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FACULTY OF CIVIL ENGINEERING

Department of Concrete and Masonry Structure

Bio-active concrete tile

Bachelor thesis

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4.Numerical analysis of the tile

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III. ASSIGNMENT RECEIPT

I declare that I am obliged to write the Bachelor Thesis on my own, without anyone’s assistance, except for provided consultations. The list of references, other sources and consultants’ names must be stated in the Bachelor Thesis and in referencing I must abide by the CTU methodological manual “How to Write University Final Theses” and the CTU methodological instruction “On the Observation of Ethical Principles in the Preparation of University Final Theses”.

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ABSTRACT

The aim of this thesis is to design and fabricate bio-active concrete tiles which encourage rapid plant coverage of building walls and urban spaces with vegetation. A design comprises two different types of tile, which one of them intends to be used as a planter for a variety of climbing vegetation. Through the process of designing a and manufacturing suitable mould for tiles, a complex macro pattern was developed to ensure water retention on the structural surface. The concrete properties were tuned in order to improve bioreceptivity of the tiles. The concrete was modified by changing the mix design and using a different type of hydraulic binder to fulfil the required condition for biological growth. Two main properties of concrete were considered in this work, the pH and porosity. The results of this thesis provide an alternative solution to the existing green wall systems by the implementation of a bioreceptive cementitious material. The proposed solution creates an opportunity for further research on the aforementioned topic.

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1. INTRODUCTION

Today, more than half of the world's population live in the cities. With the rapid growth of the population, this number is still increasing and the situation in the urban areas are getting worse. Cities have become a huge built impervious environment, and they are facing enormous problems connected with the loss of natural green areas. A dense city infrastructure leaves no space for implementing the greenery on a ground level. This has resulted in the high demand for the green walls and roofs since they required little or no ground space. In particular, the living walls effectively uses vertical spaces as an opportunity for greenery. Their environmental and health benefits, as well as appealing aesthetics positively influence life in the urban area and lessen the environmental impact of the city. Unfortunately, the problem regarding these living walls rests on their usually very costly and demanding maintained system. The plants need a supporting structure with the complex watering system and sometimes the costs might outweigh the benefits. Therefore, an innovative new solution is needed.

As opposed to the typical green walls a new approach of integrating the vegetation directly on the building surfaces has been developed. By altering the physical and chemical properties of traditional concrete a new type of biologically receptive concrete has been produced. This concrete encourages and sustain the growth of the microorganisms such as mosses lichens and algae directly on its surface and thus increases the cryptogamic cover of the material. The bioreceptive concrete supports a plant life to thrive on buildings in a way that is both more sustainable and more efficient than existing green walls. It brings an interdisciplinary approach of architecture, engineering and biology.

A use of bioreceptive concrete for the integration of microflora directly on the building structure is still in a stage of development. But an ongoing effort of making our cities greener and more sustainable creates and potential for these new type of bio-active cementitious material to reduce the ecological footprint of the concrete based infrastructure.

2. STATE OF ART

2.1. Green cities

Cities are now-days, facing big pressure from increasing urbanisation. According to the United Nations report, the world population is expected to increase from 7.6 billion to 8.6 billion in 2030, reaching 9.8 billion in 2050. This rising trend is assumed to be continued (Population.un.org, 2019) and by 2050 75% of the world population will live in cities (Eames et al., n.d.). Accelerated population growth leave the mark on earth rapidly and associated urban development increasingly transforms natural areas into engineers infrastructure and creates enormous challenges for maintaining the urban ecosystem. This built environment has created large impervious paved surfaces, leading to loss of vegetations, increased surface runoff and retention of solar energy (Growinggreenguide.org, 2019). There is a great need for rethinking and rebuilding the urban infrastructure in response to these problems and many cities starting to recognise the importance of green infrastructure in the city. Incorporation of greenery into the dense city areas for an environmental uplift is in high demand.

Public green space has a positive effect on biodiversity, climate, wellness and air quality. It supports physical activities, relaxation and creates space for social interactions. Plants produce oxygen and polluted air particles are filtered out. Moreover, green areas play a critical role in cooling cities. All these impacts ensure that cities are becoming better places to live and work, with a positive influence on our mental health and well-being. Therefore, natural green assets, parks or water systems are in great need, unfortunately, they acquire a lot of ground spaces which are in scarcity. In a dense urban centre with insufficient space, it is an obstacle to implement these green areas (Growinggreenguide.org, 2019).

Green roofs, walls and facades seem to be the solution to the problem since they require a little or no space on the ground level. There are a great many free spaces, naked facades, retaining walls which surface potential could be in better used. Architect and engineers should have these green solutions in their minds while designing a new city infrastructure. An example is the city of Singapore, where the government launch the program called LUSH to support and encourage and architect in incorporating flora into their design leading to the boom in living walls and roofs constructions (Greenroofs.com, 2019).

Architects have applied green walls and roofs worldwide. However, the green walls are more spatial effective since the vertical areas are up-taking more space than roofs and therefore the primary focus shifted from roof structures to the plant integration for the walls system.

2.2. Green walls

Green walls, also called vertical gardens or living walls refer to all forms of vegetated vertical surfaces (Manso and Castro-Gomes, 2015). They can be incorporated into the new buildings as well as the already existing one. There is a great demand to involve innovative green technologies for architectural and construction design. The green roof and green walls are highly popular among developers for their aesthetic features and sustainable character.

Greening of the surfaces is not just the idea of modern society. Its history is dating more than 2000 years ago when Hanging gardens of Babylon were built. Later on, in Greek and Roman Empires, vines were used to cover and shade pergolas and building a wall to cool down building envelope in hot climate regions. The modern version of green walls was used since the 1980s when the idea of green walls as contributors to the environmental city planning, arose (Livingwallart.com, 2019). However, only in the latest years these living walls rapidly rose on popularity. According to greenroof.com, 80% of green walls databased online were built after 2009. And the popularity has been rising since then. The most seen benefit is it's aesthetic. It is adding colour and texture and it drives interest of walk by people. It creates a great comparison to the sharp building materials. But this is not the most valuable aspects of the green wall.

At the city scale, green walls and green roofs contribute to the preservation of green areas and the recovery of degraded areas without occupying extra space. They improve the city environment by improving the biodiversity, stormwater management, air quality and reducing the heat island effect (Urbanhabitats.org, 2019). But the greening has not only environmental aspects, but it also contributes to social and economic benefits. Vegetation has a positive impact on psychological wellbeing and it is a form of therapy for some people. A city image is improved as well which leads to an increase in property value (Ichihara and Cohen, 2010).

At the small building scale, green walls, help and protect the building itself. They contribute to the sustainable performance of the building and improve the microclimate. Plants add to the air quality through oxygen production and reduction of atmospheric CO_2. High foliage cover captures pollutants as well (Urbanhabitats.org, 2019). Recent studies show that green walls systems have the ability to influence the heat gain and loss of the building and therefore decrease the energy demand of the building and improve indoor thermal comfort (GhaffarianHoseini et al., 2013). Moreover, living walls are passive acoustic insulators as well.

Green wall systems

There are many types of green wall systems. Generally, they can be divided into two major categories: Green facades and Green walls, both of which are described below (Greenscreen.com, 2019).

Green facades are a type of green wall system consisting of a supporting structure for the plants to climb up to cover the wall area. (See Fig. 1) These climbing plants can be rooted on the ground, rooftops or in intermediate planters and it takes more than 3 years to cover the entire area. Facades can be built as separate structures or the framework could be fixed to the existing walls as well (Greenscreen.com, 2019).

Green walls consist of pre-vegetated panels, vertical modules or planters that are attached vertically to a structural wall or frame. (See Fig. 2) The most usual materials for these panels are plastic, expanded polystyrene, synthetic fabric, clay, metal. One of the benefits of this system is its diversity and density of green coverage. However, due to this diversity, the plants need more extensive care and maintenance than the facade system (Greenscreen.com, 2019).

Fig. 1. Green facade

Fig. 2. Green wall

Unfortunately, green walls have their drawbacks as well. They are very demanding on maintenance and they need a highly elaborate watering system leading to the high cost. There is a need for more efficient technical solutions. With new technologies in building and architectural industry, there is an attempt for a more innovative approach to green walls systems, combining environmental and structural aspects. It was observed that there is generally low integration between vegetation and structural elements. Therefore, the new concept of integrating plant directly into the structure as an additive to the construction material, has been developed (Ottelé, 2011).

