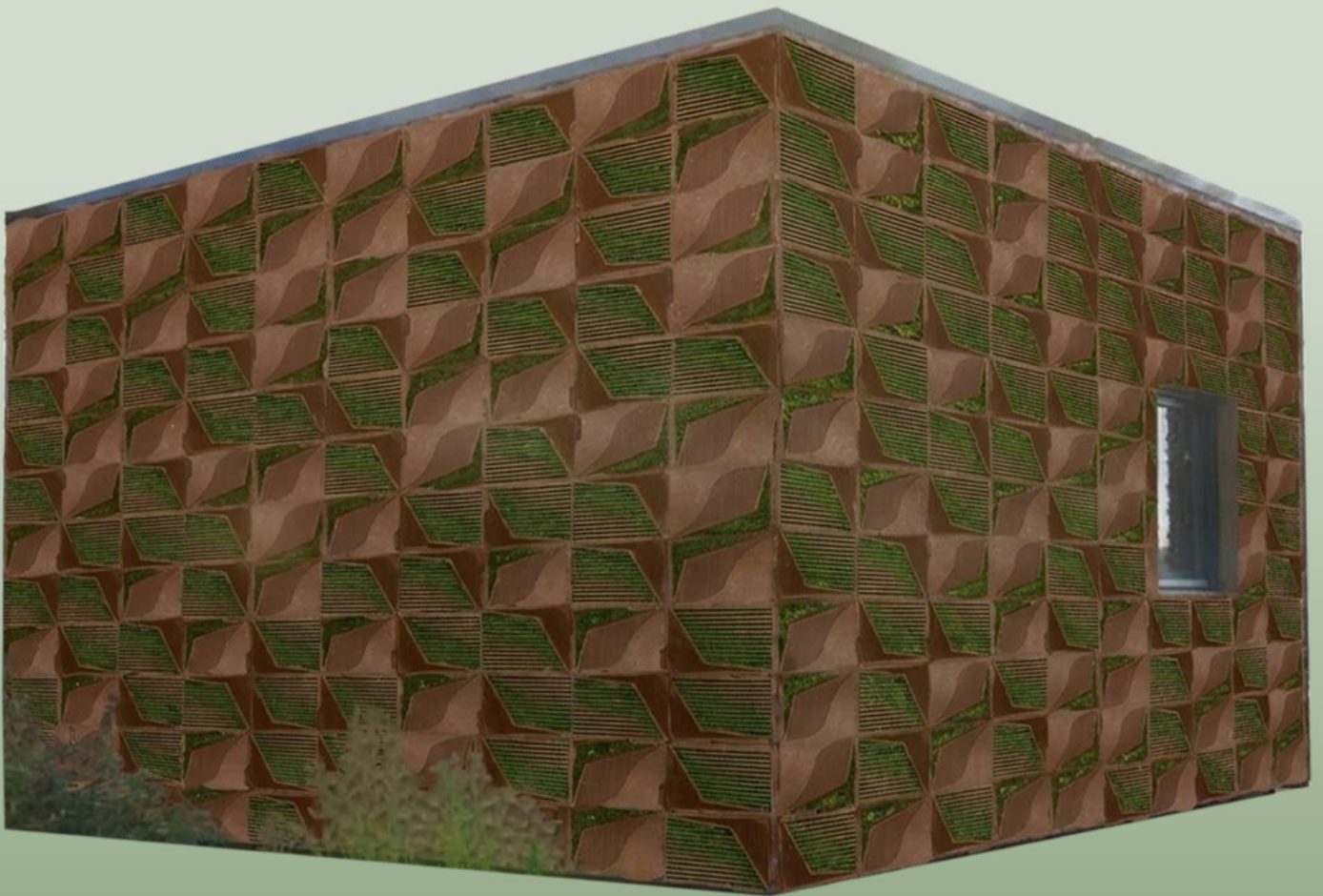


Designing for Spontaneous Growth

Towards a Biobased and Bioreceptive Facade Supporting Pioneer Organisms



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MSc Integrated Product Design

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Colofon

Designing for Spontaneous Growth: Towards a Biobased and Bioreceptive Facade Supporting Pioneer Organisms

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Abstract

As urbanisation continues to increase, the built environment faces growing challenges related to biodiversity loss and environmental impact. At the same time, building facades offer opportunities to support ecological processes within cities.

NPSP already develops facade materials with a reduced environmental footprint, but its current material portfolio involves a trade-off between achieving a fully biobased composition and maintaining visual freedom. The development of the fully biobased and colour-neutral Oribond resin creates an opportunity to address this challenge, while the spontaneous colonisation of pioneer organisms is explored as a bottom-up strategy to support ecosystem development on facades.

The aim of this project was to investigate how an Oribond-based composite can be developed into a biobased and bioreceptive facade material suitable for NPSP facade applications. The project explored both the technical performance of the composite and the potential of the facade panel to support biological colonisation. Factors influencing colonisation were translated into design interventions, after which surface roughness concepts were developed and evaluated through condition-based validation methods.

The developed composite achieved mechanical performance within the range of existing Nabasco facade materials. Surface roughness was identified as a key design parameter for bioreceptivity and was shown to improve water retention and protection against shear forces during early-stage attachment, with directional groove structures demonstrating the most promising performance. In addition, a practical validation approach was developed to assess bioreceptive surface conditions within product development timeframes.

The project demonstrates the potential of combining a fully biobased composite with bioreceptive surface design for facade applications. While long-term biological validation remains necessary, the research contributes a fully biobased facade material, insights into factors influencing biological colonisation, a transferable roughness design strategy, and a practical approach for evaluating bioreceptive design interventions within product development processes.

Glossary

- **Biobased materials:** are regenerative and made from living natural resources, like plants, animals, fungi, algae and bacteria, which can grow back within 100 years.
- **Resin:** the matrix used in a composite that holds everything together.
- **Fibres:** elongated particles used in a composite.
- **Fillers:** small particle matter used in a composite.
- **Bioreceptive:** the aptitude of a material to be colonised by living organisms without necessarily undergoing any biodeterioration.
- **Spontaneous growth:** the development of living organisms on non-living matter without inoculation.
- **Pioneer organisms:** The first organisms to colonise the facade surface, creating conditions for further ecological development.
- **Climax vegetation:** the stable biological communities that represents the final stage of ecological succession, existing in equilibrium with its local climate.
- **Photosynthesis:** The biological process by which green plants, algae, and some bacteria convert light energy (sunlight) into chemical energy.
- **Photoautotrophs:** organisms that produce their own organic matter through photosynthesis.
- **Cryptogamic cover:** a thin surface layer composed of a complex community of cryptogamic organisms, typically including cyanobacteria, algae, fungi, lichens, and bryophytes.
- **Bryophytes:** a group of non-vascular, green land plants that include mosses, liverworts, and hornworts

Preface

As a child, I was already fascinated by natural processes. I still have childhood drawings showing the stages of a tadpole transforming into a frog. I could spend hours watching fish in rivers and ants walking across my hand. Growing up surrounded by nature fostered a deep connection with the natural world. From weekly trips to the forest and camping outdoors in nature during the summer to caring for plants in the garden and later in my student room allowed me to experience that connection firsthand.

I remember watching a documentary about a plant in the Amazon that depended on animals for nutrients. The idea that completely different organisms could support one another fascinated me. It sparked my curiosity about how living systems are interconnected and how species thrive through collaboration rather than isolation. Could we develop a more symbiotic relationship with nature and create habitats for other species instead of only consuming natural resources? After all, our own survival depends on them as well.

My production experience at Loop, a company producing biobased coffins, taught me that nature is a living system that does not like to be fixed in time. We can only guide and facilitate it. Organisms grow, decay, and regenerate, and we are part of that natural cycle.

During the second year of my bachelor's degree, I was introduced to biobased materials through the course Materials & Manufacturing. We were challenged to create leather-like materials from mango waste. The fact that this was even possible inspired me. Could we create more sustainable products by working with natural and discarded resources?

Through Integrated Product Design, I discovered that design can act as a bridge between technology, materials, people, and nature. Rather than studying natural systems from a distance, as a designer I have the opportunity to translate insights from nature into tangible interventions that shape the environments in which we live.

Over time, I became increasingly aware of the influence that the built environment has on both people and ecosystems. Buildings occupy large areas of our cities and often replace natural habitats, yet they also offer opportunities to integrate ecological value into the places where we live. This sparked my interest in designing not only for people, but also for the broader ecosystems of which people are a part. This project reflects that ambition. Rather than creating a product that controls nature, it explores how design can create favourable conditions for natural processes to emerge.

Thank you for taking an interest in my work. I hope it offers a new perspective on how we can collaborate with nature through design. Creating entirely new ecosystems is a complex challenge, but nature has remarkable resilience when given the opportunity to grow. I hope this research contributes to a future of biobased and bioreceptive product design in which humans and nature can thrive together.



Acknowledgement

I would like to thank my supervisors Stefano and Jelle for their guidance throughout this graduation project. Their combination of enthusiasm, critical feedback, and encouragement continuously motivated me to strive for the best possible outcome and gave me confidence throughout the graduation process. Stefano's experience in biodesign and Jelle's expertise in composite design provided valuable perspectives throughout the project. In addition, they connected me with relevant people, methods, and sources of inspiration that helped shape both the research process and the development of the project.

I would also like to thank Nina for her support and guidance from the company side. Our weekly conversations provided a valuable space to exchange ideas, reflect on challenges, and explore new directions. Her enthusiasm, openness, and efforts to involve me in company activities made me feel welcome at NPSP and contributed greatly to an enjoyable graduation experience.

Furthermore, I would like to thank the entire team at NPSP for providing me with the opportunity to conduct this research and for generously sharing their knowledge and expertise. Access to materials, production facilities, and testing equipment significantly supported the development of the project. The team's engagement in discussing ideas, sharing insights, and supporting the creation of prototypes greatly enriched both the project and my learning experience. Above all, their welcoming atmosphere made working at the company an enjoyable and memorable experience.

I would also like to acknowledge the PMB team at TU Delft for their willingness to support my unconventional ideas. Their advice on manufacturing possibilities and their assistance with the laser-cutting facilities enabled me to explore and prototype concepts that otherwise might not have been feasible.

In addition, I would like to thank Tim and Yi from the Applied Labs team for sharing their expertise and contributing to the development of the validation methods. Their willingness to think along, challenge ideas, and discuss different approaches significantly strengthened the research process.

Finally, I would like to thank the many researchers, experts, friends, and my parents who shared their knowledge and perspectives throughout this project. Their insights and conversations provided valuable inspiration and helped shape the direction of this research.

Thank you all for your support.

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1 Introduction

1.1 Introduction

Urbanisation and environmental challenges

Urbanisation has led to the expansion of densely built environments, often at the cost of natural spaces (Zaťovičová & Majorošová, 2023). The United Nations Department of Economic and Social Affairs, Population Division (2019), projects a continued increase in urbanisation, with 68% of the global population and 74% of the European population expected to live in urban areas by 2050. The built environment represents a significant source of greenhouse gas emissions, accounting for more than 30% of global emissions and exceeding those generated by the transport sector (Fink, 2011). Furthermore, several environmental challenges occur in urban areas, including poor air quality due to high concentrations of particulate matter, the Urban Heat Island effect in which urban surfaces retain more heat than natural environments, and the extensive use of impermeable artificial materials, which alters natural water cycles and degrades urban ecosystems (Perini et al., 2020).

Potential of biological growth

Integrating vegetation into urban environments has been shown to mitigate many of these issues. Photoautotrophic species, such as plants, algae, and cyanobacteria, are capable of capturing and storing atmospheric CO₂, thereby acting as natural carbon sinks and reducing the overall carbon footprint (Jozay et al., 2024). According to Elbert et al. (2012), cryptogamic communities, including cyanobacteria, algae, fungi, lichens, and bryophytes, capture and store approximately 3.9 Pg of carbon annually, representing around 7% of the net primary production of terrestrial vegetation. Besides carbon, these organisms can fix phosphorus and nitrogen, with a nitrogen uptake of approximately 49 Tg per year, representing nearly 50% of the total biological nitrogen fixation on land (Elbert et al., 2012; Bozan et al., 2024). Furthermore, the communities can contribute to bioprotection and biomineralization, further enhancing their ecological value within the built environment, while potentially strengthening the facade material itself (Favero-Longo & Viles, 2020). Additionally, urban greening shows the potential to reduce the Urban Heat Island effect, capture fine particulate matter, mitigate noise pollution, reduce surface water runoff, remove pollutants from water, enhance human well-being and support biodiversity within cities (Srbínovska et al., 2020; Cardinali et al., 2023; Ghazalli et al., 2019; Perini et al., 2020). Besides ecological

enrichment, urban green spaces can strengthen the relationship between citizens and nature by showcasing ecological processes in action and contributing to greater environmental awareness (Lepczyk et al., 2017).

Challenges of convential green facades & the bottom-up approach

In practice, the installation and maintenance of vegetated facades remain difficult. Often, these vegetated facades are designed using a top-down approach with insufficient consideration for ecological factors. For this reason, Schilthuizen et al. (2025) recommend a bottom-up approach that recreates natural ecosystems based on ecological principles, rather than merely mimicking them. Consequently, this project investigates a theoretical framework regarding the ecological processes and pioneer organisms that inhabit vertical walls, as well as the specific conditions that enable these organisms to attach and grow spontaneously.

NPSP and biobased facades

To bridge the gap between ecological theory and practical material application, this research is conducted in collaboration with NPSP, a research and design company that produces building facades. Their work focusses on maximizing the use of biobased and circular materials through the development of innovative composite products (NPSP, n.d.-b). Their current materials, such as Nabasco 8010, already demonstrate a significantly lower environmental impact, with a CO₂ footprint of 13 kg/m² compared to 86 kg/m² for traditional concrete (Nabasco, n.d.). They are currently conducting pilots that involve integrating insect hotels and planters into their facade, demonstrating that NPSP is already actively participating in increasing biodiversity on facades (The Green Village, 2025; Studio Marco Vermeulen, 2023). This initiative aligns with their broader mission to reduce the environmental footprint of the built environment.

Material challenges and opportunities of Oribond

However, a challenge with current composites is the trade-off between sustainability and architectural visual freedom. While NPSP's fully bio-based furan resin composites are currently limited by their black colour, their transparent bio-polyester alternatives are only partially biobased. To address this, a new potential



Figure 1.1. Example of a current NPSP facade design using polyester resin, including integrated insect hotels and bird nesting features

resin named Oribond has been developed by Orineo, a company that produces fully bio-based thermosetting resins (Orineo BV, n.d.). This new resin is fully biobased and transparent in colour, which offers a promising solution for achieving architectural freedom while meeting ecological goals. Furthermore, its non-toxic nature reduces health and environmental risks during production.

Research gap

Despite these promising characteristics, no research has yet been conducted on integrating the Orineo resin into a facade composite or the existing NPSP production workflow with the heat press. In addition, the bottom-up approach demands the incorporation of ecological principles and material properties to enhance the habitability of facades for resilient, self-sustaining pioneer organisms. This graduation project aims to bridge this gap by exploring how this new composite can be developed into a strong and bioreceptive facade panel that facilitates the spontaneous growth of pioneer organisms in urban environments.

Design assignment

The design question is as follows:

How can an Oribond-based composite be applied in the development of a biobased and bioreceptive facade panel for NPSP facade applications?

To answer this design assignment, the research was structured around two interconnected directions: 1) the development and validation of the composite material, and 2) the enhancement

of bioreceptive growth conditions for pioneer organisms. In Figure 1.2, is an overview of the subquestions.

A. Material development and facade applicability

A1. How can a composite with the Oribond resin be developed within existing NPSP production workflows?

A2. To what extent does the Oribond composite meet the technical and mechanical requirements for facade applications?

A3. What material characteristics of the developed Oribond composite contribute to its potential for bioreceptive applications?

B. Designing for bioreceptivity

B1. Which factors influence spontaneous attachment and growth of pioneer organisms on vertical surfaces?

B2. How can surface roughness be designed to enhance conditions for pioneer organism attachment?

B3. How can the influence of surface roughness on early-stage attachment conditions be validated?

B4. How can the developed roughness concept be integrated into a facade application?

Figure 1.2. Overview of subquestions

1.2 Stakeholder



Figure 1.3. Examples of NPSP composite applications

NPSP

This graduation thesis is conducted in collaboration with NPSP, a research and design company based in Delft specialising in the development and production of sustainable composites. The materials developed by NPSP are applied in various products across the fields of public space, construction, design, and mobility (Figure 1.3). One significant application is building facades (Figure 1.4), which are marketed by NPSP's sister company Nabasco Products B.V., whose name stands for Nature Based Composites (Nabasco, n.d.). The unique selling points of these facades include their biobased and waste-based composition, high quality, and design freedom. Architects are able to design customised shapes, allowing for a high degree of architectural freedom.

Since its founding in 1998, the company has fostered extensive knowledge of composite production processes and established a network for sourcing raw materials. Furthermore, NPSP provides a specialised experimental lab, where production and test equipment are available, such as raw ingredients, moulds, heat presses, and mechanical and impact characterisation tools. These facilities enable the experimentation with the material and the immediate validation of these properties.

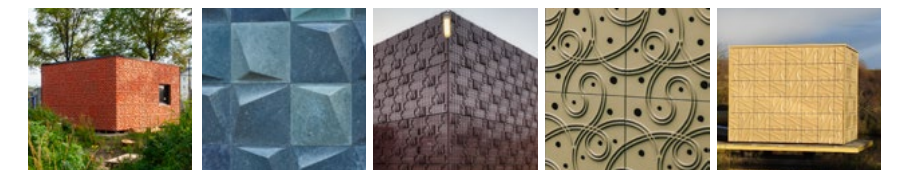


Figure 1.4. Examples of customised facades design from Nabasco

Orineo

Orineo B.V. develops and supplies the new biobased resin, Oribond, which is used in the facade composite development in this study.



TU Delft

Another stakeholder in this project is the Technical University of Delft (TU Delft). This thesis is conducted within the master's programme in Integrated Product Design, which is part of the Faculty of Industrial Design Engineering. To complete a graduation project, TU Delft requires the application of appropriate methodologies and ensures that the research and writing meet academic standards, including the use of relevant literature.



1.3 Approach & methodology

Figure 1.5 presents an overview of the project process. The overall design process was inspired by the Double Diamond model (Design Council, n.d.), following alternating divergent and convergent phases. During diverging, there is explored and opened up to new possibilities, while during converging, the process is narrowed down to the most suitable solutions. The model consists of four stages: Discover, Define, Develop, and Deliver. The process is iterative, and smaller cycles of divergence and convergence are continuously repeated throughout the project.

Discovering & Define

This project starts with two parallel investigations: 1) a hands-on exploration of material properties to assess the potential of the Oribond resin as a facade composite within the NPSP production process, and 2) research into conditions for bioreceptive design and resilient biological growth on facades.

1) Material study approach

Due to the limited knowledge available on the new composite in combination with the Oribond resin, its material potential was explored using Material Driven Design-inspired methods (Karana et al., 2015). To better understand the material, 'tinkering' with various ingredients was conducted, informed by NPSP's expertise and the materials available within the company. A material diary was maintained to document observations and track variable changes during the experimentation process. Following this phase, a process diagram and morphological overview were developed. The most promising samples were then selected for technical characterisation with ISO-based methods. Based on this material study, the initial potentials and limitations of the material were identified.

2) Ecological design approach

In parallel, a literature review and expert consultation were conducted to define the material's application and develop a theoretical framework on bioreceptive facades and the ecological conditions that support them. This resulted in an overview of desired facade conditions.

To create resilient green facades, a bottom-up approach based on regenerative design principles is applied. Regenerative design focuses on human systems that co-evolve with self-renewing natural systems. It advocates for the exploration of perceived beauty shaped by natural processes (Karana et al., 2023).

In addition, it can facilitate societal transitions towards new aesthetic values and ecological understanding. This approach is combined with biophilic and bioreceptive design, which are emerging approaches in the built environment. Biophilic design centres on the innate human affinity for nature and the integration of nature into design to enhance the human-nature connection (Wolfs, 2015). Bioreceptive design focuses on enabling built structures to function as thriving habitats for flora and fauna (Guilliette, 1995).

The goal is to create a living facade, which can also be understood by the framework of living artefacts (Karana et al., 2020). The framework suggests the principles such as living aesthetics, mutualistic care, and habitability. Karana et al. (2023) propose five pillars, which will be used to assess how the final concept contributes to biodiversity and cultural shifts.

Develop

Based on the findings from the ecological and material investigations, the development phase focuses on creating a more bioreceptive surface on the selected Oribond composite. Through the HKJ-method, existing process techniques were analysed as inspiration for surface modification strategies. In parallel, relevant roughness parameters for early-stage attachment were defined. Multiple surface modification techniques and geometries were then prototyped and iteratively refined. The most promising concepts were selected and evaluated using self-developed

validation methods focused on ecological factors involved in the initial attachment phase of pioneer organisms. Since no standardised methods exist for evaluating pioneer organism attachment on bioreceptive facades, the methods were iteratively designed and refined throughout the project to improve experimental relevance and repeatability. These methods specifically investigate conditions related to moisture retention and protection against shear stress.

In parallel, the facade applicability and bioreceptive potential of the composite were evaluated through technical and environmental testing, including weathering behaviour, water behaviour, pH indication, and ignitibility indication.

The development phase is highly iterative, involving multiple smaller cycles of exploration, evaluation, refinement, and selection.

Deliver

The final deliverable consists of the written thesis and a physical demonstrator based on an existing NPSP facade panel with the developed surface modification integrated. In addition, a spirulina-based simulation is created to communicate the intended bioreceptive potential. Furthermore, visualisations are developed to present future integration possibilities. Finally, a poster may be designed to communicate the key findings and outcomes of the project in a concise and accessible manner.

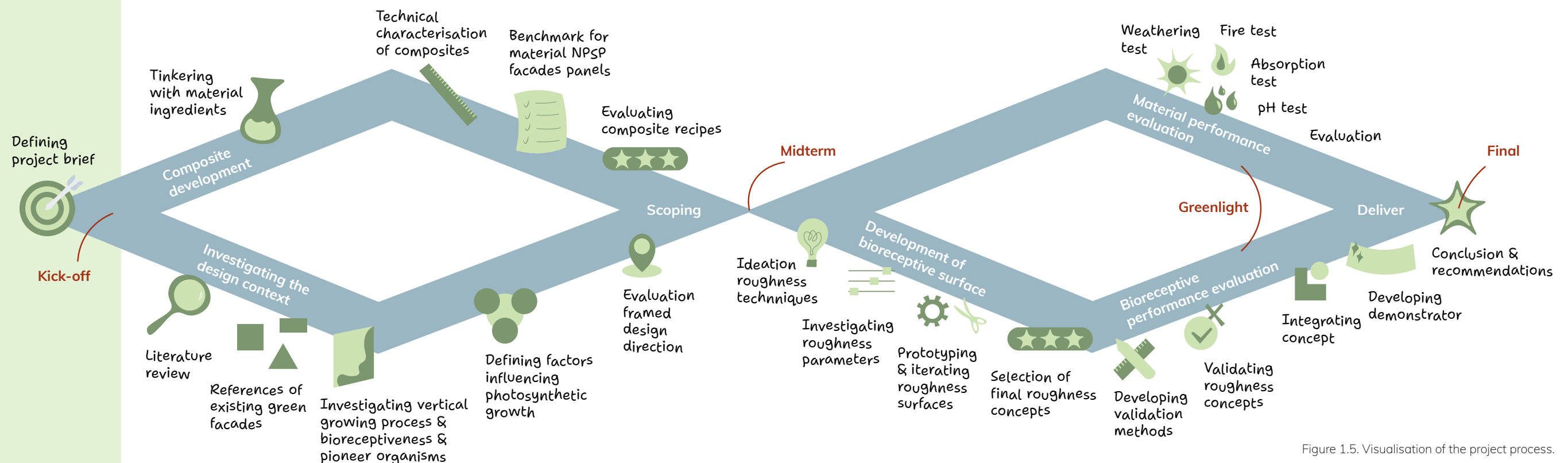


Figure 1.5. Visualisation of the project process.

2 Material Context

2.1 Composite background

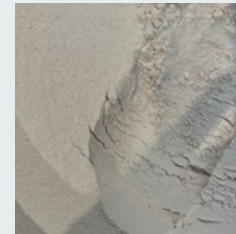
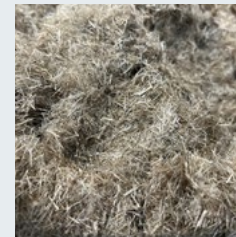


Figure 2.1. Overview of ingredients composite with examples

Composites: resins, fibres, and fillers

Npsp develops facades made from biobased composites consisting of resins, fibres, and fillers (Figure 2.1). Composite materials combine different raw materials to achieve superior mechanical performance. Fiber-reinforced composites consist of fibres embedded in a weaker material, the resin, which functions as the matrix (Gay, 2022).

According to Gay (2022), the matrix maintains the geometric arrangement of the fibres and transfers the load acting on the composite to the stronger reinforcement fibres. As a result, the composite exhibits mechanical properties that are superior to those of the matrix alone, while differing from those of the fibrous reinforcement. Composite materials are heterogeneous, meaning they consist of different non-uniform components, and they are anisotropic, meaning that their mechanical properties depend on the direction of the applied load.

Another type of additive that can be incorporated into composites is particulate fillers. These fillers are solid additives that are primarily distinguished from fibres by their aspect ratio. According to GlobalSpec (n.d.), can it be characterised as a fibre when the aspect ratio between the longest and the shortest dimension of a particle is greater than 25. In other words, elongated particles are considered fibres, such as flax, whereas more granular materials, such as crushed shells, are classified as particulate fillers. The original purpose of adding no strengthening fibrous fillers was to reduce cost, but it has been established that particulate fillers also play an important role in modifying material properties, such as improving processing behaviour, controlling density, creating optical effects, and enhancing thermal conductivity (Zurale & Bhide, 1998; Park & Seo, 2011).

In short, fibres primarily provide mechanical reinforcement, while the matrix binds the fibres together and transfers loads, and fillers are used to modify specific properties of the material.

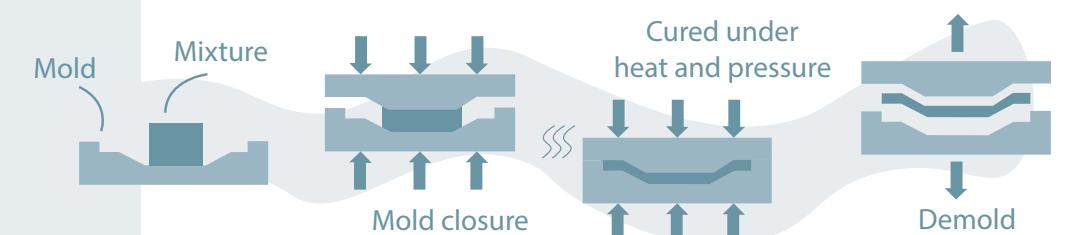


Figure 2.2. Process of compression moulding used by NPSP

Production process

To develop a strong composite, the production process at NPSP involves mixing fibres, fillers and resin, followed by compression moulding under heat (Figure 2.2). This is a commonly used method in which thermosetting plastics are heated in a mould close to their curing temperature, enabling the material to flow (Cheremisinoff, 2001). By closing the mould and applying further heat and pressure, the material flows into the mould cavity and completely cures. The mould is then opened, and the fully cured part is released. The design of the mould provide the development of the desired geometry of facade panels. This production process results in compact plates with low porosity and a smooth surface.

2.2 Npsp composites & requirements

Current composites NPSP

Currently, NPSP is working with different composite materials based on two types of resins.

The first resin, a bio-polyester, consists of approximately 50% bio-based material. Composites using this resin are already on the market under the Nabasco brand, such as Nabasco 5010, 8010 and 8012. These composites are used in facade applications and are certified according to the EN 13501 B-s1, d0 fire classification standard (nabasco, n.d.). Nabasco 8010, for example, consists of reed fibres, softening lime, the bio-polyester resin. This material is fully circular, produced without generating residual waste, and can be recycled into new panels after use. The CO₂ impact of this material is 13 kg/m², which is significantly lower than that of precast concrete, a widely used building material, with an impact of 86 kg/m² (NPSP, 2026).



The second resin is a fully bio-based furan resin, which has a black colour. Composites created with this resin have biobased fillers and fibres, making the composite fully biobased. The composite developed using this resin, Nabasco 8040, is currently in production for its first commercial pilot project for a sports complex commissioned by the municipality of Amsterdam.



However, it should be noted that obtaining a fire classification requires higher fire resistance, which is currently achieved by adding non-biobased fire retardants, thereby reducing the overall biobased content of the composites.

	CO2 (kg/m2)	Visible ingredients (visual freedom)	Biobased (excluding fire retarder)	Price (eur/m2)	Toxic process
Nabasco 8012 (Bio-polyester)	13	Yes	Partly	150-175	Yes
Nabasco 8040 (Furan)	-14	No	Fully	175-200	Yes

Figure 2.3. Comparison overview of current composites with different resins

Figure 2.3 presents a comparison between the two most promising composites based on these resins. As shown, the main difference lies in the trade-off between sustainability and visual freedom. The bio-polyester resin offers greater design freedom due to its transparent colour but is only partially bio-based. In contrast, the fully bio-based furan resin has a black colour, which limits architectural visual freedom.

New potential resin

A new third resin has recently been developed by Orineo, a company that produces fully bio-based thermosetting resins (Orineo BV, n.d.). This resin has the potential to combine the

advantages of both Nabasco composites. Firstly, it is based on epoxidised linseed oil combined with a biobased hardening component containing citric acid. Both components are biobased and could reduce the overall CO₂ footprint, while the resin's transparent appearance may provide greater visual freedom. In addition, it offers further sustainable benefits, as it is non-toxic during production of the composite, which enhances air quality and workplace safety. The resin also has the potential to be biodegradable, enabling a more closed material cycle from nature back to nature.

Despite the promising characteristics of this resin, no research has yet been conducted on its integration into the existing NPSP production workflow or on the production of strong and durable composites using this resin. The first research gap addressed in this graduation project is therefore the validation and exploration of the potential of a new facade panel based on the Orineo resin. Through material experimentation and prototyping, the feasibility of this resin within the NPSP composite system will be investigated.

Criteria for NPSP facade panels

A criteria framework was developed based on NPSP's ongoing efforts to define desired performance ranges for facade composites. To contextualise these targets, the characteristics of existing Nabasco facade materials were analysed and incorporated into the framework, resulting in a set of performance criteria for evaluating the suitability of composites for facade applications. Chapter 5.5 (Figure 5.15) presents an overview of this criteria framework, including the performance of the developed Oribond composite alongside the existing Nabasco materials.

However, NPSP indicates that it is also open to other potential applications, particularly within the built environment.

3 Ecological & Biological Framework

3.1 Shifting role of organisms on buildings

Throughout history, the growth of organisms on buildings has shifted from an unwanted nuisance to a recognised ecological and design opportunity. This section touches upon that shift through three key concepts: biodeterioration, bioprotection, and bioreceptivity. Examples of organisms growing on buildings are shown in Figure 3.1.

Biodeterioration

The growth of organisms on buildings used to be perceived as negative because it could change the initial intended properties of the facade, such as its aesthetic colour or potentially other chemical and physical properties (Guilliet, 1995; Noeiaghahi et al., 2017; Stohl et al., 2023). In 1965, the changes induced by these organisms were termed biodeterioration (Hueck, 1965). Consequently, research focused primarily on how to discourage biological growth.

Bioprotective

However, a counter-narrative has evolved, stating that colour changes could be aesthetically pleasing, that colonisation could play a protective role against weathering and human-induced interference, and that these organisms have a beneficial effect on the environment and human health. Besides causing biodeterioration, organisms can also play a bioprotective role. Previous studies have shown that cyanobacteria and fungi may contribute to the case-hardening of sandstone through mineralisation processes (Favero-Longo & Viles, 2020), while lichen cover can reduce thermal stress on limestone surfaces by increasing moisture retention (Carter & Viles, 2003).

Bioreceptive

In 1995, Guilliet shifted this perspective by developing the term 'bioreceptivity', defining it "as 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". This concept implies a fruitful ecological relationship between the material and the colonising organisms. Guilliet (1995) distinguishes different types of bioreceptivity: 1) primary bioreceptivity which indicates the initial potential of attachment and colonisation, 2) secondary bioreactivity which is about these first characteristics that change over time, and 3) tertiary bioreceptivity which happens due any human activity that affects the material, for example coating or treatments. Beside intrinsic bioreceptivity caused by the properties of the material, there is also an extrinsic bioreceptivity, where accumulation of dust and soil modify the initial conditions. The environment and biosphere in where the material is exposed has influence on the colonisation (Stohl et al., 2023).

However, natural colonisation is a long-term process that eventually will occur on all vertical man-made surfaces due to weathering and ecological succession (Jakubovskis, 2025; Schilthuizen et al., 2025). The specific design of the facades can significantly influence the optimising and acceleration of these organisms while preserving the structural integrity of the facades.



Figure 3.1. Observations of organisms on buildings and stones (Source: Favero-Longo & Viles, 2020)

3.2 Existing green facade projects

The following section provides an overview of current projects within and outside NPSP in the field of green facades. This overview functions as a benchmark for existing developments in this design direction.

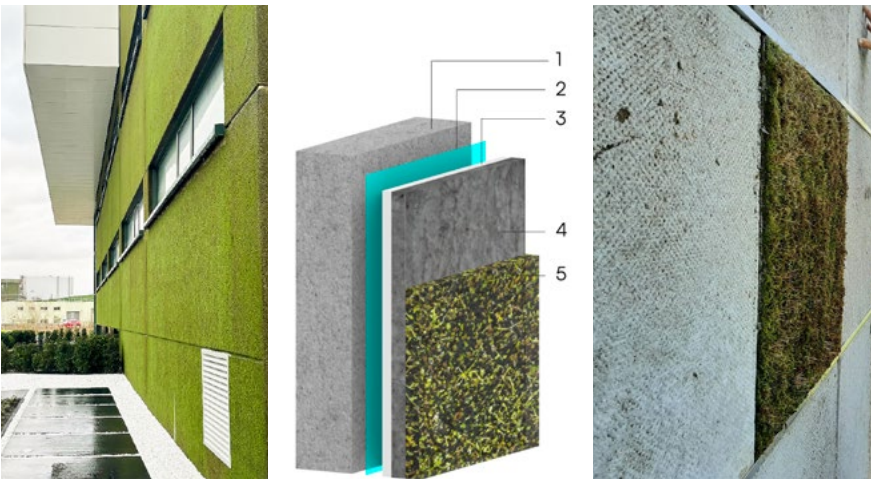


Figure 3.2. Facade panels from Respyre with moss growth (Source: Respyre, n.d.)

Respyre: Respyre is a Dutch company that develops bioreceptive concrete facades for mosses. Their product, Vertiscape, consists of multiple layers: the existing facade, a water retention system, an adhesion layer, their specialised concrete and finally a moss layer. The company expects a fully green facade after a year. To achieve this, they created an advanced moss gel that enhances growth and a temporary irrigation system is applied during the initial phase.



Figure 3.3. Leafy facade system incorporating planting pockets and substrate (Source: Leafy, n.d.; The Green Village, n.d.)

Leafy: Leafy B.V. sells facade panels with integrated plant constructions. The panels are filled with regenerative substrate that retains water and nutrients. The system is connected to rainwater drainage to facilitate water flow. Leafy offers personalised analyses to determine which plants are best suited for a specific context. Beside smaller plants, they supply the installation of bigger climbing plants. To control growth, they provide a yearly maintenance service by subscription. NPSP currently has a collaboration pilot with Leafy at the Green village to develop facades that incorporate plants (The Green Village, 2025).

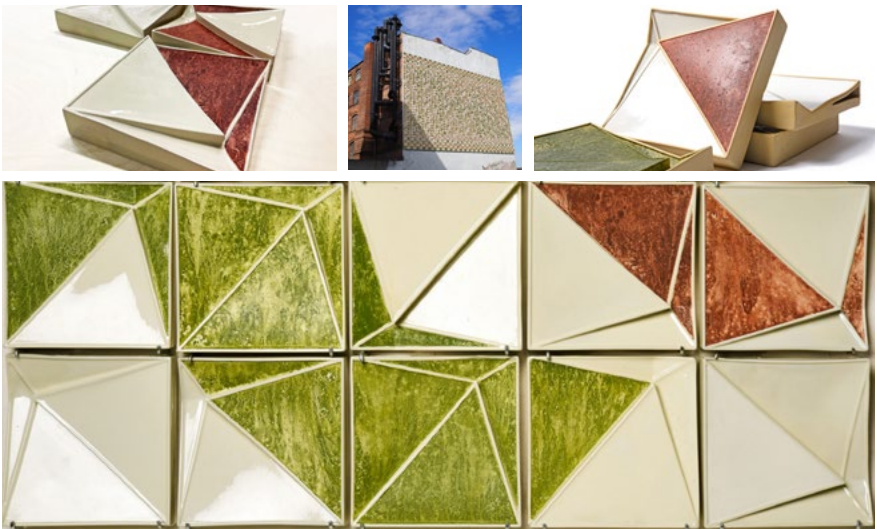


Figure 3.4. Cellular panels from Vivian Tamm with algae growth (Source: MaterialDistrict, 2023; European Green Award, n.d.)

Cellular: These panels are designed by Vivian Tamm and enable the natural growth of algae. The panels are hollow and made of ceramic, which makes them porous and suitable for water storage. This creates a humid habitat for the algae. The algae produce oxygen and absorb air pollutants, while the humidity also contributes to natural air cooling. The variety in surface coatings can determine where and in which colours the algae will grow. This design supports the intentional integration of algae for both aesthetic and sustainable purposes, instead of viewing natural algae growth as deterioration.

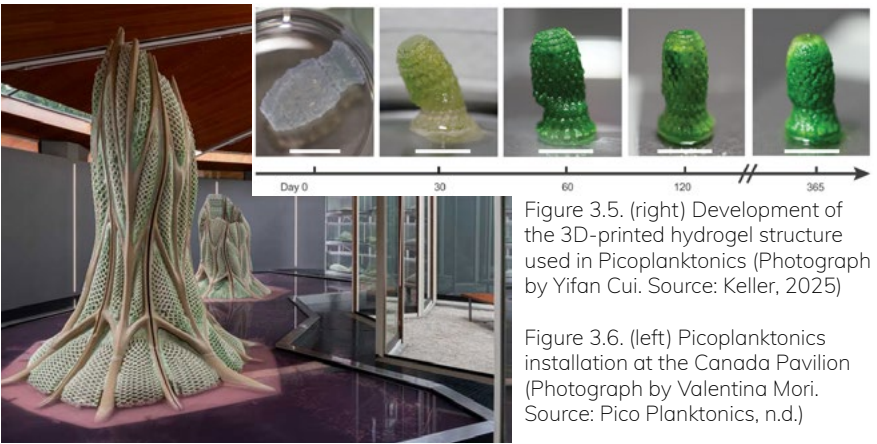


Figure 3.5. (right) Development of the 3D-printed hydrogel structure used in Picoplanktonics (Photograph by Yifan Cui. Source: Keller, 2025)

Figure 3.6. (left) Picoplanktonics installation at the Canada Pavilion (Photograph by Valentina Mori. Source: Pico Planktonics, n.d.)

