.

For the final product, Necuron (Hardfoam) is cut in the dimension 350mm x 250mm with thickness 20mm. A total of 4 foam plates is CNC milled according to the given designs, each requiring a time of 1.5 hrs (approx.). The total cost involved is 36euros, as per the price 6euros per hr. After the milling process the foam molds are air brushed to remove any excess dust on the surface.

6.2. Mold preparation

The negative foam mold made from Necuron (hardfoam) has high adhesion quality to concrete. Therefore, for easy demolding, the designed foam molds are sprayed with a sealing agent, such as silicone, 24hrs before the casting. At the time of the casting, the molds are placed inside wooden frames and a final coating of mineral oil SOK912 is brushed in and around the foam mold and wooden frame. The extra coating was applied to ensure the foam molds to remain intact while demolding (Fig 6.2a).

Apart from the design foam molds, two extra molds are prepared, one with a plain foam base and another with a layer of sand(0-4mm). These molds required minimum surface coating owing to the plain surface (Fig 6.2b, c).

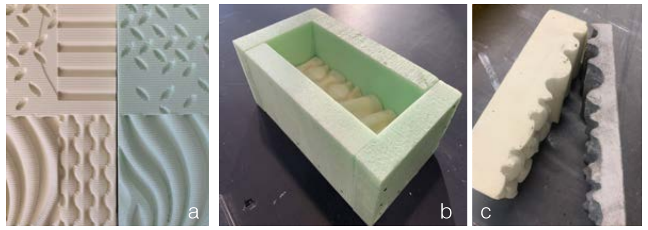


Fig 6.1a,b,c: a. Foam types, b. Sample casting, c. Demolding

Fig 6.1d: Final CNC milled molds in Necuron

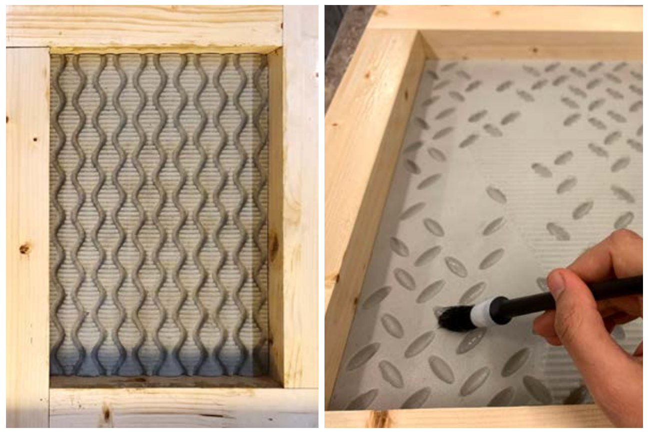


Fig 6.2a: Coating the designed molds with releasing agent

Fig 6.2b, c: b. plain mold & c. sand layer mold

6.3. Material composition

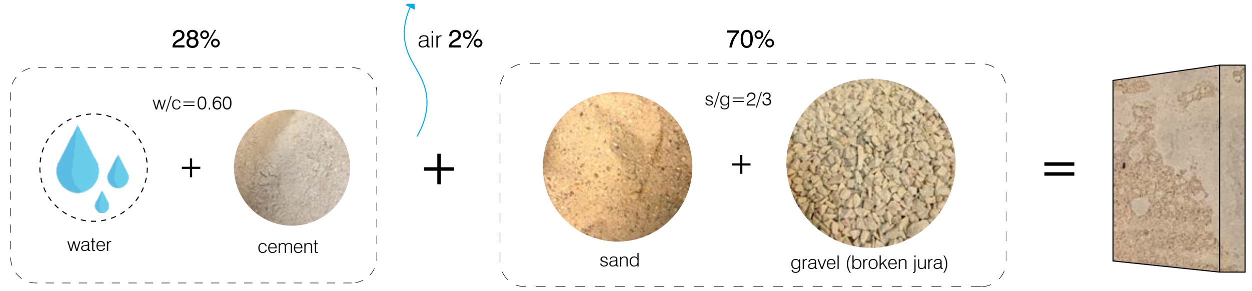


Fig 6.3: Ratio of material used to make concrete blocks

The raw materials:

Density in Tonne Per Cubic Meter (t/m^3)

1. Blast furnace cement CBR CEM III/B 32.5 N with a slag content of 75% - (2.95 t/m^3)
2. Concrete sand 0-4 mm - (2.65 t/m^3)
3. Broken Jura yellow 5-8 mm - (2,725 t/m^3)
4. Water supply - (1.00 t/m^3)

Calculation:

Base amount: A cement content of 300 kg/m3
Water cement ratio, w/c 0.60

density= mass/volume
1 ton = 1000 kg
1m³=1000 litres(l)

Concrete 300/2.95 = 101.7 *l*
Air 2% = 20 *l*
Water = 0.60 x 300 = 180 *l*
} 301.7 *l*

Aggregate materials sand and gravel = 1000 - 301.7
= 698.3 *l*

40% sand 0-4 mm
-> 0.40 x 698.3 = 279.32 x 2.65
= 740 kg of dry sand

60% jurassic yellow 5-8 mm
-> 0.60 x 698.3 = 418.98 x 2,725
= 1142 kg dry jurassic yellow

The raw material and the water/cement ratio used are decided according to the literature study to create concrete blocks with lower ph and higher porosity than conventional structural concrete.

1 m3 of concrete

300 kg CEM III/B 32.5 N

740 kg of dry sand 0-4 mm

1142 kg dry jurassic yellow 5-8 mm

180 liters of water

For each tile 3.25 litres are needed and this is mixed in a 10 litres Hobart mixer with a flat mixer.

Material proportion and calculations have been given by Byldis

6.4. Casting process

Step 1 Weighing   Step 2 Mixing   Step 3 Pouring   Step 4 Vibration

Fig 6.4a: Casting process for concrete panels

The casting process has been carried out under the assistance of Gerard Brood at the concrete lab at Byldis, Veldhoven (Fig.6.4a).

Step 1 - Weighing

1. All the ingredients are weighed according to the material composition as explained in the previous section.

Step 2 - Mixing

2. First sand and cement are added into the mixer and mixed for 30 seconds.

3. Next 3/4 of the measured water is added into the mixer and the mixer is started again.

4. While the mixer is running, Jura gravels are added in small portions within a span of 2mins.

5. The machine is turned of and the last portion of the water is added and the mixer is run for another 1min.

Step 3 - Pouring & Step 4 - Vibration

6. The mixture is scooped well with a hand scoop before pouring

7. The mold frame is filled halfway with the mixture and the vibrator is operated until the side edges are closed with cement porridge

8. Then the vibrator is stopped and the remaining height of the mold frame is filled with the mixture.

9. Lastly the vibrator is run again until the surface becomes flat and smooth with visible air bubbles.

Step 5 - Setting/Drying

10. The mixture is left to set in the wooden frame for 48hrs, keeping it uncovered with no curing. This was done with the aim to create a porous bio-receptivity concrete panel.

Step 6 - Demolding

11. After 48hrs, the wooden frame is unscrewed and the mold with the harden concrete is separated from the frame.

12. The concrete panel is gently separated from the foam mold by injecting air pressure into the gaps

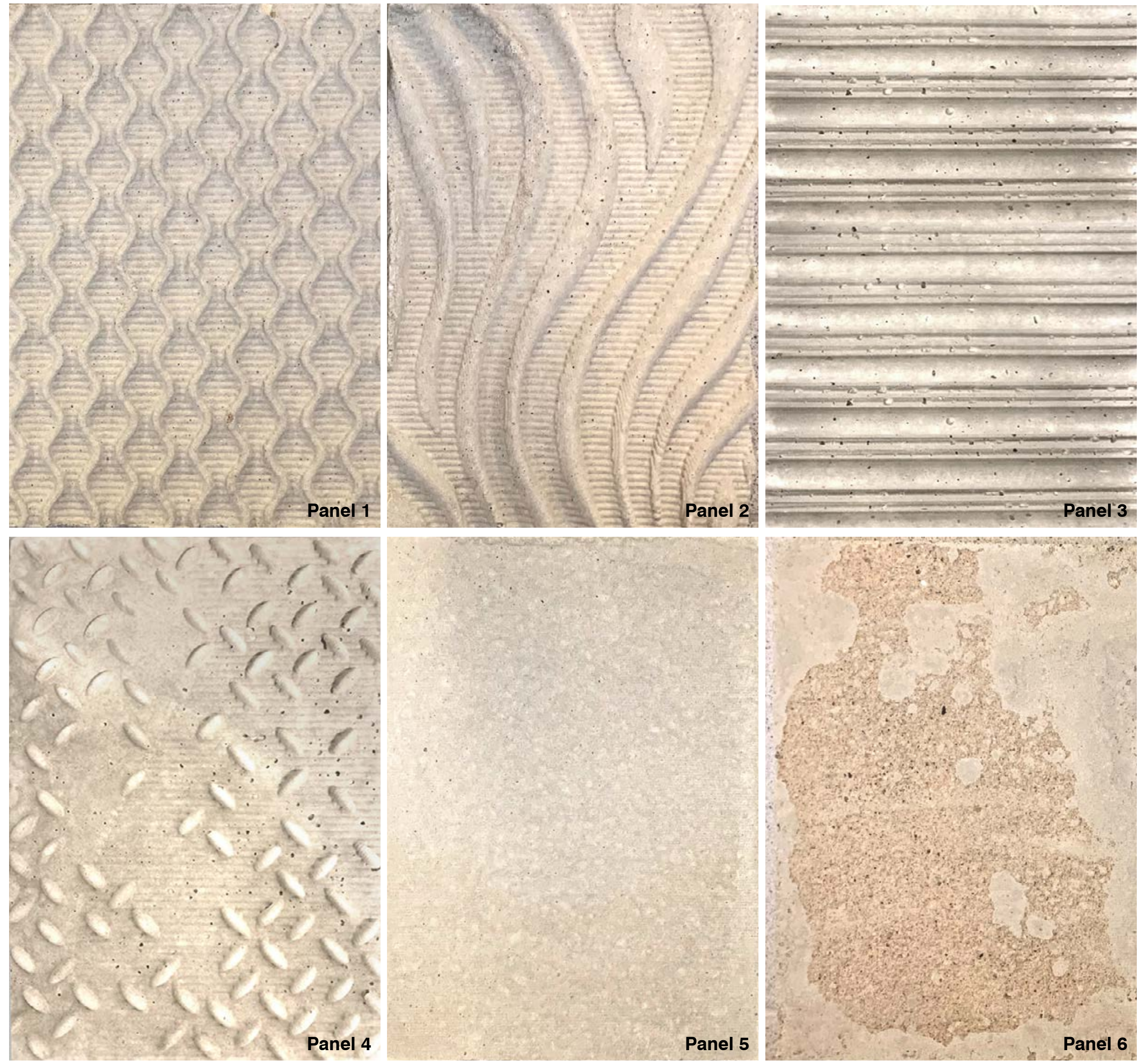


Fig 6.4b: Demolded concrete panels

Two sets of concrete panels were made (12 nos.)

Each weigh 7.5-8 kg

Size: 350mm x 250mm

Thickness: 40mm

6.5. Observations

1. Vibration period is crucial (5-10sec) under vibration can cause uneven mixing and over vibration can dense the concrete.
2. Setting time should be 48hrs, early demolding weakens the panels. Fragile patterned parts and corners can break off.
3. Use of excessive protective coating on molds, created an water absorption barrier on the concrete surface.

7. Design validation

7.1. Moss growing experiment

One set of the freshly cast panels are used for the moss growing experiment. The experiment is carried out in the greenhouse of the TU Delft botanical garden, under the supervision of Bob Ursem and Lewie van Wingerde. The experiment is dated between end february to mid-May, after a trial phase for the first three weeks of February.

7.1.1. Moss slurry application

The saxicolous moss fragments with rip spores are collected from the botanical garden stone surfaces (Fig 7.1a). The moss fragments are lightly brushed to remove any external dust. Then the slurry is prepared, according to the procedure followed in section 4.2., based on literature study. Buttermilk and moss fragments in (1:1) ratio are blended together 24hrs before application. Plain yogurt is replaced with buttermilk due to its higher acidic base. The panels are prepared by polishing the ridges with sand paper for a smoother finish and then thoroughly cleaned with water and vinegar to remove any surface contaminants. On the day of application the panels are wetted with vinegar to create an acidic base and after an hour the prepared slurry is painted in desired areas using a paint brush (Fig 7.1b).

Fig 7.1a, b: a. Saxicolous mosses on rock, b. Moss slurry

7.1.2. Trial and observations

During the 3 -week trial, some important information is learned which greatly influenced the moss growth. The best temperature to accelerate moss growth is between 20-24°C, though according to literature, the most suitable temperature is around 15°C. The growing process is prolonged in the colder weather and not suitable for a controlled growth within a short time. After about 7-8 days of application, signs of fungus growth is observed over the applied slurry (Fig 7.1c). This process is called Symbiosis, where two organisms living together undergo an ecological interaction. Symbiosis is known to exist in the early stages of plant growth, where both the parties benefit from increase in uptake of nutrients ("Mutualistic relationships | Biology for majors II," n.d.). This stage is the early colonizing phase by the fungi and spores before appearance of moss.

Fig 7.1c: White fungus growth

Fig 7.1d: Cooler greenhouse

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

Fig 7.1e: Warmer tropical greenhouse

7.1.3. The experiment

After the trial period, the panels coated with moss slurry are shifted from the colder greenhouse (Fig 7.1d) to the warmer greenhouse. The experiment is carried out in a span of 12-weeks, from end February to mid-May. It is done in two phases, where the first 6 weeks the panels are placed in horizontal position and the last 6 weeks in upright position (Fig 7.1e).

The temperature ranging between 20-24°C and RH 75-85% is maintained within the greenhouse and rainwater is sprayed onto the panels twice or thrice daily depending on the weather conditions. During the dark cycle of the day, the panels are kept uncovered due to the high humidity (RH 60% +) inside the greenhouse.

7.1.4. Growth progress

During the first 6 weeks, the panels are kept in a horizontal position to allow them to remain wet for a longer time and create the required moist conditions for moss growth. Around the 4th week, small patches of green algae are seen on the surface of panel 2, while the others remained unchanged as dark brown. On the 6th week, bright green layers of algae is grown in the central alcoves of panel 2; while light patches are also seen in panel 1, 3 and 4 mostly around their central area, due to higher concentration of water spraying along this region (Fig 7.1g). Among all the panels, the macro geometry of panel 2, has the greatest depth which allowed higher water retention on the surface and subsequently more algae formation (Fig 7.1f). The appearance of the green algae confers to the Bio-receptive character of the concrete panels.

At the end of week 6, all the panels are placed in a upright position, to observe the role of geometry on water flow movement on the surface of the panels. After a weeks' time, the green patches on the panels appeared lighter and the panels seemed drier than before. The sudden change is assumed to be for two reasons, first around mid-April, due to warmer outside temperature, the tropical greenhouse recorded a high temperature of 32°C resulting to rapid drying by evaporation and secondly the upright position allowed lesser time for the water to remain onto the surface due to the lack of water catchment micro-grooves (Fig 7.1g).

On week 8, the panels are shifted to another region of the greenhouse, to maintain a temperature of 20-24°C, and slow down the drying effect. The progress is still found to be minimal, the panels showed some dark patches of algae growth near the lower edge of the panels, indicating the presence of moist condition around this region (Fig 7.1g). Thus week 10 onwards, the panels are laid horizontally again, to increase the water retention onto the surface. By the beginning of week 12, bright green patches of algae is seen on the textured surfaces. Panel 2, showed the highest growth followed by Panel 1, owing to their textured macro depths and continuous flow path, allowing a trail growth in desired areas.

Fig 7.1f: Green algae growth on Panel 2

7.1.5. Conclusion

Based on the growth progress, the concrete panels can be conferred to have Bio-receptive character, owing to its material property and surface textures. The presence of water is found to be essential for the growth of mosses on concrete surfaces. The following points need to be considered for successful moss growing experiment.

- Controlled growing conditions: 20-24°C, RH 80%, three times watering of the surface.
- 12 weeks is not enough to propagate moss growth on concrete surfaces.
- Estimated time for algae appearance 8-12weeks and moss growth 18-20weeks.
- The panels should be placed in horizontal position until visible moss growth occurs.
- Panels should have growth areas of connected macro depths to allow continuous trail of growth along with deep micro-grooves to allow sufficient water retention in upright position.
- Further testing is required for mature moss grown panels in vertical position, extending the spraying duration to 2mins once daily, for a period of approx. 3-4 weeks.

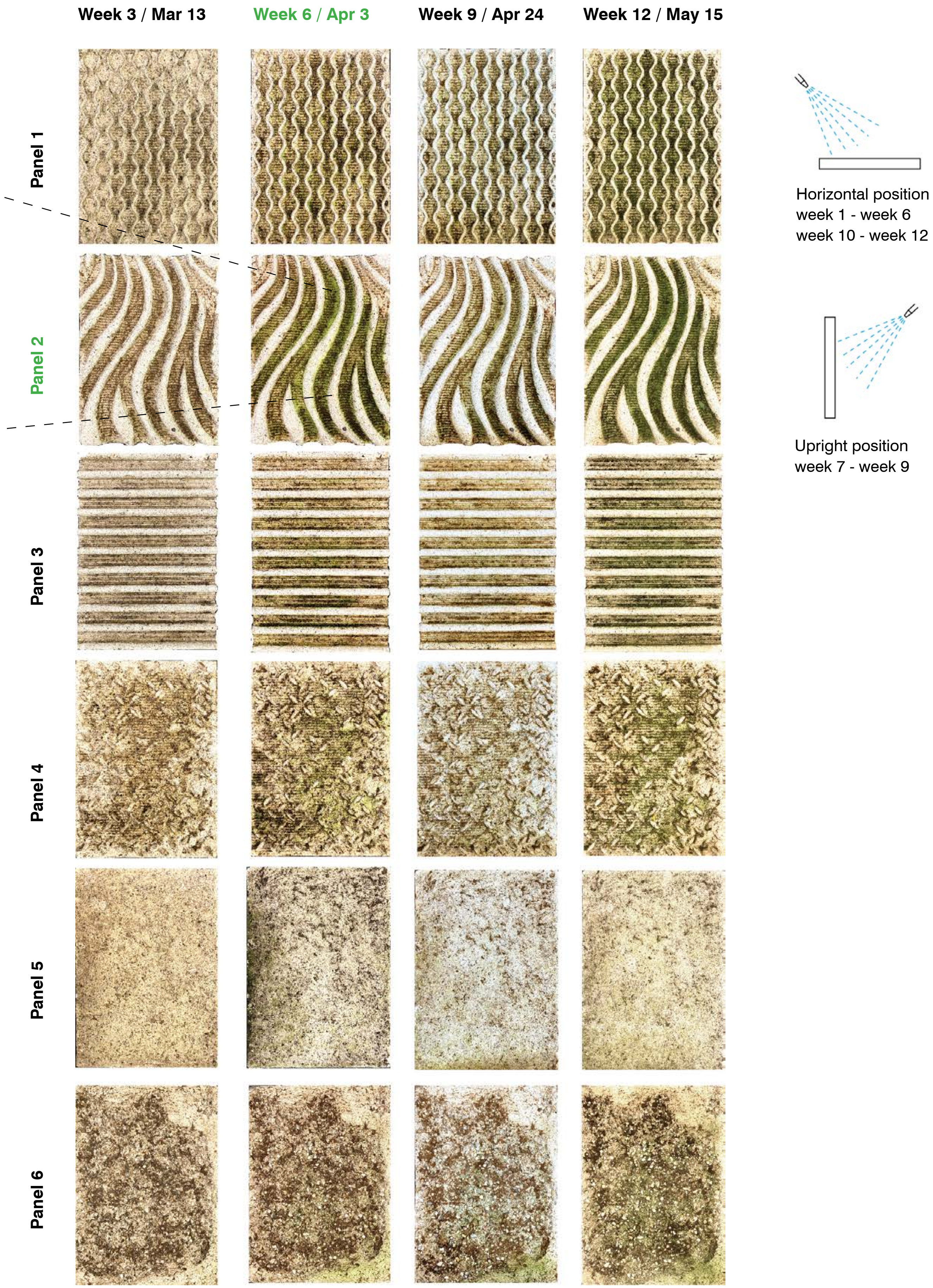
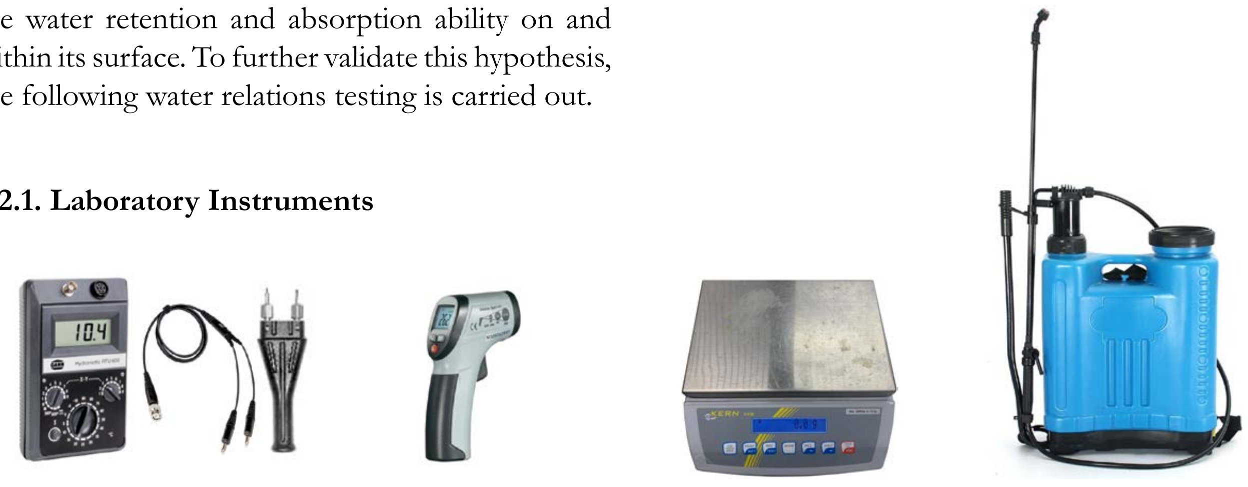


Fig 7.1g: Photographic observation of the 12 week growth pattern for the 6 panels

7.2. Water relations laboratory experiment

As already found, water is essential for the growth and survival of mosses. The designed geometric patterns on the concrete panels are used to influence the water retention and absorption ability on and within its surface. To further validate this hypothesis, the following water relations testing is carried out.

7.2.1. Laboratory Instruments



Gann Hydromette RTU 600
Use: Relative humidity measurement

Infrared thermometer
Use: Temperature reading

Kern FKB 36K0.1 table scale
Use: Weight reading

20L Pressure Water Sprayer
Use: 30° water spraying

Fig 7.2a: Types of Instruments used for water relations testing

7.2.2. Laboratory Setup

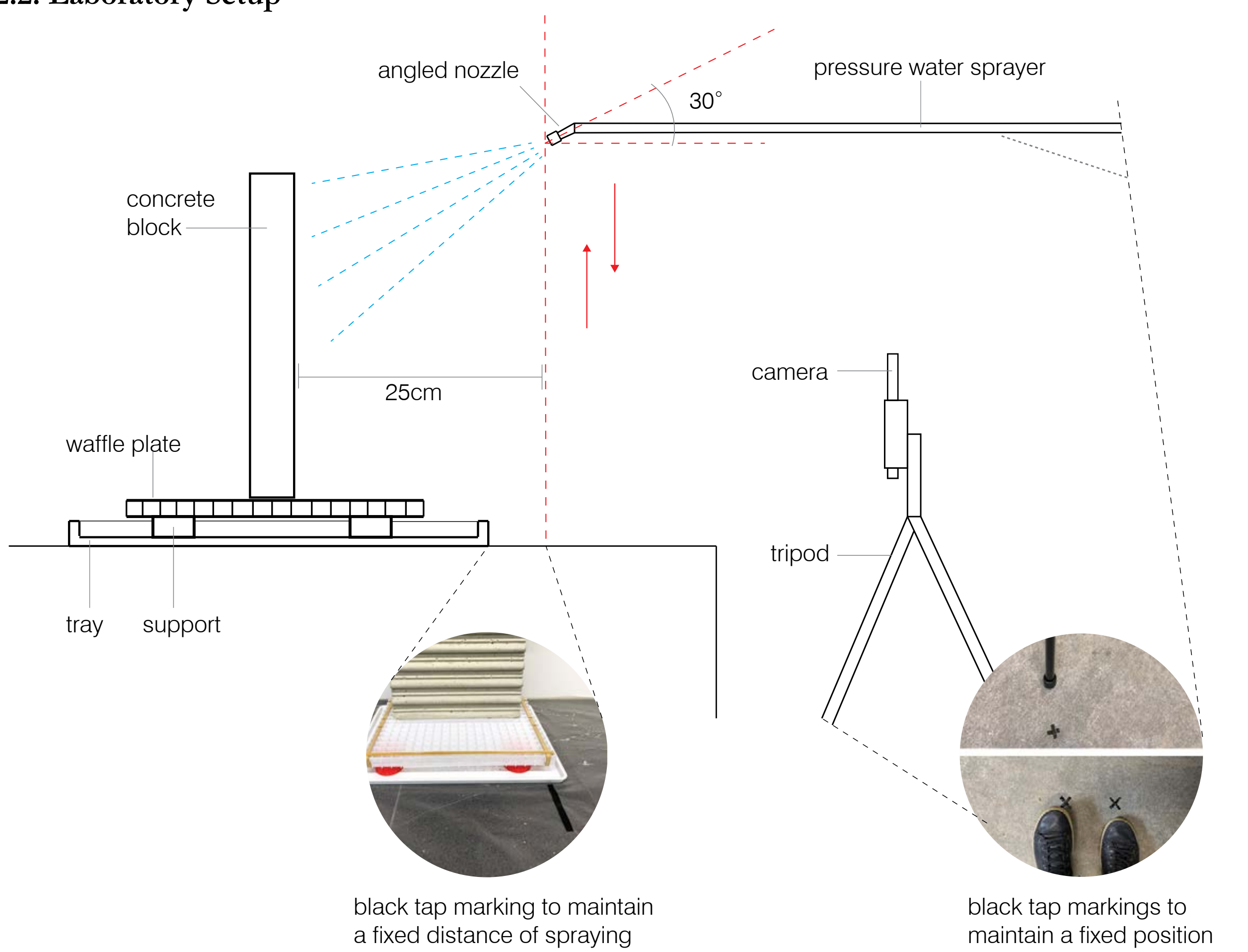


Fig 7.2b: Setup for water relations testing on concrete panels

As shown in Fig 7.2b, the panel is placed over a waffle grill to allow the sprayed water to drain out into the tray below. Next a camera is set from a desired distance to record the water movement on the surface. For better visibility, water soluble beetroot juice is diluted with water for spraying. A pressure water sprayer with a 30° nozzle angle is filled with the red-colour water and positioned at a fixed distance of 25cm from the concrete block. Black tap markings are used to demark the standing position for spraying, the distance of spray nozzle from the block and the position of the tripod for the camera.

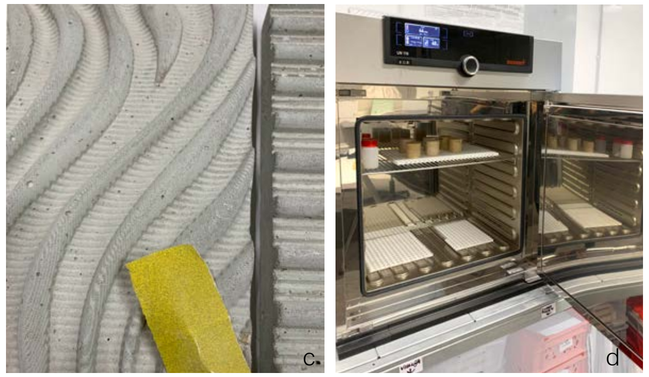


Fig 7.2c, d: c. Polishing, d. Oven drying

The ridge part of the designed panel surfaces are sand polished to smoothen it for efficient redirection of water from ridges towards the alcove. Next the panels are oven dried for a period of 6 hrs at 45°C. Due to the capacity of the oven, only two panels can be oven dried at a time. The oven drying is only done once at the beginning of the experiment (Fig 7.2c, d).

Fig 7.2e, f: e. Water straying, f. Temperature recording

7.2.3. Experiment procedure

Step 1: The weight before spraying is recorded

Step 2: The panels are calibrated vertically according to the setup described in the previous section.

Step 3: The coloured water measuring 150ml is sprayed for a duration of 30sec, in an up and down motion of the sprayer to allow even wetting of the panel (Fig 7.2e).

Fig 7.2g: Relative humidity measurement

Step 4: After a period of 2mins, the amount of water drained out into the tray is measured and the readings for temperature, surface relative humidity and weight of the panels are recorded (Fig 7.2f-h).

Step 5: The temperature, humidity and weight readings are recorded twice more, after 10mins and 20mins from the spraying time.

The procedure is repeated for day 3 and day 7 to test the water relations ability of the panels over a period of 7 days.

Fig 7.2h: Weight recording

7.2.4. Redundancy

The whole laboratory setup and experiment procedure is repeated a 2nd time to check for any discrepancies in the two sets, due to following errors:

- Some water lost due to spilling while spraying.
- Human error on the amount of water sprayed due to change in spraying speed and duration.

7.2.5. Results for change in weight

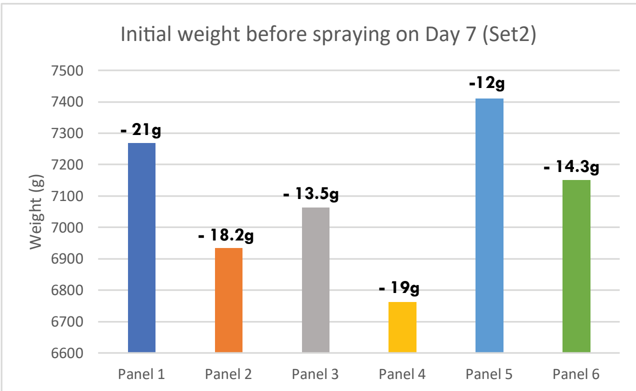
As shown in Fig 7.2i, the initial weight of the panels before spraying are found to decrease slightly through the two sets of experiment. Panel 1, 2 and 4 shows the maximum weight loss and Panel 5 shows the least weight loss as indicated with the negative values.

The reasons for the weight loss may be varied, but mostly the fragility of the patterned parts, breaking of corners while transfer and the internal moisture evaporation from the porous concrete over the period of time may be the predictable reasons.

In Fig 7.2j, the graph shows an average change in weight value at 2mins and 20mins after spraying for the total 6 days of readings. Due to a gradual drop in weight at 2min, 10min and 20min, the bar chart only shows the change in weight values for 2min and 20mins. The average change in weight expressed as a percentage of its initial weight at 2mins is found to be highest for panel 6 and panel 5.

Panel 6 shows highest weight gain owing to its natural surface roughness, while panel 5 contradicting to its plain surface shows the 2nd highest weight gain. Due to the absence of a surface repellent layer, panel 5 exhibits the high porous quality of the concrete itself. Panel 3 also shows moderately high weight gain value owing to the water catchment onto its deeper alcove spaces but it also shows the highest weight lost at 20mins due to loss of its surface water.

Panel 1, 2 and 4 shows the least weight gain at 2mins, mostly owing to its shallow micro-grooves and the presence of the surface repellent layer adhered from the mold surface while casting.



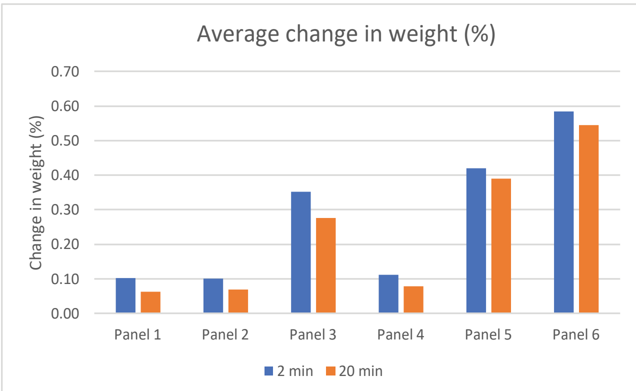
Initial weight loss

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

Fig 7.2i: Initial weight and weight loss before spraying

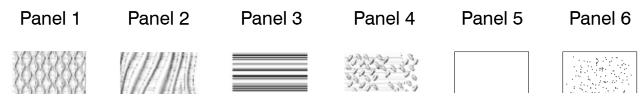


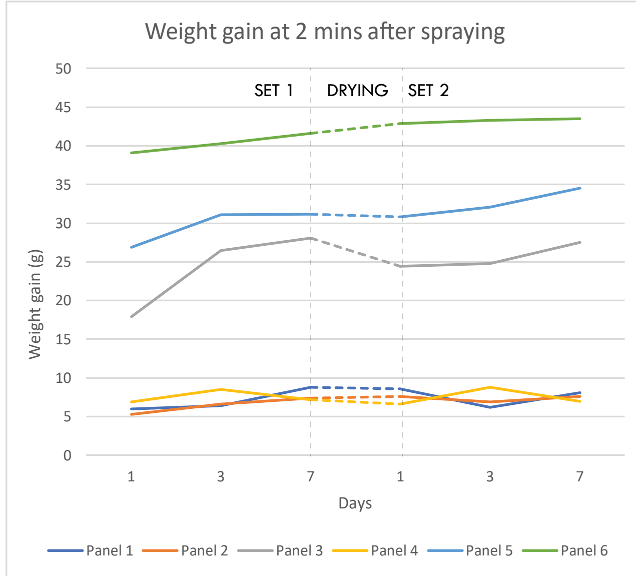
Weight gain in relation to initial weight

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

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

Fig 7.2j: Average change in weight





Weight gain at 2 mins after spraying

Highest Panel 6 **Range** (39-44g) ✓
Panel 5 (27-35g)
Panel 3 (18-28g) ✓

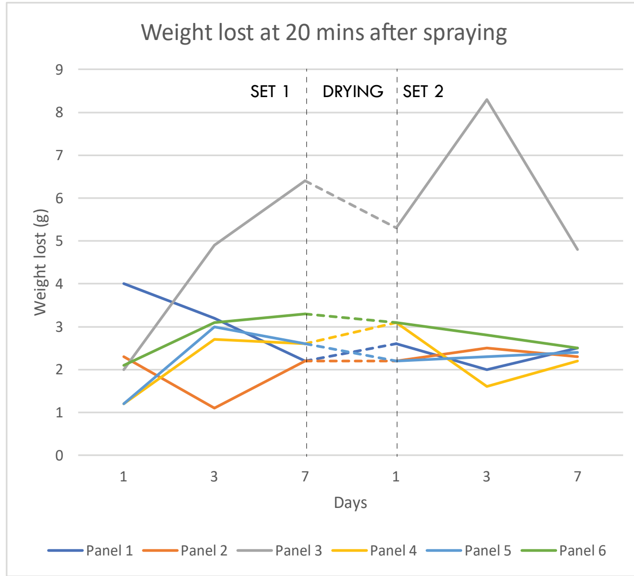
Lowest Panel 2 **Range** (5-7g)

Exception: Panel 5 shows high water absorption due to absence of surface repellent quality and exposed material porosity.

Fig 7.2k: Weight gain at 2min after spraying for all 6 days

The graph above shows a cumulative display of values for weight gain at 2mins for the two sets of experiment. Panel 6 and panel 5 shows the highest and a nearly steady increase in weight gained at 2mins for all six days. Panel 3 shows the highest fluctuation in weight gain due to surface water lost during transport for weight measurement.

An over the time increase in weight gain is seen for Panel 6, 5 and 3, which is presumed to be due to a break in water tension in the capillary pores of the concrete panels. However, Panel 1, 2, 4 shows a mirror result for set 2 owing to its poor water relations quality.



Weight lost at 20 mins after spraying

Highest Panel 3 **Range** (2-8g)

Lowest Panel 2 **Range** (1-2.5g) ✓

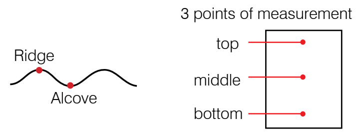
Note: Panel 6 shows 2nd highest weight loss due to its rough surface quality.

Fig 7.2l: Weight lost at 20min after spraying for all 6 days

The above graph shows a cumulative result for weight lost at 20mins for all the six days of experiment. Panel 3 shows the highest weight loss with highest fluctuation among the six days, which is due to different amounts of surface water lost on each day. Panel 6 shows an improvement in absorption capacity with descending weight lost values in set 2, owing to its natural rough surface.

The rest of the panels shows high fluctuation in weight loss in set 1 moving towards lower fluctuations in set 2, with Panel 2 reaching a flattened curve.

