Exploring the Possibility of Using Bioreceptive Concrete in Building Façades

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Abstract

A bioreceptive material allows for biological content (biofilms) to grow on it, without necessarily affecting the material itself. If a bioreceptive concrete could therefore be integrated into a building façade, it could lead to green façades that do not need additional technical systems. As part of previous research by the authors, a promising bioreceptive concrete mixture was formulated. The aim of this research is to develop this concept by using the previously developed mixture to create a bioreceptive concrete façade panel prototype, made using commonly available materials, that can direct where the biological growth takes place. The latter is done by combining the bioreceptive concrete with a non-bioreceptive (UHPC-based) concrete in the same panel, through a two-stage pouring process. A biofilm was developed on this prototype panel and results show that full coverage of the bioreceptive parts of the panel can be achieved within two weeks under optimal growing conditions and biological growth can be directed. However, exterior survivability is an issue for now. The concept of bioreceptive façades therefore shows promise, yet further investigation into improving exterior survivability is necessary, while further research into the underlying ecology, material, economics, and climate effects is also necessary.

Keywords

Bioreceptivity, biofilm, concrete façade panel

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1 INTRODUCTION

Increased urbanisation and the associated loss of green spaces, in combination with climate change, are leading to a range of problems in our cities, including but not limited to a loss in biodiversity, heat stress, increased air pollution, and more, bringing with them concerns for ecological and public physical and mental health (Beatley & Newman, 2013; Kleerekoper, van Esch, & Salcedo, 2012; Lai & Cheng, 2010; McKinney, 2008). In a bid to increase the amount of green in our cities, the use of green roofs and façades has become more common. These have been found to play a positive role in reducing building surface temperatures, capturing airborne pollutants, increasing biodiversity, and sequestering carbon (Charoenkit & Yiemwattana, 2017; Kleerekoper et al., 2012; Perini & Rosasco, 2013). However, at the same time, green roofs and façades incur additional costs both in construction and maintenance, while they also put higher structural demands on the buildings they are attached to (Li & Yeung, 2014; Perini & Rosasco, 2013).

Recently, a new typology of green building envelope has been proposed, based on the principle of bioreceptivity. Bioreceptivity is a term originally coined by Guillitte (1995), which he defined as: "the aptitude of a material to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration" (p.216). If a material with a high bioreceptivity were applied on a building surface, a green surface could therefore be achieved. The biological growths that develop on these surfaces are called biofilms and consist of bacteria, algae, fungi, lichen, and mosses. These biofilms can survive under virtually all natural environmental conditions, provided the substrate they grow on is suitable (Gorbushina, 2007; Pentecost & Whitton, 2012). Therefore, they can theoretically be placed anywhere on a building envelope. At the same time, similar to regular green façades, they can affect the building surface temperature, digest some airborne pollutants, and sequester carbon through calcite precipitation (Freystein, Salisch, & Reisser, 2008; Mayaud, Viles, & Coombes, 2014; Zhang & Klapper, 2010). They do all this while not requiring additional technical systems or maintenance, thereby opening up the possibility of creating green building envelopes with reduced costs and embedded energy.

The main challenge in the creation of bioreceptive concrete façades lies in the material itself. Based on existing literature, the main requirements for biological growth appear to be a substrate pH below 10, sufficient surface roughness to protect the biofilm from environmental influences, high water absorbing capacity and retention within the substrate, and the presence of nutrients within the substrate, in particular phosphorus (Guillitte & Dreessen, 1995; Jones & Bennett, 2017; Miller et al., 2010; Prieto & Silva, 2005; Tiano, Accolla, & Tomaselli, 1995; Vázquez-Nión, Silva, & Prieto, 2018; Wiktor, De Leo, Guyonnet, Grosseau, & Garcia-Diaz, 2009; Grosseau, Guyonnet, & Garcia-Diaz, 2010). If these requirements can be met using common materials and methods, it could then form the basis for a bioreceptive concrete mixture that can be used on a large scale in building façades.

In previous research conducted by the authors, the underlying ecology of the colonisation of stony substrates by biofilms was used to develop and test several bioreceptive concrete mixtures (Veeger, Prieto & Ottelé, 2021). This resulted in the formulation of a concrete mixture that was found to be highly bioreceptive (see Table 1). The blast furnace slag cement was used to lower the concrete pH (although a pH lower than 10 was not found to be necessary), crushed expanded clay (CEC), and a high water cement factor (wcf) were used in combination with a low overall cement content to improve the porosity and thereby water absorption of the concrete, and bone ash was added to provide the biofilm with phosphorus.