2.3. Bioreceptivity of materials

As the attempt of integration plants to the structure rises, the relationship between living organisms and the building materials should be established. The study of the natural colonisation of building materials is commonly studied from a negative point of view. There is a general belief that the microorganisms are harmful to structural materials in terms of biodegradation and biodeterioration. These terms are widely used and relate to the unfavourable chemical and physical changes of materials (Guillitte, 1995). Biodeterioration defined by Hueck (1965), refers to "*any undesirable change in the properties of a material caused by the vital activities of living organisms*". However, colonisation does not have to necessarily cause degradation of structures. It can primarily lead to the changes of colour which could not only be harmless but can be considered as aesthetically pleasing and have a positive impact on the environment. Guillitte (1995) studied the effects of bio-colonisation on the materials and he used a different term, bioreceptivity. This new term in ecology, bioreceptivity, stands for the ability of materials to be colonised by living organisms. It comprises the impact of colonisation on the material without being necessary deteriorated. It also implies the material properties necessary for attachment and further development of vegetation on material surfaces such as porosity, roughness, moisture and chemical composition of the surface layer. Guillitte (1995), divided bio-receptivity into three categories: primary, secondary and tertiary. Primary bioreceptivity refer to initial state of colonisation when the material properties remain the same or very similar. Over time the bio-colonisation can enhance the change of material properties and therefore the secondary bioreceptivity is established. Further modification of secondary characteristic by human activity, consolidation of particles, surface polishing, is called tertiary bioreceptivity (Guillitte,1995). This new perception of the biological colonisation in civil engineering establishes a new concept for building and ecology.

In order to be colonised by a living organism such as algae, fungi and lichen, a certain condition has to be met for receiving living organisms and for their further development. Important aspects without which the colonisation could not take place are environmental conditions and chemical and physical properties of the material. Bioreceptivity represents material properties suited for colonisation. However, a degree of bio-colonisation does not depend only on material properties but also on environmental factors.

The necessity and importance of the environmental conditions such as temperature, light, water and exposure of materials to these sources were discussed in Miller (2012) studies of bioactivity of stone material. Natural stone material, widely used for monuments, is the favourite object for colonisation (See Fig. 3). It is clear that it's surface roughness, pore space structure, permeability are favourable properties for assessing the bioreceptivity of this material independently on environmental conditions (Miller et al., 2012). Another study suggests that environmental factors play an even more important role in bio-colonisation, especially the availability of water and light regime (Bellinzoni, Caneva and Ricci., 2003, Gorbushina., 2007). Although there are many discussion about the bigger importance of environmental or material properties, the fact remains that they both are responsible for biological colonisation. The availability of water depends on surrounding conditions, however, the ability to capture and retain the water strictly depends on the porosity of the material and its rough structure (Miller et al., 2012).

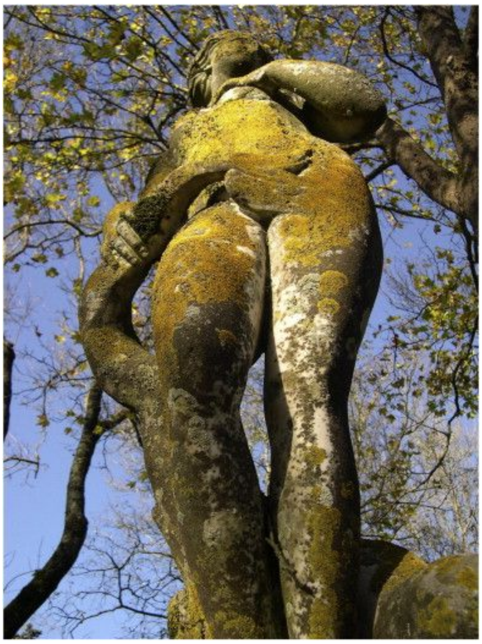


Fig. 3. Result of bio-colonisation of stone material (Portugal).

To sum it up, bio-colonisation on the stone material is principally depended on the environmental condition, microclimatic parameters and bioreceptivity of the material.
There are still further investigations required for fully understanding to what extent the material properties are affected in certain conditions. However, the information about bioreceptivity of natural stone can supply us with the knowledge needed for studies of other materials susceptibility to colonisation such as concrete.

2.4. Bio-active concrete

Concrete is the most widely used building material. In the second half of the 20th century, the construction industry focuses primarily on the use of Ordinary Portland Cement (OPC) (Walling and Provis, 2016). With the effort of a more environmentally friendly and sustainable solution in the construction industry, alternatives to the conventional concrete are sought. Not only for decreasing the environmental impact by OPC production but as well for implementing a more greener solution to the city infrastructure.

Accordingly, a new concept of integrating microflora directly on the concrete structures by improving concrete bioreceptive properties has been developed. In this sense, the Spanish researchers of Structural Technology Group proposed the solution of plants integration into the building material by means of designing bilayer concrete. The concrete consisting of three layers, waterproof layer, the internal biological microstructure and the porous coating. Each of these three layers works in synthesis in order to encourage and sustain the biological growth on its surface. Similarly, the BiotA Lab developed the facade concrete panels, which promote bio-colonisation on their surfaces (See Fig. 4). By using the novel type of concrete and environmentally driven design, the panels enhance the growth of microorganisms such as mosses, lichen and algae (Richard-beckett.com, 2019).

Fig. 4. Bioreceptive concrete panels-BiotA Lab

Another company, ECOncrete, is focusing on the environmentally friendly solution for concrete structures in coastal areas and its impact on urban infrastructure. With bio-enhancing concrete additives, they support marine biodiversity and offer a more aesthetical solution instead of grey coastal walls. They are as well producers of concrete tiles for green walls and were the main inspiration for my project (See Fig. 5) (ECOncrete, 2019).

Fig. 5. ECOncrete tide pool and wall tile

In all cases, the chemical and physical properties of concrete were altered, namely pH, porosity and roughness. Traditional concrete has very high initial alkalinity and the low porous structure which are not ideal conditions for bioreceptivity. Its pH reaches value 12−13 and the suitable pH value for the growth of microorganisms ranges from 5.5 to 8.5 (Iyengar, S. and Al-Tabbaa, A.,2007). Only after the drop of pH due to the carbonation, the biological colonisation can take place. There are several options on how to decrease the alkalinity of concrete. The additives such as silica fume and fly ash can decrease the alkalinity. However, the value is still fluctuating around 10 and is depending on the amount of cement replacement. Another solution is decreasing the pH of concrete by adding the acid solution into the mixture. In this case, acid addition could lead to a negative influence on material properties (Manso et al., 2014). So the idea of using a different hydraulic binder with naturally low pH has been developed. These types of cement usually consist of oxides and phosphate acids as the main compounds and offer an alternative solution to the Ordinary Portland Cement. The most widely used acid-based cement is Magnesium Phosphate Cement.

Magnesium Phosphate Cement (MPC)

Magnesium phosphate cement is a relatively new type of binder. It was firstly used at the end of the 19th century as a dental cement and later on used mainly for a repair construction due to its excellent mechanical properties (Feng et al., 2018). Comparing it to the Ordinary Portland cement it has some advantages such as very quick setting time, high early strength, low setting and hardening temperature up to −20℃, low drying shrinkage and very high bonding strength with old concrete. All these properties are essential in repair construction. That is why the magnesium phosphate cement is mostly used as a mortar for rapid repair of concrete structures, such as pavement, airport runways, bridge decks, etc. (Yang et al., 2000). The MPC is derived from the reaction between phosphate and metal oxide. Three different types of phosphate salts are generally used: ammonium, potassium and sodium. However, the ammonium was restricted to the outdoor use due to its release of ammonia during the reaction (Feng et al., 2018). The reaction between oxide and phosphate in the presence of water is very quick thus the addition of retarder is needed to slow down and control setting time.

Properties of MPC

Mechanical properties, as well as setting time, are depended on the w/c ratio, addition of retarder and ratio of phosphate and magnesium (P/M) (Yang et al., 2014). Strength is highly influenced by the P/M ratio. A decrease in the ratio leads to the increase of the strength (Yang and Wu, 1999). However, the high amount of magnesium causes very quick hydration and high released heat, leading to potential damage to the product. Therefore the optimum ratio of P/M has to be chosen. According to the experimental study of Li, Sun and Chen (2014), the maximal compressive and flexural strength were reached with the P/M ratio of 0.2−0.25. Similarly, as in OPC, the w/c ratio is an important parameter. With decreasing w/c ratio the compressive strength increases (Li and Chen, 2013). The early strength develops very fast reaching 70 % in 3 hours. The positive effect on this early strength has the very high hydration heat of MPC (Yang et al., 2000). The additive such as fly ash can be used up to 50 % to improve the properties, adjust the colour and decrease the overall cost (Li and Chen, 2013).

Many research works have been carried out on phosphate cement-based materials, most of them are mainly centred on chemical compositions and mechanical properties of the mortar used for repair of concrete. There are only a few papers subjected to the bioreceptivity of this concrete substratum, which is a very important property for the successful application for the green walls (Manso et al., 2014.) Certainly, the biocompatibility would become one of the most important properties of the material and further studies have been carried out regarding optimisation of this new cementitious material.