Picoplanktonics: Research at ETH Zurich led to the development of Picoplanktonics, a living material that absorbs CO₂ through the metabolic processes of cyanobacteria. The cyanobacteria are housed in a 3D printed hydrogel with cross-linked polymers that holds a high water content and functions as a transport system for nutrients and organism spreading. During the Picoplanktonics installation at the Canada Pavilion, two tree-trunk-like objects were created from this living material, each capable of absorbing 18kg of CO₂ per year, equivalent a 20-year-old pine tree in a temperate environment. The structure became more rigid and greener over time. It demonstrates that materials do not have to be passive but can actively participate in climate regulation. Cruz (2025) envisions this living material as a building facade capable of directly absorbing CO₂ from the air.



Figure 3.7. Structures to enhance biodiversity in cities from Urban Reef (Source: Urban Reef, n.d.)

Urban Reef: Urban Reef is a start-up located in Rotterdam that designs habitats to encourage biodiversity in urban environments (Oskam & Latour, n.d.). These habitats are based on 3D-printed structures made from natural materials. The designs include structures placed on the ground, on walls, and under rain pipes. Their research includes the process of 3D printing biobased materials such as coffee, mycelium, seeds, paper, and silt, as well as natural growth processes that enhance biodiversity and the interaction between nature and humans (Stichting Rotterdamse Dakendagen, 2022).



Figure 3.8. Indus tiles with structures (Source: The Design Museum, 2021; Hahn, 2019)

Indus Tiles: These tiles were created by students from the Bio-Integrated Design Lab at University College London (UCL). The leaf-shaped panels actively clean pollutants from rainwater by using living algae structures (Rogers, 2022). Driven by gravity and optimised by the panel shape, rainwater flows through the structures, where the algae are embedded and reduce levels of heavy metals in the water, such as cadmium. The tiles are made of clay and contain a hydrogel that houses the algae and keeps them alive. The hydrogel can be stored in a dry form and needs to be reapplied over time.



Wonderwoods: Wonderwoods is a large apartment complex in the center of Utrecht featuring integrated concrete planters for plants and even trees. The buildings were designed by Roberto Meyer, MVSA Architects and Stefano Boeri Architetti. Instead of facade panels, these planters are integrated into the balcony structures of the building, with a primary focus on larger vegetation.

Figure 3.9. Wonderwoods building with plants integrated on balconies (Source: Stefano Boeri Architetti, 2025)



Figure 3.10. Examples of bioreceptive facade research (Source: Karmoker et al., 2023; Mustafa et al., 2021; Jakubovskis et al., 2023; De Graaf, 2025; Veeger et al., 2021)

Green walls in research: Multiple research experiments investigate green facades (Jakubovskis et al., 2023; Mustafa et al., 2021; Karmoker et al., 2023; Veeger et al., 2021). These studies mainly focus on concrete materials and ways to enhance bioreceptivity. The growth is often limited by irrigation maintenance, the manual addition of organisms, and laboratory-based cultivation. Jakubovskis et al. (2023) developed a bio-booster, consisting of recycled paper pulp mixed with forest topsoil, where the pulp functions to enhance the strength and stiffness of the booster and the topsoil naturally contains many spores. A recent master's thesis, conducted by de Graaf (2025) in collaboration with NPSP, investigates the surface geometry of facades made from Nabasco 8040 (a furan resin composite) to enhance bioreceptivity for mosses. This research focuses on geometric structures that retain water, support moss growth, and contribute to aesthetic design.



Figure 3.11. Pictures from climbing plant constructions observed at Delft Campus

Climbing plant constructions at Delft Campus: These examples were observed on the TU Delft campus at Leeghwaterstraat. An additional layer of support nets is placed alongside the facades to enable climbing plants to grow up the building. The nets are not directly integrated into the facade itself, but function as a separate layer positioned in front of it.

Other 'green' buildings

These examples do not directly implement greenery, but demonstrate the integration of other organisms and alternative approaches to enhancing sustainability and biodiversity in urban environments. As such, they serve both as inspiration and as a benchmark for possible future applications.



Figure 3.12. Prototype of self-healing brick by university of Colorado Boulder (Source: Self-healing Bricks Eat CO₂!, 2020)

Self-healing materials: A research project at the University of Colorado Boulder is developing self-healing bricks (Self-healing Bricks Eat CO₂!, 2020). This project utilises the biomineralisation capabilities of cyanobacteria. By absorbing CO₂ from the atmosphere, the cyanobacteria produce calcium carbonate, which subsequently mineralises the gelatine binder that holds the sand particles together. At Delft University of Technology, Jonkers (2007) investigated self-healing processes, where interactions between alkaline concrete and embedded bacteria stimulate mineral formation that seals cracks in concrete structures. Although these technologies demonstrate significant potential, their application remains at an early stage of development and further research is needed.



Figure 3.13. Facade panels from NPSP with integrated holes for insect and bird habitats (Source: NPSP, n.d.-a)

Insect and bird habitats: In addition to plant integration, NPSP aims to enhance biodiversity by incorporating holes in facades for insects and birds. Behind these openings, insect hotels can be mounted, while larger holes allow birds can nest. These features were tested during a pilot at the Innovation Paviljoen Amsterdam. Monitoring results indicated that the activity of insects and birds were significantly higher in the surrounding environment than on the facade panels (Van Leuven, 2024). The report suggests that the busy location may negatively affect animal attraction. It also indicates that increasing vegetation could improve habitat quality and food availability, thereby attracting more species. An iteration in which vegetation was incorporated showed a clear increase in insect activity on the facade panels.



Figure 3.14. Facade of De Bijenkorf, Rotterdam, showing the accumulation of dirt due to the ribbed texture (Source: Sullivan, 2016)

Bijenkorf building Rotterdam:

The facade panels have a beehive-like shape and are made of travertine stone, with surfaces that are post-processed to form fine ribs. The building of De Bijenkorf in Rotterdam was designed by architect Marcel Breuer and completed in 1957 (Van Der Burgh, 2024; Warenhuis De Bijenkorf, n.d.). These ribs play a key role in the material's behaviour, as they collect dirt from rain and smog (Van Der Burgh, 2024). This ribbed, groove-like texture could serve as inspiration for promoting the accumulation of soil and cells on the surface.

3.3 Understanding growth on vertical walls

Designing bioreceptive materials requires an integrated understanding of material properties and production processes, as well as the biological and ecological processes that shape organism attachment, colonisation, and growth on facade. This chapter dives into how to approach vertical growth.

Vertical growth & metabolism

Building facade surfaces initially represent harsh abiotic terrestrial environments with minimal water and nutrients availability, intense UV radiation, and rapid fluctuations in temperature and moisture (Jakubovskis, 2025). Organisms that can survive in such conditions rely on stress-resilient survival strategies. Tripathi et al. (2025) show a study on defence mechanisms cyanobacteria developed in order to be better resistant against oxidative stress, salt stress, temperature stress, photodamage. Another key adaptation that species of cyanobacteria, algae, fungi, lichens and mosses all possess against water scarcity is poikilohydry, the ability to almost completely dry out and become metabolic inactive (Green & Lange, 1995; Tripathi et al., 2025; Jakubovskis, 2025; Steer, n.d.). When rehydrated, these organisms become photosynthetically active again. These species are primarily dependent on the environment for their water intake because, unlike vascular plants, they lack internal mechanisms to regulate their internal water balance. The of Gambino et al. (2018) highlighted that (oxidative) stress management is a critical factor for growth. Gambino reported that the level of reactive oxygen species (ROS), a strategy which helps cyanobacteria to become more resistant against oxygen stress, is generally higher on surfaces with less biomass. The cyanobacteria diverted their energy away from biomass accumulation and towards the production of thick extracellular polymeric substance (EPS) for protection against stress, resulting in the overall growth rate of biofilms to be significantly hindered.

Attachment

Jakubovskis (2025) explains the stages of biological colonisation of these surfaces in Figure 3.15. The phototrophic organisms, such as cyanobacteria and green algae are usually the first ones to settle on the surface, also known as pioneer organisms (phase A). The studies by Gaylarde and Gaylarde (2005) and Barberousse, et al. (2006) also showed that these organisms represent the majority of the biomass on buildings in Europe. After this initial microbial cell adhesion, the cells form a subaerial biofilm (SAB), consisting of a matrix of extracellular polymeric substances (EPS), which irreversibly attaches to the surface (Stohl et al., 2023; Bozan et al., 2024). This biofilm acts as a protective layer for the organisms, protecting them against ultraviolet radiation, retaining water and nutrients, and serving as a communication tool (Yang et al., 2025; Stohl et al., 2023). As the photosynthetic cells supply nutrients and organic matter (dead cells), heterotrophs like fungi can develop on the surface (phase B). Subsequently, lichens can form as well, which represents the symbiosis between the pioneer organisms and fungi (De Santis, 1999; Asta, 2025). The mature crust of these organisms accumulates atmospheric dust, small particulate matter, and decaying organic matter, creating a substrate that supports the establishment of early plants, typically bryophytes like mosses (phase C). Mosses do not have a vascular system but use rhizoids, a root-like structure, to adhere to the surface (Lueth & Reski, 2023; Lee, 2025).

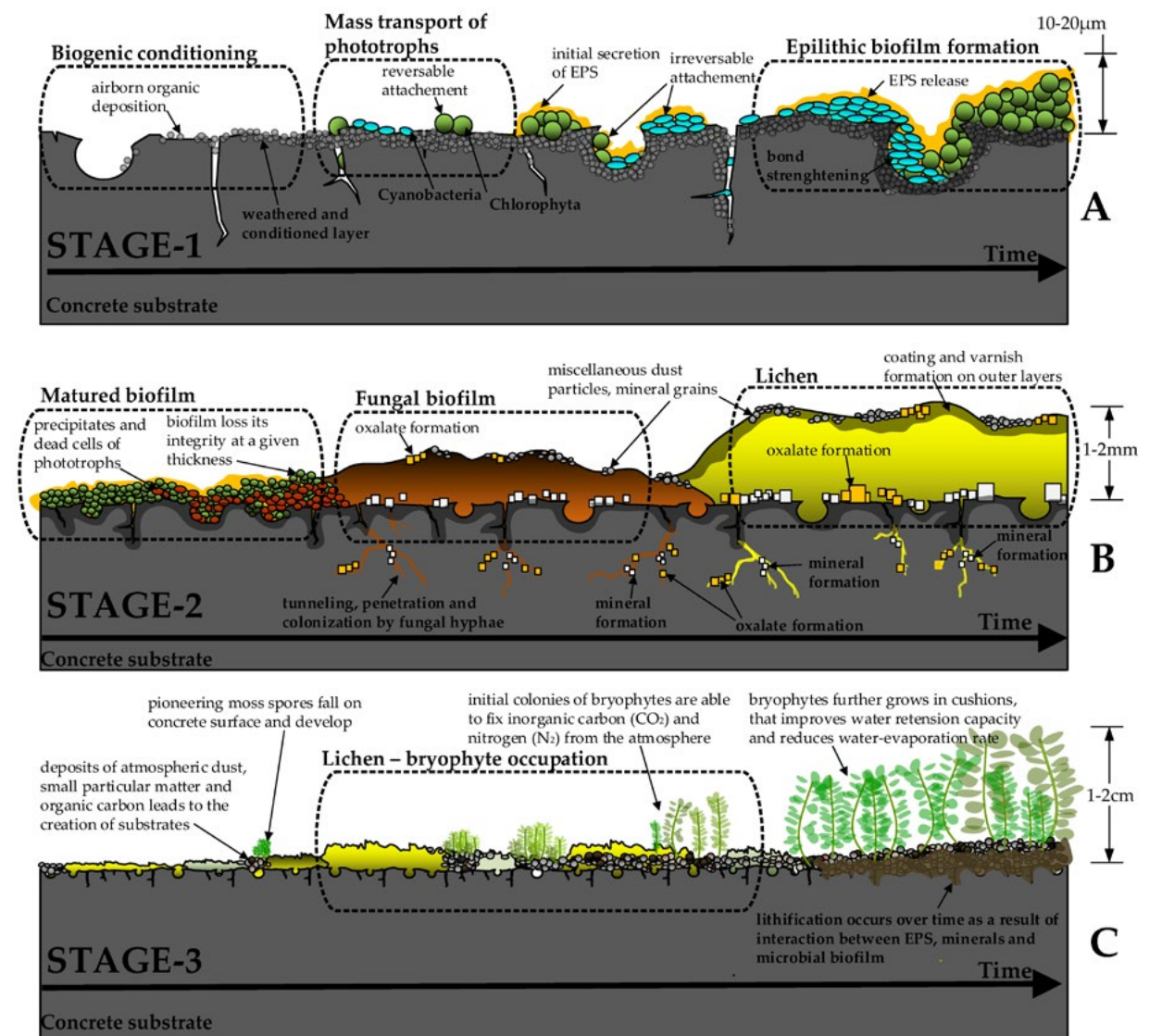


Figure 3.15. Representation of biological colonisation of concrete surface (Source: Jakubovskis, 2025)

Bottom-up approach

Currently, many projects focusing on mosses and plants aim to accelerate ecological processes by promoting the growth of specific target species rather than facilitating the spontaneous colonisation of pioneer organisms. However, designing systems solely around organisms higher in the ecological succession process leads to high installation costs and maintenance demands, as they often lack the balanced ecological foundation required to support climax vegetation (Schilthuizen et al., 2025). These walls often require irrigation systems and the inoculation of organisms. Schilthuizen et al. (2025) therefore advocates for a bottom-up approach, in which naturally vegetated walls are supported to develop without irrigation or inoculation and can sustain themselves.

Nevertheless, it can take one to five years for natural biocovers to develop under optimal conditions (Jakubovskis, 2025). The communicated lifespan of NPSP facades is 30 years. Therefore, this research aims to incorporate the material

conditions to support initial attachment and spontaneous growth. Additionally, the perspective of this study differs from existing solutions, such as Respyre. Instead of providing a facade with a pre-established biomass cover, this research focuses on the beauty of aging facades through directed growth. By implementing directed growth, biological development can be steered via material properties and surface geometry, ensuring that the transition from a clean surface to a colonised facade remains aesthetically intentional. This approach lowers overall maintenance, the need for antimicrobe coatings, promotes broader biodiversity on NPSP facade systems, and fosters a deeper human connection with the ecological cycles.

These initial pioneer organisms, such as cyanobacteria and algae, are crucial for spontaneous growth and, because of their immense ecological role on facades, represent the focus of this graduation project.

3.4 Growth requirements

To define the requirements for a bioreceptive facade design, this section explores the favourable growth conditions of photoautotrophic pioneer organisms, which are influenced by both environmental and material properties.

Complexity

The scope of this project focuses on the photoautotrophic pioneer organisms cyanobacteria and algae, as they are often the first organisms to colonise a surface and provide organic matter that supports the establishment of subsequent organisms, such as fungi. At first, it must be stated that determining the specific influences of these organisms was complex. On one hand, requirements can be highly specific per specie and the number of cyanobacteria species alone is already estimated to reach 8000 (Allaf & Peerhossaini, 2022). The study of Gaylarde and Gaylarde (2005) and Barberousse, et al. (2006) investigates some specific microbial types that were found to be growing on exteriors of buildings in Europe. Because the aim for this project is to design for the spontaneous growth of multiple pioneer species, there is primarily focuses on facade conditions and experiments that are already known to be habituated by organisms. However, most research is conducted on concrete surfaces, which limits the findings. Schilthuizen et al. (2025) also identified the gap between ecological knowledge and design as a significant limitation in bioreceptive design.

Physiological Needs

The physiological needs (Figure 3.16) contain the aspects that these photoautotroph pioneer micro-organisms directly require for their metabolism which affects their growth.

Water

Water is often a limited factor on vertical facades for the growth of photoautotroph species (Bellinzoni et al., 2003). The water is needed to execute photosynthesis resulting in the growth of biomass, in other words, water means life.

Sunlight

To execute photosynthesis, these organisms need sunlight (Q. Li et al., 2016; Reboah et al., 2023).

Nutrients

Furthermore, these pioneer communities need several nutrients to make metabolic processes possibly. For the photosynthesis, they take up carbon dioxide and water, and release oxygen into the environment again. The nutritional needs are already available through rainwater or originated airborne and can be directly taken up through the surface of the organism. Cyanobacterial growth depends on the availability of both macro- and micronutrients (Markou & Georgakakis, 2011; Markou et al., 2014). Among these nutrients, carbon, nitrogen, phosphorus, and calcium have been identified as particularly important for biofilm growth and development (Jones & Bennett, 2017; Kolodkin-Gal et al., 2023).

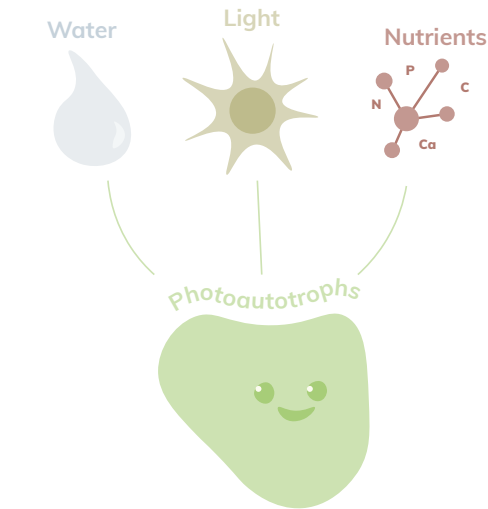


Figure 3.16. Visual overview of physiological needs

Factors

Factors Influencing the Establishment and Growth of Pioneer Organisms

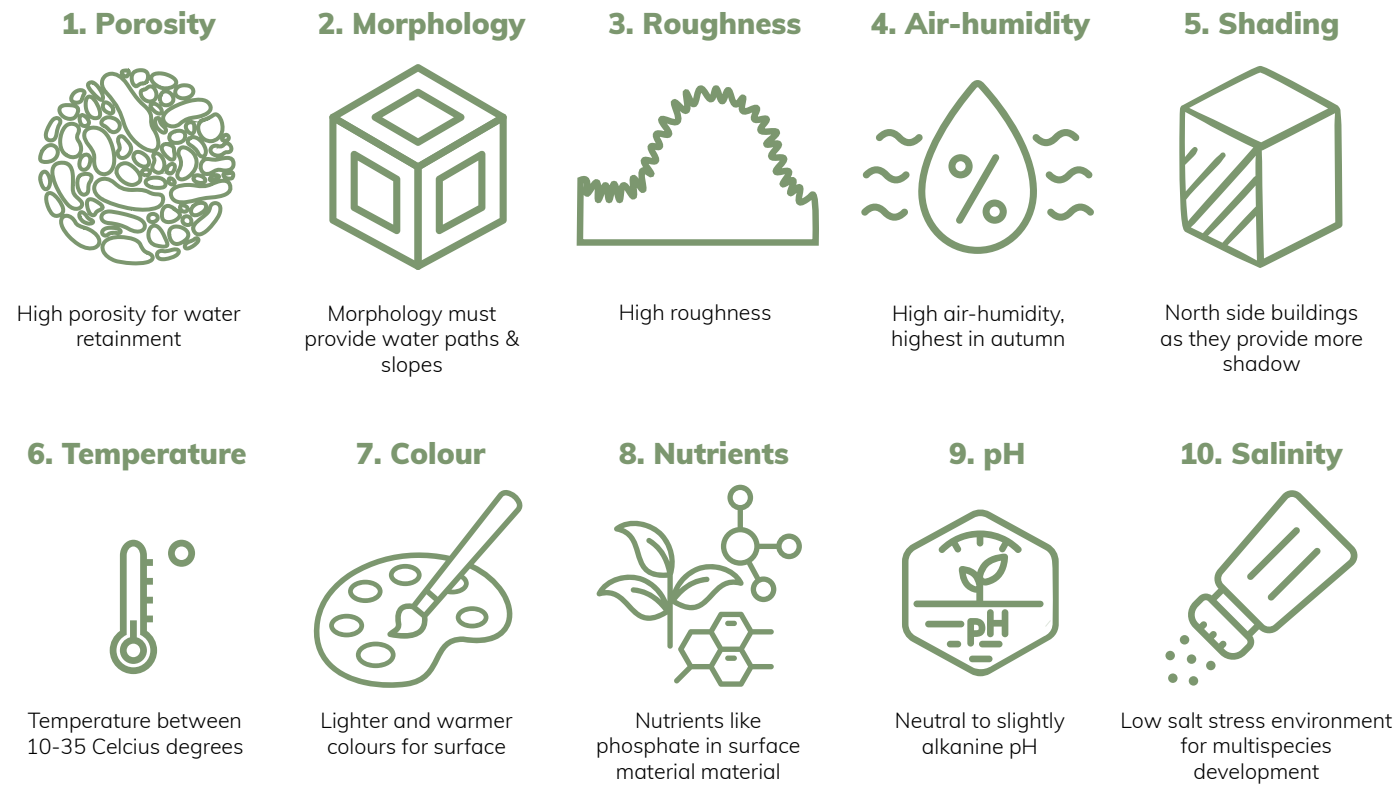


Figure 3.17. Factors influencing the establishment and growth of pioneer organisms

Favourable growth conditions

Based on an in-depth literature review, the factors in Figure 3.17 were identified as influencing the spontaneous growth of pioneer organisms on building facades. The influence of each factor is described below.

1. Porosity

One way to enhance water retention is to increase the porosity of the material, meaning that more open spaces are present that can hold water within the material (Mustafa et al., 2021; Stohl et al., 2023). Nevertheless, excessive porosity may negatively affect material durability by reducing mechanical strength and increasing vulnerability to freeze-thaw damage (Stohl et al., 2023). Stohl et al. (2023) investigated different pore classifications and their effect on bioreceptivity. One major requirement is the connectivity between the pores, as closed pores do not contribute to water transport. Capillary pores are considered particularly important for bioreceptivity because they facilitate both vapour and liquid transport through the material and contribute to freeze-thaw resistance.. In addition, larger macropores improve overall water retention and show an increase in bioreceptivity. Porosity may also develop over time through weathering processes (Schilthuizen et al., 2025). Furthermore, Schilthuizen et al. (2023) note that incorporating a passive water retention

system, such as reservoirs, can help capturing excess water during wet periods and gradually release it under drier conditions. However, achieving sufficient porosity may be challenging within NPSP's production process, which relies on heat pressing to obtain the required mechanical performance of the biobased composite. Limited porosity may therefore constrain bioreceptivity, but additional factors influencing growth and water retention are explored in the following subsections.

2. Surface morphology – macrostructure

Surface morphology can significantly enhance water retention. Research indicates that water paths are closely related to building architecture (Fuentes et al., 2022). Macro-scale geometries can support a continuous paths to direct water flow in specific directions (Mustafa et al., 2021). Inclining the surface between 30 and 45 degrees prolongs the duration of water flow, which enhances moisture retention (Fuentes et al, 2022). Slopes may also be effective because sediment and species deposit more easily on such angles



Figure 3.18. Observation of biological growth on wind turbine

(Francis, 2010). In Figure 3.18, an old wind turbine shows biological growth on its surface. It can be observed that the sloped surface exhibit more growth than vertical or upside-down surfaces, likely due to longer water retention on this geometry. The macrostructures are more effective when combined with a microstructure.

3. Surface roughness – microstructure

Roughness is the most critical physical property of the material because it can retain water, dew, nutrients while facilitating the initial attachment of organisms (Mustafa et al., 2021). A bioreceptive surface should incorporate a significant number of horizontal or near horizontal microfeatures to enhance the capture of these attachments (Schilthuizen et al., 2025).

Water adhesion on hydrophobic surfaces can occur through the petal effect, a phenomenon observed on the surface of red rose petals. This mechanism enables water droplets to remain attached even when the surface is upside-down. The effect relies on a hierarchical surface structure at the micro- and nanolevels to capture dew from the environment. Droplet volume is a critical factor in this process. Small dew droplets can be retained within micro-scale surface features because surface tension dominates over gravitational forces at this scale, whereas larger raindrops are more likely to run off the surface.

In addition, Stohl et al. (2023) highlighted surface roughness as playing a crucial role in supporting biofilms by protecting cells from shear forces generated by wind and flowing water. The roughness may be intentionally incorporated during the design process, but it can also

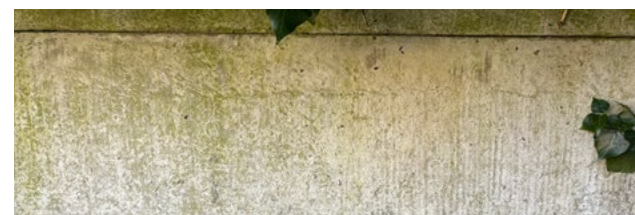


Figure 3.19. Personal observation of roughness on concrete wall with biological growth

develop gradually through material weathering (Schilthuizen et al., 2025). An example of biological growth associated with surface roughness on a concrete wall is shown in Figure 3.19.

4. Air-humidity

Reboah et al. (2023) demonstrate that microorganisms, such as cyanobacteria and green algae, develop on walls after rainfall events, especially during winter when the temperatures are lower and relative humidity is higher. Cyanobacteria are less sensitive to seasonal effects than green algae, as they can recover more quickly from desiccation (Reboah et al., 2023) and possess pigmented cells that protect them against ultraviolet radiation (Gaylarde and Gaylarde 2005). According to Jakubovskis (2025), cryptogamic covers quickly adapt to the seasonal and local climate changes, which enhances human engagement with nature and its natural flow of time. The timing of growth tests should be considered to ensure a moist environment. Optimum photosynthesis in phototrophs is reached at 100% air humidity (Gladis & Schumann, 2010), meaning the air is saturated with water vapor. Cyanobacteria can only survive if air humidity remains above 50% (Faas, 2020). Observations from Weerplaza (n.d.) indicate that the relative air humidity over the last ten years has been highest in autumn and winter, with an average of 87.5%, and lower in spring and summer, on average 77%. Reboah et al. (2023) found a higher concentration of organisms on vertical samples during winter compared to spring, which is attributed to higher humidity levels that favour microbial development. However, during severe frost, humidity decreases rapidly (AirSain, n.d.), which suggests that cold winters are not always optimal for growth and identifies autumn as the most favourable season for microbial development.

5. Shading

The orientation of a building also influences growth, as the north-facing sides receive more shade than those facing south. Greater development of microorganisms, including cyanobacteria and green algae, is typically found on north-facing walls (Reboah et al., 2023). This is due to locally lower temperatures and the fact that these surfaces remain wet for longer periods.

6. Temperature

A study by Lüring et al. (2012) states that the mean optimal growth rate is 29.2 degrees Celcius for both cyanobacteria and green algae (chlorophytes). According to Berg et al. (2015) these organisms begin growing at temperatures around 10 degrees and flourish between 25 and

35 degrees Celcius (in water). High temperatures may stress phototrophic species, leading to reduced biomass growth. Especially on non-porous surface, the moisture layer from morning dew dries more rapidly due to warming at higher temperatures (Gladis & Schumann, 2010). This highlights the effect of temperature on the moisture level.

7. Surface Colour

Gambino et al. (2018) investigated the influence of surface colour on the growth of phototrophic biofilms, a factor not yet mentioned in research on bioreceptive requirements. By the end of a 30-day study, the biofilm on the white surface achieved the highest growth with 0.335 mg cm⁻² of biomass, followed by the red surface. The blue and black surfaces performed significantly worse, with black yielding a biomass of 0.143 mg cm⁻².

While darker colours typically absorb more radiation, the temperature differences recorded in the study by Gambino et al. (2018) were found to be too minimal to be the primary driver of growth variations. Instead, the enhanced growth on white and red surfaces is primarily attributed to light quantity and quality. White and red surfaces reflect a much higher photosynthetic photon flux (PAR), providing more available energy for the photoautotrophic cyanobacteria. Furthermore, these surfaces reflect the 611 nm wavelength (red light) toward the biofilm, which is known to stimulate growth via specific photoreceptors. This spectral band was absorbed by the blue and black surfaces and was therefore unavailable to the organisms.

A study from Gladis & Schumann (2010) shows that the heat capacity storage and temperature of black tiles is higher than that of red tiles, resulting in lower biofilm growth. Black tiles can reach temperatures of 50°C higher than that the ambient air. However, in this specific case, beside the colour, the coating also differed in porosity which influenced the phototrophic growth.

Overall, darker and 'colder' colours perform worse and lighter and 'warmer' colours are preferred for faster biofilm growth.

8. Nutrients in surface material

According to Stohl et al. (2023), photoautotrophic organisms do not require a nutrient-rich substrate, but instead primarily rely on carbon dioxide, sunlight and water. The small quantities of nutrients these organisms need, such as nitrogen and phosphate, are typically accessible through the particulate matter in the air. On the other hand,

some studies suggest that adding nutrients to the surface material can improve bioreceptivity, and the research of Veeger et al. (2021) demonstrated increased biological growth when phosphorus was added. Therefore, it is expected that the absence of nutrients in the substrate will not be a limitation for biological growth, but their presence has the potential to increase the total biomass.

9. pH

For bioreceptive experiments on concrete, it was found that materials with very extreme pH values can negatively affect biomass growth (Manso et al., 2014; Frantová et al., 2025). Consequently, several studies have focused on lowering the pH of cement-based materials to a less alkaline level (below 10) or even to a neutral level (~7) to create more favourable conditions for bioreceptive concrete buildings. Nevertheless, Veeger et al. (2021) also observed biological growth at pH levels above 10.

Nayak (2007) reports that neutral to slightly alkaline pH conditions are favourable for cyanobacterial growth. However, acidic soils can nevertheless support cyanobacterial communities, although generally with lower diversity and abundance. Nowicka-Krawczyk et al. (2025) also suggest a neutral to slightly alkaline preference for algal biomass, although optimal pH ranges may vary between species. Tyler and Olsson (2016) found that bryophytes, including mosses, are generally associated with slightly acidic to neutral substrate conditions, with the taxa analysed in their study occurring across a pH range of 4.7 to 7.2.

Overall, although pH preferences vary between species, these findings suggest that a neutral pH provides the most favourable conditions for supporting a broad range of pioneer organisms and maximising overall bioreceptivity. This conclusion is consistent with Mustafa et al. (2021), who identified a neutral pH as a desirable characteristic of bioreceptive materials.

10. Salinity

Cyanobacteria and algae can be found in saline environments, such as the sea (Naselli-Flores & Barone, 2009). However, exposure to a high salt concentration for a long period can cause salt stress in cyanobacteria, which results in a reduced growth rate. Mosses on the other hand, do not thrive in salt areas (Marsaglia, 2019). Environments with lower salt stress offer better potential for the growth of a multispecies green wall. This factor should be considered when choosing the location for the facades.

4 Composite Development

This chapter focuses on understanding the material and the potentials and limitations of a composite with the biobased Oribond resin as an NPSP facade panel. To understand the material and gain knowledge of its potential, limitations, and production process, a Material Driven Design-inspired approach is used to explore the material's behaviour.

4.1 Tinkering

In the first weeks of the project, multiple plates were created through tinkering: 'a kind of explorative process of creation and evaluation' (Karana et al., 2015). The ingredients were inspired by NPSP's expertise and the materials available within the company (Figure 4.1). An overview of the used fibres and fillers during the tinkering process are shown below in Figure 4.2. Notes and changes were documented in a material diary, see Appendix A for a glimpse in this journey. The plates were iteratively developed to explore mechanical strength, homogeneity, flow and especially a lighter colour. On the next page, an overview of the developed plates is shown (Figure 4.3). Some samples were rejected based on visible observations, such as cracks or inhomogeneous mixing. The promising plates were then tested for their technical properties, analysed in Chapter 4.4.



Figure 4.1. Variety of fibres and fillers directly available at NPSP

	1	2	3	4	5	6	7	8
Resin	Oribond	Oribond	Oribond	Oribond	Oribond	Oribond	Oribond	Oribond
Filler	Egg shell course	Egg shell fine	Egg shell fine	Olive stone	Olive stone	Carbon black	Olive stone	Glass bubbles
Fibre	Flax long	Flax long	Leather shavings	Flax long	-	-	Wool cut by hand	Viscose

	9	10	11	12	13	14	15	16
Resin	Oribond	Oribond	Oribond	Oribond	Oribond	Oribond	Oribond	Oribond
Filler	Cork fine	Pistache shell	Olive stone	Olive stone	Olive stone	Diatomaceous earth	Egg shell fine	Seashell flour
Fibre	Flax short	Flax short	Flax short	Viscose	Biosorbe	Viscose	Viscose	Viscose

Figure 4.2. The recipe versions with the combination of ingredients used during tinkering

4.2 Production process



Figure 4.3. Overview of developed plates through tinkering

This section describes the production processes used, with an overview illustrated in the process diagram on the next page (Figure 4.6).

1. Material treatment

Firstly, the material is treated to optimise its mixing and curing properties. This step is informed by the guidelines provided by Orineo and NPSP. The fillers and fibres are supplied in pre-granulated or chopped form by external providers. The resin consists of two components: A) the epoxyeed linseed oil, and B) the hardener. The fibres and fillers are dried until their moisture level is below 2%, measured using a professional moisture analyser. Both components of the resin are heated in a water bath to 50°C. At this temperature, they become more fluid. Once heated, components are combined and manually stirred using a wooden stirring stick for approximately 2 minutes.

2. Mixing

Order

The prepared ingredients are mixed together. A key property of this new resin is that it has a high viscosity and adheres to metal. It was important to first add the dry filler to absorb the resin, which was slowly poured onto it while mixing. However, this order resulted in a clumpy and non-homogeneous mixture. When the mixture was ready, the mixture bowl was cleaned to avoid material hardening onto the surface. Nevertheless, it was already difficult to remove the mixture from the metal material. Due to the resulting inhomogeneity of the mixture, the mixing process was subsequently iterated in parallel to improve its homogeneity.

Tools

On one hand, the mixing machine was explored (Figure 4.4). An initial KitchenAid with a dough hook was used, after which an accu drill and electrical drill were tried. These drills work better than the hook, but were not available later on. Then a new attachment of the KitchenAid was tried, namely the whisk. This one worked better than the hook.

Proportion

On the other hand, the proportions were explored. In the beginning it was attempted to maintain the same resin:filler:fibre ratio for better comparability, but some samples failed due to being too dry and having poor homogeneity. A reason for this difference was that the proportions were based on mass, while some ingredients have a higher or lower density, resulting in an imbalanced mixture. For example, glass bubbles and cork have a very low density. To avoid more failed samples, the mixture was adapted based on visual and tactile observations, allowing extra resin to be added or omitted depending on whether the mixture appeared sufficiently wet. All proportions were consistently measured and recorded during the experiments. The proportions vary between 30% and 45% resin (with cork requiring the highest proportion). In addition, the fibre content was varied to enhance flowability and homogeneity.

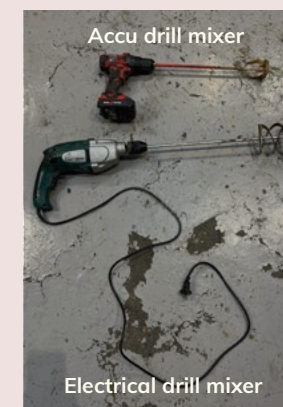


Figure 4.4. Explored mixing tools

Process diagram

Composite plates

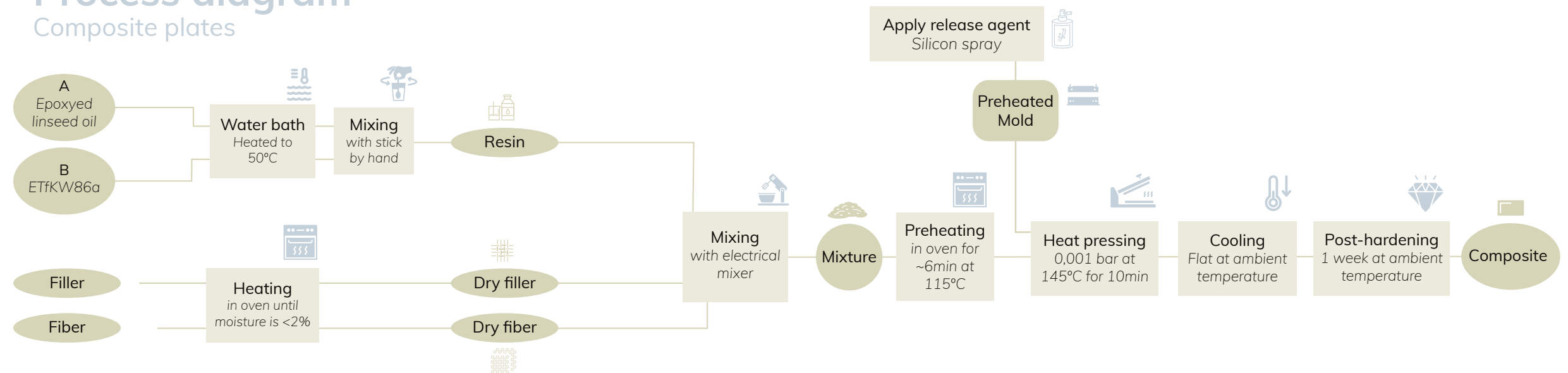


Figure 4.6. Process diagram with overview of the production



Figure 4.5. Heat pressing tools used

Time

It was also noted that a longer mixing time, such as 5 to 10 minutes, improved homogeneity compared to shorter mixing times of only a minute.

3. Preheating

Some samples came out of the heat press with dry spots, and during the heat pressing process, it was observed that there was leakage of the resin from the mould. Orineo recommended preheating the mixture in order to partially cure it before pressure is applied. For almost every recipe, the effect of preheating was compared, resulting in significant less leakage and fewer dry spots on the material surface when preheated. This step is therefore included the process diagram.

4. Heat pressing

To develop a strong composite, the compression moulding step is crucial for achieving its mechanical properties. The metal mould is first prepared with a release agent. In this case, a silicone spray was selected, because the resin adheres to metal and organic materials, but not to plastics. Although the silicon spray performed well, a more sustainable release agent could be investigated, such as vegetable oils. The mixture is then applied into the mould, which is closed and placed into the heat press (Figure 4.5). The heat press is set to a temperature of 145°C and a pressure of 80 bar for 10 minutes. The optimisation of the pressing time has not yet been properly investigated. When finished, the cooling of the plate is slightly accelerated by placing it between two metal plates at ambient temperature.

5. Post-treatment

It was recommended by Orineo to cure the resin and composite for one week after processing. This procedure was followed prior to measuring the mechanical properties.

4.3 Material taxonomy

This material taxonomy represents the organisation of variables affecting the composite properties.

In particular, variables related to material ingredients are explored. The selected fillers and fibres are identified in Figure 4.7.

The initial setup for the variables of material processing performed well, except for the mixing process, which was only partially investigated and is further explained in Chapter 4.2.2. Due to time constraints, it was chosen not to further explore the variables of the material processing, although it is recommended for achieving an even better-performing outcome.