7.2.6. Results for alcove and ridge relative humidity



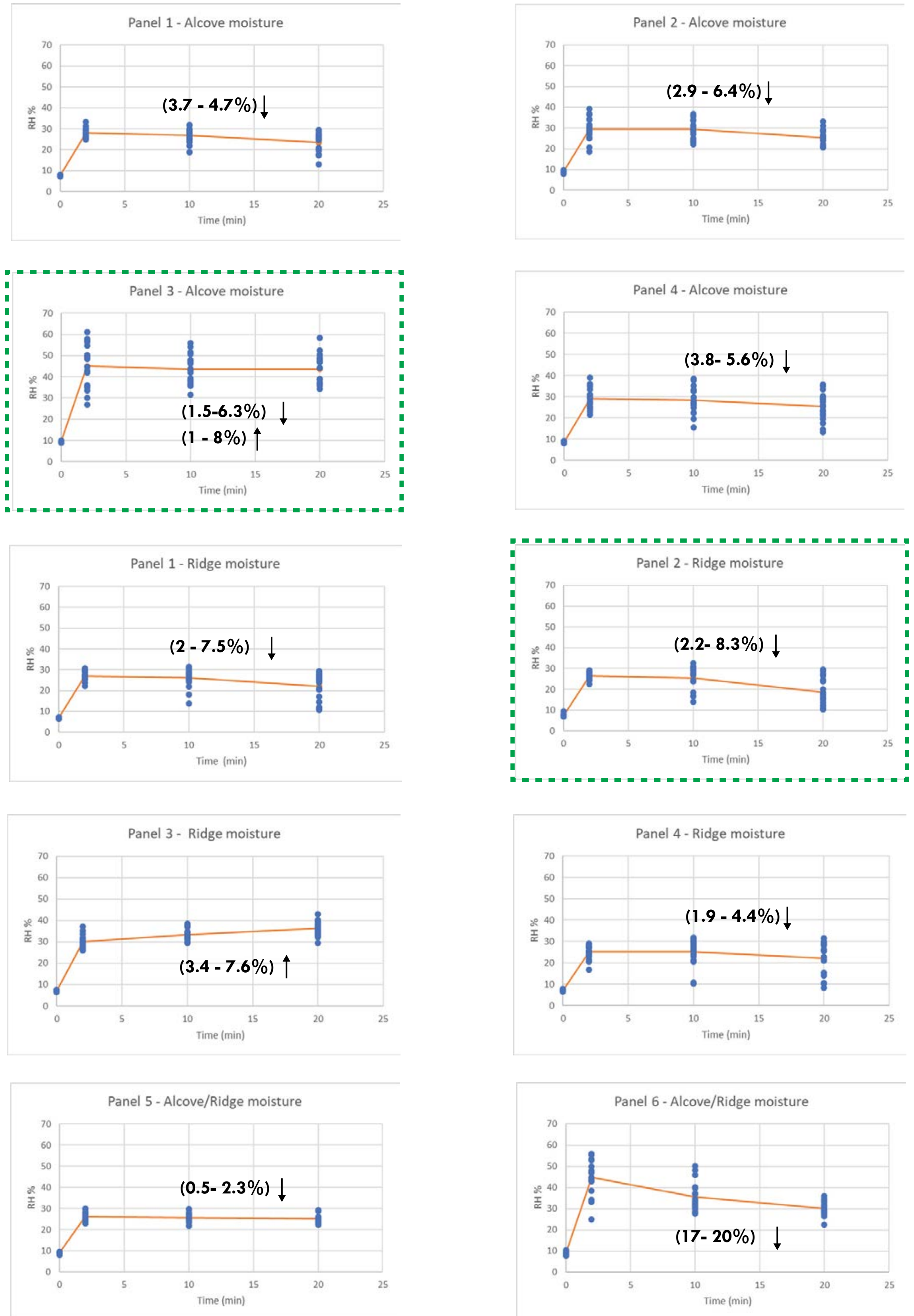
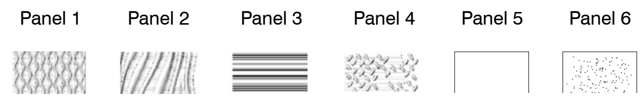
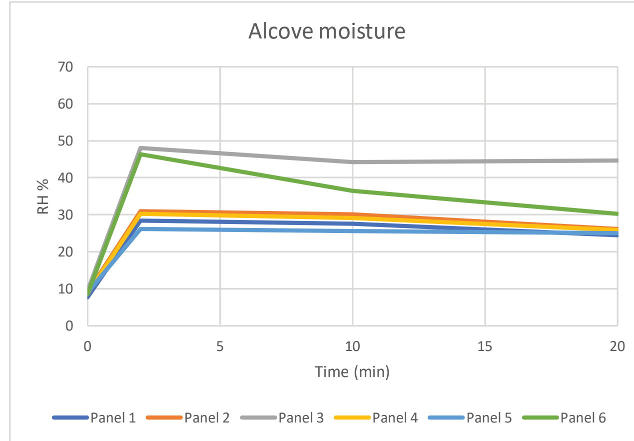


Fig 7.2m: The graphs plot alcove/ridge moisture values measured at 3 points on the surface at 2min, 10mins and 20mins for the six days of experiment.





Alcove moisture after 2 min

Highest Panel 3 **Range** (RH 26.8 - 61.2%)

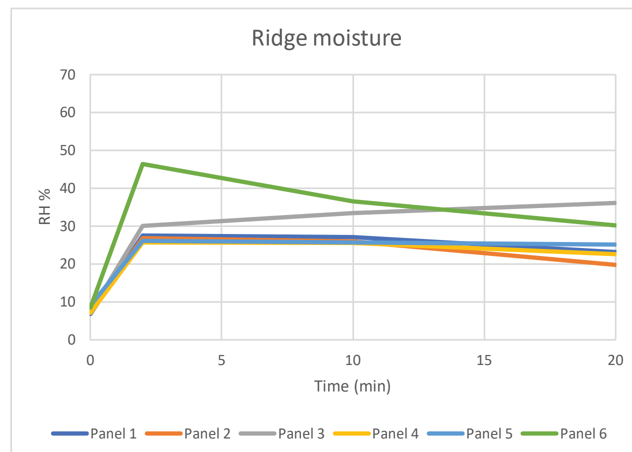
Lowest Panel 5 (RH 23 - 30%)

Alcove moisture after 20 min

Highest Panel 3 **Range** (RH 34.3 - 58.4%) ✓ Deep micro-grooves

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

Fig 7.2n: Average alcove relative humidity



Ridge moisture after 2 min

Highest Panel 6 **Range** (RH 33.5 - 55.6%)

Lowest Panel 4 (RH 20.7 - 29%)

Ridge moisture after 20 min

Highest Panel 3 **Range** (RH 29 - 43.5%) Against the flow micro-grooves

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

Fig 7.2o: Average ridge relative humidity

Due to the 3d patterns on the surface, largely two horizontal surface planes are present, alcove, the recessed part and ridge, the raised part, giving two types of Relative humidity (RH) values. The alcove/ridge readings for the RH are taken at 3 different points, top, middle and bottom along the middle of the panels. This is done to get a more distinct range of moisture value through the concrete surface. The alcove/ridge readings are taken at 2mins, 10mins and 20mins after spraying and repeated for 2 sets of experiment giving a total of 18 RH values for each time frame, as plotted in Fig 7.2m. The numbers in bold with the direction of arrow gives the change in RH values indicating an increase or decrease in surface moisture from 2min to 20mins for each panel (Fig 7.2m). The RH values at a point in time shows a large range, mostly due to varied amount of surface water lost, by dripping off while weight measurement, change in spraying time/amount sprayed, instrument error etc. (Fig 7.2m).

For alcove moisture panel 3 shows the highest RH values at both 2min and 20mins, with a slight dip in alcove moisture at 10mins (Fig 7.2n). The high value is due to the presence of deeper alcove spaces with 4mm deep micro-grooves and against the flow obstacles which creates more hindrance to the linear flow path compared to other panels. Panel 6 shows a significant drop in alcove moisture from 2min to 20mins due to its better absorption capacity with absence of surface repellent layer. All other panels show low and nearly constant RH values, due to its shallow groove depths (Fig 7.2n).

For ridge moisture, Panel 6 shows the highest RH value at 2mins, significantly dropping until 20mins due to high absorption captivity. Panel 3 on the other hand, shows an increase in ridge moisture over time, owing to its against the flow macro geometry, which gradually gets more wet as the water drips down from the alcove to the ridges. All the other panels show low and nearly constant values through time, with panel 2 showing the lowest ridge moisture due to its wider and higher macro-geometries (Fig 7.2o).

7.2.7. Visual representation of surface water movement

Panel 1

Due to the shallow micro-grooves, there is no water retention possible, water is dripping out in straight lines. The thin and low depth macro-geometries make it difficult to create a distinction between growth and no growth areas.

Panel 2

The wider macro-geometries with greater height helps to redirect water towards the micro-grooves, showing higher concentration of water in the growth areas. Due to the shallow micro-grooves, water catchment is not possible.

Panel 3

The against the flow macro-geometries create an obstacle to water flow, allowing more water retention into the deep alcove spaces. These obstacles also keep the ridges constantly wet, making it difficult to direct growth route.

Panel 4

The shallow micro-grooves help to retain more surface water compared to smooth surface, showing a clear distinction on surface performance. The size and the discontinuous nature of the macro-geometries make it difficult to direct growth.

Panel 5

The plain surface shows no obstruction on water movement causing quick drying of the surface. The porous quality of the concrete material increases the absorption capacity due to absence of surface contaminants (release agents).

Panel 6

The natural rough surface texture allows water retention into it depth, showing more red patches. The absorption quality of the panel is also high due to porous material quality and absence of surface contaminants.

Fig 7.2p: Visual representation of water movement on the surface of the panels at the end of 30sec of spraying.

7.2.8. Results for change in temperature

All the panels showed an initial temperature of 20-21ºC. After spraying at 2mins the panels showed a sharp decrease in temperature by 2-3ºC and in the 10min and 20mins the temperature gradually increased by 0.5ºC. The results are found similar for all the panels and does not hold significance for the purpose of research (see appendix 2).

7.2.9. Discussion of results

Panel 2, 3 and 6 gives significant results in terms of change in weight, surface moisture and water movement pattern, which can be used to create the guidelines for Bio-receptivity concrete facade panels.

Panel 2:

- Greater macro-geometry height provided lower ridge moisture.
- Along the flow obstacles direct water to growth areas
- Lack of water catchment areas caused low surface moisture.

Panel 3:

- Deeper alcove spaces created greater water catchment areas allowing higher surface moisture.
- Against the flow macro-geometry, increased the ridge moisture, hampered the directed growth route.

Panel 6:

- Natural rough texture, created water catchment within its depth, increasing surface moisture.
- Absence of surface contaminants caused high water absorption, exhibiting the porous material property.
- Absence of change in surface depth, hampered the directed growth route.

7.2.10. Conclusion

According to the results of this laboratory experiment, geometries play a profound role on the movement of water on a concrete surface. Deep micro-grooves of around 4-5mm with wider macro depth/alcove spaces is crucial to create areas of water catchment and subsequently increased surface moisture. Wider and pronounced 'along the flow' macro-geometries are preferred due to its ability to create clear distinction between growth and no growth areas, complimenting the research objective. The panel with the natural rough surface shows high water absorption into the concrete, this is found mostly due to the absence of a surface contaminant layer, exposing the porous material property. Thus, use of simpler geometry for easy demolding process and better ways to remove surface contaminants of freshly cast concrete can greatly faciliate the water retention and absorption quality of the designed concrete panels.

Please refer to appendix 14.2 for all the detailed graphs for the two sets of experiment.

7.3. CFD Simulation for micro-grooves

The following exercise is carried out to identify the type of micro-groove most suitable for the retention of water onto the surface. The CFD software Ansys Fluent is chosen to simulate the rate of flow of water over the different groove types and compare how the change in shape and size of the grooves affect the flow rate.

7.3.1. Setup

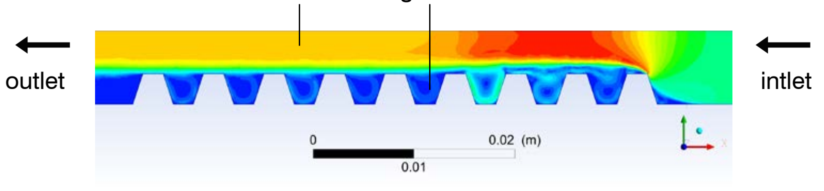
For the simplicity of meshing, a 2D flow model is created using rhinoceros. The model is imported to Ansys Fluent and a mesh model is generated with triangular meshing of size 0.0005m. The meshing near the groove area is made smaller (0.0001m) to obtain better results. The aim of the CFD simulation is to replicate the behaviour of rainfall moving over the micro-grooves. Due to the limitation on software knowledge and time constraint it has not been possible to model rain. However, the setup of the simulation is done to create a condition similar to rainfall.

The model is aligned to the horizontal plane and a flow path is created with inlet on the right and outlet on the left (Fig 7.3a). The simulation is carried out under transient state, where the rate of flow of the fluid particles can change with time and position along the groove depth. A gravity of 9.8m/s is set to act along the direction of flow. The model type chosen is laminar instead of turbulent as the groove scale is too small to create a turbulent effect.

For the motion at the edge of flow domain specified shear condition is chosen, indicating a presence of air layer above the flow domain while the grooves are set to no slip condition. The calculation is run for a time step of 30sec with total number of 300 iterations *(See appendix 14.3 for setup details).*

7.3.2. Stages of testing

Fig 7.3b shows the summary of all the stages of testing carried out to reach the suitable groove type. The inlet velocity is set to 5m/s, an average value for rainfall. In stage 1, three groove types of different shape is chosen. In stage 2, the grooves types that showed better results are further simulated by changing the width while keeping the height to 1.5mm. In stage 3, the grooves from stage 2 are doubled in height to 3mm and simulated. In stage 4, the best groove type is chosen and increased to a height of 5mm. The particular type is also altered in width, creating two new types and the 3 types are simulated. Finally, in the stage 5, the 3 grooves are tested with two new inlet velocities 2m/s for light rainfall and 9m/s for heavy rainfall, to verify the suitability of the chosen type.



Triangular Meshing
Mesh size: 0.0005m
Edge mesh size: 0.0001m

Transient state
Gravity 9.8 m/s
Atmospheric pressure 1atm

Laminar model
No slip condition for grooves

Solution
Method: Coupled
Initialization: Hybrid

No. of iterations: 300
Results at 30sec

Fig 7.3a: CFD model and setup parameters

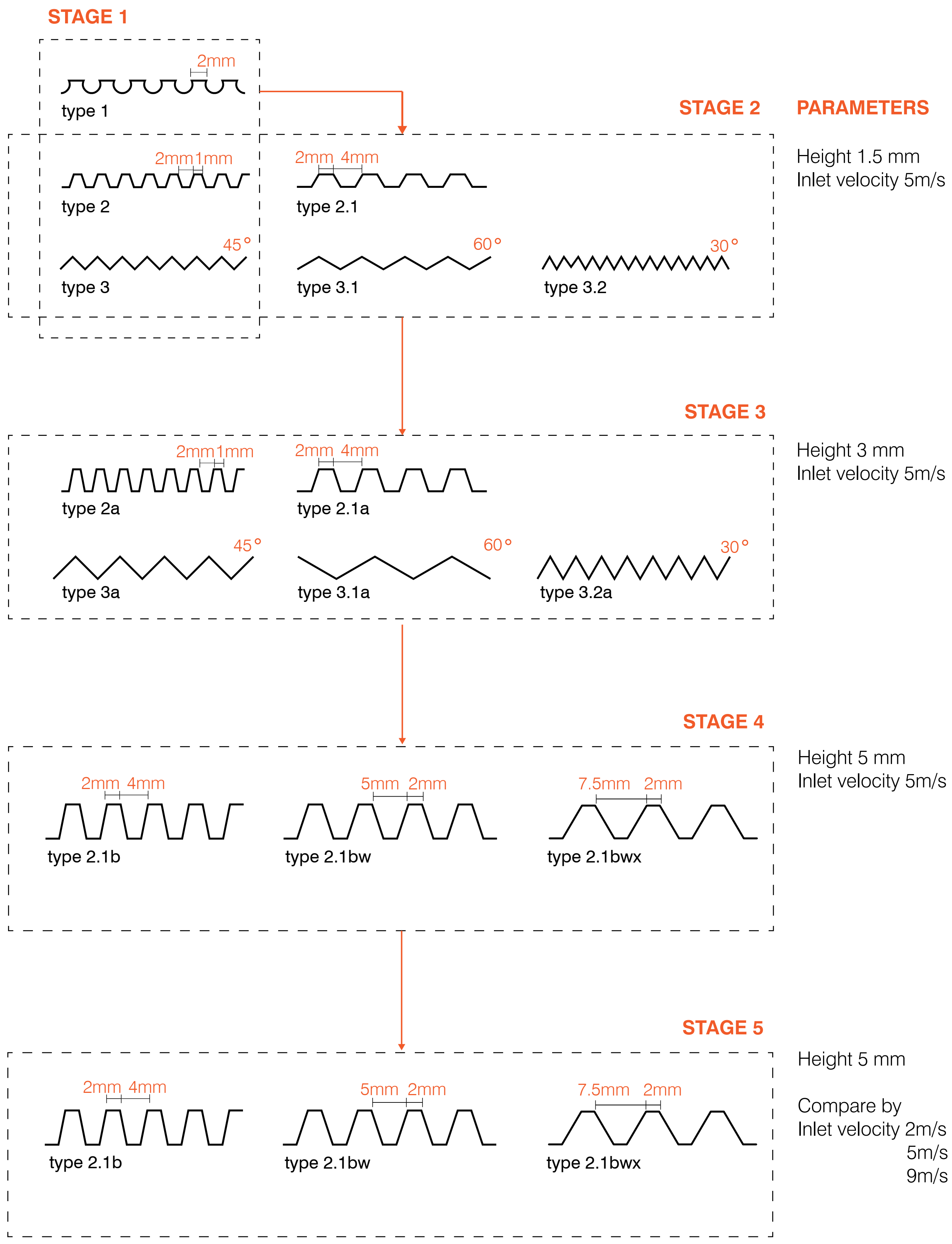


Fig7.3b:: Summary of stages for the CFD simulation of micro-grooves

7.3.3. Results of CFD simulation

STAGE 1 & STAGE 2

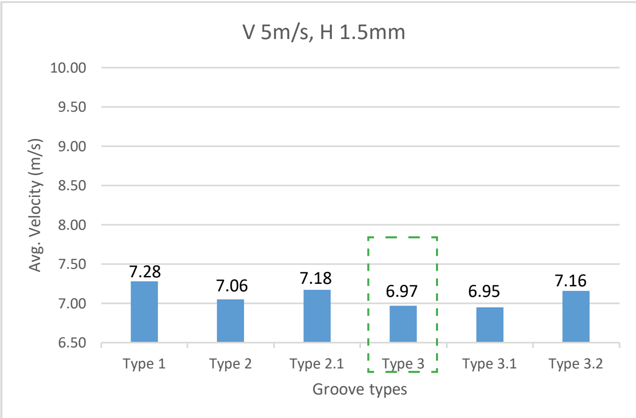


Fig 7.3c: Highest velocity in flow domain

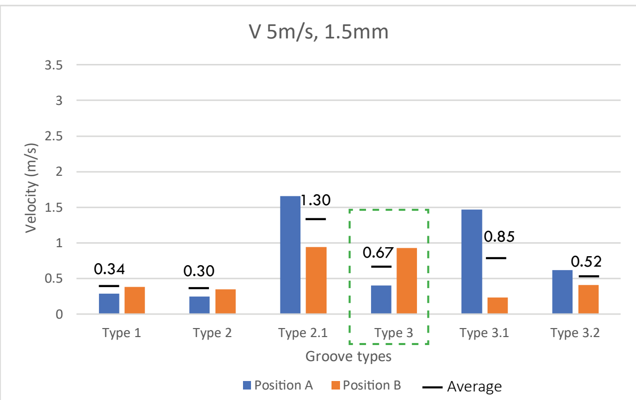


Fig 7.3d: Highest velocity in grooves

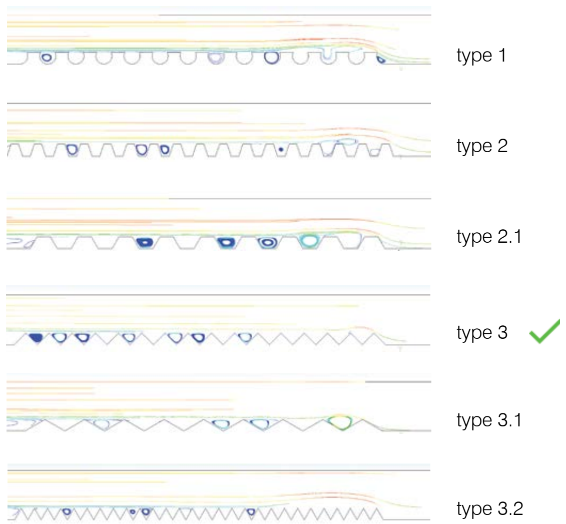
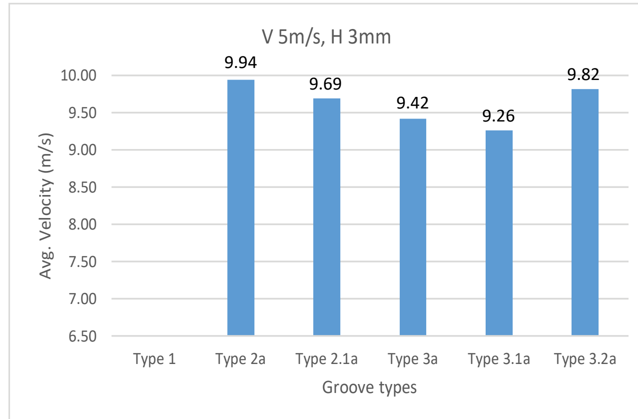


Fig 7.3e: Streamline vertex diagram

In stage 1 and stage 2, the inlet velocity of 5m/s and the groove depth of 1.5mm is kept constant. Fig 7.3c shows a comparative bar chart for the highest average velocity in the flow domain. Fig 7.3d plots a comparative bar chart showing the highest groove velocity at two distinct position along the model, this is done to verify the effect of distance from inlet point on groove velocity. Fig 7.3e is a visual representation of vertex created inside the grooves, with colour coding ranging from red indicating highest velocity to blue indicating lowest velocity.

The flow domain velocity is found to be highest for Type 1(Fig 7.3c). This high velocity causes the water to pass over the grooves without reaching its depth, as can be seen in Fig 7.3e, thus Type 1 is discarded from further investigation. Among the remaining groove types, Type 3, shows the best results, with lowest flow domain velocity, where the 45° V grooves succeeds to create resistance to the incoming water flow. Type 3 also has a moderate vertex velocity, which helps to create a water circulation within the groove depth (Fig 7.3d, e). If the groove velocity is too high, as can be seen for Type 2.1 and Type 3.1, it will create a wash away affect, damaging the early stages of moss growth.

STAGE 3



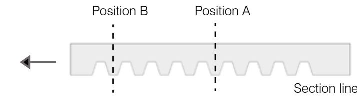


Fig 7.3f: Highest velocity in flow domain

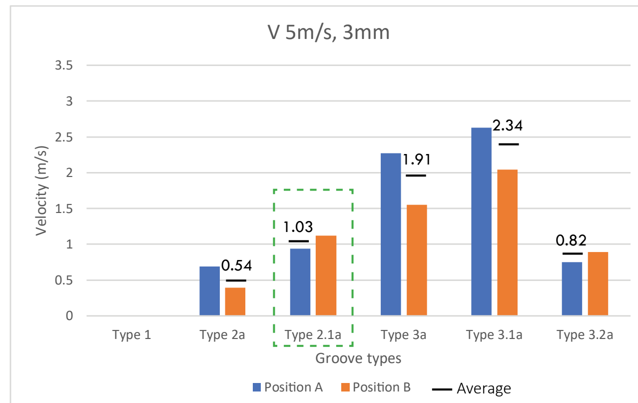


Fig 7.3g: Highest velocity in grooves

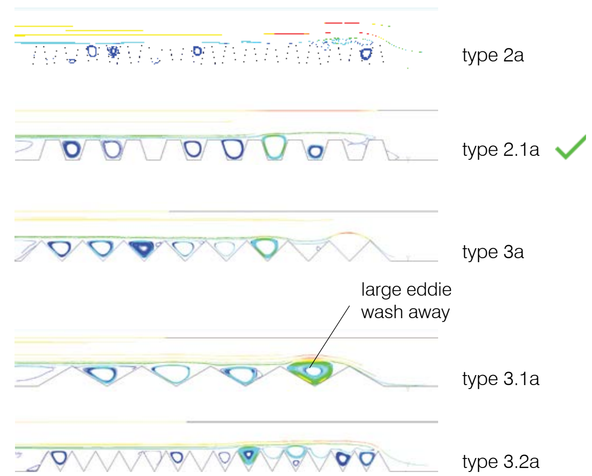


Fig 7.3h: Streamline vertex diagram

In stage 3, the inlet velocity of 5m/s is kept constant and the groove depth for all the types is doubled to 3mm. With the increase in groove depth the overall velocity in the flow domain is increased, this is mostly due to the tunnel effect created by narrowing of the flow domain with increased groove depth. As this flow velocity values are due to the specific modeling case, the velocity values are only used as a comparison between the different groove types and are not comparable to actual rainfall velocity.

In Fig 7.3f, the highest flow domain velocity is found in Type 2a, this is due to the deep narrow grooves, which creates a smooth flow over the surface, making it difficult to reach into the depth of the grooves (Fig 7.3g, h). The lowest flow domain velocity is found in Type 3.1a, a 60° V groove type, where a large amount of water flows into the wide grooves, increasing the flow domain area and decreasing the velocity. However, the groove velocity for Type 3.1a, is the highest, which can create a wash away affect, due to the large eddies formation (Fig 7.3h). Type 2.1a is found to have a moderate flow domain velocity and groove velocity, which creates vertex within the grooves allowing water circulation (Fig 7.3g, h). Thus Type 2.1a is chosen for further investigation.

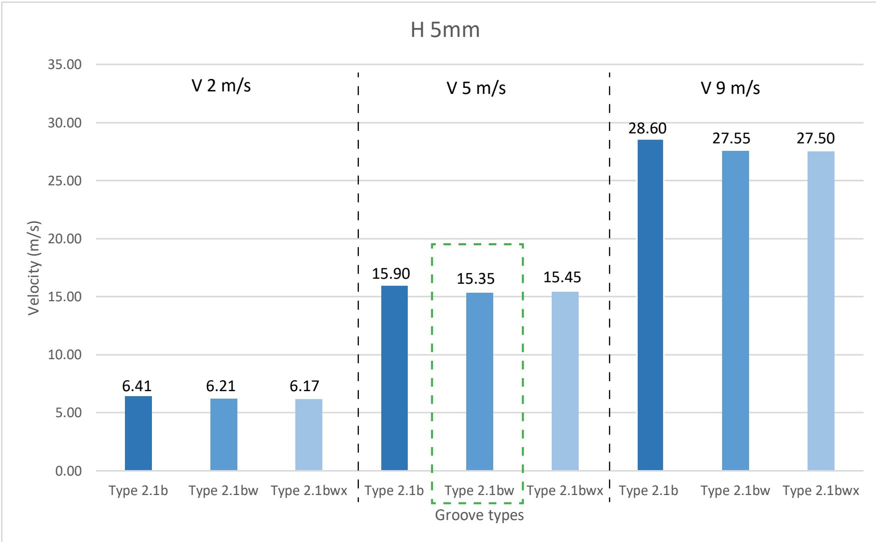


Fig 7.3i: Highest velocity in flow domain

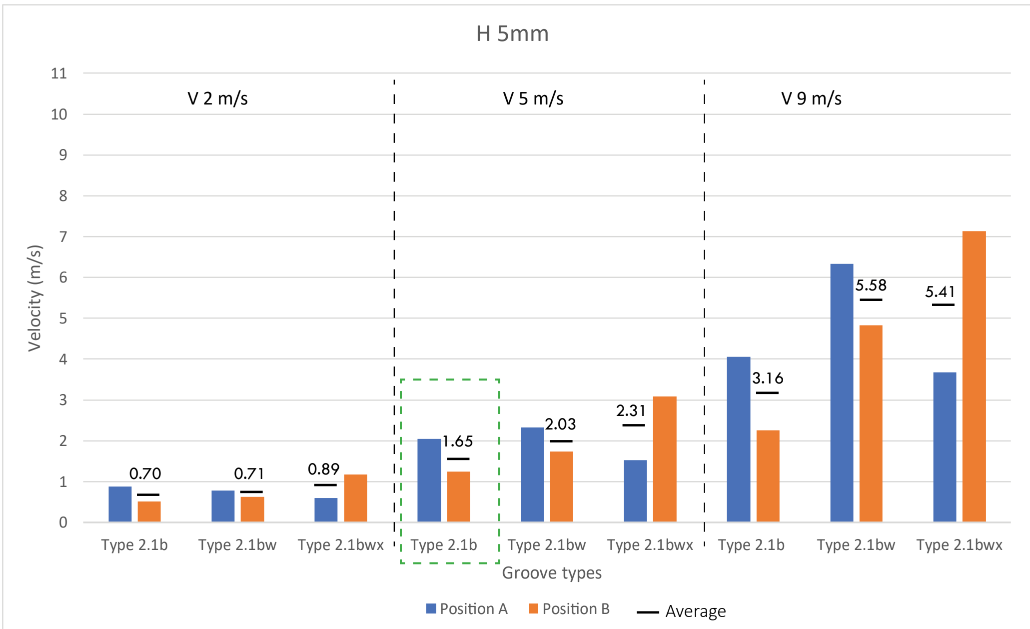
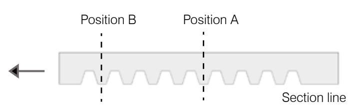


Fig 7.3j: Highest velocity in grooves



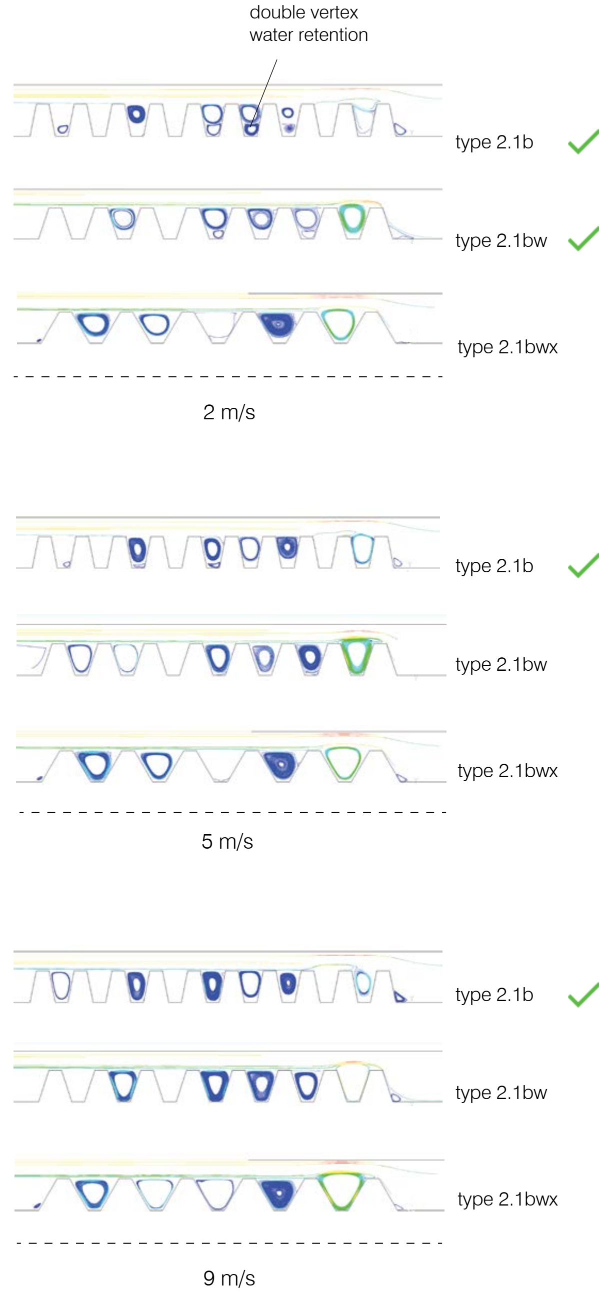


Fig 7.3k: Streamline vertex diagram

In stage 4, Type 2.1a is further investigated by increasing its depth to 5mm and also two new types are introduced with opening widths of 5mm and 7.5mm, resulting in Type 2.1b, Type 2.1bw and Type 2.1bwx respectively. These types are simulated with an inlet flow velocity of 5m/s, where Type 2.1b shows the highest flow domain velocity, owing to its lowest w/h ratio (Fig 7.3i). However due to the increased depth, the amount of water that reached into the grooves creates double vertex, allowing greater water retention (Fig 7.3k). This stored water provides more time for the water to sip into the concrete. Type 2.1bw shows a slightly higher groove velocity with moderate vertex formation within the depths, while Type 2.1bwx has the highest groove velocity, increasing chances of wash away effect (Fig 7.3j).

In stage 5, the three groove types are simulated by changing the inlet velocity to 2m/s, the speed of light rainfall and 9m/s, the speed of heavy rain. With an inlet velocity of 2m/s, the overall flow domain velocity is low, with the highest for Type 2.1b, due to its low w/h ratio (Fig 7.3i). The low inlet velocity also results in high amount of water retention within its narrow depths, creating double vertex (Fig 7.3k). Similar double vertex are also seen in Type 2.1bw but is absent in Type 2.1bwx. Therefore, it can be said that for lower inlet velocity, the narrow grooves work better to create water retention.

For the inlet velocity of 9m/s, the overall flow domain velocity is very high, with highest again for Type 2.1b (Fig 7.3i). The highest groove velocity is seen in Type 2.1bwx, creating large eddies, which can cause wash away effect. Its groove velocity is also found to increase with increase in distance (at position B) from inlet point, a trend opposite to what noticed in most other groove types (Fig 7.3j). Thus for higher inlet velocity, Type 2.1b shows better results with moderate vertex formation for water circulation and retention (Fig 7.3k).

Please refer to appendix 14.4 for all the detailed graphs for the CFD simulations

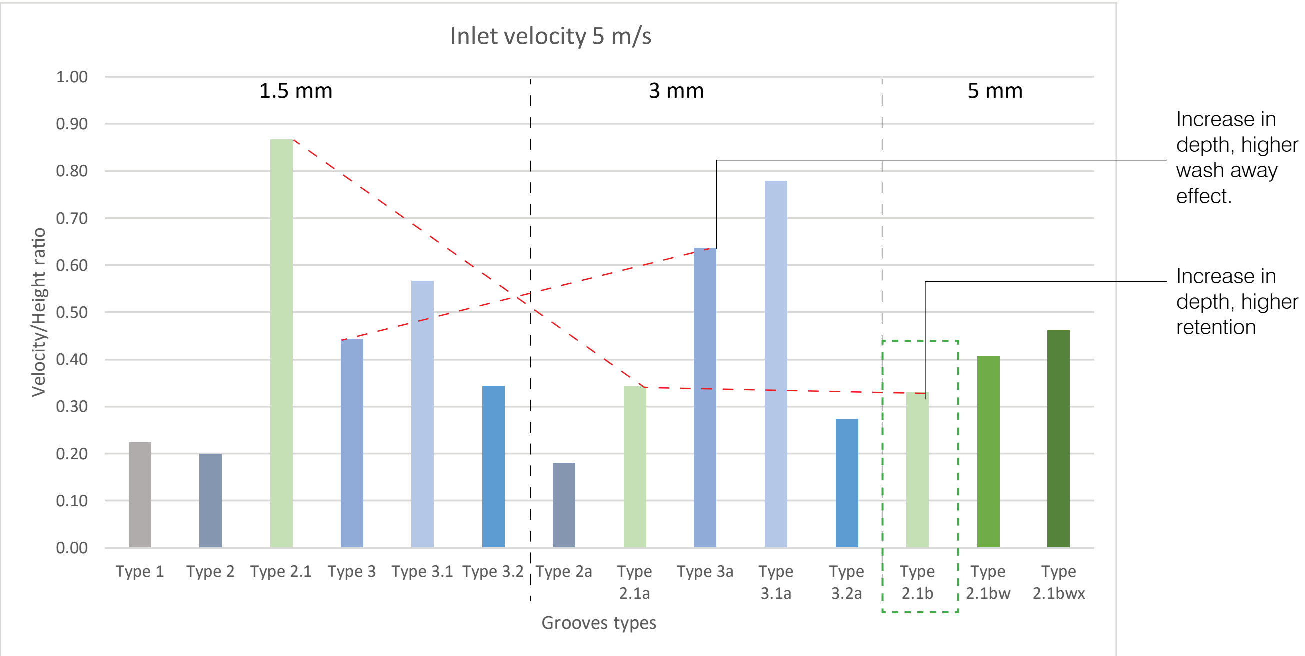


Fig 7.3l: A comparative groove velocity/height bar chart for an inlet velocity of 5m/s

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					

Table 4: A summary table for the vertex formation in different groove types

7.3.4. Discussion of results

Fig 7.3l shows a comparative bar chart of velocity in relation to groove depth. For groove depth of 1.5mm, Type 2.1, a flat wedge shape, with a high width(w)/height(h) ratio, shows very high velocity compared to other types of the same depth. The wide opening creates a smooth flow path for the water to pass through without hindrance, washing away nutrient on its way. The same groove type, when doubled in height Type 2.1a, shows a drastic fall in groove velocity, with good vertex formation. As the height is increased to 5mm, the velocity decrease more with visible water retention. For a depth(h) of 5mm as the opening groove width (wx) is increased from 4mm to 5mm, the groove velocity increases, again, as seen with Type 2.1bw. On the other hand, Type 3, a 45° V groove, shows a moderate groove velocity for a depth of 1.5mm. As the depth is double, there is a proportionate increase in velocity, resulting to wash away effect. Thus, it can be said, that with adjusted wx/h proportion Wedge shaped grooves works better with increased depth than V shaped grooves.

Table 4 shows at an inlet velocity of 5m/s, for a lower groove depth of 1.5mm, a w/h ratio of 2, gives the best results. A ratio lower than 2, creates no vertex, subsequently no water circulation into the grooves, while a w/h ratio higher than 2, increase the velocity to a great extent, causing wash away effect due to its shallow depth. As the groove depth is increased to 3mm, a w/h ratio of around 1.33~1, gives adequate results. Higher values than 1.33 creates wash away effect and values lower than 1 forms no vertex. With deeper groove depth of 5mm, the w/h ratio around 1, gives the desired results. Thus, it can be said with increased groove depth, a lower w/h ratio (less than or equal to 1) is found to work best, having low velocity and high water retention ability.

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

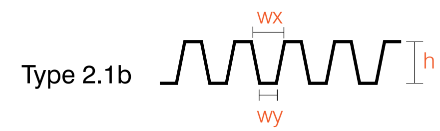
For 5mm groove height
Shallow w/h > 1

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

For ideal vertex formation

7.3.5. Conclusion

The results of the practical experiment has shown a groove depth of 5mm is most suitable, thus the CFD simulations are performed to the maximum depth of 5mm and the suitable groove type for the corresponding depth is chosen. Type 2.1b and in some cases Type 2.1bw are found to give the best results for efficient water retention ability for moss growth. A wedge shaped groove, with opening width/height ratio of 0.8 and a change in width ratio of 0.4 is suggested based on the results of these two groove types(Fig 7.3m).



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

Moderate to low vertex velocity
Water retention

Fig 7.3m: Chosen groove type

8. Guidelines for design

8.1. Re-evaluation of ordered system in moss growth

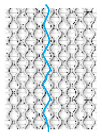
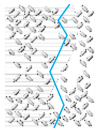
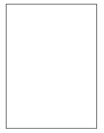
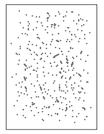
OBSTACLE DIRECTION	GROOVE DEPTH	AVG.WEIGHT GAIN (%) (at 20 min)	WEIGHT LOSS (%) (from 2 - 20 min)	ALCOVE MOISTURE (RH %) (at 20 min)	ALCOVE MOISTURE LOSS (%) (from 2 - 20 min)	RIDGE MOISTURE (RH %) (at 20 min)	RIDGE MOISTURE LOSS (%) (from 2 - 20 min)	MOSS GROWTH (week 12)	REMARKS + -
PANEL 1 	along 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

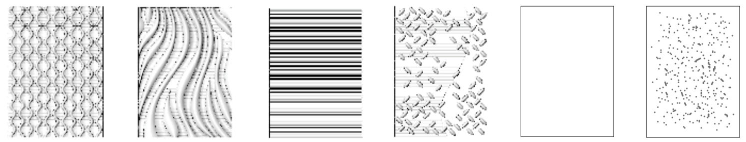
Table 5: Comparative analysis between water relations at 20mins after spraying and max.moss growth results

Based on the results of the design validation section, the moss growing experiment, the water relations testing and the micro-grooves simulations, this chapter aims to provide a comprehensive guideline for the design of Bio-receptive concrete panels.

Table 5 is a comparative chart between the water retention/absorption capacity of the panels and the practical moss growth progress in the greenhouse. In terms of the water relations, Panel 3, 5 and 6 shows the best results. While Panel 3 has higher surface water due to deeper alcove spaces and against the flow obstacles, Panel 5 and 6 shows high absorption due to the absence of surface contaminants like silicone/oil remains from the molds. However, Panel 5 and 6 is not suitable for the ordered growth desired in this research. Panel 3 though shows a high surface water, the against the flow macro-geometries also tends to hinder the ordered growth requirement.