3. AIMS AND OBJECTIVES

The fact remains that the cities are in great need for an innovative green solution. Incorporation of the green areas directly on the structural surface seems to be a new concept for plant implementation to the city infrastructure.

The main aim of the thesis is to design and fabricate bio-active concrete tile which will enhance the growth of vegetation on its surface without additional maintenance.

Thesis objectives:

1) Design and fabricate concrete wall tile as an alternative solution to the existing green walls

2) Combine interdisciplinary processes of design and digital fabrication to create tile form

3) Apply newly developed bio-receptive concrete to stimulate micro-organic growth on the tile surface

4. MATERIALS AND METHODS

4.1. Design of tile

The aim of the bio-receptive tiles is to promote micro-organic growth directly on their surface and thus create the green patina. The tiles are intended to be applied over a range of urban contexts with a particular opportunity for green walls, building facades and retaining walls. The main inspiration for tile design is the characteristic shape of nature with its multilayering and irregularities creating suitable embedding for the growth of microflora (See Fig. 6).

Fig. 6. Shapes of nature

The tiles were geometrically designed to promote the growth and latching of the greenery on the material surface. To mimic natural surfaces, the complex 3D structure with different elevation levels of tile outer face was designed. These risen steps serve as water retention on the unit surface as well as supporting elements for climbing vegetation. The range of elevation is between 5−20 mm and steps vary by its length. The tile is designed to be from two-layered concrete. The first layer is made out of OPC and has a load-bearing character. The second bioreceptive layer is from acid-based cement and its purpose is to support the development of microflora and to capture and accumulate water.

In order to maximize the green coverage and biodiversity, I have decided to combine both before mentioned green walls technologies. A vision to create a wall that will support climbing plants and at the same time serve as a module for pre-vegetated rich flora led to the decision of designing two types of tiles, Standard tile and Pocket tile (See Figs. 7 and 8) The size and shape of the tile units could be modified according to specific requirements of the area.

Standard tile

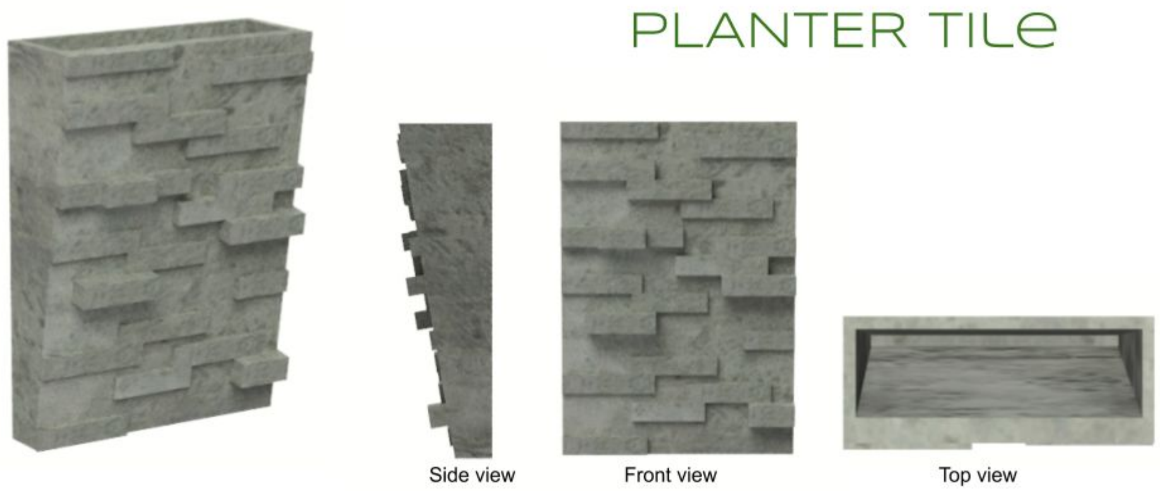
The tile represents an elevated 3D design for microflora to be established and proliferates on its surface. The tile consists of two-layered concrete. The structural layer is 100 mm thick. while the outer bioreceptive layer with a thickness of 10 mm consists of multileveled steps ranging from 5_20 mm. The parameters of the tile can be seen in Fig. 7.

Height (mm)	Width (mm)	Depth (mm)	Volume (l)	Weight (kg)
350	250	40	2.15	5.37

Fig. 7. Standard tile parameters

Planter tile

The planter tile or so-called pocket tile represents the same elevated 3D design, however, the pocket for planting is added in order to keep a wide variety of plants and to control the density of greenery covering the walls. A structural part creates a pocket for seeding with the thickness 10 mm. The front face layer is designed to be out of the bioreceptive concrete with the thickness varying from 10_30 mm. The volume of the pocket is 3 litres which are suitable for providing enough soil for a variety of climbing vegetation. At the bottom of the tile two drainage holes were designed as a precaution for over-watering, as well as for decreasing the risk of damage from freeze-thaw action. The tile parameters are shown in Fig. 8.



Height (mm)	Width (mm)	Depth (mm)	Volume (l)	Weight (kg)
350	250	40-100	3.22	08.05

Fig. 8. Planter tile parameters

Anchoring

There are two ways of attaching tiles to the building structure, adhering and anchoring. Tiles could be attached directly to the wall structure by wall tiles adhesives. However, due to the weight of the concrete tiles, the installation would be more complicated and precaution of the slipping should be in concern.

With mechanical anchoring, the tile would be attached to the wall by a suitable anchor. The anchor consists of two parts: the anchor and the bolt (See Fig. 9 and 10). Instead of the drilling a hole to the tile, the anchor would be embedded to the fresh concrete during the manufacturing of the tile and therefore the possible damage of tile by drilling could be avoided. The number and size of anchors could vary according to the specific requirements. The benefits of this system are the faster installation and the easy replacement of tile in a case of damage. The aesthetic of the tile is not compromised by any visible installation components.