The variables for the material structure were mainly based on ISO standards. Furthermore, homogeneity could be further improved.

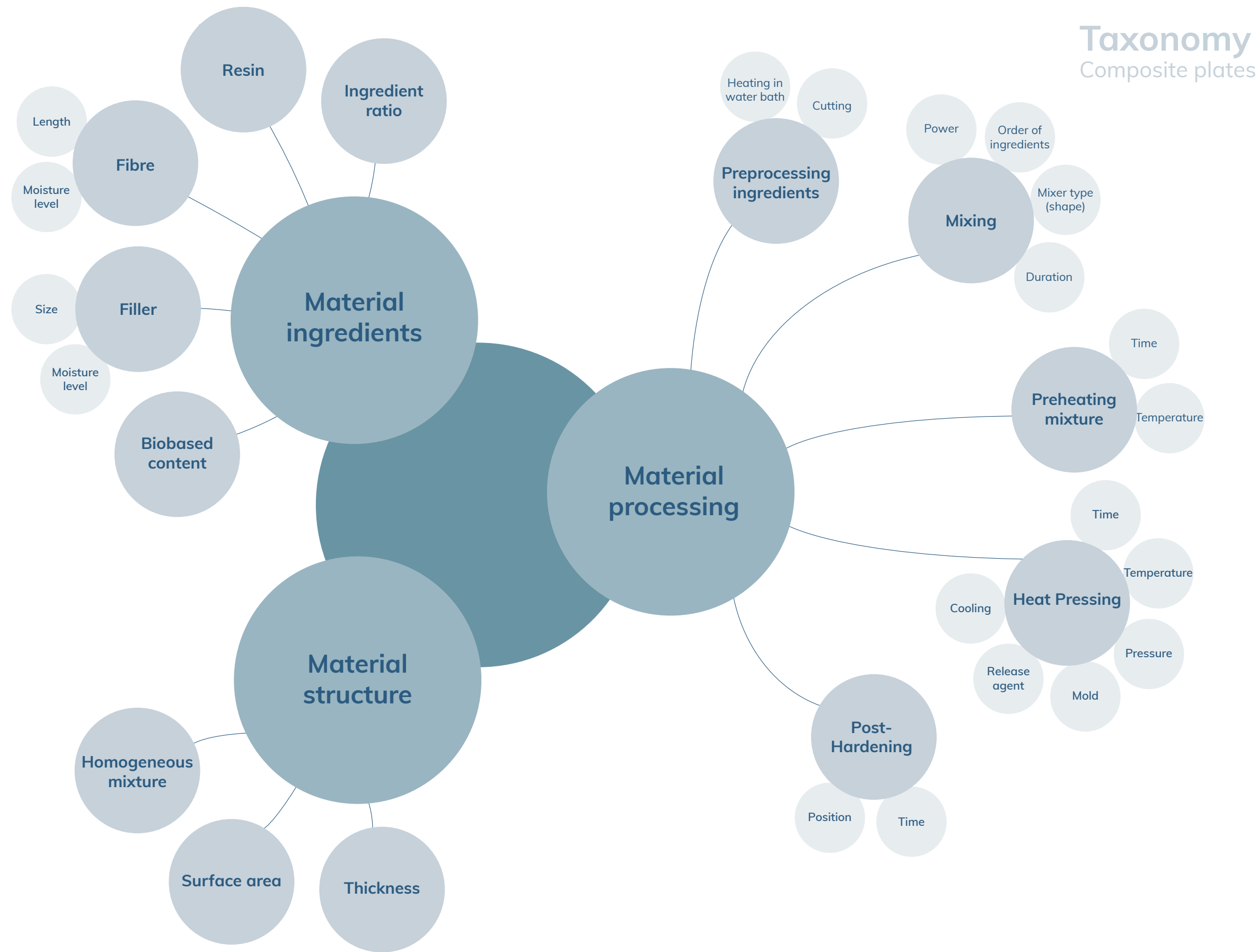


Figure 4.7. Material taxonomy with organised overview of variables affecting properties outcome of composite

4.4

Characterisation & benchmark

To evaluate the material, it is compared to the existing materials from NPSP, Nabasco 8012 and 8040, as well as to existing facade materials.

Technical characterisation results

Nine out of sixteen plates showed potential and were tested for mechanical properties. In Figure 4.11, on the next page, an overview of the mechanical properties of the Oribond plates compared to Nabascos products is presented. For each property, the standard deviation (S.D.) is shown, where a high deviation indicates non-stable results.

Flexural strength

Nabasco 8012 is currently on the market, and its strength of 32 MPa is considered the minimum benchmark. The Oribond composite shows a flexural strength of 3.36 to 45.4 MPa. Six out of eleven samples showed a higher flexural strength than 8012. No plates were stronger than 8040, which has an outstanding flexural strength of 72 MPa.

Flexural modulus

The flexural modulus of all Oribond plates is lower than that of Nabasco 8012 and 8040. Nabasco 8012 has a flexural modulus of 7.48 GPa and Nabasco 8040 5.3 GPa, whereas the Oribond plate range between 0.60 to 3.88 GPa.

Impact

The reported impact strength of Nabasco 8012 is 3.8 kJ/m² and of Nabasco 8040 is 5,7 kJ/m². The Oribond plates have an impact strength between 4.82 and 11.59 kJ/m², showing that they are all higher than that of Nabasco 8012. Six out of nine plates are even higher than that of Nabasco 8040.

Density

Nabasco 8012 has a density of 1.78 g/cc, whereas Nabasco 8040 has a density of 1.38 g/cc. The density of all Oribond plates are lower than that of Nabasco 8012, and seven out of ten are even lower than Nabasco 8040.

Technical characterisation analysis

These results validate the potential of this Orineo composite to be strong enough to function as a facade panel. The flexural strength in certain recipes is already sufficient. The flexural modulus is lower than that of the current Nabasco composites, meaning the material is more flexible and less stiff. However, the impact strength of several Oribond plates is significantly higher than that of the Nabasco plates. If, for example, someone bumps their bicycle against the wall or a small stone from the road flies against the surface, these Oribond plates are better able to resist such forces without breaking. Additionally, the density of most Oribond plates is lower than that of the current composites, meaning that less material is required to achieve similar stiffness. To enable visual comparison, the materials are plotted in modulus–density and strength–density charts in Figure 4.9 & 4.10. They exhibit characteristics similar to existing Nabasco materials and fall within the polymer material group.

	Concrete	Aluminium sheet	Red brick	Stainless steel	Nabasco 8012	Nabasco 8040
CO2 impact	86 kg/m ²	79 kg/m ²	40.5 kg/m ²	22 kg/m ²	13 kg/m ²	-14 kg/m ²

Figure 4.8. Overview of CO2 impact of existing facade composites (from NPSP).

CO2 impact analysis

In Figure 4.8, an overview of the CO2 impact of the current Nabasco plates and other facade materials is presented. As shown, Nabasco already represents a significant improvement compared to concrete, which is the most widely used building material. Nabasco 8040 even has a negative CO2 impact, mainly because it is biobased. This indicates that the footprint of the biobased Oribond plates may also be negative.

Colour analysis

One key potential of this new resin is the increased visual freedom compared to the furan resin used in Nabasco 8040. For this, light biobased ingredients were selected during the tinkering process. However, some light materials became darker when combined with the resin, indicating a similar darkening process to that observed when linseed oil is applied to wood. Despite this, all the potential samples appeared lighter than Nabasco 8040. The plate with fine eggshell (2) appeared very light, enabling better colouring, but these plates exhibit poor mechanical properties.

Promising material compositions

The plate that performs best on average across all mechanical properties, with particularly high impact strength, is number 12, consisting of approximately 40 % Oribond resin, 55 % olive stone filler and 5% viscose fibre. Regarding colour, there is no significant difference compared to the other strong plates and some are even darker.

The coarse eggshell (1) as a filler also scores significantly on flexural strength and could be interesting due to its light appearance. However, the coarser the filler, the poorer the flow and form freedom. Furthermore, the fine eggshell performs poorly. Orineo suggests that this may be due to the acidic nature of the resin and the alkaline composition of the eggshell. As a result, an acid–base reaction may occur between the resin and the calcium carbonate in the eggshell, weakening the composite.

Another interesting plate is the one with cork (9). The flexural strength is significantly lower, but the density is very low and the impact strength is high. The high impact strength of 9 and 12 could also be interesting for other applications. NPSP has, for example, suggested street light covers, which require high impact resistance.

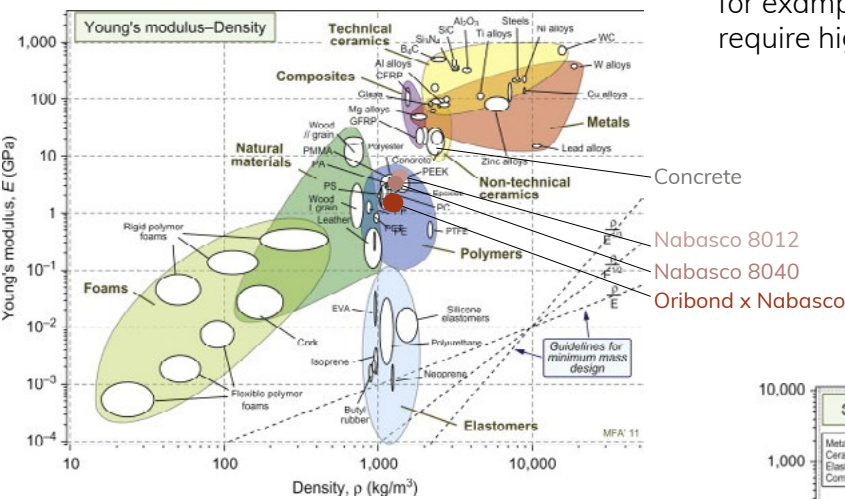


Figure 4.9. Young's modulus-density chart showing the distribution of concrete, Nabasco 8012, Nabasco 8040, and Oribond plates

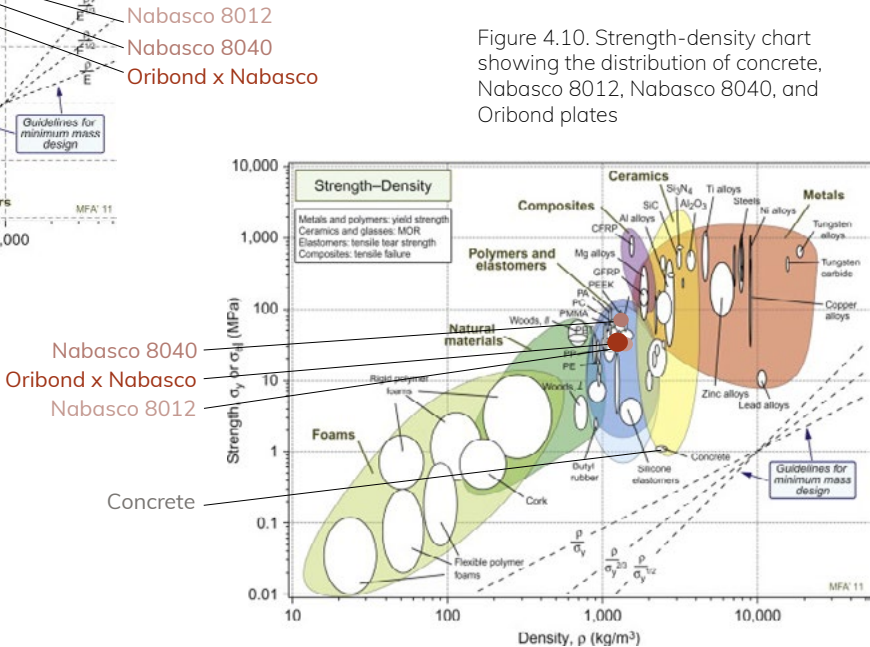


Figure 4.10. Strength-density chart showing the distribution of concrete, Nabasco 8012, Nabasco 8040, and Oribond plates

Figure 4.11. Technical properties overview of developed Oribond plates in comparison with the current Nabasco plates

Technical overview recipes



Recipe name		Nabasco 8012 Reed Fire	Nabasco 8040 Furan	1	2	4	5	9	10	11	12	13	15	16
Making date				11 feb	11 feb	13 feb	13 feb	18 feb	20 feb	20 feb	24 feb	24 feb	11 mrt	11 mrt
Ingredients		- 50% bio-based BioPolyester - Lime - Reed	- Fully bio-based Furan - Nut shells -	30% Oribond 50% Egg coarse 20% Flax long	30% Oribond 60% Egg fine 10% Flax long	30% Oribond 60% Olive stone 20% Flax long	30% Oribond 70% Olive stone -	45% Oribond 45% Cork 9% Flax short	37% Oribond 53% Pistache shell 10% Flax short	37% Oribond 53% Olive stone 10% Flax short	40% Oribond 55% Olive stone 5% Viscose	40% Oribond 55% Olive stone 5% Biosorbe	32% Oribond 62% Egg fine 6% Viscose	22% Oribond 71% Seashell flour 7% Viscose
Specific density (g/cc)	ISO 1183	1,78	1,38	1,53	1,57	1,21	1,25	1,15	1,27	1,22	1,29	1,24	1,72	1,85
Flexural strength (MPa)	ISO 14125A	32	72	40,6	22,3	39,5	32,7	20,0	28	37,6	45,4	42,3	3,36	9,83
S.D. strength				4,55	5,17	3,97	16,48	2,46	2,35	3,62	4,29	2,59	1,65	4,80
Flexural strain (%)	ISO 14125A	0,67	1,4	2,2	2,8	2,0	3,2	6,8	2,6	2,0	3,7	3,0	1,1	1,9
S.D. strain				0,40	0,71	0,41	1,38	0,88	0,28	0,41	0,82	0,39	0,45	0,37
Flexural modulus (GPa)	ISO 14125A	7,48	5,3	3,88	2,05	3,01	1,73	0,741	1,95	2,97	2,13	2,39	0,597	1,45
S.D. modulus				0,51	0,38	0,36	0,72	0,16	0,14	0,21	0,14	0,27	0,24	0,89
Charpy impact (kJ/m^2):	ISO 179	3,8	5,7	6,71	6,40	5,25	8,67	8,41	5,32	4,82	11,59	9,72	-	6,53
S.D. impact				0,79	1,50	0,96	1,04	1,60	0,96	0,34	1,93	1,43	-	1,98
Water absorption 48hr, 23°C (%)	ISO 62	0,6	1,6											
Notes				- Slightly smelly	- Slightly smelly - Bit of bumpy surface - 'body hair' - light colour	- Some dry areas	- No fibres - One came out with crack in corner - Dry stains	- Light weighted - Bumps on surface	- darker colour than olive stone as filler	- Some small dry areas in corners	- white fiber - strongest & highest impact	- You almost do not see the fiber, transparant fiber	- Very light - fine dust is coming off the sample	- High density and bit dark

5 Composite Performance Evaluation

5

Out of the mechanical characterisation, recipe 12 was identified as the most promising formulation using the Oribond resin and was therefore selected for further evaluation. Multiple samples were produced in several batches (Figure 5.1) to investigate the durability and bioreceptive performance of the material.

To assess its suitability for facade applications supporting pioneer organisms, additional tests were conducted on water absorption, pH, weathering behaviour, and fire performance. These properties involve potential trade-offs. From a durability perspective, low water absorption and resistance to weathering are desirable, whereas increased moisture availability and weathering-induced surface changes may support biological attachment and growth. The pH was evaluated to determine whether the material remains within a range that is unlikely to inhibit pioneer organisms.

The investigated properties address both facade performance and bioreceptivity, including pH behaviour, water absorption, weathering behaviour and fire behaviour. Together, these evaluations provide insight into the suitability of the developed composite for bioreceptive facade applications.

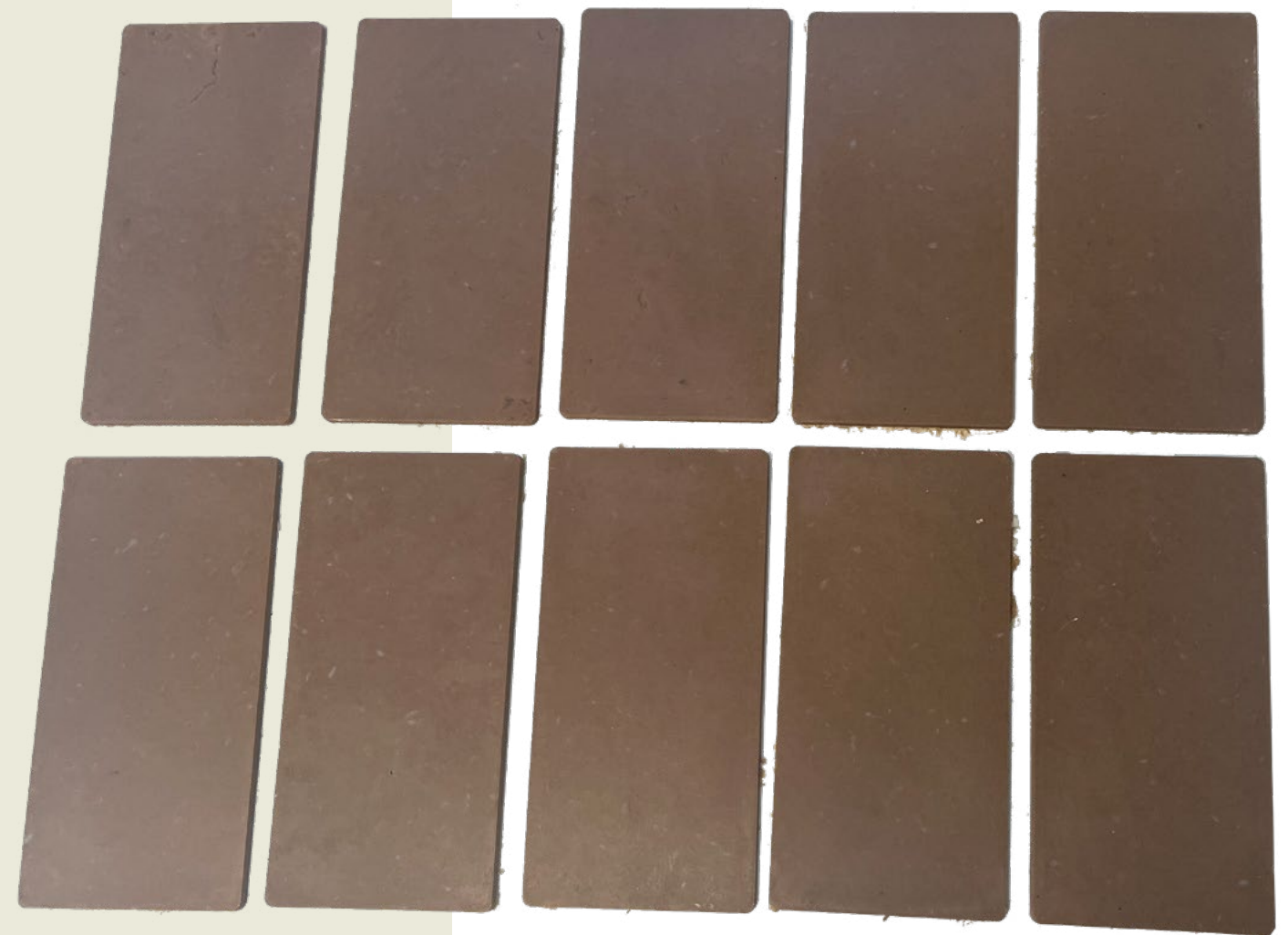


Figure 5.1. Sample batch creation of chosen recipe (version 12)

5.1 pH behaviour

The pH level can significantly influence the growth of organisms, particularly at extreme values. As discussed in Chapter 3.4.9, a neutral pH (~7) is considered desirable for supporting a broad range of bioreceptive growth. As fillers and other ingredients can influence the pH of the material, an initial pH test was conducted to assess whether the developed material provides favourable conditions for bioreceptive growth.

The pH was expected to be neutral to slightly acidic, as the resin is derived from an acidic component (Component B is from citric acid) prior to curing and no strongly alkaline fillers (such as egg shell) were included in the final recipe. However, the exact pH contribution of the individual ingredients is difficult to predict through literature, as it depends on their processing methods.

Method

The pH level expresses the concentration of hydrogen ions in a liquid and indicates how acidic or alkaline a solution is on a scale from 0 to 14, with pH 7 being neutral (PH, 2026). As the pH of a solid material cannot be measured directly, an indirect measurement approach was used. To obtain an indication of the pH of the material when interacting with water, an initial test was conducted inspired by the slurry method. In this method, a pulverised solid material is mixed with water and the pH of the resulting suspension is measured (Bista, 2024). A similar approach was used by Veeger, Ottelé et al. (2021) to determine the pH of concrete samples for bioreceptive research, and a comparable method is also applied at NPSP.

The following procedure was conducted based on these sources and the method used by NPSP:



Figure 5.2. Material before and after pulverisette

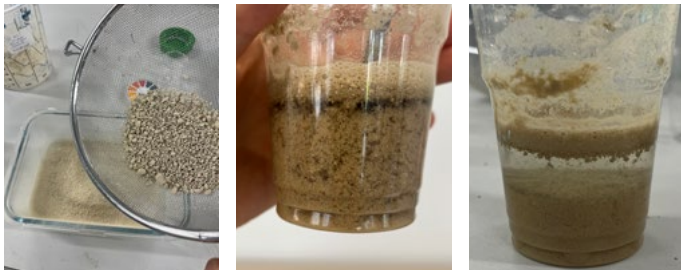


Figure 5.3. (left) Filtering material, (middle) slurry right after mixing, (right) slurry after 15 min rest

First, the solid material was pulverised into a fine powder. Pulverising the material manually using a mortar and pestle proved too difficult, therefore a Pulverisette available at NPSP was used (Figure 5.2). To remove large clumps, the pulverised material was filtered through a sieve, after which it was mixed with distilled water. The ratio between powder and water is not standardised and depends on factors such as density and solubility. Based on previous testing at NPSP, mixtures below a 1:5 ratio generally formed a paste, whereas a ratio of approximately 1:10 resulted in a fluid suspension. Therefore, a 1:10 ratio was selected for this initial indication test. Consequently, 10 g of powder was mixed with 100 g of distilled water.

The mixture was stirred manually for approximately 2 minutes until thoroughly mixed, and subsequently allowed to settle. One sample was settled for 15 minutes and another mixture settled for 5 days (Figure 5.3). Finally, a pipette was used to transfer the liquid onto pH indicator paper. When the result fell within either the acidic or alkaline range, a second, more specific indicator paper was used to determine the pH value.

To verify the responsiveness of the indicator paper, distilled water and a citric acid solution were also tested to confirm that the indicator paper was capable of distinguishing differences in pH.

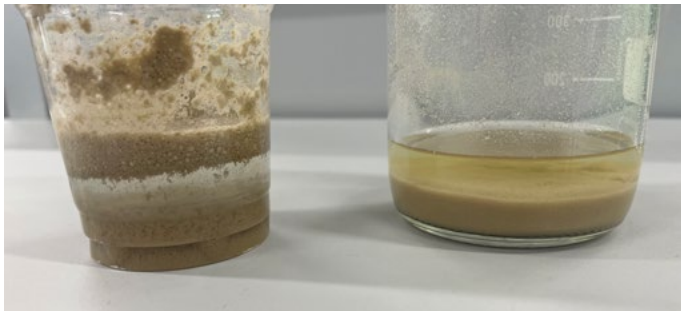


Figure 5.4. (left) mixture after settling for 15 minutes & (right) for 5 days

pH behaviour

The indicator paper exposed to the liquid phase of the slurry mixture showed a visible colour

change towards acidic colours, corresponding to approximately pH 4 (Figure 5.5). No visible difference was observed between the measurements after 15 minutes and after 5 days of settling, suggesting that the pH of the suspension remained relatively stable over this period.

Implications for bioreceptivity

Although a pH of approximately 4 is not extremely acidic, it is lower than the neutral pH generally considered most favourable for supporting a broad range of pioneer organisms. Neutral conditions can support species with preferences extending towards both slightly acidic and slightly alkaline environments, thereby maximising the potential diversity of colonising organisms. Nevertheless, a moderately acidic pH does not necessarily prevent biological colonisation, but may influence the composition of the resulting community and reduce the suitability for species that prefer neutral to alkaline conditions.

Most studies on bioreceptive growth have been conducted on concrete-based materials, which are alkaline. As a result, many of the cyanobacteria and algae reported in these studies are adapted to alkaline conditions. However, pH preferences within algae and bacteria also vary between species, and the observed pH may favour species adapted to slightly acidic conditions. In addition, other members of cryptogamic communities, such as bryophytes (mosses), are commonly associated with slightly acidic to neutral environments and may find more favourable conditions on this material than on conventional alkaline concrete surfaces. Further research is required to determine which communities are most likely to establish under these conditions and whether the pH of the composite can be adjusted towards more neutral conditions through modifications to the ingredient composition.

Test limitations

Nevertheless, this test should be regarded as an initial indication only. A precise pH determination would require the use of a calibrated pH meter rather than pH indicator paper.

In addition, the material was pulverised prior to testing. As biological growth occurs on the material surface rather than on pulverised particles, the measured pH may not fully represent the conditions experienced by organisms on the facade. Pulverisation increases the exposed surface area of the ingredients and may therefore influence the measured pH.

Furthermore, no conclusions can be drawn regarding long-term changes in pH behaviour. Environmental weathering, water exposure, and interactions with inhabiting organisms may alter the pH of the material over time. Organisms can modify their local pH through metabolic activity and the release of acidic or alkaline compounds (Ratzke & Gore, 2018). Therefore, the measured pH should be regarded as an initial indication rather than a fixed long-term condition.

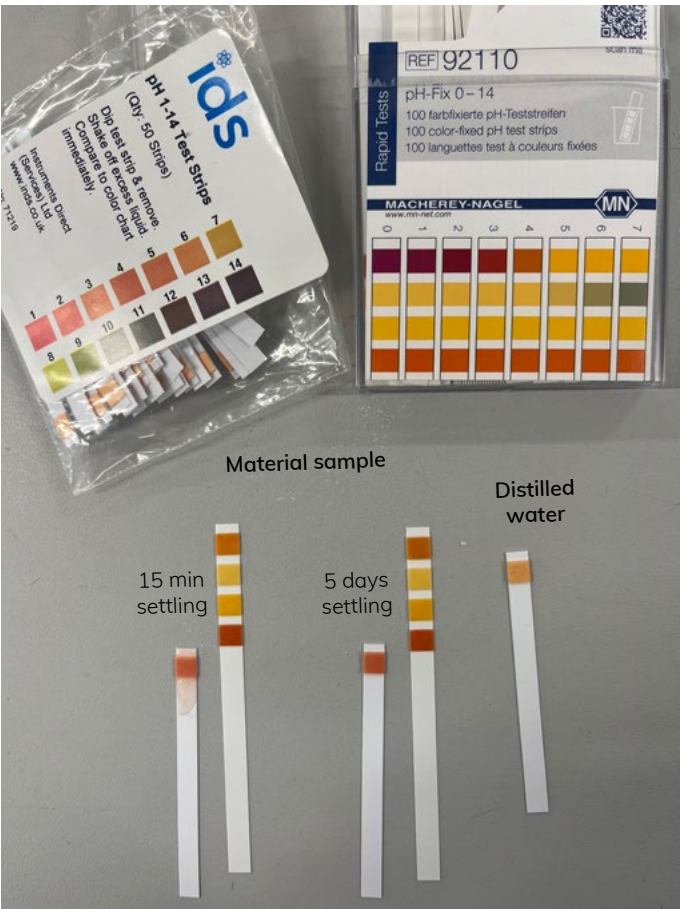


Figure 5.5. pH indicator paper results of the material samples with different settling durations and of the distilled water

5.2 Absorption behaviour

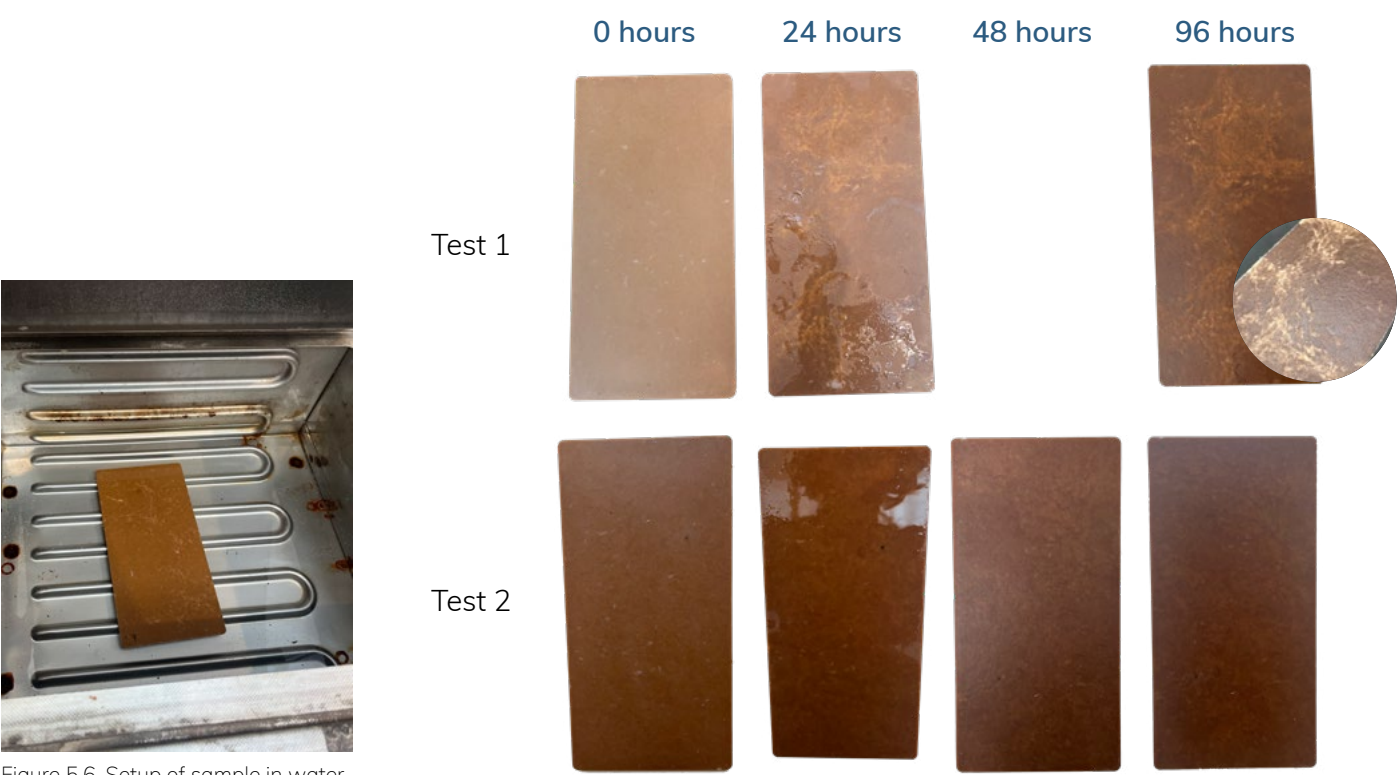


Figure 5.6. Setup of sample in water bath at 23°C

Figure 5.7. Overview of observed absorption behaviour over time

Absorption method

The water absorption behaviour of the developed composite was evaluated according to ISO 62. Samples were submerged in a water bath at approximately 23 °C for 96 hours (Figure 5.6). The mass of the samples was measured at regular intervals during immersion. Prior to weighing, excess surface water was removed and the samples were allowed to dry at room temperature. Flexural strength was determined after 96 hours of water exposure.

Water absorption is relevant from a bioreceptive perspective because absorbed moisture may increase water availability for pioneer organisms. At the same time, excessive water uptake may negatively affect durability and mechanical performance. To provide context for the results, the absorption behaviour and flexural strength retention were compared with available data for the Nabasco 8040 and 8012 facade composites.

The absorption test was conducted twice. The first test was repeated because the 48-hour mass measurement was missing and the samples were dried using a paper cloth prior to weighing. Nevertheless, the first test was retained because it provided additional information on water uptake trends and visual changes during immersion.

Absorption behaviour

Visual observations

After 96 hours of immersion, the material appeared darker than before exposure (Figure 5.7). In the first test, lighter patches were observed within the darker surface, whereas these were absent in the repeated test. Additional testing is required to determine whether this observation is material-related or caused by experimental variation.

Water uptake

Both test series showed a clear increase in mass during immersion (Figure 5.8). After 48 hours, test 1 with the Oribond composite showed a mass increase of approximately 4.3%, compared to 1.6% for Nabasco 8040 and 0.6% for Nabasco 8012. This indicates substantially higher water absorption than the existing facade composites.

Flexural strength

After 96 hours of immersion, the flexural strength of the Oribond composite decreased by approximately 39 to 48% (Figure 5.9). For comparison, Nabasco 8040 showed a reduction of approximately 31% under similar conditions. Comparable flexural strength retention data after water exposure were not available for Nabasco 8012. The results indicate a greater sensitivity to

		0 hours	24 hours	48 hours	96 hours
Test 1	Mass (g)	127,89	133,3	-	138,8
	Percentage (%)	100 %	104,23 %	-	108,43 %
Test 2	Mass (g)	133,69	137,51	139,45	142,44
	Percentage (%)	100 %	102,86 %	104,31 %	106,54 %

Figure 5.8. Water uptake over time based on measured mass increase

		Test 1		Test 2
		Without absorption	96 hours	96 hours
Flexural strength (MPa)	45,4	21,9	17,6	
Percentage (%)	100 %	48,24 %	38,77 %	

Figure 5.9. The flexural strength before and after 96 hours with two repetitions

prolonged water exposure than the existing furan-based composite.

Implications for bioreceptivity and durability

The higher water absorption of the Oribond composite may increase moisture availability for pioneer organisms and is therefore potentially beneficial from a bioreceptive perspective. However, the accompanying reduction in flexural strength demonstrates that water exposure also affects the mechanical performance of the material.

Although continuous immersion for 96 hours represents a relatively extreme scenario compared to typical facade conditions, the results indicate that prolonged exposure to moisture may influence long-term durability. Further testing, including cyclic wetting and drying, freeze-thaw resistance, and long-term outdoor exposure, is recommended to better understand the durability limits of the material and identify opportunities for further optimisation of the composite design.

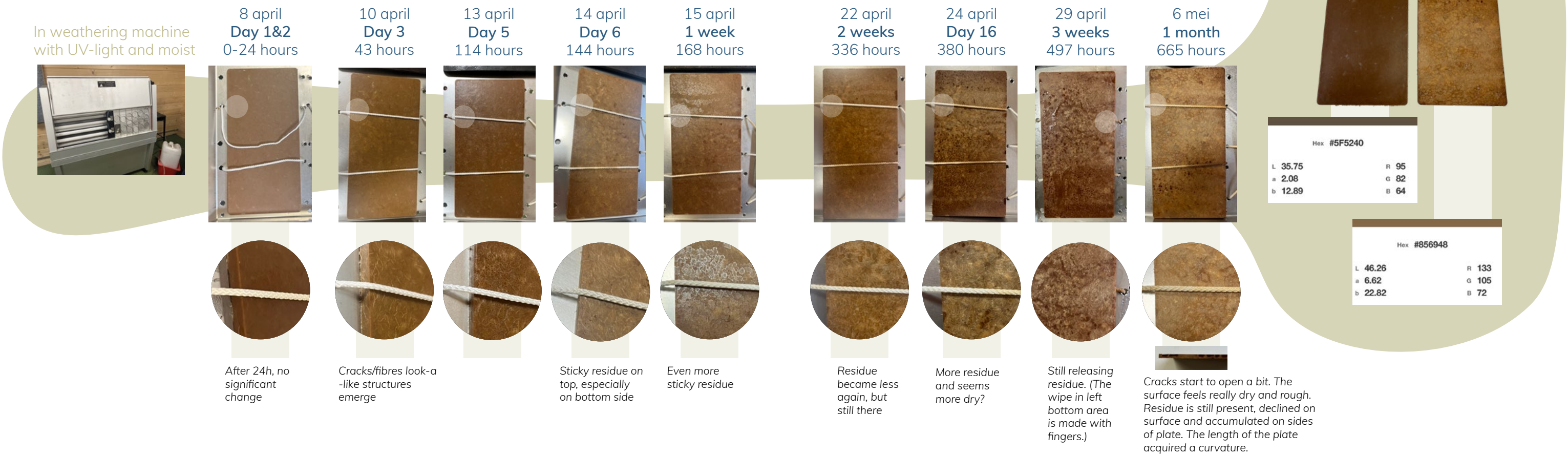
Test limitations

The water absorption and flexural strength measurements were performed on the same samples. During the absorption test, the specimens were repeatedly removed from the water and dried for weighing. This repeated wetting and drying may have introduced additional stresses due to cyclic swelling and shrinkage, potentially affecting the measured flexural strength.

Furthermore, the sample surfaces in the first absorption test were dried using a paper cloth prior to weighing. Previous observations on the Nabasco 8040 furan composite indicated that this procedure can negatively affect the measured flexural strength after water exposure. To minimise this effect, excess surface water in the repeated test was removed by allowing the samples to dry at room temperature and by gently blowing air over the surface rather than wiping it with a cloth. Nevertheless, the influence of the drying procedure on the measured mechanical performance cannot be fully excluded.

5.3 Weathering behaviour

Figure 5.10. Overview of observed weathering effect over time through QUV chamber



Accelerated weathering method

QUV machine

To gain insight into the weathering behaviour of the developed composite, samples were exposed in a QUV chamber. The QUV chamber reproduces and accelerates weathering effects caused by sunlight, rain, and dew. The samples were positioned vertically, comparable to a facade application, and fixed in place using a rope.

Correlation between accelerated and natural weathering

To approximate the correlation between accelerated weathering in the QUV chamber and natural outdoor exposure, an estimation from NPSP was used based on the Weathering Testing Guidebook (McGreer, 2001). Using KNMI UV exposure data of eight months and standardising to an irradiance of 0.89 W/m² at 340 nm, a conversion factor of 17.1 was established. This indicates that 1 hour in the QUV chamber is approximately equivalent to 17.1 hours of outdoor exposure, making 1 month (665 hours) of accelerated weathering approximately equal to 1.41 years of natural weathering.

In situ exposure

To complement the accelerated weathering experiment, an additional in situ exposure test was conducted. A sample was mounted on an exterior wall and exposed to natural weather conditions for eight weeks, from 21 April to 16 June 2026 (an analysis of location shown in Appendix B). The purpose was to provide a qualitative reference for comparison with the accelerated weathering results obtained in the QUV chamber. Based on the estimated conversion factor, eight weeks of outdoor exposure is theoretically equivalent to approximately 79 hours (3.3 days) of accelerated weathering in the QUV chamber.