The results from the greenhouse is obtained from week 12. The panels are placed on a horizontal position till week 6 and again from week 10 onwards to proliferate the moss growth. Panel 2 shows the highest algae coverage on the surface followed by Panel 1 due to the along the flow obstacles. The design features of Panel 2 provide a clear distinction between growth and no growth areas, with its deeper and wider macro-geometry creating moist conditions on the surface in the horizontal position. However, a drastic drop in growth occurs when the panels are placed in vertical position. This is due to the quick drying of the surfaces from absence of enough water catchment areas. Panel 3 though showed good surface water failed to show adequate moss growth due to limited growth areas and insufficient micro-groove presences.

According to the analysis of the results, the presence of water is found essential for growth, which can be greatly influenced through geometry. A geometrical combination of macro depth with deep micro-grooves along a larger surface area can allow better water catchment, while well-defined 'along the flow' macro-geometry can redirect water to growth areas; which can subsequently enhance the Bio-receptive quality of the concrete panels.



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	✓	✓	✓	✓		

Table 6: The feedback loop for the geometry features of the designed panels

CHOOSEN PANELS	MACRO GEOMETRY/ OBSTACLE DIRECTION	MACRO DEPTH	MICRO DEPTH
PANEL 2 — macro, micro	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
PANEL 3 — macro + micro	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
PANEL 1 — macro, micro	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 + -

Table 7: The pros and cons of the geometry features of the chosen panels

GENERAL GUIDELINES	MACRO GEOMETRY/ OBSTACLE DIRECTION	MACRO DEPTH	MICRO DEPTH
	Along the flow Continuous obstacles (flowing/alternating rhythm)	H<= 20mm W 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

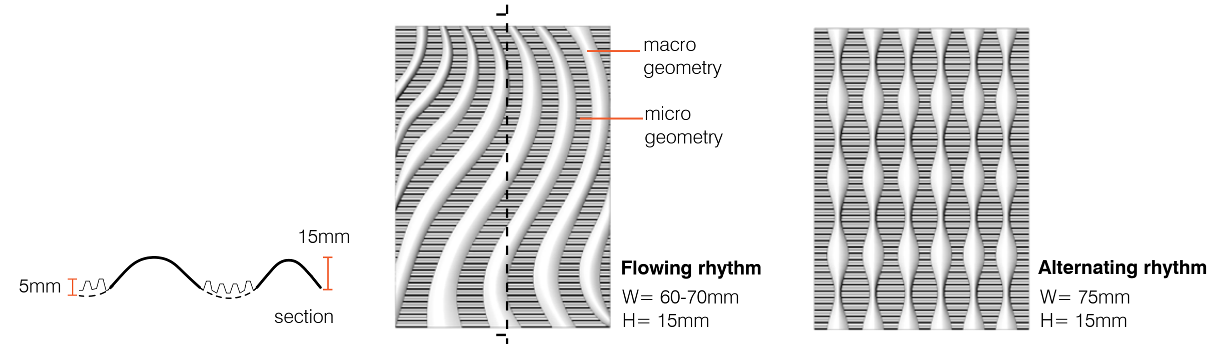


Fig 8: Design options based on general guidelines

Table 6. provides a feedback loop by highlighting the geometrical features of the panels which created the maximum positive impact in water absorption/ retention onto the surface. Features like continuous along the flow obstacles in flowing/alternating rhythm helped to direct water to growth areas by prolonging the flow path. Greater macro depth provided the moist condition to promote cushion growth and deeper micro-grooves helped to increase surface water catchment and gather nutrients. A combination of rough and smooth surfaces with the micro and macro geometries arranged in the desired rhythm can create an ordered growth system.

The selected panels are further analysed in detail as shown in table 7. For Panel 2, along the flow macro geometry with a depth of 10-15mm is positive features while its shallow micro-grooves has poor water holding capacity, deemed as a negative feature. The 4mm deep micro-grooves of Panel 3 is a positive feature, while its limited space for growth and the 'against the flow' macro-geometry which hinders the directed growth objective are negative features. For Panel 1 along the flow obstacles prolonging the flow path is a positive feature, however its shallow and thin macro-geometries limiting the directed growth is a negative feature.

8.2. The guidelines for ordered growth

Based on the geometrical analysis so far, a general guideline is provided to create surface geometries which can enhance the Bio-receptive character. The type of macro geometry which is the most suitable are continuous 'along the flow' obstacles. These obstacles can be arranged in a flowing/alternating rhythm prolonging the flow path to varied lengths and promote a continuous trail of growth. A maximum macro depth of 20mm with a H/W ratio of 0.2-0.3 can provide larger defined space for growth and mirror the cushion growth form of mosses in nature. Finally, according to the results of the CFD simulation, 5mm deep micro-grooves with adjusted w/h ratios can create greater water catchment through increased surface area. In addition to these geometrical features, the absorption quality of the surface is also equally important. Therefore, these geometric guidelines can be utilized to create a Bio-receptive facade, addressing its overall order and balance aesthetic character.

As in Fig 8, two design options are created with these suggested ingredients, expanding the possibility for infinite more designs.

9. Production to assembly

9.1. Production technique

For the manufacture of the designed concrete panels, the use of molds is an essential part to create the desired patterns on the surface. First a sample design is created and then the negative of the design is cast in an elastic material to create the mold for the actual casting. Though the process is elaborate, the reusability of the elastic molds makes it an economically feasible technique.

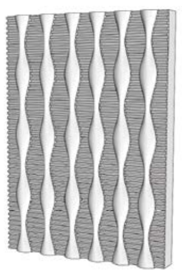
9.1.1. Creating the sample design

Most commonly this can be done in two ways CNC milling and 3D printing. CNC milling is used more often due to its dimensional accuracy and material variety; however 3D printing can also be an alternative option contributing to its low material wastage and lower cost. Based on the comparative analysis shown in Table 8, CNC milling is a found to be a better option for the sample creation, due to its precise and smooth finish whereas the 3D printing process tends to leave layer imprints on the surface.

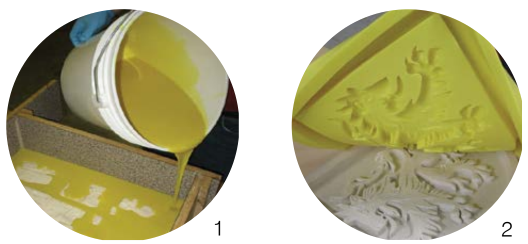
9.1.2. Creating the elastic mold

The most common reusable material for concrete casting available in market is Polyurethane rubber. Polyurethane rubbers are two-component mixture (base plus curative), mixed together forming a thick liquid. It can be sprayed, brushed or poured over models to harden into a sturdy rubber mold ("Using urethane rubber to make molds for casting concrete has many advantages," n.d.).

The material is reusable to over 100 times, does not undergo shrinkage, has good abrasion resistance, high strength and is economical. However, these elastic molds have a high adhering tendency requiring a coating of release agent. Also, CNC milling on these rubber material is not advisable due to heat generation and subsequent expansion and contraction ("Machining of Polyurethanes," n.d.).

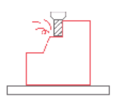
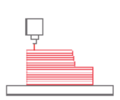


design model
CNC milled in wood



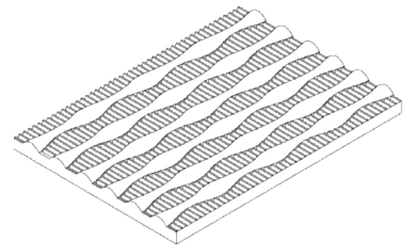
1. Pouring 2. End product
Polyurethane rubber mold *(Images from internet)*

Table 8: CNC milling vs 3D printing [1, 2]

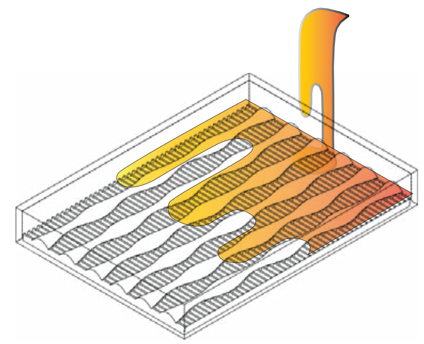
Type	Method	Features	Material	Surface finish	Others	Remarks + -
CNC milling	Substractive manufacturing 	Tolerance ± 0.025–0.125mm Min. thickness 0.75mm Volume 2000x800x1000mm	Metals Plastics Hardwood Softwood Modeling foam	Smooth	$$ Workflow - Labour intensive Low post processing	- high precision - variety material - smooth finish
3D printing Fused diffusion modeling(FDM) - Industrial	Additive manufacturing 	Tolerance ± 0.2 mm Min. thickness 0.8 - 1.0mm Volume 900x600x900 mm	Plastics Ceramic Wax Metals Sand	Textured	$ Workflow -less labour intensive High post-processing -sanding -polishing -blasting	- less precise - limited work volume - layer imprints - high post processing

[1] 3D printing vs. CNC machining. (n.d.).
[2] CNC vs. 3D printing: What's the best way to make your part? (2019)

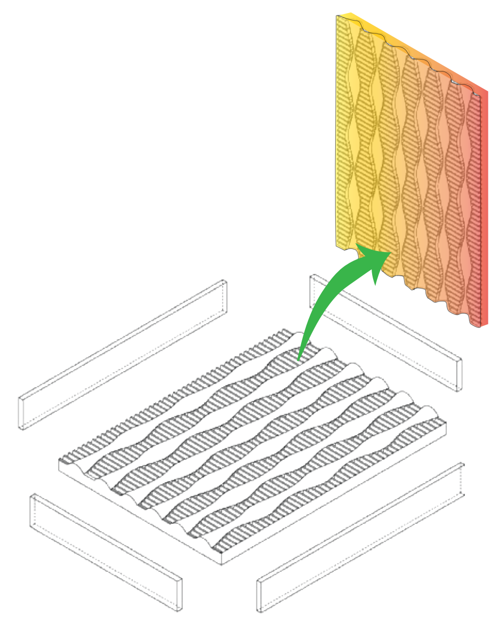
9.1.3. The Manufacturing process
(Reckli, n.d.)



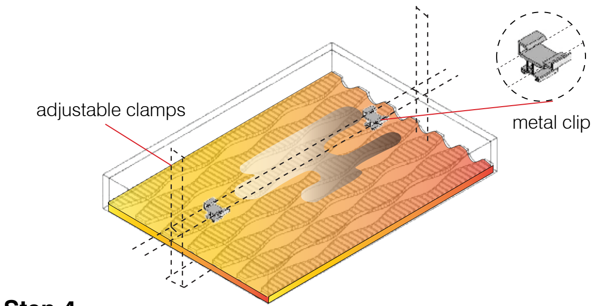
Step 1
The digitally created design is reproduced on a wooden board or modeling foam through the process of CNC milling.



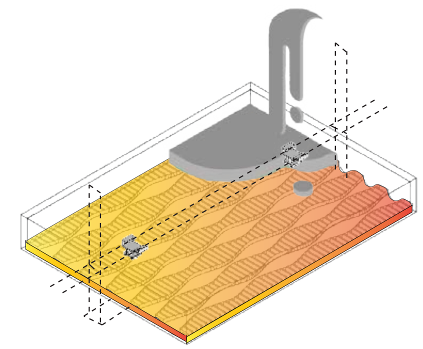
Step 2
The positive cast is placed inside a forming frame and sealed with a release agent before pouring the Polyurethane liquid over it.



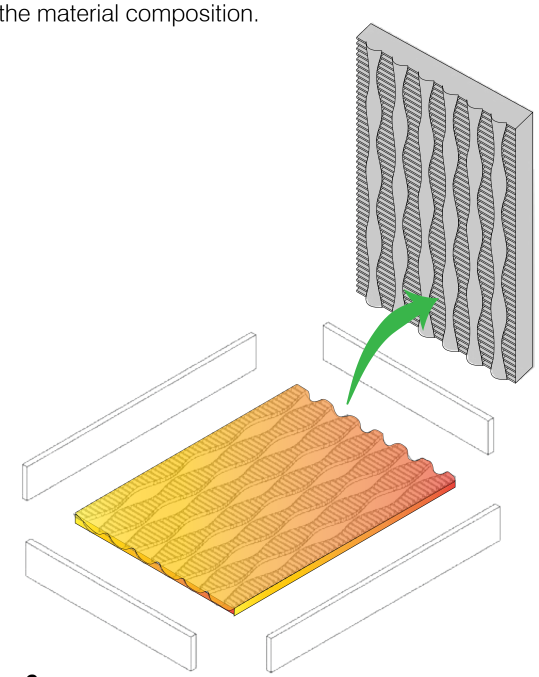
Step 3
The hardened synthetic rubber created an elastic mold /mat with the negative of the design. The mold is strong enough to be reused up to 100 times.



Step 4
The negative elastic mold is placed face up inside a forming frame and a release agent is again applied on it. Then using adjustable clamps metal clips are hold in place on the frame.



Step 5
The concrete mixture is poured into the mold, embedding the metal clips into it. Demolding is done after 24-48hrs depending on the material composition.



Step 6
The hardened concrete is easily removed from the elastic mold. This designed concrete block is then cleaned to remove surface contaminates by the use of detergent scrubbing, low pressure water cleaning, steam cleaning, or chemical cleaning (GUIDELINE INSTRUCTIONS FOR CONCRETE SURFACE PREPARATION, n.d.).

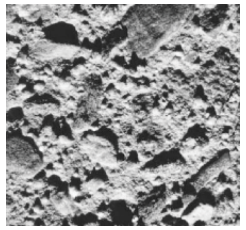
9.1.4. Surface treatment methods

The CNC milling of the micro-grooves involves long milling hours and very high machining precision, which increases the cost to produce the sample designs and ultimately the overall production cost. Table 9 below explores some alternative surface treatment techniques, which can create a rough surface texture similar to that created by the micro-grooves. Grit blasting and Negative wash process are found to be suitable techniques to produce uniform rough textures in desired depths and desired areas. These techniques can also help to reduce the use of releasing agents for the molds in growth areas, making it easier to clean off the surface after the casting process.

Table 9: Surface treatment methods

Methods	Materials/Tools	Exposed depths	Application	Patterns/designs	Advantages	Disadvantages	Remarks + -
Grit blasting [1] Abrasive materials fired through nozzle using compressed air Micro-Abrasive blasting /Pencil blasting (for intricate details)	Silica sand Garnet Crushed glass Mineral sands Plastics Metals	~ 20mm - bigger aggregates 3/4-11/2" - low sand content - low water content 1-3" slump	blasted 24-72 hrs after casting	- uniform - stensils, rubber mats, plywood templates	- No chemicals - Accurate patterns	- labour intensive - health hazards - heat generation	- can be used to create deep grooves - use of pencil blasting and stensils can direct grooves in specified areas - concrete composition
Wash [2] **Positive process (PV)**	Surface retarders (paint like emulsion)	0.1- 7mm depends on cement class, w/c ratio, aggregate size/shape, grain size distribution	- sprayed over fresh cast concrete - wash within 1-3 days	- uniform - full coverage	- short drying time (15-30mins) - no health hazards - eco-friendly - low labour intensive - economic	- cannot be designed, only uniform application possible	- can be used to create deep grooves - retarders applied to specified areas to create grooves - demolding time
Negative process (N)			- sprayed/painted to mold before casting - demold after 18-24hrs and wash	- uniform - in specified areas		- cannot be used on styro foam - sandblasting may be required if not demolded within 24hrs	
Acidification [2]	Sulfamic acid Phosphoric acid Muriatic acid	0.05 - 0.075mm Sand finish	sprayed over fresh concrete after demolding	- uniform - smooth finish		- labour intensive - low exposure depth - acid corrosion - health hazards	not suitable
Bouchardeeren/ Bush hammering [3, 4] manual/pneumatic	Jack hammer/ Chipping hammers with conical or pyramidal points	depends on frequency of application/ hammering	- done on 2-3week old concrete - minimum concrete strength 4000psi	- non uniform - punctured/broken stone texture	used on hard granite and quartz aggregates	- high labour intensive - only for high strength and thick concrete walls - random and non-uniform	- can be used to create deep grooves - suitable for high strength structural concrete - not suitable for details
Sanding/brushing [4] Intentional adding of materials in mold	brick/stone chips glass beads stainless steel	depends on brushing or scrubbing depth	- materials sprinkled in molds before casting - surface brushed to expose the layer	- non uniform - random	- no chemical used - economic	- labour intensive - less accurate - difficult to design	not suitable

[1] Hunt, T. W. (1968)
[2] Reckli. (n.d.). Surface Retarder.
[3] ARCHITECTURAL PRECAST CONCRETE (2007)
[4] U.S. Army Corps of Engineers (1997)


Grit blasting


Washing

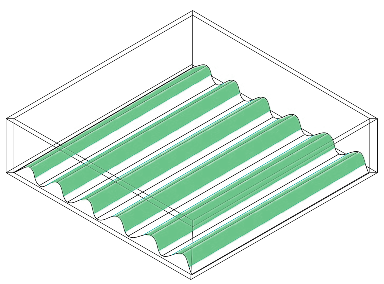

Acidification


Bush Hammering


Sanding/Chiseling (sand+gravel layer)

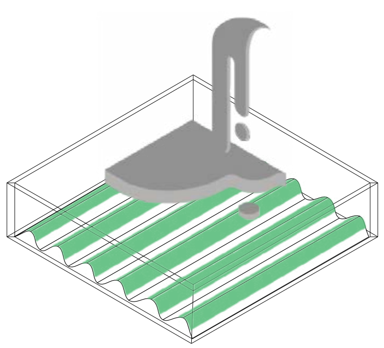
9.1.5. Wash (surface retarder)

Negative process (N)
(Reckli, n.d.)



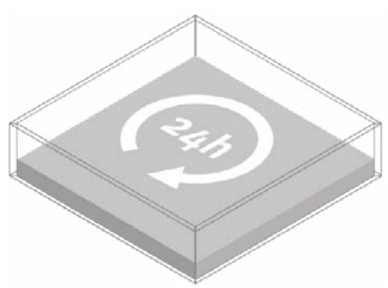
Step 1

The surface retarder is evenly applied on desired areas of the mold where the concrete needs to be roughened, using a paint brush or sprayer.



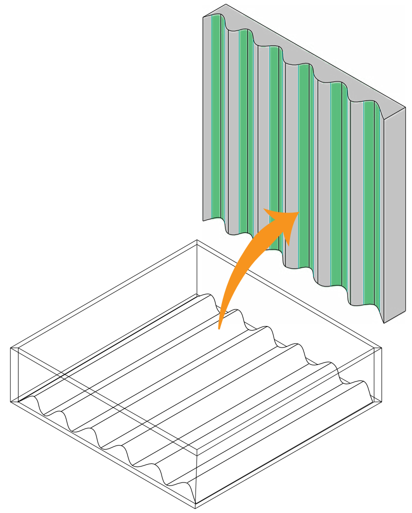
Step 2

After a drying period of 15-60mins, the concrete mixture is poured into the mold.



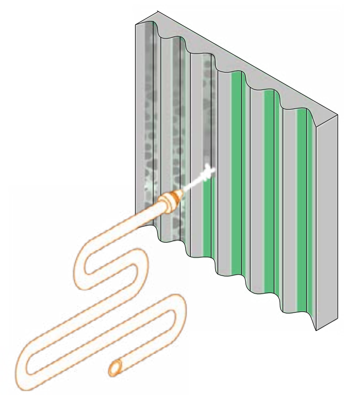
Step 3

The concrete mix should be left to set for a minimum of 8hrs to a maximum of 24hrs. Higher than 48hrs may harden the concrete too much requiring sandblasting.



Step 4

The retarder helps to delay the setting process of the specified areas on the hardened concrete.



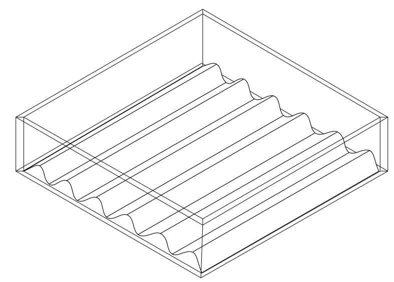
Step 5

In the final step, the specified areas are washed with high pressure hose, dry brushing out followed by subsequent water wash.

Positive process (PV)

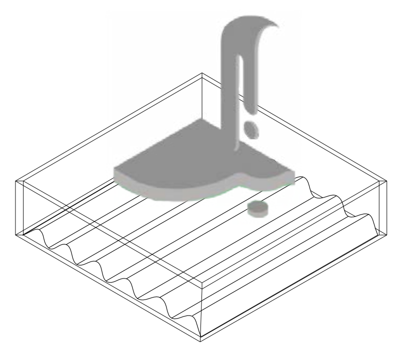
The positive process involves applying the retarder on the top surface of newly poured concrete. Once the mixture is smoothed and air bubbles are vibrated out, the retarder is sprayed evenly and kept covered. Demolding can be done within 1-3days. This process is suitable when the whole surface needs an even texture with no macro geometry involved, like paving, planters, concrete surfaces etc.

9.1.6. Grit blasting (sandblasting)
(Hunt, 1968)



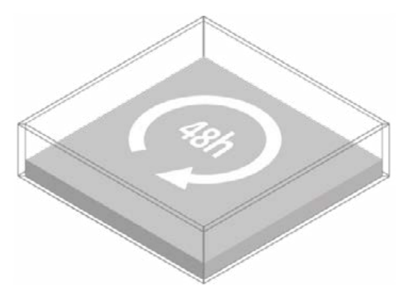
Step 1

The reusable form is created with the macro geometry and placed inside a mold.



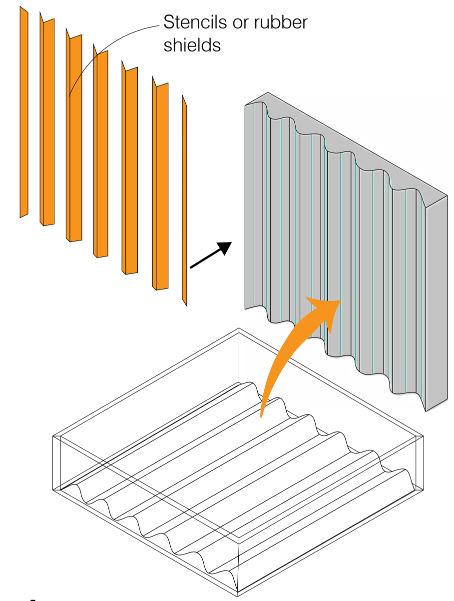
Step 2

The form is sprayed or brushed with a release agent and the concrete mixture is poured.



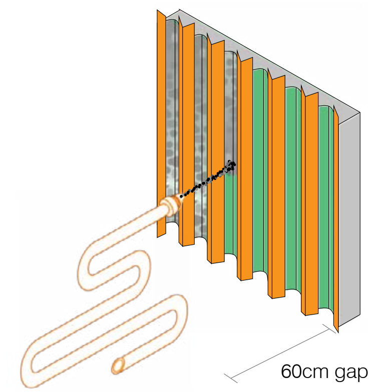
Step 3

The mixture is allowed to set for a period of 48hrs for proper hardening.



Step 4

The hardened concrete is released from the mold. Stencils or rubber shields are made to cover the elevated part of the macro geometry.



Step 5

The rubber shields help to expose the areas which require to be grit blasted to create the rough micro-texture. Depending on the scale of the panels and for better workmanship micro-abrasive blasting can be used. Micro-abrasive blasting employs a nozzle of diameter (approx)1.5mm to deliver a high-pressure stream of fine abrasive, covering an area of $1mm^2$-$3cm^2$. The nozzle should be held perpendicular to the concrete surface maintaining a safe distance of 60cm. After the blasting process the rubber shields are removed and a combination of rough and smooth surface can be obtained.

Note: This process works better for concrete with lower w/c ratio, therefore sample testing is required to check its appropriate use for Bio-receptivity concretes.

Original diagram credit: Reckli.com

Modified diagram: Author

9.1.7. Cost estimation

Material content:

For 1m³ of Bio-receptive concrete
(Byldis BV)

300 kg Blast Furnace slag cement

740 kg of dry sand 0-4 mm

1142 kg dry jurassic yellow 5-8 mm

180 liters of water

For 1m3 of Standard concrete
(Concrete mix design - planete-tp. 2008)

350 kg Portland cement

700 kg of dry sand 0-4 mm

1200 kg dry jurassic yellow 5-8 mm

150 liters of water

Cost for concrete mixture

Blast Furnace slag cement
= 50 euro/1000kg (alibaba.com)

Portland cement
= 45 euro/1000kg (alibaba.com)

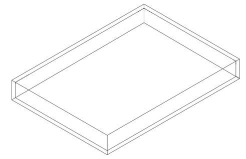
Sand 0-4mm
= 60 euro/1400kg (bouwmaat.nl)

Jura gravel
= 45 euro/500kg (bouwdepot.be)

$1m^3$ bio-receptivity concrete costs = 150 euro
$1m^3$ standard concrete costs = 154 euro
(when mass produced can be reduced to 80 euro per m^3)

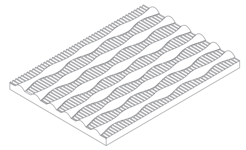
From $1m^3$ mixture, 25 panels of 1m x 1m x 0.04 m can be made. Therefore,
Material cost of 1 panel = 6 euro (approx.)

Cost for wooden frame:



Solidwood block
= 300 euro/m^3 (alibaba.com)
Labour wage
= 35 euro/hr (Byldis BV)
2hr labour charge 70 euro + material cost 6 euro + others =~80 euro (reusable)

Assume 20 panels being made, 80/25 = 3.2 euro cost included to produce one panel

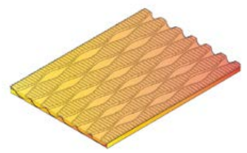


Cost for CNC milling:

Milling cost to produce 1m x 1m panel
= 13.5 hr x 6 = 81 euro (6 euro/hr)
Solidwood block
= 300 euro/m^3 (alibaba.com)
material cost 12 euro + milling cost 81 euro
= 93 euro (reusable)

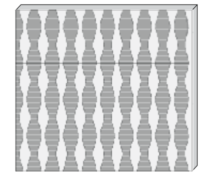
Assume 100 panels being made, 80/100 = 0.8euro cost included to produce one panel

Cost for elastic mold:



Polyurethane mix (A+B)
= 8 euro/kg (alibaba.com)
Polyurethane rubber density
= 1050kg/m^3 (alibaba.com)
Wooden frame
= 80 euro
1hr labour charge for casting
= 35 euro
cost to make a mold (1m x 1m x 0.02m)
= (21kg x 8) + 80 +35
= 283 euro (reusable)

Assume 100 panels being made, 203/100=2.83 euro cost included to produce one panel



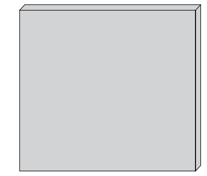


Table 10: Cost for 1 panel (1m x 1m x 0.04m)

	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

As seen in Table 10, the cost of the designed Bio-receptive concrete panel is greater than the cost of a plain concrete panel without post-processing. The addition cost for the Bio-receptive panel is due to the steps of CNC milling and elastic mold making needed to create the surface patterns. As already discussed, the benefits of a Bio-receptive facade is way higher than an ordinary concrete cladding, making the extra cost far compensated. However, this extra cost can be reduced to a significant amount in mass production. To decrease the production time, multiple elastic molds can be made, to carry out the casting process simultaneously. Though this will seem to increase the cost involved in mold making, the overall production cost can decrease with lesser production days, contributing to lesser labour cost and lower factory cost.

9.1.8. Summary

The most suitable production technique to manufacture the designed panels involves the process of CNC milling to create the sample design and further make the negative elastic molds to cast the actual concrete panels. This CNC milling process can accurately replicate the designs developed digitally and further transfer the details into the elastic molds.

The intricate detailing of the micro-grooves which can increase the milling time significantly, may be replaced using post processing techniques like, Grit blasting and Washing with surface retarder. These techniques can help to reduce the use of mold release agents in growth areas. However, the impact of chemical reaction caused by surface retarders and also the accuracy in terms of depth and surface texture still needs further testing to prove the Bio-receptive character of the panels.

Lastly the elaborate production technique results to a higher cost for the Bio-receptive panels as compared to standard concrete panels. This can be reduced significantly through mass production by lowering the production time, subsequently the labour cost and factory expenses.

9.2. Assembly process

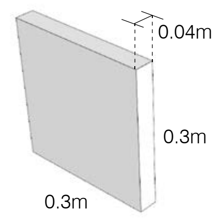
The first part of the assembly process is to determine the panel size for produciton which can be installed fast and efficiently in site. Next the panels need to be well packed to avoid any damage while transport. The size and type of transportation vehicle depends on the total volume of panels to be transported and the distance of transportation. Lastly in site, clear installation drawings have to be supplied to the workers, for them to carry out the installation process in correct order and precision.

9.2.1. Panel size

According to the book, Architectural Precast Concrete (3rd ed.). (2007), the following points are important to consider while determining the panel size.

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

For the Bio-receptive designed panels, the panel size most importantly depends on the production capacity and the inherit strength of the panels. As the production process involves the technique of CNC milling, the panel size has to be in accordance with the machine capacity. Further due to the porous nature of these panels, the strength capacity is lower than standard concrete panels, limiting the panel size within its stress allowance.



Prototype panel size:

Area= 0.3x0.3=~0.1m2
Density=~ 2000kg/m2

Weight for 0.1m2 = 7kg (approx.)
Weight for 1m2 = 70kg

According to the labour law, Manual Handling Guidelines for Maximum Weight (n.d.).

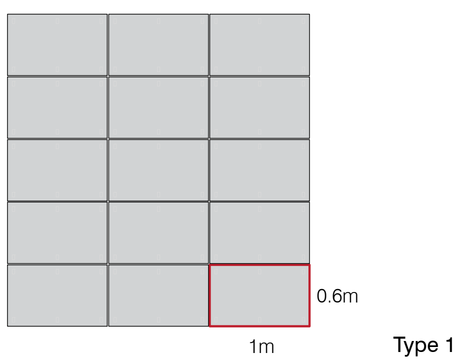
Handling weight per person = 20-25kg (elbow height)
Two person carrying capacity = 50kg (approx)

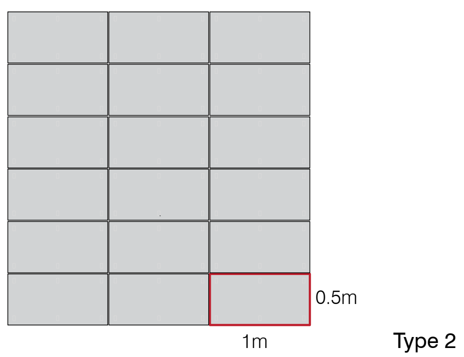
Actual Panel sizes:

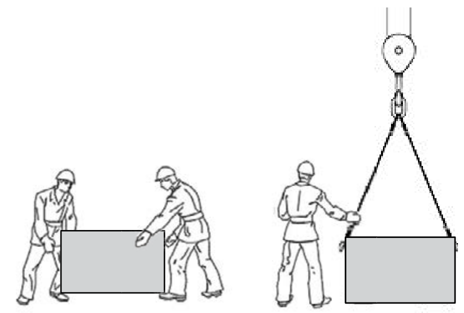
1mx0.5mx0.04m (35kg)
or
1mx0.6mx0.04mm (42kg)

Panel arrangement for a 3mx3m wall area:

Type 1 requires 15panels
Type 2 requires 18panels





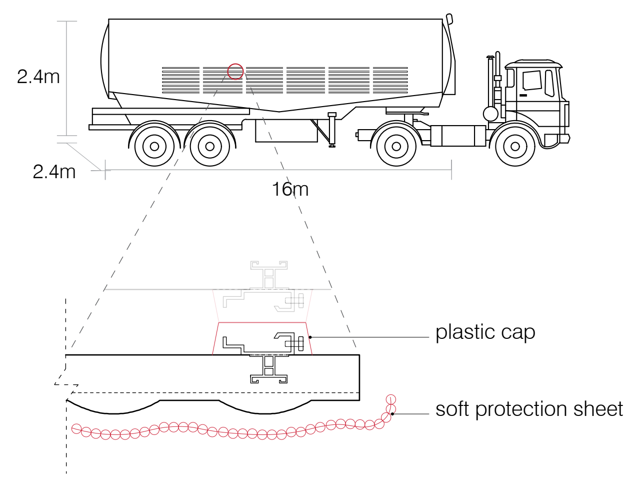


9.2.2. Packing and Transportation

The porous quality of these concrete panels due to high water/cement ratio, results in lower strength compared to commercial structural concrete. To avoid damage to corners or to the patterned surface, extra packing measures are needed:

- The embedded metal clips should be covered with plastic cap for easy piling of the panels.
- Soft protection sheet (bubble sheet) can be placed in-between panels to secure the corners and patterned surface.

The common overall truck volume 2.4x16x2.4m
Maximum load carried 18-20 tons (20,000kg)
Maximum number of panels per trip 450 (approx.)



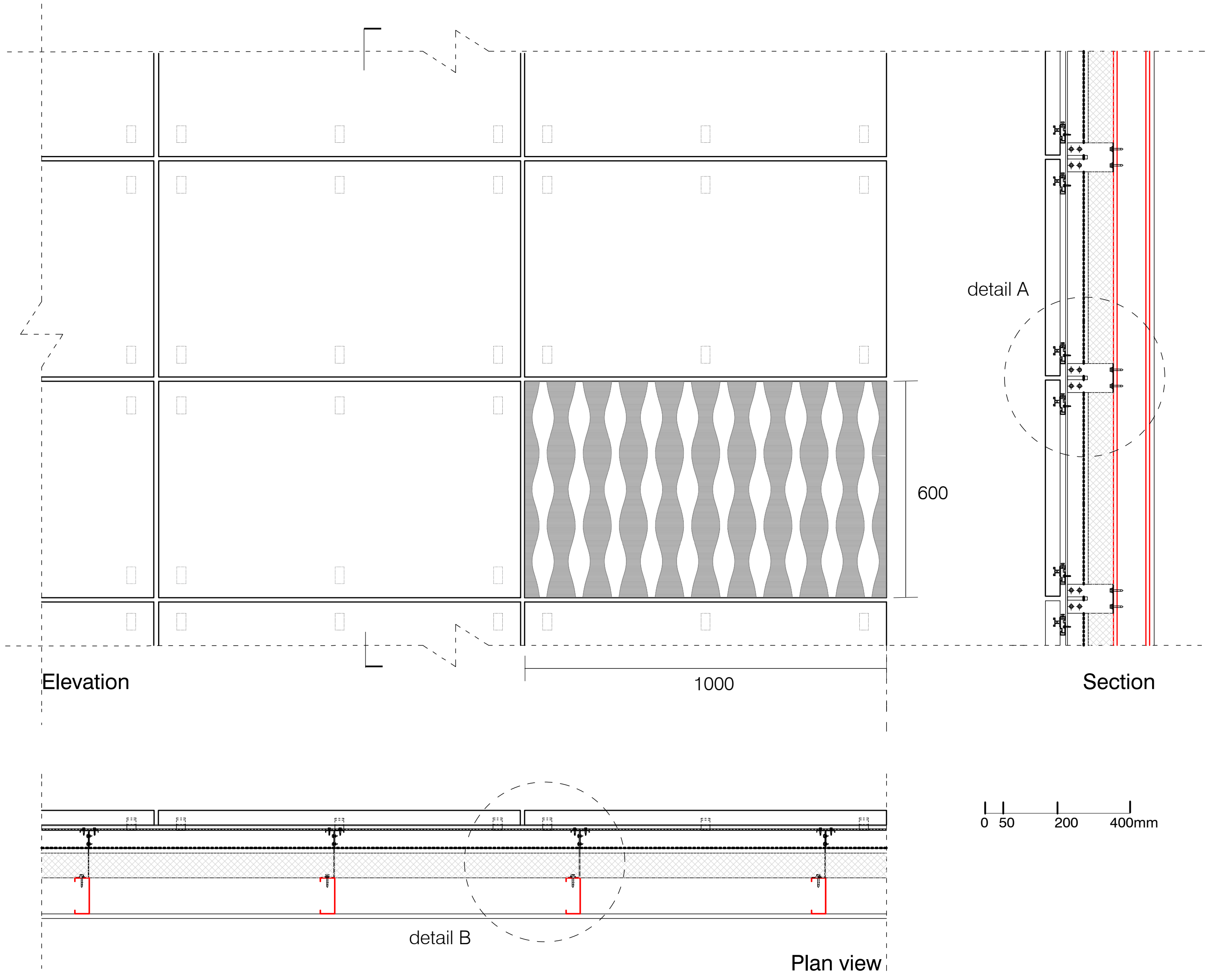
9.2.3. Maintenance

The Bio-receptive concrete panels have been designed to be self-sustaining requiring minimum external maintenance. However, the panels will require periodic inspection once every 6 months:

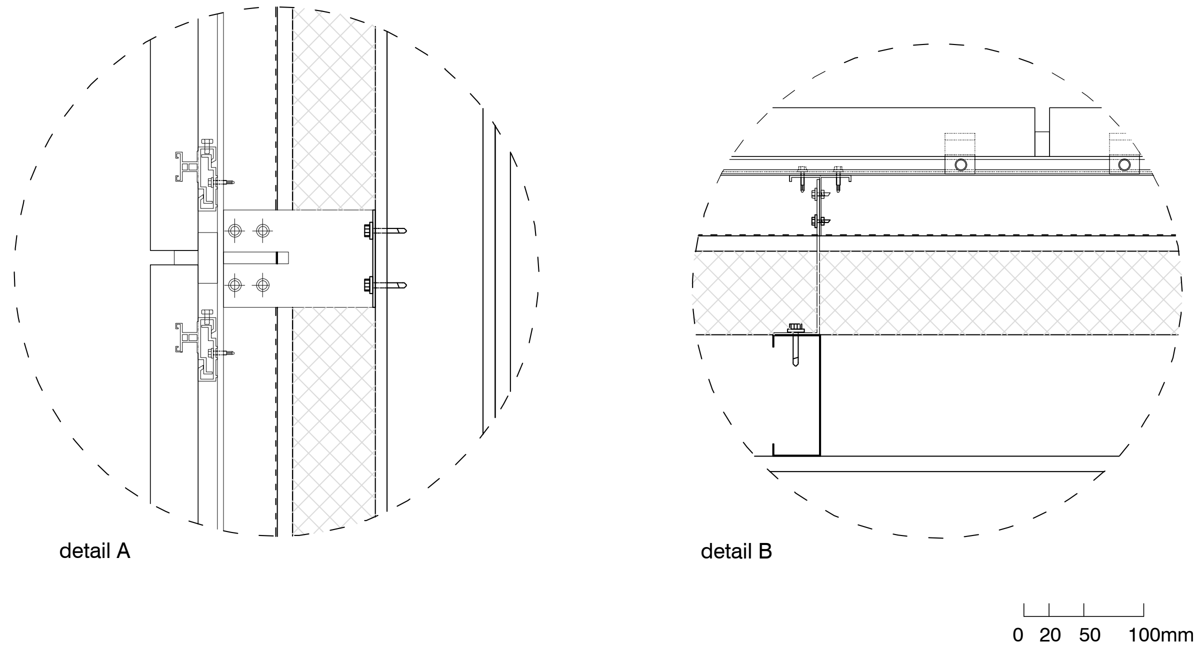
- To check and remove any unhealthy moss patches, which may hamper the overall growth trail.
- To re-inoculate with moss spores where growth is inadequate.
- To dust away external surface containinants which may clog the pores hampering the callipary action of the mosses.