TABLE 1 Bioreceptive concrete mixture as formulated in previous research by the authors (Veeger et al., 2021)

CONSTITUENTS	BIORECEPTIVE CONCRETE
Cement	300kg/m^3 OPC cement (62.5% slag)
Aggregate	578 kg/m^3 Argex AG4/8 (crushed expanded clay) / 762 kg/m^3 sand (0-4mm)
Water	150kg/m^3 (wcf 0.50)
Mineral admixture	30kg/m^3 Bone ash
Plasticiser	None

However, whilst this gives us a suitable bioreceptive substrate, it needs further development to be used in a building façade. In its current form, growth is uncontrolled and takes place on the entire surface, which is not always preferable. Also, due to its high porosity, this mixture is expected to have a reduced compressive strength and increased susceptibility to freeze-thaw damage (McCarthy & Dyer, 2019; Paine, 2019). Additionally, its high susceptibility to carbonation, whilst positive for the biological growth, reduces the pH of the concrete, removing the passive protection layer that is usually present around steel rebar, making it susceptible to corrosion (Mindness, 2019). Based on this, the use of the formulated bioreceptive concrete mixture cannot be recommended in structural or otherwise critical applications.

As such, in this research we investigate how bioreceptive concrete can be used to create a bioreceptive façade panel that can control where biological growth takes place. A panel system was chosen as this decouples the exterior part of the façade from the load-bearing structure, eliminating one of the constraints of bioreceptive concrete and allowing for more design flexibility. This research will include the materialisation, design, production, and the testing of the façade panel prototype.

2 METHODOLOGY

This paper starts with the creation of a façade panel design and its production methods. For the façade panel, two criteria were observed. First of all, the façade panel is preferably produced using existing methods and common construction materials. To make the façade panel economically and practically feasible the use of exotic construction methods and materials should be minimised, as these would drive up the cost and complexity of the design significantly. Secondly, the façade panel should be able to direct biological growth. The usability and design flexibility of this panel would be increased if it were possible to direct where biological growth occurs.

Once the design and production methods were finalised, these were used to create two prototype panels, the exact production of which will be discussed later on in this paper. After creation, these panels were tested to ascertain whether they were in fact bioreceptive and able to direct biological growth.

This testing was done by producing two prototypes of these façade applications. These were then inoculated with the same liquid biofilm that was used in our previous research (Veeger et al., 2021). This biofilm was originally sourced from an existing biofilm growing on an exterior concrete structure of the Faculty of Architecture, TU Delft. It was originally kept in a BG-11 liquid growth medium under optimal growing conditions (room temperature, ~90% humidity, 12h day/night cycle with a light intensity of 40 µmol m-2s-1; (see Veeger et al. (2021) for full test set-up).

However, after the initial experiment the BG-11 stock was depleted, therefore a solution of 10mL liquid NPK fertiliser (1:1 water diluted 7-2-7 NPK fertilizer with added trace minerals and humic acid) and 450mL distilled water was used instead. During this period, every three weeks 50mL of the old liquid biofilm was added to a new water and liquid fertiliser solution, to avoid cell senescence. Per prototype, 350mL of this liquid biofilm was added, which is a higher relative amount than used in our previous research and should therefore show faster results.

After inoculation, the prototypes where kept in a distilled water bath, with the water line just below the concrete surface, under the same optimal growing conditions as described above. They were kept there until almost full coverage of the panel surface was achieved, after which they were kept outside for a period of 1 week. As our previous research had already found some type of additional nursery was likely needed once placed outside, the surface of the panels was wetted twice daily during this period to avoid extended desiccation of the biofilm. Growth progression was recorded throughout the experiment.

3 PANEL DESIGN

3.1 DIRECTING BIOLOGICAL GROWTH

The most obvious way to direct biological growth is to make some parts of the façade panel hospitable and other parts of the panel inhospitable to biological growth. In previous research conducted by the authors it was found that the bioreceptive concrete substrate needs a high water-absorbing capacity, and must provide nutrients and shelter the biofilm from environmental stressors in order for it to be bioreceptive (Veeger et al., 2021). In this same research, it was also shown that when these conditions are met, concrete does indeed become bioreceptive, whereas a concrete substrate that does not meet these criteria shows very little to no biological growth. The question therefore becomes how to achieve the optimal conditions for bioreceptivity in some parts of the panel, whilst creating the opposite conditions on other parts of the panel.

One of the most essential inputs for photosynthesis is light. Therefore, changing lighting conditions on the concrete surface might at first glance seem a relatively straightforward way to achieve differing conditions for the micro-organisms, thereby influencing bioreceptivity. In theory, one could, for example, create a bioreceptive part of the panel which is exposed to the sun and shades the non-bioreceptive part of the panel, thereby limiting growth due to a lack of photosynthetically active radiation (PAR; the part of the solar spectrum used for photosynthesis) from the sunlight. However, in practice, light is hardly ever the factor that stops biological growth from occurring. In fact, from field observations it has been found that micro-organisms that occurred in full sunlight in the tropics, under PAR radiation levels of 2,000 μmol $m^{-2}s^{-1}$, were also found in cave thresholds where the PAR levels were as low as 0.4 μmol $m^{-2}s^{-1}$ (Pentecost & Whitton, 2012). As such, it seems unlikely that restricting the access the micro-organisms have to light by shading certain parts of the panel, will have a significant impact on the bioreceptivity of these areas.