Weathering behaviour

Surface changes

Figure 5.10 presents the progression of weathering during QUV exposure over time, together with the corresponding observations. After one month in the weathering chamber, the plate remained structurally intact and showed no signs of major disintegration. However, the surface developed visible cracks and exhibited a drier and rougher

texture. In addition, a surface residue gradually formed during weathering, which may indicate degradation of the resin. As this behaviour was not observed during the moisture retention test described in Chapter 5.2, the residue may be associated with the prolonged UV exposure and accelerated ageing conditions within the QUV chamber.

Mechanical considerations

After one month of accelerated weathering, the flexural strength decreased to 25.9 MPa (SD ± 5.9), representing a reduction of 43%. This is comparable to Nabasco 8040, which showed a decrease of 42.3% under similar conditions (Tsolli, 2024). Although this reduction is not desirable, the observed decrease in flexural strength is comparable to that of the existing material, indicating the potential of the Oribond composite for facade applications.

Colour changes

Weathering resulted in noticeable colour changes (Figure 5.10 (right)). The lightness value (L)

increased, indicating a lighter surface colour. In addition, both the redness (a) and yellowness (b) values increased.

As discussed in Chapter 3.4.7, these lighter and warmer colour changes may be favourable from a bioreceptive perspective, particularly for photosynthetic pioneer organisms.

In situ observations

Figure 5.12 presents the observations of the panel exposed to natural outdoor weathering. During the eight-week exposure period, no visible surface residue developed and no major signs of structural degradation were observed. However, lighter areas emerged across the surface, resulting in a more undulating surface texture. A similar visual appearance was observed in the samples from the moisture retention test.

Based on the estimated conversion factor, the eight-week in situ exposure corresponds to approximately 3.3 days of accelerated weathering in the QUV chamber. Consequently, no direct

comparison can be made regarding the surface residue observed in the QUV experiment, as this residue only became apparent after a longer exposure period.

Although both the QUV-exposed and in situ-exposed samples exhibited visible surface changes, the nature of these changes differed (Figure 5.11). The QUV-exposed samples developed fine crack-like surface features, whereas the in situ-exposed sample showed a more undulating surface structure. This difference may be related to the distinct environmental conditions experienced during the two exposure methods. While the QUV chamber subjects the material to controlled and repetitive UV and moisture cycles, natural outdoor exposure involves more variable environmental conditions, including fluctuations in temperature, solar radiation, humidity, and precipitation.



Figure 5.11. Visual comparison of weathered composite surfaces after exposure in the QUV chamber (left) and under in situ weathering conditions (right). The in situ exposure duration corresponds to approximately 3.3 days of accelerated weathering in the QUV chamber.

Implications for bioreceptivity and durability

The accelerated weathering experiment suggests that weathering may positively influence several parameters associated with bioreceptivity. Surface cracking and increased roughness create additional micro-scale attachment sites for pioneer organisms, while the lighter colour may provide more favourable conditions for photosynthetic organisms.

At the same time, these changes may indicate the onset of material degradation. From a facade durability perspective, maintaining mechanical integrity over long exposure periods remains important. Further research is required to determine the non-accelerated and long-term effect of weathering on mechanical performance and durability.

Overall, the results suggest that weathering may contribute to the development of a more bioreceptive surface while retaining structural integrity in the short term, although a reduction in mechanical performance was observed.



Day 1, 21 April 2026



2 weeks, 4 May 2026



8 weeks, 16 June 2026

Figure 5.12. Overview of observed weathering effect over time through natural weathering

Test limitations

The accelerated weathering experiment provides only an approximation of natural outdoor exposure. The estimated equivalence of approximately 1.4 years of weathering is based on conversion factors derived from UV exposure data and should therefore be interpreted as an indication rather than an exact representation of outdoor ageing. In addition, the QUV chamber was periodically paused to manually replenish the water supply, resulting in minor interruptions to the exposure cycle.

The in situ exposure test should be regarded as a qualitative reference rather than a direct validation of the accelerated weathering results. The exposure period was limited to eight weeks and conducted at a single outdoor location during spring and early summer. Consequently, the observations provide only an initial indication of the material's behaviour under natural weathering conditions.

5.4 Ignitability behaviour



Figure 5.13. Setup of ignitability test and observed burning behaviour over time



Figure 5.14. Measured flame height is below 150 mm

Ignitability method

For safety reasons, achieving an EN 13501-1 fire classification is desirable, and for certain applications even required. Obtaining an official classification is costly and considered too early at this initial stage of the project. However, to gain an indication of the fire performance potential of the material, the ignitability test according to EN 13501-1, as described by Efectis, was conducted. Efectis is an independent third party that also performs official fire classification assessments. During the test, a burner was applied at a 45° angle to the edge of the sample for 60 seconds (Figure 5.13).

According to this test method, the following criteria apply:

- Fire classification B to D: exposure to fire for 30 seconds, after which the flame height should not exceed 150 mm within 60 seconds.
- Fire classification E to Efl: exposure to fire for 15 seconds, after which the flame height should not exceed 150 mm within 20 seconds.

Ignitability behaviour

After removal of the flame source, the material self-extinguished and no sustained combustion was observed. The charred area remained below the 150 mm limit (Figure 5.14), while the plate maintained its structural integrity and showed no signs of disintegration during testing.

Implications for facade application

Although the test was conducted as an indicative

assessment and deviated from the standardised method, the results provide an encouraging indication of the fire performance potential of the developed composite. Despite being exposed to a flame for twice the duration specified in the indicative method, the material self-extinguished and remained below the critical flame spread limit.

These observations suggest that the developed composite has potential for facade applications and may be capable of achieving a fire classification within categories D, C, or B. However, official classification requires testing under standardised laboratory conditions. Future optimisation of the formulation, for example through the incorporation of fire-retardant additives, may further improve fire performance and increase the likelihood of achieving higher fire classifications.

Test limitations

The test should be regarded as an indicative assessment rather than a certified laboratory test. Moreover, the experimental setup deviated slightly from the indicative method described by Efectis. The experiment was conducted outdoors rather than in a controlled testing environment. In addition, the sample dimensions differed from the prescribed dimensions of 250 × 90 × 40 mm and measured approximately 200 × 100 × 50 mm. Finally, the flame exposure duration was increased from 30 to 60 seconds, resulting in more severe test conditions than those prescribed by the standard.

5.5 Synthesis of composite evaluation

The material evaluations indicate that the developed Oribond composite shows promising potential for both bioreceptive and facade applications. The material exhibited favourable initial characteristics for bioreceptivity, including weathering-induced surface changes, while the ignitability assessment provided an encouraging indication of facade applicability. In addition, the pH assessment indicated moderately acidic conditions. Although this may influence the composition of the resulting biological community, it is not expected to prevent biological colonisation. Future iterations could explore adjustments towards more neutral pH conditions to support a broader diversity of pioneer organisms.

At the same time, the results highlighted the importance of further durability validation and material optimisation, particularly regarding long-term moisture and weather exposure and mechanical performance.

Figure 5.15 presents an overview of the facade application assessment based on the developed criteria framework. The criteria are expressed as a range with a minimum and maximum target value, where Level 1 (light blue) represents the minimum requirement and Level 5 (dark blue) the desired target for a composite to be considered suitable for facade applications. The performance of the current Nabasco facade composites and the developed Oribond composite is assessed against these criteria and indicated using coloured markers, with darker colours representing better performance. A dash (-) indicates that the property has not yet been investigated.

Based on this facade application assessment, the material demonstrated sufficient potential to justify further investigation into the bioreceptive enhancements presented in the following chapter.

Figure 5.15. Developed facade application criteria framework for NPSP composites, including a comparison between existing Nabasco composites and the developed Oribond composite (Recipe 12).

		1 minimal required	2	3	4	5 maximal required	Nabasco 8012 (bio- polyester)	Nabasco 8040 (furan)	Developed Oribond composite (recipe 12)
Mechanical performance	Flexural strength (MPa)	30	60	90	120	150	32	87	45,5
	Stiffness (GPa)	2	4	6	8	10	7.48	5.5	2,13
	Impact resistance (KJ/m2)	2	4	6	8	10	3.8	6.1	11,59
	Water resistance: Flexural strength decrease after 96h water immersion (%)	100	80	60	40	20	-	31	38,77
	Freeze-thaw resistance: (%)	20	40	60	80	100	-	-	-
	Fire rating (EN 13501-1)	fails	class D	class C	class B	class A	B	B	Potential for B
	Heat resistance: Thermal expansion coefficient (x10-6/K)	0.8	0.7	0.6	0.5	0.4	-	-	-
Sustainability	Biobased (%)	<20	20-40	40-60	60-80	>80	26	90-100	90-100
	Waste based (%)	<20	20-40	40-60	60-80	>80	48	90-100	90-100
	Bio- degradable	none	lab potential	lab proof	pilot	industrial	none	lab proof	lab potential
	CO2 impact (kg/m2)	>40	40 to 20	20 to 0	0 to -20	<-20	13	-14	-
	Safety process: Hazardous statements in resin (amount)	>15	14-10	9-5	4-1	Non- hazardous	7	8	3: Comp A: 0 Comp B: 3
Design performance	Visual freedom	Opaque	Very dark	Slightly darker	Light	Transparant	Light	Very dark	Slightly darker
	Form freedom	rigid	limited	moderate	flexible	highly designable	Highly 5	highly 5	-
	Aging Aesthetics	Severely degrades	Noticable undesired change	No change	Noticable desired change	aesthetically aging	Noticable undesired	Noticable desired	-
Viability	Density (g/cc)	>1.8	1.8-1.6	1.6-1.4	1.4-1.2	<1.2	1.78	1.4	1,29
	Press time (min)	>16	16-12	12-8	8-4	4-0	6min	15 min	10 min
	Costs of composite per m ² (euro)	<200	175-200	150-175	150-125	<125	150-175	175-200	? but resin is more expensive

6 Bioreceptive Surface Development



6.1 Design framing

This section evaluates the factors influencing bioreceptiveness and assesses their potential as drivers for design intervention. The factors are categorised in Figure 6.1 and analysed in relation to the composite material outcome presented in Chapter 4, distinguishing between factors already constrained by the material properties and factors that still provide opportunities for further exploration and development.

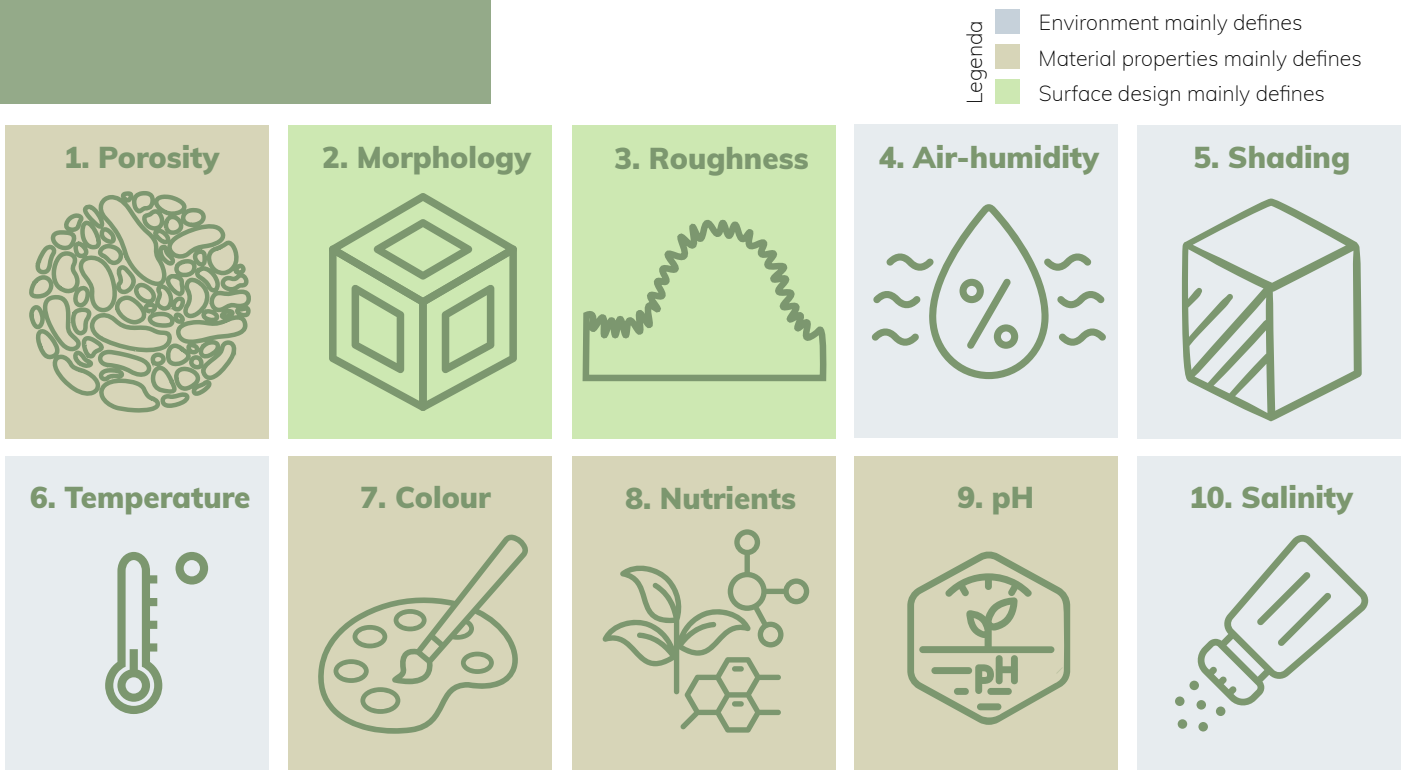


Figure 6.1. Categorisation of the factors influencing bioreceptiveness of the facade design.

Environment

The blue-coloured factors are mainly affected by the location and environment in which the facade is placed. These factors are important to consider when testing in context and to define the appropriate placement of the facade.

Material properties

Porosity, colour, nutrient content and pH value of the facade are mainly influenced by the material properties and ingredients of the composite.

Porosity can be affected by the composite production process, for example by the amount of pressure applied. However, a low porosity is preferred by NPSP to maintain a sufficiently long lifespan of the facade.

The pH level of the composite was found to be moderately acidic (Chapter 5.1). The pH is primarily determined by the material formulation and therefore falls outside the scope of the surface design interventions explored in this project.

The colour has already been iteratively explored in the initial material experiments by choosing lighter-coloured ingredients. Most biobased fillers tend to darken when mixed with the

Oribond resin, except for the eggshell, which shows poor mechanical properties. Nevertheless, being lighter than the black furan composite already makes it a more suitable option for photosynthetic growth, while still consisting of biobased ingredients.

Material attraction could be enhanced by adding nutrients such as phosphorus to the substrate, although the influence on mechanical properties requires further investigations.

Surface design

Morphology and roughness fall under the light green category, meaning that these factors are mainly defined by the surface design, such as the mould.

Morphology includes slopes and macro-scale surface shapes. Several studies have explored which macro-scale surface geometries best retain water, including work by De Graaf (2025) in the NPSP context using furan composite, as well as research with concrete materials (Mustafa et al., 2021; Karmoker et al., 2023). Due to the mould-based production process, there is a high degree of shape freedom, meaning that these geometry studies should be easily applied. One main limitation is that these designs have not yet been tested over the long term and in situ, although such testing is also not feasible within the timeframe of this project.

Roughness, on the other hand, has mainly been investigated with concrete materials, for example by using a retarder, which slows down the curing process (Veeger et al., 2021). This method is not directly applicable to the NPSP with Oribond composites, as both the material and production process differ significantly. However, the NPSP with Oribond plates do have a very smooth surface and show almost no physical texture (Figure 6.2).

Framing: Roughness

Limited water availability is the main constraint on the growth of photosynthetic organisms on vertical walls. Porosity, geometry, and roughness, which can be influenced by design, determine water availability and are therefore considered the most critical factors to enhance. Because the level of porosity is limited and the geometry has already been investigated on a higher level, a remaining opportunity lies in enhancing surface roughness of the smooth NPSP with Oribond plates. Roughness also plays a crucial role in the initial attachment of pioneer organism cells. Another advantage from NPSP's perspective is that a rougher material surface aligns more closely with a natural appearance. In contrast, the current smooth finish is frequently perceived as plastic-like, which conflicts with the intended sustainable appearance (N. Rodenburg, personal communication, 2 april 2026).

“We often get the feedback that the material looks like plastic through its smooth surface and they ask for a more natural look” - N. Rodenburg from NPSP

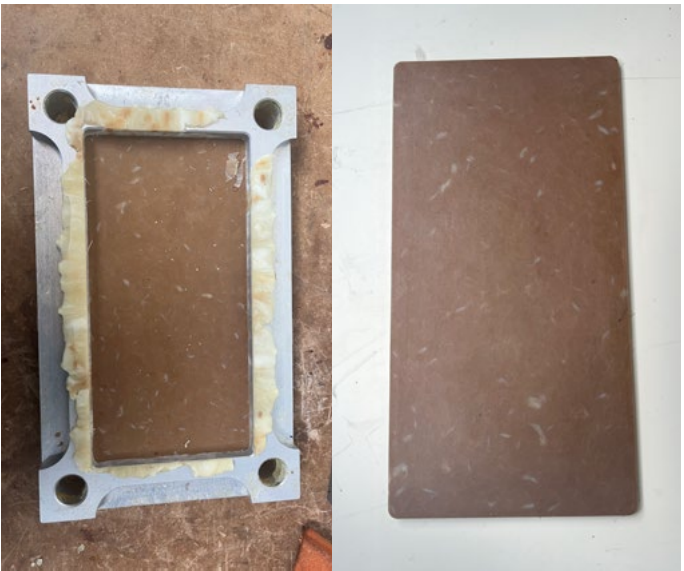


Figure 6.2. The material with smooth surface due compression moulding

Roughness Motivation overview



Figure 6.3. Main takeaways of why roughness as design direction

6.2 Roughness parameters

Roughness should not be applied randomly, as different parameters determine whether a surface becomes water-retaining or water-resistant. Significant parameters for the pores are investigated and a realised overview is provided in Figure 6.4.

Parameter	Details	Effect	Desirable?	
Pores configuration				
Inverse pores	Positive		Water resistant	X
Pores	Negative		High water retention	✓
Angularity of pores				
Vertical U-shape	90°C		Trapped gass in micro grooves. Liquid is not able to flow into pores.	X
Steep slopes V-shape	45°C		Liquid can flow into pores. Vortices are created functioning as anchor points.	✓
Shallow slopes V-shape	60°C		No vertices emerge, cause water to be washed away.	X
Size of pores				
Macro	~ mm - cm		Water will be easily washed away.	X
Hundreds of micrometres	>100 μm and <1 mm		Size protects liquid from shear-stress. Through anchor points, water, nutrients and biofilm retains.	✓
Units to tens of micrometres	~ nm - 10 μm		Water cannot reach the pores due surface tension and pressure difference between water and trapped air.	X

Figure 6.4. Overview of roughness parameters and its effect and desirability

Pores configuration

MacGregor-Ramiasa and Vasilev (2017) discuss the relationship between material microstructures and its wettability. To illustrate this, they draw on analogies from nature, where lotus and rose petals demonstrate contrasting wettability behaviours driven by their microscale surface texture. Lotus leaves exhibit water

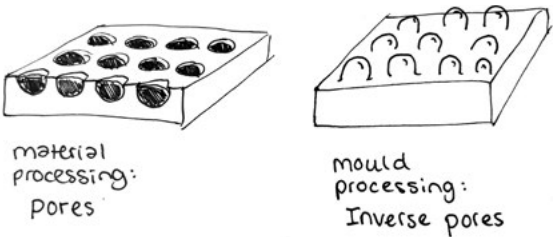


Figure 6.5. Desired configuration of pores in material and in mould design

repellent properties, while rose petals show high adhesion to water.

The micro-bumps on lotus leaves trap air, preventing water from making proper contact with the surface. In contrast, rose petals allow water to penetrate the microtexture and adhere to the surface rather than rolling off, while still exhibiting hydrophobic characteristics due to air gaps at nanoscale. In physics, these two conditions are described by the Cassie and Wenzel models. The Cassie state describes water resting on air pockets trapped beneath a droplet, while in the Wenzel state water fills the surface roughness. Both models are based on energy balance and thermodynamic equilibrium, and can be characterised by the contact angle between a water droplet and the surface as well as the adhesion energy between water and surface.

Conversely, Rawlett et al. (2007) demonstrate that the inverse pores, referred to as pillars, enhance water resistance by increasing air gaps beneath the water droplet.

For bioreceptive applications, pore structures are therefore desirable, while pillar structures are not. It is important to note that when a material is created with a structured mould, the pattern on this mould must consist of inverse pores in order to produce pores in the final material (Figure 6.5).

Angularity of pores

Angularity influences the formation of air gaps and water infiltration on the surface. Huang et al. (2018) investigated the attachment of algal cells to surfaces by studying microgrooves, which can act as anchor points and provide protection against hydraulic shear stress. They experimented with different groove shapes by introducing water containing microalgal cells in a horizontal setup.

V-shaped grooves were found to be preferable to U-shaped grooves, as they allow air to escape when water flows into the gaps. Furthermore, vortices emerge which function as anchor points. However, slopes that are too shallow, for example 60°, cause water to be washed away more easily

due the lack of these vortices.

Size of pores

Beside the configuration of the pores, their size has a major role on water retention.

Pore sizes that are too small (towards the nanoscale) can limit water infiltration due to pressure differences between the liquid and trapped air (Laplace pressure), surface tension, and liquid pinning effects (MacGregor-Ramiasa & Vasilev, 2017). On the other hand, when the pore sizes are too large, water and cells are more easily washed away. When the diameter of a cavity exceeds approximately 1 mm, gravitational forces become more dominant than surface tension (MacGregor-Ramiasa & Vasilev, 2017), resulting in reduced water retention. At an optimal size, these cavities can act as anchor points for both water and organism cells.

For biological attachment, the ideal roughness should be slightly larger than the diameter of the target cell (Stohl et al., 2023; Palmer et al., 2007). Single-celled organisms typically measure around 10 µm, whereas filamentous species can be as large as several 100 µm (Stohl et al., 2023). Precipitation water droplets vary in diameter from approximately 100 µm to 5000 µm (heavy rainfall) (Bouma, 2009; Takeuchi et al., 2002). The creation of dew drops is a transient process and the water droplets will start with a diameter of 20-200 µm. They will grow via direct condensation and contact with neighbours until they reach approximately a diameter of 2000 µm, at which gravitational forces can overcome contact line pinning and the droplet slides down (Weisensee et al., 2017).

In an algae attachment experiment from Blersch et al. (2016), different pore sizes ranging from 100 to 2000 µm were tested. The greatest diversity in algae species growth was observed on structures with cavity of sizes of around 500 µm. Huang et al. (2018) also states that mature algal biofilms can reach a size of 100 µm, suggesting that cavities larger than this may enable irreversible attachment. In their study, grooves with widths of 200 to 500 µm and a depth of around 100 µm were used in experiments with water flow containing algal cells.

To be larger than the target cell and remaining small enough to function as an anchor point, the ideal cavity size for roughness is estimated to be greater than 100 µm and smaller than 1 mm.

6.3 Surface roughness exploration & development

This section explores the development of surface roughness concepts aimed at improving the bioreceptive potential of the Oribond composite. Initial ideas were generated through the HKJ-method and evaluated on manufacturability and geometric suitability. Selected concepts were physically prototyped to investigate their feasibility and potential to create suitable surface roughness for bioreceptive attachment.

Two main production approaches emerged from the exploration phase: modifying the surface during compression moulding and post-processing the surface after curing. Through iterative prototyping, microscopic evaluation, and refinement, the most promising surface roughness concepts were selected for further validation.

Ideation from processing techniques

Appendix C provides additional details on the ideation sketches created using the HKJ-method. This method explored processing techniques for increasing surface roughness. Concepts were developed across different stages of the production process, including approaches based on adding, modifying, and subtracting material. Additional inspiration was derived from existing tools and processes available at NPSP and within the Faculty of Industrial Design Engineering.

In Figure 6.6, the ideas are evaluated using the C-box method, which positions different concepts along two axes: feasibility and scalability. The C-box represents the initial exploration phase and does not include all roughness concepts investigated during the project, as additional ideas and modifications emerged through iterative prototyping and experimentation.

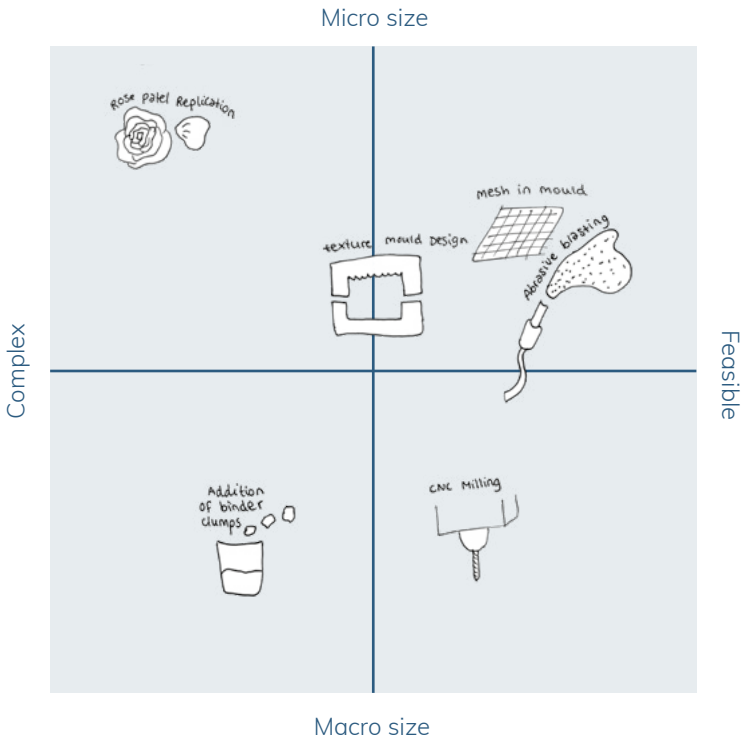


Figure 6.6. C-box evaluation of the initial processing ideas

Out of the desired roughness parameters (Chapter 6.2) it was concluded that the scale should not exceed the millimeter level. However some techniques create roughness in the millimeter to centimeter level, which are therefore not suitable.

The rose petal replication has strong water retention potential due to its complex micro and nano scale structure. However, it is a study in itself to create a proper replication method compatible with the current production process, and it is therefore too complex.

Abrasive blasting and mesh in the mould are easy and low-fidelity methods to test and are also applicable at the microscale. In the end, a certain texture could be integrated into the mould design. While this is currently too expensive to realise at this stage of the design, it would ultimately fit within the existing process steps of NPSP.

Explorations during moulding

One approach explored the creation of surface roughness during the compression moulding process itself. Integrating texture directly into the moulding stage could potentially allow roughness to become part of the standard production workflow while maintaining a controlled and repeatable surface geometry.

Surface textures inserts

Several concepts were investigated, including mesh layers, sandpaper textures, silicone and aluminium textures, and dissolvable salt particles positioned between the mould and the composite surface. These experiments aimed to create pore-like surface structures during curing. The mesh and sandpaper shown in Figure 6.7 and 6.8 were physically tested and further analysed based on the resulting samples and observations. The remaining concepts were not explored further in practice, as the initial findings already revealed

Figure 6.7. Experiments on adding mesh layer in mould

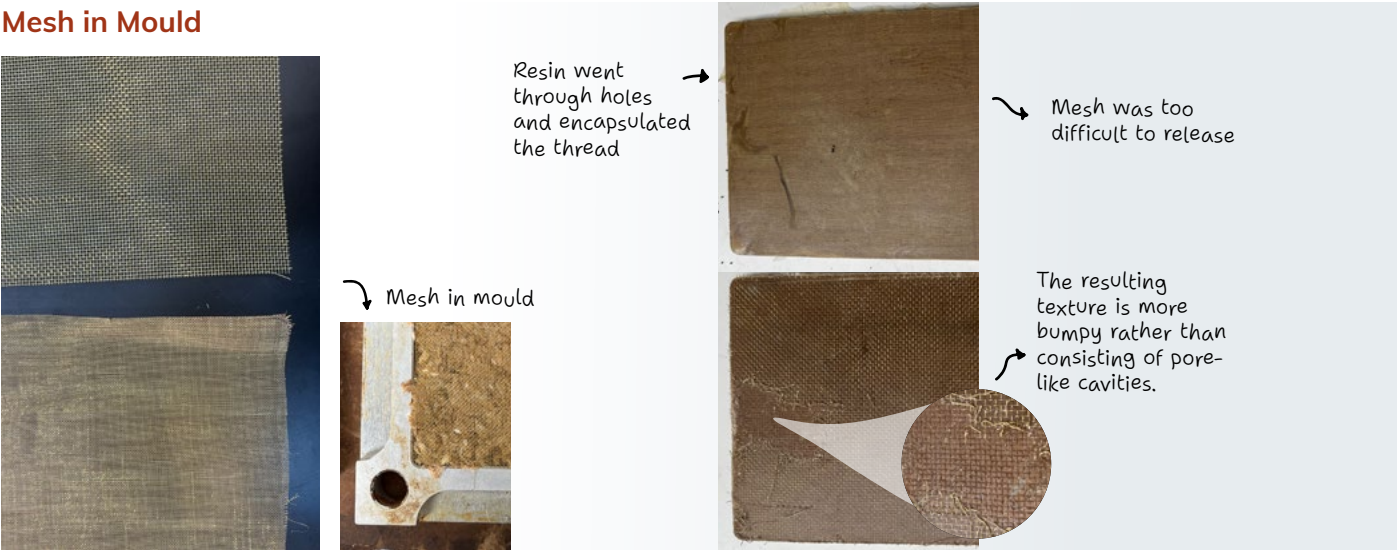


Figure 6.8. Experiments on adding sandpaper in mould



significant limitations related to encapsulation and texture transfer.

Production Imitations

The experiments revealed significant limitations. Due to the flowability of the resin during pressing, the resin tended to flow through or around the inserted layers, encapsulating them within the composite. Although silicone-based release spray was applied to reduce resin penetration, encapsulation could not be fully prevented, causing the added textures to become integrated into the composite surface.

In addition, some materials degraded or deformed under the elevated pressure and temperature conditions, limiting reliable texture transfer. For example, the adhesive layer of the sandpaper appeared to delaminate during pressing, causing part of the material to remain stuck within the composite surface.

Other explored concepts included dissolvable salt particles and silicone- or aluminium-based texture layers. However, these concepts were also expected to become partially encapsulated within the resin matrix. In addition, silicone is highly flexible and could deform under pressure, while aluminium-based layers proved challenging for creating or sourcing inverse pore geometries at this small scale.

Another potential direction would be direct modification of the mould itself. However, at this exploratory stage, modifying the mould was considered too high-fidelity and costly.

Potential for mould integrated textures

Nevertheless, the produced plates demonstrated that micro-scale textures could be transferred

through the moulding process. Micro-scale sanding marks from the mould surface were consistently visible on the produced plates, while even millimetre-scale details, such as elements of the mould logo, were repeatedly replicated in the composite surface. This indicates potential for future mould-integrated texture development.

Post-processing explorations

A second approach focused on modifying the surface after curing through post-processing techniques (Figure 6.9 until 6.13). The explorations investigated different methods for creating controlled pore geometries while balancing manufacturability and scalability. The resulting surface structures were further analysed through microscopic observation and through water and particle retention validation in Chapter 7.

Abrasive blasting

Abrasive blasting was explored as an initial post-processing technique due to its low-fidelity ability to create distributed micro-scale roughness across the surface. The process generated pore-like surface features and visibly altered the smooth appearance of the composite (Figure 6.9). However, controlling the resulting pore geometry proved difficult, as the surface outcome strongly depended on manually controlled parameters such as blasting angle, distance, duration, and abrasive particle size.

Although larger cavities could potentially be achieved using larger abrasive particles, these were not available during the experimentation phase. Alternative post-processing techniques were therefore explored. Additional explorations investigated the creation of larger and more controlled cavities through direct surface displacement and perforation techniques.

Figure 6.9. Experiment of post-processing surface with abrasive blasting

Abrasive blasting: Blasted



Manual perforation (chiseled)

Manual chiselling using the conical tip of a screw appeared promising for creating water-trapping geometries and anchor points for initial attachment (Figure 6.10). However, the process was highly labour-intensive and difficult to scale consistently.

Laser engraving pores

Laser engraving enabled more controlled and repeatable perforation patterns. Initial laser tests produced cylindrical pores rather than the desired conical geometries. To create a more gradual pore slope, multiple laser passes with varying diameters and engraving depths were combined by adjusting the laser speed (Figure 6.11). The final pore design consisted of three nested geometries with increasing diameters (0.2, 0.6, and 1.0 mm) and

decreasing engraving depths achieved through varying laser speeds (25%, 50%, and 75%), creating a conical approximation. See Appendix D for the laser explorations.

The laser setup was not recalibrated for the changing engraving depths, which may have introduced small dimensional deviations. Nevertheless, the process demonstrated strong potential for producing controlled and repeatable pore geometries.

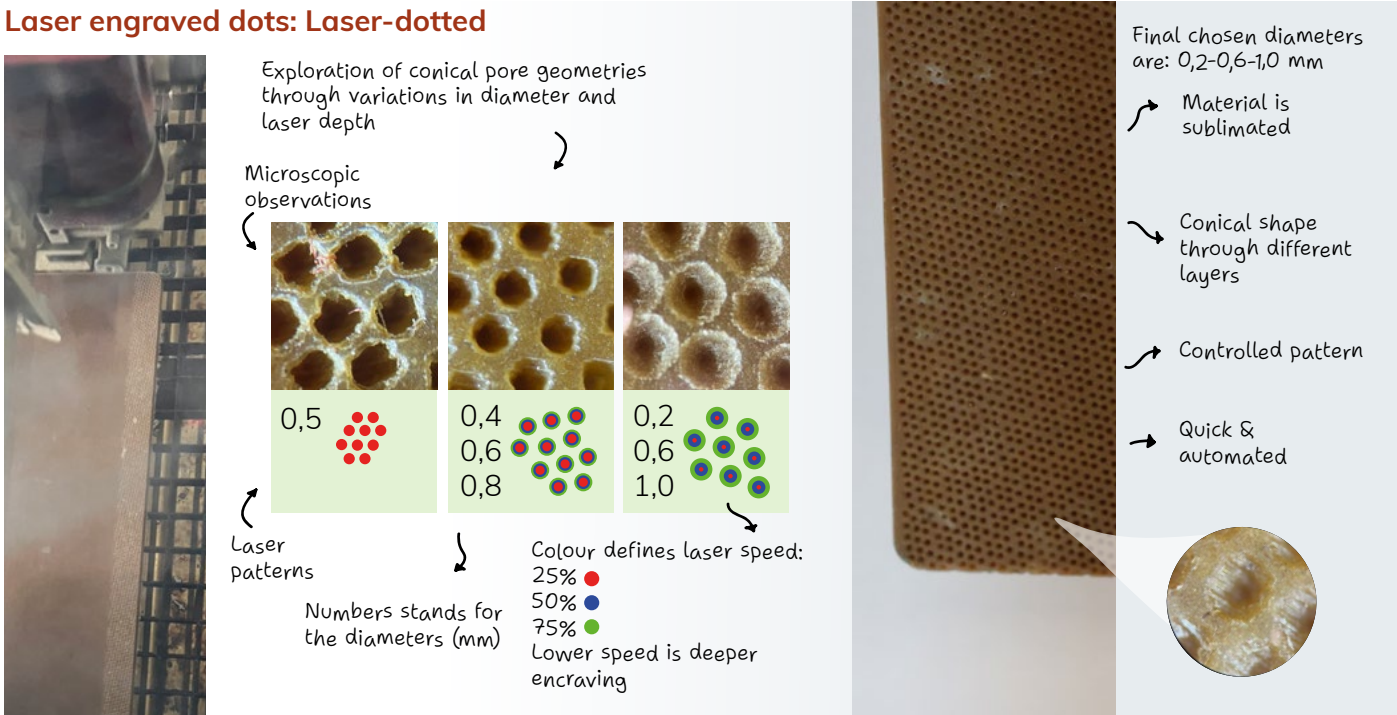
Hybrid

To combine the larger water-retaining pores created through laser engraving with the finer micro-scale texture generated by blasting, abrasive blasting was applied to laser-engraved plates (Figure 6.12). This hybrid approach could

Figure 6.10. Experiment of post-processing surface with manual perforation



Figure 6.11. Experiment of post-processing surface with laser engraved dots



potentially combine larger cavities for water retention and biofilm formation with smaller surface features below 200 μm that may support initial cell attachment.