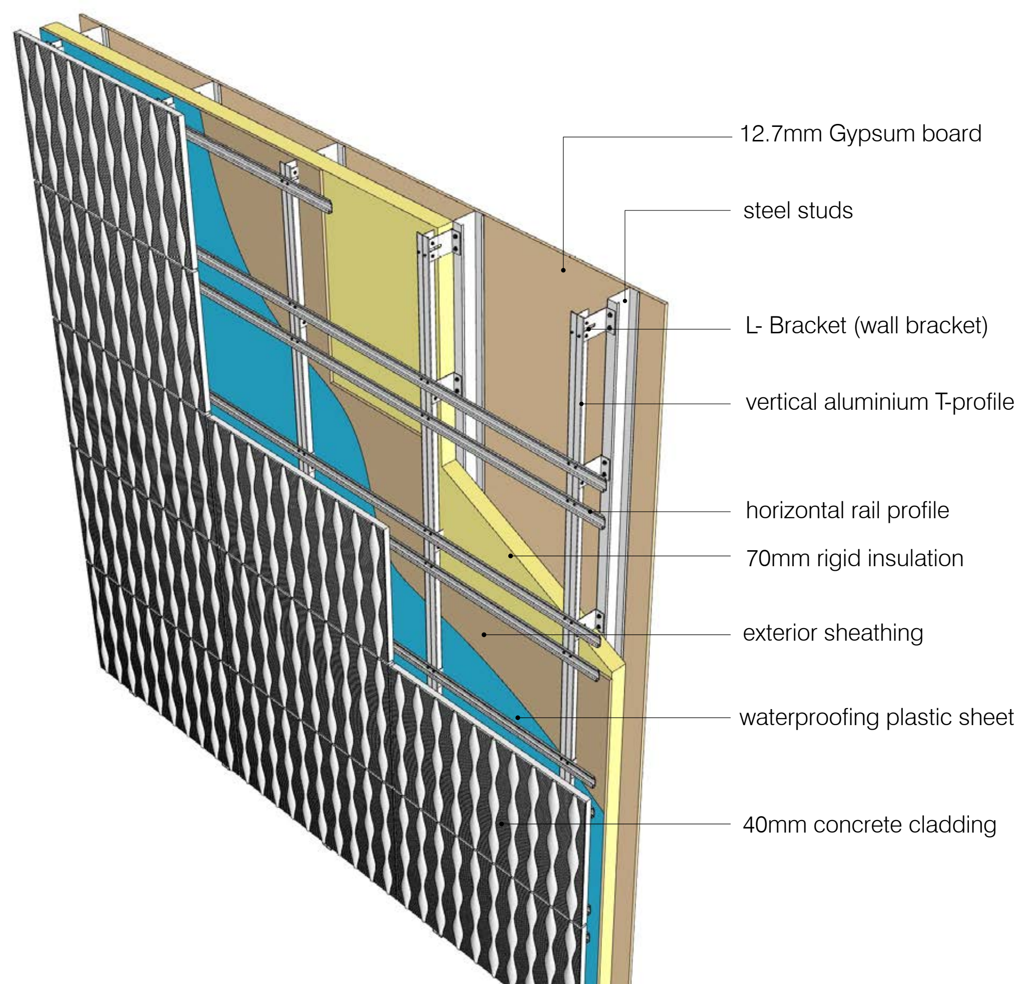
Note: If drought period exists for longer than 3 months external watering may be required to rehydrate the dormant mosses. It is also important to note that these Bio-receptive panels work best in mild temperate to tropical climates where the humidity in air is high, facilitating the self-sustaining ability of the mosses on stony materials.

9.2.4. Construction and Installation drawings

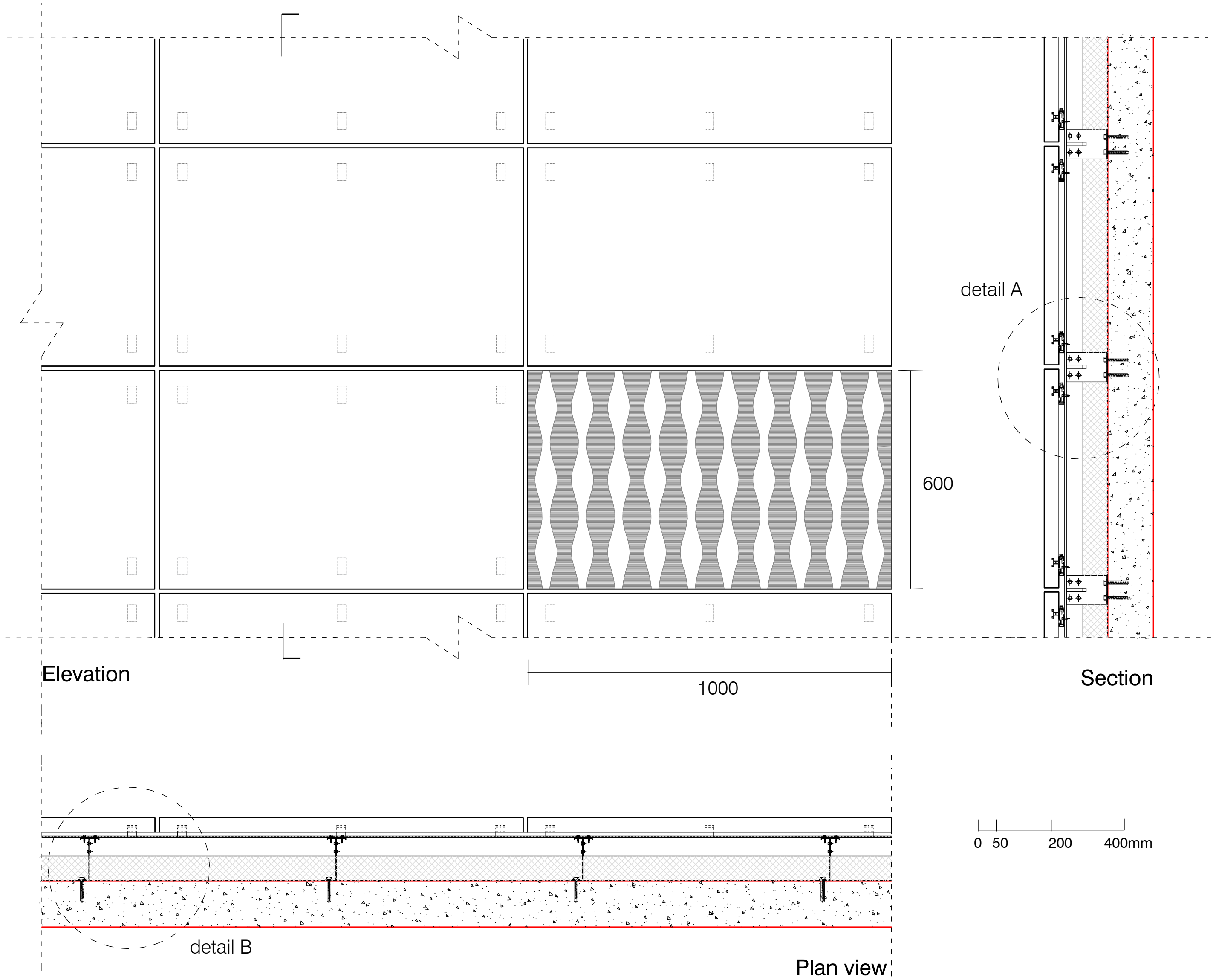


**Concrete cladding
on steel frame structure**

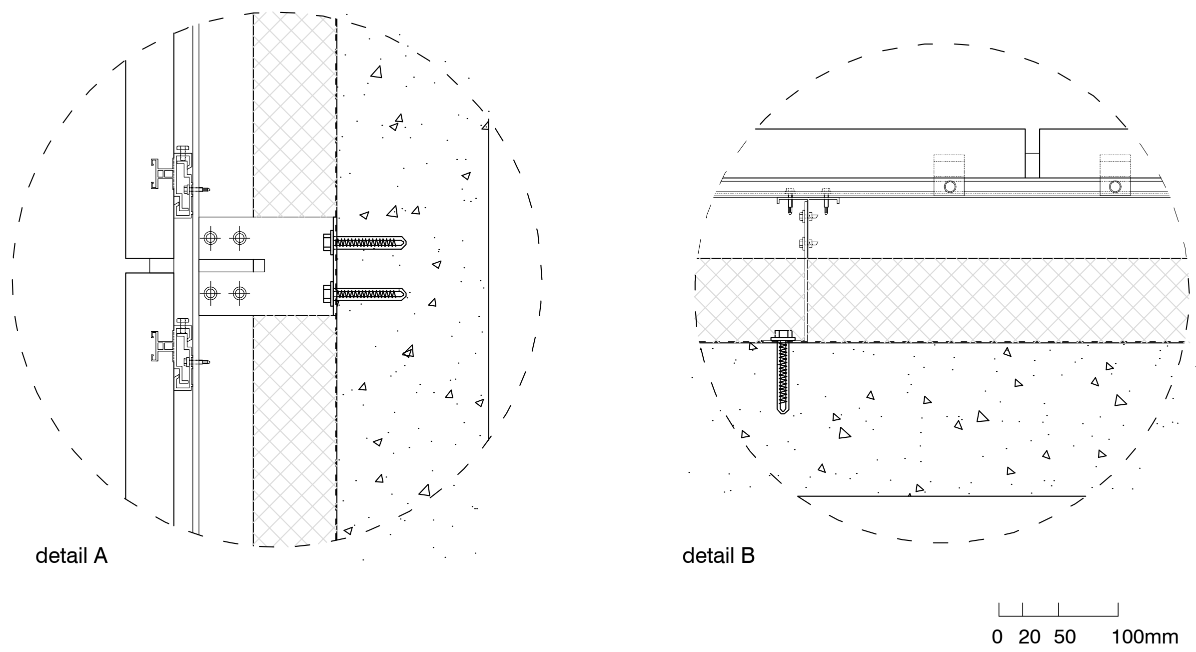


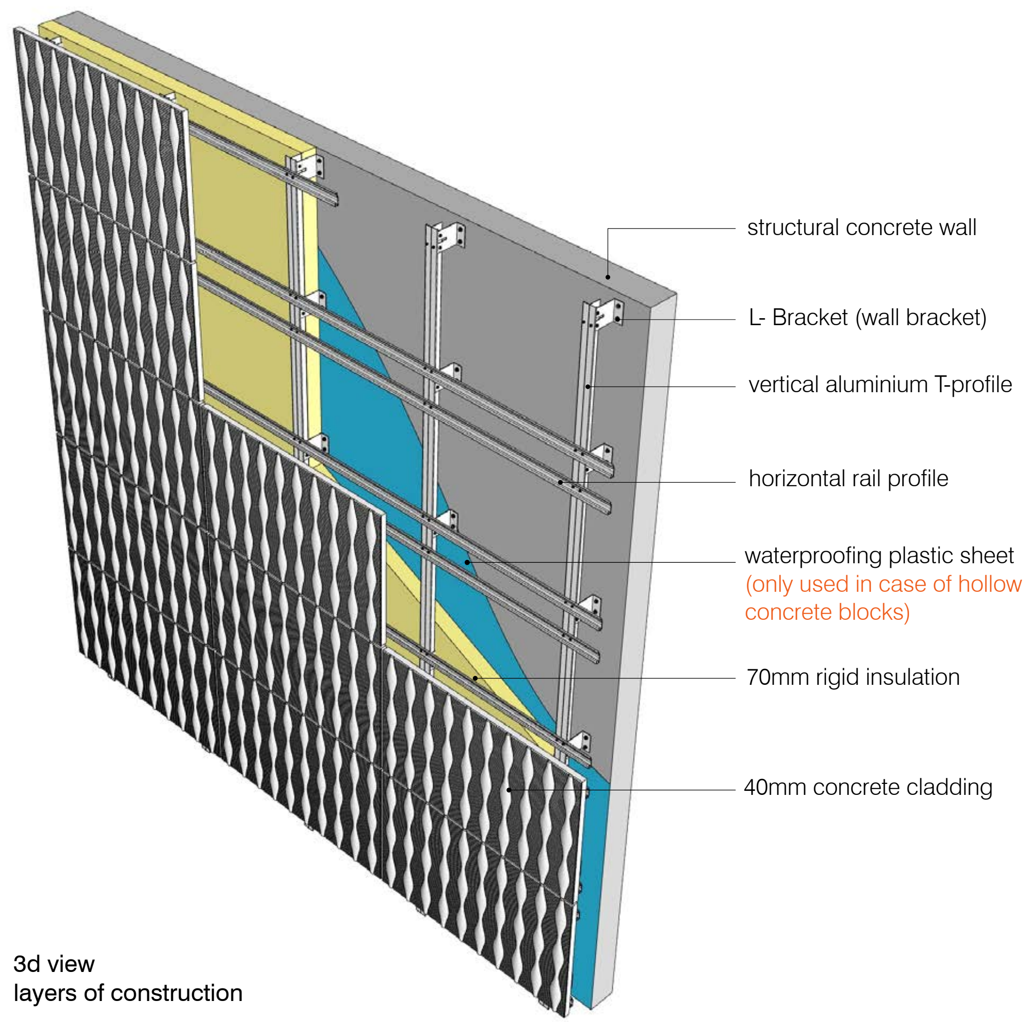


3d view
layers of construction



Concrete cladding
on structural concrete wall

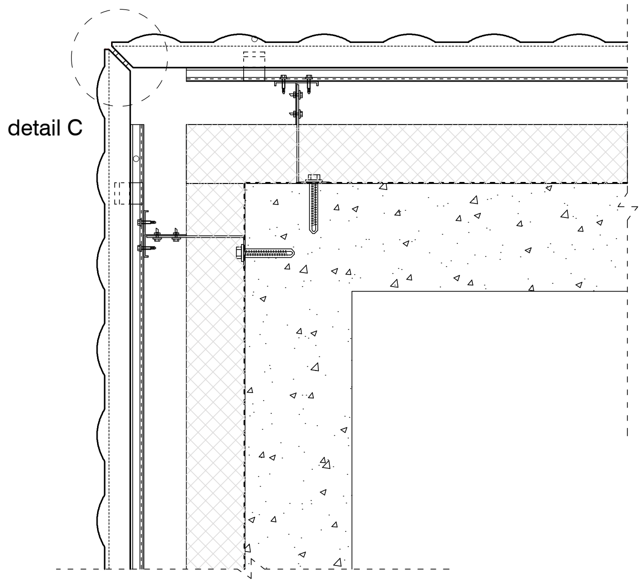


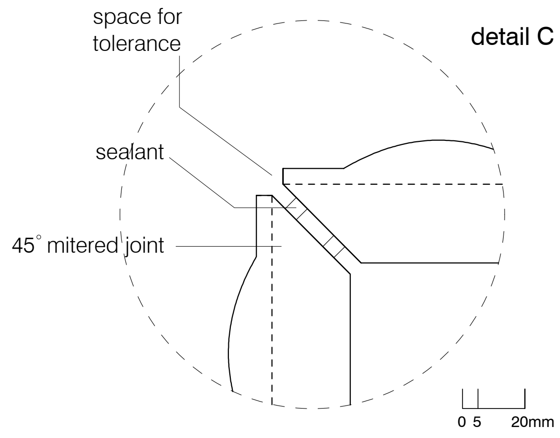


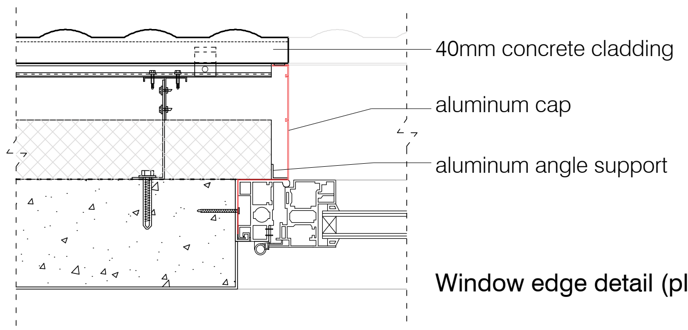
3d view
layers of construction

Details with structural concrete wall

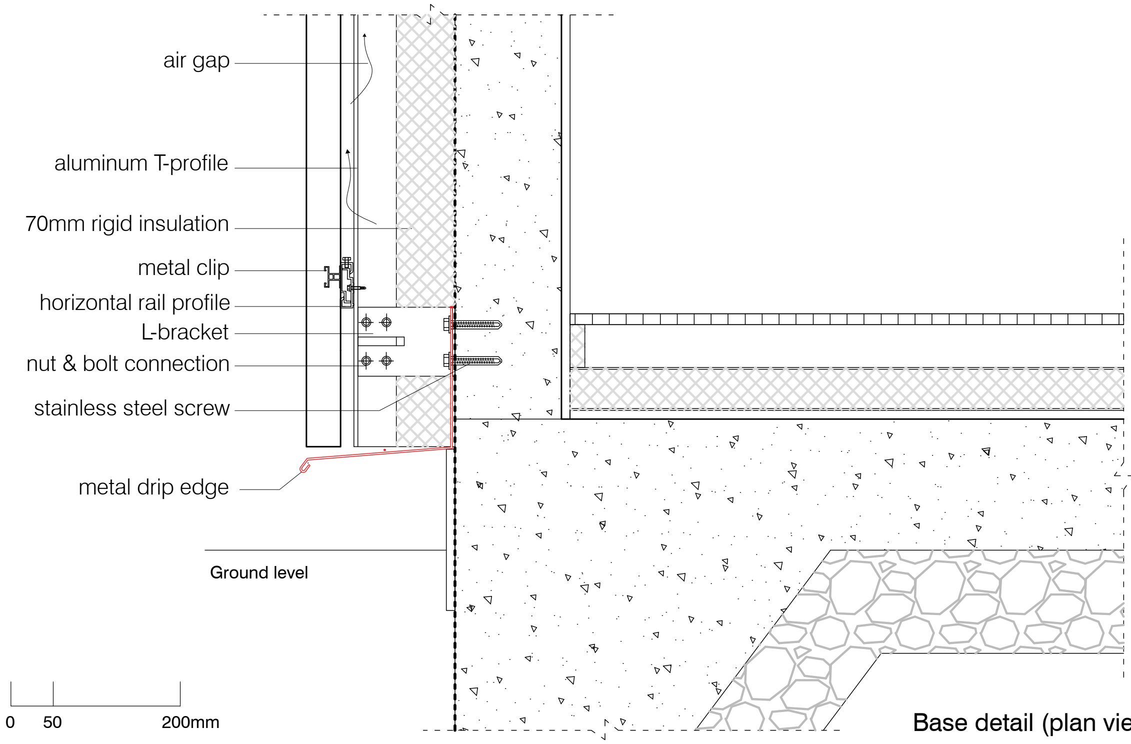
Corner detail (plan view)





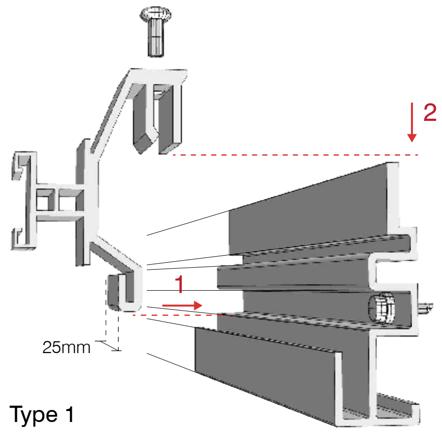


Window edge detail (plan view)



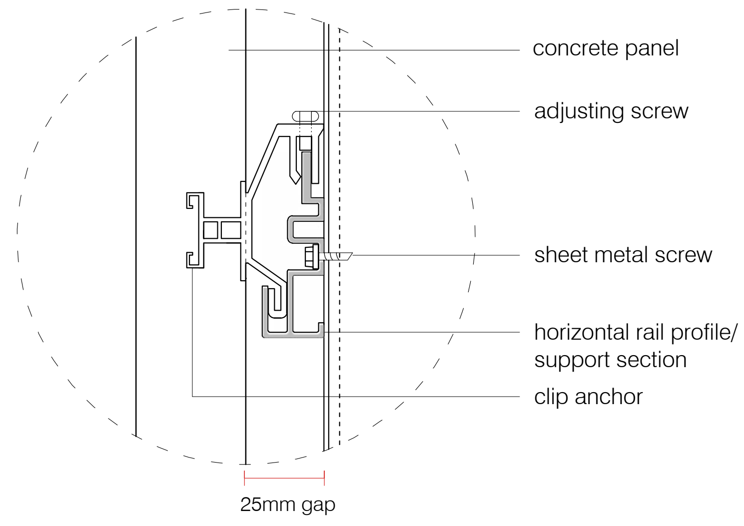
Base detail (plan view)

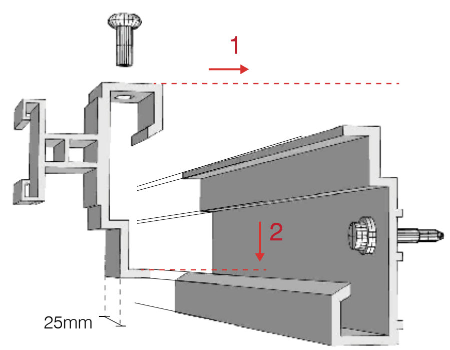
Types of connector/clip



Type 1

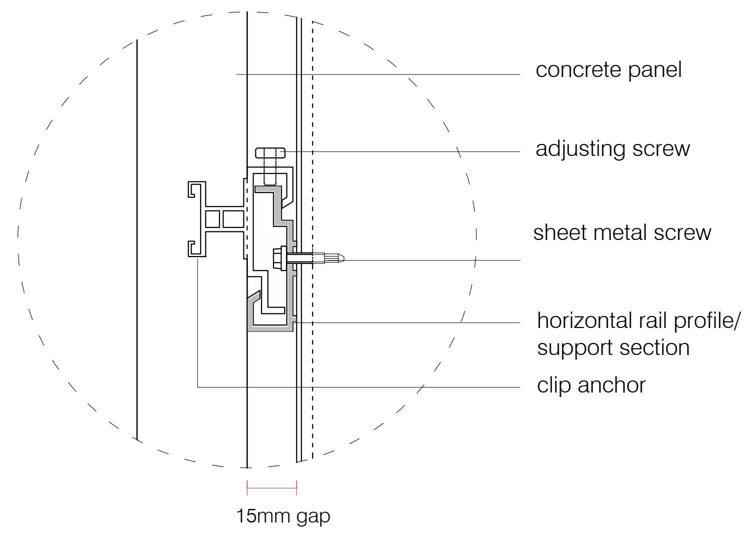
Heavy weight
Panel length ±100cm

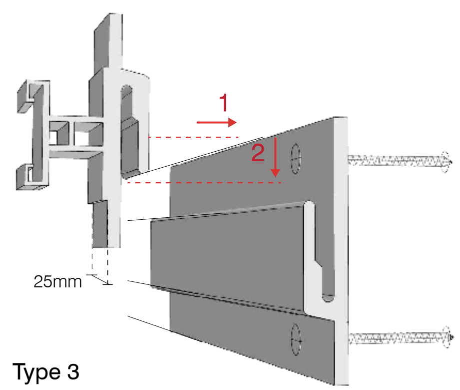




Type 2

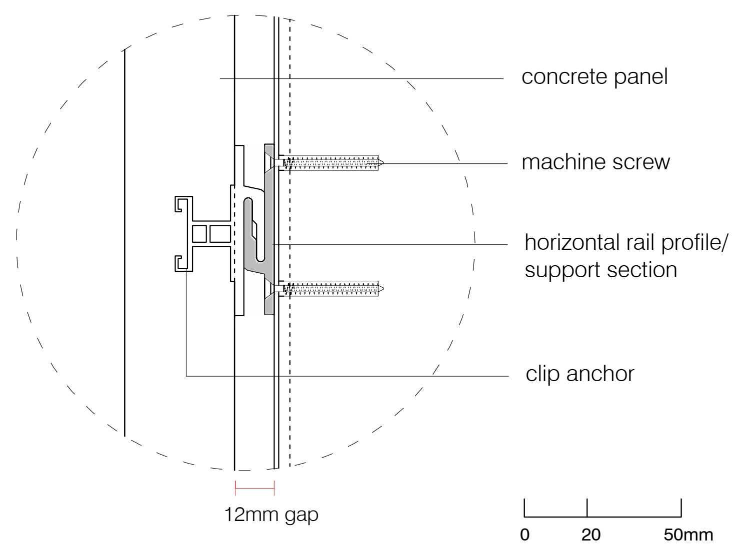
Medium weight
Panel length ±70cm





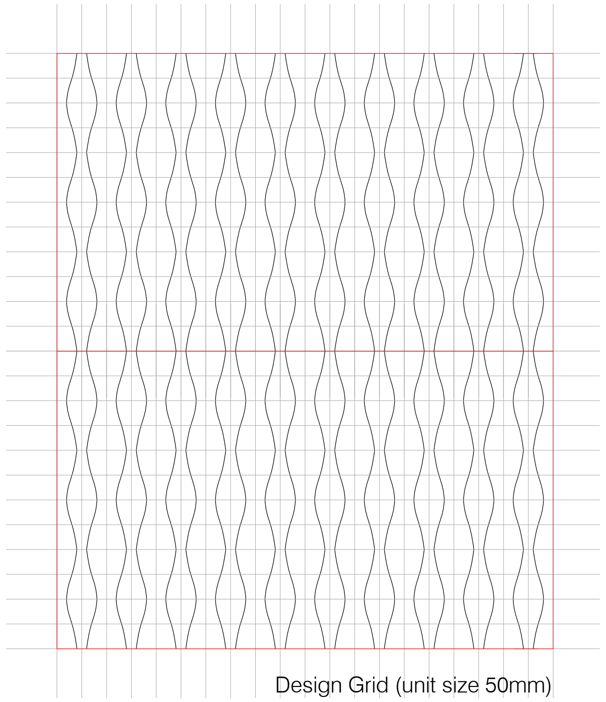
Type 3

Light weight
Panel length ±50cm

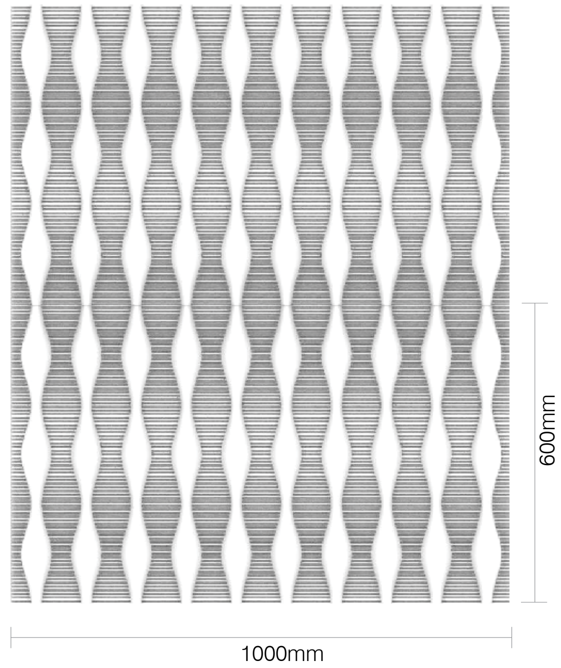


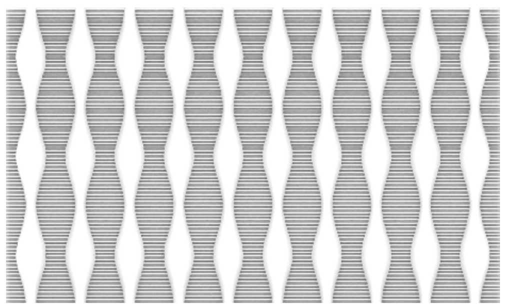
10. Visualization

10. Scale and Proportion



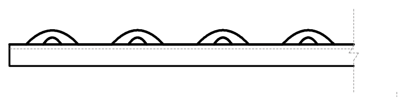
Example 1

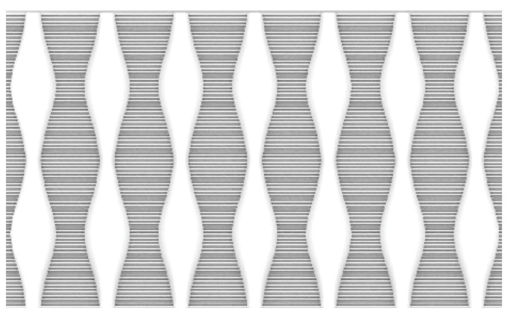




Type A (IDEAL estimated 100% coverage)

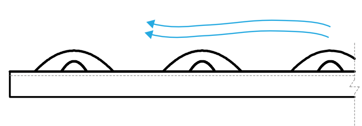
Groove depth, H=20mm
Groove width, W= 60-85mm
H/W=0.2~0.3



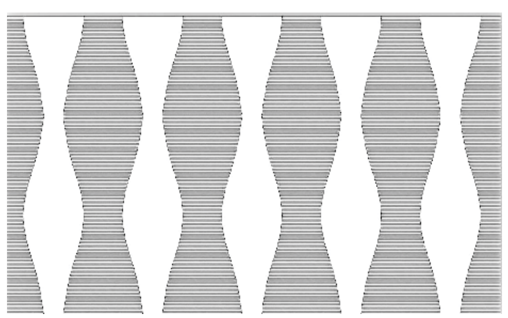


Type B (Scale up:1.5 estimated 70% coverage)

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

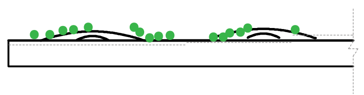


Depth > 20mm
wind barrier
hamper spores dispersal

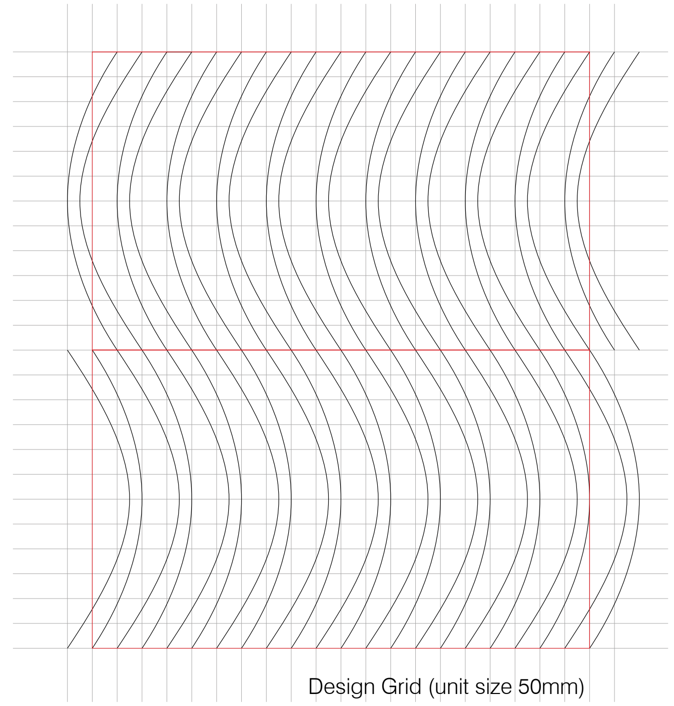


Type C (Scale up:2 no ordered growth)

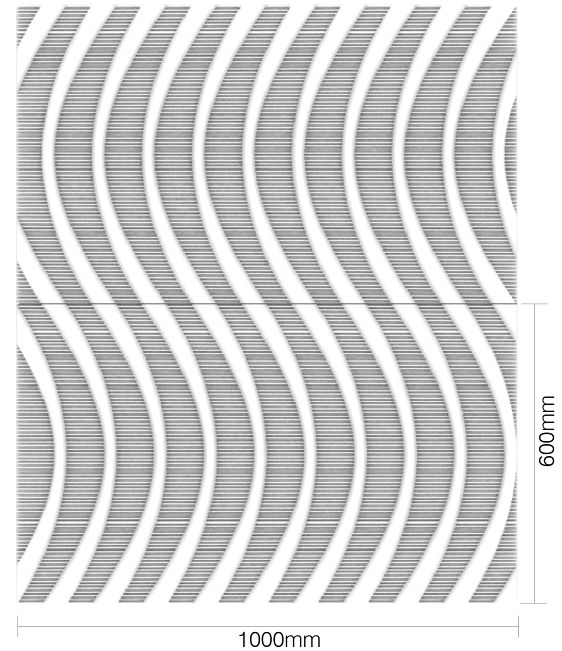
Groove depth, H=15mm
Groove width, W= 125-160mm
H/W=0.09~0.12

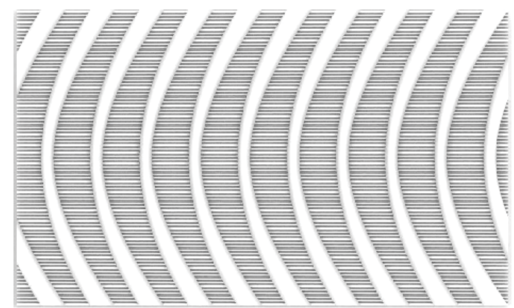


Width >~
a flattened surface,
random moss coverage



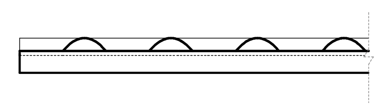
Example 2

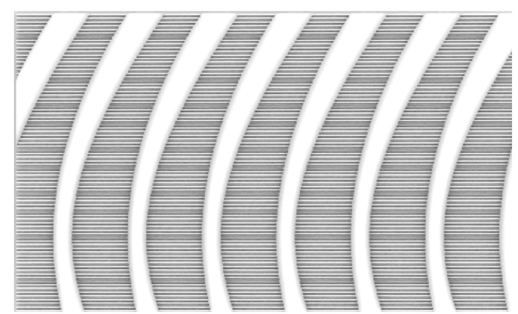




Type A (IDEAL estimated 100% coverage)

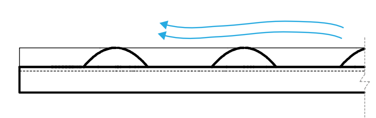
Groove depth, H=20mm
Groove width, W= 50-75mm
H/W=0.2~0.3



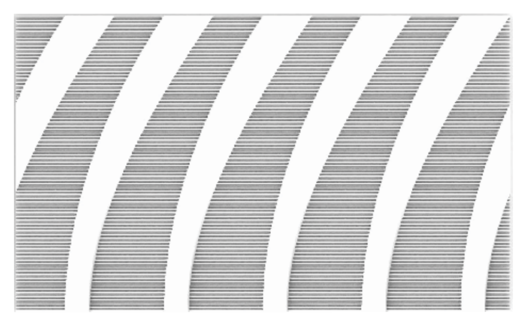


Type B (Scale up:1.5 estimated 70% coverage)

Groove depth, H=27mm
Groove width, W= 75-115mm
H/W=0.2~0.3

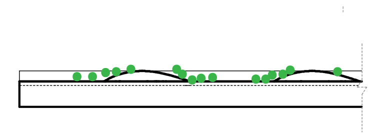


Depth > 20mm
wind barrier
hamper spores dispersal



Type C (Scale up:2 no ordered growth)

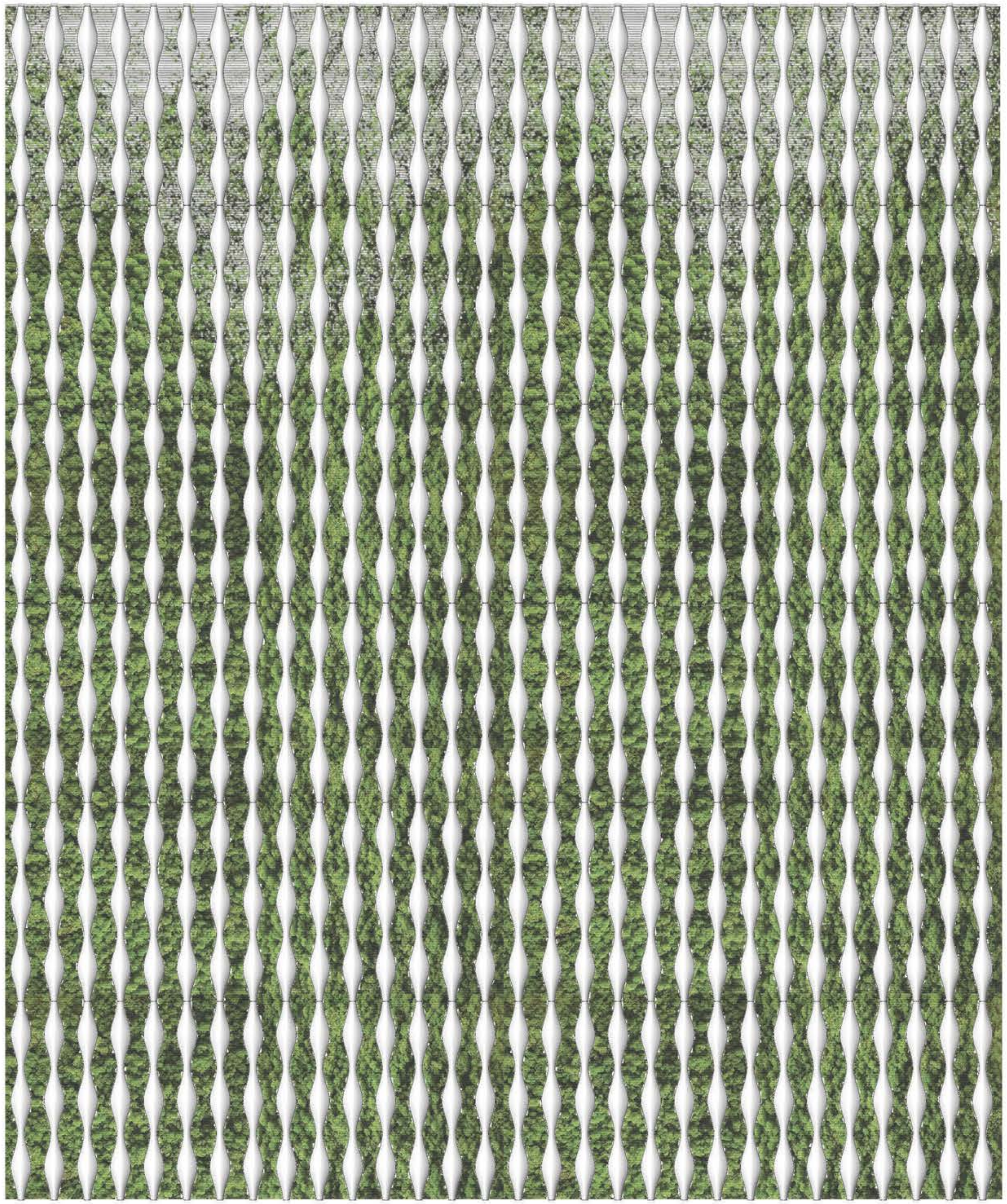
Groove depth, H=15mm
Groove width, W= 125mm
H/W=0.12