Restricting the nutrients in certain parts of the panel is the next possible option. In nature, nitrogen and phosphorus are often limiting factors for biological growth, with the latter being especially limiting in the growth of biofilms on stony materials (Johansson, Johansson, Giesler, & Palmqvist, 2011; Mostert & Grobbelaar, 1987; Pentecost & Whitton, 2012). As such, it is expected that limiting access to these nutrients will severely limit biological growth. However, while restricting the nutrients that are available within the substrate in certain parts of the panel is possible up to a point, it is likely not enough to create a severe enough nutrient limitation. This is because limiting the nutrient input from the surrounding environment (i.e. the air) is not always possible. Heterotrophic organisms in the biofilm (organisms using organic molecules as nutrients) are highly dependent on the nutrients that are available on the concrete surface and organic atmospheric particles, as they cannot extract inorganic nutrients from the air (Gorbushina, 2007). As such, limiting the organic nutrients that are available on the surface should severely inhibit their growth. This means that the substrate should contain no nutrients, but also that there should be little to no organic material from the air that gets attached to the substrate, as this is their main nutrient input. This can be done by creating a smooth surface, with as few attachment points for this organic material to settle as possible. This has an added advantage in that it also limits the attachment points and refuges for the micro-organisms themselves.

Nonetheless, heterotrophic organisms are only part of the total biofilm. Autotrophic organisms such as algae and cyanobacteria do not need organic material as their nutrient input and can instead get most nutrients from the air. Of the two elements that were identified earlier, nitrogen and phosphorus, nitrogen is usually not a limiting factor. This is due to the ability of several organisms within biofilms to fix N_2 from the air, making phosphorus the element that is usually in limited supply, due to it not being an aerosol (Pentecost & Whitton, 2012). Restricting the amount of phosphorus in the substrate can therefore limit growth up to a point, however, previous research has shown that whilst not adding phosphorus to the substrate can slow biological growth, it does still take place (Veeger et al., 2020). The other elements these autotrophic organisms need - carbon, hydrogen, nitrogen, oxygen, and sulphur - are readily available in the air and therefore cannot be limited on the substrate surface. As such, limiting nutrient access will need to be combined with other measures.

The most promising measure is to limit the access to water. As all biofilm organisms need water, restricting their access to it in part of the panel could severely limit growth in that part. In fact, in previous research conducted by the authors, water was proposed to be the main driver for the differences between different bioreceptive concrete mixtures (Veeger et al., 2021). Limiting this access is also relatively straightforward. If the porosity is kept very low, not only is the total water absorption of the concrete reduced, but the movement of water to the surface is also very restricted. In previous research it was also shown that if a surface is not treated with a surface retarder, water transport into the substrate is also severely reduced, thereby further restricting water access.

It is therefore suggested that using a combination of a smooth surface texture, and a concrete with low porosity and phosphorus content could make part of the panel inhospitable to biological growth. This is corroborated by previous research, where it was found that the reference samples, with their low porosity and no phosphorus content, showed very little to no biological growth, especially when no surface retarder was used. If this concrete is then combined in a panel where the other part uses a highly bioreceptive concrete, it should be possible to direct growth and achieve partial biofilm coverage of the panel.

TABLE 2 Overview of proposed measures to direct biological growth and their expected impact

PROPOSED MEASURES	EXPECTED IMPACT
Restricting PAR radiation	Extremely limited due to high range of acceptable PAR levels for organisms
Restricting nutrients	Limited due to nutrient input from the atmosphere, although it could limit growth of heterotrophic organisms
Restricting access to water	High based on previous research and easy implementation of water restrictions

3.2 CONCRETE MIXTURES

Both a bioreceptive and non-bioreceptive concrete have to combined in the panel to be able to direct biological growth. For the bioreceptive concrete, the mixture that was tested in previous research conducted by the authors will be used (Veeger et al., 2021). The non-bioreceptive concrete mixture needs to be one that has the exact opposite properties from this mixture. As determined in the previous paragraph, this means that it should have a low porosity and a smooth surface. A concrete mixture with these properties is already being used in the concrete industry, under the name of ultra high-performance concrete (UHPC).

Developed to increase the strength and durability of concrete, its properties should make it highly effective as a concrete that inhibits biological growth. Due to a combination of pozzolanic mineral fillers, high cement content, and a very low water/cement factor (made possible through the use of a superplasticiser) UHP concrete has a very low porosity, low water permeability and high carbonation resistance (Wang et al., 2015). As such, it has the ideal properties to form the non-bioreceptive part of the panel, as access to water should be severely restricted and its high carbonation resistance makes it so that the pore structure will remain stable over time, thereby ensuring that water access will remain low on this concrete throughout its lifetime.