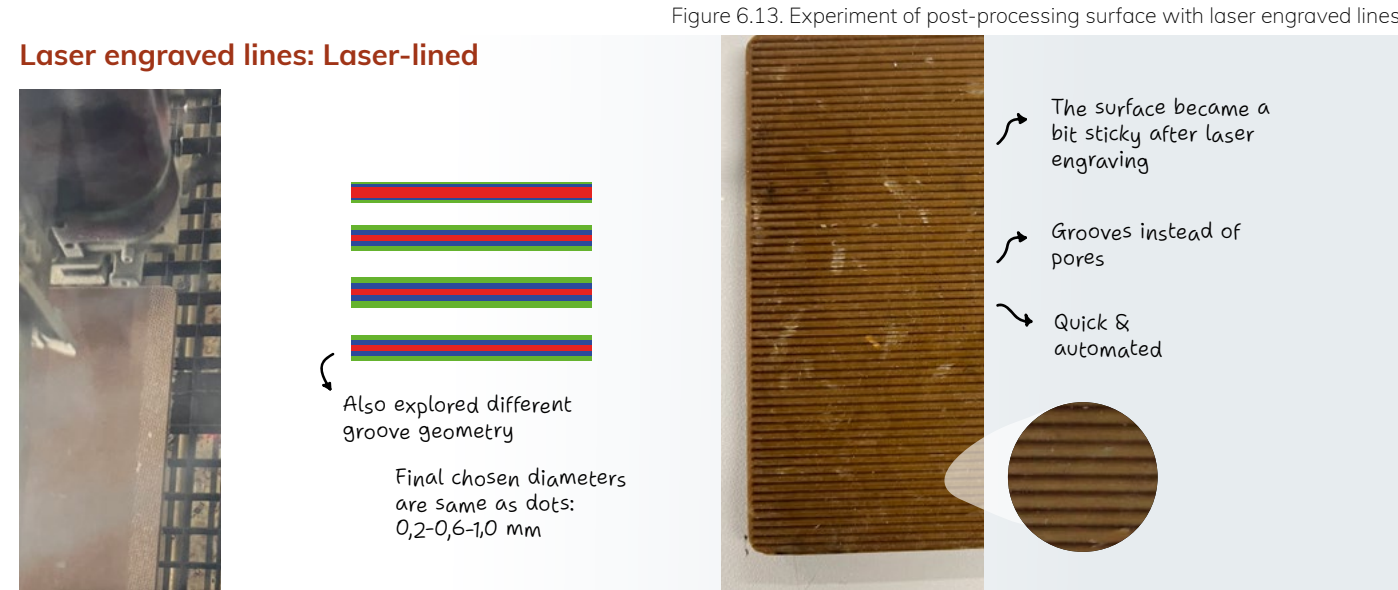
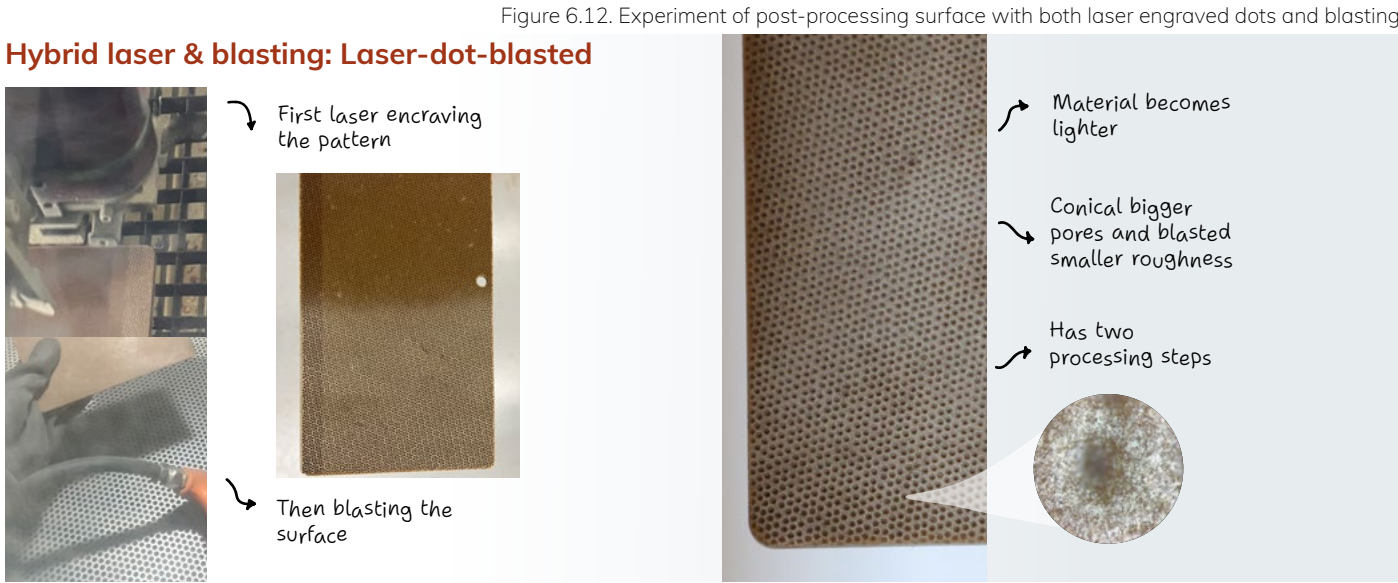
Laser engraved lines

Lastly, one exploration investigated grooves instead of pores (Figure 6.13), as grooves were also identified in literature as a potential strategy for improving water retention and attachment (Huang et al., 2018). Similar to the pore experiments, the grooves were laser engraved

using varying depths and widths to create sloped geometries. See Appendix D for explorations.

Potential for post-processing techniques

The post-processing explorations were able to be properly produced and are further investigated under the microscope.



6.4 Microscopic evaluation of roughness

To evaluate the developed roughness concepts in relation to the defined roughness parameters, the surfaces were analysed using a Keyence VHX-6000 microscope. This microscope could also generate three-dimensional visualisations of the surface structures by using reflected-light scans. Appendix E provides a detailed overview of the microscope images of the different surface modifications.

The microscopic evaluation focused on the desired roughness parameters defined in Chapter 6.2, including pore geometry, pore scale, slope formation, and surface morphology. Approximate pore dimensions were estimated using the scale reference visible in the microscope images by comparing the diameter of representative pores with the scale indicator.

Unprocessed

Although this surface was perceived as the smoothest, microscopic observations already revealed small roughness structures in the form of linear grooves (Figure 6.14). These lines were also visible to the naked eye and likely originated from the mould surface, which itself showed slight sanding marks. The approximate width of these grooves was estimated at around 5 μm , which is significantly below the desired roughness scale of 100 μm . The unprocessed surface can therefore still be considered relatively smooth.

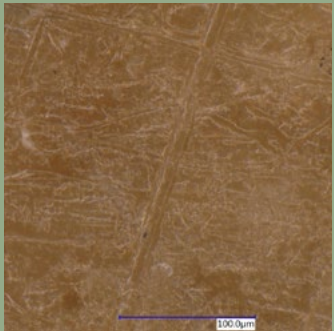


Figure 6.14. Unprocessed sample under the microscope, already showing some relief.

Blasted

The blasted surface was observed to be rougher than the unprocessed sample. The pores showed a granular morphology, with estimated diameters mostly ranging between approximately 50 and 200 μm . Some pores therefore fall within the desired roughness scale. However, the generated 3D visualisations indicated that the pore depth remained relatively shallow (Figure 6.15).

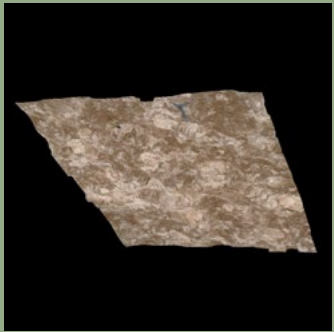


Figure 6.15. 3D visualisation of blasted sample, has roughness but no deep pores.

Weathered

The roughness of the weathered surface originated mainly from crack formation, resulting in a more linear roughness morphology. The cracks showed relatively straight geometries with limited slope formation, although they appeared deeper than the pores created through blasting (Figure 6.16). The approximate crack width was estimated at around 50 μm , which is still relatively small compared to the desired pore scale. In addition, the cracks were unevenly distributed across the surface, resulting in larger spacing between roughness features compared to other concepts. Furthermore, the orientation of the cracks is also variable.

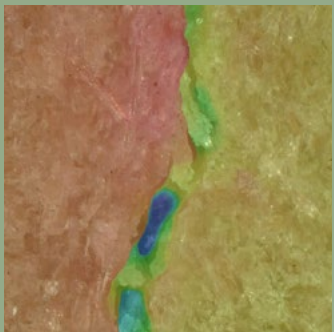


Figure 6.16. Weathered sample under microscope, showing the depth of a crack

(Laser)Dotted

For the dotted concepts, several iterations were microscopically evaluated, including manually chiseled dots created using a hammer and screw, laser-engraved dots with a single depth and diameter, and laser-engraved dots consisting of multiple diameters and engraving depths.

Single-depth laser-dotted

The laser-engraved dots with a single depth created relatively straight cylindrical pores with limited slope

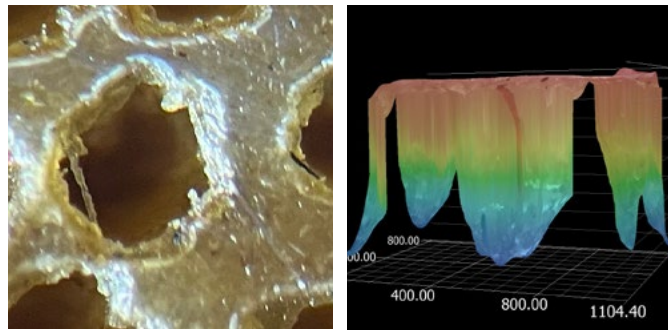


Figure 6.17. Single-depth laser-engraved pore shown through microscopic observation and 3D surface scan.

formation (Figure 6.17). Only near the bottom of the pore did a slight slope become visible. According to the defined roughness parameters, this geometry is considered less desirable.

Chiseled dotted

The chiseled sample was developed to create a more sloped pore geometry. The 3D scans indeed showed increased slope formation resulting from the conical geometry of the screw tip used during chiselling (Figure 6.18). However, the scans also revealed raised edges surrounding the pores, likely caused by material displacement during impact. These convex deformations may negatively influence water retention behaviour. In addition, the manual chiselling process was highly labour-intensive and difficult to scale consistently.

Figure 6.22 additionally shows microscopic observations during wetting, in which the chiseled pores appeared to visually expand when exposed to water.

Multi-depth laser-dotted

To create more conical laser-engraved pores, multiple diameters and engraving depths were combined. Figure 6.19 shows a microscopic 3D scan of the pore geometry using diameters of 0.4, 0.6, and 0.8 mm. Compared to the single-depth laser pores, the geometry showed a more gradual slope formation. The resulting slope was visually comparable to the chiseled sample.

However, the slope angle still did not approach the desired 45° angle. For this reason, the differences between the diameters were further increased while remaining within the desired roughness scale, resulting in final diameters of 0.2, 0.6, and 1.0 mm. Although this final iteration was not analysed through 3D scanning, the microscope images already indicated a more conical pore geometry (Figure 6.20). In the right image, a hybrid exploration is shown in which the laser-engraved pores were additionally abrasive blasted after engraving. This resulted in a lighter surface appearance combined with micro-scale pores and additional smaller-scale surface relief.

Laser lined

Similar iterative explorations were conducted for the laser engraved line-based roughness concepts. By combining multiple groove widths and engraving depths, more sloped groove geometries were created. The microscope images (Figure 6.21) currently show an earlier iteration using smaller groove dimensions (0.4, 0.6, and 0.8 mm), while the final grooves selected for further validation used the same larger dimensions as the final laser-

dotted concept (0.2, 0.6, and 1.0 mm). The figure already shows a degree in slopes, however these are not 45 degrees either

Based on the microscopic evaluation, the chiseled sample was excluded from further validation due to its labour-intensive production process and limited geometric advantages compared to the laser-engraved alternatives. For the laser-dotted concept, the most conical iteration with multiple engraving depths and diameters was selected for further validation, together with a hybrid variation combining laser engraving and abrasive blasting. The remaining selected concepts were subsequently evaluated through water retention and particle retention experiments to further assess their bioreceptive potential.

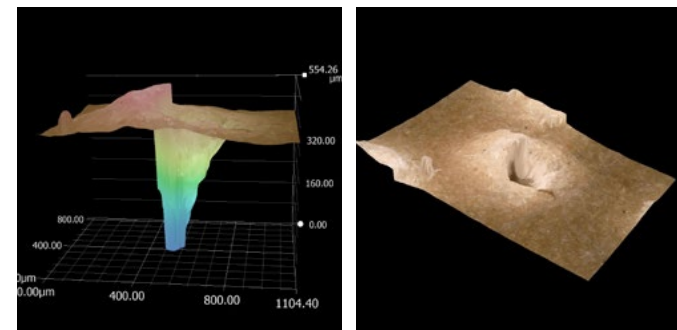


Figure 6.18. Three-dimensional scan of manually chiseled pore geometry.

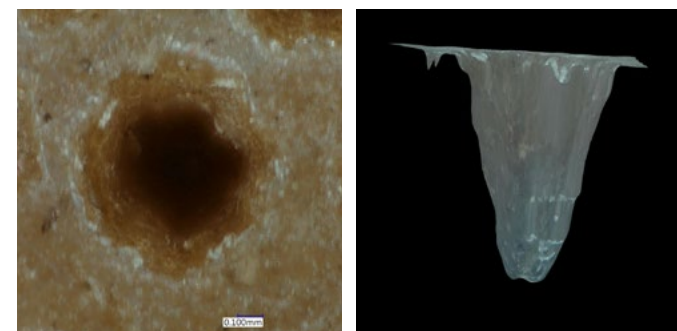


Figure 6.19. Multiple-depth laser-engraved pore geometry with diameters of 0.4, 0.6, and 0.8 mm.

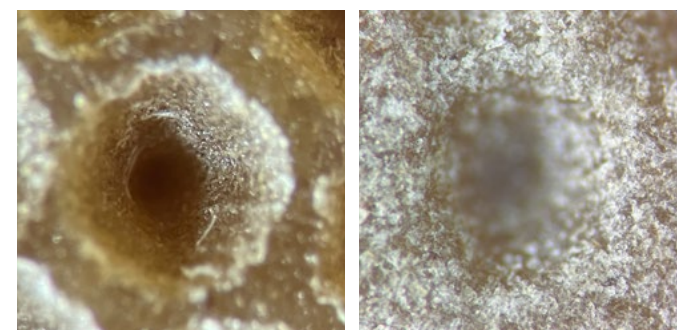


Figure 6.20. Final selected laser-engraved pore geometry with diameters of 0.2, 0.6, and 1.0 mm, shown with and without abrasive blasting.

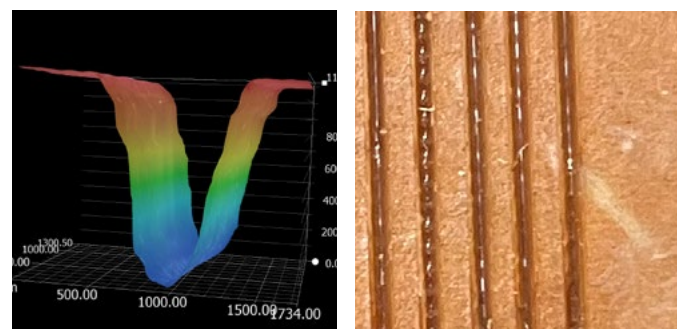


Figure 6.21. Grooves created through line pattern engraved with laser.

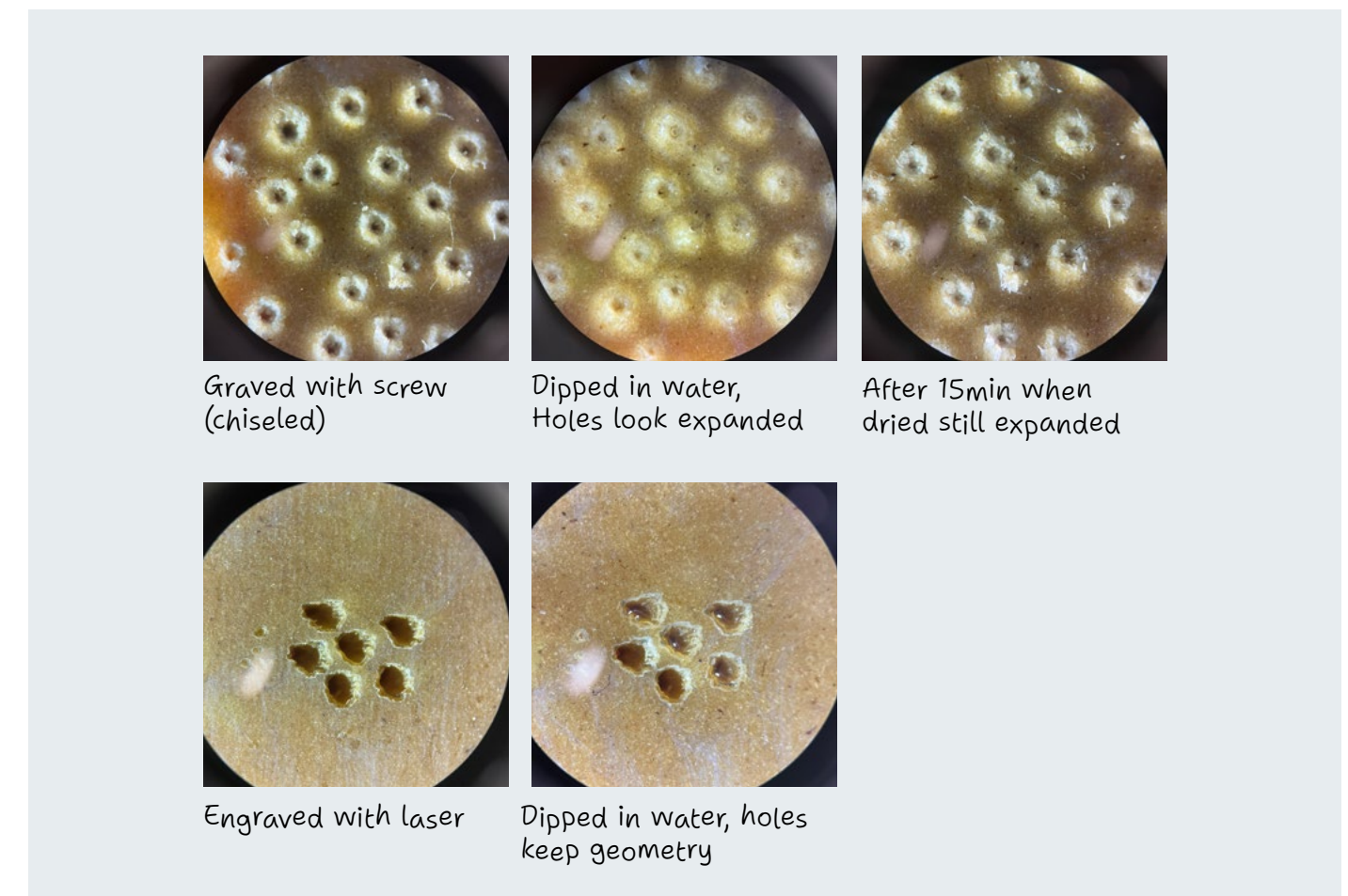


Figure 6.22. Exploring pore geometry after wetting.

6.5 Final surface roughness concepts

Based on the surface roughness explorations, six final surface concepts were selected for further validation in Chapter 7. These included the unprocessed reference sample and the QUV-weathered sample presented in Chapter 5.3. The weathered concept was included to investigate whether roughness generated through weathering processes could enhance bioreceptive potential over time without requiring additional manufacturing or post-processing steps. Figure 6.23 provides an overview of the selected concepts.

Figure 6.23. Overview of the selected surface roughness concepts and their corresponding labels.



Unprocessed



Blasted



Weathered



Laser-dotted



Laser-dot-blasted



Laser-lined

7 Bioreceptive Performance Validation



7.1 Validation approach

To validate the bioreceptive performance, multiple approaches can be considered. The different approaches are analysed below, together with their potential and limitations within the scope of this research project.

Approach analysis

Validation can be performed either through actual biological growth or by assessing whether the optimal conditions for growth are present. Experiments involving biological growth can be conducted *in situ* (in context) or *in vitro* (in a laboratory environment), each with its own limitations.

In situ growth experiments often require long periods of time. A review of conducted experiments by Jakubovskis (2025) shows that directed growth in context can take between 5 and 12 months, indicating that a fully validated growth study is not feasible within the 100-day timeframe of this graduation project.

In vitro experiments are generally shorter and can take between 2 and 12 months (Jakubovskis, 2025). However, these experiments are typically conducted with single species under controlled and optimal conditions using pre-inoculated biofilms. In addition, these biofilms are cultivated under ideal growth conditions, causing the organisms to prioritise biomass production rather than developing stress-survival strategies (Veeger, 2021; Fuentes et al., 2022; Veeger et al., 2025). As a result, they are highly vulnerable to environmental stress, reducing their chance of survival when introduced into real-world conditions. Furthermore, laboratory setups do not fully represent natural environmental conditions and cannot adequately validate the ability of organisms to initially attach to the surface.

To validate a bioreceptive panel that supports spontaneous attachment, this project therefore focuses on ecological principles that define favourable growth conditions for pioneer organisms to attach and establish. It must be stated that biological growth is not solely affected by the type of roughness on the material surface. Bioreceptivity is influenced by multiple interacting factors, such as macro-scaled geometry and environmental conditions. Within this project, the scope is focused on enhancing surface roughness as one step towards a more bioreceptive facade design. This factor is therefore validated based on its potential to create favourable growth conditions. The designed roughness could enhance conditions for water retention and provide protection against shear stress during the irreversible attachment phase of cells. For this reason, qualitative and quantitative water behaviour on the surface, and particle retention under flowing water conditions are investigated.

7.2

Development of validation methods

Ecological phase	Included?
Initial deposition of cells	No
Water availability	Yes
Protection of cells against shear stress	Yes
Long-term biofilm formation	No

Figure 7.1. Overview table of attachment stages included within the scope of the validation experiments

A standardised method to directly measure water or particle retention on vertical bioreceptive facade surfaces does not yet exist. For this reason, adapted validation methods were developed to investigate both water retention behaviour and the potential protection against shear stress during initial attachment. Figure 7.1 provides an overview of the attachment stages included within the scope of this validation approach.

Due to the limited timeframe of the project and the long-term nature of biological colonisation processes, the validation focused specifically on conditions that may support early-stage attachment behaviour. This included analysing water retention zones and the potential protection of particles against shear stress under flowing water conditions. Initial environmental deposition of cells and long-term biofilm formation were considered outside the scope of this research, as these processes depend on a large number of environmental and biological variables and would require long-term in vivo testing. In addition, regions reached and retained by water are considered potential locations where cells transported through rain may initially deposit.

To investigate these conditions, a quantitative water retention method was developed to compare retained water mass and drying behaviour between different surface geometries under controlled conditions. In addition, a qualitative particle retention method was developed to observe whether surface geometries could protect cell-sized particles from wash-off under flowing water conditions.

Water retention

An adapted vertical setup was developed to measure retained water mass on vertically positioned samples under controlled wetting conditions (Figure 7.3). Development iterations of the setup and wetting conditions are described in Appendix F.

Weighing setup

To compare different surface concepts, the retained water mass needed to be measured. If the plate is measured on a standard scale, it must be placed in a horizontal position, which is not representative of the intended facade context. In addition, runoff droplets would fall onto the weighing tray and be included in the measurement. For this reason, a weighing setup was desired to measure the plate while stabilised in a vertical position, ensuring that only the water retained on the sample is included in the mass measurement.

A scale with a precision of 0.001 g was required, with a maximum capacity of 200 g. Since the mass of a plate was approximately 145 g, the weighing setup had to remain below 55 g while also being sufficiently controlled to allow consistent repetition across different concepts.

After several iterations, the weighing setup shown in Figure 7.2 was realised. The realised setup, consisting of a foam block and screws, weighed approximately 43 g. By adjusting the length of the setup and adding an extra counterweight at the back, the center of gravity was positioned above the weighing tray. To maintain the sample in a controlled vertical position, a

Weighing set-up

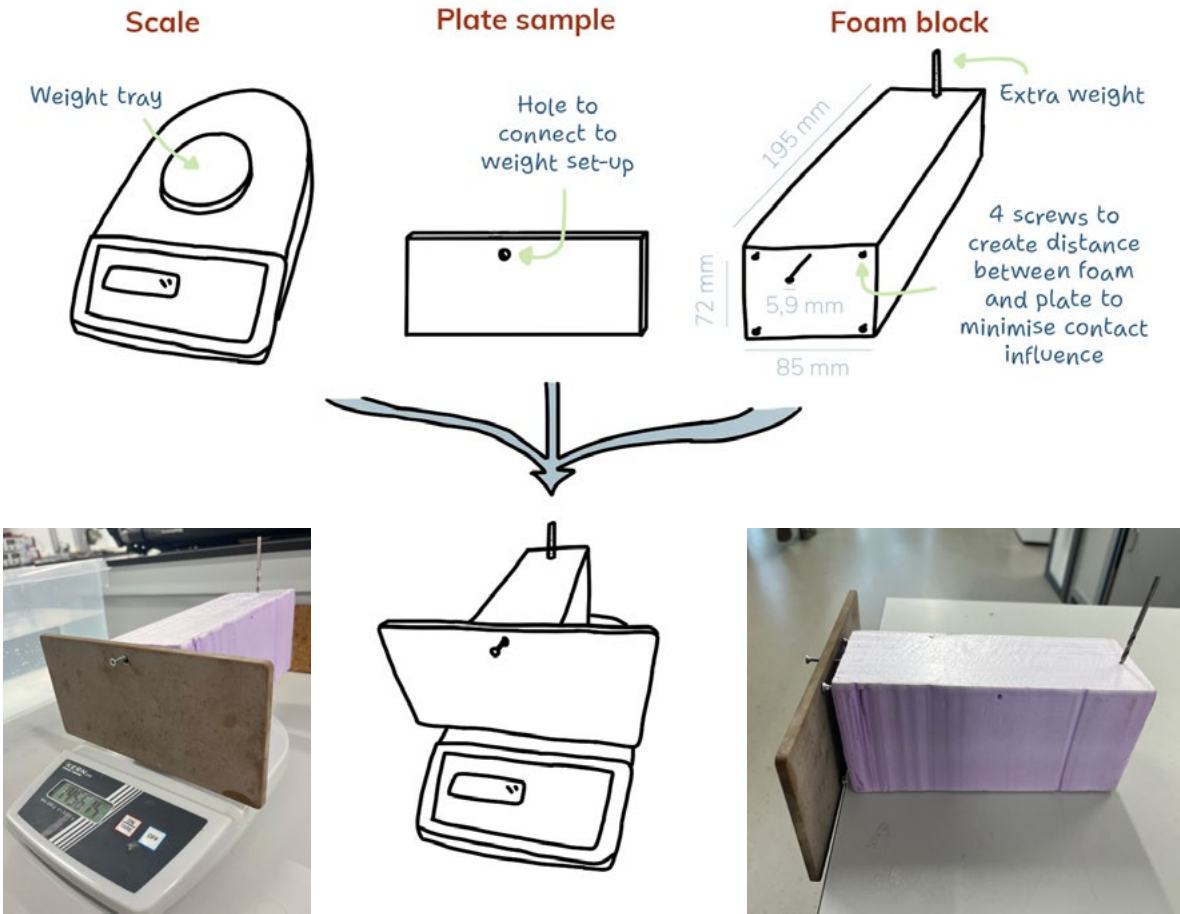


Figure 7.2. Visual of the designed weighing setup

hole was created to attach it to the foam block of the weighing setup. Contact between the foam block and the sample could influence the water retention behaviour, therefore a gap was preserved between them. This enabled a more controlled measurement of the influence of surface roughness alone on water retention. The spacing was controlled using four screws positioned between the foam block and the sample at a fixed distance, improving the repeatability of the tests.

Wetting conditions

Several alternative wetting methods were explored before selecting the final submerged approach. Spray bottle experiments more closely resembled rainfall conditions, but variations in droplet size and applied water quantity reduced repeatability between measurements. Additional condensation-based experiments using a climate chamber were also investigated to recreate dew formation on the surface. However, environmental fluctuations, airflow disturbances, and temperature-dependent variations between samples proved difficult to control consistently.

For this reason, a submerged wetting method was selected as the final approach, as it provided the most controlled and repeatable starting condition for comparison between samples. Following submersion, each sample was allowed to drain for 25 seconds before weighing. This drainage period was included to remove excess free-flowing water from the surface and edges of the sample, preventing the formation of pooled water beneath the sample that could interfere with the measurement.

Environmental conditions

All tests were conducted at the same location within the Applied Labs at IDE, TU Delft, to maintain relatively consistent environmental conditions. Because continuous air filtration is present in the lab, the environmental conditions remain relatively stable. However, small fluctuations can still occur because the conditions are not actively controlled. To gain insight into the possible influence of these variations on water retention and account for them during analysis, the temperature and humidity were recorded on each testing day.

Data acquisition

The mass of the sample was measured using a precision scale and recorded through a GoPro camera capturing a timelapse with an interval of 30 seconds (Figure 7.4). Because the largest fluctuations in retained water occurred during the first minutes of drying, the initial five minutes were additionally recorded using a phone camera to observe qualitative water behaviour. Measurements were stopped when the sample appeared visually dry, approached its initial dry mass, or reached a stable mass. The intended measurement duration was one hour (3600

seconds). However, some samples stabilised earlier and were therefore measured for a shorter duration, while other samples continued to show gradual drying behaviour beyond one hour. In these cases, measurements were stopped once sufficient insight into the drying trend had been obtained. Because the dry mass of the samples differed slightly, the raw mass measurements could not be directly compared. Therefore, the dry mass of each sample was subtracted from the measured mass to isolate the retained water mass. The resulting data were analysed in Microsoft Excel.

Water retainment setup

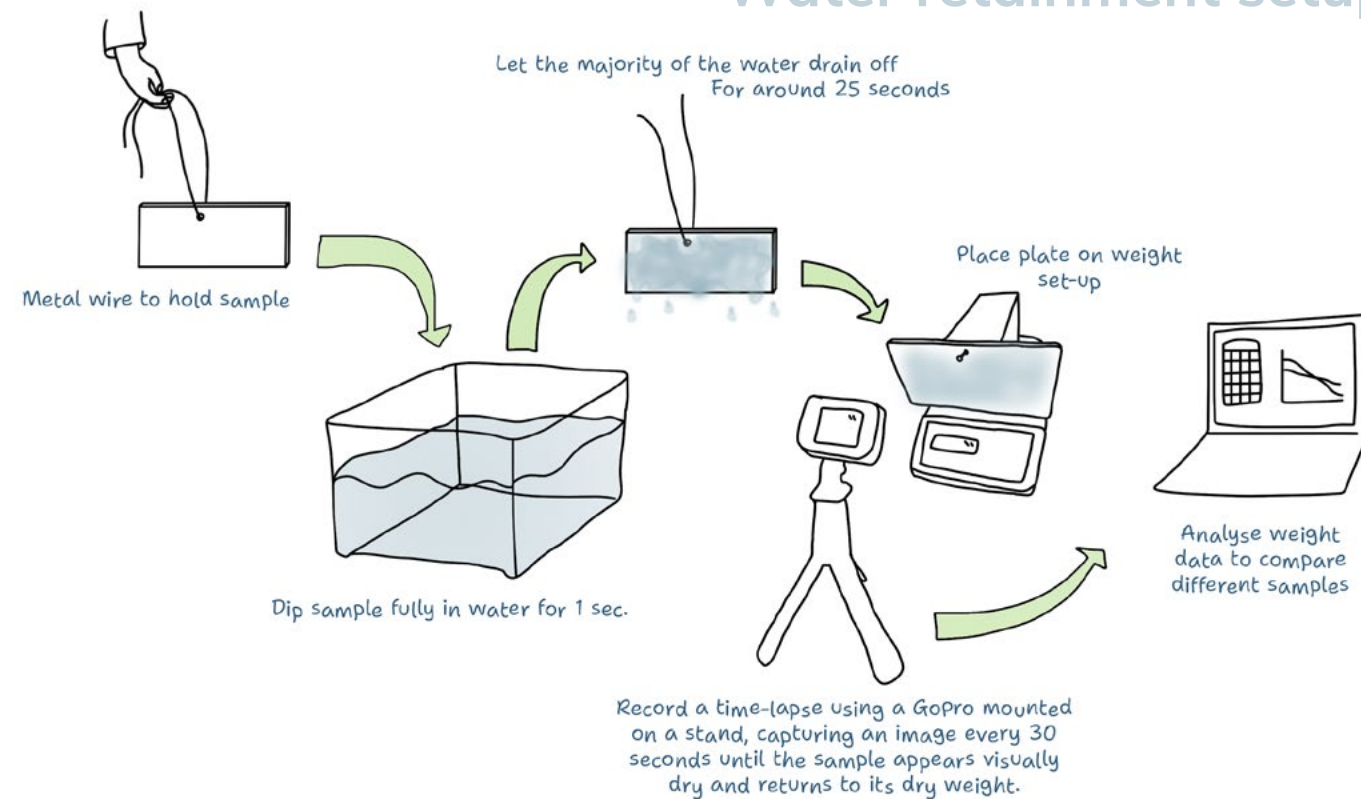


Figure 7.3. Visual of the designed method to compare the different surface roughnesses on their capability of water retainment



Figure 7.4. Photograph of realised water retention setup



Figure 7.5. Manual particle deposition for particle retention setup

Particle retention

Another important role of surface roughness could be protecting cells against shear stress during initial attachment. To investigate this behaviour, an additional particle retention test was developed in which particles were visually observed under flowing water (Figure 7.6).

Particle deposition

The particles were manually applied onto the surface prior to testing (Figure 7.5) so that the experiment specifically focused on protection against shear stress during water flow. This reduced the number of interacting variables within the setup. In natural conditions, cells are deposited onto facade surfaces through environmental factors such as rain and wind transport. Regions reached and retained by water are considered potential locations where cells may accumulate, while the surface geometry influences whether particles remain attached.

The particles were spread across the surface using a spoon and fingers.

Particle characterisation

Instead of using living cells, the test was simplified by using particles of a comparable size range. The particles were observed under a microscope to estimate their size (Appendix G). The estimated particle size ranged between 5 and 30 μm , which overlaps with the typical size range of single-celled organisms, generally around 10 μm (Stohl et al., 2023). Different powders were explored, including spirulina powder from Purasana

and a quinacridone-based magenta pigment obtained from Verfmolen De Kat. Spirulina visually resembles algal growth more closely because it consists of dried and grinded algae and has a natural green colour. While the magenta pigment provided higher visual contrast and did less dissolve and spread through water, making differences between concepts easier to observe. It also emphasised the simulated nature of the experiment.

Water flow conditions

The setup was designed so that the sample was held in a vertical position while water was sprayed across the surface from a downward inclined angle for approximately 35 seconds. During spraying, the spray bottle was manually moved across the surface to expose all areas. Rather than quantitatively measuring retained mass, the test focused on qualitative observation of where and whether particles remained attached after water exposure. Particular attention was given to whether particles accumulated within pores, grooves, or other protected surface regions.

Data acquisition

The samples were photographed after particle deposition and again after water exposure. The water exposure process was additionally recorded using a phone camera to observe particle behaviour during water flow. The photographs and videos were analysed and compared to evaluate particle behaviour under water-induced shear stress across the different surface modifications.

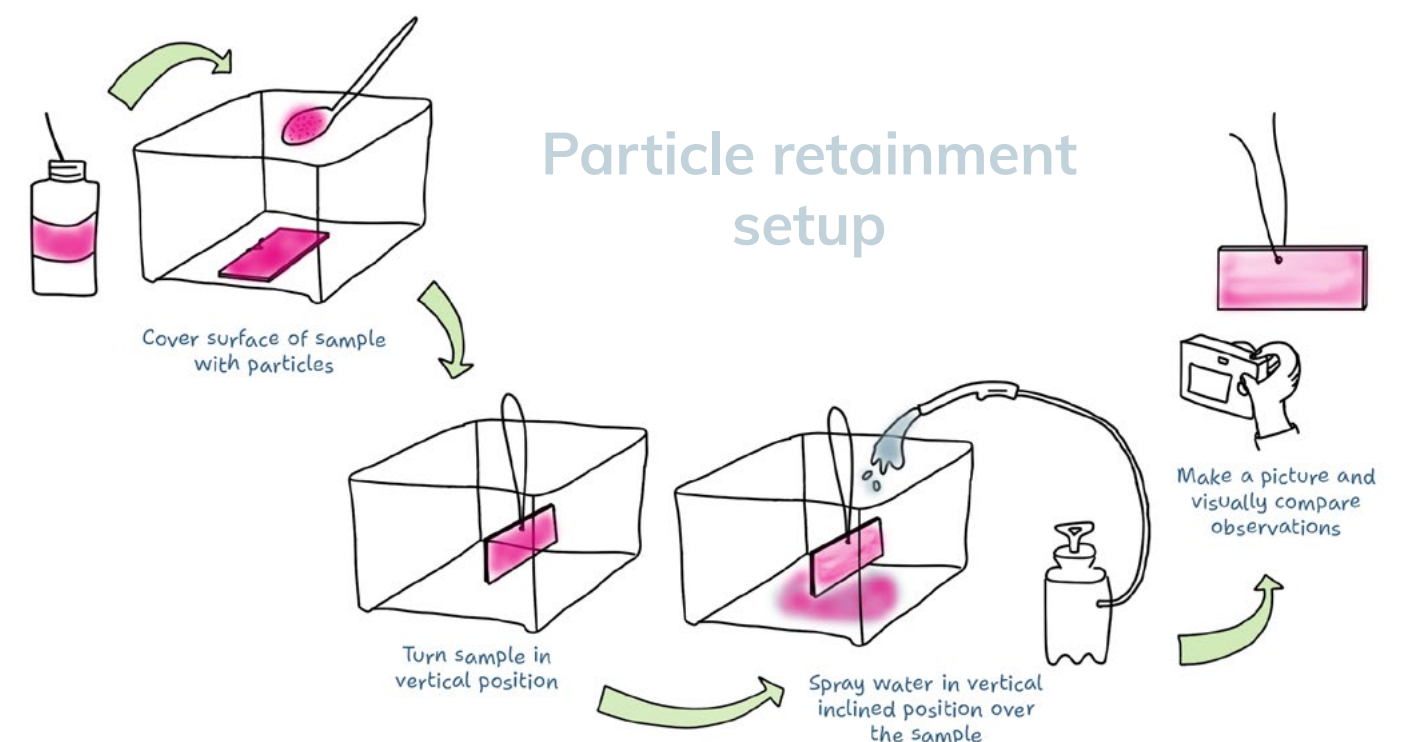


Figure 7.6. Visualisation of the particle retention method used to observe particle behaviour

7.3
Water
retention
behaviour

This section analysis the results from the water retention experiment.

Initial conditions
Environment
Figure 7.7 provides an overview of the environmental conditions during each testing day. No significant differences in temperature were observed between test days. However, the humidity on the first testing day was approximately 11% lower compared to the other days, likely due to increased rainfall in the outdoor environment. This may have contributed to faster drying behaviour of the samples tested on that day and should therefore be considered during interpretation of the results.

Date	13 may	19 may	20 may
Samples tested	Unprocessed Blasted	Weathered Laser-dotted	Laser-dot-blasted Laser-lined
Temperature of environment	22,8 °C	22,6 °C	22,4 °C
Humidity of environment	38 %	49 %	49 %

Figure 7.7. Overview of environmental conditions measured per test day

Dry mass of the samples
The initial mass of the six samples was measured before wetting and is shown in Figure 7.8. The initial masses varied significantly and, to normalise the graph, these values were subtracted from the measured mass.

Sample	Unprocessed	Blasted	Weathered	Laser-dotted	Laser-dot-blasted	Laser-lined
Dry initial mass	135,9 g	145,5 g	150,6 g	136,6 g	124,9 g	138,6 g

Figure 7.8. Dry initial mass of sample before testing

Quantitative water retention behaviour
Figure 7.9 shows the normalised retained water mass over time for the six tested surface concepts: unprocessed, blasted, weathered, laser-dotted, laser-dot-blasted, and laser-lined.

The retained water mass of the unprocessed sample stabilised after approximately 2580 s, after which no substantial decrease in mass was observed. The blasted sample initially retained more water than the smooth sample but showed a more rapid drying behaviour afterwards. The weathered sample demonstrated relatively fast drying behaviour, although residual retained water remained visible towards the end of the measurement period. Both laser-dotted and laser-dot-blasted samples showed increased water retention compared to the unprocessed surface. The laser-lined sample demonstrated the highest retained water mass and the slowest drying behaviour of all tested concepts.