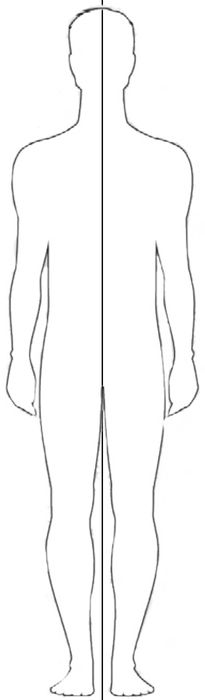


Width >~
a flattened surface,
random moss coverage

Example 1

Type A



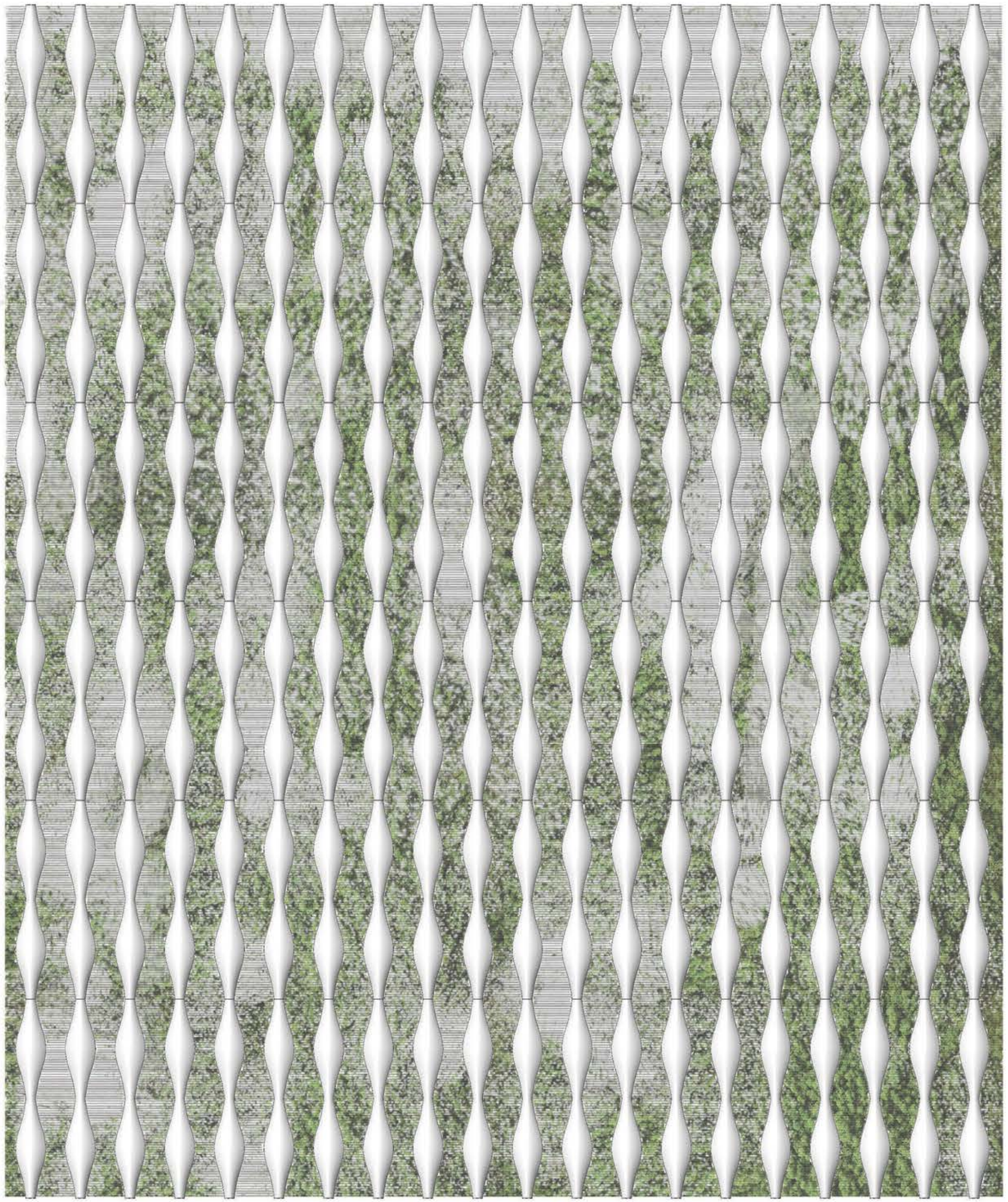


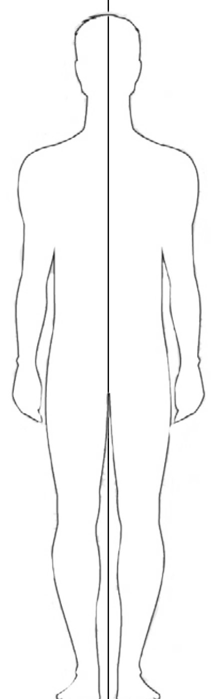
Example 2

Type A

Example 1

Type B





Example 2

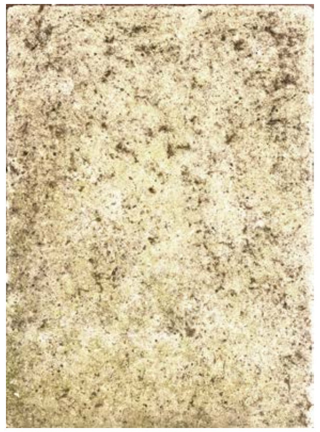
Type B

11. Reflection

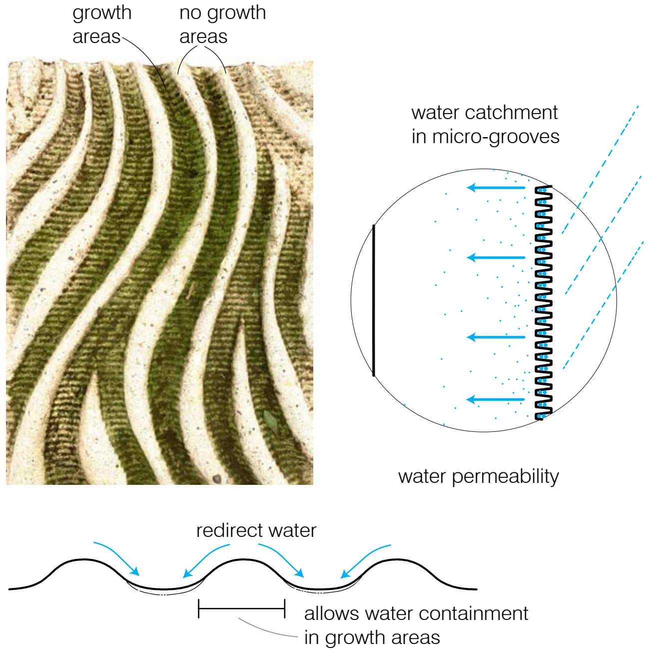
Main Research question:

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

This research has investigated the use of geometry to facilitate an engineered growth of mosses on concrete panels with suitable material properties. An engineered growth refers to employing surface geometry to create a self-sustaining system for the growth of mosses in desired areas and in desired coverage. Water availability is the most important parameter required for the self-sustaining criteria. Four distinct geometric panels have been designed based on literature study and field survey and are further compared with two extra concrete panels, a plain panel and a natural rough surface panel. Based on the comparative results of water relations testing and moss growing experiment on all the six panels, it is evident that surface geometry does play a vital role, in terms of intensity of growth and an ordered system of growth. The geometric features of each designed panel are classified into two geometry levels, macro and micro level geometry. A combination of both these geometric levels helps to influence the water relations of the panels and direct growth in desired areas on the surface. The micro geometric features called micro-grooves are used where moss coverage is desired creating anchorage facility. These micro-grooves of around 5mm depth provide water catchment areas to store water for longer time and further facilitate the water absorption capacity. The macro level geometries create the overall surface undulations which help to distinguish between the growth and no growth areas. The deep macro geometries help to redirect the water flow towards the microgrooves to increase the water concentrations and containment in the growth areas. Among the designed panels, the deep micro-grooves create better surface water retention and anchorage facility, while the along the flow macro-geometries helps to create a continuous trail of moss growth in the desired areas. On the other hand, the plain panels due to absence of surface texture lacks the ability for anchorage and surface water retention, showing no moss growth and the natural rough surface, though allows for some extent of anchorage and surface water retention, exhibits random and low patches of moss growth due to the absence of macro surface geometry. Thus, in this research it has been testified that a right combination of surface geometry with the required depth and width can create an engineered/ systematic growth of moss on concrete panels.


plain surface


natural rough surface



Main Objective:

Creating order and balance

The natural random and spontaneous growth of mosses due to shabby conditions on stony materials, makes it a deteriorating factor in the eyes of the common people. The main aim of this research has been to achieve order and balance in the random growth pattern, highlighting its benefits and promoting mass use of these Bio-receptive concrete façade panels. Through decades geometry in architectural façade design has been used mostly to achieve different environmental qualities while vegetation or green walls are seen as a separate and secondary layer over the building surface. In this research, the geometry has been used to create a co-existence between building envelope and plant growth, where the surface geometry facilitates an ordered and systematic growth of mosses on the concrete façade panels. The geometric features investigated in this research has been inspired from the pattern found in nature depicting different functional qualities, as discussed in section 3.4. The patterns are further translated into surface geometry on the four panels through a method of repetition called rhythm, creating a sense of harmony and order aesthetically pleasing to the human eye (Soegaard, 2018). Panel 1 has been designed in an alternating rhythm method, Panel 2 in a flowing rhythm, Panel 3 in a regular rhythm and Panel 4 followed a random rhythm. Among these designed panels, Panel 2 showed the best results in terms of moss growth due to its pronounced along the flow geometric features which helped to create a clear distinction between the growth and no growth areas. Panel 1 also showed a moderate growth owing to its along the flow obstacles. Therefore, for an ordered and balanced growth of mosses in desired areas, the 'along the flow' macro-geometries can be arranged in a flowing/alternating rhythm in adjusted width and depth for any scale and any type of surface plane. A combination of these along the flow obstacles to direct water to growth areas and deep micro grooves allowing greater surface water retention together can engineer a self-sustaining system.

No order and balance:

A. Grit blasted surface without macro-geometry

B. Micro-grooves without macro-geometry

Order and balance:

C. A combination of micro and macro-geometry arranged in a flowing rhythm

D. Areas with and without micro-grooves further defining growth and no growth areas

12. Conclusion and discussion

Conclusion

This research is a testimony that Bio-receptive concrete material can be geometrically articulated to engineer a self-sustaining process and manipulate the organic growth of mosses in an ordered system. The research followed a top-down approach where, first designs are developed based on literature and field survey and then validated through practical experimentations and simulations, finally providing a general design guideline.

Despite the several benefits of bio-receptivity studied and researched through the past decade, the organic growth of mosses is viewed as a deteriorating factor on the building envelop. This research has created a self-sustaining ordered growth system through geometrical articulation, which is not only functionally viable but also aesthetically pleasing, in an attempt to change the perception of people towards Bio-receptivity. The building material chosen to be investigated is concrete, due to its inherent bio-receptive quality and reduce its carbon footprint with a more sustainable and greener version. Though geometry influenced Bio-receptivity has been investigated in some earlier research works, this research is an unique extension to the existing body of work, where the problem has been addressed through solutions based on real time practical experimentations.

Through detailed research, the presence of water is found to be the primary criteria for the growth and development of mosses on stony surfaces. Among other factors the material properties of concrete are also important that influenced the Bio-receptive character. The research has been conducted in several steps, starting with the development of geometrical patterns addressing the order and balance objective, primarily focused on water movement on the surface, 2nd prototype making and finally validation through practical experimentations and CFD simulations. The prototype making with the correct material composition has been a crucial stage which created the Bio-receptive material base for the validation process. The water relation testing provided a clear visual on the performance of the geometry on the water absorption and retention quality of the panels. Based on the results of this practical testing, the CFD simulations checked and verified the most suitable micro-groove type for the maximum surface water retention. Further the results of the laboratory experiment and simulation are cross-checked with the moss growing experiment and the influence of surface geometries on the Bio-receptive quality of the panels is found to be evident.

The most crucial geometric feature responsible to facilitate moss growth is the deep micro-grooves with increased surface areas for greater water catchment facility. Secondly, the pronounced and continuous 'along the flow' macro geometries which can be arranged in a flowing/alternating rhythm helped to prolong the flow path creating a clear distinction between growth and no growth areas. Based on the combination of these micro and macro geometric features, a general design guideline has been proposed to formulate the ordered growth system of mosses. In addition to these geometric features, the absorption quality of the surface is equally important, any chemical contaminants must be thoroughly washed to avail the full absorption capacity of the material. Using these guidelines, countless options of surface morphology can be possible to create a self-sustaining Bio-receptive concrete façade panel.

In terms of technical and economic feasibility of a concrete façade panel, the most efficient manufacturing process and installation method has been proposed. Due to an elaborate casting process of the designed geometries, the overall production cost for the Bio-receptive panels is higher compared to standard concrete cladding, which can be significantly reduced through mass production of the panels.

Thus, it can be concluded that the geometrical articulation is a viable approach to engineer a self-sustaining and ordered growth of mosses on concrete surfaces, promoting its several benefits through an aesthetic quotient and encouraging its widespread use.

Discussion

Limitations: Bio-receptivity is a natural process and its growth occurs in an unpredictable and spontaneous manner over a prolonged time, taking several years. For the time constraint of the research project, an ideal condition is created in a greenhouse to propagate moss growth on the designed concrete panels. The self-sustaining ability of the panels in terms of surface water retention is tested within the controlled setting which is not necessarily an ideal replica of natural rainfall and moisture conditions. Thus, to ensure successful performance of such designed panels in natural environment further testing needs to be done in outdoor settings for an extended period, before it can be brought into practice. Furthermore, due to the pandemic situation, the original plan to cast a modified design panel based on the proposed guidelines and carry out water relations testing for rechecking the results have not been possible. Though the final validation is out of scope, the general guidelines can still be considered valid, relying on the thorough investigation process followed to formulate these guidelines.

Future recommendations:

- The objective of this research has been to investigate and formulate the guidelines for Bio-receptive design. Based on these outcomes, further research can be done, assigning these rules/guidelines into a parametric platform to generate multiple iterations for a chosen design within shorter time.
- The quantitative analysis of moss growth on the different panels has not been within the scope of the project. Further research can be done on ways to quantify the influence of geometry on moss growth by measuring the different environmental impacts, like air purification, dust removal, temperature change etc.
- This research has been focused on the Bio-receptive character of concrete material only. Further research on other kinds of materials, like limestone, brick, wood or even metals can be carried out to check and compare the Bio-receptive property of the different materials for better applicability.

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14. Appendix

14.1. Field Survey documentation







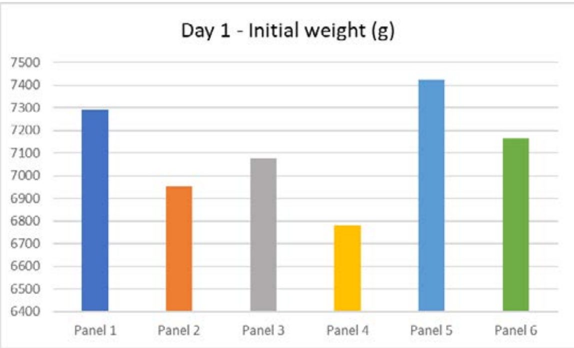


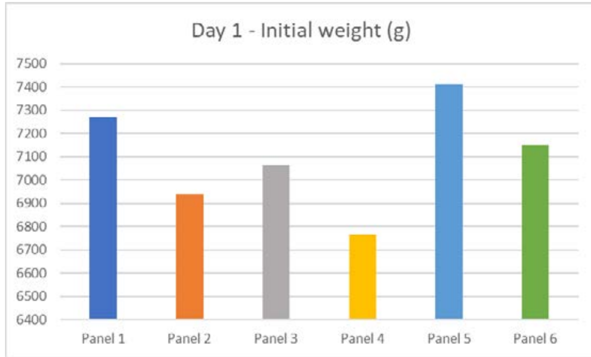


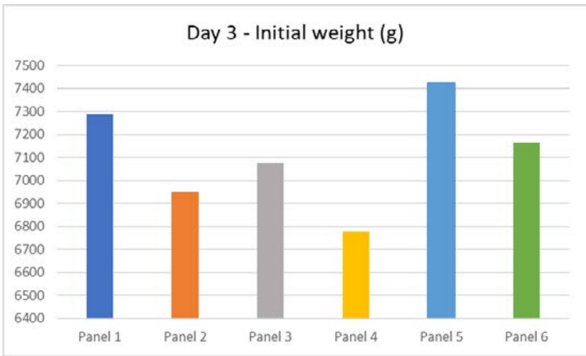


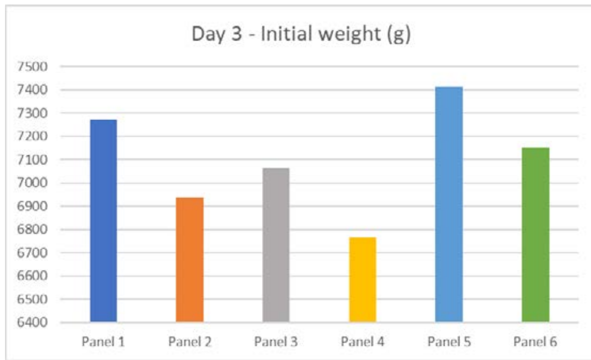
14.2. Graphs for water relations laboratory experiment

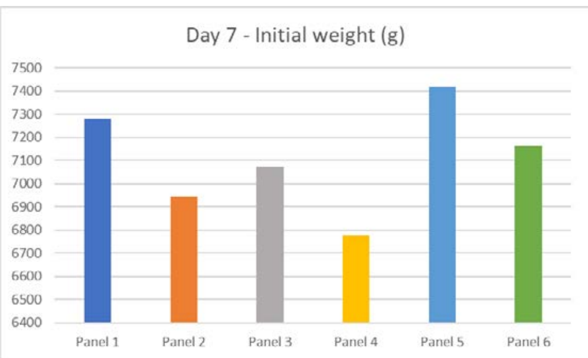
Iniitial weight **SET 1** **SET 2**

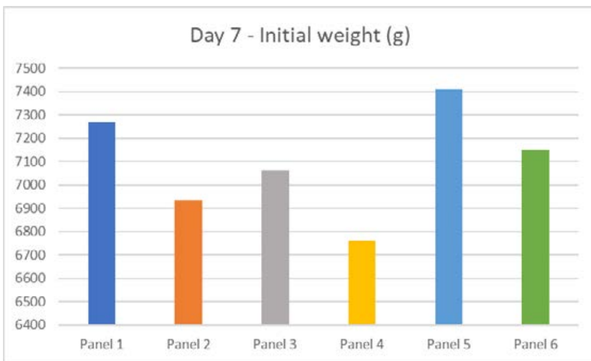




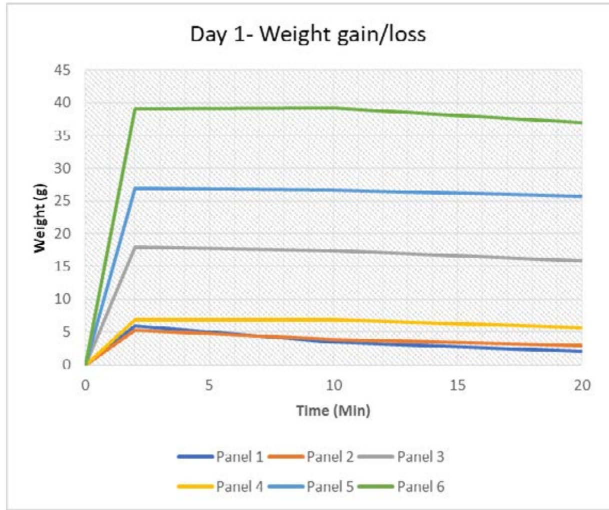


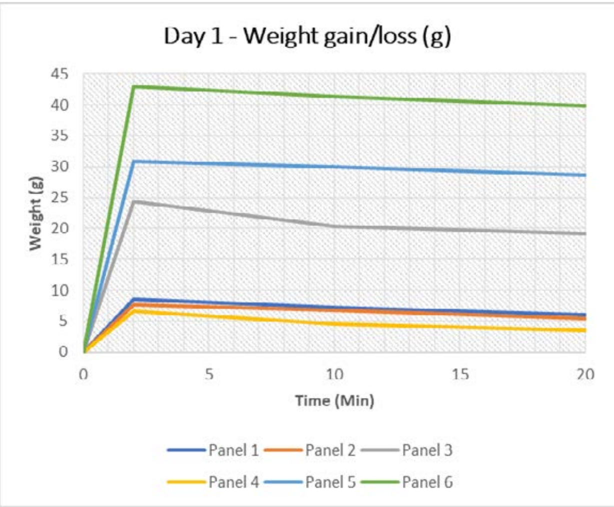


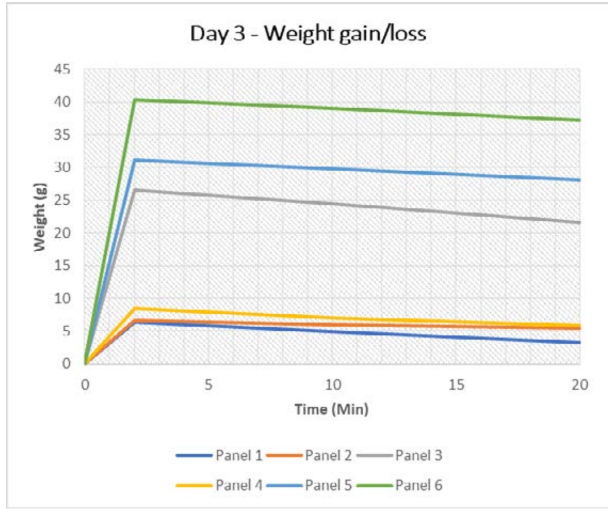


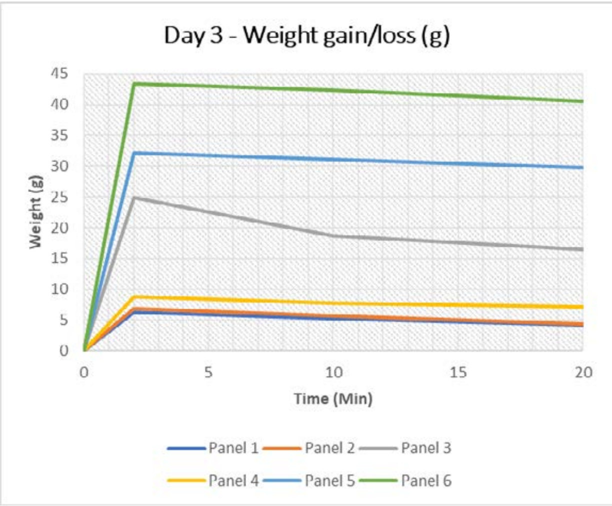


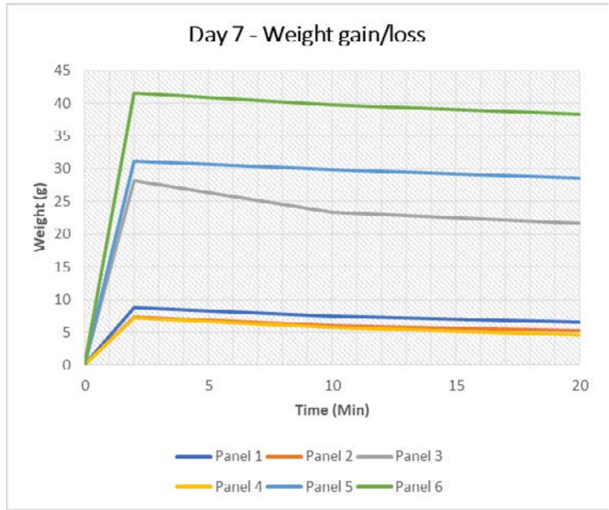
Weight loss/gain **SET 1** **SET 2**

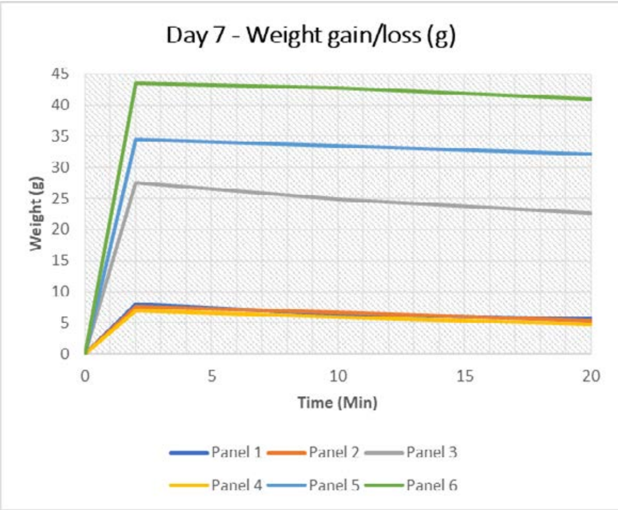






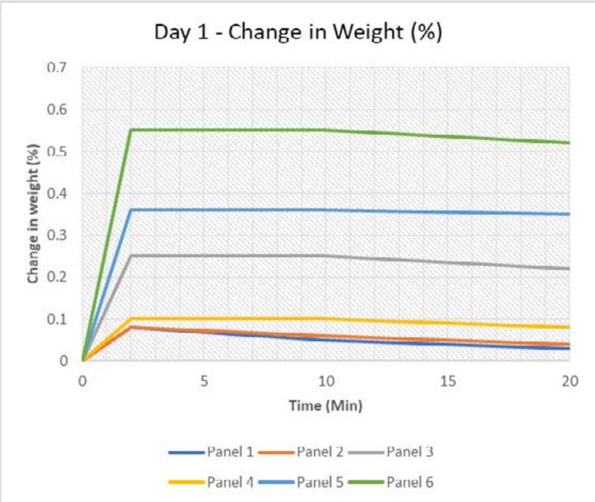


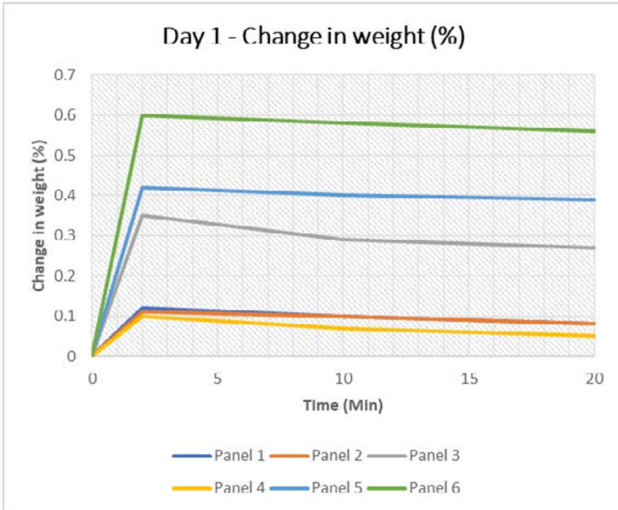


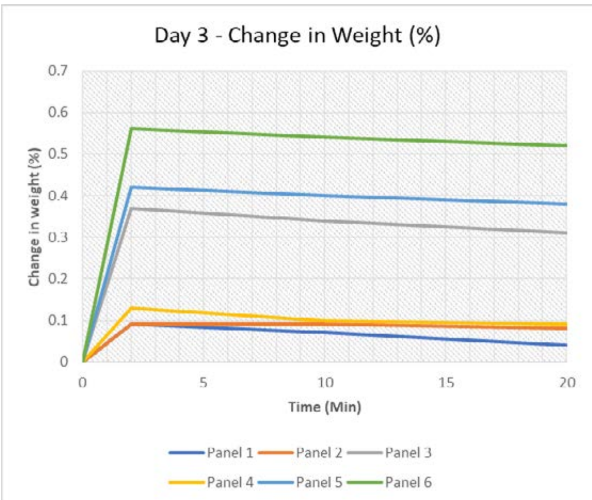


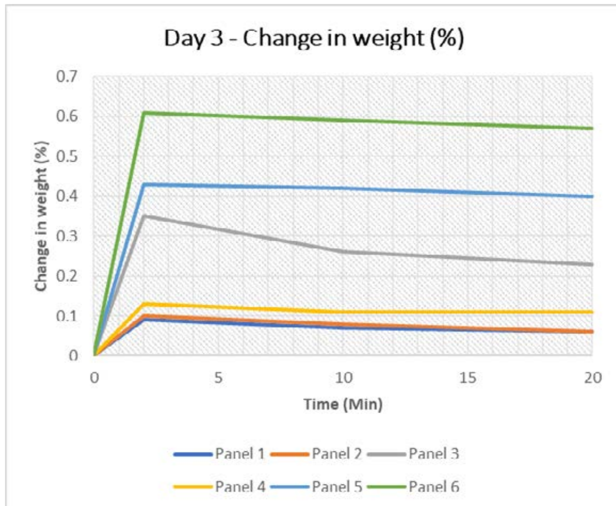
Change in weight

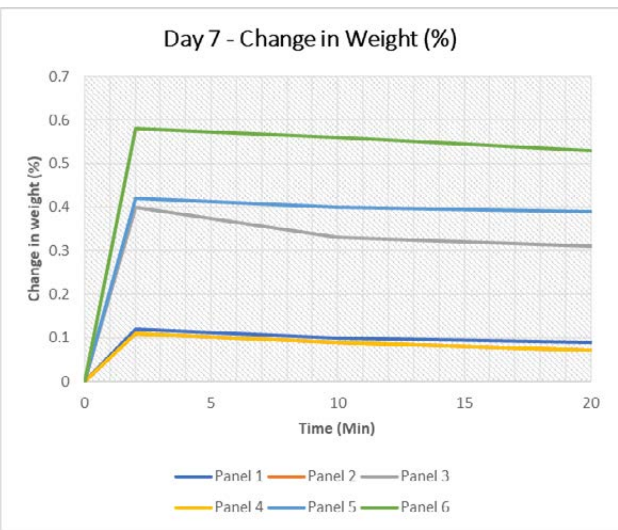
SET 1 **SET 2**

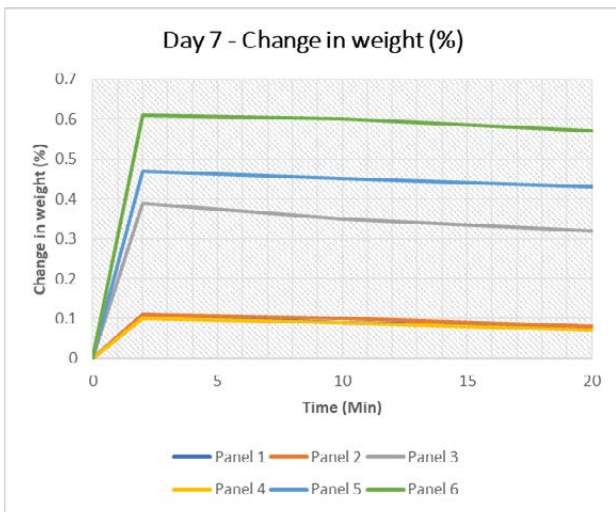






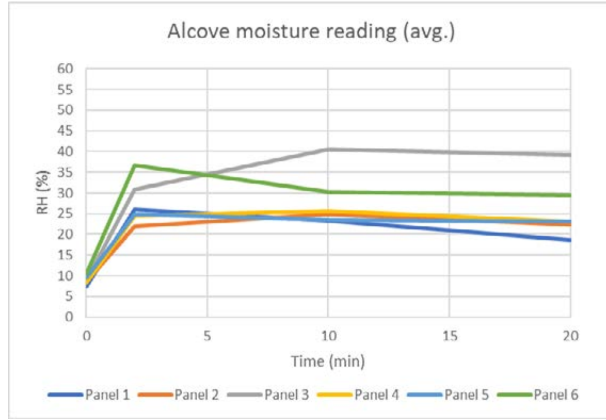


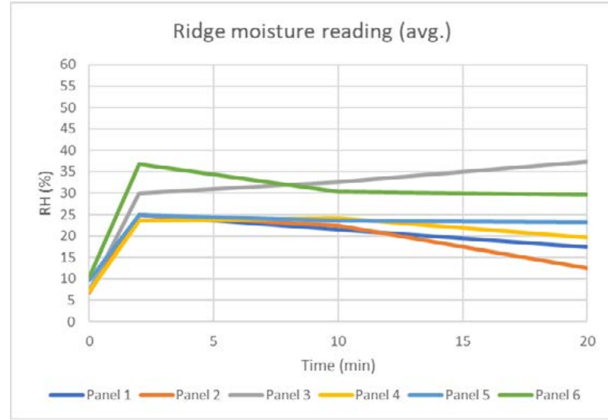


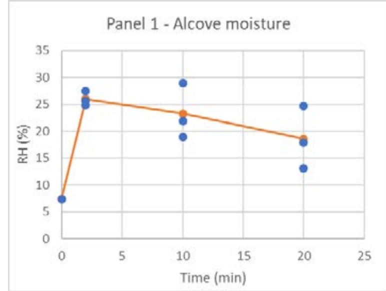


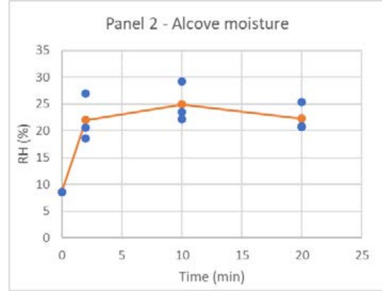
Surface humidity

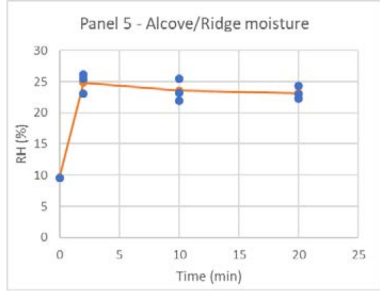
SET 1 - DAY 1

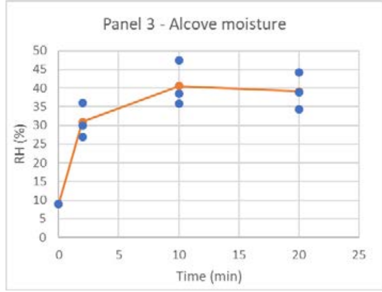


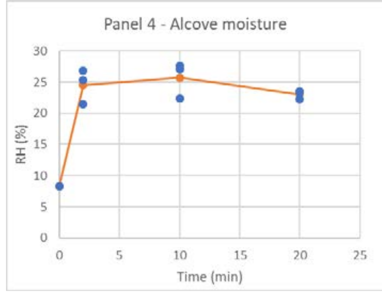


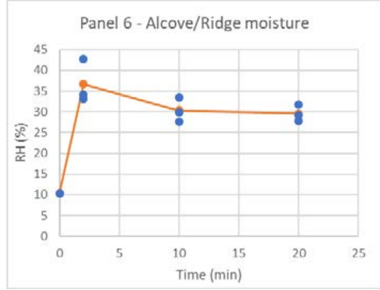


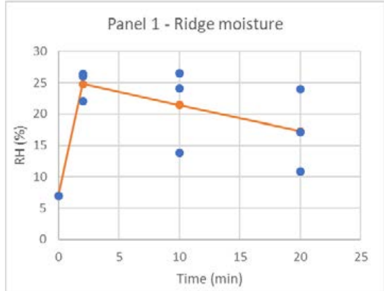


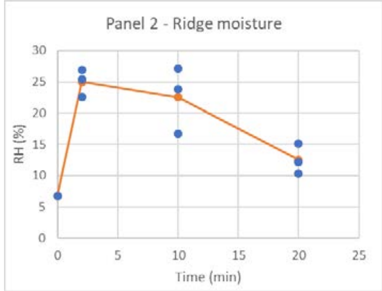


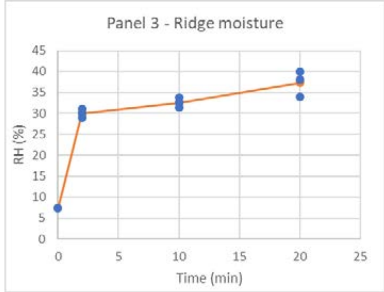


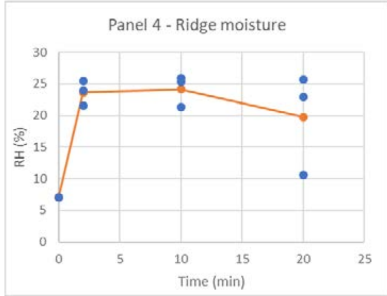












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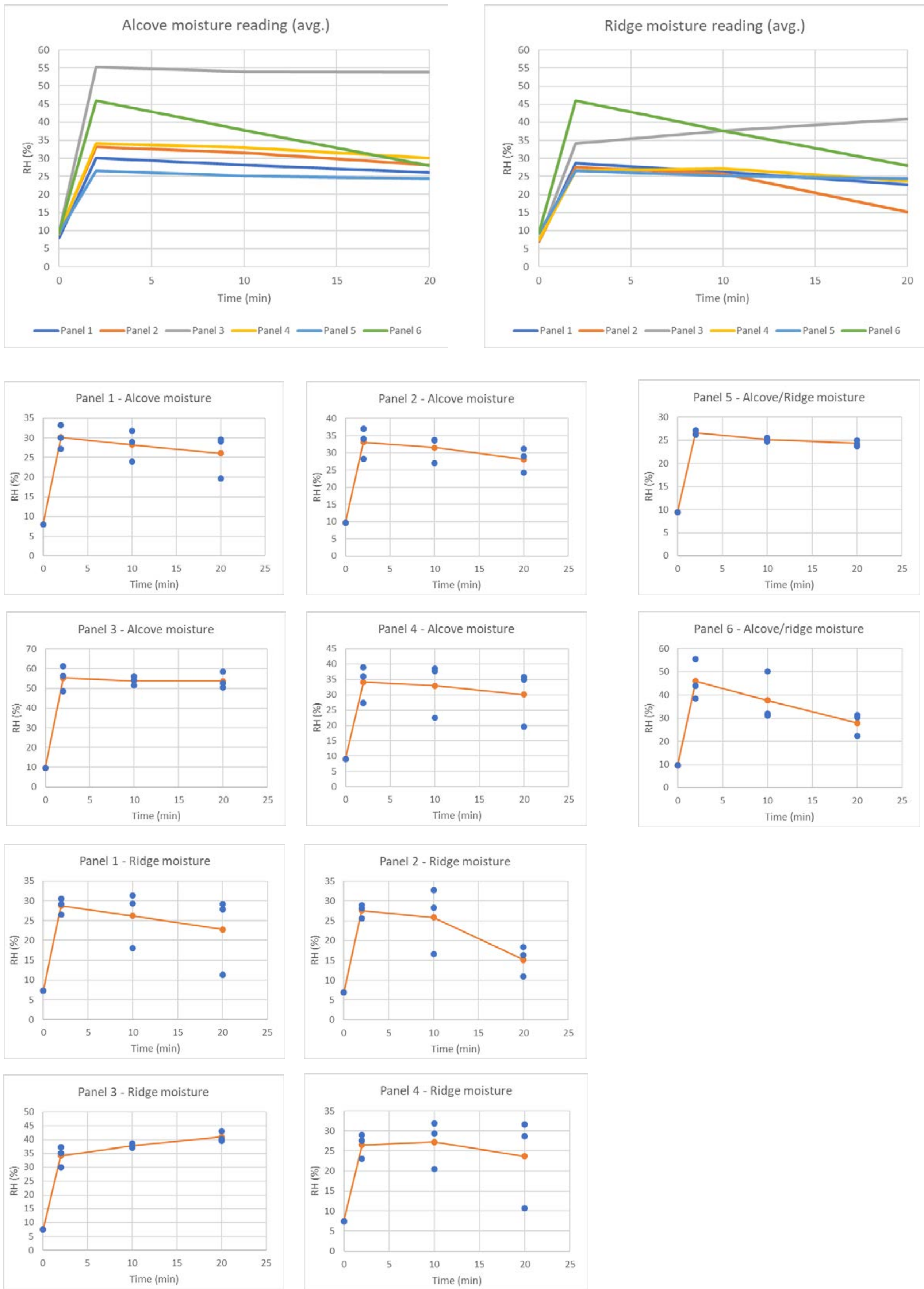
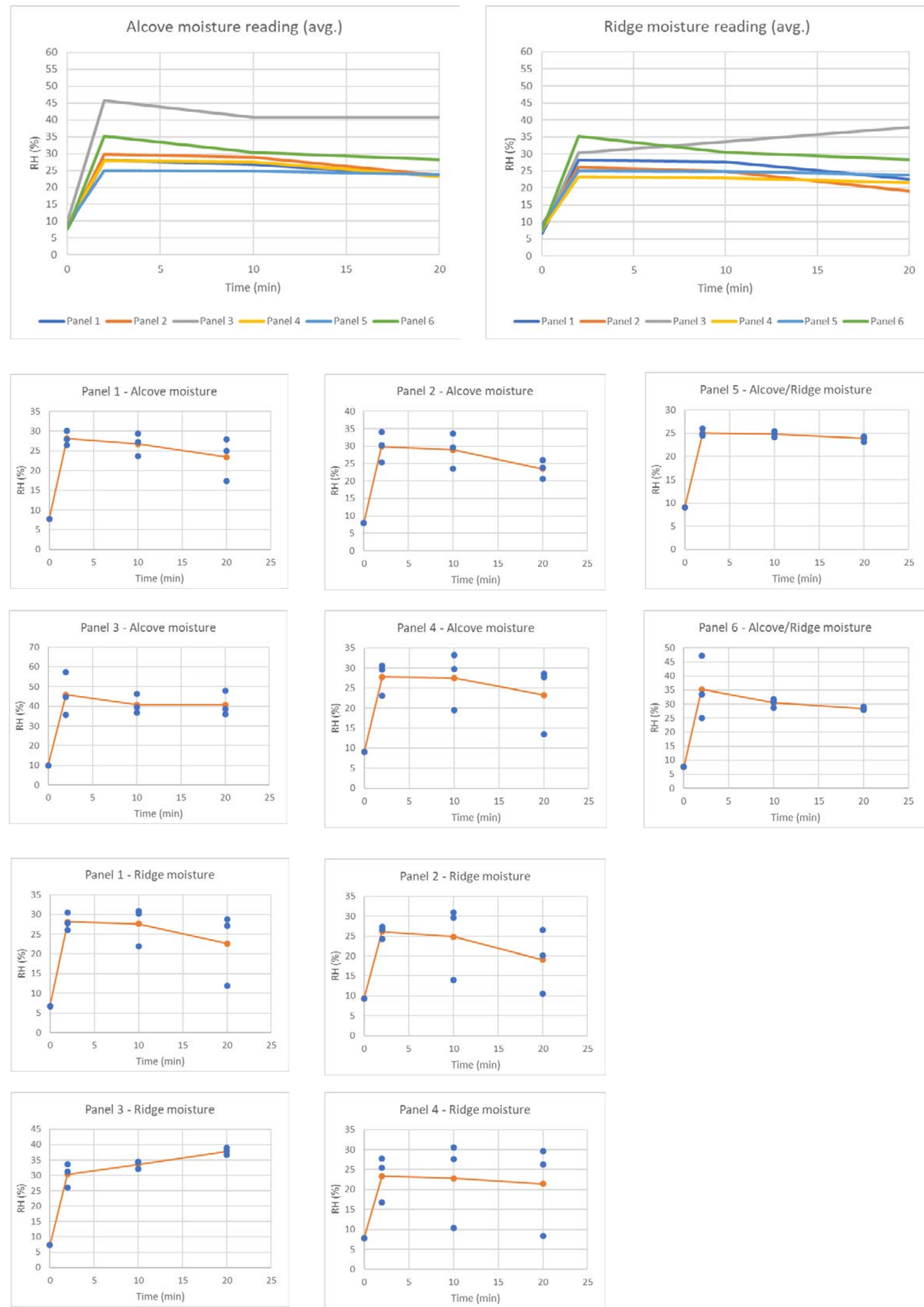