We will therefore use an existing UHPC mixture employed by our company partner, Byldis, with one small adjustment. Most UHPC mixtures (including the one used by Byldis) use fibres to increase the tensile strength of the concrete (Shi et al., 2015). However, as high tensile strength is not a necessity for this application, this ingredient will be omitted to simplify the mixture and keep costs down. This leads to the two concrete mixtures in Table 3.

TABLE 3 Concrete mixtures used for the creation of the prototype panels

CONSTITUENTS	BIORECEPTIVE CONCRETE	UHPC CONCRETE
Cement	300 kg/m^3 OPC cement (62.5% slag)	700 kg/m^3 OPC cement
Aggregate	578 kg/m^3 Argex AG4/8 (CEC) 762 kg/m^3 sand (0-4mm)	Crushed gravel (4-11mm) Sand (0-4mm) 50:50 ratio
Water	150 kg/m^3 (wcf 0.50)	189 kg/m^3 (wcf 0.27)
Mineral admixture	30 kg/m^3 Bone ash	25 kg/m^3 silica fume 115 kg/m^3 limestone powder
Plasticiser	None	Yes (including additives)

3.3 PANEL STRUCTURE

In order to create a panel that is partially covered by a biofilm, these two types of concrete have to be combined within the same panel. However, if this is achieved by using the two types of concrete over the full depth of the panel, not only is the length of the joint minimal, reducing the bonding strength between the two types of concrete (exacerbated by the joint shape), but it also limits the amount of water that can be stored within the panel (see also Figure 1; option 1). Especially considering the latter, it would be better to use the bioreceptive concrete for a larger part of the panel, and only using the non-bioreceptive concrete on that part of the surface where biological growth is not desired (see also Figure 1; option 2). This way a large amount of storage capacity for water is provided in the form of the pores within the bioreceptive concrete, and joint length increased.

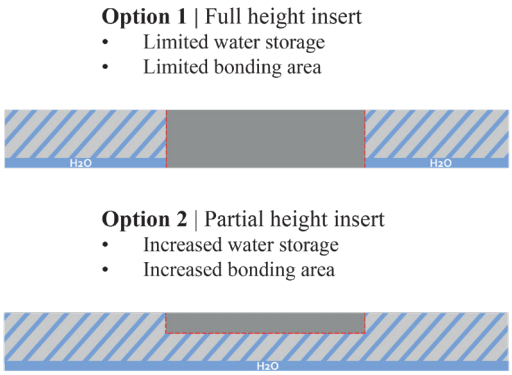


FIG. 1 Sectional overview of different insert options

This water can only reach the surface on the bioreceptive part of the panel, as the UHPC severely limits the transport of water to the non-bioreceptive parts of the panel. Combined with a smooth surface for the non-bioreceptive part of the panel, biological growth should be sufficiently hampered. On the bioreceptive part, on the other hand, water transport to the surface is already higher due to the used concrete and can be further improved by using a surface retarder on this part. This also increases the surface area, and nutrient and microorganism entrapment on this part of the panel. One more thing to consider is the aggregate on the surface of the washed concrete. In previous research it was shown that if the surface consists of a CEC aggregate, the complete panel will become covered with a biofilm, due to the CEC's inherent bioreceptivity (Veeger et al., 2021). The regular limestone aggregate, on the other hand, remained free of growth on the aggregate itself, giving a different visual appearance to the concrete. As such, changing just the aggregate on the surface of the panel can change the visual appearance of the bioreceptive part of the panel. Also, as long as the interior part of the panel consists of the CEC aggregate, the hydraulic properties will not be influenced extensively. Changing the surface aggregate therefore increases the range of visual options available for the panel. This leads to the final design as depicted in Figure 2.