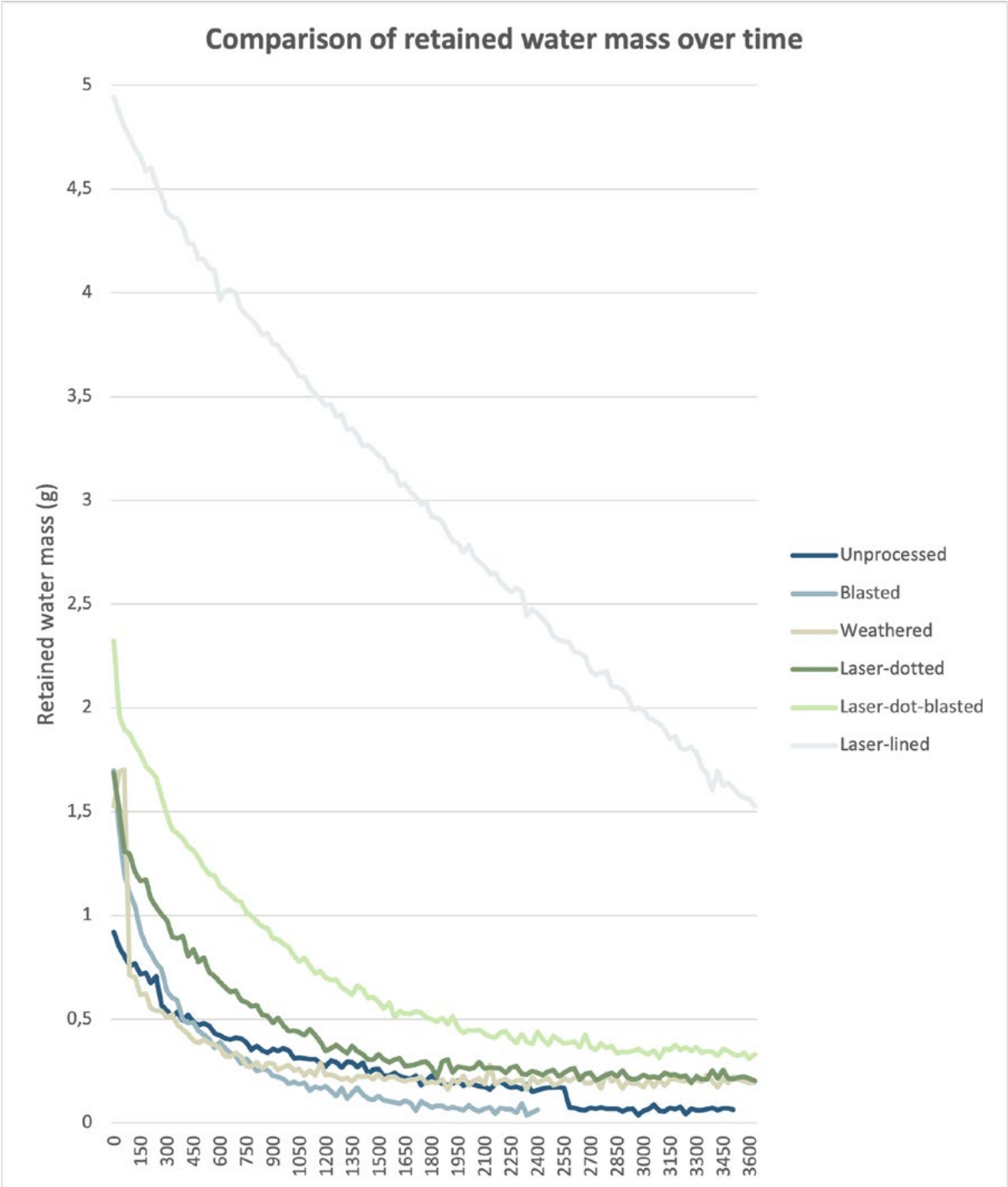


Figure 7.9. Visualisation of the particle retention method used to observe particle behaviour

Compared to the unprocessed surface, the laser-lined sample exhibited an initial retained water mass that was approximately 5.4 times higher. After 2580 s (43 min), the retained water mass remained approximately 31 times higher, demonstrating that the grooves substantially prolonged water retention.

Qualitative water behaviour observations
Figure 7.10 shows representative visual observations of drying behaviour over time for each sample. The observations are described below.

Unprocessed
When wetted, water was observed to spread across the surface and merge into larger droplets. After the first five minutes, most of the surface appeared visually dry, while only a few larger droplets remained attached and dried slowly over time. Some of these droplets remained located in the middle of the sample, while an elongated droplet formed horizontally along the bottom edge of the plate.

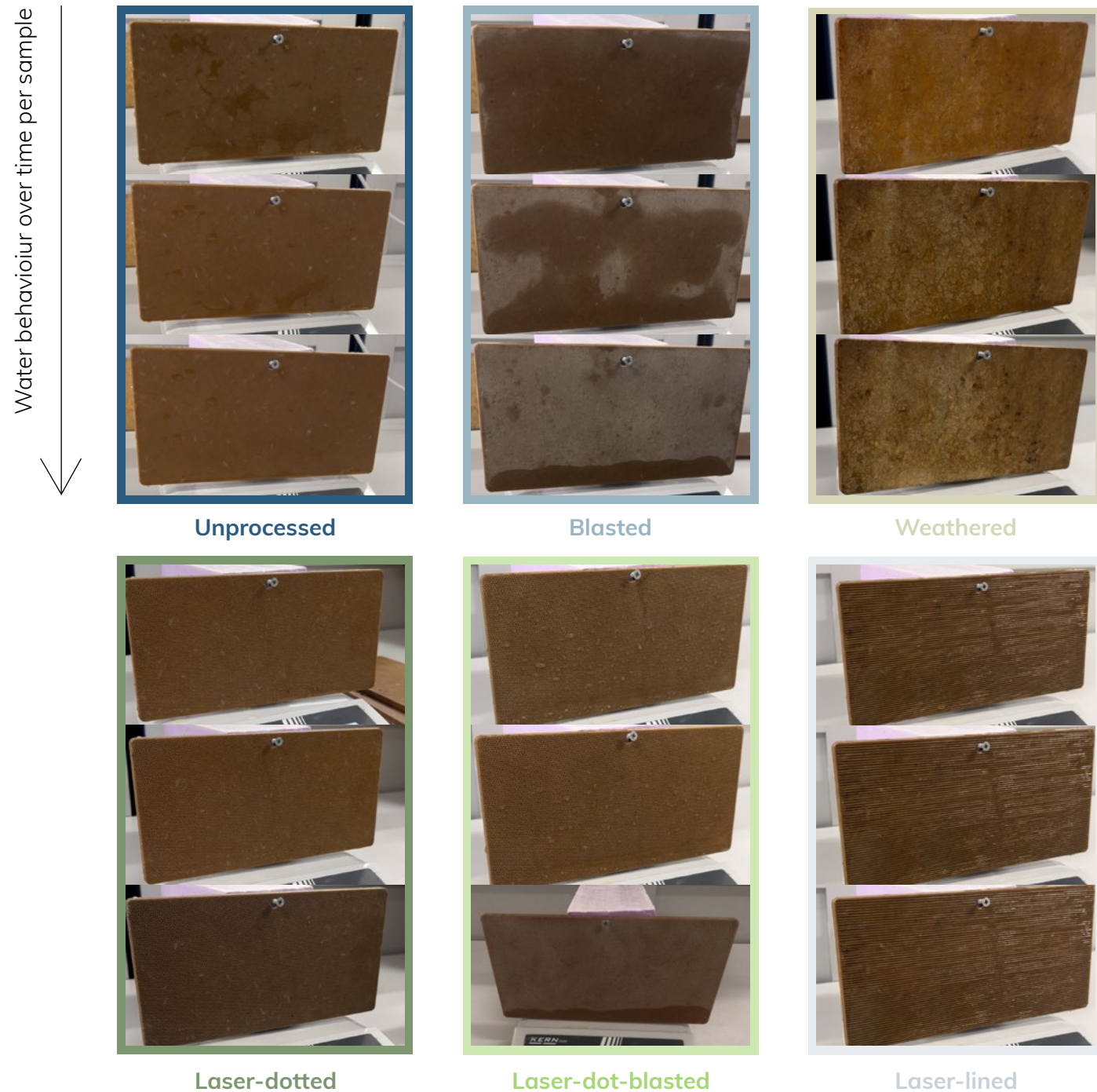


Figure 7.10. Representative photographs of drying behaviour over time for the different surface concepts (note: images do not represent the final drying stages of the experiment).

Blasted

When exposed to water, the initially lighter blasted surface darkened to a tone similar to the unprocessed sample. No large droplets were observed on the surface, unlike the unprocessed sample. Instead, the entire surface appeared evenly darkened, indicating a more uniformly wetted surface. When droplets formed, they moved downward across the wetted surface relatively quickly compared to the droplets observed on the untreated sample. During drying, the surface gradually became lighter, starting from the edges and continuing towards the middle and upper regions, while the bottom part remained wetted the longest.

Weathered

After water exposure, the sample developed a warmer colour tone rather than the darker appearance observed for the blasted sample. No large droplets were visible on the surface. During drying, the sample gradually became greyer again, while the cracks in the surface became increasingly visible, suggesting that water remained present in these regions for a longer time. In addition, a droplet became trapped between the weighing holder and the bottom edge of the sample. This droplet was manually removed during the experiment, causing a visible drop in the measured mass values during the initial stage of the measurement.

Laser-dotted

Several droplets were observed across the surface, together with a small water stream in the middle of the sample. A droplet slowly moved downward through this stream and appeared to be slowed down by the pore geometry. Water droplets were also visible inside the pores. After several minutes, many droplets remained distributed across the surface and within the pores, whereas only a limited number of droplets remained visible on the untreated sample at the same stage.

Laser-dot-blasted

Similar to the blasted sample, the lighter blasted colour disappeared after wetting. Many droplets were observed distributed across the surface, visibly more than on the unblasted laser-dotted sample. Water was also observed within the pores. Over time, the surface gradually became lighter starting from the top, followed by the middle regions, indicating progressive drying behaviour. The bottom part of the sample remained wetted the longest.

Laser-lined

When wetted, no large droplets were observed on the surface. Instead, the grooves appeared to become filled with water. During the experiment little visible change in the wetted grooves was observed, and the grooves remained visually saturated with water.

Comparative analysis

The untreated sample showed the lowest initial water retention and primarily formed larger separate droplets on the surface. Although these droplets remained attached for a relatively long time, the overall retained water mass was limited. In contrast, the blasted surface initially retained more water, which may be related to the increased roughness holding water more evenly across the surface. However, this distributed wetting behaviour also appeared to increase the exposed contact area with air, possibly resulting in faster evaporation over time.

The weathered sample showed limited surface retention behaviour, although residual retained mass remained visible towards the end of the experiment. This may suggest that weathering increased the material porosity and absorption capacity, allowing water to penetrate into the material rather than remain solely on the surface. However, the overall retained water mass remained relatively low compared to the laser-modified samples.

The laser-modified samples demonstrated

the strongest improvements in retained water behaviour, which may be related to their larger pore geometries and increased surface roughness. Both laser-dotted and laser-dot-blasted surfaces retained more water over time compared to the untreated sample. In addition, the laser-dot-blasted sample demonstrated higher retained water values than the unblasted laser-dotted sample. Similar to the normal blasted sample, this may suggest that the additional blasting process enabled water to remain attached across a larger surface area, while the laser-generated pores additionally supported the formation of larger localised water bodies, potentially slowing evaporation over time.

The laser-lined sample demonstrated the highest retained water mass and slowest drying behaviour of all tested concepts. The grooves appeared to form connected water bodies, which may have reduced the exposed contact area with air compared to smaller separated droplets. This may explain the slower evaporation behaviour compared to the laser-dotted concepts, where water remained distributed across multiple smaller pores. However, whether these elongated grooves sufficiently protect against shear stress is further investigated in Chapter 7.4.

7.4 Particle retention behaviour

A particle retention experiment was conducted to evaluate the ability of the surface concepts to retain particles under flowing water conditions, as protection against wash-off is considered an important function of surface roughness. While water retention is important for maintaining moisture availability, deposited cells must also remain attached under conditions involving water flow and wind exposure. The experiment functions as a qualitative proxy for protection against shear-like forces and provides insight into the role of surface roughness during the early attachment phase of pioneer organisms.

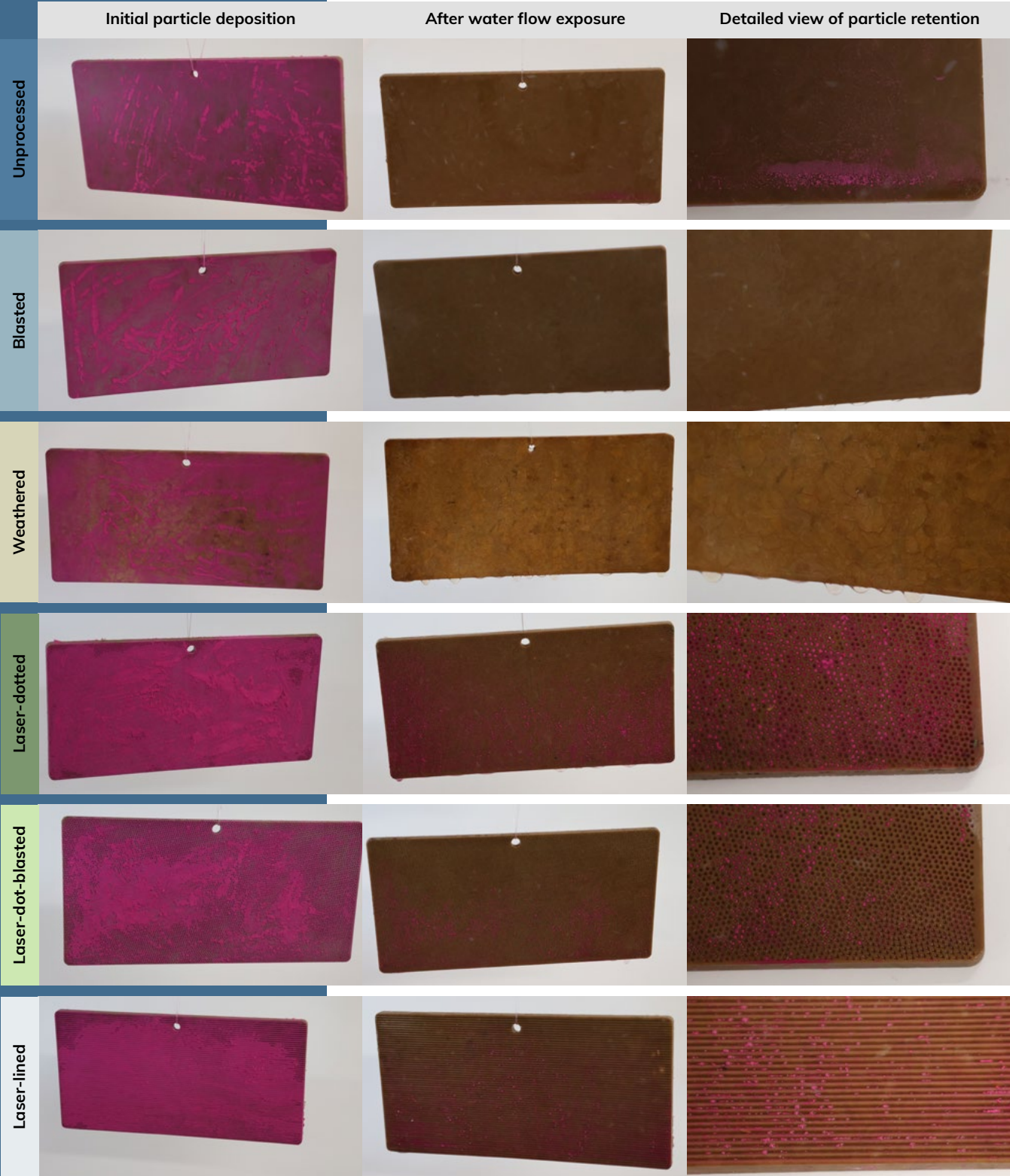


Figure 7.11. Visual comparison of particle retention across the investigated surface concepts before and after wetting, including close-up images of the observed behaviour

Qualitative particle retention behaviour

Figure 7.11 presents visual observations of the particle retention behaviour.

Unprocessed

No clear particle retention on the unprocessed surface was observed. A small accumulation of particles was visible in the lower-right corner of the sample. This accumulation could have resulted from local water retention or a region with reduced water flow. However, because particle retention was limited to a single location while the remainder of the surface was largely cleared of particles, this observation does not provide evidence of effective protection against wash-off under repeated rainfall events or other shear forces.

Blasted

No noticeable particle retention was observed on the blasted surface. Unlike the unprocessed sample, no local accumulations of particles were visible.

Weathered

No significant particle retention was observed on the weathered surface. Although the crack-like roughness created local surface features, these did not appear to provide sufficient protection against water flow. Some local particle retention was observed, visible as a pink residue within certain cracks. These retained particles were primarily found in horizontally oriented cracks, suggesting that crack orientation may influence local retention behaviour.

Laser-dotted, Laser-dot-blasted, and Laser-lined
Visible particle retention was observed within both the pores and grooves of the laser-modified surfaces. Retention appeared to be lower in the upper half of the samples, likely because this area was exposed more directly to the incoming water flow. Nevertheless, particles remained visible even in these more exposed regions (Figure 7.12), while larger accumulations were retained in areas subjected to lower flow intensity. This indicates that the pores and grooves provided protection against wash-off under the applied flow conditions.

Comparative analysis

Although the particle retention experiment was qualitative in nature, a clear distinction could be observed between the tested concepts. The untreated, blasted, and weathered surfaces retained little to no visible particles after exposure to flowing water conditions. In contrast, the laser-dotted, laser-dot-blasted, and laser-lined concepts consistently retained visible particles within their surface features.

The experiment showed that both the laser-lined and laser-dotted concepts retained substantial amounts of particles after exposure to flowing water conditions. Further quantitative investigation under more controlled shear conditions would be required to determine potential differences in retention performance between these concepts.

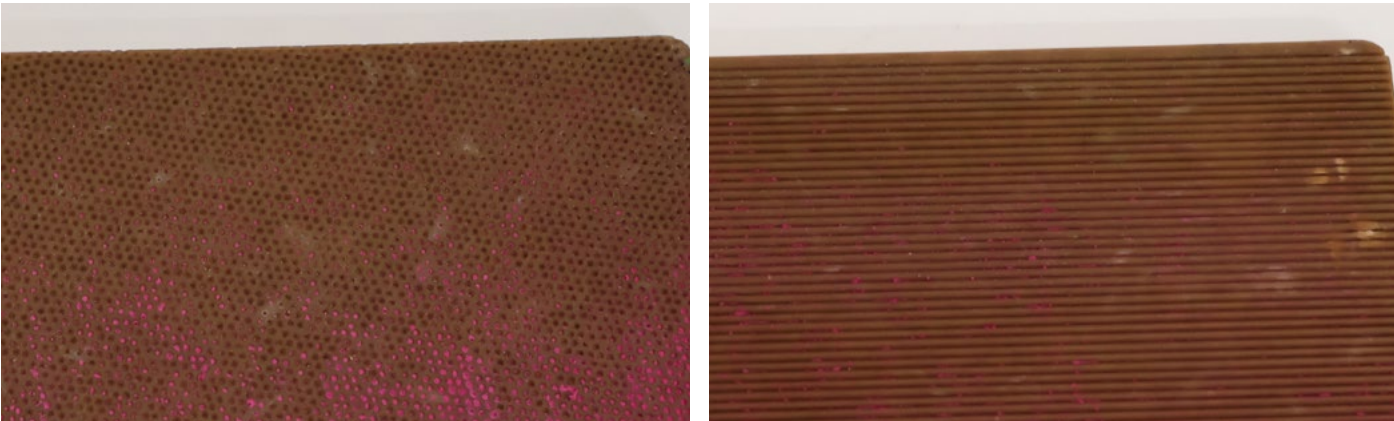


Figure 7.12. Detailed views of the upper regions of the Laser-dotted and Laser-lined samples, where visible particle retention remained despite more direct exposure to the incoming water flow.

7.5 Comparative evaluation

Overall comparison

The validation experiments reveal a clear distinction between the investigated concepts. The untreated, blasted, and weathered surfaces showed relatively low water retention and retained little to no particles after exposure to flowing water conditions. In contrast, the laser-modified concepts performed substantially better in both experiments, indicating greater potential to support early-stage attachment conditions.

A key question was whether the larger water bodies formed within the laser-lined grooves would reduce protection against

wash-off compared to the more enclosed pore geometries of the laser-dotted concepts. The particle retention experiment did not indicate such a disadvantage, as both concepts retained visible particles after exposure to flowing water. However, the qualitative nature of the experiment does not allow a quantitative comparison between the concepts. Further testing under more controlled shear conditions would be required to determine potential differences in particle retention performance.

Final concept selection

Because the laser-lined concept achieved substantially higher water retention than all other concepts, including the initial unprocessed sample, while also demonstrating potential for particle retention, it was identified as the most promising surface roughness concept within this study and was therefore selected for further integration into the facade demonstrator.

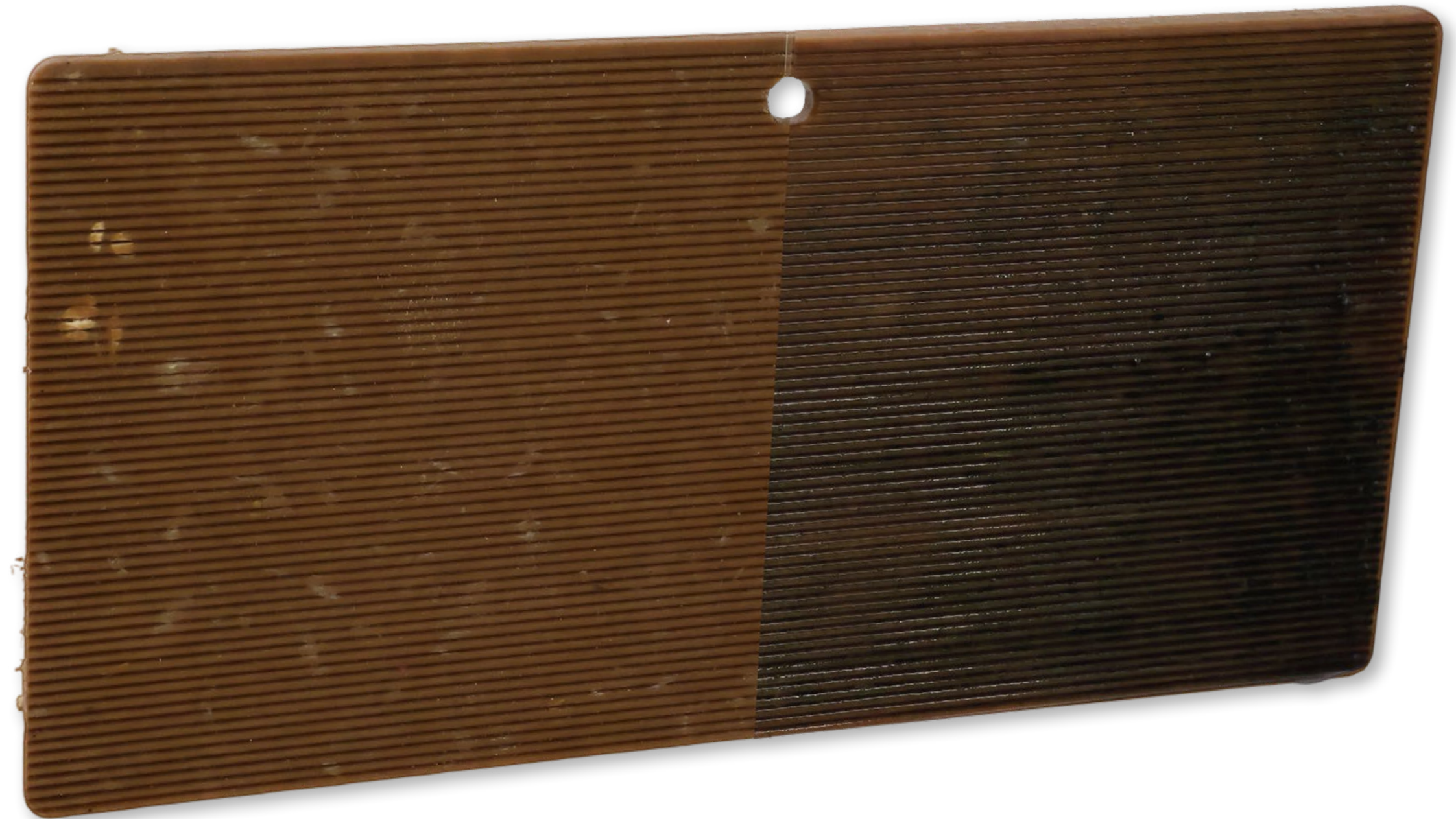


Figure 7.13. Final laser-lined roughness concept, showing simulated algae growth on the right half of the sample

7.6

Limitations of validation experiments

The validation methods developed in this project were intended as comparative proxy tests to assess factors that may support the spontaneous attachment of pioneer organisms. While the methods provided useful insights into the relative performance of the different surface concepts, several limitations should be considered when interpreting the results.

Water retention experiment limitations

The water retention experiment does not fully represent natural environmental conditions. The selected submerged wetting method was chosen to maximise repeatability between samples, but differs from natural wetting processes such as rainfall, dew formation, and condensation. In addition, the experiment focused on short-term drying behaviour and did not investigate long-term weathering effects or seasonal environmental fluctuations.

Environmental conditions were not fully controlled throughout all measurements. Variations in temperature and humidity occurred between testing sessions and may have influenced drying behaviour. For example, the untreated and blasted samples were measured at a humidity approximately 11% lower and a temperature approximately 0.4 °C higher than those of the best-performing concepts. These differences may have contributed to faster drying rates. However, both concepts already showed relatively low retained water values at the start of the measurement period, after the standardised 25-second drainage phase. Therefore, while the environmental conditions may have influenced the absolute drying rates, they are not expected to substantially alter the relative performance of these concepts compared to the other tested surfaces.

Measurement uncertainty should also be considered. During weighing, the scale readings fluctuated by approximately ± 0.07 g, resulting in a potential difference of approximately 0.14 g between two recorded values. Although this uncertainty was present for all samples and the experiments were conducted at the same location to minimise variations caused by airflow, small differences between concepts should be interpreted with caution. Larger differences and overall trends between concepts are considered more reliable than individual measurements.

Furthermore, occasional droplets became trapped beneath the samples during weighing, requiring manual removal. In some cases, this resulted in sudden fluctuations in the recorded mass when the droplet was removed during one of the 30-second measurement intervals. To minimise the influence of these measurement irregularities, the first five minutes of each experiment were video recorded. This allowed the mass to be determined from moments immediately before or after the disturbance when necessary. This correction was applied to the Weathered, Laser-dotted, and Laser-dot-blasted samples. The most noticeable effect occurred for the weathered sample, where removal of the trapped droplet resulted in a visible drop in the measured mass. Although these events may have influenced individual measurements, they occurred primarily during the initial stages of the experiments and were addressed consistently using the recorded video observations.

Particle retention experiment limitations

The particle retention experiment should not be interpreted as a direct representation of biological attachment. Although the particles were selected within a similar size range to the target organisms, they differ from living cells in shape, density, surface properties, and biological behaviour. Furthermore, biological mechanisms such as adhesion and biofilm formation were not represented.

The experiment primarily evaluates protection against wash-off after particles have already been deposited on the surface. It therefore provides insights into the ability of a surface geometry to protect deposited particles from shear-like forces, but does not assess the initial deposition or capture of airborne cells. As a result, the findings should be interpreted as indicators of post-deposition retention rather than the likelihood of initial organism attachment to the facade.

In addition, the applied water flow was manually controlled. Although efforts were made to standardise the procedure by maintaining a similar spraying duration (approximately 35 seconds), spraying direction, and sample orientation, variations in spray angle, movement, water pressure, and local water distribution could not be completely eliminated. The results should therefore be interpreted qualitatively rather than quantitatively. Consequently, the experiment is most valuable for comparing general retention behaviour between concepts rather than for determining exact retention performance.

Furthermore, the experiment specifically evaluates resistance to removal under water-induced shear

forces. While the findings may provide a general indication of the ability of surface geometries to protect deposited particles against external forces, wind-induced transport and removal were not investigated. Wind may act from different directions and under different flow conditions than the applied water flow, potentially influencing particle retention behaviour in other ways.

General limitations

Both validation methods focus on early-stage attachment conditions rather than long-term ecological establishment. The experiments do not assess biological growth, competition between organisms, succession processes, or long-term biofilm development. As a result, the findings should be interpreted as indicators of bioreceptive potential rather than predictors of actual colonisation performance on facades.

In addition, both validation experiments were conducted once per concept. As a result, the experiments primarily provide comparative indications rather than statistically robust results. Repeating the experiments multiple times would improve confidence in the observed trends and provide insight into measurement variability and repeatability.

Despite these limitations, the developed methods enabled a structured comparison between surface concepts and provided valuable insights into the role of surface geometry in supporting conditions associated with the initial attachment phase of pioneer organisms.

8 Facade Integration & Application



Figure 8.1. Conceptual facade visualisation showing the integration of the biobased material and bioreceptive roughness within a Nabasco facade system. The visualisation depicts a transformer substation, a building typology that already represents an existing application context for NPSP facade systems.

8.1 Design integration

This section investigates how the developed roughness concept can be integrated into facade applications. Although roughness was the primary design intervention explored in this project, bioreceptivity remains dependent on a broader set of environmental and material-related factors discussed in Chapters 3.4 and 6.1.

Interaction between roughness and macro-scale morphology

One of the key values of NPSP facade panels is the design freedom they offer architects in shaping macro-scale geometries. As the developed roughness structures will ultimately be integrated into such facade panels, it is important to consider how micro-scale roughness and macro-scale morphology can complement one another.

Water paths

The macro-scale morphology can have a significant influence on water retention by directing water flow across the surface (Chapter 3.4.2). Figure 8.2 illustrates how macro-scale geometries can guide water towards areas containing micro-scale roughness structures. While vertical channels and flow-oriented features can enhance the transport of water and nutrients across the facade, the roughness structures can subsequently retain these resources locally. In addition, sloped areas may increase water retention by reducing flow velocity and creating shaded areas. Therefore, the effectiveness of the roughness structures is likely to depend on their location within the larger facade morphology.

Based on this, it is recommended to first identify locations where water naturally flows and accumulates due to the macro-scale morphology. Applying roughness structures in these areas may create more favourable conditions for bioreceptive growth.

Orientation

The orientation of the roughness can also influence its performance, as the developed structures are directional. Horizontal grooves provide small horizontal surfaces on which water can be retained, whereas vertically oriented grooves are more likely to facilitate drainage. As many existing NPSP facade geometries can be rotated, the relationship between panel orientation, water flow, and roughness direction should be considered during the design process. While panel rotation is not required, it enables greater design variation from a single mould and may therefore influence the aesthetic expression.

Guiding growth through design

Together, water paths and roughness orientation provide opportunities to influence where favourable conditions for biological growth emerge on the facade. Beyond its functional role, roughness introduces an additional design layer to the facade. By combining roughness patterns with macro-scale morphology, biological growth can be encouraged in selected areas, allowing ecological and aesthetic considerations to be integrated within a single design strategy.



Figure 8.2. Example of a macrostructure which redirects coloured water to certain areas (Source: Mustafa et al., 2021)

Facade composition

Although roughness could be applied across the entire panel surface, incorporating it into deliberate patterns may improve the aesthetic acceptance of biological growth. Such an approach allows colonisation to occur in intended areas, creating a more controlled and designed appearance rather than being perceived as deterioration or poor maintenance (Figure 8.3).

In addition to aesthetic considerations, pattern design can be inspired by natural organic forms and visual design principles such as the Gestalt principles, which describe how people perceive and organise visual information.

Beyond visual appearance, the connectivity of roughness patterns may also influence biological establishment. While isolated roughness areas require organisms to colonise each area individually, connected structures may facilitate the gradual spread of organisms across the facade once colonisation has occurred. Further research is required to determine the extent to which pattern connectivity influences long-term biological development.

Finally, environmental conditions across the facade should also be considered when determining the placement of bioreceptive areas. Since non-retained water flows downward, moisture accumulation is generally highest in the lower parts of the facade. Consequently, these areas may offer the most favourable conditions for the integration of bioreceptive panels.

Limitations of control

It should be recognised that bioreceptive facades interact with living organisms, making the outcome



Figure 8.3. Example of a facade without predefined colonisation areas, where biological growth appears unintentional and is often perceived as deterioration (source: BN De Stem)

inherently dynamic and only partially controllable. The purpose of the design is therefore not to determine exactly where organisms will grow, but rather to create favourable conditions that guide colonisation and support native species.

In addition to surface design, many environmental factors influence biological establishment, including rainfall, salinity, wind exposure, temperature, competition between organisms, and the local availability of propagules. Consequently, the developed roughness should be regarded as a tool for influencing growth patterns rather than a means of fully controlling them.

Applicability to other Nabasco materials

As the developed roughness is a surface design intervention rather than a material property, the concept is not limited to the Oribond composite investigated in this project. In principle, the same roughness structures could be applied to other Nabasco materials without substantial changes to the production process.

However, material properties remain an important factor in bioreceptive performance. For example, the dark colour of the furan composite may influence colonisation and reduce the visual contrast between the facade and biological growth. In contrast, the lighter biopolyester composite may provide greater colour, but its synthetic content raises questions regarding the long-term interaction between biological growth and plastic-containing materials. Consequently, while the roughness concept is transferable, the suitability of each material should be evaluated in relation to both facade requirements and bioreceptive objectives.

8.2 Design translation

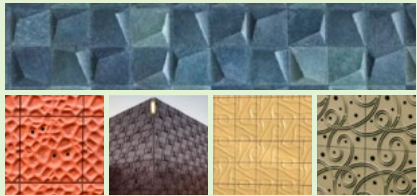


Figure 8.4. Available facade moulds, with the blue one being chosen

This section translates the research findings into a conceptual facade application. Through a case study, the developed roughness concept is integrated to explore its design potential and visualise possible implementation strategies.

Case study selection

To explore the integration of roughness within a realistic facade application, an existing NPSP facade mould was selected as a case study (Figure 8.4). The chosen geometry provides sufficient three-dimensional features to demonstrate the integration of roughness, while not drawing excessive attention away from the roughness itself. Compared to the flat plates used during the material and roughness development phases, the mould better represents a realistic facade application.

In addition, the selected mould is relatively small, reducing material consumption and by using an existing one and less material the prototyping costs lowers. As such, it serves as a demonstrator of the design vision rather than a final facade design.

Water path analysis

As a next step, the water paths on this morphology were investigated. This was done by manually spraying water coloured with spirulina powder onto the panel from above (Figure 8.5). The coloured water was used to simulate rainfall and visualise the resulting flow paths. For this exploration, an existing Nabasco panel was used instead of the developed composite, as this panel was readily available. Since the objective was to investigate the influence of the macro-scale morphology on water flow, this was considered sufficient for the purpose of the study.

As shown in Figure 8.6, the water paths are not strictly constrained by the morphology, as the panel contains only limited height differences and water spreads across most of the surface. Nevertheless, the coloured water reveals a tendency to follow the sloped geometries, particularly in the downward direction. In addition, the area below the intersection of several slopes received little to no water.



Figure 8.5. Water path analysis using spirulina-coloured water to visualise flow patterns across the selected facade morphology

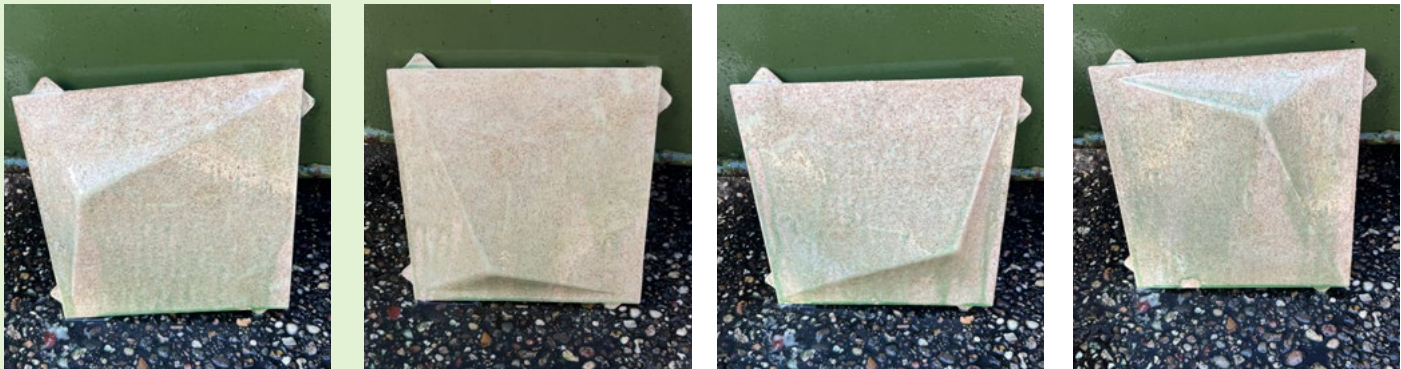


Figure 8.6. Wetting behaviour of the selected facade geometry in four possible panel orientations

Roughness placement

As water accumulation was observed primarily around the central sloped geometry rather than on the flat outer areas, the roughness structures were concentrated in this region.

Figure 8.7 presents two possible design concepts. The first follows a geometric language with sharp edges inspired by the macro-scale morphology of the panel, whereas the second adopts a more organic form intended to create a more natural appearance. To support the nature inclusive message, the organic design is chosen for further facade integration visuals.

To maintain design flexibility, the roughness was applied in two different orientations, ensuring that horizontal grooves remain present regardless of the panel orientation. Although rotating the panel inevitably positions some grooves vertically, these grooves may still contribute to guiding water towards the horizontal grooves located below them.

Figure 8.8 illustrates the possible panel orientations within the same mould design. The green lines represent horizontally oriented grooves, where water retention and biological establishment are expected to be more favourable. The brown lines indicate vertically oriented grooves, which remain visible through shadow effects but are expected to contribute less to biological growth.

Facade composition

Different composition patterns were explored within the facade geometry. The arrangement of panels can be determined either by customer preferences or by connectivity to support the spread of colonisation. Figure 8.9 presents examples of both patterned and randomised facade compositions. Roughness may also be applied selectively, allowing some facade areas to remain untreated. For the demonstrator, a randomised composition was chosen, inspired by the panel arrangements currently used for this panel design in NPSP facade projects.