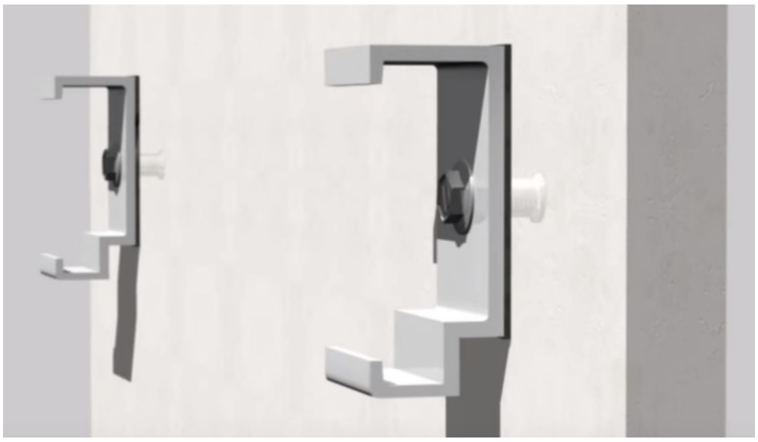


Fig. 9. Keil anchoring system with a support structure

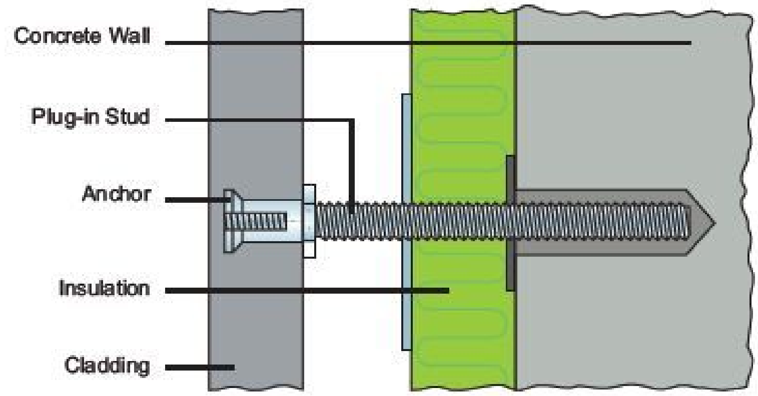


Fig. 10. Keil anchoring system without the support structure

4.2. Numerical analysis

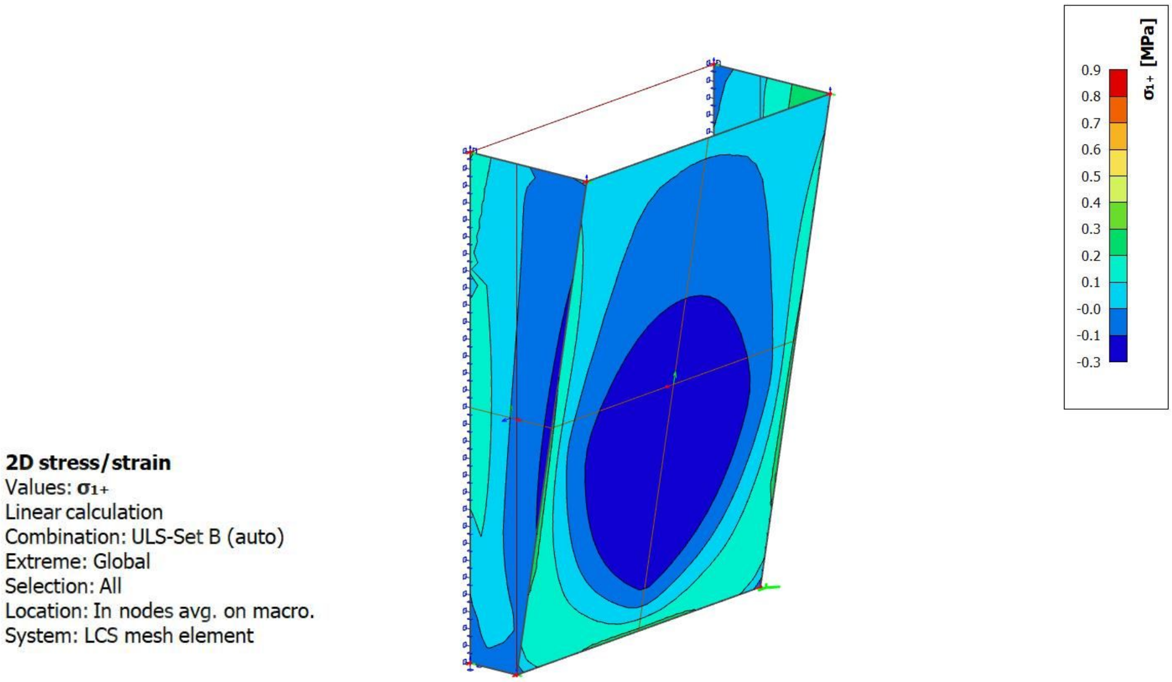
Numerical modelling in program SCIA Engineering was used to analyse the behaviour of planter tile under the load action of soil and water inside the tile. The tile was considered as fully fix supported on the backside.

The lateral soil and water pressure were applied on the three sides of the tile and the vertical load on the bottom of the tile.

Considered load cases: Permanent load- self-weight, soil pressure

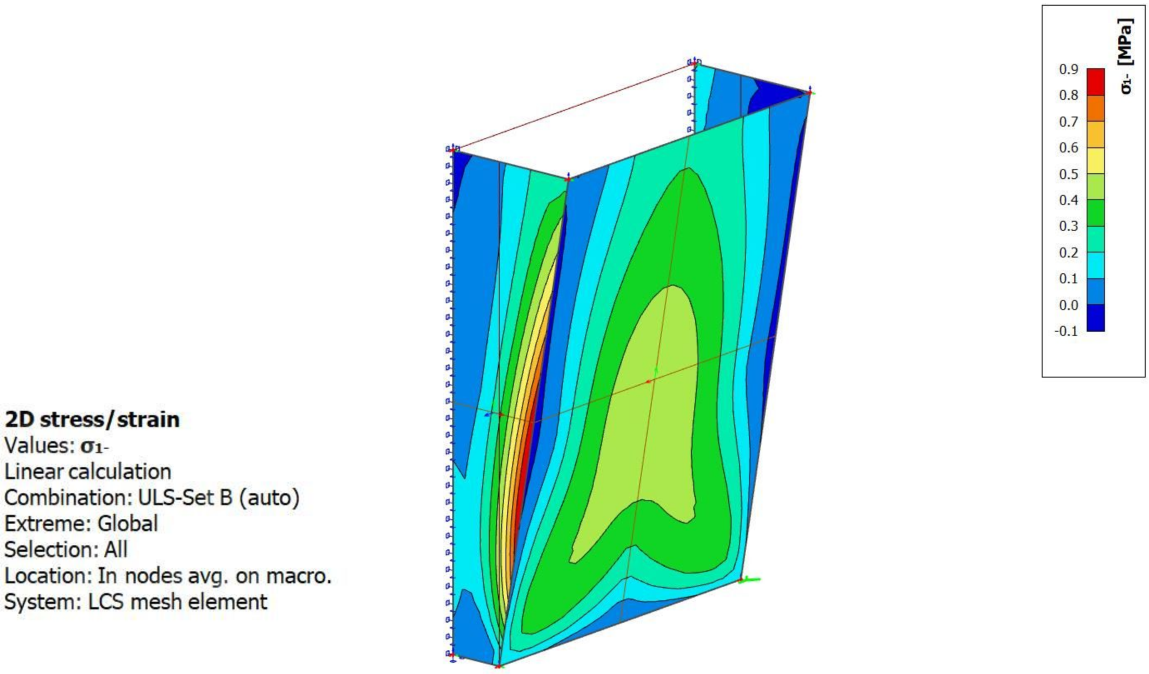
Variable load- water pressure

Numerical simulation results were obtained for the main stresses at both surfaces of the tile. Greatest tension strength was 0.3 MPa and 0.9 MPa at compression at the inner surface (See Fig. 11). For the outer surface, the highest tension was 0.9 MPa and 0.1 MPa at compression(See Fig. 12). Detailed results on the sections are shown in the Appendix.



2D stress/strain
Values: σ_{1+}
Linear calculation
Combination: ULS-Set B (auto)
Extreme: Global
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

Fig. 11. Resulting principal stresses at inner surface of tile.



2D stress/strain
Values: σ_{1-}
Linear calculation
Combination: ULS-Set B (auto)
Extreme: Global
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

Fig. 12. Resulting principal stresses at outer surface of tile.

4.3. Design and manufacturing of tile forms

Planter tile form

The planter tile was made out of flexible silicone rubber after mixing with the catalyst at normal room temperature. This silicone rubber is suited as a mould for casting of various materials, in my case for concrete.

Firstly, the envisioned tile model was made out of XPS material (See Fig. 13). The model was placed in enclosed space and the silicon (Lukopren N1522) was poured into it. The hardened silicon created a front face and side walls of the tile form (See Fig. 14). The inner fill for the designed hollow space of the pocket tile was made out of XPS and its surface was covered with a fluid sealant of Lukopren S3782 as a separation layer. This assembly was secured with clamps for rigidity and tightness of the form. The mould made out of silicon benefits from its easy unforming due to its flexible structure. However, the replica model has to be made very precise in order to obtain an exact shape that we wished for. Special care should be during the mixing of Lukopren with catalyst, where exact amounts are necessary for suitable form structure.

Fig. 13. Model of Planter tile

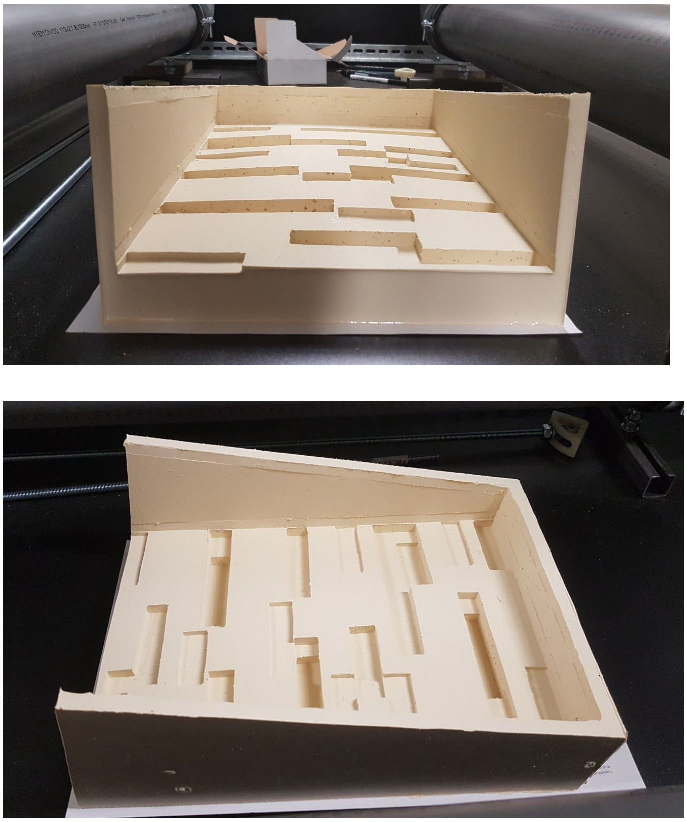


Fig. 14. Silicon tile form

Standard tile form

Regarding the form for Standard tile, I have decided to use digital fabrication for this model. In a case of digital fabrication, digital data drives manufacturing equipment such as 3D printers, laser cutters and CNC machines, to form various geometrical shapes.

The first step was creating a virtual model of a tile form using Fusion 360 software (See Fig. 15). The model served as an input for the fabrication tool, in my case CNC milling machine. (CNC -Konečný s.r.o) In the machine, the tool-paths were generated to guide the cutting tool (See Fig. 16). A solid block of XPS polystyrene of thickness 80 mm was used for the fabricated model. The XPS block was shaped by removing material through cutting, drilling, boring and grinding (See Fig. 17). The form was cut in the middle into two pieces for later easier unforming. The finishing layer of silicon sealant, Lukopren S3782, was used as a separation layer between XPS form and concrete.