SET 1 - DAY 7



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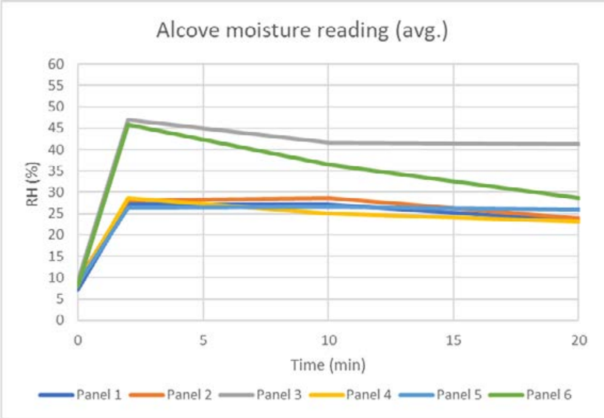

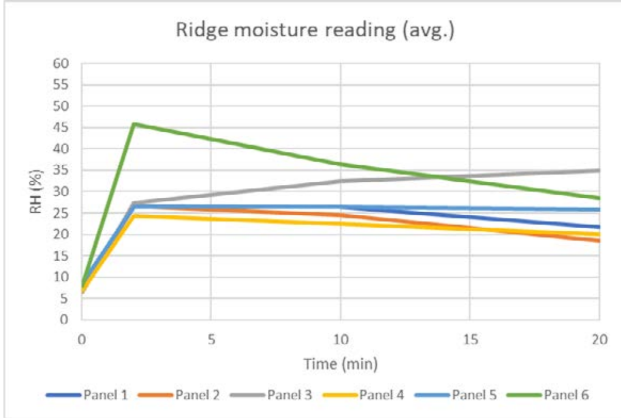

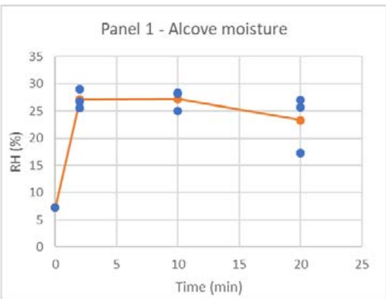

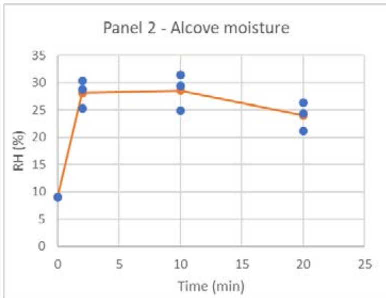

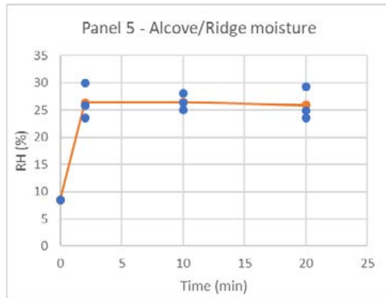

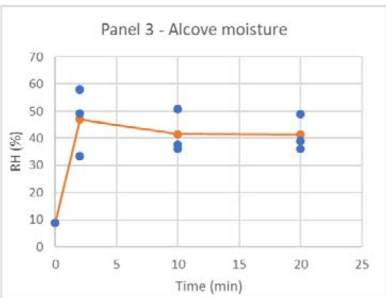

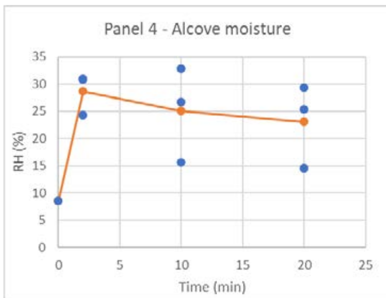

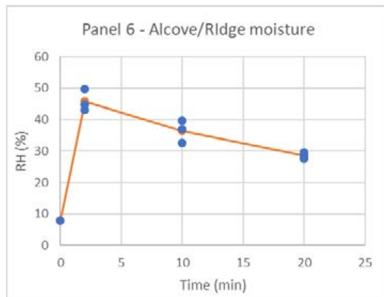

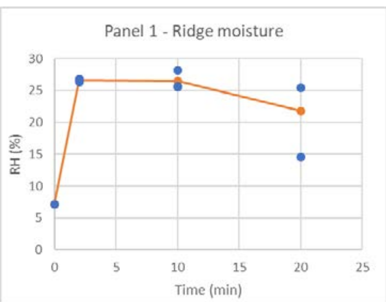

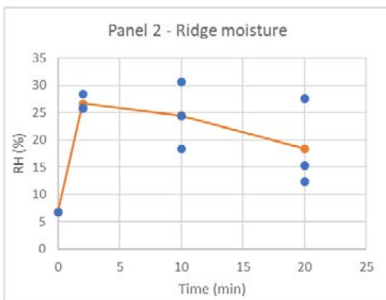

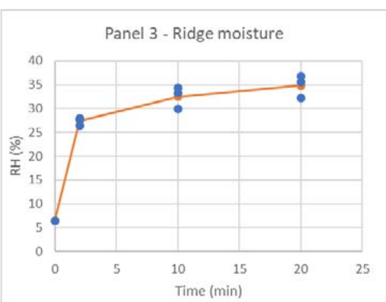

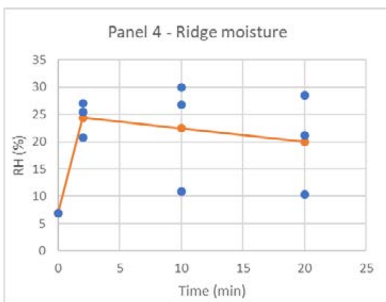

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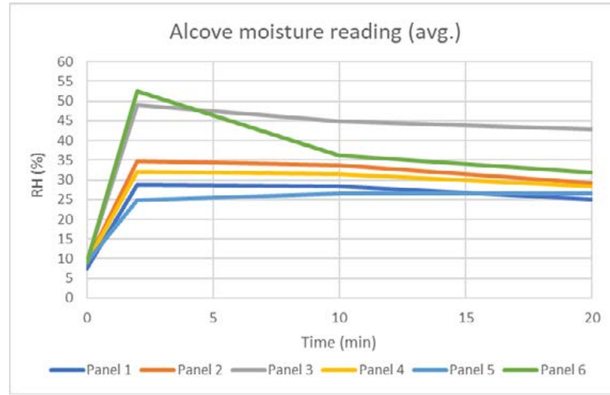
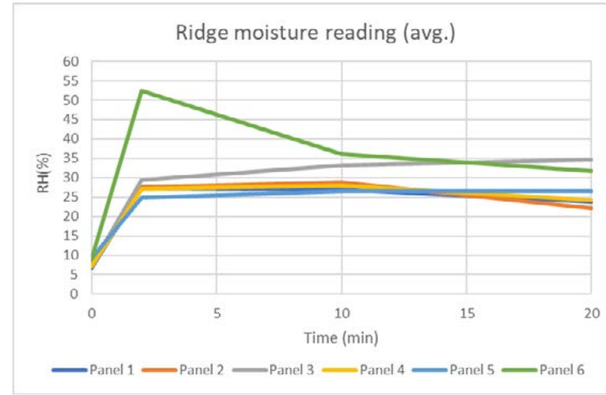
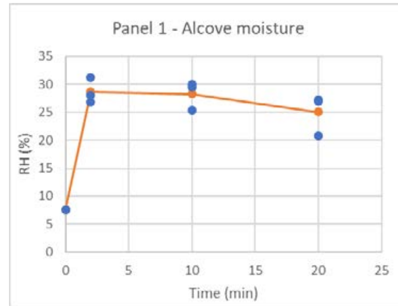
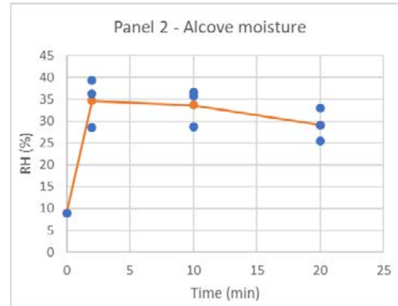
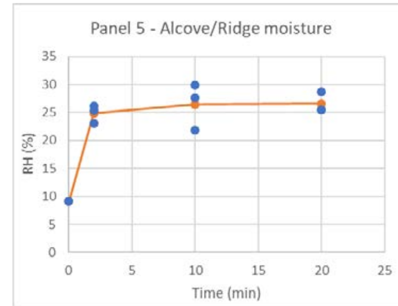
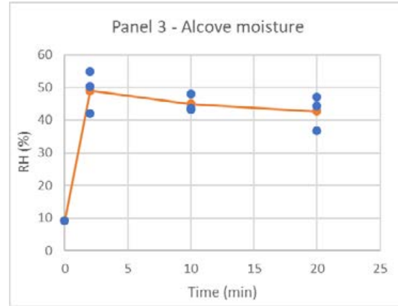