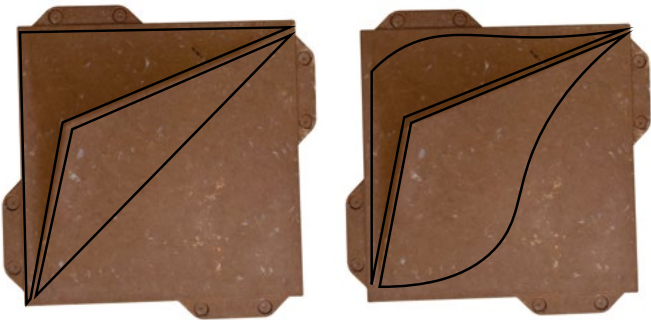


Figure 8.7. Two roughness placement concepts developed from the water path analysis: a geometry-inspired concept (left) and an organic concept (right)

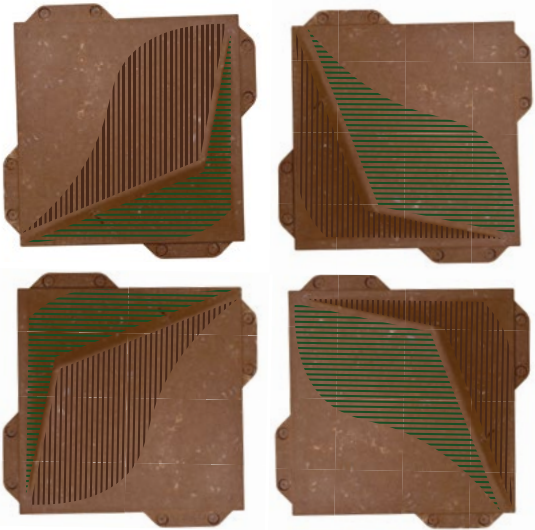


Figure 8.8. Illustration of possible panel orientations within the same mould with horizontal (green) and vertical (brown) positioned lines

Patterned compositions



Randomised compositions

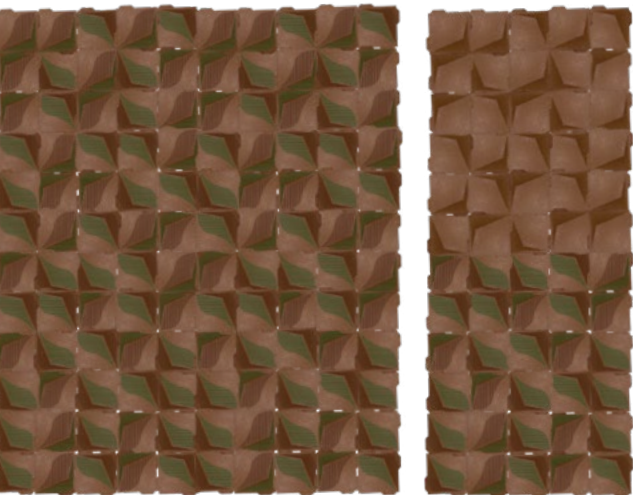


Figure 8.9. Examples of facade compositions created from a single panel mould through rotation and repetition

8.3 Demonstrator development

Manufacturing parameters	
Recipe	Version 12 ≈ 40% Oribond, 55% Olive stone, 5% Viscose
Mould volume	194 cc/ml
Mould area	400 cm ²
Weight mixture per sample	350 g
Pressure during pressing	45 tonnes
Temperature during pressure	145°C
Width grooves	Red: 0,2 mm Blue: 0,6 mm Green: 1,0 mm
Speed engraving laser (defining depth)	Red: 25% Blue: 75% Green: 100%

Figure 8.10 Manufacturing parameters for demonstrator

The demonstrator (Figure 8.17) was developed to communicate the envisioned facade application and provide a tangible representation of the developed material and roughness strategy within a single three-dimensional artefact. As the demonstrator incorporates both the developed material and roughness structures, it may also serve as a pilot for future outdoor testing of biological colonisation and related performance indicators.

Demonstrator Fabrication

During fabrication, several observations were made that may be relevant for future prototyping activities. See the final manufacturing parameters in Figure 8.10.

Composite fabrication

Initial panels showed local dry areas and voids. Increasing the amount of composite mixture from 275 g to 350 g improved mould filling and resulted in more homogeneous panels (Figure 8.13). Because the material was manually distributed throughout the mould before pressing, the flow behaviour of the composite within the mould was not systematically evaluated.

Roughness fabrication

The roughness structures were applied through laser engraving. As the demonstrator had a three-dimensional geometry, accurate engraving proved challenging because laser focus depends on a fixed focal distance. To improve engraving quality, a setup was developed to position the engraved surface as horizontally as possible (Figures 8.14 and 8.15). Nevertheless, local height variations remained present, resulting in minor variations in engraving depth. While these variations did not significantly affect the appearance, they may become more critical when evaluating biological growth performance.

In addition, aligning the engraving pattern with the three-dimensional geometry required several iterative adjustments because the panel could not be positioned completely flat during engraving. Although the resulting structures were visually satisfactory, the process was time-intensive and not sufficiently precise for large-scale production. Due to this, the roughness was limited to a single panel area rather than the multiple locations explored in Section 8.2.

For future implementation, it is recommended to integrate the roughness directly into the mould design rather than applying it as a post-processing step.

During post-processing, Spirulina powder used to simulate biological growth remained trapped within the engraved grooves and could not be removed by rinsing alone. Although qualitative, this observation provides an additional indication that the grooves may effectively retain particles and support the accumulation of biological material.

Growth simulation

To communicate the intended integration of biological growth within the facade, Spirulina powder was used to simulate a desired colonisation scenario, as actual colonisation may take months or years to establish under natural conditions. The

demonstrator therefore represents the envisioned facade concept rather than actual biological performance. As biological colonisation is a dynamic process that develops over time and is

influenced by various biological and environmental factors, actual growth may not follow the roughness patterns as precisely as represented in the demonstrator.

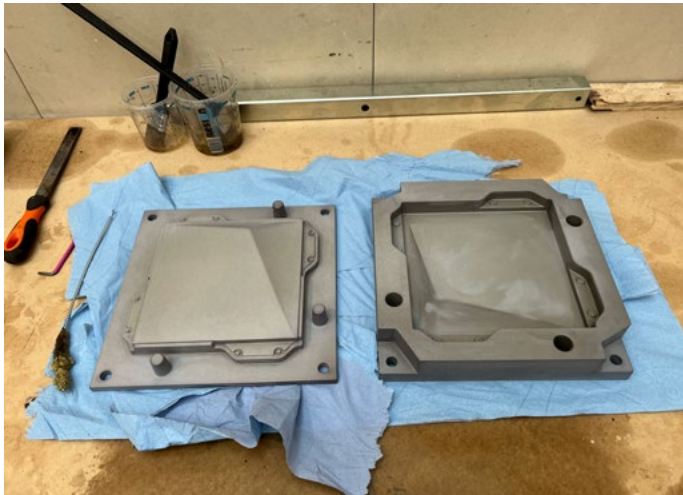


Figure 8.11. Used mould from NPSP

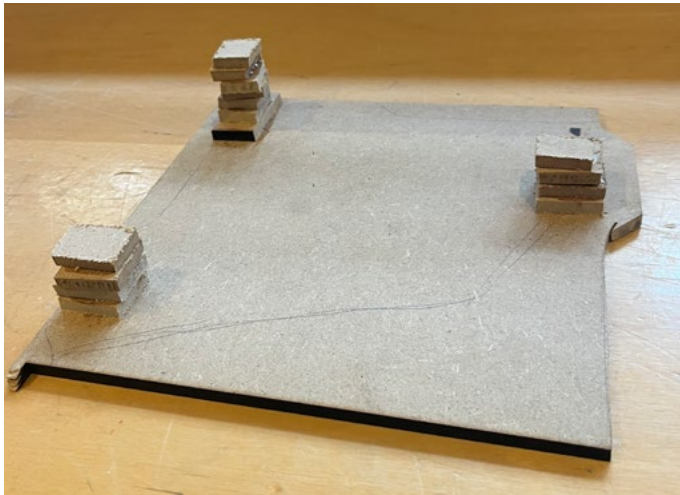


Figure 8.14. Developed setup to position surface more horizontal

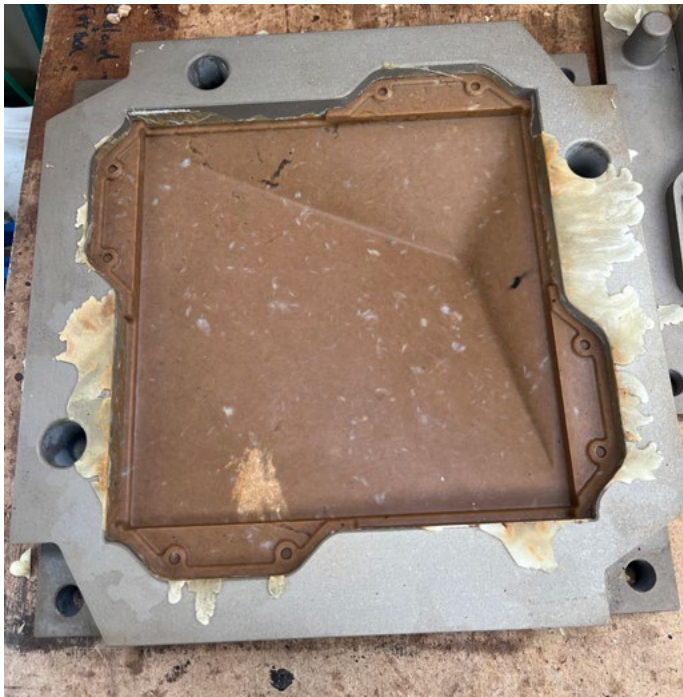


Figure 8.12. Pressed sample in mould



Figure 8.15. Sample placed in setup for laser engraving

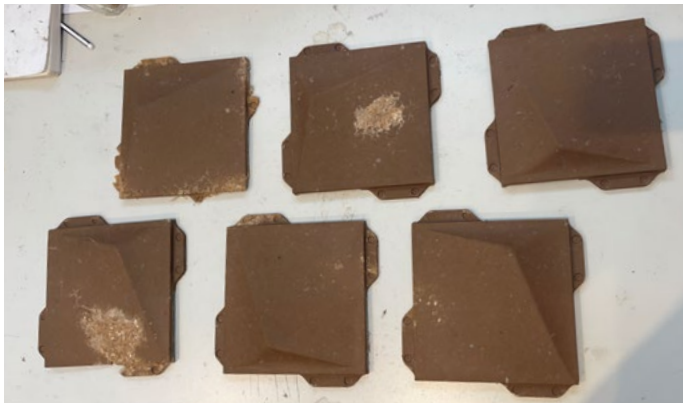


Figure 8.13. Different composite pressing attempts, showing improved results in the samples on the right due to an increased inserted material

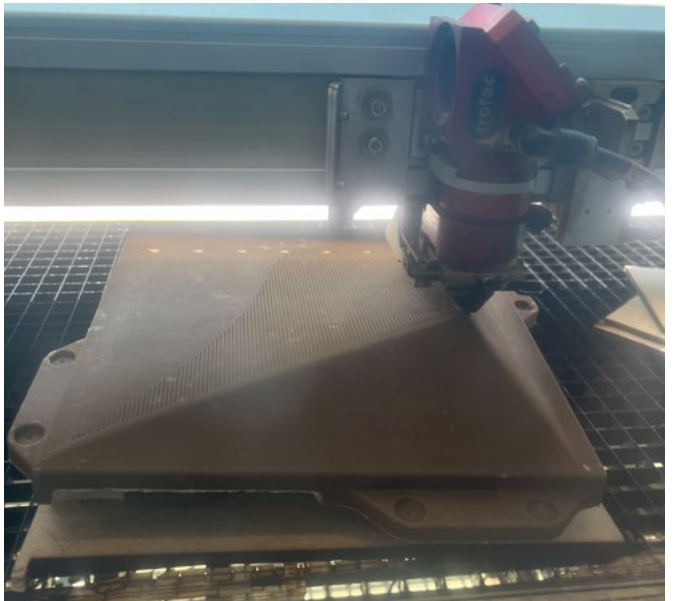
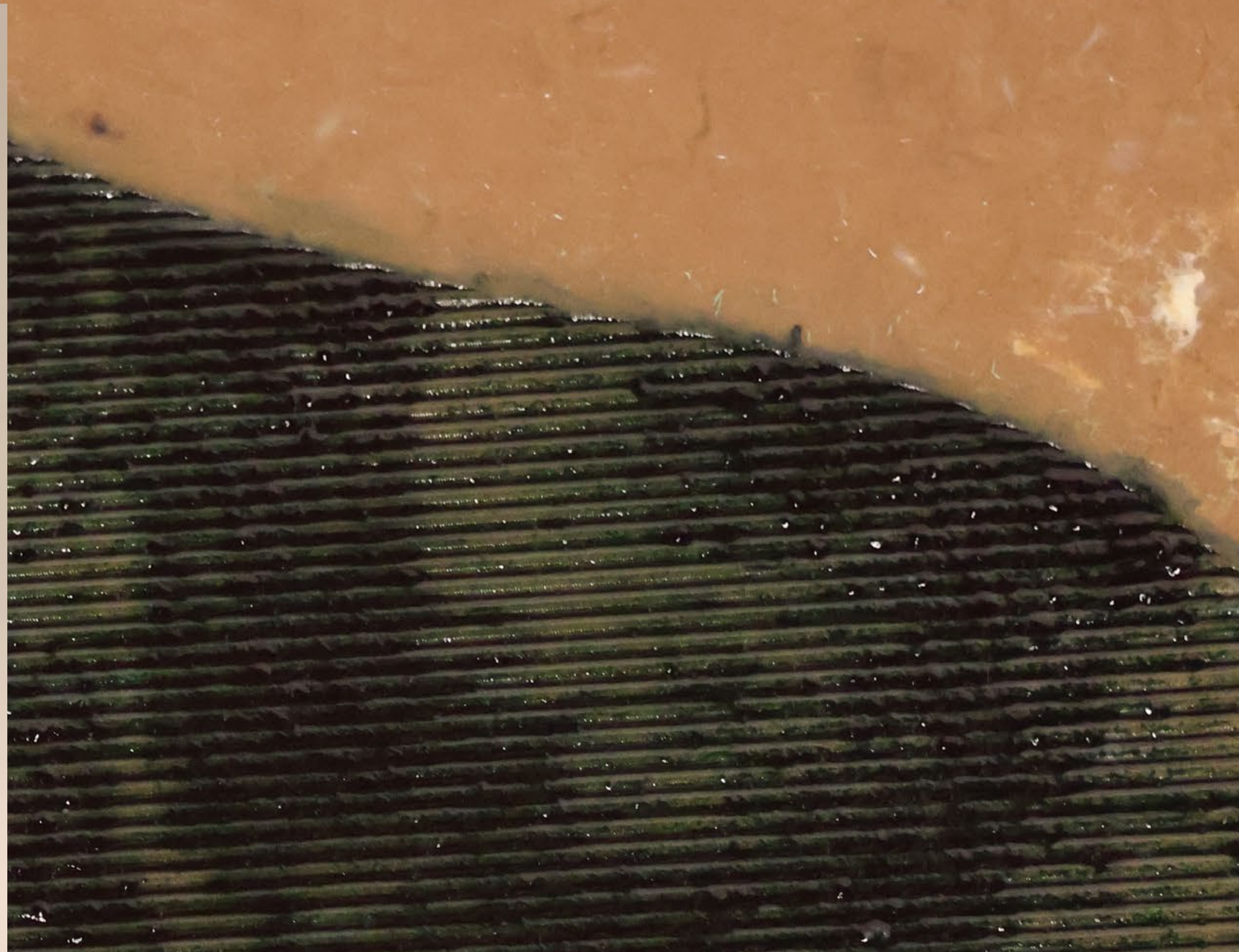
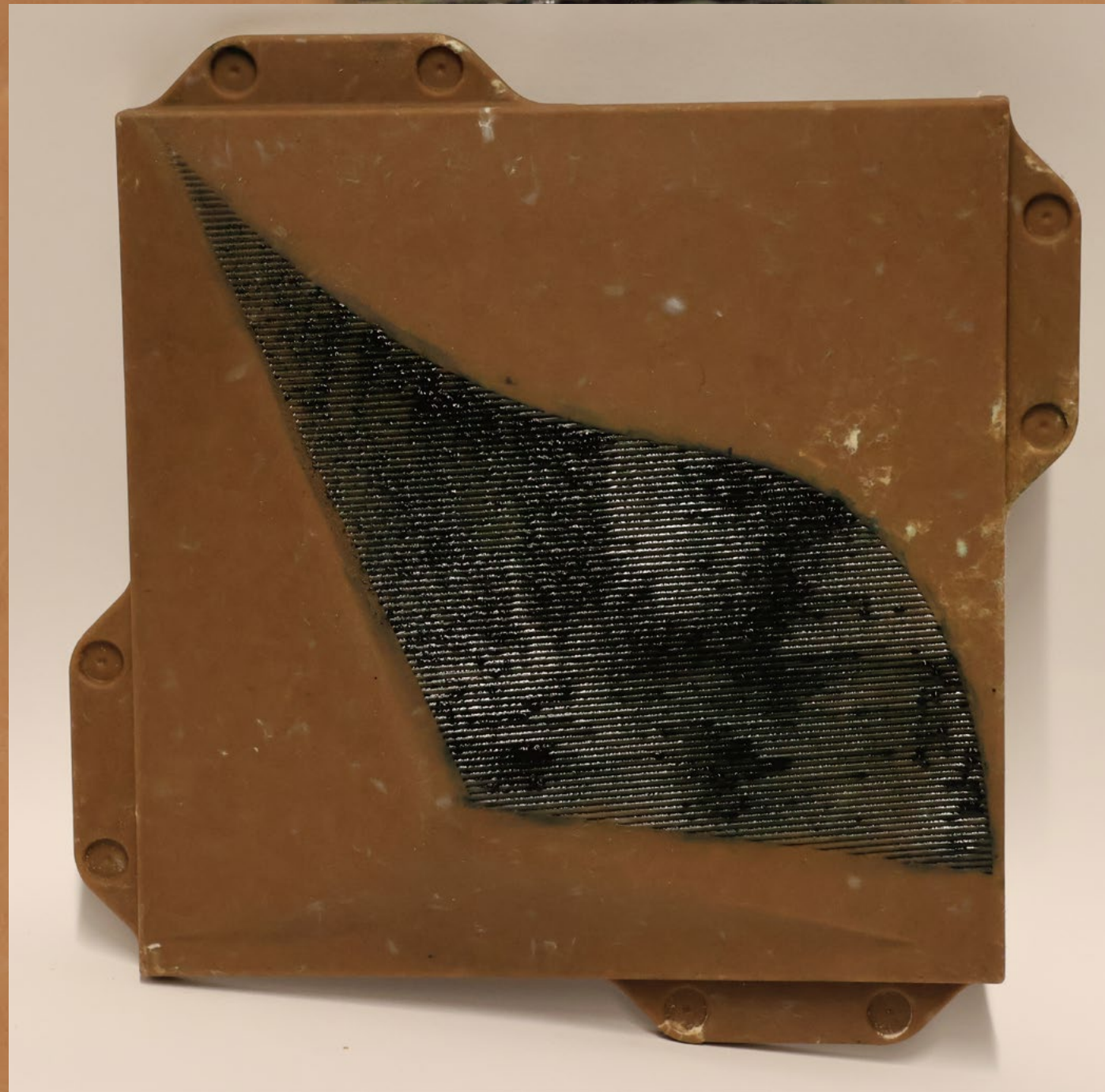


Figure 8.16. Laser engraving of the composite sample.

Figure 8.17. Photographs of the demonstrator, showing the developed composite material, the integrated roughness structures, and the simulated biological colonisation.



8.4 Towards Implementation



Figure 8.18. Photograph of a 200 × 100 mm plate with two magnified views of the logo detail

This section explores the potential for scaling and implementing the proposed concept, focusing on production aspects, economic considerations, and market adoption.

Production

The developed roughness concept can potentially be implemented directly within the mould design, eliminating the need for additional post-processing steps such as laser engraving. According to Frank Bleeker, Senior Product Developer at NPSP responsible for mould design (personal communication, June 8, 2026), the investigated roughness dimensions fall within the capabilities of existing CNC-based mould manufacturing processes. Existing mould plates already contain engraved logo features at a comparable scale (Figure 8.18), demonstrating that fine surface details can be reproduced through the current production process. Such structures can be created using different CNC machining strategies, including angled milling operations or pointed milling tools that directly generate V-shaped geometries. As NPSP already incorporates surface features of approximately 0.1 mm into mould designs, the proposed roughness structures of 0.2–1.0 mm are considered technically feasible for mould-level implementation.

When integrating surface structures into a mould, demoulding requirements must be considered. Features containing strong undercuts may complicate release, whereas shallow tapered geometries are generally preferred. The developed roughness concept consists primarily of angular grooves without pronounced undercuts, making it compatible with existing mould manufacturing and release practices. However, the orientation of the roughness structures should also be considered. Since demoulding occurs along a single release direction, roughness features should be designed to remain releasable from that direction. In more complex geometries, additional mould design considerations may be required, such as the use of multiple demoulding parts or alternative release directions.

A key advantage of mould-level implementation is that the roughness is reproduced automatically during manufacturing. Once incorporated into the mould, no additional processing steps are required for individual facade panels, supporting repeatability and large-scale production.

The production process of the Oribond composite itself also presents opportunities for further optimisation. Although successful facade panels were produced within the scope of this project, additional development is required to improve manufacturing consistency, process robustness, and scalability. Future optimisation of the material formulation and production process will therefore be important for successful large-scale implementation.

Economic aspects

As both the material and its application are still in an early stage of development, a detailed cost analysis is currently not feasible. The economic aspects are therefore assessed qualitatively, considering both opportunities and limitations. The developed Oribond composite currently remains more

expensive than conventional Nabasco materials, primarily due to the resin costs. According to NPSP, resin costs are estimated at approximately €10 per square metre, compared to approximately €3 for the polyester and furan systems currently used. As Oribond is still under development, these costs may decrease as production scales up and the formulation is further optimised.

Despite this initial cost disadvantage, NPSP indicated that material value should not be assessed solely on raw material costs. The developed composite offers additional qualitative value through its fully biobased composition, visible natural fibres, and non-toxic production process. Furthermore, its lower density may reduce material consumption and handling requirements.

Production costs may also be reduced through process optimisation. Pressing time is a major contributor to overall manufacturing costs, and initial production trials indicate that Oribond requires approximately 10 minutes of pressing time, compared to 15 minutes for the furan system. Further reductions in resin content and processing time could therefore improve the economic competitiveness of the material.

The implementation of the roughness itself is not expected to significantly increase production costs. As the structures can be integrated directly into the mould design, they are reproduced during standard manufacturing without requiring additional processing steps.

Market adoption

The proposed facade concept offers value through its biobased composition, nature-inclusive appearance, ecological benefits, and limited maintenance requirements. To explore its potential adoption, insights from discussions with Jet Wiersma, Technical Advisor at NPSP (personal communication, June 12, 2026), were used to identify relevant markets, target groups, and implementation challenges.

Market potential

According to NPSP, there is growing interest in nature-inclusive and regenerative building solutions. Clients from sectors such as housing, infrastructure, and railway projects have already shown interest in biodiversity-supporting products, including insect hotels, bird nesting boxes, and bat-integrated facade elements (Wiersma, personal communication, 12 June 2026). One of the main barriers to adoption is maintenance. Many nature-inclusive facade systems require irrigation, monitoring, and vegetation management, which

can be costly and time-consuming. In addition, poorly maintained or dried vegetation may raise concerns regarding fire safety. Consequently, there is a preference for self-sustaining systems that can support ecological value with minimal intervention. As a result, the limited maintenance requirements associated with this bottom-up colonisation approach may represent an important selling point of the proposed facade concept. Furthermore, educational buildings may represent a suitable application context, as visible biological growth could contribute to environmental awareness and learning opportunities.

Target groups

NPSP identified two broad customer groups (Wiersma, personal communication, 12 June 2026). The first group prefers a clean and static facade appearance throughout the building lifetime. The second group values biobased materials that also convey a natural appearance through visible characteristics such as colour change and fibre visibility. As a result, the concept is expected to align most strongly with clients and architects who already embrace regenerative and nature-inclusive design approaches.

Potential early adopters are architects who are already engaged with regenerative design, such as architect Marc Vermeulen, who has previously collaborated with NPSP to create bird and insect inclusive facades (Wiersma, personal communication, 12 June 2026). The design freedom is interesting for this group, but these projects are often relatively small in scale. Large-scale projects typically must meet higher standards and therefore require stronger evidence regarding durability, bioreceptive performance, and fire safety before adoption becomes feasible. In these projects, proven facade systems and performance data are often valued more highly than design freedom alone. A predefined range of validated facade panels may therefore be more attractive than fully customised solutions, as standardisation can simplify implementation, reduce costs, and facilitate certification.

User expectations

The concept should not be marketed as a facade that immediately becomes green, but rather as a facade that gradually develops ecological and aesthetic qualities over time. Biological colonisation may take years and remains dependent on environmental conditions. Clear communication regarding both the expected benefits and limitations of biological growth is important for successful market adoption.

8.5 Final facade concept

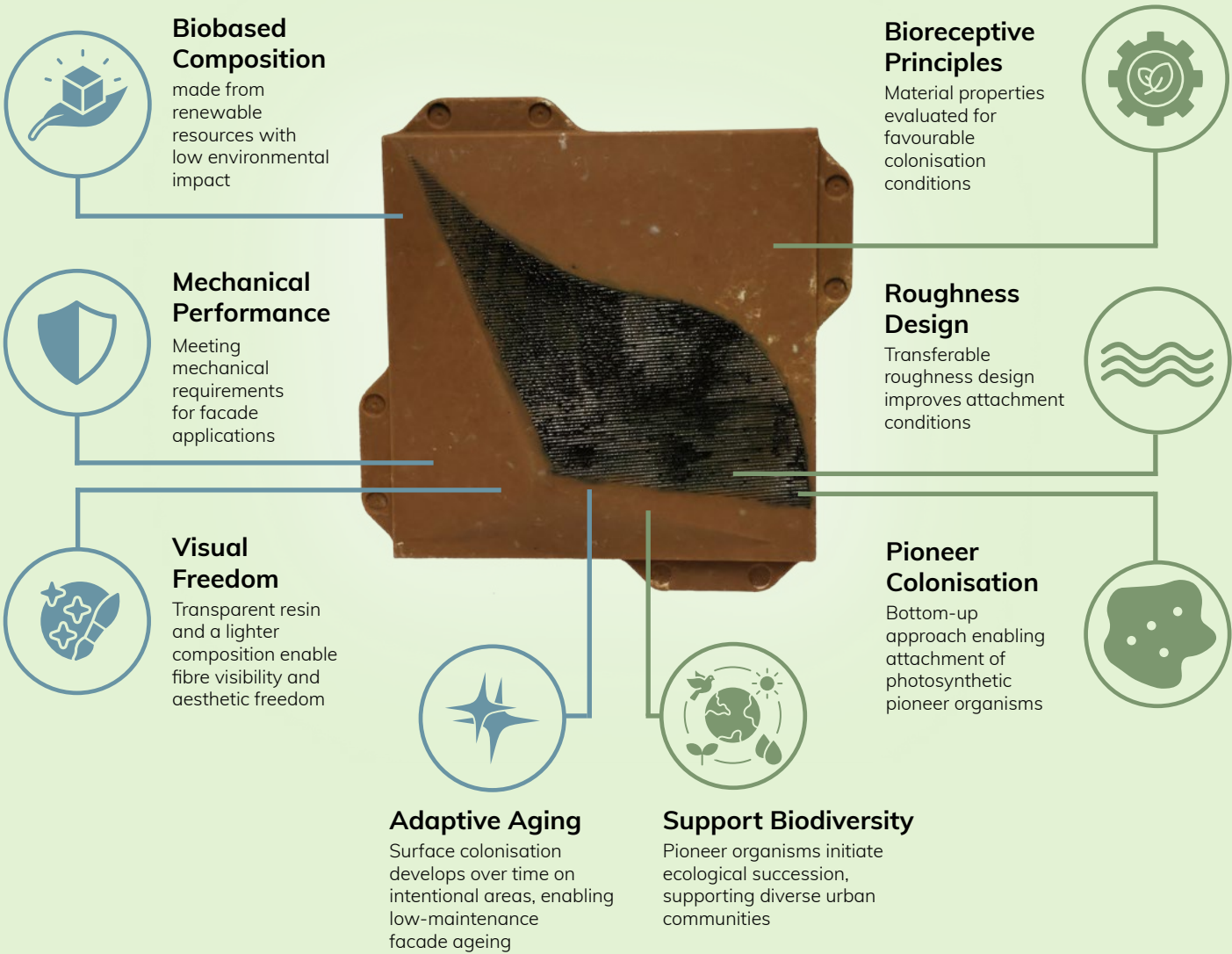
Figure 8.19 Final facade concept



Nabasco Living

A biobased and bioreceptive facade combining lower-impact materials and spontaneous colonisation for urban biodiversity

Facade application



Performance

Flexural strength 45.4 MPa Suitable for facade application	Charpy impact 11.59 kJ/m ² High impact resistance	Flexural modulus 2.13 GPa Strong yet less stiff	Density 1290 kg/m ³ Lightweight building element	Ignitability indication No high flame Potential for fire classification D, C, B	Weathering < 43 % strength Decrease but comparable to existing composites
Water retention > 5.3x initially & 31x after 43 min Higher water retention and slower drying behaviour	Particle retention > Particle retention behaviour under shear stress	Water absorption 4.3 %, 48 h Positive for growth, negative for mechanical performance	pH pH = 4 Supports colonisation, but may favour acid-tolerant species	Colour Lighter & warmer Favourable for photosynthetic growth	

9 Discussions, Recommendations & Conclusion

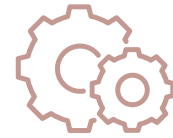


9.1 Overall assessment

While Chapter 8 translated the research findings into a potential facade application and implementation strategy, this chapter critically evaluates the concept from the perspectives of feasibility, desirability, viability, and regenerative potential.

Feasibility

The concept demonstrates promising technical feasibility. The developed Oribond composite showed encouraging performance for facade applications, while the roughness concept can potentially be integrated into existing NPSP production workflows through mould-level implementation. However, further validation is required regarding long-term durability and biological colonisation under outdoor conditions.



Desirability

The concept aligns with growing interest in nature-inclusive, biobased, and regenerative solutions and builds upon NPSP's existing ambition of developing biodiversity-supporting applications through biobased materials, integrated greenery, and products such as insect hotels. By enhancing conditions for spontaneous biological colonisation, the concept has the potential to support the mitigation of environmental pressures associated with urbanisation. Its ability to support ecological value while requiring limited maintenance makes it attractive for stakeholders seeking nature-inclusive solutions within the built environment. However, stakeholder acceptance will depend on perceptions of biological growth and aesthetic ageing.



Viability

Initial viability appears promising because the concept builds upon existing NPSP facade systems and production methods. The roughness structures can potentially be integrated directly into mould designs, limiting additional manufacturing costs and reducing implementation barriers. However, the production process of the material composite still requires further optimisation to demonstrate consistent and scalable manufacturing. In addition, the higher material costs of the Oribond resin and the need for further validation regarding durability, fire performance, certification, and biological effectiveness currently limit market implementation.



Regenerative design assessment

To assess the regenerative potential of the proposed facade concept, the five pillars proposed by Karana et al. (2023) were applied. These pillars support designers in critically evaluating how living artefacts may contribute to regenerative ecologies. The following assessment reflects on the extent to which the proposed facade concept addresses each of these pillars.



1. Cyclical material and energy systems

The concept aligns with the principle of cyclical material systems through its use of biobased and waste-derived resources. The developed composite incorporates waste-based fillers, including olive stone. In addition, the intended biological colonisation has the potential to contribute to natural ecological cycles through carbon uptake, nitrogen fixation, water retention, and the absorption of pollutants.

At the same time, the concept only partially fulfils this pillar. The resin system is not derived from waste streams, as linseed oil is also used as a feedstock for food production. In addition, the end-of-life potential and recyclability of the composite have not yet been fully assessed, and the use of a silicone-based release agent may limit compatibility with natural material cycles.

Overall, the concept demonstrates a clear move towards cyclical material systems, although material circularity across the full product life cycle remains to be established.

2. Biodiversity

The concept aligns with the biodiversity pillar by creating conditions for the spontaneous colonisation of pioneer organisms. Rather than introducing predefined species, the roughness modifications invite locally available organisms to establish themselves over time and evolve into an ecosystem. As biological growth becomes part of the material's ageing process, the facade evolves together with its surrounding ecosystem. In this way, the facade supports cohabitation between the built environment and living species while requiring minimal human intervention.

In addition, the long-term interaction between biological growth and facade performance remains largely unknown. While biological colonisation may provide ecological value, biomass accumulation, retained moisture, and ecological succession may also alter facade properties over time.

3. More-than-human sensibilities

The concept partially aligns with this pillar by making the presence, development, and temporalities of pioneer organisms visible within the built environment. By allowing biological growth to gradually influence the appearance of the facade, the project encourages users to perceive these organisms as active participants in the built environment rather than as signs of deterioration.

However, as the facade does not require direct interaction or care practices, its ability to foster long-term reciprocal relationships between humans and non-human species remains limited.

4. Ecological literacy

The concept aligns with the ecological literacy pillar by making ecological processes visible within the built environment. As the facade evolves over time through biological colonisation, users can observe natural processes such as growth, succession, and material ageing. By introducing living systems into an urban context, the concept may help strengthen the connection between people and nature and increase awareness of ecological processes.

The facade therefore has the potential to function not only as a building element, but also as a medium for learning about the natural world. However, ecological processes may not always be recognized or understood by users, and additional communication or educational interventions may further enhance ecological literacy.

5. Culture change and holistic worldviews

The concept aligns with this pillar by integrating ecological processes into the urban environment and encouraging a closer relationship between people and nature. Rather than perceiving nature as separate from the built environment, the facade invites users to experience natural processes and ecological change as part of everyday urban life.

In addition, the concept challenges conventional perceptions of biological growth on buildings. Whereas biological colonisation is often associated with deterioration or neglect, the facade reframes it as a natural process that can contribute to ecological value, aesthetic ageing, and ecosystem support. It also challenges conventional expectations of permanence and control in architecture by embracing change and ecological development over time. In doing so, the concept encourages a broader understanding of buildings as active participants within ecological systems rather than isolated human-made objects.

9.2 Limitations & recommendations

This section discusses the main limitations encountered during the project and identifies opportunities for further development.

Composite development

The production process of the Oribond composite revealed challenges related to homogeneous mixing, suitable mixing equipment, material flow, and temperature-dependent processing requirements, which affected manufacturing consistency and scalability. In particular, resin adhesion to metal mixing tools prevented the use of standard mixing equipment and required alternative mixing methods. Another limitation is the limited processing window, as the resin already cures at room temperature, restricting the storage time of the mixed material and potentially complicating the batch-based production methods currently used by NPSP. In addition, the relatively high resin content and current processing requirements affect the economic competitiveness of the material. While the material demonstrated encouraging fire behaviour in the initial ignitability assessment, its fire performance has not yet been validated through formal certification procedures.

Opportunities include optimising mixing procedures and batch-based production methods, as well as reducing resin consumption and determining the minimum required pressing time without compromising material performance. According to Orineo, the resin exhibits lower adhesion to plastic surfaces than to metal surfaces, making plastic-based mixing systems a promising route for process optimisation. Fire performance could potentially be improved through the addition of fire retardants, such as ammonium polyphosphate (APP), although such additives may reduce the fully biobased character of the composite. Ongoing developments of the Orineo resin system may further improve processing behaviour and material properties in future iterations.

Beyond facade applications, the material may also offer potential in domains that could benefit from its relatively high impact resistance or utilise the visual possibilities provided by the transparent biobased binder.

Surface roughness design

The project demonstrated that surface roughness can improve conditions associated with the spontaneous colonisation of pioneer organisms. However, the investigated roughness concepts do not represent the full range of possible roughness configurations. Only a limited number of geometries, scales, and configurations could be investigated within the project timeframe.

Future research should further refine the roughness geometry, including groove angle, spacing, scale, and orientation. Alternative surface structures, such as curved patterns, hierarchical roughness, or combinations of multiple roughness scales, may further improve performance. In addition, the results suggest that combining laser-induced structures with blasting may provide additional benefits. For example, the laser dot pattern showed improved performance when combined with blasting compared to the non-blasted variant. However, the potential performance benefits should be evaluated against the additional production step required. Furthermore, the integration of roughness within mould designs should be investigated in greater detail, including demoulding requirements and the

interaction between roughness orientation and complex facade geometries.

Biological colonisation

A major limitation of the project is that biological growth was not directly validated. Due to the limited project duration, the developed roughness concepts were evaluated using condition-based indicators, namely water retention and protection against shear forces during early-stage attachment. Although these indicators are supported by literature as important factors in colonisation, their relationship with actual biological establishment remains uncertain. Furthermore, bioreceptivity is a multifactorial phenomenon in which material properties, environmental conditions, and facade design interact. As biological establishment may take months or even years under natural conditions, it remains unclear whether the observed improvements in attachment conditions are sufficient to significantly accelerate colonisation.

In addition, the long-term interaction between biological growth and facade performance remains largely unknown. While biological colonisation provides biomass accumulation, retained moisture, and ecological succession may alter facade properties.

Future research should therefore focus on long-term field validation under real outdoor conditions. Such studies should investigate not only whether growth occurs, but also the rate of colonisation, the extent to which growth patterns can be influenced through design, and how biological development affects facade performance over time. Further opportunities may lie in combining roughness with other bioreceptive design strategies, such as localised porous zones, rainwater management, or bioboosters that accelerate early-stage establishment. Future monitoring of facade performance should also assess weathering behaviour, freeze-thaw resistance, fire safety, and the interaction between biological communities and material degradation.

User perception and acceptance

Unlike conventional facade systems, bioreceptive facades interact with living organisms, making the outcome inherently dynamic and only partially controllable. While facade design can influence where favourable conditions for growth emerge, the exact location, extent, and composition of biological growth remain dependent on environmental conditions and ecological processes. Consequently, successful implementation depends not only on technical

performance but also on stakeholder acceptance. Perceptions of biological growth vary considerably. While some stakeholders may value ecological development and aesthetic ageing, others may associate biological growth with deterioration, poor maintenance, or safety concerns. Furthermore, little is currently known about how different growth patterns are perceived by users or to what extent biological growth can be guided through design in ways that are both ecologically beneficial and aesthetically desirable.

Future research should investigate user perception, aesthetic preferences, and stakeholder acceptance, particularly the relationship between facade design, biological growth patterns, and public acceptance. In addition, communication strategies should be developed to manage expectations regarding the gradual and partly unpredictable nature of biological colonisation. Supporting interventions, such as information panels explaining the organisms present and the ecological processes taking place, may increase public understanding and acceptance of bioreceptive facades while also fostering awareness of the natural world.

Knowledge gap

Another limitation encountered during the project was the gap between ecological knowledge and design practice. Translating ecological knowledge into actionable design requirements proved challenging due to the complex interactions between species, materials, and environmental conditions.

While this project contributed to bridging this gap by translating ecological insights into design interventions and validation methods, further research could help establish more comprehensive design guidelines and assessment frameworks for bioreceptive design. Such efforts could benefit from closer collaboration between ecologists, architects, material scientists, and designers.

9.3 Conclusion

This section reflects on the main findings of the research and answers the research questions introduced in Chapter 1.

In the introduction, the following design assignment was defined: *“How can an Oribond-based composite be applied in the development of a biobased and bioreceptive facade panel for NPSP facade applications?”*

This project demonstrates that an Oribond-based composite has the potential to be developed into a biobased and bioreceptive facade material for NPSP applications through the combination of suitable material performance and surface roughness modifications that enhance conditions for spontaneous colonisation by pioneer organisms. While further validation of long-term material performance and biological colonisation remains necessary, the results demonstrate a promising direction for future development.