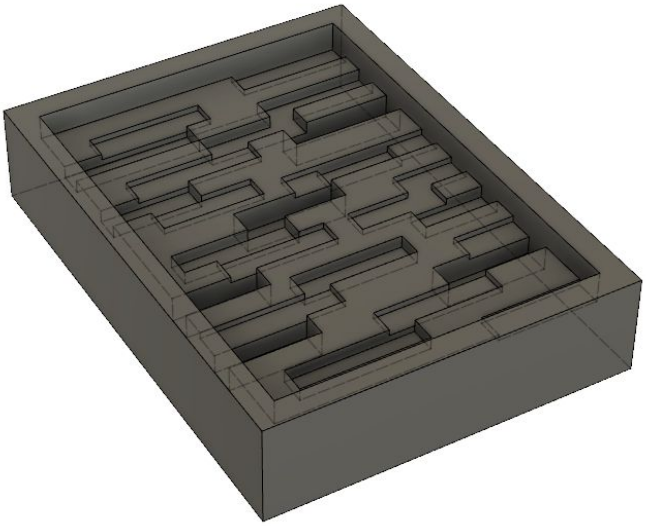


Fig. 15. Modelling of 3D form in Fusion 360.

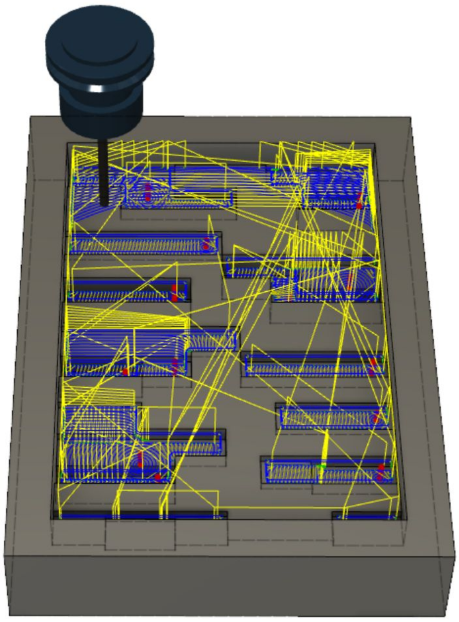


Fig. 16. Simulating of tool-path for drilling machine.

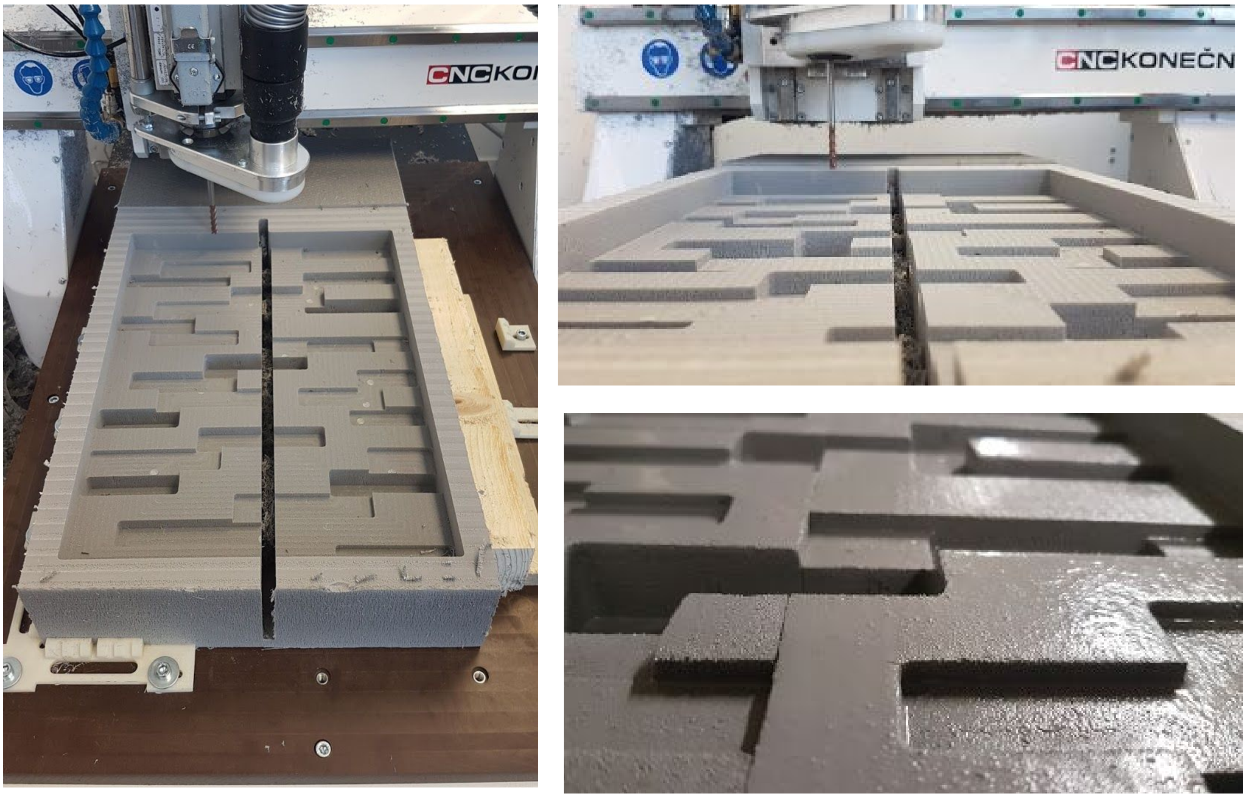


Fig. 17. Fabrication of tile model by using CNC milling machine

One of the advantages of using digital fabrication is that it makes more precise shapes and details for a model which could be easily altered in the future if necessary. Work is more efficient and previewing and simulating the tool-paths prevents future problems during manufacturing. On the other hand, the design is limited to the size of the manufacturing machines and the thickness of the material.

By utilizing novel design and digital fabrication methods, multileveled surface and elevations were created to improve the facade performance. All of the designed formwork is repeatable and can be used for further series production.

4.4. Developing of low pH concrete

For developing low-pH cementitious materials, Magnesium Phosphate Cement (MPC), was chosen as a hydraulic binder to improve bioreceptive properties of concrete.

Materials

MPC is prepared by mixing MgO (M) and NH4H2SO4 (P) with retarder in a given proportion. Dead-burned magnesia (MgO) calcinated in temperature over 1400 ℃ with low reactivity was used. The content of MgO was at least 89 % with the particle size 0−0,1 mm. The phosphate source used was dihydrogen ammonium phosphate. For the retarder, 6 % of Borax was used as a weight of a total cement mix. The reaction of MPC is acid-based neutralisation and it is strongly exothermic. The main reaction product is Struvite (Yang and Wu, 1999)(See Fig. 18). However, the reaction is still not well understood. A chemical reaction of magnesium and phosphate is as follow:

$$MgO + NH_4H_2PO_4 + 5H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O$$

Samples preparation

In order to obtain the best pH values, the samples of different P/M ratios were tested ranged from 1:1−1:1.75. The detail of all mixes is presented in Tab. 1.

The cement paste was prepared by mixing the solid components first in a dry form and then together with water to create a cement paste. For the good workability, the optimum w/c ratios of 0.25 and 0.3 were used for the specimens. The content was then poured into the molds of circular shape with a diameter of 50 mm. All the samples were demolded around a period of two hours (See Fig. 18). These samples were then tested for their pH value. The pH of cement paste was measured by a pH strip. The surface of the samples was cleaned and then the fresh water was dropped on it with a small plastic squirrel. After the 60 s the pH strip was inserted into the water on the surface. The colour of the strip was then compared to the colour chart. The pH was measured after 1 day, 4 days and 28 days.

Tab. 1. pH value for various MPC mixes tested in a range of 28 days.

Sample mix: 60 g of MPC, 18 g / 15 g water, 6 % of retarder					
P/M	B (%)	w/c	pH at 1 d	pH at 4 d	pH at 28 d
1:1	6%	0.25	6-7	7	7
1:1.5	6%	0.3	6-7	8	8
1:1.75	6%	0.3	6-7	8	8-9

P/M 1:1 P/M 1:1.5 P/M 1:1.75

Fig. 18. Samples of different MPC mixes.

Evaluation of pH

After evaluation of pH for different P/M ratios, the best results were obtained for the sample with the highest amount of phosphate. All results ranged from 6−9 pH over a period of time.