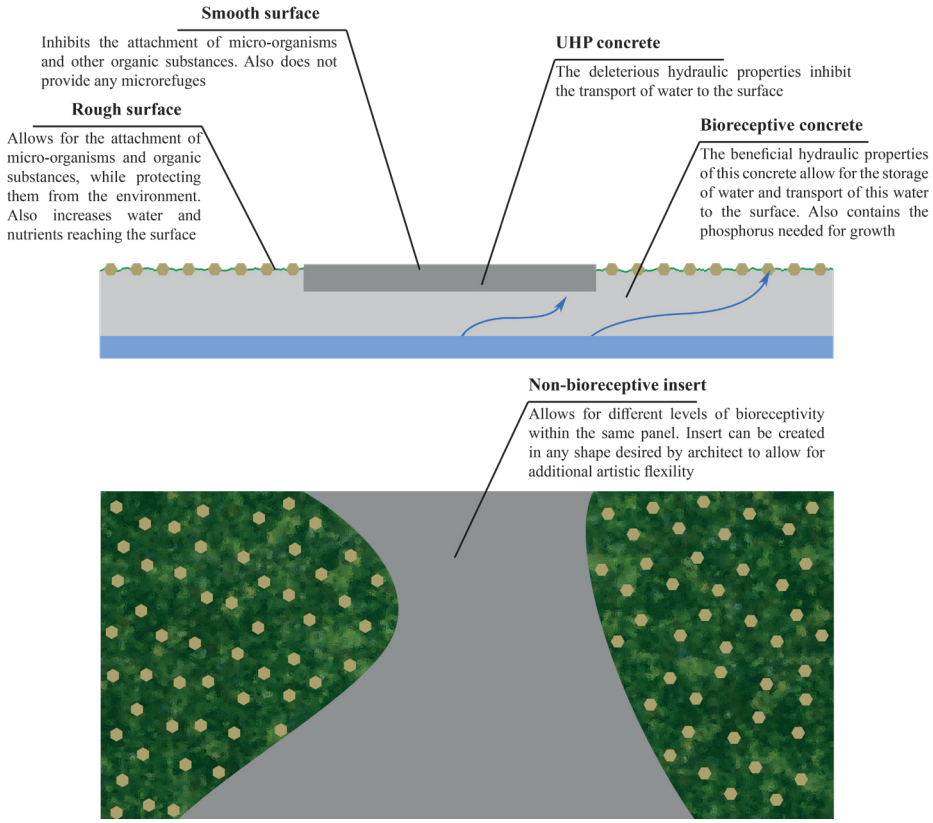


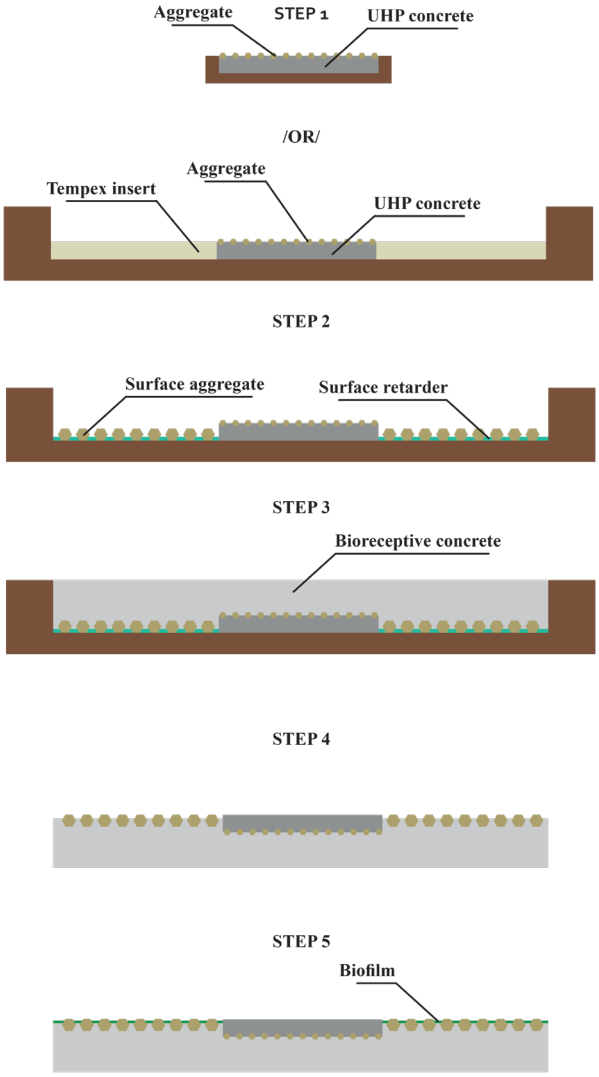
FIG. 2 Overview of the final panel design

3.4 PANEL PRODUCTION

The first step is to create the UHPC insert, which can later be embedded into the panel by pouring the bioreceptive concrete over it (similar to the way prefab brick façades are made). The UHPC insert can either be created in a separate mould, which has the size and shape that is required, or it can be created in the panel mould itself. By placing tempex or similar inserts the mould for the UHPC insert can be created within the larger mould. This also reduces the risk of breaking the insert, which is relatively thin and therefore could be fragile. By adding extra aggregate to the surface of the UHPC insert after pouring, the total surface area to which the bioreceptive concrete can bond in the next step is increased, as such increasing the total bonding strength.

The UHPC is then removed from its own mould and placed in the panel mould (in case a separate mould is used), or the tempex inserts are removed (in case the UHPC inset is made inside the panel mould). Next, the bottom of the panel mould is prepared. As this will become the exterior surface of the panel, this is where the surface retarder is applied in the area around the UHPC insert. If a surface aggregate other than CEC is preferred, this aggregate is added to the bottom of the mould as well. In this way, the panel itself will have the CEC aggregate that is present within the bioreceptive concrete mixture, whereas the aggregate that is visible on the surface is the one that is placed on the bottom of the mould. The surface appearance thus can be easily changed, without changing the bioreceptive concrete mixture.