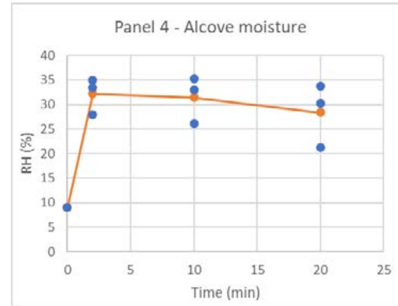


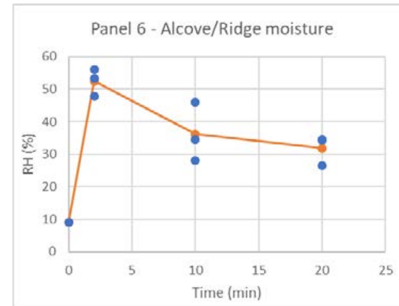


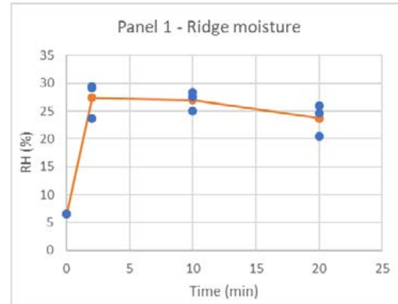


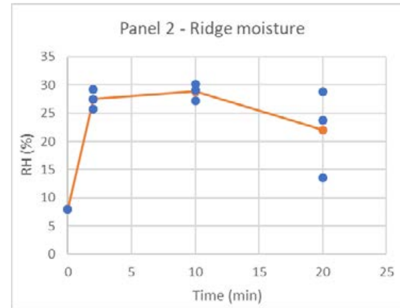


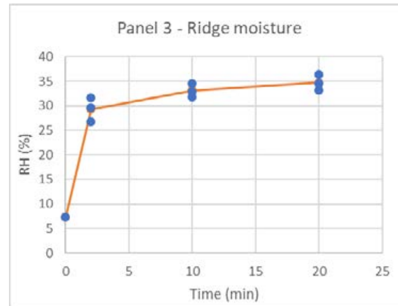


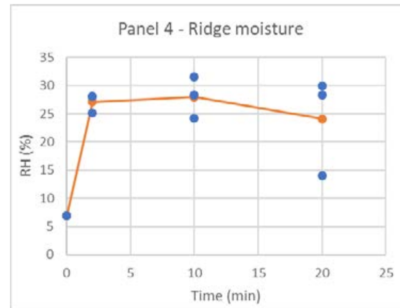




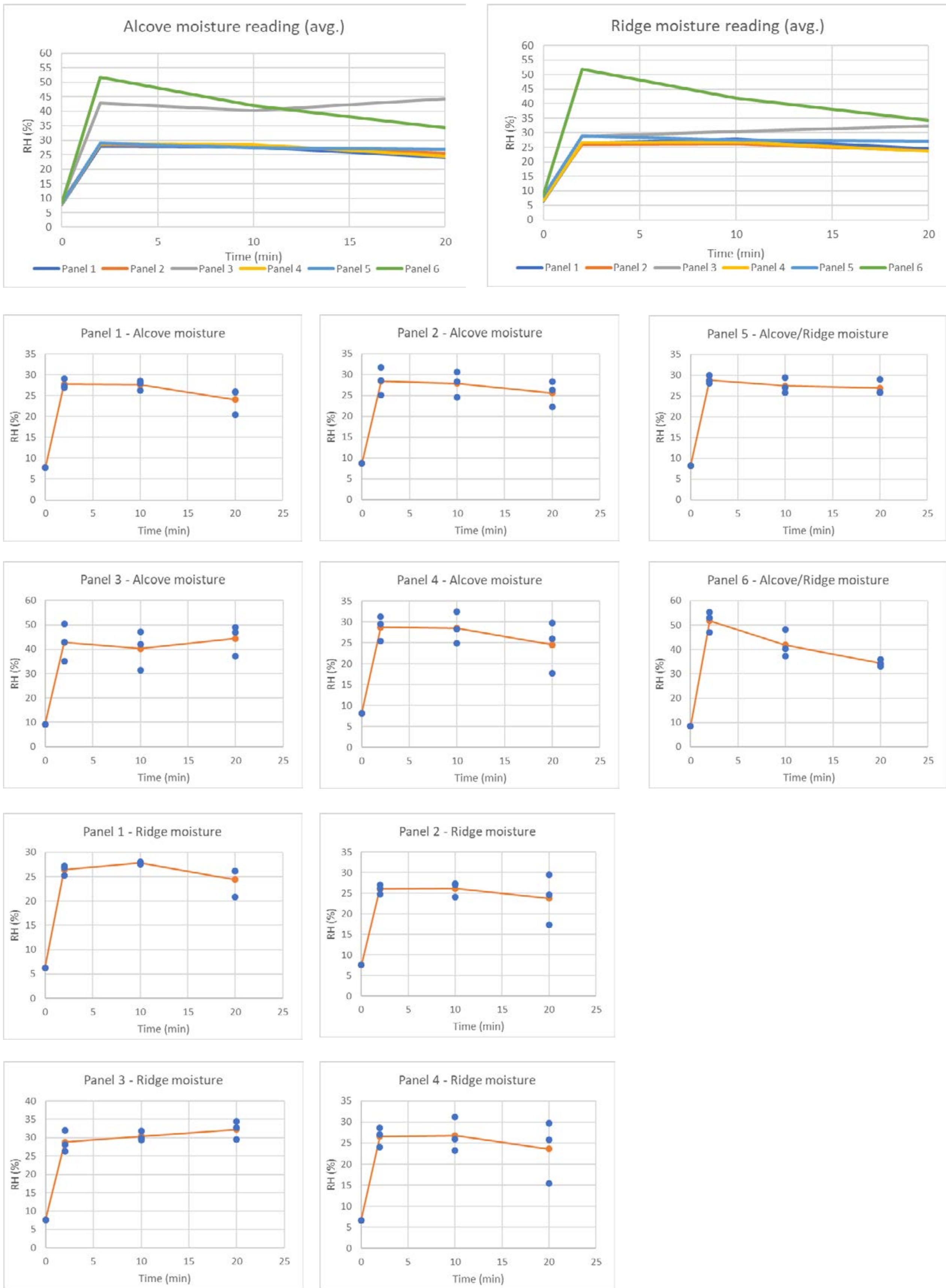




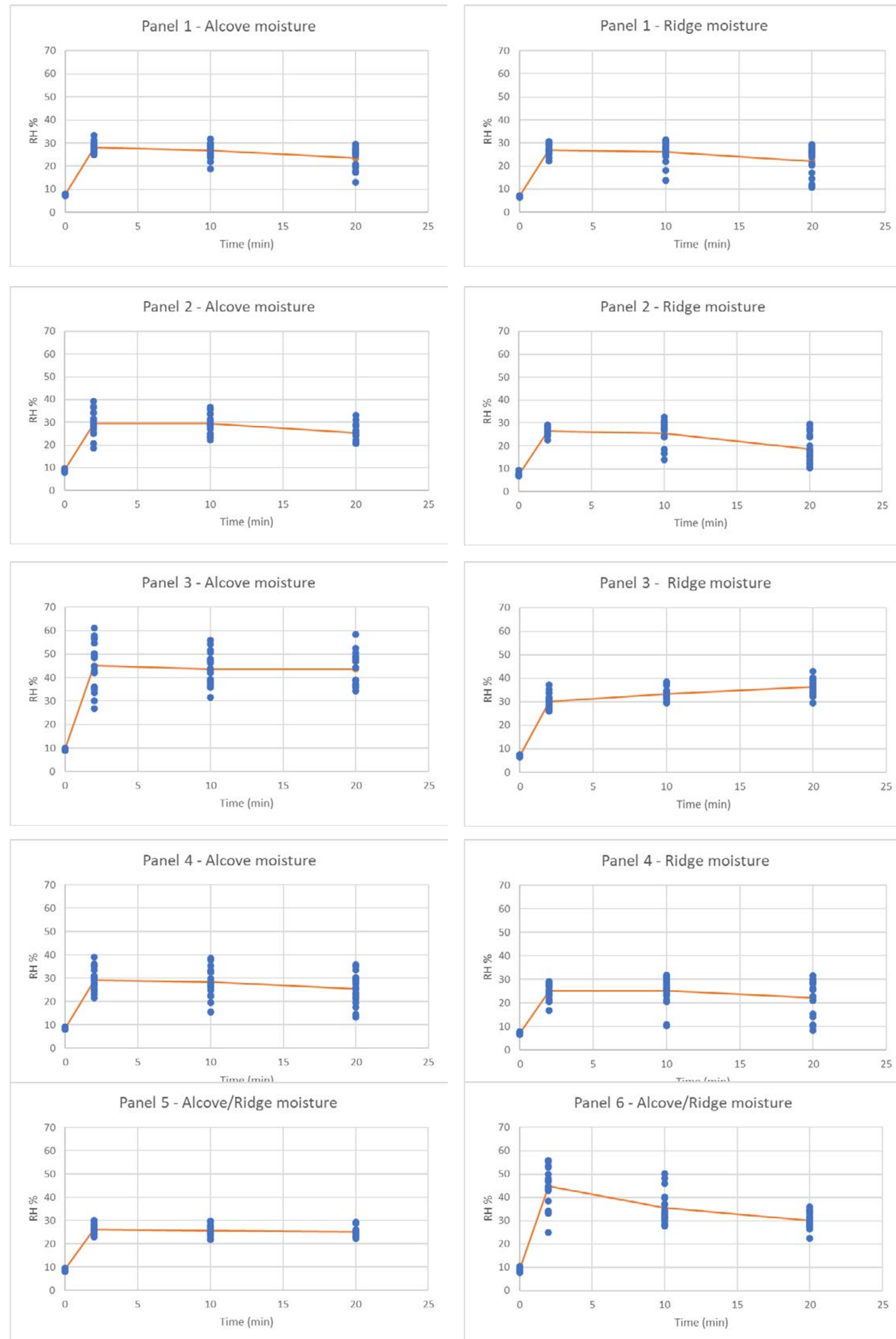




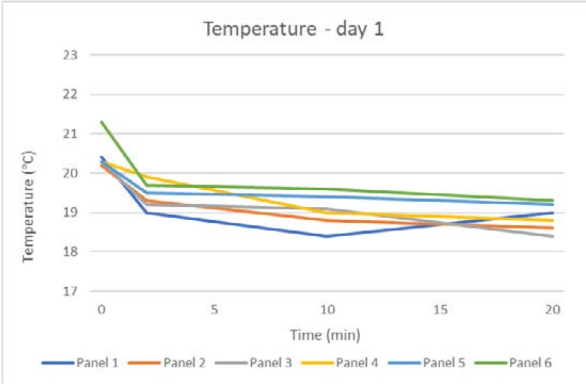
SET 2 - DAY 7

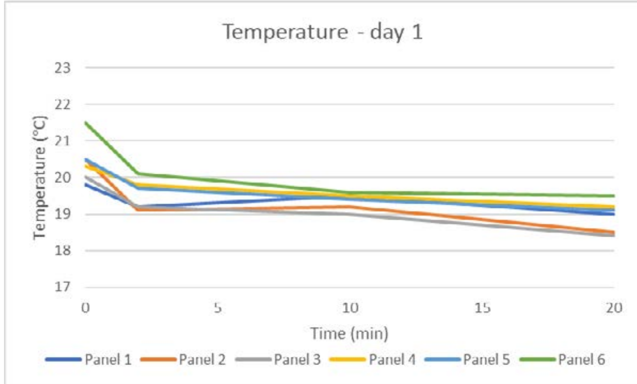


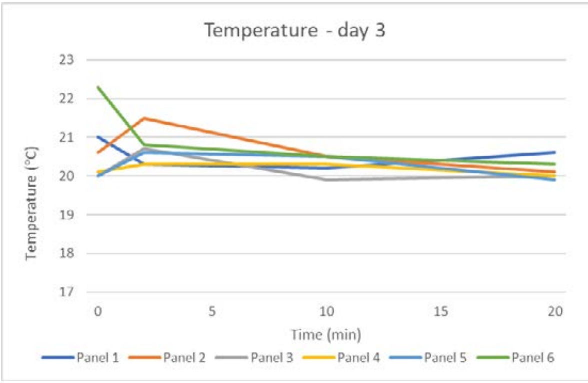
Accumulated surface humidity results

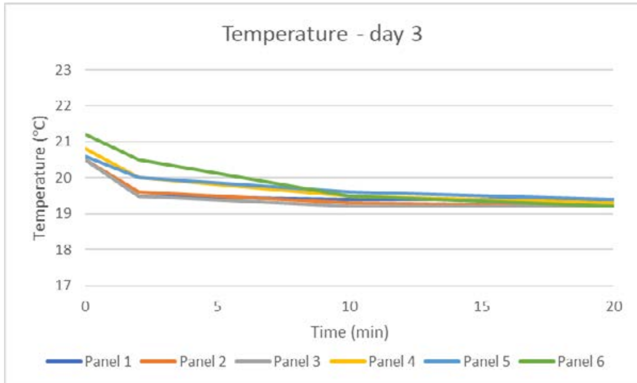


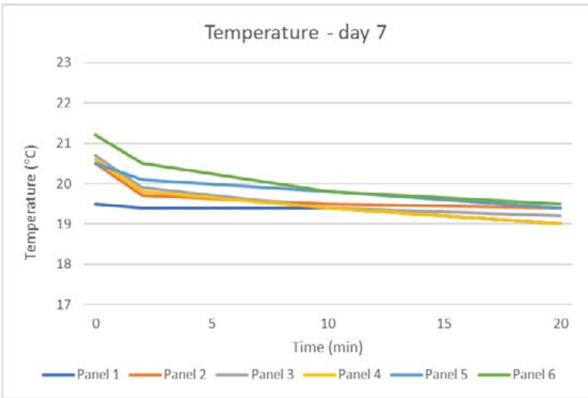
Temperature **SET 1** **SET 2**

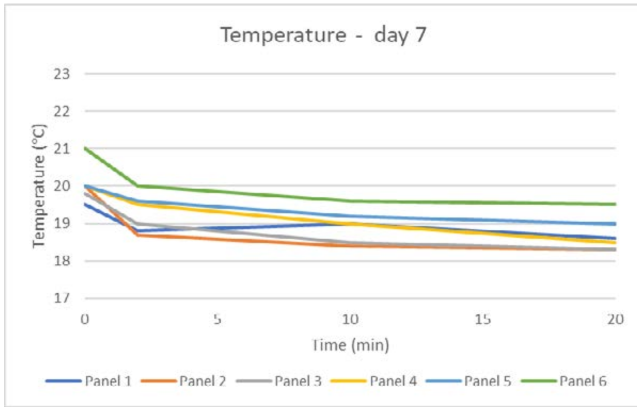






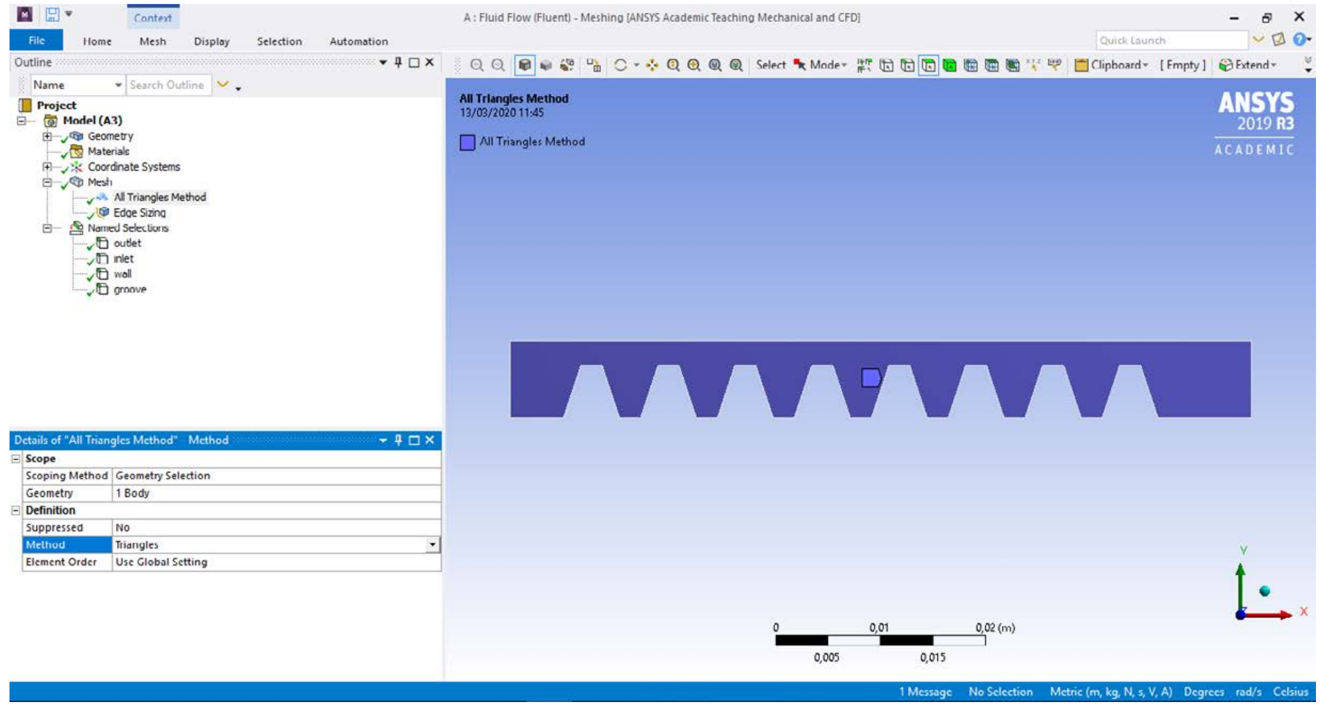




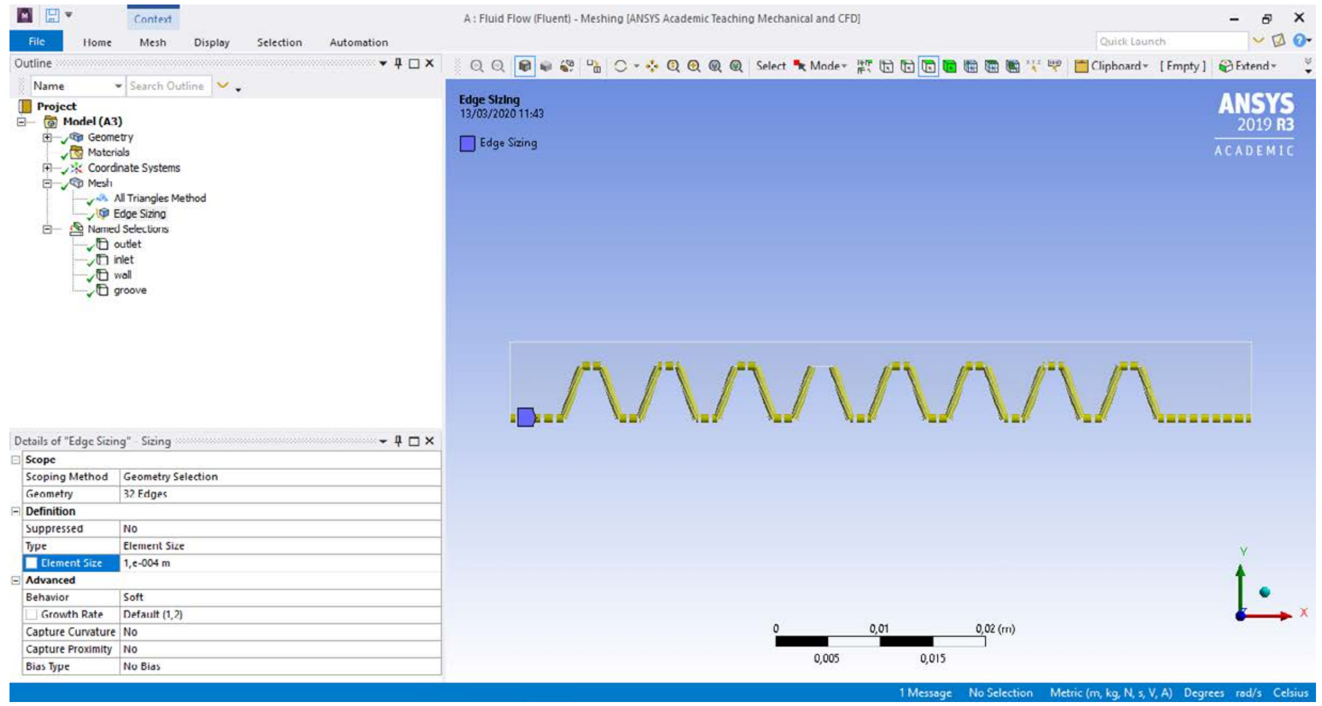


14.3. Setup for Ansys Fluent

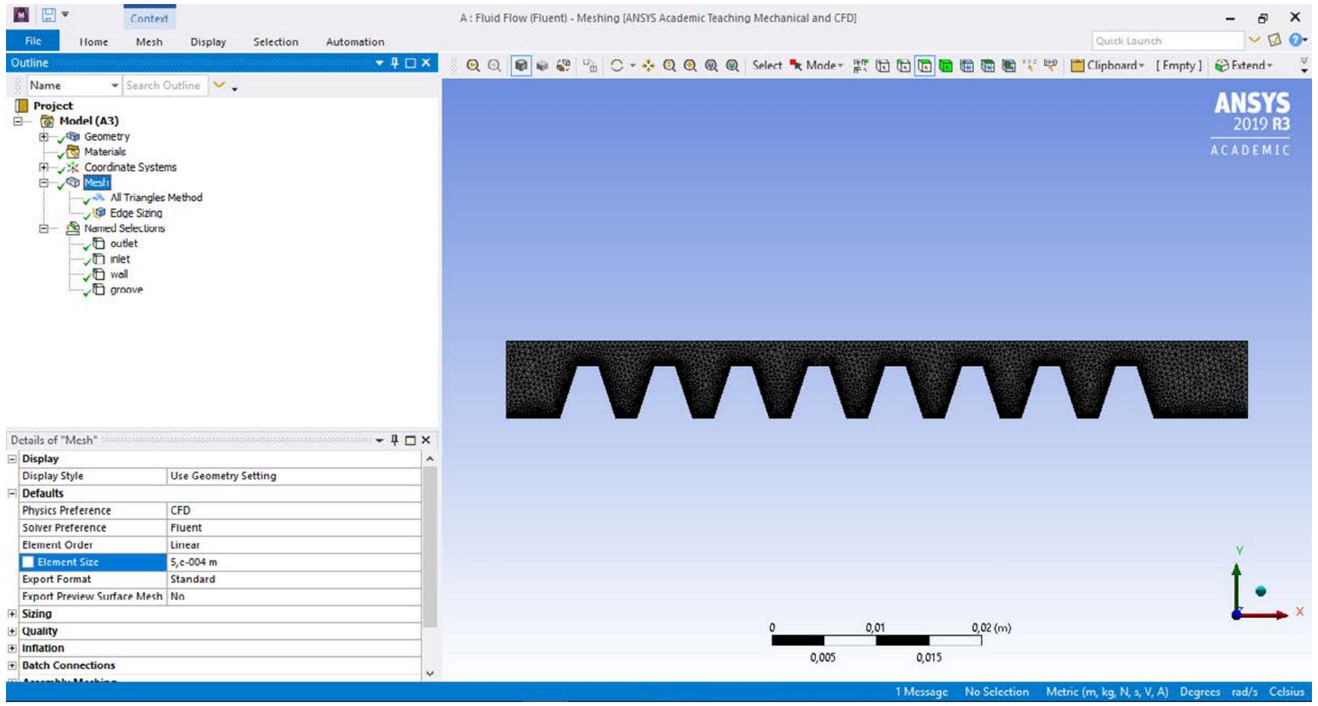
Step 1 Meshing



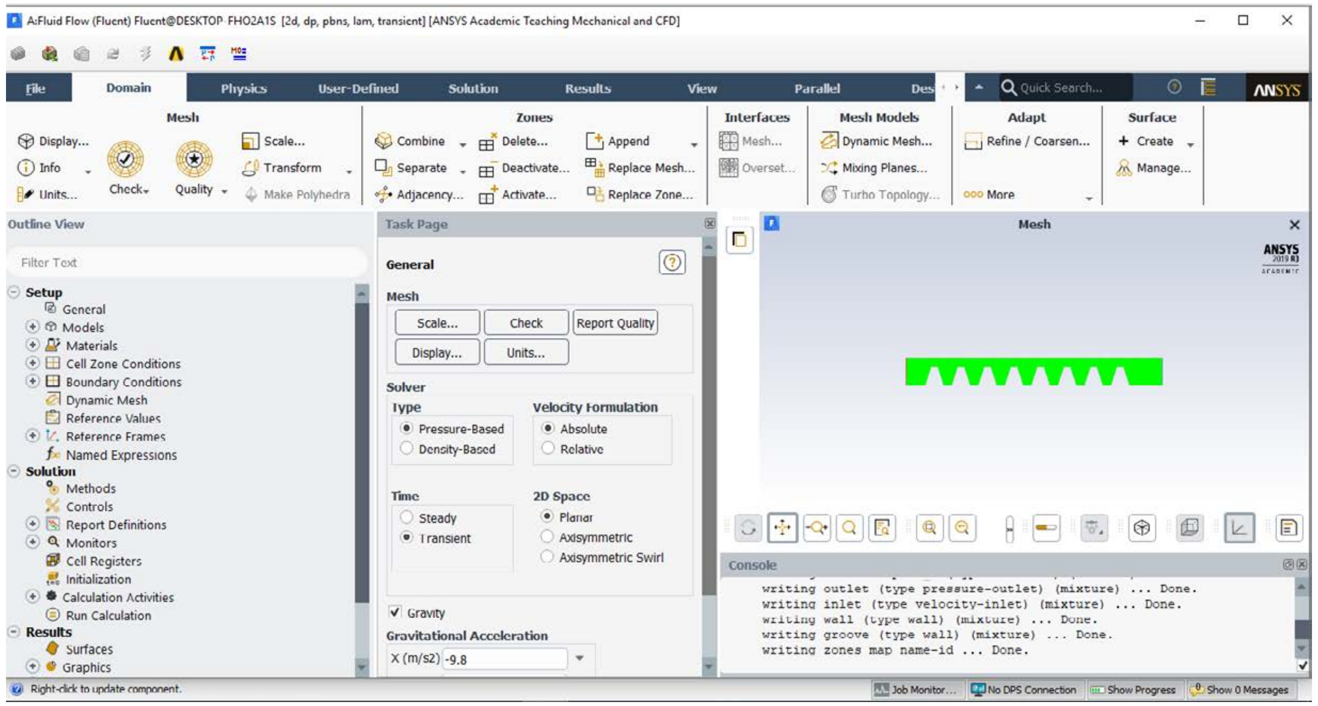
Step 2 Meshing



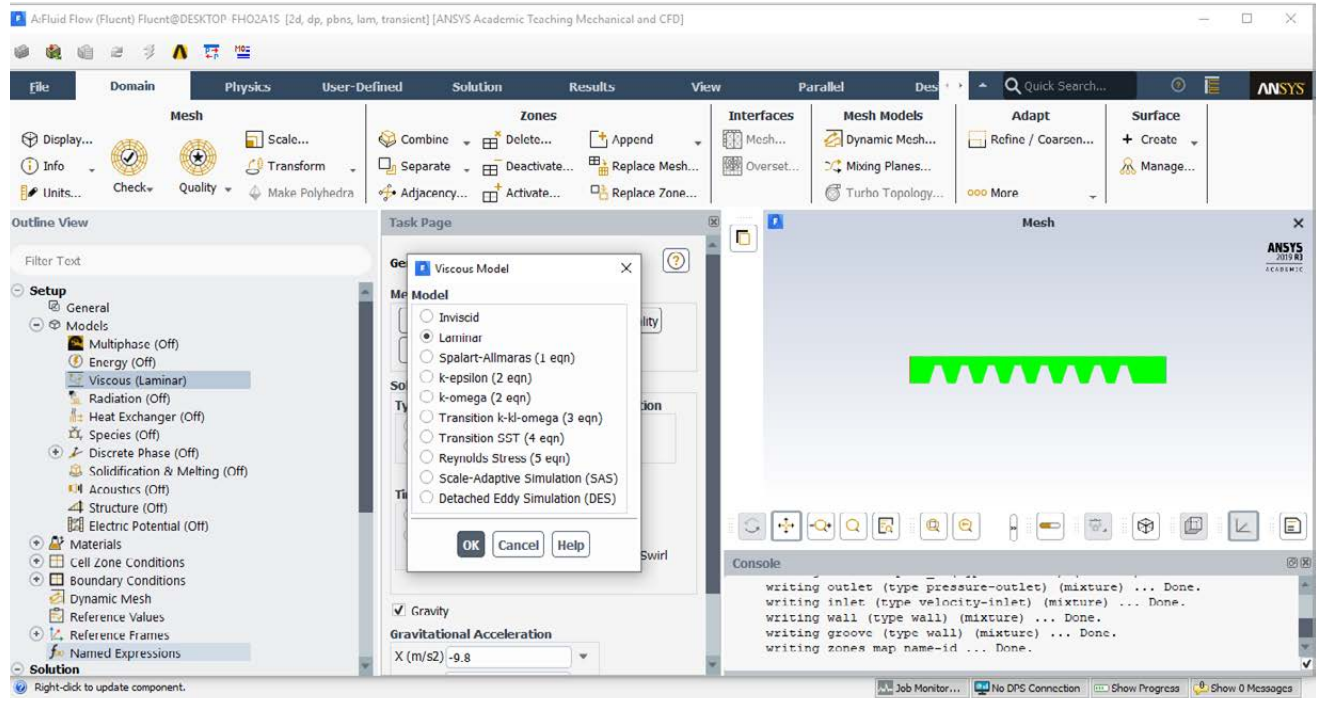
Step 3 Meshing



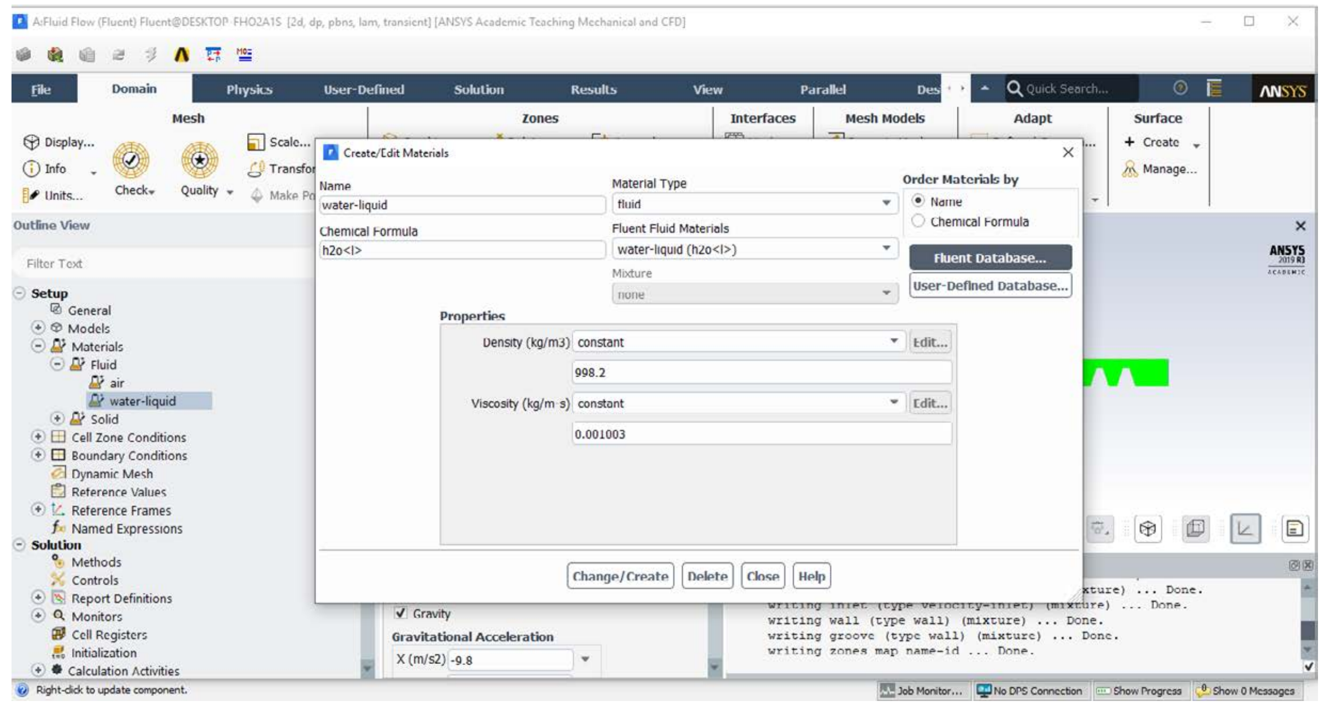
Step 4 General setup



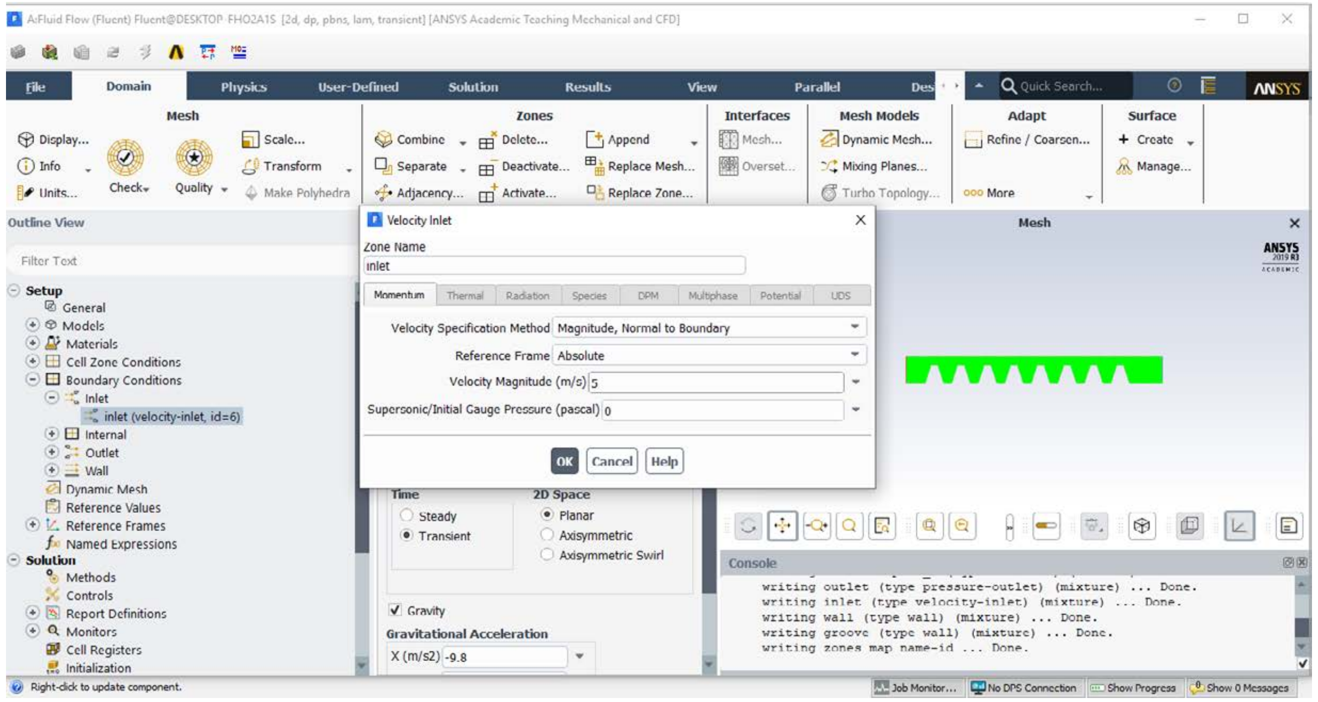
Step 5 Model setup



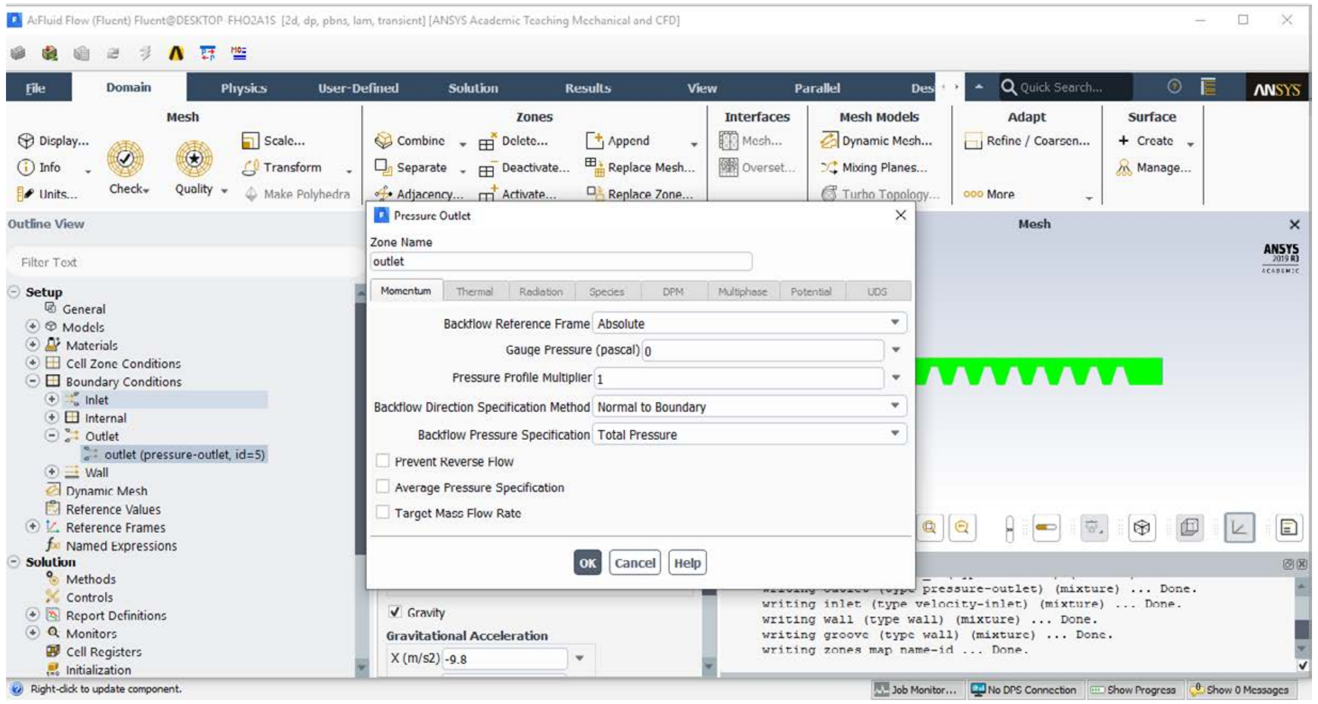
Step 6 Material setup



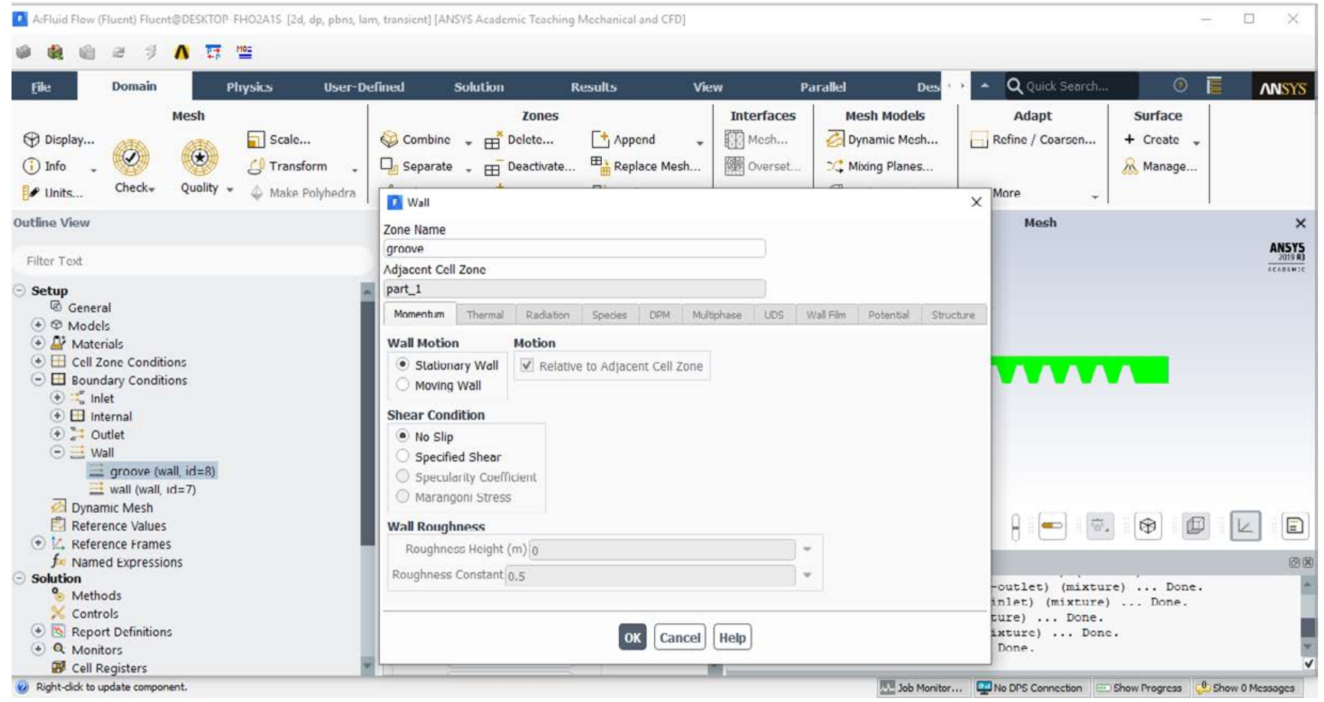
Step 7 Inlet boundary conditions



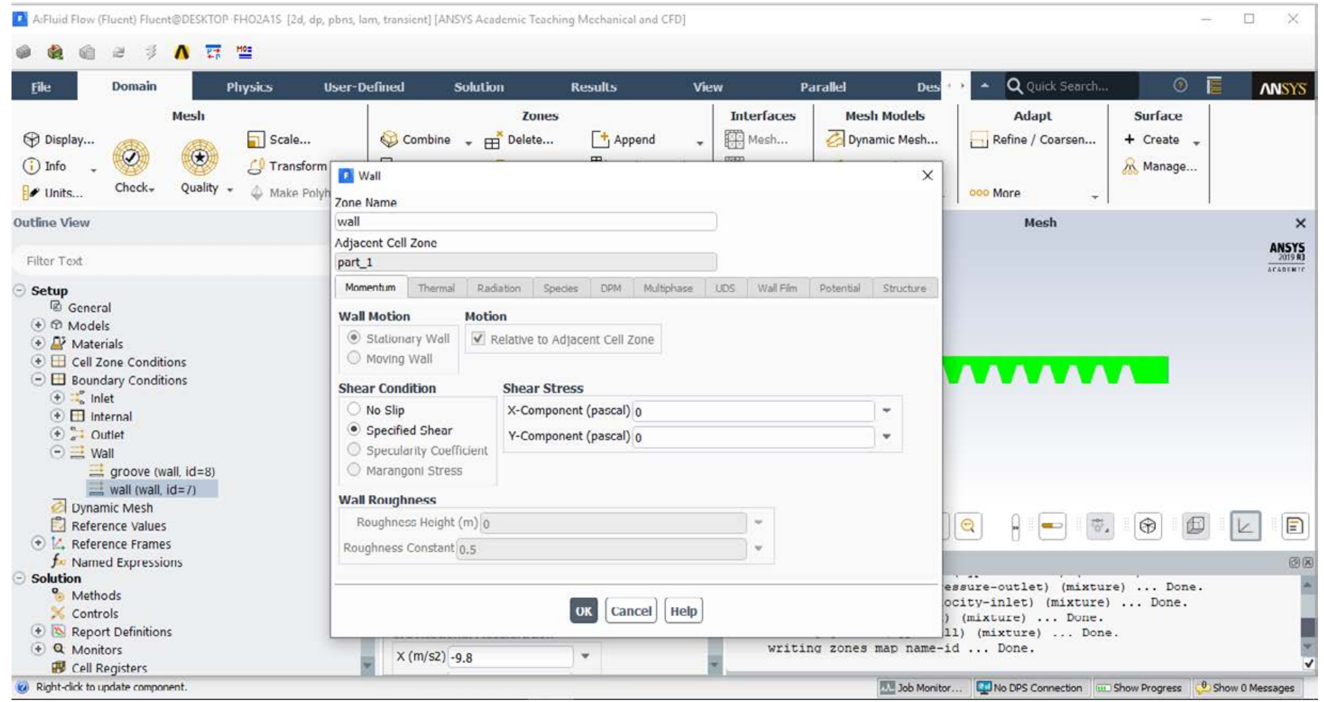
Step 8 Outlet boundary conditions



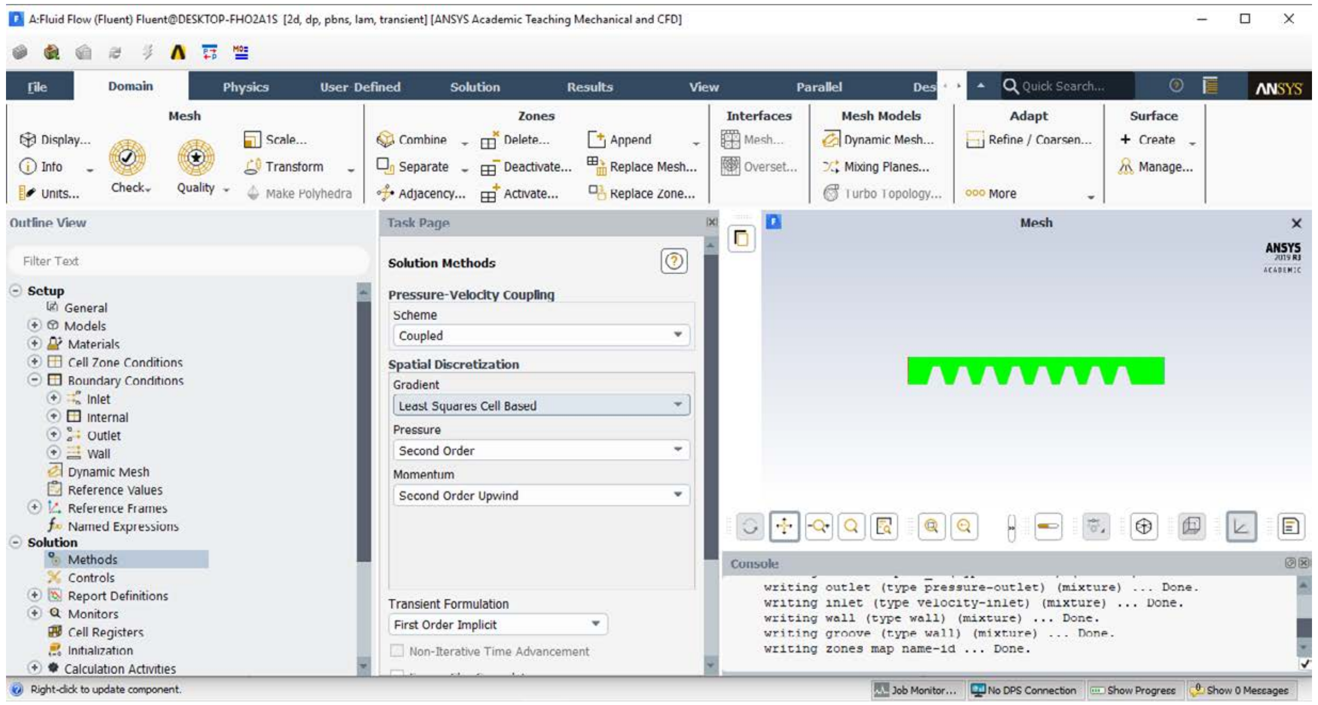
Step 9 Groove boundary conditions



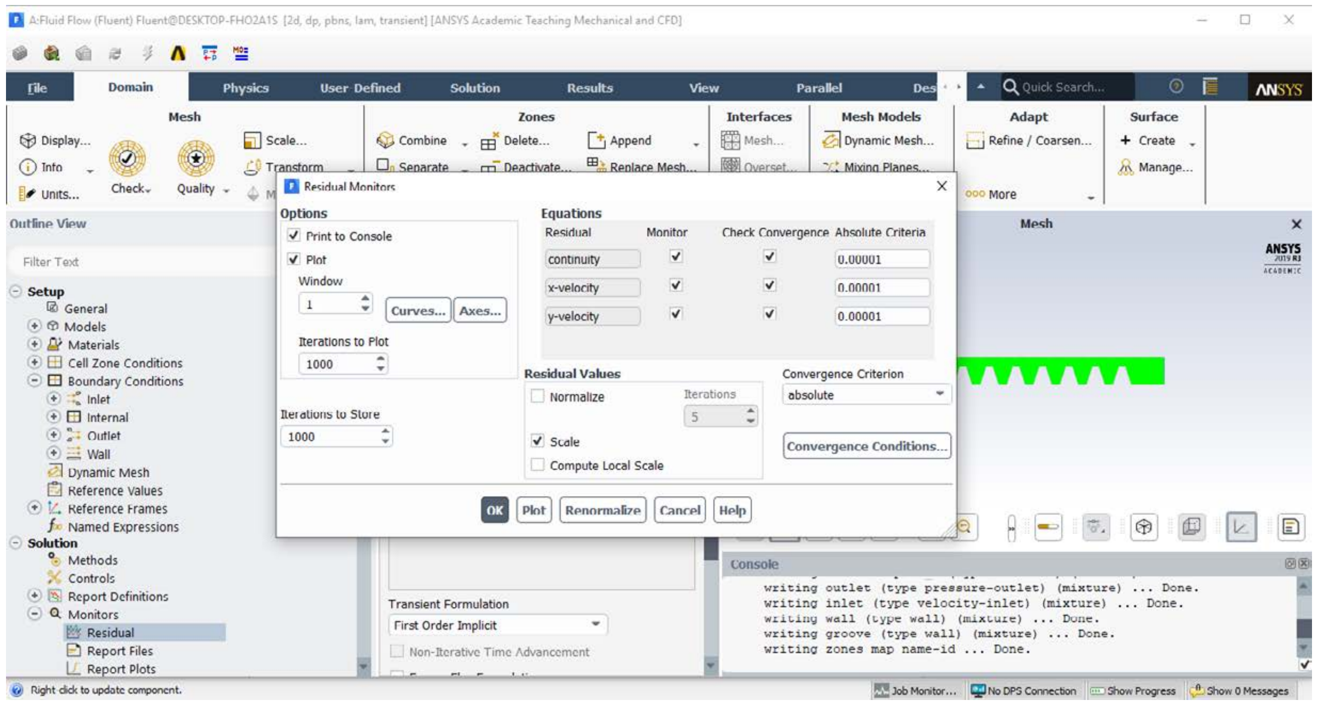
Step 10 Wall boundary conditions



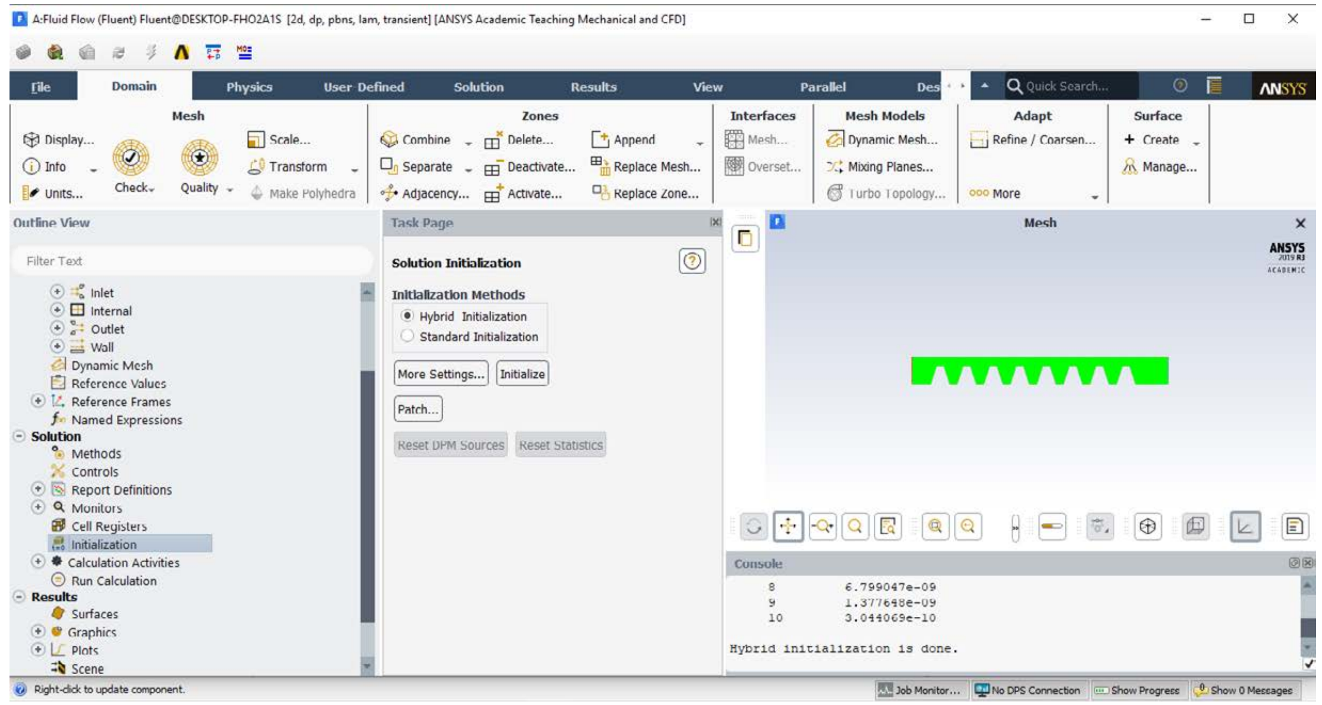
Step 11 Solution method



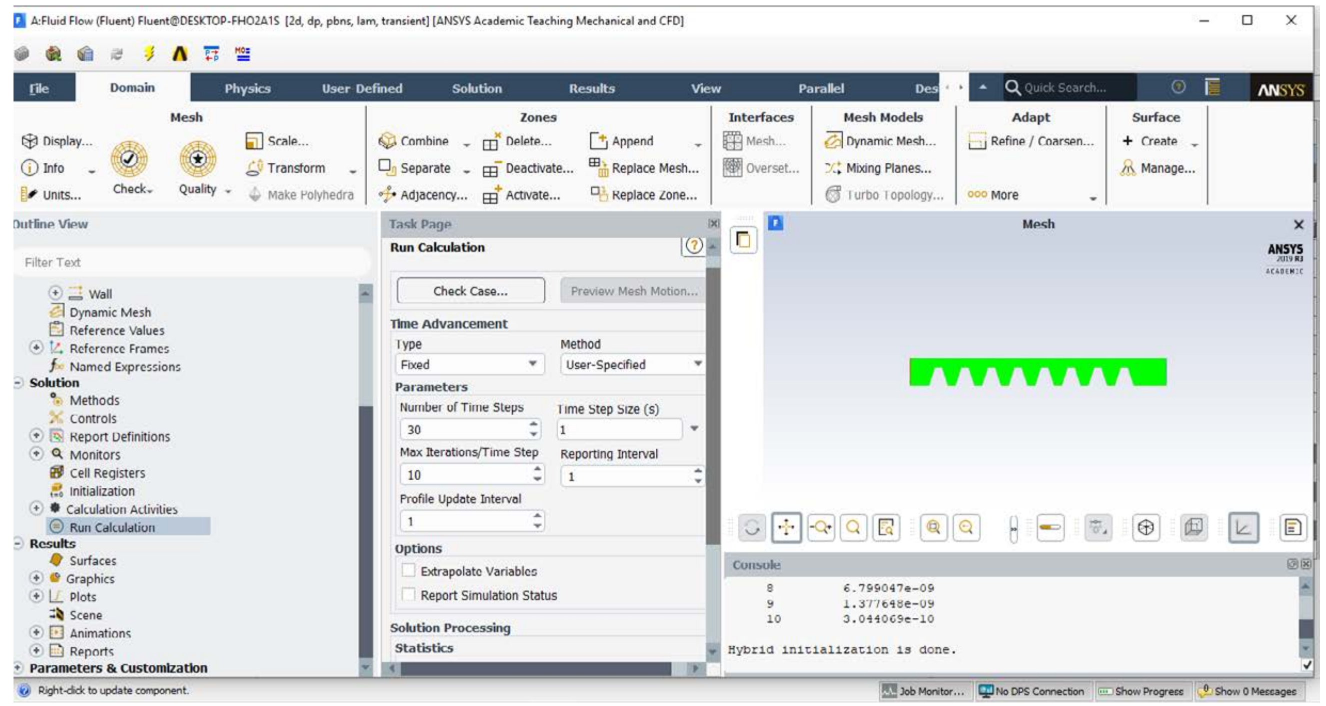
Step 12 Monitoring



Step 13 Initialization

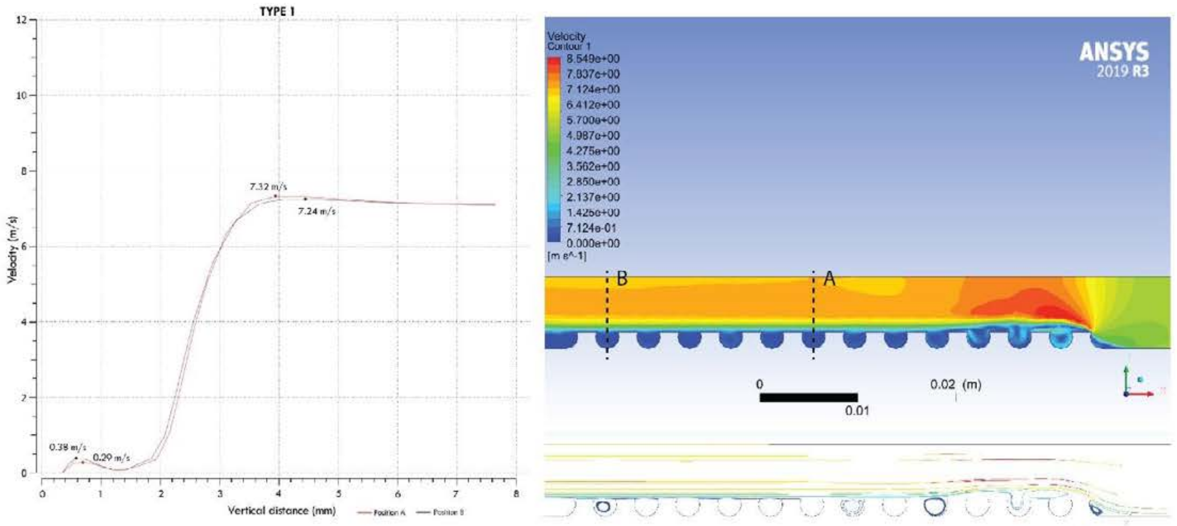


Step 14 Run calculation

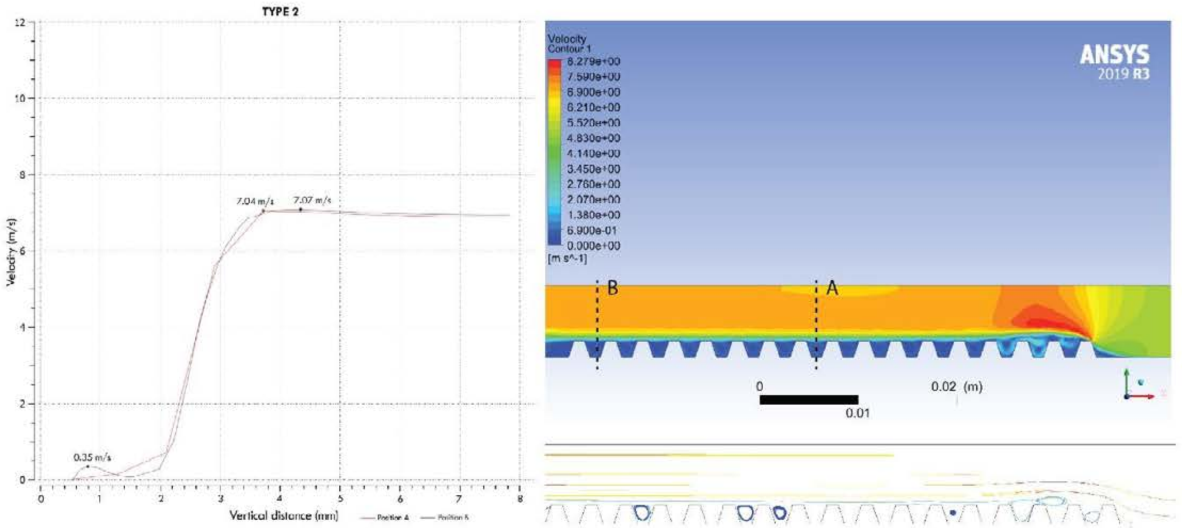


14.4. Graphs for Ansys Simulation results

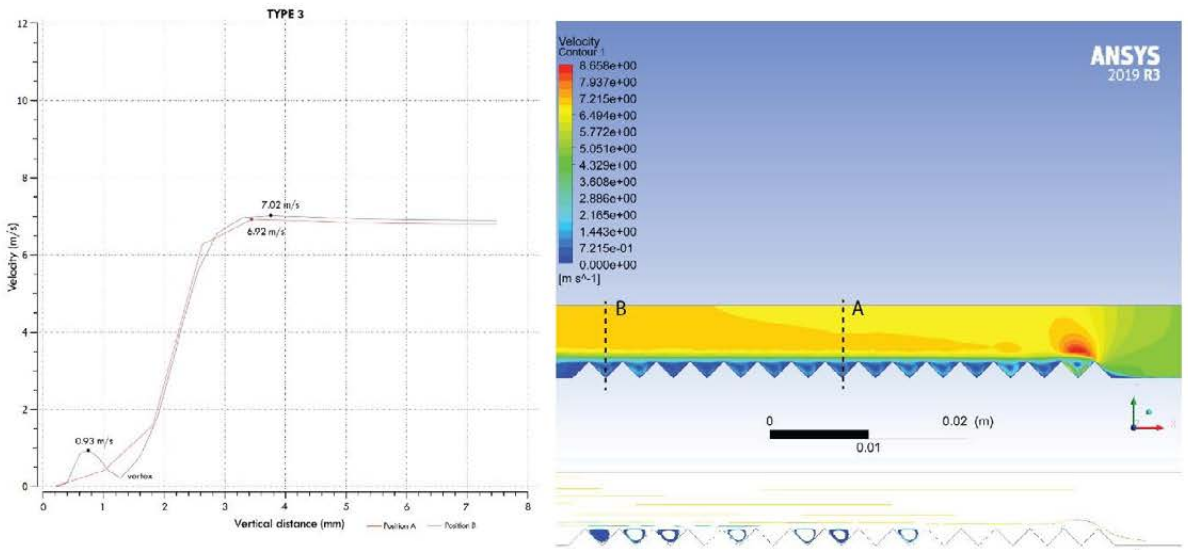
Stage 1 Different options



Vertex formation

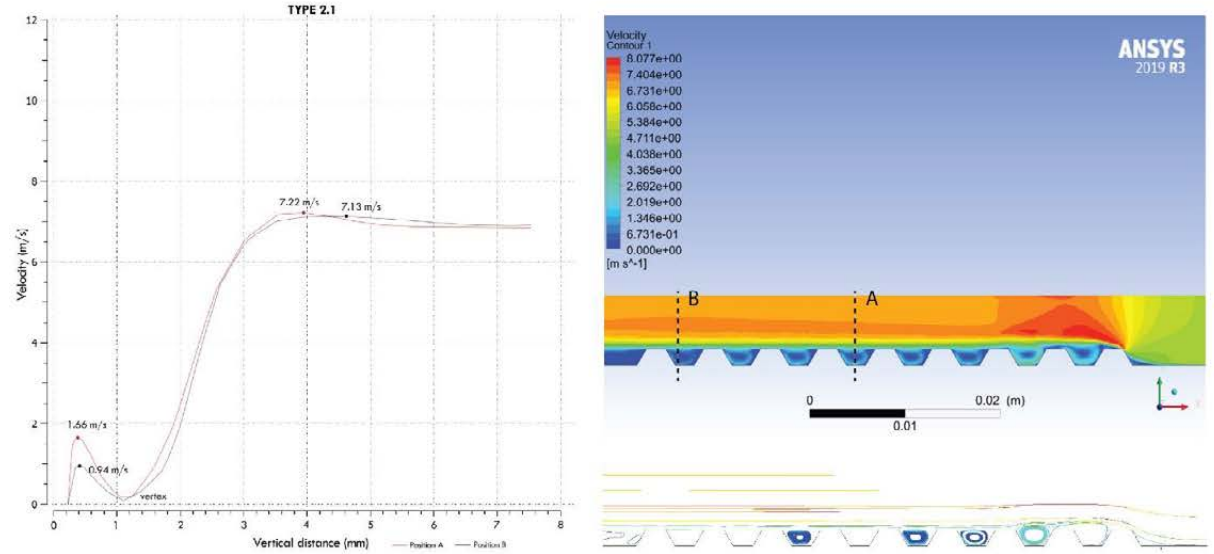


Vertex formation

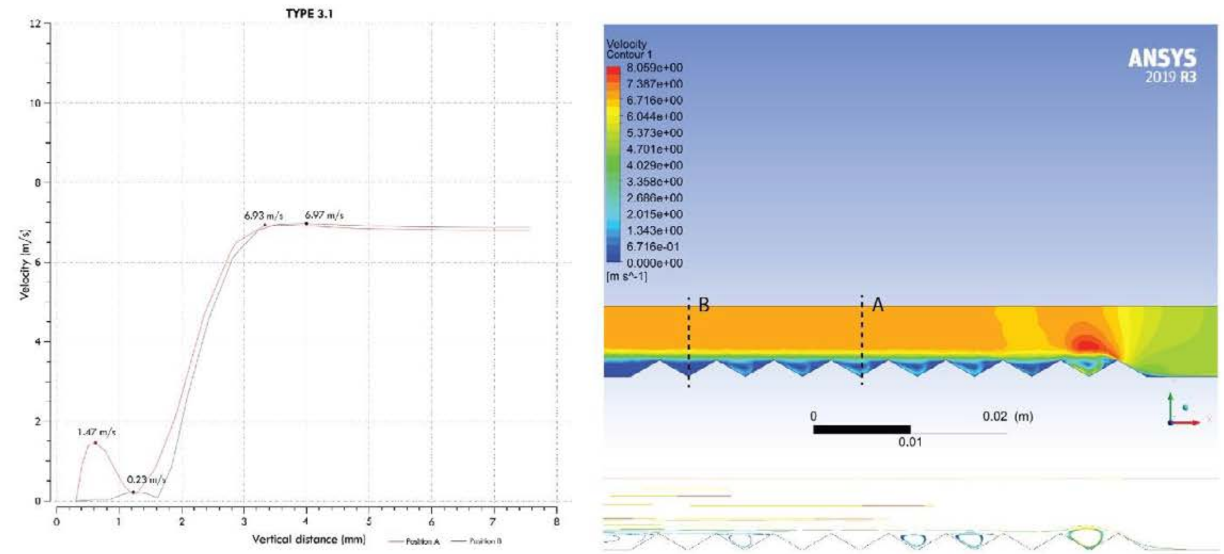


Vertex formation

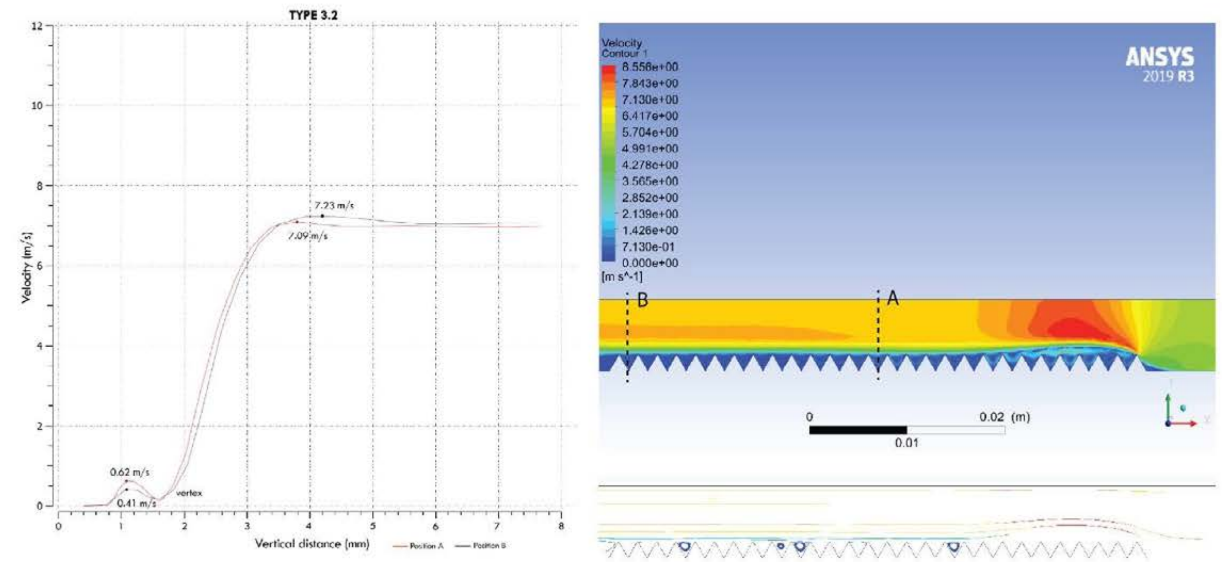
Stage 2 (width)