The following observation was made :

The general trend observed is that the pH value increases with the decreasing of P/M ratio. It was observed that with the time up to 4 days the pH gradually increases reaching a stable value at the age between 4 and 28 days. The resulting tests indicate that all mixes are suitable for the targeted pH of 5.5−8.5 with a slightly more alkaline solution for the ratio of 1:1.75.

4.5. Alteration of physical properties of concrete

Although microorganisms are good at adapting to their environments, certain conditions and material properties could be improved to help prompt biological development. The high surface rugosity with the macropore texture increases the ability of the wall to retain water on its surface and thus creating a moist environment supporting the floral growth. For these reasons, the porosity was the main physical property observed in my thesis.

Porosity

The pore structure of concrete is one of the most important characteristics of concrete with a strong influence on its mechanical properties, most notably the strength, elasticity and creep strains (Lian, Zhuge and Beecham, 2011). In general, we are trying to avoid pores in the concrete and create well-compacted concrete with low porous structure. For my purpose, I have the opposite aim. I want to create a porous structure for the better accumulation and retention of water on its surface. The porosity of concrete is influenced by several factors such as water-cement ratio, aggregate size distribution and inadequate compaction of a cement-based material. The main focus for pore characterisation was on the use of different aggregate sizes in the concrete mixture.

For my project, I prepared 6 samples with different grading curves (See Tab. 2 and Fig. 19). A concrete mixture of 1 litre was prepared from 500 g of cement, 1600 g of aggregates and 0.3 of w/c ratios for all samples. The size of aggregates was taken from 0−0.25 mm up to 3−4 mm. For these samples, I used OPC instead of MPC in order to save material and money for further manufacturing.

Tab.2. Variation of aggregates for concrete samples made from OPC.

Mixture (1L) : Cem I 42.5R - 500 g, water - 175 g, Plasticizer - 15 g					
Aggregate Size (mm)	**Weight (g)**	**Aggregate Size (mm)**	**Weight (g)**	**Aggregate Size (mm)**	**Weight (g)**
Sample 1		**Sample 2**		**Sample 3**	
3-4	-	3-4	-	3-4	-
2-3	160	2-3	320	2-3	480
1-2	480	1-2	-	1-2	-
0.5-1	480	0.5-1	640	0.5-1	640
0.25-0.5	320	0.25-0.5	400	0.25-0.5	320
0-0.25	160	0-0.25	240	0-0.25	160
Total	1600	Total	1600	Total	1600
Sample 4		**Sample 5**			
3-4	160	3-4	160		
2-3	480	2-3	480		
1-2	-	1-2	240		
0.5-1	480	0.5-1	320		
0.25-0.5	320	0.25-0.5	240		
0-0.25	160	0-0.25	160		
Total	1600	Total	1600		

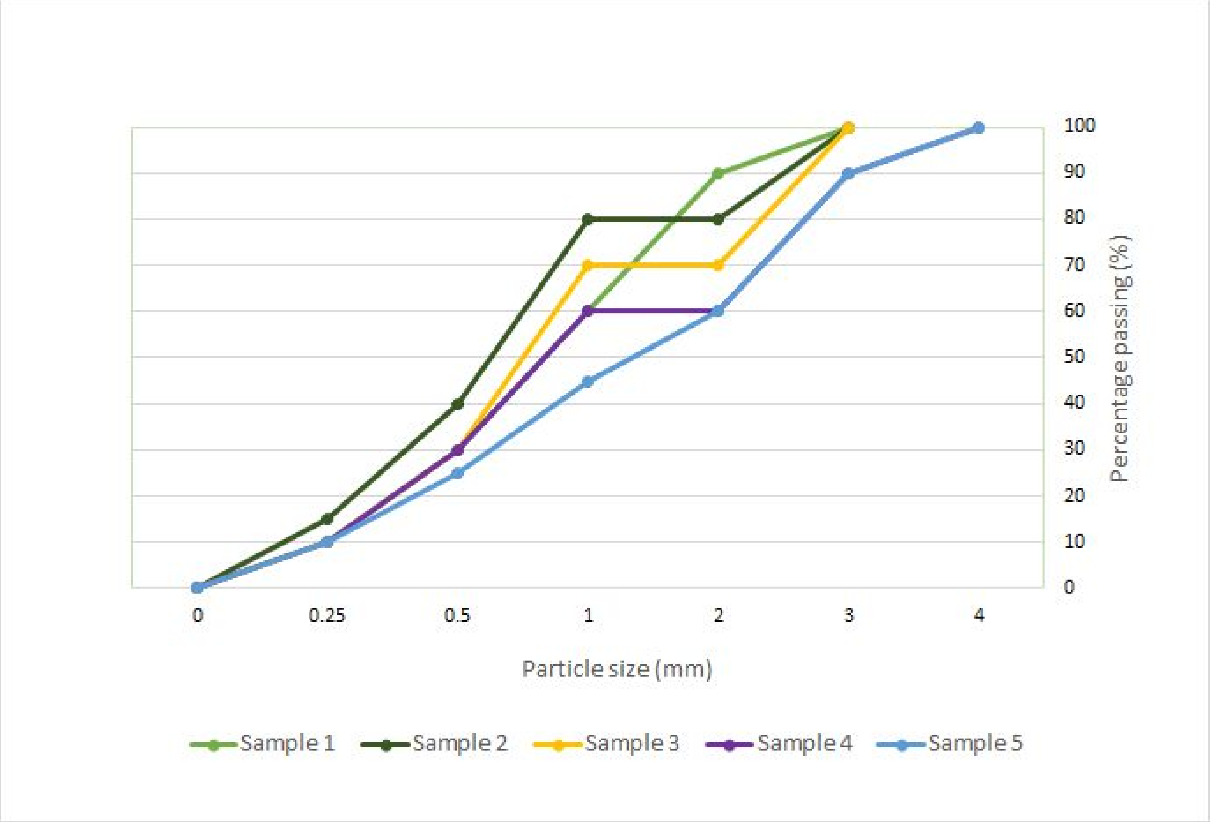


Fig. 19. Aggregate grading curves

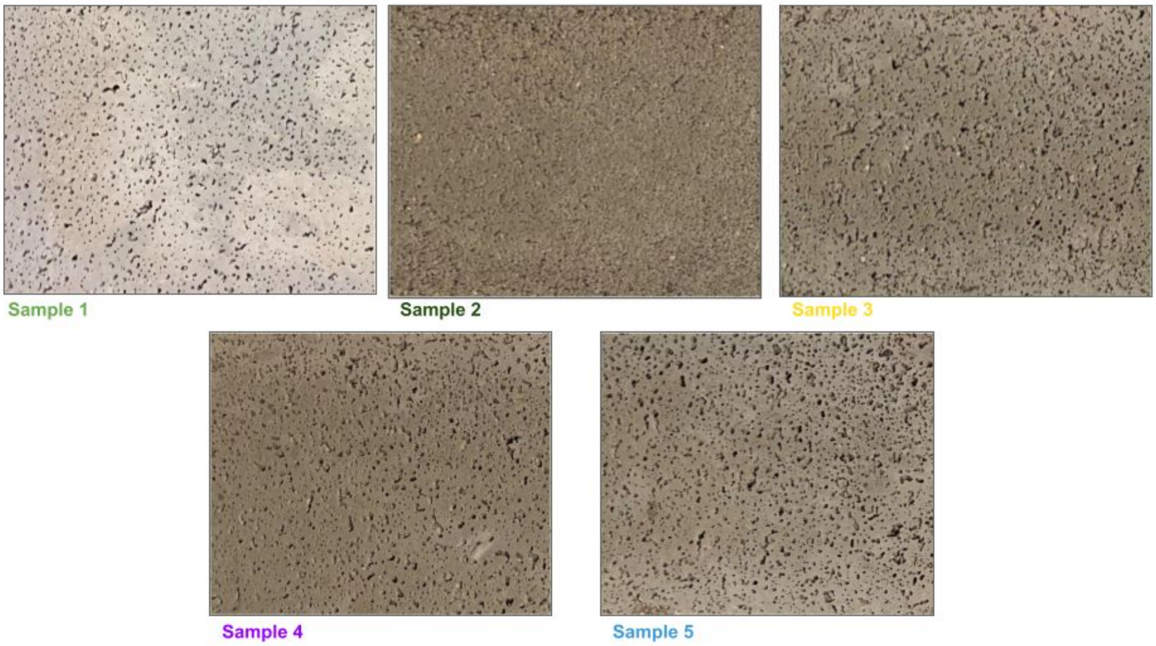

Sample 1
Sample 2
Sample 3
Sample 4
Sample 5

Fig. 20. Samples of concrete with different aggregate grading curves

From the sample analysis, it can be seen that the best results were obtained with the addition of aggregate size 3–4 mm. The highest porosity was reached in sample 4 and 5 with very similar results (See Fig. 20). After setting the grade curve of sample 4 as the most favourable option the sample from MPC was prepared.