After this, the bioreceptive concrete can be poured into the mould. When it has hardened, the panel can be demoulded and the unhardened cement on the surface of the bioreceptive part of the concrete can be washed away, revealing the aggregate. After some initial carbonation (28 days in our prototypes' case), the biofilm can be applied to the panel and initial biofilm growth can take place. A graphical overview of the production process can be found in Figure 3.



Step 1
The UHP concrete insert is made either using a dedicated mould or by placing tempex (or similar) inserts in the panel mould, which can later be removed. After pouring the UHP concrete, extra aggregate is placed on top, to increase bonding with the bioreceptive concrete.

Step 2
The insert is demoulded and place in the panel mould. The bottom of the mould is covered with surface retardant and the chosen surface aggregate.

Step 3
The bioreceptive concrete is poured into the mould.

Step 4
The panel is demoulded and the top surface is washed to remove the top cement layer.

Step 5
The liquid biofilm is added to the bioreceptive part of the panel and incubated for 2-4 weeks.

FIG. 3 Graphical overview of the panel production process

4 PANEL TESTING

4.1 RESULTS AND DISCUSSION

As a proof of concept, two prototype façade panels were made, one with CEC as a surface aggregate and one with limestone as an added surface aggregate. The production process is as discussed before (see also Fig. 3) and can be seen in Fig. 4. The mixtures used can be found in Table 3.

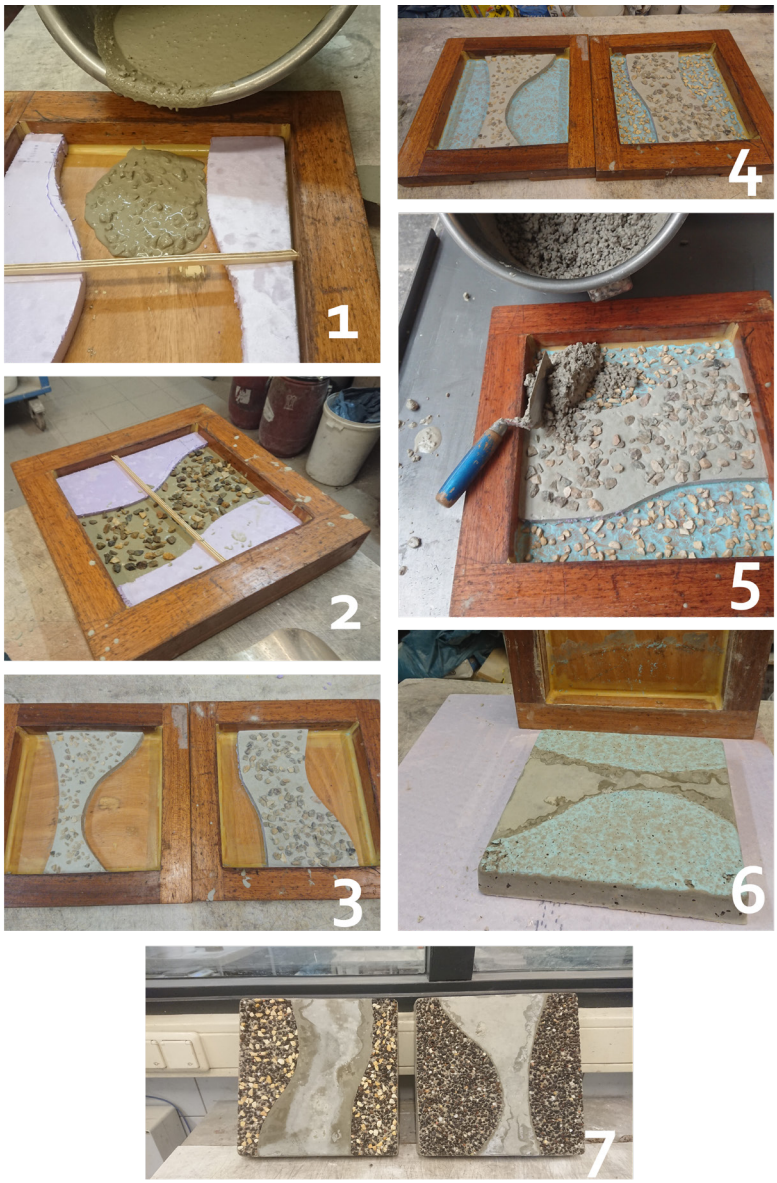


FIG. 4 Overview of the production process of the prototype panels. (1) UHPC concrete is poured into the mould using tempex inserts. (2) Aggregate is added to the top of the UHPC. (3) Tempex inserts are removed. (4) Surface retarder and surface aggregate are added to the bottom of the mould. (5) Bioreceptive concrete is added on to the mould. (6) The panel is demoulded and washed. (7) Final prototype panels.