Answers to sub-questions

A. Material development and facade applicability

A1. How can a composite with the Oribond resin be developed within existing NPSP production workflows?

Oribond composites can be produced using NPSP’s existing compression moulding workflow with limited process adaptations. Material mixing equipment, heating of the resin components, and optimisation of processing parameters were found to be important for achieving consistent results.

A2. To what extent does the Oribond composite meet the technical and mechanical requirements for facade applications?

The selected formulation demonstrated sufficient flexural strength, high impact resistance, relatively low density, and encouraging fire behaviour in the initial ignitability indication test. In addition, preliminary weathering assessments showed performance comparable to existing Nabasco materials. However, the flexural modulus remained lower than that of the reference materials, and long-term durability under outdoor facade conditions still requires further validation. Overall, the results indicate sufficient potential for facade applications, although further optimisation and validation are required.

A3. What material characteristics of the developed Oribond composite contribute to its potential for bioreceptive applications?

The Oribond composite contributes to bioreceptive potential through several material characteristics. Its lighter colour compared to the black furan composite may be more suitable for photosynthetic organisms, while weathering-induced surface changes and moisture-related behaviour may support attachment and water availability. The pH was found to be moderately acidic rather than neutral, which is not expected to prevent colonisation but may influence the species composition. Overall, the material provides a promising starting point, although the underlying composite alone is not sufficient to guarantee biological growth.

B. Designing for bioreceptivity

B1. Which factors influence spontaneous attachment and growth of pioneer organisms on vertical surfaces?

Spontaneous attachment and growth of pioneer organisms on vertical surfaces are influenced by environmental, material, and surface design factors, including porosity, morphology, roughness, air-humidity, shading, temperature, colour, nutrient availability, pH, and salinity. Water availability was identified as the main constraint for photosynthetic pioneer organisms on vertical structures. Surface roughness was selected as the primary design parameter due to its influence on both water retention and initial cell attachment.

B2. How can surface roughness be designed to enhance conditions for pioneer organism attachment? Surface roughness can be designed to enhance attachment conditions by creating micro-scale structures

that retain water and provide shelter from shear forces. Roughness parameters influencing water retention, including scale, angle, and configuration, were investigated. Multiple roughness modifications were developed and validated, of which the directional groove structure showed the most promising performance in terms of bioreceptive conditions. While surface roughness does not directly induce biological growth, it can create more favourable local conditions that support initial attachment.

B3. How can the influence of surface roughness on early-stage attachment conditions be validated?

The influence of surface roughness on early-stage attachment conditions was validated through condition-based tests rather than long-term biological growth experiments. Water retention behaviour and particle retention were used as indicators of moisture availability and protection against shear forces during early-stage

attachment. These methods provided a practical means of comparing surface concepts within the project timeframe. However, long-term in situ biological validation remains necessary to confirm their relationship with actual colonisation behaviour.

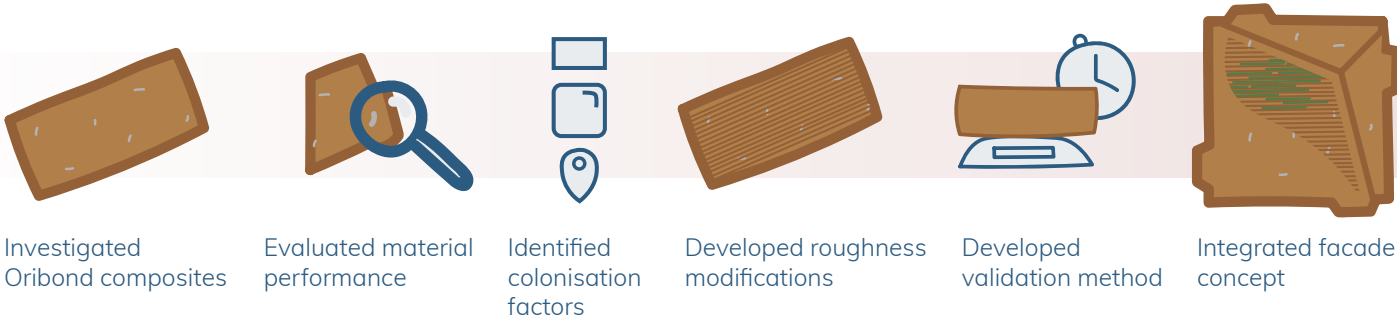
B4. How can the developed roughness concept be integrated into a facade application?

The developed roughness concept can be integrated into a facade application by combining micro-scale roughness with macro-scale facade morphology. Water path analysis can identify where water naturally flows and accumulates, after which roughness can be applied in these areas to enhance local bioreceptive conditions. Because roughness is a surface geometry intervention, the concept can be incorporated into existing NPSP facade geometries without fundamentally altering the panel composition or production process. While environmental conditions influence colonisation outcomes, the strategic placement of roughness structures can help guide biological growth patterns and support a more intentional form of ecological and aesthetic ageing.

Contribution of the research

This research contributes a fully biobased composite material and an evaluation of its material performance for facade applications and bioreceptive potential. In addition, it provides an overview of the factors influencing biological colonisation and their relation to material, surface, and environmental conditions, develops roughness modifications to improve bioreceptive conditions, proposes a practical validation approach for assessing bioreceptive surface conditions within product development timeframes, and demonstrates the integration of bioreceptive design within a facade concept. Figure 9.1 provides an overview of these contributions.

Figure 9.1. Overview of research contributions



10 References

10

AI disclosure

AI is consulted reflectively, using the large language models NotebookLM and Chatgpt. NotebookLM is employed to locate and analyse specific information within selected sources. It only draws from the sources that are explicitly provided and does not introduce additional information retrieved from the internet. The extracted information is not copied blindly, but is analysed and verified by checking its location and context within the original source. For refining academic writing style and minimising spelling and grammatical errors, Chatgpt is used. The text was initially written in English by the author and subsequently reviewed using AI. This resulted in AI preserving the original writing style, while correcting some repeated words and errors. Again, sentences are not blindly copied, but critically analysed to determine whether the suggested changes are logical and to learn from the feedback. Lastly, AI was used as a sparring partner for exploration and to overcome writer's block. However, this was purely inspirational and, again, not something that was blindly copied.

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11 appendices



Appendix A.

Examples of notes from the material diary

DATE:11 february 2026

VERSION:1(A,B,C,D,E)

PURPOSE:Production test plates for testing material characterisation

RECEPT:Binder: Oribond30%240g
Filler: Course egg shell50%400g
Fiber: Flax long20%160g+
5 samples of 150 g800g

PROCESS STEPS:

Mixing

- 1) Mixed dry ingredients with kitchen-aid
- 2) Slowly poored resin into mixture
- 3) Broke up remaining clumps by hand

Press

- 1) Mould and press are preheated to 140°C
- 2) Only for sample C,D,E, the mixture is preheated at around 105°C for 5-7 min
- 3) Silicon spray applied in mould
- 4) Into press at 200kN (80 bars) for 10 min

Demould

- 1) Demolded using a suction cup
- 2) Sample is directly cooled between cold metal

PROCESS TAKEAWAYS:

- Note: The mixer struggles due to the mixture's stiffness
- Note: not very homogene mixed
- Oribond leaks out of the mould. Mixtures of sample C-E are therefore preheated to start hardening component B of the resin already a bit. This works to prevent leakage!



TAKEAWAYS:

Overall: well-bonded composite

- Smooth texture
- Uniform thickness
- Feels stiff (high tone) and strong
- Hardly shrinks due low amount of moist
- Brownish colour & natural look due shells
- Has a slight smell when smelled closely

1A, B: Mix not preheated, had leakage of resin

1C: A corner without resin, indicating not well mixed

1D:

1E:

mix A not preheated

mix B not preheated

1A: m= 127g d= 4,4mm

1B: m= 127g d= 4,1mm

1C: m= 145g ad= 4,8mm

1D: m= 136g d= 4,4mm

1E: m= 135g d= 4,4mm

NEXT STEPS:

- Less fibers
- Finer shell particles
- Preheat mixture first to not let it leak out of the press
-
-

DATE:24 february 2026

VERSION:12(A, B, C)

PURPOSE:production test plates for testing material characterization

RECEPT:Binder: ETFKW86A Oribond40%193g
Filler: Olive stone pulverised55%250g
Fiber: Viscose5%25g
3 samples of 150 g+ 468,8g

CHANGES:

Divided on grams

Viscose Cordenka as fiber



TAKEAWAYS:

12. Smooth, brownish caramel colour with white spots (cordenka tufts)

A)

- Not preheated and had a lot of leakage
- repressing a lot
- Light big stain on top edge
- Was already loose in the mould, had shrunk.

C, D)

- Still shrunk a bit, so came out of mould easily.
- Still some repressing
- No hard chunks after preheating

A is not preheated

12A: m= ~120 g d= 4,7mm

12B: m= ~135g d= 5,3mm

12C: m= ~140g d= 5,4mm

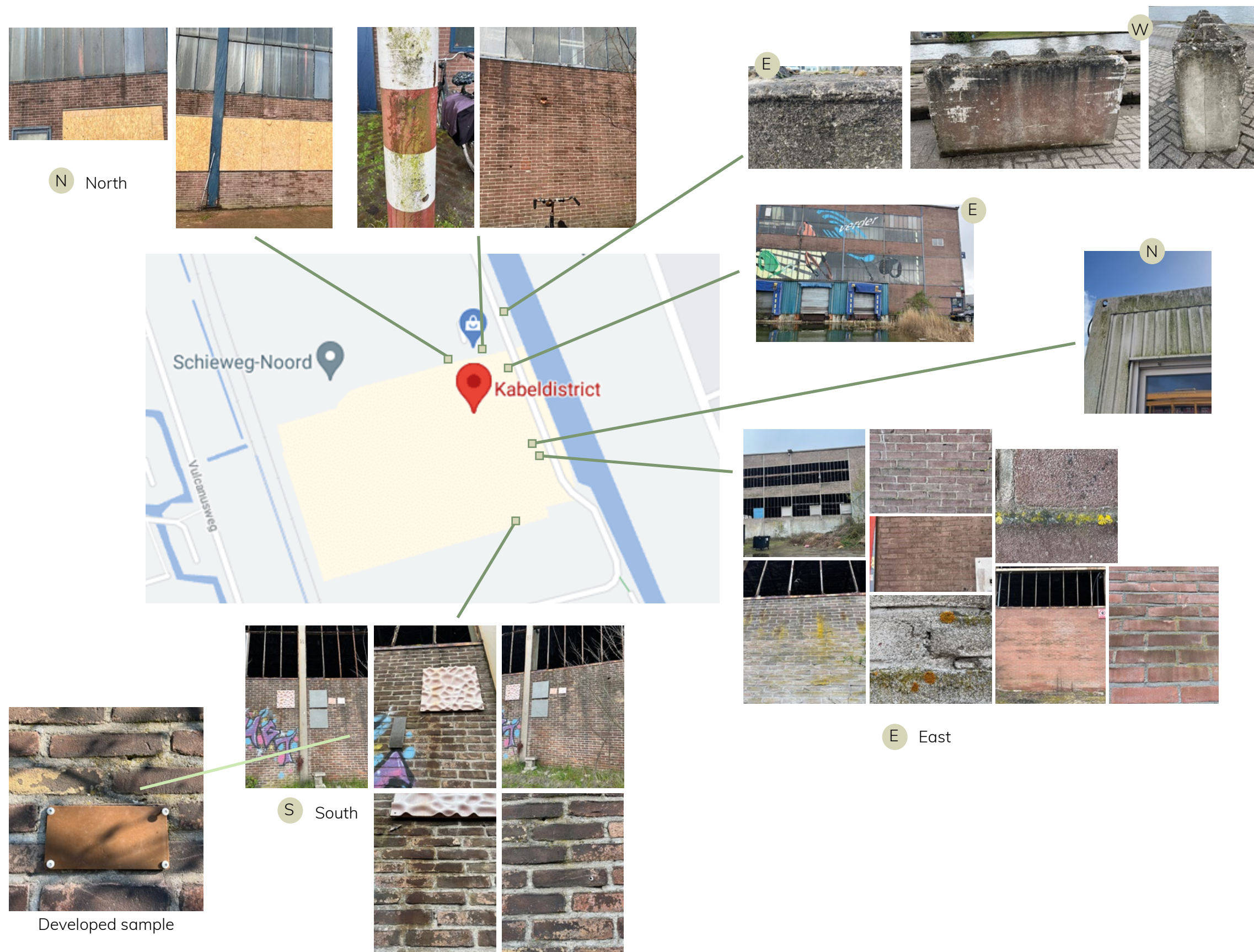
NEXT STEPS:

-
-
-
-



Appendix B.

Investigation location for in situ experiment



Here an overview of the biological growth around the Kabeldistrict building, where NPSP is located. The lines indicate the locations where the pictures were taken, and the annotations N (north), E (east), S (south), and W (west) represent the orientation to the sun.

It was expected that there would be more growth on the north orientation than on the south orientation, because the conditions are more moist there due more shadowed areas. However, all locations show some degree of biological growth on the facades, with the north side showing significantly less.

A possible explanation for this outcome is that the north side appears to have been renovated, and therefore the walls may have been maintained. Additionally, because the building is relatively old, approximately 70 years, this may contribute to the presence of biological growth on all sides.

On the south side of the building, there is already a structure for panels to be hung, and because this side shows significant growth, it is considered a suitable location to install the samples. to be hanged, and because here it shows significant growth, it is chosen as a valide place to hang the samples.

Appendix C.

Sketches of ideation on processing techniques

MILLING CNC

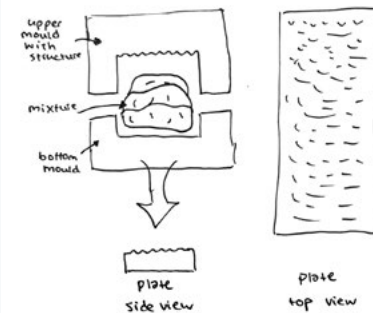


order of magnitude
300 to 5000 μm

► A computer-controlled cutting tool that subtracts material from the surface

- + controlled pattern is possible
- order of magnitude is a bit bigger ranging between 300 to 5000 μm → better for raindrops (current drill is 3000 μm) than water dew.
- upper fillers/fibers are exposed and not protected by resin anymore which could accelerate deterioration
- computer model is needed, not 'quick and dirty'
- extra step in process

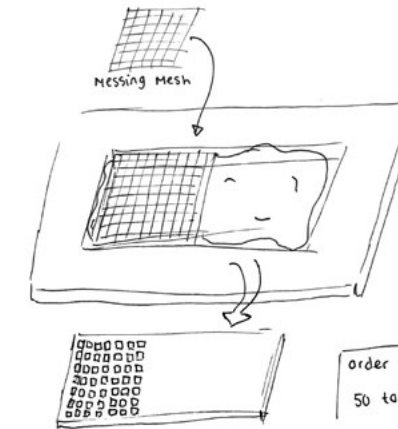
TEXTURE IN MOULD DESIGN



► applying a texture directly in the design of the mould.

- + no extra steps in process
- high-fi and costly, computer model is needed, & production mould.
- + texture in current mould is already duplicated on the plates, this texture is smaller than $\pm \text{mm}$.
- + controlled pattern is possible

MESH IN MOULD

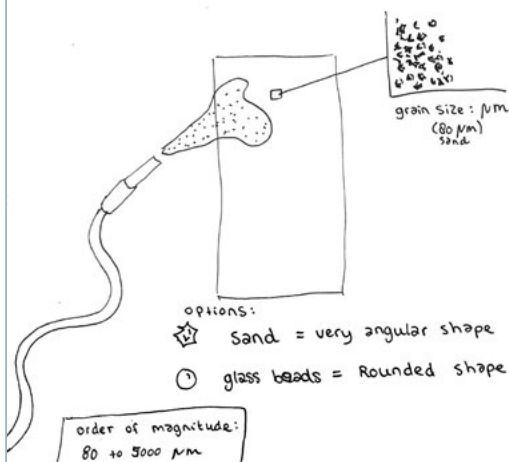


► a meshing mesh is added as a layer in the compressing mould

- + low-fi and quick implementation
- extra step to add it in
- might be hard to remove
- + cheap, low cost
- + small micro scale is possible
- + controlled texture
- could be inspiration for mould design.
- + not subtracting material, keeping composite properties intact.

order of magnitude
50 to 200 μm

ABRASIVE BLASTING



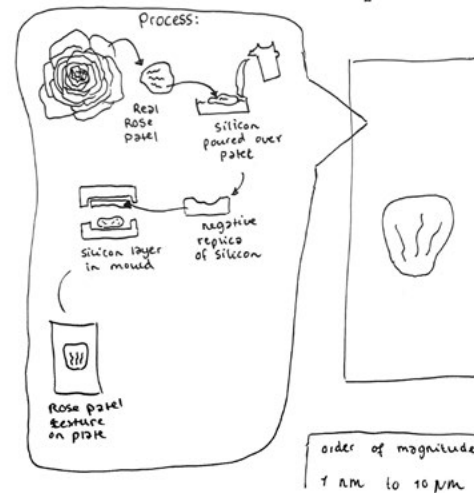
order of magnitude:
80 to 3000 μm

► upper layer is removed by pressuring abrasive media (i.e. sand) against the surface

- upper fillers/fibers are exposed and not protected by resin anymore which could accelerate deterioration
- + small micro texture is easily and quickly applicable on material
- extra step in process

options:
☆ sand = very angular shape
○ glass beads = rounded shape

ROSE PATEL REPLICATION

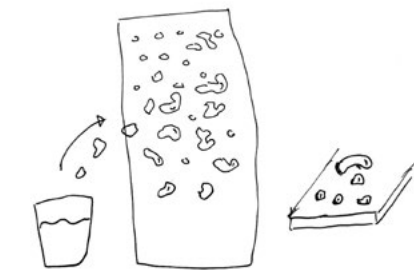


► Replicate the texture of a rose petel on a silicon layer which is implemented in the mould.

- complex
- limited by ~~max~~ size of petel, not whole plate is covered
- + copy of texture created by nature and proven to ~~work~~ retain water on a hydrophobic surface.
- creating a rose petel texture ~~identical~~ on nano-level is a whole study on itself.
- + not subtracting material, keeping composite properties intact.

order of magnitude
1 μm to 10 μm

ADDITION OF BINDER CLUMPS



► Adding clumps of resin (combined with fibre/filler) onto the surface

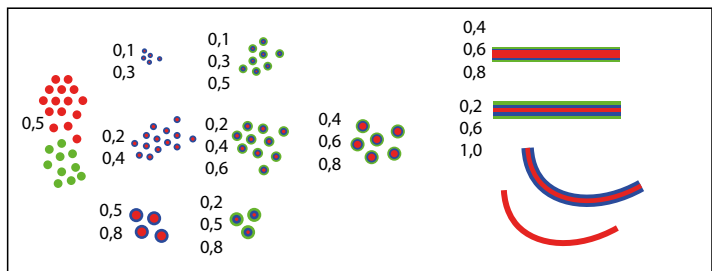
- complex; it will adhere when not cured yet, but then it is still liquid. The material tends to smooth then again or it does not directly adhere
- + Addition instead of subtraction which keeps composite properties intact.
- + low-fi
- time intensive due manual addition
- Extra step in process
- not in really small (μm) scale but on mm to cm level.

order of magnitude
mm to cm

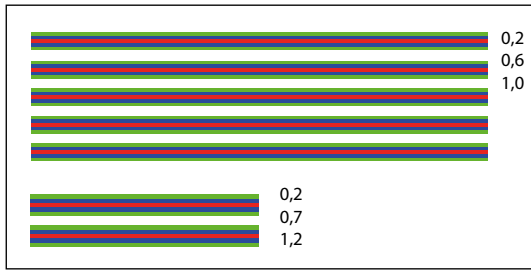
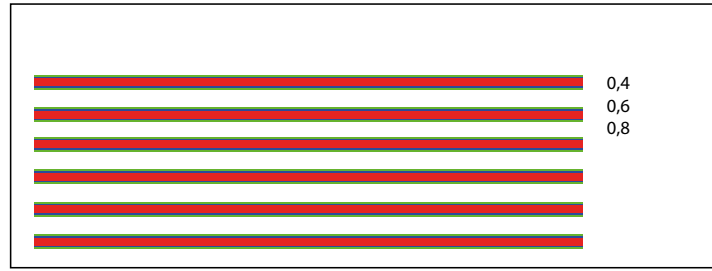
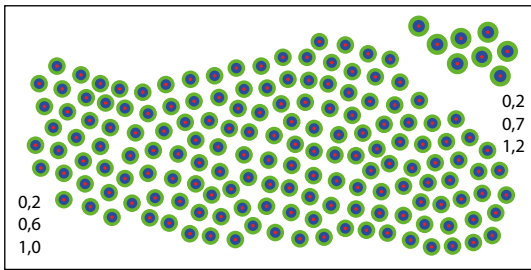
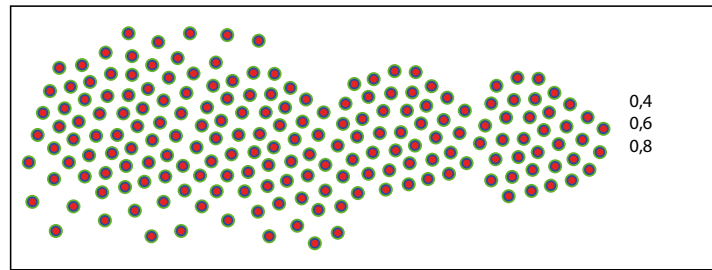
Appendix D.

Illustrator files for the laser printer of the tested and final roughness geometries

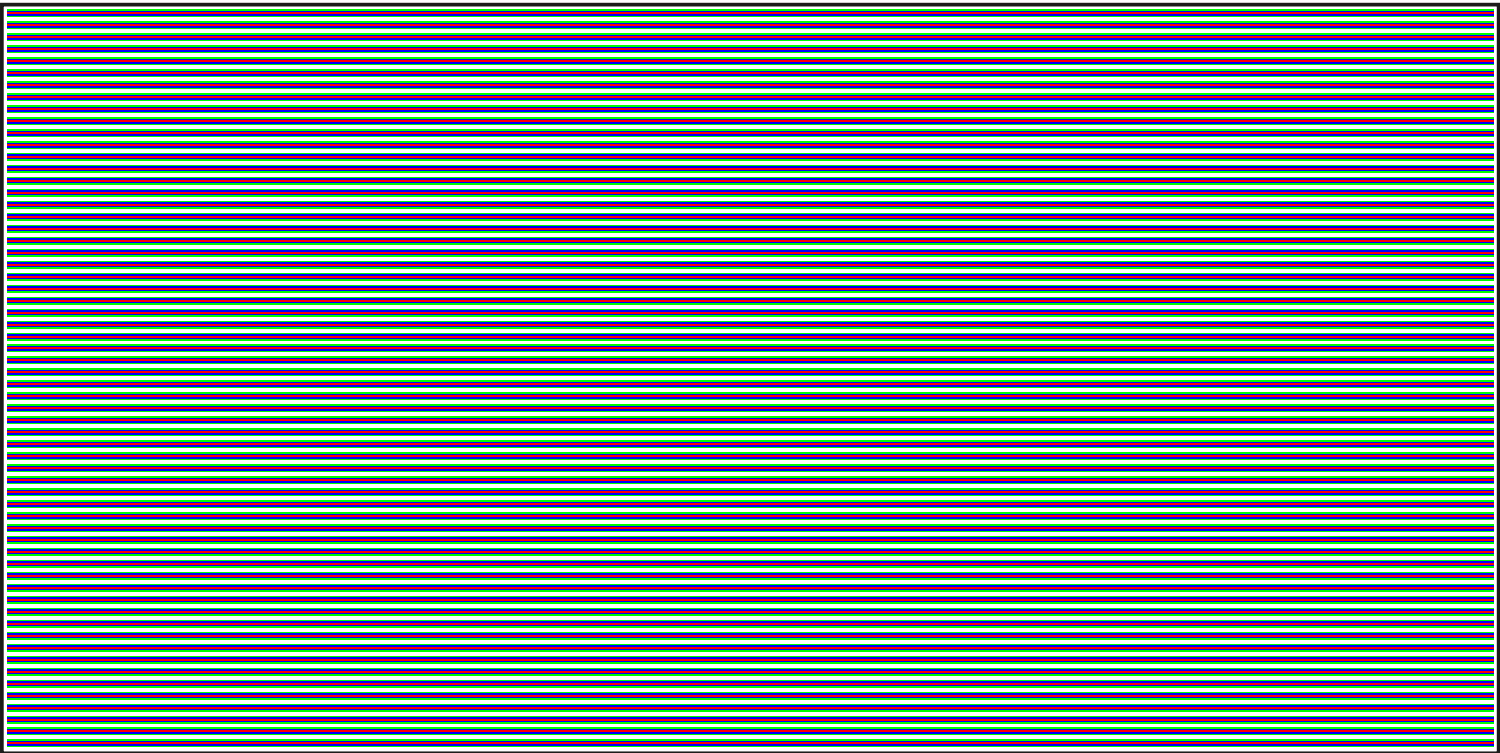
D1 - Overview of iterations of laser engraved geometries



Settings laser engraving
Numbers next to dots are the diameters of the circles from red (smallest) to green (biggest)
Power = 100%
Speed:
Rood = 25% (deepest)
Blauw = 50%
Groen = 75% (shallowest)



D2 - Final laser-lined geometries



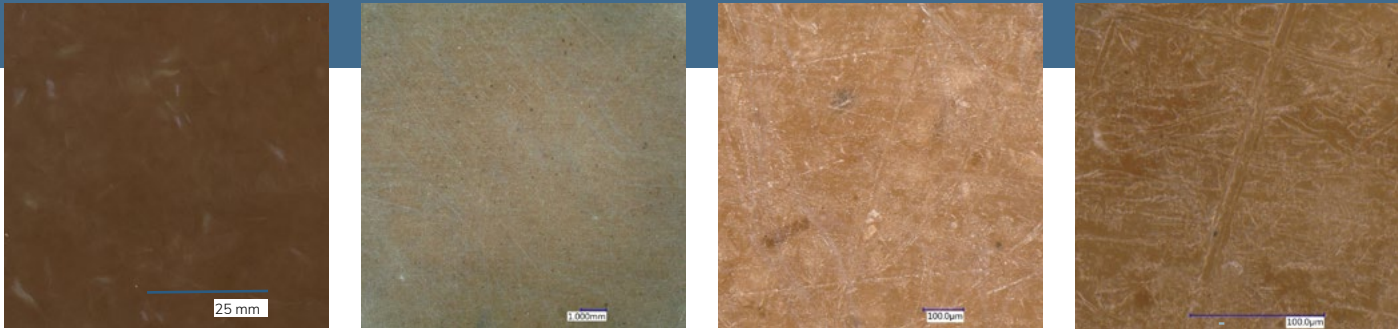
vermogen: 100%
snelheid:
Rood: 25%
Blauw: 50%
Groen: 75%

Diameters:
0,2
0,6
1,0

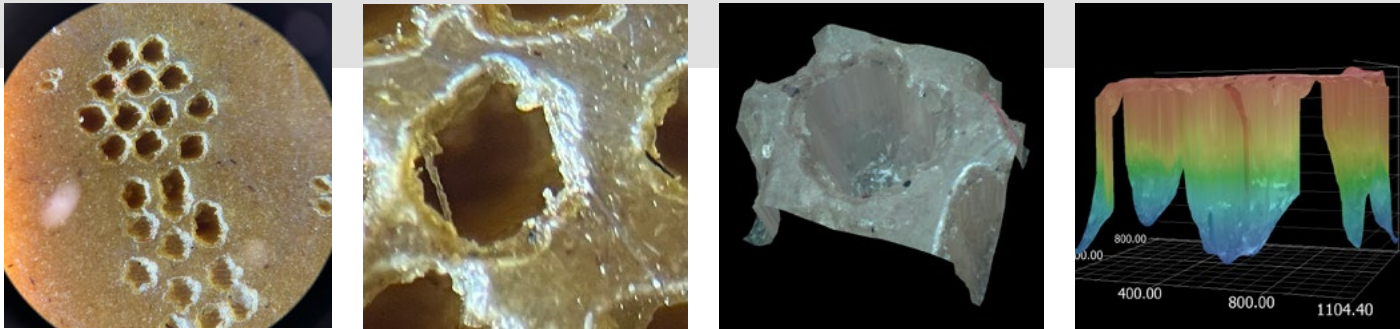
Appendix E.

Images from microscopic observations

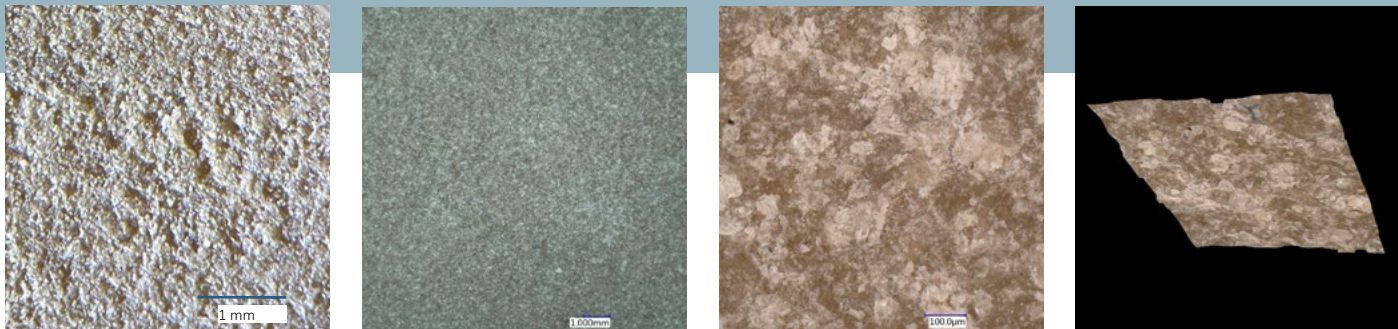
Unprocessed



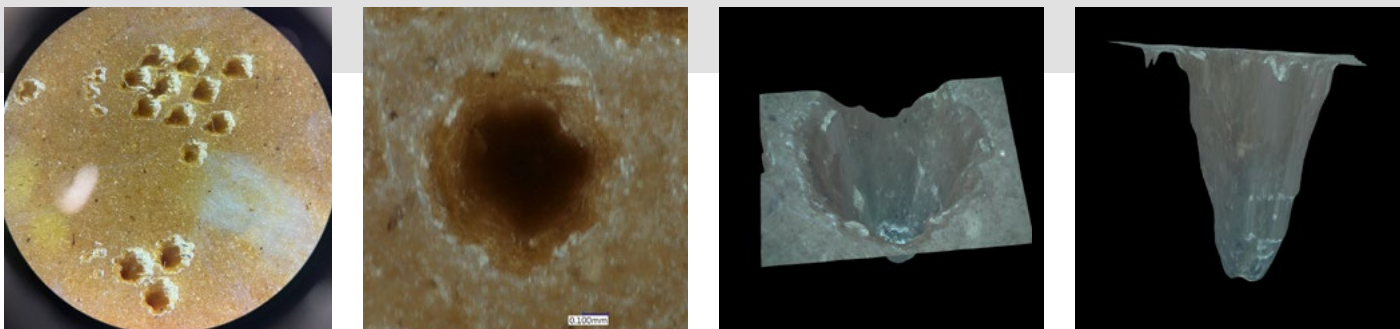
Laser dotted 1 depth



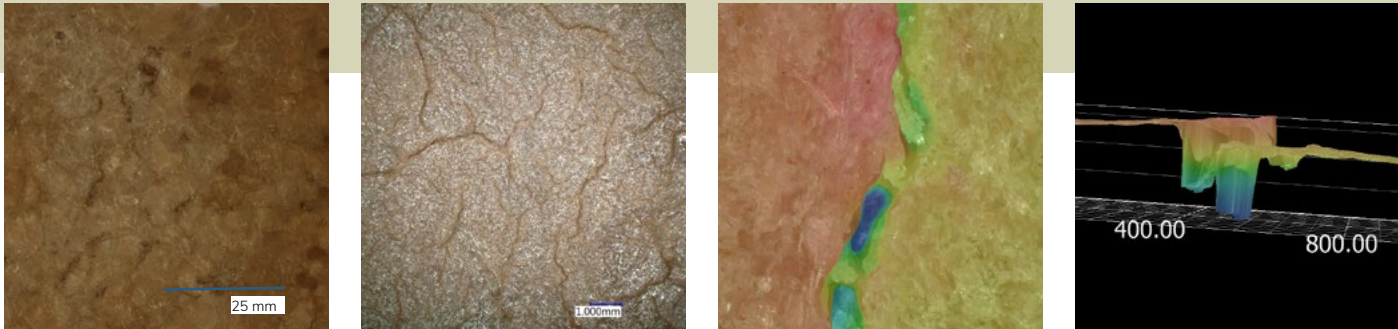
Blasted



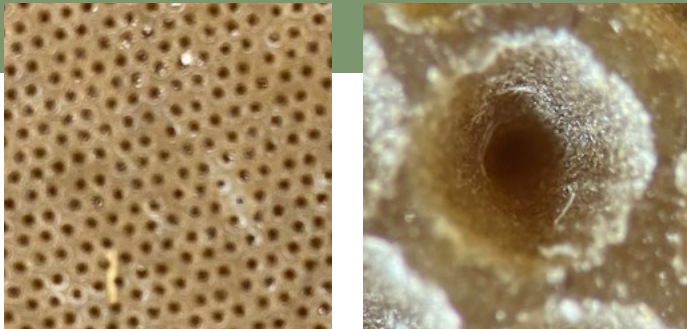
Laser-dotted multiple depths (diameter: 0,4-0,6-0,8 mm)



Weathered



Laser-dotted final (multiple depths & diameter 0,2-0,6-1,0 mm)



Chiseled dotted



Laser-lined (not final) (multiple depths & diameter 0,4-0,6-0,8)



Appendix F

Development of water retention method

F1 - Weighing setup iterations

Weight set up iterations



Scale

- ⊖ sample will not stay vertical (fall over)
- ⊖ water run off will fall on scale and will be included in measurement
- ⊕ is available within specific ~~range~~ (0,001g) precision



Hanging scale

- ⊖ was not available in desired weight ~~range~~ (0,001g) precision



Vertical foam block on scale

- ⊕ sample can be kept vertical in controlled situation
- ⊖ center of gravity was not on scale (fall over)
- ⊕ water could drop off outside the range of the scale



Rope to manipulate center of gravity

- ⊖ not controllable how tight rope was tensioned, making setup unrepeatable



Horizontal foam block

- ⊕ center of gravity is on scale within weight constraints of scale
- ⊕ water runoff will fall outside range of scale plate and will not be included
- ⊕ sample can be kept in vertical position (controllable)

F2 - Wetting condition iterations

Spray bottle

Spray bottle experiments were initially explored to simulate rainfall conditions. However, the amount of applied water varied between measurements due to inconsistencies in droplet size and spraying distance. The table below shows the variation in spray mass, which already differed by several tenths of a gram. This significantly affected the measured retained water mass and reduced the repeatability between tests.

	Weight (g) of 1 spray of mist spray	Weight (g) of 1 spray of plant spray
	0,31	0,648
	0,289	0,694
	0,102	0,486
	0,107	0,5
	0,089	0,669
		0,736
		0,79
		0,8
Range	0,221	0,314



Mist spray



Plant spray

Condensation chamber

Because retaining dew-like droplets was one of the intended functions of the roughness, additional experiments attempted to recreate condensation conditions. Initial pilots involved cooling the samples in a freezer, after which they were placed inside a climate chamber with high humidity to stimulate condensation formation while measuring the mass in real time.

However, controlling the environmental conditions with sufficient precision proved difficult. The climate chamber regulates humidity and temperature through airflow, which already introduced fluctuations of approximately 1 g on the scale, exceeding the required measurement precision. An additional iteration attempted to stabilise the chamber at 25 °C and 100% humidity before placing the sample inside and switching the chamber off. However, opening the chamber caused rapid drops in humidity, resulting in significant variations between attempts within only a few seconds. Humidity levels could decrease from 100% to between 60% and 80%, strongly influencing both the amount of condensation forming on the surface and the duration for which it remained present.

Another influencing factor was variation in sample thickness. Small differences of approximately 1 mm affected the heat transfer behaviour of the samples, influencing the amount of condensation formed on the surface.

Due to the large number of interacting variables and the limited environmental control, the setup proved too complex and insufficiently repeatable for reliable comparison between concepts. For this reason, a setup outside the climate chamber was selected, as the environmental conditions remained more stable and controllable.

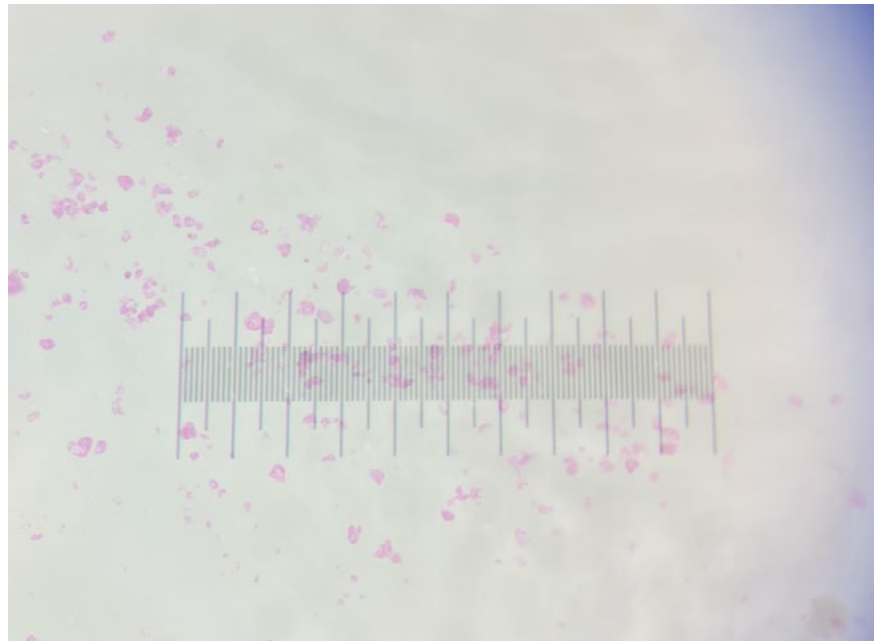


Climate chamber

Appendix G.

Defining size of particles under the microscope

The particle size was approximated through microscopic observation using a reference microscope slide ranging from 0.01 to 1 mm. The figure below shows the particles under the microscope together with the overlaid reference slide used for estimation. Based on these observations, the particles were estimated to range between approximately 5 and 30 μm .



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Facade Supporting Pioneer Organisms

Milou Eijsbroek

Msc Integrated Product Design
TU Delft · 2026