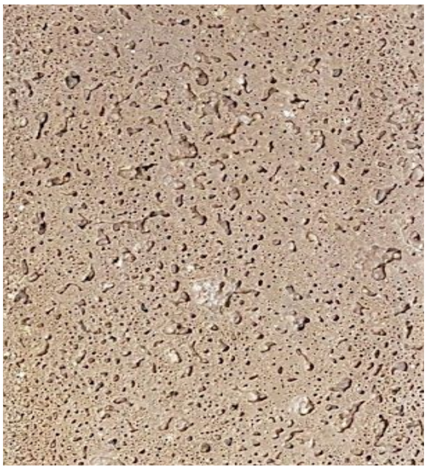


Fig. 21. MPC sample

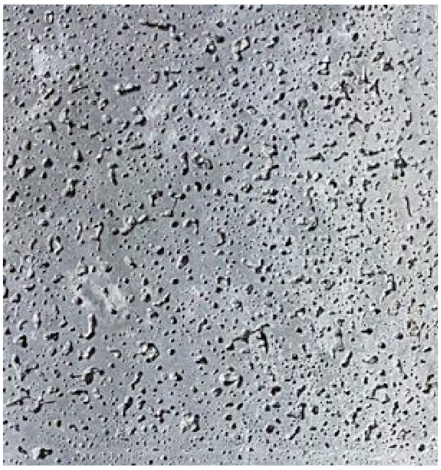


Fig. 22. OPC sample (sample 4)

From a comparison of OPC and MPC samples with the same aggregate size distribution, we can say that the behaviour regarding the porosity of MPC concrete is very similar to the one of OPC concrete (See Fig. 21 and 22).

4.6. Concreting of tiles

After setting all necessary values and proportion for concrete mixtures, I could proceed to the concreting of both tiles.

Standard tile: The first layer of MPC paste was poured. The substance had dry consistency and was spread across the tile form by hand, not to consolidate it much in order to maximize the porous structure. For the better bonding connection of two layers, the surface of MPC was roughened. After that, the second layer of OPC was poured on top of it. The anchor with bolt was embedded into the fresh concrete (See Fig. 23).

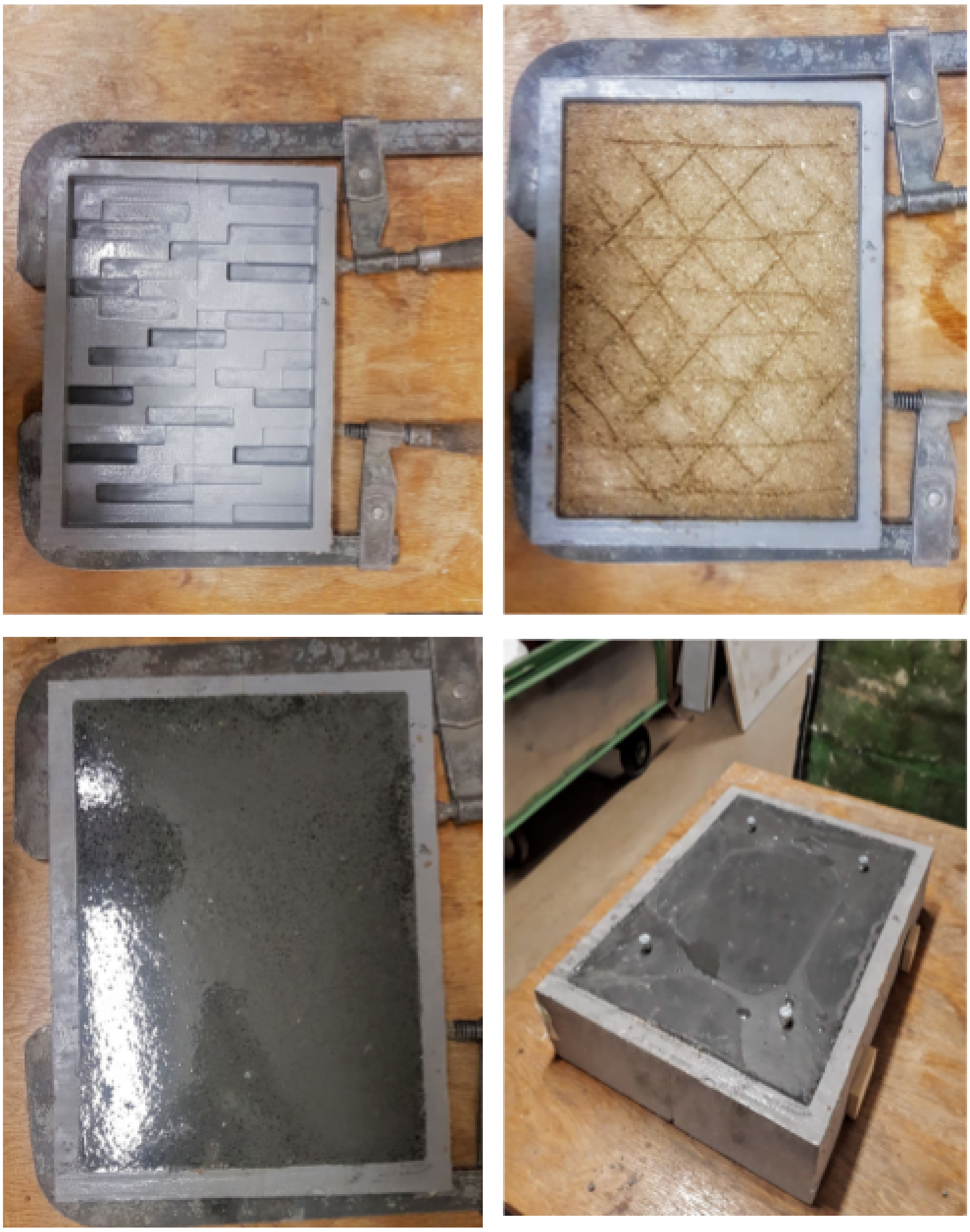


Fig. 23. Concreting procedure of Standard tile

Planter tile: The tile was concreted in a horizontal position. The first layer of MPC was placed into the silicon form. Right after, the XPS pocket form was placed and attached in the form, leaving a free space of 1 mm underneath. The mixture of OPC needed to be very fluid in order to fill the space beneath the XPS form. The problem became when the concrete was filling the space under the pocket form and at the same time started to uplift form from its position. As a result, an alteration of the form was necessary and the four points, for pressing and holding the form in the right position, were installed. This has created the four holes on the tile backside. Another problem becomes while unmolding the tile. The inner part of the tile form was not able to be taken off. Therefore, it was necessary to dig it out (See Fig. 24).

Fig. 24. Concreting and removing of Planter tile form

5. RESULTS

In the end, two types of bi-active concrete tile were fabricated.

Standard tile

Planter tile

Both tiles are made out of two-layered concrete. Layers can be distinguished due to their different colouring. The first layer made out of OPC with the reinforcement of dispersed PVA fibers has grey colour adjusted by the presence of microsilica. The second, bioreceptive layer of MPC mixture was successfully designed in order to support microorganism growth on its surface. The brown colour of the layer is due to the natural colour of MPC. The colour of tiles could be altered by concrete pigments, or by addition of microsilica.
The final parameters for both mixtures of concrete layers are shown in Tab. 3.

Tab. 3. Mixture proportion of two layers of concrete

1st layer	g/l	2nd layer	g/l
OPC	630	MPC	500
		M/P	1:1.5
w/c	226	w/c	150
aggregates	880	aggregates	1600
microsilica	60	Borax	6 %
limestone	200		
PVA fibres	10		
Plasticizer	30		

Porosity

From Fig. 26 porosity and roughness of the biorecaptive concrete layer can be clearly seen compared to the non-porous structural layer made out of OPC. The difference in aggregates composition of both layers is shown in Fig. 25. To achieved a suitable porosity of the outer concrete layer, the proportions of fine aggregates were modified and aggregates of 2−3 mm and 3−4 mm were added.

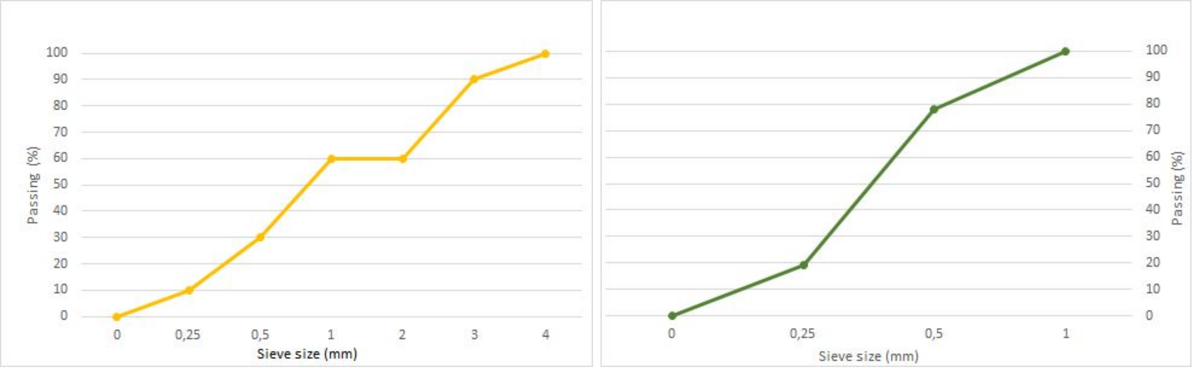


Fig. 25. Comparing aggregate grade curves of OPC and MPC concrete.