After inoculation these panels were kept under the same growing conditions as described in the methodology. It was found that after only 2 weeks under these conditions, the bioreceptive areas of the panels were almost fully covered (see Fig. 5). This shorter time to full colonisation as compared to the samples in our previous research, which were not yet fully covered after a period of 8 weeks, can likely be explained by the higher concentration of biofilm used for the inoculation of the panel and the higher surface area allowing for more refuges for the biofilm, acting as sources of biological growth.

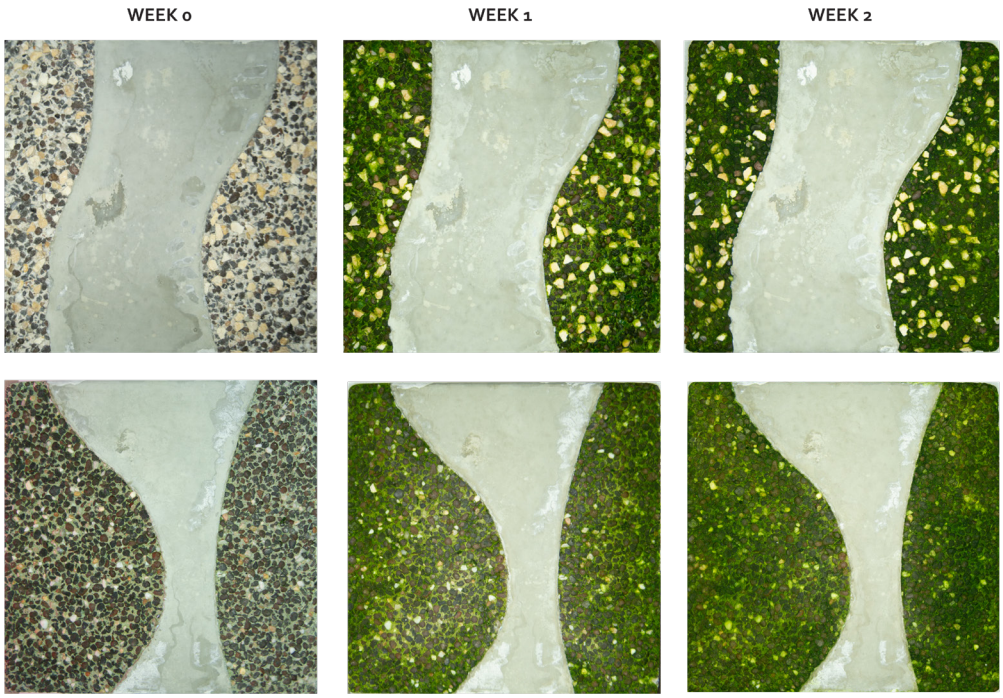


FIG. 5 Biofilm growth progression during the period under optimal growing conditions

It can also be seen that while the bioreceptive parts of the panel are fully covered, the non-bioreceptive part remains free from growth. Although this does not prove that this will remain so in the long-term, it does prove that the panel has the ability to direct growth, at least in the short-term.

The panels were then placed outside for a period of 1 week, to see how the biofilm responded to external conditions. During this period, the panels were placed on an exposed roof surface (height circa 12 metres). The surface was wetted twice daily, as discussed in the methodology. However, the rapid change in environmental conditions still proved too sudden and harsh for the biofilms, resulting in a significant deterioration of the biofilm (see Fig. 6).

Whilst the testing of the prototype panels under optimal growing conditions shows their ability to harbour and direct biological growth, the period spent outside shows that additional steps are necessary to make it a viable façade product. However, as the used biofilm was originally harvested from a biofilm growing under similar circumstances as those experienced by the panels on the exposed rooftop, this deterioration in the biofilm under exterior conditions cannot be caused by the fact that the organisms are inherently unable to grow under these exterior conditions, as they have done so before. There is also some evidence of a small recovery of the biofilm after 5

months, suggesting that the biofilm can grow under these conditions. Instead it likely has to do with the so-called 'lag-phase' microbial and algal organisms experience when a sudden change in environmental conditions takes place. This lag-phase is the period during which the biofilms cells adjust themselves to their new environment and no growth can take place, the duration of which is dependent on several factors, amongst which are the amount of change between environments, the type of cells, and the growth stage of the microbial cells (Swinnen, Bernaerts, Dens, Geeraerd, & Van Impe, 2004). This lag effect was also seen when the initial biofilm was harvested and added to a liquid growth medium, where it took a few days for exponential growth to start as the biofilm adjusted to its new environment. Based on this, if the environmental changes can be made to be more incremental, survivability of the biofilm will likely be higher, as it reduces the duration of this lag-phase.