Vertex formation

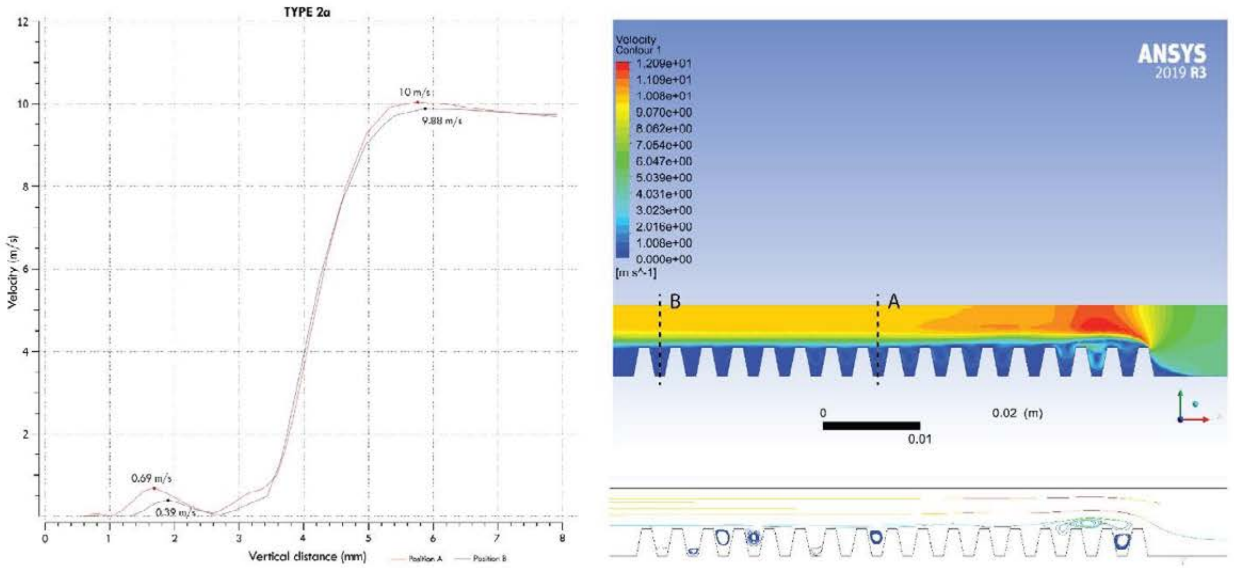


Vertex formation

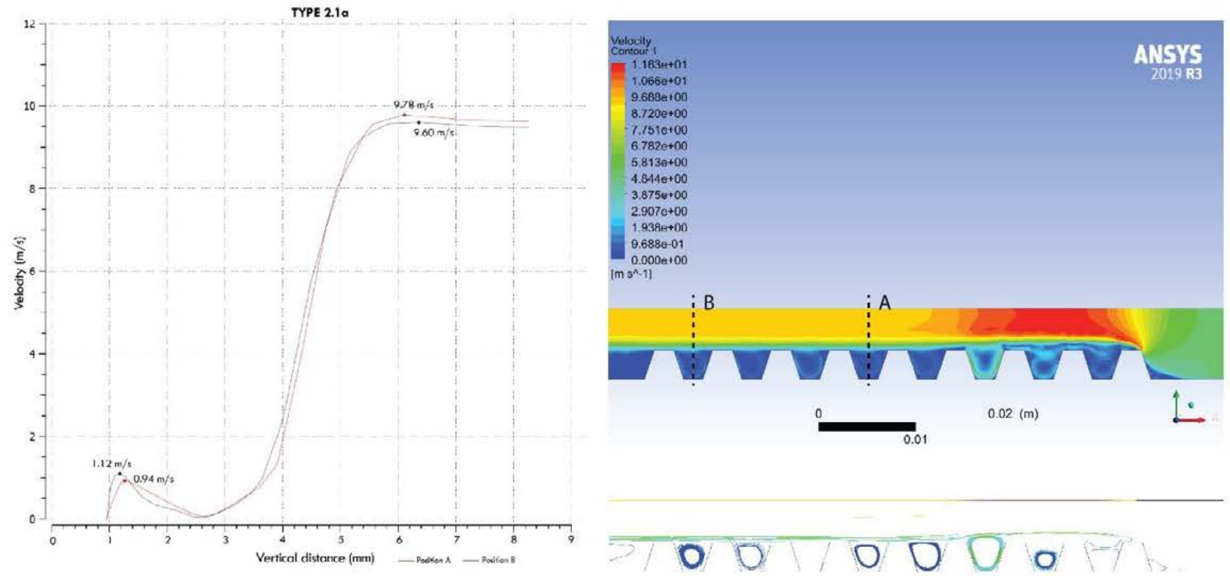


Vertex formation

Stage 3 - Type 2 (height)

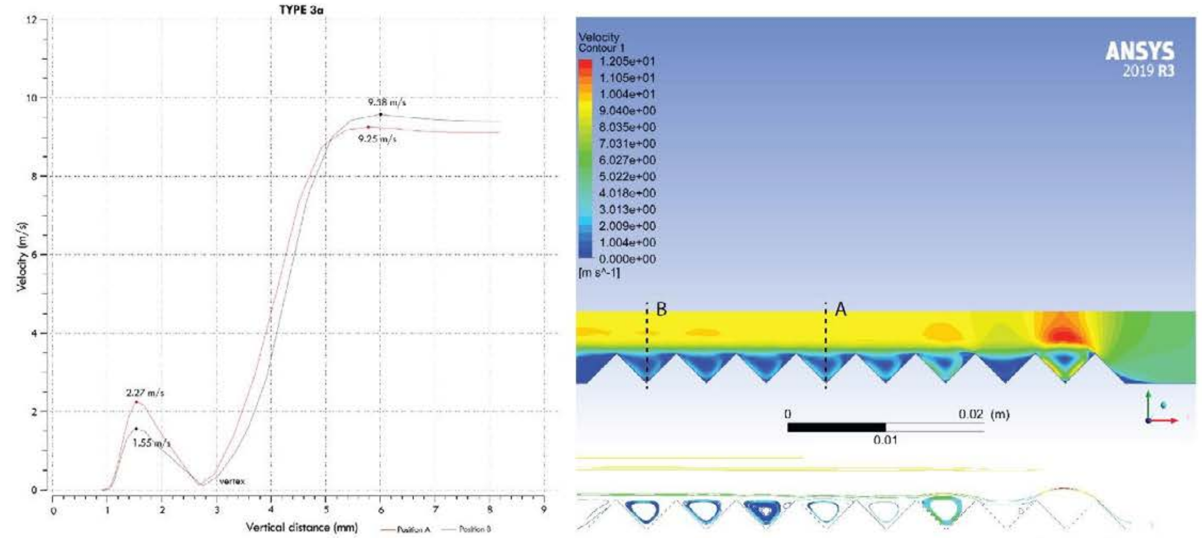


Vertex formation

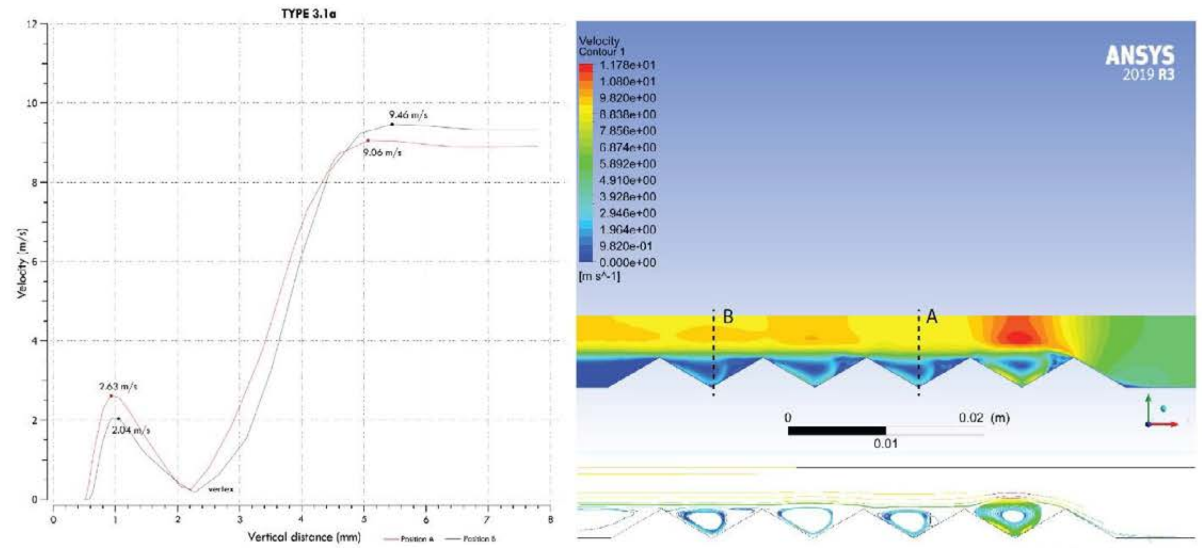


Vertex formation

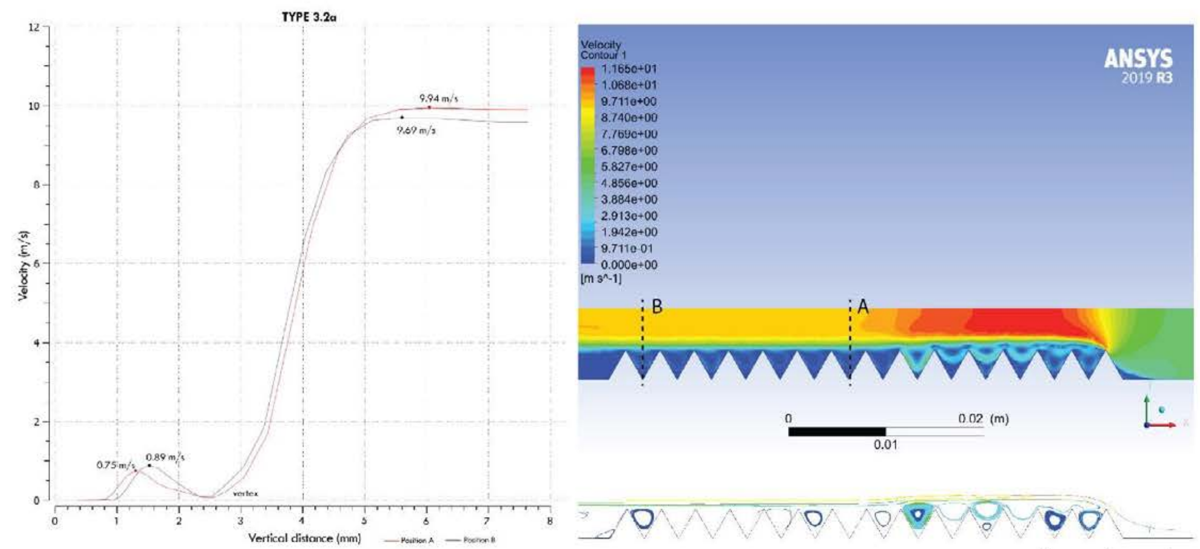
Stage 3 - Type 3 (height)



Vertex formation

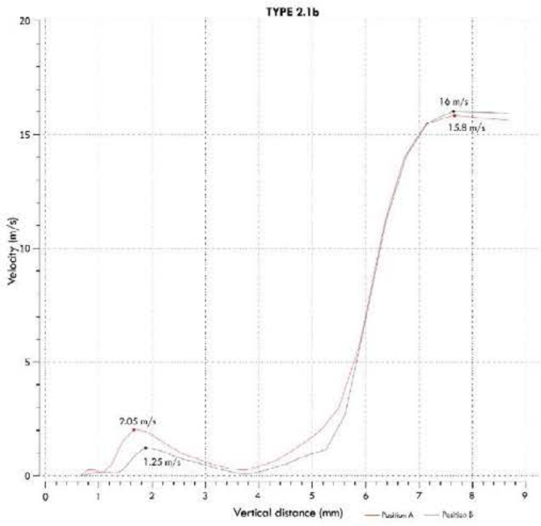


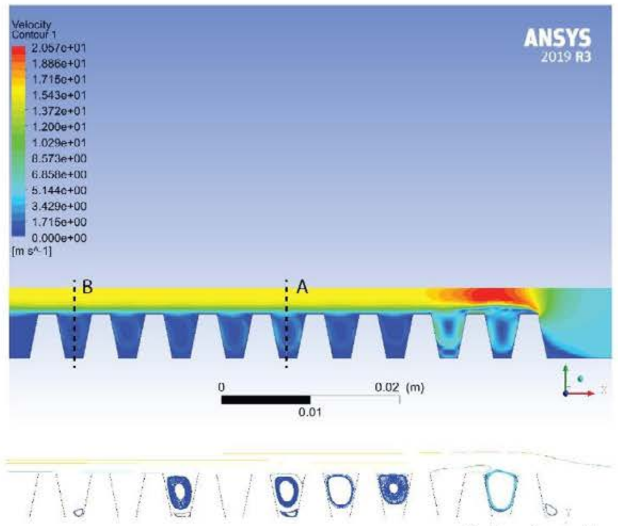
Vertex formation



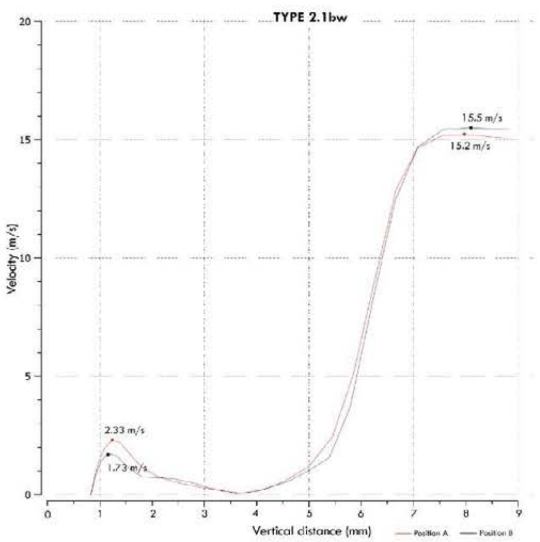
Vertex formation

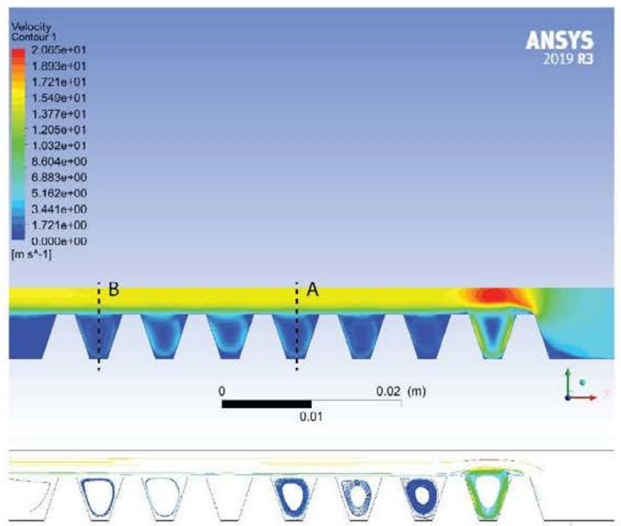
Stage 4 (5m/s)



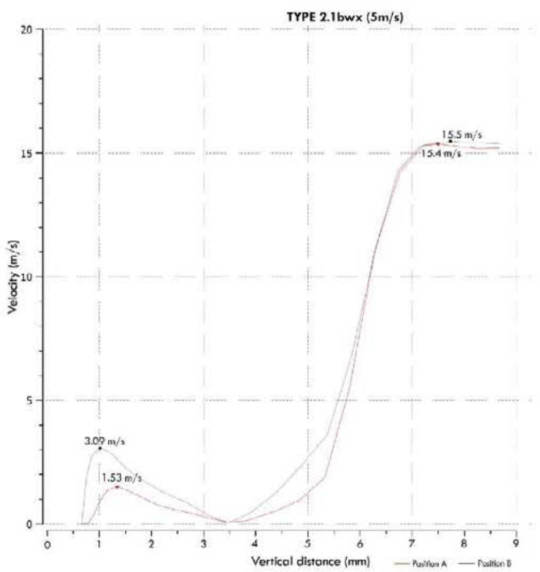


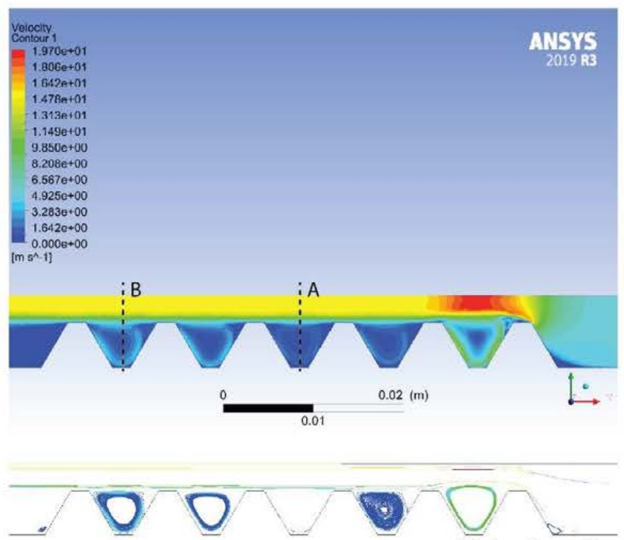
Vertex formation





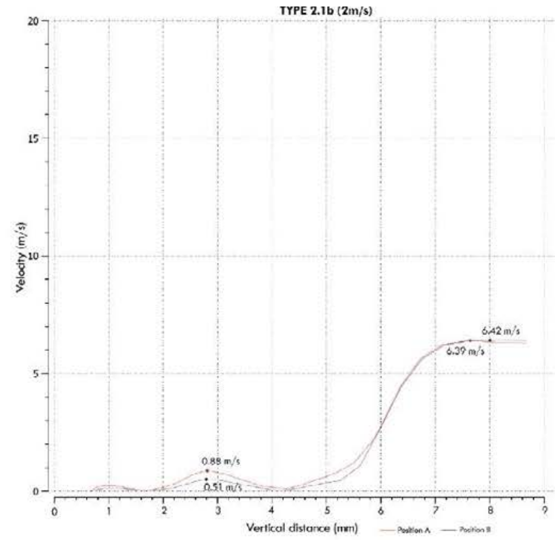
Vertex formation

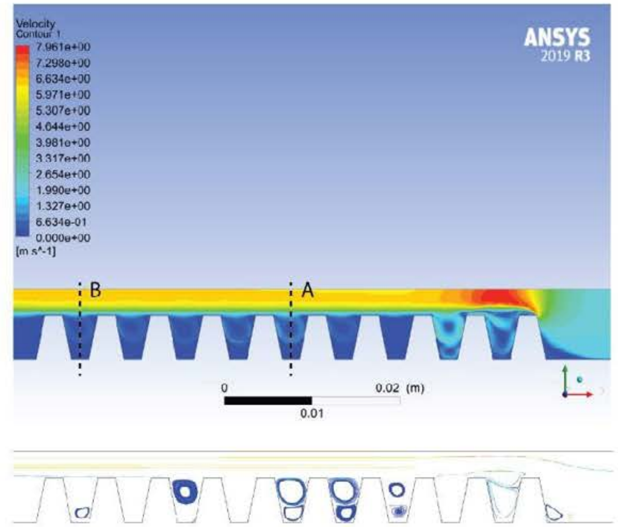




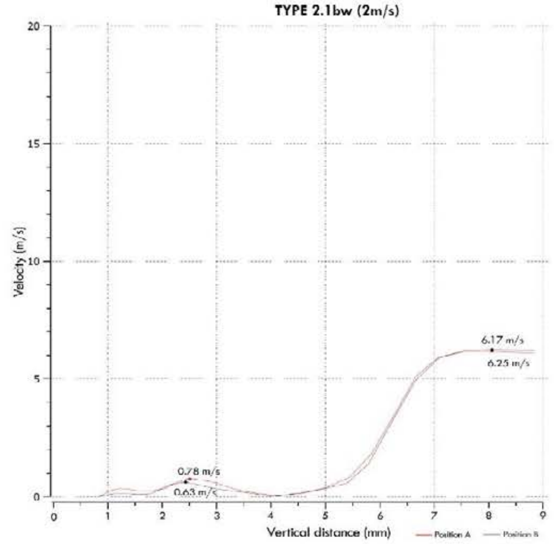
Vertex formation

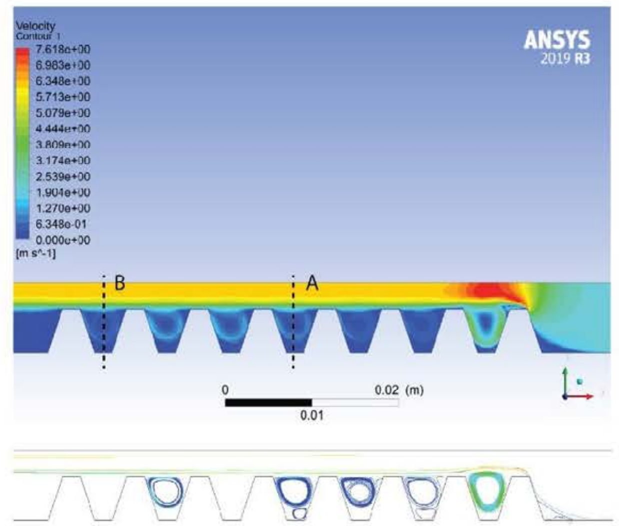
Stage 5 (2m/s)



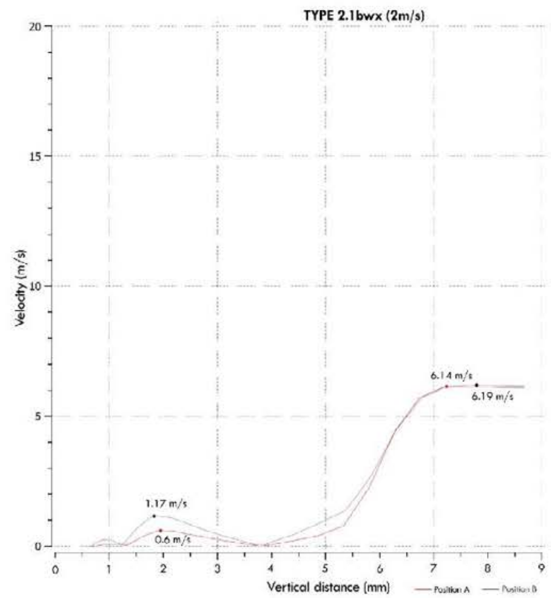


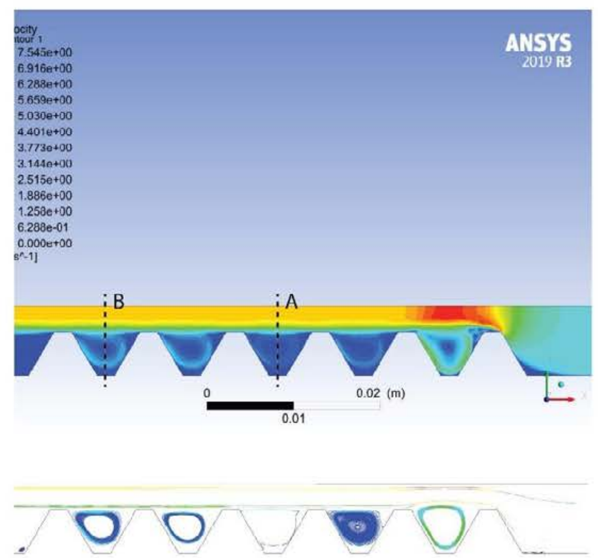
Vertex formation





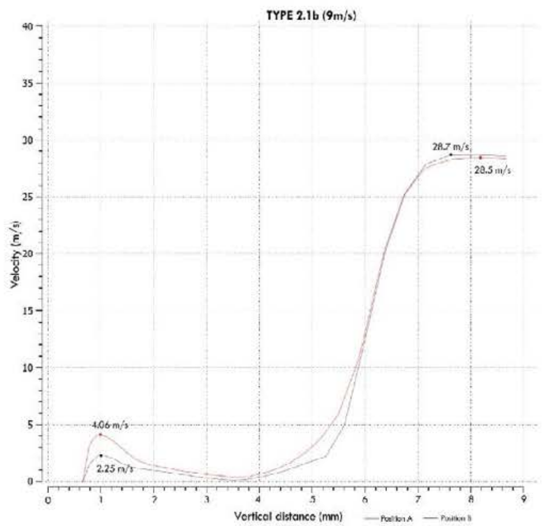
Vertex formation

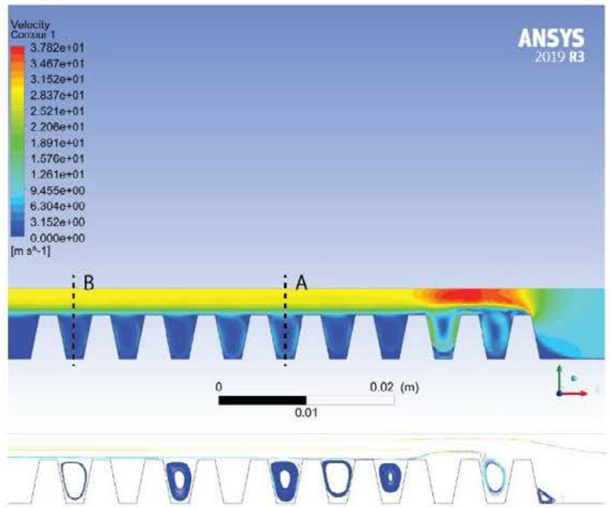




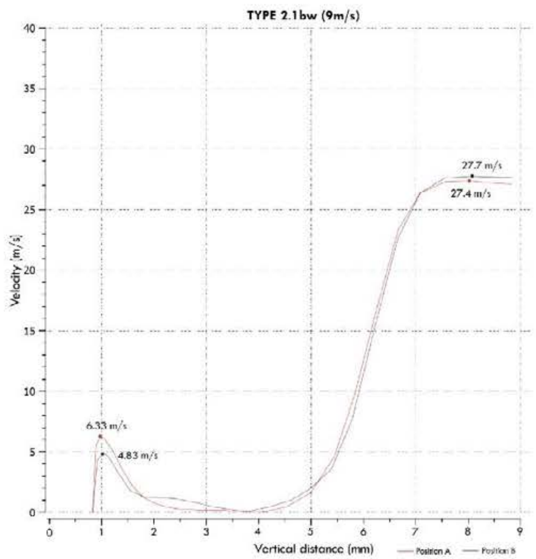
Vertex formation

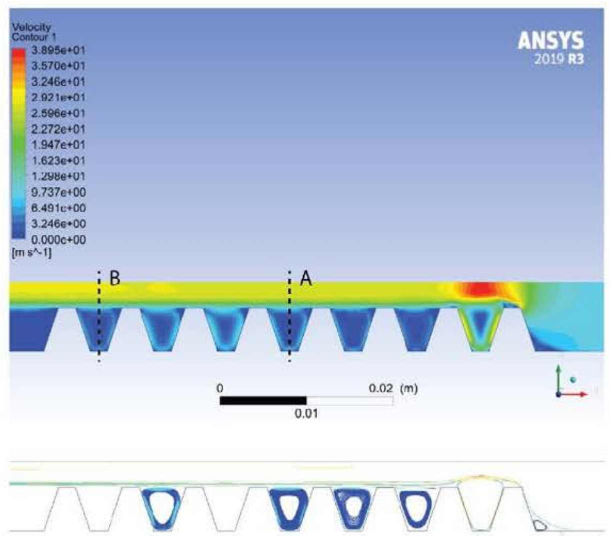
Stage 5 (9m/s)



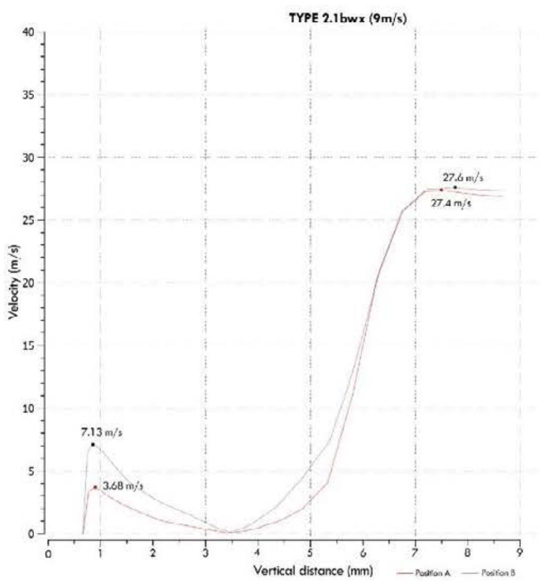


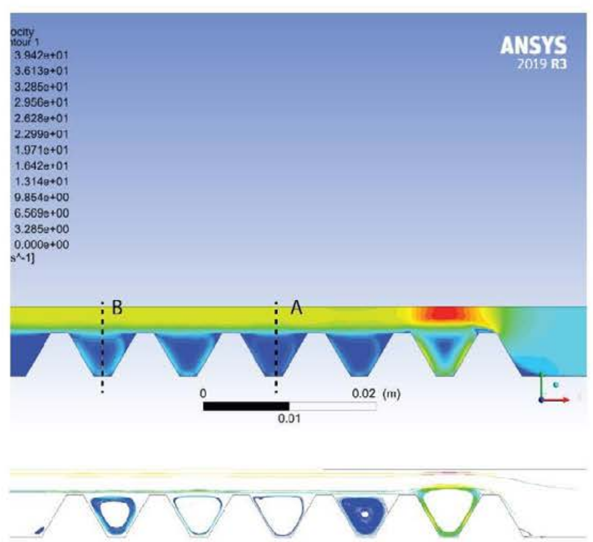
Vertex formation





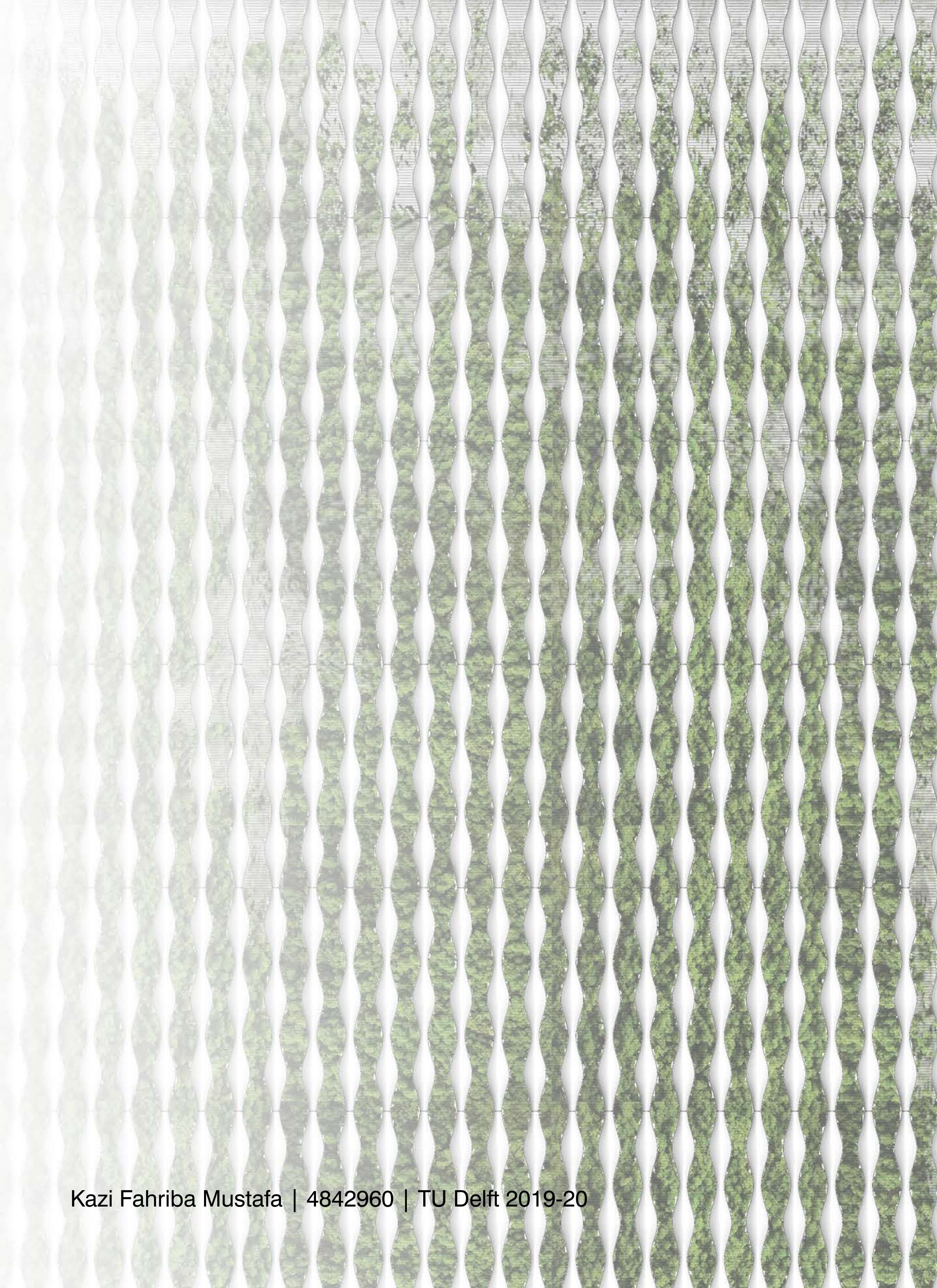
Vertex formation





Vertex formation

Blank



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