Fig. 26. Rough and porous surface of tile.

pH

Evaluating the pH value of concrete tiles resulted in expected values. The P/M ratio of 1:1.5 was used for cement mixture with 6% of Borax addition. The pH of 6−7 was achieved after 1 day and increased to a value of 8−8.5 in 4 days. After that, the pH has remained stable.

Discussion of production quality

As a result of complications during the concreting of Planter tile, few imperfections were detected (See Fig. 27). The OPC mixture did not entirely pass under the inner part of the tile form, creating a small area with only one layer of magnesium phosphate concrete.

Another unexpected result of concreting is the presence of four holes caused by fixing of inner form against the uplift. However, these holes could be used for anchoring of the tile as well for the drainage of water at the bottom of the tile.

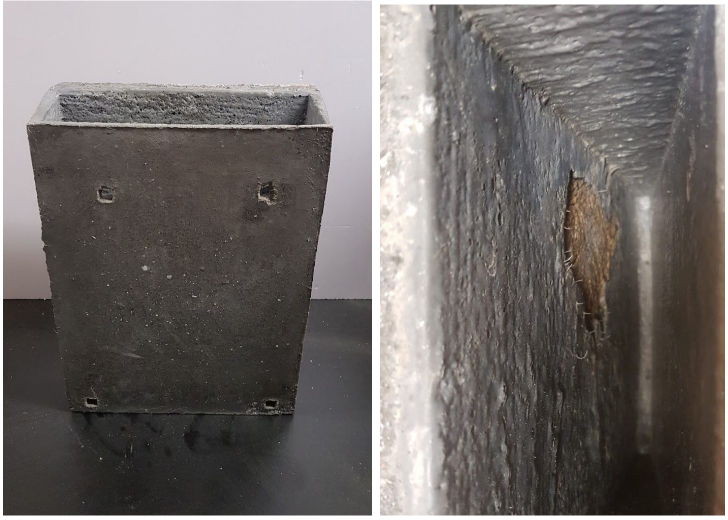


Fig. 27. Defects of Planter tile.

To overcome the problems in the future, an alternative solution for tile manufacturing is suggested (See Fig. 28.). The new inner part of tile form is hollow and made out of wood. The concreting of the tile will be proceeding in a vertical position for better form fixing and space controlling around the inner form.

Fig. 28. New form for Planter tile.

The tiles have been installed in the outdoor environment for observation of plant coverage development as well as to analysed the long-term performance of the tile. Further investigation would be necessary for evaluating the benefits of the entire wall composed out of the bio-active concrete tiles.

6. CONCLUSION

This project presents an alternative to the traditional green wall systems by designing and producing a bio-active concrete tile. The tile is made of two concrete layers, a structural (load-bearing) layer and a bioreceptive layer. Two types of a tile were designed. One is of the regular flat shape and the other serves as a plater enabling growth of variety of plants.

An environmentally driven design with a multileveled surface structure creates suitable niches for plant embedding and at the same time increases the ability of the climbing plants to adhere to the surface of the wall. Moreover, the combination of various elevated steps helps to retain and accumulate water necessary for bio-colonisation.

Regarding manufacturing of the tile moulds, the digital fabrication, which utilized CNC milling for shaping the XPS-based moulds, proved to be very effective and precise compared to the hand-made silicon forming which required tedious modification due the its imperfection. A disadvantage of the digital fabrication was its manufacturing dimensional limitations. The advantage was the precision of CNC milling which ensured desired angling the sides of the moulds so that the moulds could be reused for further concreting.

In order to produce a low-pH cementitious material, a special type of concrete binder, Magnesium Phosphate Cement, was used. The P/M ratios within the range used for the samples satisfied conditions of pH for microorganism growth. It is important to note that a decrease in P/M ratio leads to an increase in pH value. The P/M ratio of 1:1.75 showed a slightly higher pH value after 28 days than the rest of the concrete mixes, or mortars. Accordingly, the P/M ratio of 1:1.5 was selected to be used for the final mixture of the bioreceptive concrete layer.

An increased surface porosity and roughness was the result of the higher aggregate size addition, specifically, the aggregates of 2−3 mm and 3−4 mm. The high porosity and the roughened texture together with the modified chemical composition created an environment supporting the embedding and development of microflora. By allowing vegetation growth and retention of water on its surface, the tile would be a solution for improving the initial cost and the maintenance cost of green walls.

As for the future development, the tiles need to be further investigated in order to assess how much and how fast the bio-colonisation takes place.

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APPENDIX

Result: 2D stress/strain, principal stresses on the specific sections, Combination: ULS-Set B (auto)

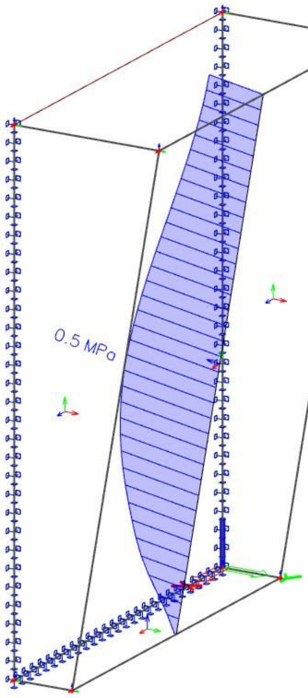

Fig. 1. Stress on section 1 at outer face

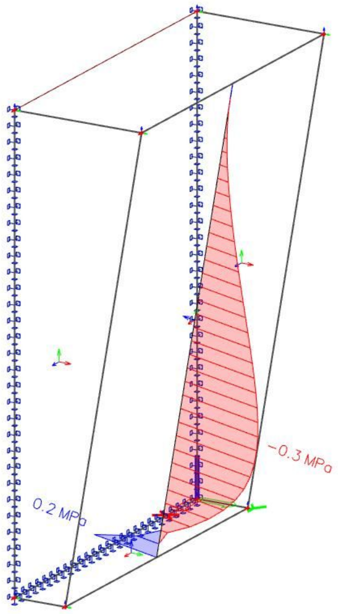

Fig. 2. Stress on section 1 at inner face

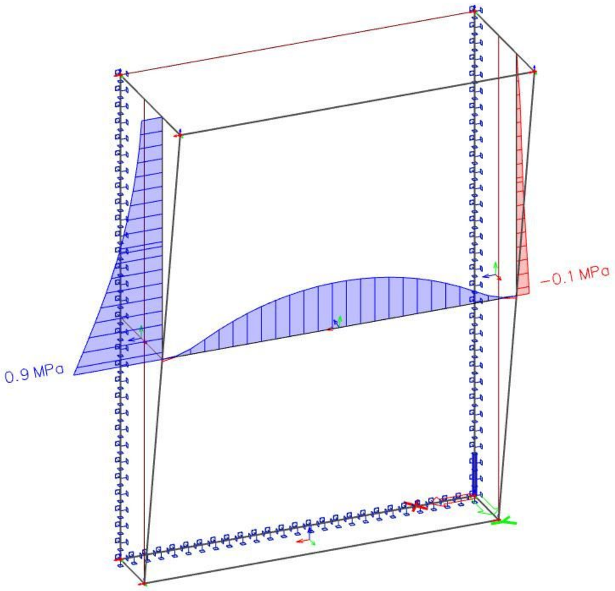

Fig. 3. Stress on section 2 at outer face

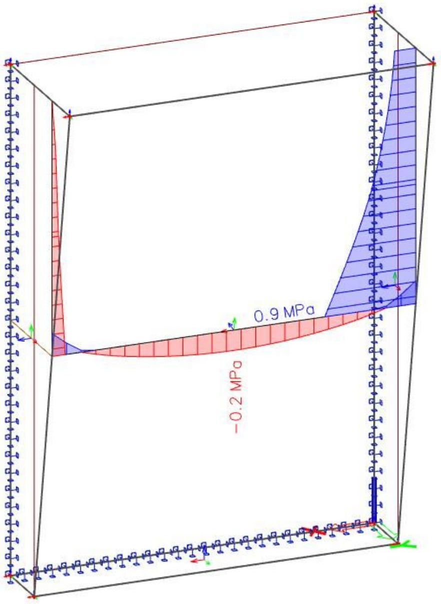

Fig. 4. Stress on section 2 at inner face