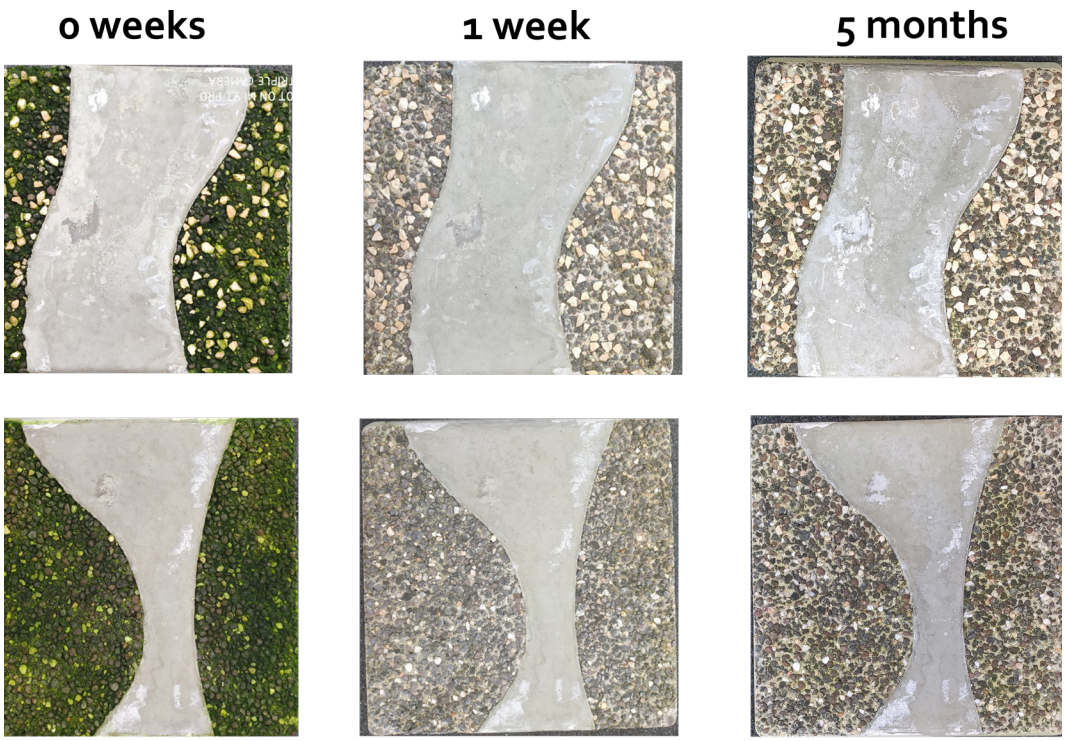


FIG. 6 Photos taken at the start of the exterior part of the experiment, and after 1 week outside and 5 months outside

Something that plays a compounding factor in the poor survival is likely the lack of extracellular polymeric substances (EPS) in the biofilm. EPS are polymers produced by organisms in the biofilm and one of their functions is to mediate environmental extremes, thereby creating a more stable microclimate for the biofilm (Wolfaardt, Lawrence & Korber, 1999). However, under optimal growing conditions, such as those used to initially develop the biofilm on the prototypes, EPS will not be produced, as its energy requirements do not outweigh the benefits under those conditions (Wolfaardt, Lawrence, & Korber, 1999). Therefore the incremental environmental changes discussed in the previous paragraph could also stimulate the productions of EPS, as under suboptimal conditions the benefits of EPS production will start outweighing the associated costs.

5 CONCLUSION

The aim of this research was to investigate how bioreceptive concrete could be used within a building façade. In order to achieve this, a design was formulated, combining bioreceptive and non-bioreceptive, UHPC-based concrete within the same panel. This allows for biological growth to be directed, allowing for more design flexibility. This was also shown as a proof-of-concept in a prototype panel using the proposed design and production guidelines, resulting in a bioreceptive façade panel using commonly available construction materials. Based on the results from the growth tests it can be concluded that these prototypes can form the basis for a bioreceptive concrete façade application. And that the concept of bioreceptive façades may provide an alternative to contemporary green façades.

Not only that, the resulting growth shows that biological growth can be directed by combing bioreceptive and UHPC concrete within the same panel. The results also show that the necessary time for biofilm's initial development is relatively short and can be achieved within two weeks if sufficient biofilm material is applied at the start of the nursery period. However, whilst initial biofilm development is rapid and relatively straightforward, the short period under exterior conditions shows that further research is necessary.

The authors suggest that this future research encompasses three different aspects:

- **Ecology**
  This would include the development of a proper nursing regime in order to increase outdoor survivability, directing the type of growth that occurs on the panel (e.g. algae or moss) and finding the best organisms to use for the colonisation of the panels

- **Material**
  This would include optimising the mixture and topology, as well as possible ways of upscaling the production

- **Economy and secondary effects**
  This would include determining whether or not bioreceptive façades can compete with contemporary green façades in terms of costs and beneficial secondary effects, such as the reduction of the UHI effect and air pollution

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